UNDERGROUND PUMPED HYDRO STORAGE
Flatland large-scale electricity supply

ONDERGRONDSE POMPACCUMULATIECENTRALE

Grootschalige elektriciteitsvoorziening voor een laag land
(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht
op gezag van de rector magnificus, prof.dr. H.R.B.M. Kummeling,
ingevolge het besluit van het college voor promoties
in het openbaar te verdedigen op
donderdag 20 september 2018 des middags te 12.45 uur

door

Johannes Marie Hubert Huynen

geboren op 18 juli 1932
te Valkenburg

Promotoren: Prof.dr. G.J. Kramer
Prof.ir.drs. J.K. Vrijling

DEDICATED TO
my guardian angel
Marjo †

incipit vita nova

Preface

I have sincere concerns that modern civilization is on its way to destroy our beautiful blue and green planet. Already, the quality of life is endangered by the extreme exploitation of our earth.

It is the obligation of everyone in this world to contribute to a change. We all share the responsibility of bringing about a cleaner environment and a more sustainable society, in order to preserve this planet for future generations, our children and grandchildren.

I have deep respect for the pioneers who initiate changes. Without them, we wouldn't have such promising technologies as wind and solar energy, electric cars, and smart grids. At the same time, questions haunt me. Such as how to power a society that never sleeps when there is no wind or sun. Or how sustainable and durable batteries in electric cars really are. And how batteries could provide economically substantial carbon-free storage power to the electricity grid in the long run. The answers to these questions will help the transition towards a more sustainable way of life, which is my first and foremost motivation for writing this monograph.

The second driver is the observation that there is insufficient awareness in scientific and engineering circles of the capabilities of pumped hydro storage. There is hardly any mention of its enabling force in the transition to a sustainable decarbonized electricity supply. It is surprising that the Dutch community of energy specialists "Watt Connects", with more than 1,000 members, is ignorant of the potential of hydro storage.

My academic fire was kindled by the eminent scientists Professor Gert Jan Kramer (Utrecht University) and Professor Han Vrijling (Delft University of Technology). Both inspired me years ago to document decades of research and development of an underground large-scale hydro storage project.

My academic motivation is not just to obtain a PhD degree. I earned one from the very same *alma mater* some 45 years ago. But, by writing about this challenging and inspiring subject, I hope to bring the realization of this innovative project closer. As this monograph shows, its technology is proven, its economics is sound and its funding is within reach. Underground pumped hydro storage is not only a flatland solution for a flat country. It is also a smart way of using the underground to preserve the surface of our dear earth – anywhere in the world.

Acknowledgements

First and foremost, I am deeply indebted to my supervisors, Professor Gert Jan Kramer and Professor Han Vrijling. Without their stimulating assistance and scientific guidance, this monograph would not have seen the light of day. Gert Jan, as a complete, sharp-witted scientist, has had the patience to explain complex processes and correct me where and when necessary. I owe him many thanks for sharing his keen insights. Also with Han – a highly experienced engineer and at the same time a fine economist – I had the benefit of a long-term training with a wealth of practical engineering advise. I want to express my deep feelings of gratitude to both.

From 1985 onwards, I had the privilege of working on the OPAC project in three consecutive study groups. I had a personal interest in this project, since I was at that time vice president of a major Belgian electromechanical manufacturer of pumped hydro installations, ACEC (Ateliers de Construction Électrique de Charleroi). In that period, Hans de Haan, project manager of OPAC and later CEO of Haskoning, introduced me to the secrets of pumped storage technology. I owe him my gratitude for his willingness to share his extensive civil engineering experience with me. The OPAC group consisted initially of Haskoning, KVS (Koninklijke Volkert Stevin), Aveco engineers, TH Delft (now Delft University of Technology), and Sogecom. A large team of specialized Dutch and German engineers, geologists and other specialists designed and developed the OPAC plan, which was coordinated by NEOM (Netherlands Energy Development Agency) and commissioned by the Ministry of Economic Affairs.

Of all who contributed in these early days of the plan, I would like to especially mention two visionaries. The Queen's Commissioner Sjeng Kremers and members of his administration visited the 1,800 MW PHS power plant in Dinorwig (Wales) and became convinced that OPAC could offer a unique opportunity for a bright energy future, replacing the lost prosperity of the then closed coal mines in South Limburg. Also the managing director of PLEM (Limburg Provincial Electricity Company) Frans van Eyndhoven, who passed away all too early, shared his expert vision as an electrical engineer. He carried out the first calculations for the revenue model.

In spite of all these efforts, Dutch Parliament decided in 1989 to abandon OPAC. The completed files about the design and construction of our energy storage plan consequently disappeared into archives, having lost their immediate relevance.

Only later did the contours of a fundamental change in power supply became visible, with an increasing role for sustainable sources such as wind and sun. In 2006, Hans de Haan (Royal Haskoning) and I took up the initiative to present the plans in an adapted form to the Ministry of Economic Affairs. This time, the plan was supported by the Queen's Commissioner Léon Frissen and Bert Kersten, member of the Provincial Executive. They deserve praise for their inspiring, sustained and public support. The then re-established study group consisted of Royal Haskoning, Hans de Haan, Leo Visser, Frank Wetzels, Lood van Velsen, along with Twan Arts and Wouter Muller of Sogecom, and Ruut Schalij, former Director of Corporate Development & Strategy for NUON. The provincial authorities assigned Professor Han Vrijling as an external advisor for his civil engineering expertise. This was the start of an inspiring relationship, which deepened my knowledge of the intricacies of this complex subject and eventually led to this monograph.

Moreover, the Province of Limburg supported the establishment of an independent foundation chaired by Jos Schneiders, with Jan Mans, Hendrik Tent, Ton Versteegh and Jacques van Geel as members. The province commissioned the chairman to complete a feasibility study of O-PAC. I am much indebted to them all. As geology is a crucial part of the O-PAC project, it was a great help to be able to deepen my knowledge of the geostructural aspects in cooperation with Professors Peter Kukla, Janos Urai and Christoph Hilgers (all from RWTH Aachen University), and Professor Christoph Clauser (E.ON Energy Research Center). Professor Hans Maks (Maastricht University) and Maurice Oude Wansink (OWP Research) provided valuable insights regarding the economic and Euregional effects. The partnership with Hochtief led to an intensive cooperation with Professor Christof Gipperich, whom I owe much gratitude during these difficult years of changing circumstances.

In the Dutch parliamentary debates on the liberalization of energy markets, O-PAC again rose to prominence on the agenda. Thanks to

MP Jos Hessels (CDA), a motion was adopted in 2008, supported by a broad majority, in which TSO TenneT is advised to facilitate large-scale storage.

DSM's chair Feike Sijbesma is a frontrunner of the industrial transition to sustainability. His inspiring and active support, by making DSM locations available, is highly appreciated.

In spite of the efforts of the King's Commissioner Theo Bovens and member of the Provincial Executive Patrick van der Broeck, political changes within the administration of the Province of Limburg ended the cooperation, and hence the plans had to be suspended again.

However, new challenges come to the fore, as recent national policy measures triggered further progress towards renewable energy. This new momentum led to the third incarnation of the project. The new O-PAC development team consists of Ruud Deckers, Twan Arts, Edwin Brouwers, Ruut Schalij and Guido Custers. The team collaborates with Wolfram Kagerer and other tunnel construction specialists from Müller + Hereth Ingenieurbüro für Tunnel- und Felsbau. One of their main tasks was to update the construction costs. These calculations are essential for attracting investors, and their efforts are the reason for me to extend my warmest thanks to all involved.

I appreciated the discussions and the help of Peter Martens, Roland Starmans, Leo Holwerda, and Bert Mulders of NIA (Netherlands Investment Agency). I also thank general director of Sustainability and Environment Peter Struik of Rijkswaterstaat, Ministry of Infrastructure and Environment, and his team for the open-minded discussions about large-scale storage technology.

In the last and probably most decisive phase, I enjoyed the professional discussions with Lucas Pollemans and Frans Nillesen, both from Netherlands Enterprise Agency, and Mart van Bracht and Ed Buddenbaum, both from Topsector Energy, as well as geologist Serge van Gessel from TNO, Frits van der Velde from VEMW, Mark van Stiphout from the Directorate-General for Energy (European Commission), Hans van der Spek from FME, Frits de Groot from VNO and Meindert Smallenbroek from the Ministry of Economic Affairs and Climate Policy.

During recent years, a great number of persons have sympathized with O-PAC out of various considerations, and foremost among these has been investment specialist Gert Jan Staal. We also experienced support from Belgium, from energy engineers Patrick Lafontaine and Jacques Schittekat. From Limburg, support was received from leading organizations and persons such as Jan Zuidam, Boy Litjens, Frans Weekers (EBRD), Paul Hamm, Gosse Boxhoorn, Koos van Haasteren, Roy op het Veld, Jacques D'Elfant, and last but not least, Professor Luc Soete, former Rector of Maastricht University. I am very grateful for their enthusiasm, which I hope will result in the realization of this ambitious project. Over the years, a great many other people shared their ideas with me; I apologize that I cannot mention them all. Be assured that I appreciated all contributions and ideas, big and small.

Having been a general aviation pilot for some 40 years, I know the concentration it takes to prepare an aircraft for landing. It is teamwork, but the captain takes the controls and responsibility for a safe landing. This metaphor reminds me how I feel in the final phase of this thesis. In my imaginary cockpit, the first pilot is Twan Arts and the flight engineer is Leendert Corbijn. Because it is a long-haul flight, there is a backup crew consisting of Ruud Deckers, Ruut Schalij and Edwin Brouwers, whilst the technical support is provided by Bram Vermeer, Joezio Skrobiszewski and Brian Wright. They all contributed to a good flight and a safe landing. Moreover, a pleasant stay on board is important, which is in the hands of our purser Marjan Huynen, who contributed more to a soft landing than anyone can imagine.

Finally, every flight needs proper guidance, therefore the survey on the tower is secured by the flight controllers Gert Jan Kramer and Han Vrijling.

Thanks for flying with me.

CONTENTS

Preface 7

Acknowledgements 9

1 **INTRODUCTION** 17
1·1 Elevations in a flat country 17
1·2 Underground pumped hydro storage in a decarbonizing electricity system 21
1·3 Approach 22
1·4 Key definitions: flexibility, balancing, volatility, arbitrage 23
1·5 Structure of this thesis 25

PART I The problem: Intermittency of variable renewable energy supply 29

2 **ELECTRICITY POLICIES OF THE NETHERLANDS –STATUS AND OUTLOOK–** 31
2·1 Key characteristics of the Dutch electricity system 31
2·2 Dutch energy policies 35
2·3 Dutch electricity sector policies and flexibility measures 43
2·3·1 Cross-border connections 43
2·3·2 Demand-side management 46
2·3·3 Decentralized storage: households 48
2·3·4 Decentralized storage: electric vehicles 50
2·3·5 Thermal backup capacity: coal and gas 56
2·4 Concluding remarks 59

3 **PRINCIPLES AND TYPOLOGY OF STORAGE** 61
3·1 Introduction 61
3·2 History of storage 61
3·3 Basic operation of electricity storage 63
3·4 Electricity storage solutions 64
3·4·1 Mechanical storage 65
3·4·2 Electrochemical storage 73
3·4·3 Electrical storage 77
3·4·4 Chemical storage 79
3·5 Characteristics of storage 80
3·5·1 Power and discharge duration 81

3·5·2 Time-to-grid and self-discharge 82
3·5·3 Lifetime and efficiency 83
3·6 SURVEY OF APPLICABILITY 84
3·7 SURVEY STATUS AND ELECTRICITY STORAGE DEVELOPMENTS 2030 – 2050 88
3·8 CONCLUDING REMARKS 92

4 PUMPED HYDRO STORAGE 93
4·1 INTRODUCTION 93
4·2 THEORETICAL BACKGROUND OF PUMPED HYDRO STORAGE 97
4·2·1 Energy and power output 97
4·2·2 Efficiency 98
4·2·3 Head capacities 98
4·3 LAYOUT AND OPERATING PRINCIPLES 102
4·3·1 Pumped hydro storage design 103
4·3·2 Pumped hydro storage electromechanical typology 105
4·3·3 Turbine technology 113
4·4 BASIC AND ANCILLARY SERVICES 120
4·5 DEVELOPMENTS IN PUMPED HYDRO STORAGE 125
4·6 PROJECT INVESTMENT COSTS OF PHS PLANTS 139
4·7 CONCLUDING REMARKS 142

PART 2 An innovative contribution to a sustainable solution: underground pumped hydro storage 143

5 O-PAC STUDY 145
5·1 INTRODUCTION 145
5·2 MINING HISTORY OF SOUTH LIMBURG 147
5·3 GEOLOGICAL CONDITIONS 148
5·3·1 Core drilling results 150
5·3·2 Suitability of the subsurface 156
5·4 LOCATION SELECTION IN THE TARGET AREA 163
5·5 GEOTHERMIC CONDITIONS 164
5·5·1 Influence on process water 165
5·6 CONCLUDING REMARKS 167

6 DESIGN AND CONSTRUCTION OF O-PAC 169
6·1 INTRODUCTION 169
6·2 PRINCIPLES OF UNDERGROUND CONSTRUCTION METHODS 172
6·2·1 Design and layout of the machine hall 175

6·2·2 Design and layout of the underground reservoir: caverns 178
6·2·3 Design and layout shafts: wet shafts, dry shafts 183
6·3 SELECTION OF PUMP-TURBINES 187
6·4 TRANSPORT; VERTICAL AND HORIZONTAL 188
6·5 UPPER RESERVOIR 191
6·6 HEALTH, SAFETY AND ENVIRONMENTAL ASPECTS 192
6·7 REFLECTION ON SITE-SPECIFIC ASPECTS 194

7 **COST-BENEFIT ANALYSIS** 197
7·1 INTRODUCTION 197
7·2 SUMMARIZED MARKET PROGNOSES 198
7·2·1 Electricity price 198
7·2·2 Frequency control reserve price 201
7·3 REVENUE MODEL FOR O-PAC 205
7·3·1 Energy arbitrage 205
7·3·2 Control reserve 209
7·3·3 Additional ancillary services 211
7·3·4 Total revenues for O-PAC 213
7·4 O-PAC COSTS OVERVIEW 216
7·4·1 Estimated construction costs 216
7·4·2 Capital costs 219
7·4·3 Operation and maintenance costs 220
7·5 INVESTMENT 221
7·5·1 Investment structure 221
7·5·2 Project financing 222
7·6 LEVELIZED COST OF STORAGE 222
7·7 REMARKS AND CONCLUSIONS 225

8 **SOCIO-ECONOMIC EFFECTS** 227
8·1 INTRODUCTION 227
8·2 CONCENTRIC ANALYSES APPROACH 228
8·3 MACROECONOMIC EFFECTS 230
8·3·1 Employment effects: direct/indirect 230
8·3·2 Investment effects 231
8·3·3 Geographical distribution of effects 232
8·4 SOCIETAL BENEFITS 234
8·4·1 Security of supply 235
8·4·2 Supporting sustainable energy 237
8·4·3 Potential CO_2 emission reduction 238

8·4·4 Facilitating affordable energy 239
8·5 INNOVATION EFFECTS: SPIN-OFF 240
8·6 CONCLUSIONS 242

9 LARGE-SCALE STORAGE IN THE FUTURE ELECTRICITY GRID 243
9·1 INTRODUCTION 243
9·2 SUPPLY SIDE OF THE DUTCH POWER SYSTEM 243
9·2·1 Electricity grid 243
9·2·2 Installed power in the future 246
9·2·3 Capacity factor: history and projection 246
9·2·4 Residual load 248
9·3 SOLUTIONS FOR SUPPLY-DEMAND MATCHING 250
9·3·1 Conventional power plants 251
9·3·2 Interconnection 251
9·3·3 Smart grids in the future power system 252
9·3·4 Large-scale electricity storage 257
9·3·5 Power-to-gas 258
9·4 CASE STUDY: GERMAN PARADOX 259
9·5 LARGE-SCALE STORAGE IN THE NETHERLANDS 261
9·6 CONCLUSIONS 263

10 CONCLUSIONS AND DISCUSSION 265

Summary 272

Samenvatting 288

References 306

Curriculum vitae 330

Abbreviations 332

Appendix I – Identification of potential locations for U-PHS: Denmark 338

Appendix II – Table of PHS plants larger than 500 MW 346

Appendix III – Motion Hessels c.s. 350

1 Introduction

This monograph discusses the technical and economic potential of underground pumped hydro storage (U-PHS) for the transition to a low-carbon energy system.

Energy storage will play a key role in enabling the further deployment of variable renewable power sources, such as electricity from wind and sun. U-PHS has been proposed for many decades and it is, as this thesis will make clear, a valuable addition to the available energy storage technologies. It is remarkable how infrequently U-PHS is mentioned in the literature. This study intends to remedy this and give U-PHS the place it deserves.

This monograph illustrates the potential of U-PHS through a Dutch case study (in Part Two). Therefore, special emphasis is on the Dutch energy transition and its European context.

1·1 Elevations in a flat country

The eventual transition from fossil fuels to a carbon-neutral power system is widely seen as a necessity. This insight came only gradually and the arguments for it have shifted over time. From the middle of the 20th century, the depletion of natural resources, pollution and population growth were discussed, as marked by the report "The Limits to Growth" (Meadows, et al., 1972). Though not all conclusions of this study were accepted at the time, it contributed to the awareness of the need for drastic changes in human behaviour. The effects of fossil fuels on the global climate became gradually clear during the subsequent decades.

From 1988 onwards, the IPCC (Intergovernmental Panel on Climate Change) has provided scientific guidance on climate change and its environmental, economic and societal impacts. Based on its findings, the UNFCCC (United Nations Framework Convention on Climate Change) was established in 1992 with the objective of the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 1992).

In the following two decades, the yearly Conference of the Parties (COP) failed to deliver a binding, global climate treaty. Eventually, on 12 December 2015, a breakthrough was reached with the first comprehensive climate agreement at the UN Climate Summit (COP21) in Paris, signed by 194 countries. Over the course of 2016, it was ratified by a qualified majority and the agreement thereby became binding on 4 November of that year. The main objective of the 'Paris agreement' is: "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (United Nations, 2015). This requires a drastic reduction of global greenhouse gas emissions over the next decades, resulting in nett zero emissions by 2050. In order to reach this goal, all countries have committed to nationally determined contributions (NDCs).

The commitments of the Netherlands, as a signatory of COP21, translate into a transition from its 95 % fossil-fuelled energy system to near-zero CO_2 emissions. Anticipating this, 47 parties concerned signed the "Energieakkoord voor duurzame groei" (Energy agreement for sustainable growth) in 2013 (SER, 2013). The Dutch government presented a sketch for the future energy policy for the period until 2050 in "Energierapport, transitie naar duurzaam" (Energy report, transition towards sustainable, January 2016), followed by the "Energieagenda, naar een CO_2-arme energievoorziening" (Energy agenda, towards a low-CO_2 energy supply, December 2016) with ambitious goals for 2030 and 2050. Dutch energy policies will be further explored in Section 2.2. (Energierapport, 2016; Energieagenda, 2016).

The transformation of the electricity system is a substantial part of the transition of the entire energy system. This can be clearly seen from these reports, agendas and agreements, both at the global and at the national levels. As the energy transition unfolds, the relative importance of electricity will become even larger, as technological advances further the electrification of industries, buildings and transport.

An uninterrupted power supply is fundamental to a developed society. It has always been difficult to secure this. Power supply has to match demand closely. In spite of the complexity of this task, most Western societies have proven capable of maintaining a reliable and affordable power supply. This is achieved almost entirely by dispatching fossil energy instantly to match market demands. As more intermittent, non-dispatchable renewable sources are used for power generation, these practices need to be overhauled. This will challenge the reliability and affordability of the electricity system.

As part of Dutch energy policy, measures are taken to guarantee the reliability of the power supply. These include extra cross-border grid connections, demand-side management and decentralized electricity storage by households and electric vehicles. These measures still assume that gas-fired power stations – eventually 'mothballed' as spare capacity – can join in when wind and sun generate insufficient power. Coal-fired power plants with carbon capture and storage to remove most CO_2 emissions are another potential backup. A report by Frontier Economics, commissioned by the Dutch Ministry of Economic Affairs, Scenarios for the Dutch electricity supply system (2015), states therefore that no power shortage will occur over the next decade (Frontier Economics, 2015).

The question arises, whether the CO_2 emissions of this spare capacity will be low enough to meet the 2050 targets. Neighbouring countries doubt this for their own energy systems and consider additional backup to guarantee a continuous electricity supply.

Globally, pumped hydro storage is the dominant technology to store energy. It uses a water reservoir at elevated heights to store a surplus of electricity supply and eventually releases it to generate electricity when there is a supply shortage. This technology accounts for 99% of all grid-connected storage, with an installed power of 141,799 MW (IRENA, 2015). Pumped hydro storage also allows for much longer storage than other technologies – hours or days rather than minutes or seconds.

The Netherlands is almost flat and lacks elevated locations suitable for pumped hydro storage. The Dutch government therefore sees no alternative to gas- and coal-fired backup capacity (Energierapport, 2016). However, there is a viable and carbon-neutral way to store energy, based on pumped hydro storage, that is tailored to the Dutch situation, with a large capacity, using proven technology. This study presents such a system for large-scale storage in the Netherlands.

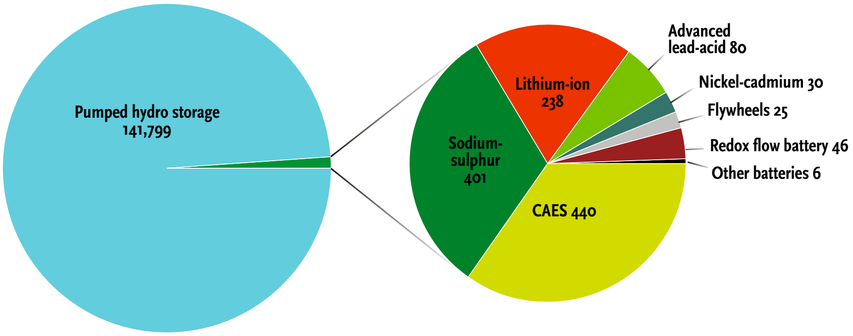


***Figure* 1 –** *Current globally installed power of grid-connected storage (MW) (IRENA, 2015)*

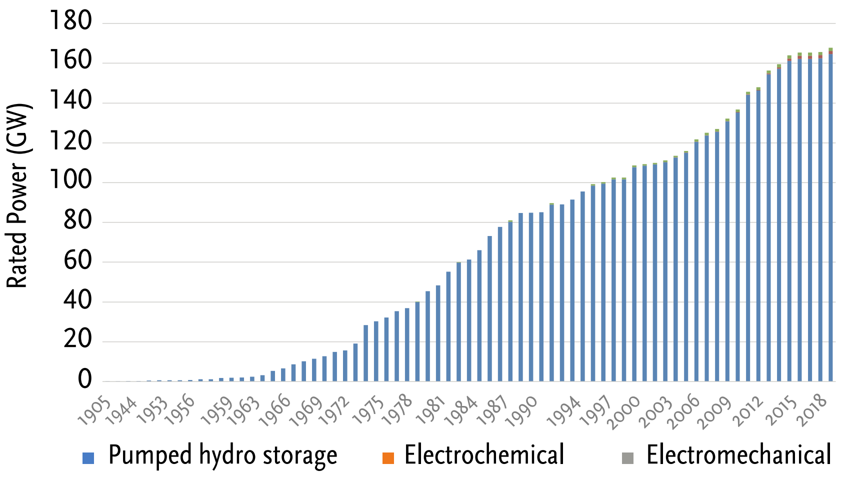


***Figure* 2 –** *Cumulative installed and projected global storage power over time (US DOE, 2016)*

The solution is to use underground water reservoirs for pumped hydro storage. This has been suggested in the past. A Dutch study group assessed this idea in the 1980s. An exploratory study was performed (OPAC-Prolongatiestudie, Hoofdrapport September 1987. NEOM, Delft University of Technology, Haskoning and Koninklijke Volker Stevin) to sketch a storage facility with an output of 1,400 MW, which was called OPAC (for Ondergrondse Pomp Accumulatie Centrale, or Underground Pump Accumulation Plant). The study covered the technical aspects from engineering to construction and operation. To be feasible, a suitable homogeneous rock formation at an adequate depth turned out to be a conditio sine qua non. These conditions were found in the south of the Netherlands. The study also assessed environmental constraints, licenses, permits, and financial feasibility.

This monograph takes the OPAC idea a step further with a comprehensive study of all aspects needed to use it as the launching project for U-PHS technology. If implemented, it would represent a 'flatland pumped hydro solution'.

U-PHS, however, is in no way limited to flat regions. It could present a generic solution for energy storage worldwide. New reservoirs are difficult to realize, as suitable locations are often found in environmentally vulnerable, mountainous locations (Die Bundesregierung, 2016). U-PHS does not disturb sensitive natural landscapes and may be an attractive alternative – provided a suitable geologic subsurface structure is in place, and a number of other conditions are met. Principal among these are a sufficient demand to store an energy surplus (e.g. from variable renewable electricity) and consumers that value an uninterrupted power supply.

1·2 Underground pumped hydro storage in a decarbonizing electricity system

The central hypothesis of this monograph is:

Surpluses and shortages of renewable electricity production will occur frequently and it is our expectation that the planned CO_2-free balancing technologies and measures will not be sufficient, and will demonstrate a considerable discrepancy, inescapably leading to the use of a fossil-fuelled backup, which will be counterproductive to the agreed CO_2 emission reduction targets.

This monograph explores whether U-PHS would significantly contribute to resolving intermittency problems in the Netherlands and assesses its role as an enabling technology for renewable power generation in the Dutch electricity grid from 2023 onward.

Related to the central hypothesis, the following issues will be explored:

1. *Which technologies and policy measures offer the potential to meet the demand for flexibility and what is their impact on sustainability?*
2. *How do the characteristics of different storage systems compare to the alternative of U-PHS, both in terms of environmental sustainability and economic considerations?*
3. *Under what conditions is an (optimized) U-PHS in the Netherlands technically, economically and financially feasible?*
4. *What are the restrictions and obstacles to be addressed to realize a U-PHS?*

These questions will be addressed as follows:

re 1. The questions related to policy measures will be considered in Chapter 2; the impact on sustainability in Chapter 8.
re 2. The different storage systems are the subject of Chapter 3, whilst aspects of sustainability and economics are covered in Chapter 8.
re 3. This is the subject of Chapters 6 to 9.
re 4. The constraints and obstacles are addressed in the Chapters 2, 7 and 9.

1·3 Approach

In science and technology, there is an ongoing discussion about the complementarity of a reductionist approach, isolating phenomena and studying them to the highest degree of specialization, and the multidisciplinary study of complex systems, in which many different phenomena are strongly interrelated (KNAW, 2011). This thesis does not reduce the study of U-PHS to one or two aspects. It does not aim at deepening scientific insights in one specific field. Instead, it takes the complexity approach, integrating such fields as mining technology, geology, civil engineering, mechanical engineering, electrical engineering and combining such factors as safety, finance, trade, marketing and law. The merit of this study is the cross-sectional application of different specialisms. In short, this thesis is about systems and designs. It uses state-of-the-art knowledge to design a novel storage system and the pathways to its implementation.

This is why the questions in Section 1.2 are addressed in the following manner:

- case studies
- cost-benefit analysis (based on investment calculation and a quantitative revenue calculation model)
- concentric cost-benefit analysis (in which societal and macro-economic effects are assessed)
- capacity factors analysis (based on the National Energy Outlook 2017 and historical data from Statistics Netherlands)

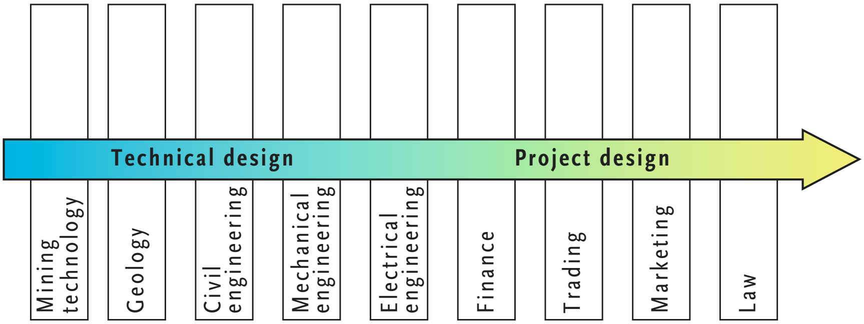


Figure 3 – *An illustration of the cross-disciplinary approach taken to design, assess and propose the pilot O-PAC project*

1·4 Key definitions: flexibility, balancing, volatility, arbitrage

There is some ambiguity in the terminology used to describe electricity grid management. Different definitions are used for the same terms in both the scientific and non-scientific literature. To avoid confusion, this monograph will apply the following definitions, all framed specifically for the context of this work.

Flexibility: *The technical ability to even out differences between the supply and demand of electricity, both foreseen and unforeseen, with a duration of seconds to hours or even months.*

This definition thus focuses on large storage capacities. The definition is in tune with the shorter and more abstract definition used in the FLEXNET project (2017): "Flexibility is the ability of the energy system to respond to the variability and uncertainty of the residual power load within the limits of the electricity grid" (ECN, 2017a).

Flexibility is essential to accommodate a larger share of variable power sources in the grid. As an IEA report put it: "Flexibility is a known need of primary importance in the planning and operation of power systems to ensure demand is reliably served, and yet it is not systematically assessed" (IEA, 2011).

The *valuation* of flexibility is also of great importance. In the abstract, it is easy to note that flexibility represents value, but in order for investments in flexibility to be made, flexibility has to materialize in products or services. Further, the market must recognize its value and regulations must allow flexibility services to be provided.

Balancing: *All the processes and measures aimed at the equalization at any time of power supply and demand, thereby providing for a stabilized energy system (TNO, 2015).*

Balancing can be considered as the application of flexibility options. Transmission system operators (TSOs) are responsible for balancing supply and demand in real time, using regulating power.

The balancing market (also called imbalance market) is a mechanism aimed at connecting electricity sources and sinks in case of shortages and surpluses. The degree of imbalance is an important factor in the price-making process for electricity.

Volatility: *The degree to which prices vary over time.*

Prices vary over many time scales (minutes, hours, days, months), and volatility is relevant (and possibly different) at each of these. For the calculation of volatility, the standard deviation is divided by the average electricity price.

Variable sources in the electricity system affect the prices in two ways (Frontier Economics, 2015):

- Prices will peak when in-feed from wind and solar electricity is low but electricity demand is high, e.g. early on winter evenings, when the sun has set, but domestic demand is still high.
- Prices are very low or even negative when feed-in from wind and solar electricity is high but demand is low, e.g. at night on a very windy weekend.

Arbitrage: *The application of energy trading strategies within an electricity market, with the aim to buy energy from the grid at a low price and to sell it back to the grid at a significantly higher price.*

In economics and finance, arbitrage is the practice of taking advantage of a price difference between two or more markets that differ in time or in place: striking a combination of matching deals that capitalize upon the imbalance, the profit being the difference between the market prices (Zafirakis, et al., 2016).

Summarizing, Figure 4 shows how the above definitions are interrelated in the context of the power system and the power market.

Action	Balancing	Arbitrage
Mitigational design	Flexibility	Market (re)design
Problem	Intermittency	Price volatility
	Power system	**Power market**

Figure* 4 – *Interrelation of terms

1·5 Structure of this thesis

Part One – The problem: Intermittency of variable renewable energy supply

Chapter 2 reviews Dutch energy policies, as this is the context in which the U-PHS technology is considered. The emphasis is on the integration of variable renewable electricity into the Dutch grid. The Dutch electricity system is represented by stakeholders such as the power, transport and distribution industries.

Chapter 3 reviews storage technologies, analysing various mechanical, electrochemical and electrical systems. Future developments of each of these system types will be assessed, with time horizons and scales on which they can be deployed. As the value of U-PHS lies in its scale (power > 100 MW; capacity > 600 MWh), special attention is given to large-scale storage. A detailed analysis is made of the advantages and drawbacks of relevant systems, drawing on such characteristics as capacity, loading and unloading specs, useful life, ramp-up times, rated power, grid integration, and applicability in relation to the energy supply mix.

In **Chapter 4**, pumped hydro storage is examined in greater detail, paying particular attention to its characteristics and ancillary services. It is shown that pumped storage solutions have proven their efficiency and reliability for more than a century in mountainous regions.

Part Two – An innovative contribution to a sustainable solution: Underground pumped hydro storage

Chapters 5 and 6 analyse the geology, technology, design, and construction of U-PHS. This constitutes the core of this monograph. It is shown how geological conditions determine underground constructions. **Chapter 7** shows the cost-benefit analysis for electricity storage with U-PHS related to the investment required for its construction.

Chapter 8 completes the system design considerations with an analysis of its techno-economic and socio-economic aspects. The implications for CO_2 emission reduction are discussed, with particular emphasis on the role of fossil fuels for balancing purposes.

Chapter 9 gives a further outlook with a discussion of the role of large-scale storage in the future electricity grid and the constraints and obstacles that need to be addressed to realize a U-PHS facility.

Conclusions are drawn in **Chapter 10**.

Figure 5 shows how the different chapters refer to policies, the market and other aspects of the electricity system.

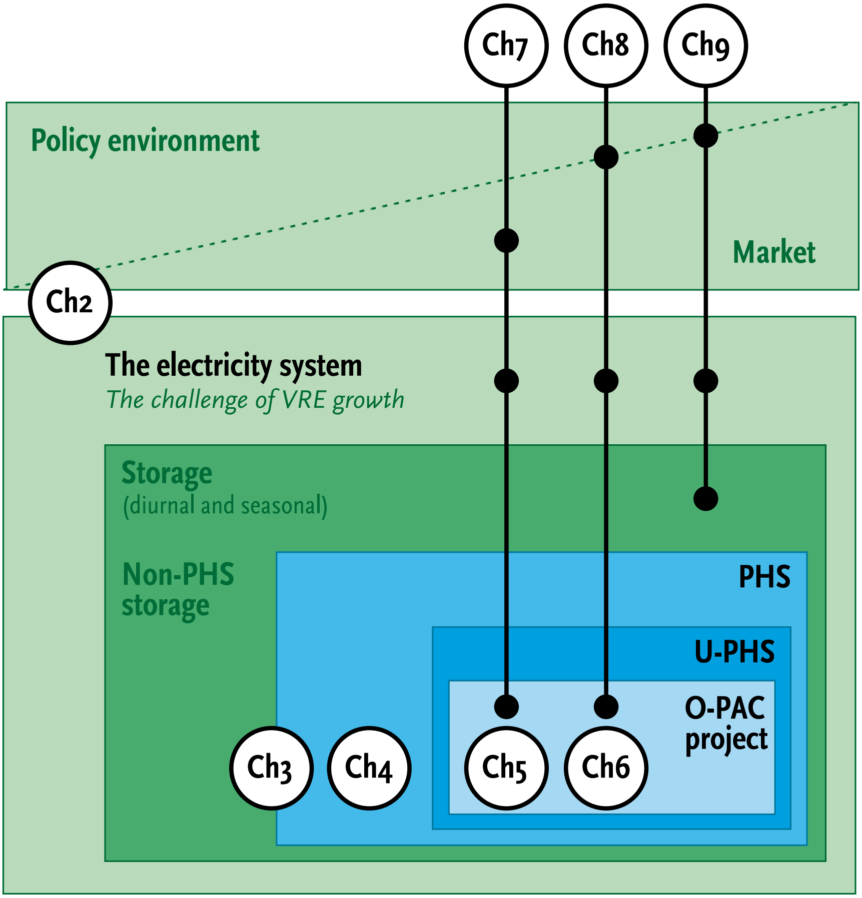


***Figure* 5 – The structure of this monograph**

PART I

PART ONE – The problem: Intermittency of variable renewable energy supply

This part discusses the intermittency of wind and solar electricity in the context of the Dutch power system. It is shown that continuity of the power supply cannot be guaranteed if the share of variable renewable electricity increases as planned. Additional measures are discussed with an emphasis on storage techniques.

Chapter 2 surveys Dutch energy policies and their challenging targets. It is shown that market forces alone will not be able to transform the entire energy system and abandon fossil fuels almost completely. As more intermittent power sources enter the system, imbalances between demand and supply need to be resolved in new ways.

In **Chapter 3**, different mechanical, chemical and electric storage technologies are presented. These are discussed in the Dutch context.

In **Chapter 4**, principles and characteristics of PHS are described. This is relevant for underground PHS (U-PHS) too, as it generally has many characteristics in common with conventional PHS, such as pump and turbine technologies. Investments in PHS projects and innovative PHS solutions are also discussed.

2 Electricity policies of the Netherlands –status and outlook–

The purpose of this chapter is to analyse the structure and status of the Dutch power system. It is shown that power sources have historically been dominated by coal and gas. Attention is also paid to the current balancing strategies in relation to ramp-up and ramp-down times. Moreover, the consequences of the planned extension of VRE for flexibility are discussed. It is shown that a large-scale U-PHS system could provide the necessary extra flexibility. Finally, the question will be addressed whether current energy policies will be effective in meeting the CO_2 reduction goals.

2·1 Key characteristics of the Dutch electricity system

The Netherlands has traditionally been strongly dependent on gas-fired electricity generation. The origin of the role of natural gas in the electricity mix was the discovery – in the 1950s – of the Groningen gas field, a huge reserve of 2,700 billion m^3. Later, this was followed by sizeable finds under the North Sea. In 2015, the share of gas-fired power generation was 41.7 %, down from 60 % a decade earlier (CBS, 2017). Hard coal represents an equally substantial part of electricity generation, based on the presence of major coal import ports in Rotterdam, Amsterdam and Antwerp. The low price of coal has resulted in an increased share (35.9 % in 2015) in electricity production, with a corresponding decrease in gas–fired electricity generation. Therefore, the Dutch power plant fleet is dominated by (circa 80 %) fossil-fuelled supply. Completing the total electricity supply mix, nuclear energy accounts for 4 % of power generation, all from a single plant, the 485 MW Borssele reactor, while a growing share comes from VRE: 7.9 % in 2015 (see Figure 6, which represents a specification of the total Dutch electricity supply from 1998-2016).

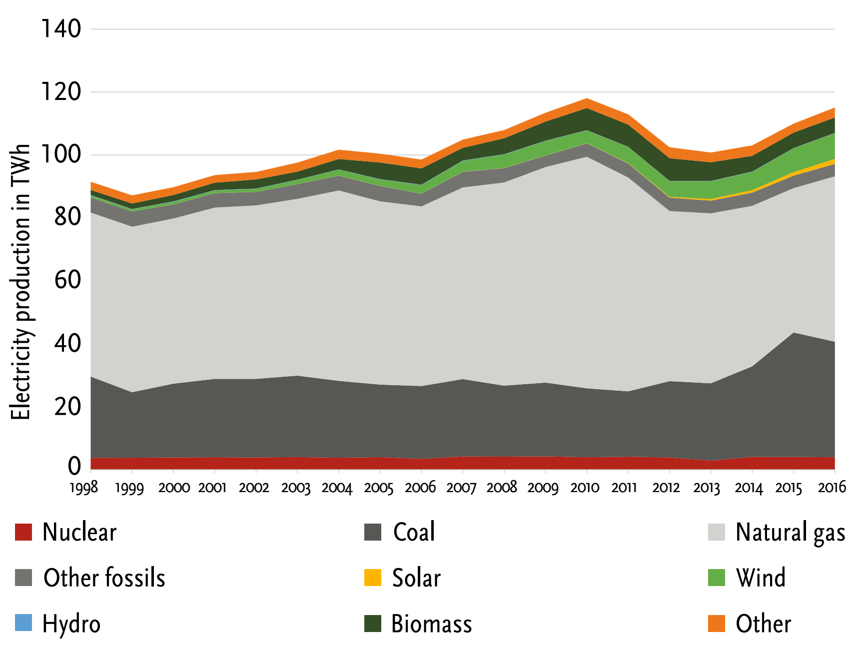


Figure 6 *– Electricity production in the Netherlands (1998-2016), figures for 2016 are provisional (CBS, 2017)*

Because of the enormous size of the Groningen gas field, neighbouring countries also have a considerable (imported) share of gas-fired power in their electricity systems. The contribution of gas-generated electricity to the total production is presented in Figure 7 for neighbouring countries.

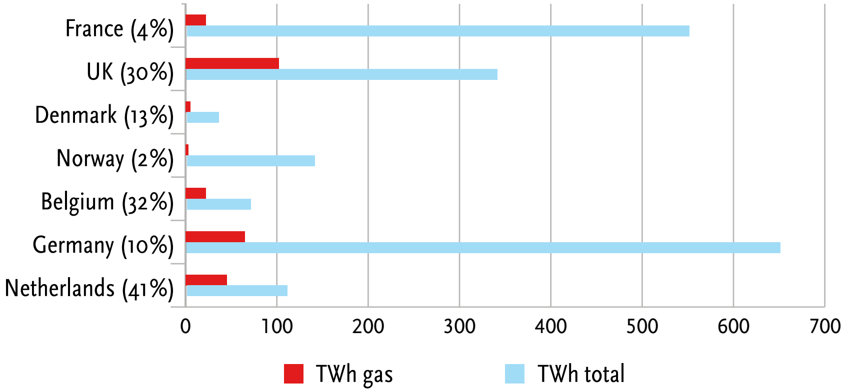


Figure 7 – *The share of gas-fired power generation in the electricity mix of North-west European countries (2015) (Destatis, 2018; ECN, 2016; ENTSO-E, 2015; Department for Business, Energy & Industrial Strategy, 2016)*

It is important to consider the different response times of sufficient rated power with regard to real-time demand that varies on different timescales, ranging from seconds to inter-seasonal. In the present Dutch electricity mix, which is mainly based on gas- and coal-fired power plants and only 7.9 % VRE, there are no significant flexibility problems. However, the planned growth of VRE will lead to a higher demand for flexibility. In view of the expected developments, it is useful to examine flexible power capacities, which enable the TSO to intervene in case of unforeseen circumstances to secure a reliable supply.

Power generation	Ramp-up/down time	Rated power (MW)
Nuclear plant	> 8 hr	100 – 1,000
Waste incineration plant	2 – 8 hr	10 – 100
Coal-fired plant	> 30 min	100 – 1,000
Gas-fired turbine (combined cycle)	< 30 min	100 – 1,000
Gas-fired turbine (single cycle)	< 15 min	100 – 1,000
Combined heat and power plant	< 15 min	1 – 10
Fuel cell	instantaneous	< 1
Hydro power plant	instantaneous	1 – 10
Wind turbine	natural fluctuation	1 – 10
Solar panel	natural fluctuation	< 1

***Table 1** – Indication of flexible power capacity sources (TNO, 2015)*

The Netherlands, like most other countries in Europe, uses a system of BRPs (Balance Responsible Parties) in order to even out the supply of power in response to variations in demand. Until now, this system has been adequate in our country for an optimal functioning of the electricity market. Dutch electricity supply has a high degree of reliability, as well as the capacity to absorb large surpluses from neighbouring Germany. Within this system, the responsibility for closing contracts related to buying and selling electricity is in the hands of the BRPs. Trade is organized in the day-ahead market, the intraday market and the spot market. This situation is satisfying as long as VRE penetration is low, the state of balance, however, can be disturbed with a high VRE share in the power mix (TNO, 2015).

The existing Dutch generation systems are not designed for the expected growth and volume of VRE from wind and solar. The necessary flexibility, in which parties – by way of production, storage or demand – react to expected surpluses or shortages of electricity supply are not yet integrated into the system. Table 1 gives an indication of the different sources of flexibility and their application in the energy mix. It is clear that not every source of flexibility is suitable for each type of flexibility demand. For instance, the need for flexibility for tuning supply and demand takes place in seconds and minutes and is related to energy quality, i.e. frequency containment (primary) and frequency restoration (secondary). There is also a need for flexibility in hours and days, which is caused by the introduction of large quantities of intermittent electricity from wind and sun. Moreover, to cope with seasonal influences, or in the case of a drop-out of an essential power plant, a long endurance flexibility of weeks or even months is required. So, each type of power generation has specific characteristics in terms of the typical scale and potential capacity of the technology, which are connected to both the nature of the energy source (sun, wind, biomass, fuel, gas, coal) and the conversion steps used to generate electricity. The table presents two important characteristics: the pace with which production can be raised or reduced and the potential power.

Traditional coal-fired power plants, nuclear plants and waste incinerators share a need for an extended period – many hours or days – for substantial increases or decreases in production. Gas-fired turbines and the combined heat and power plants are controllable within 15 to 30 minutes and hence able to meet the primary demand for flexibility. Hydro power plants and fuel cells are able to deliver electricity to the grid nearly instantaneously and therefore constitute excellent flexibility providers within their specific range of capacities. For wind turbines and PV panels, their intermittent patterns of production capacities are dependent on the natural fluctuations of wind speed and solar insolation. Thus, an increasing share of production will fluctuate and will always be beyond control – except by curtailment. Curtailment is what one does in the event that high wind coincides with low demand: the wind turbines have to be switched off (curtailed) in order to prevent exceeding the frequency margins (TNO, 2015).

The conclusion can be drawn that at present the power supply is in balance with demand, because of predictability of the demand side and control on the supply side. In case of shortages, gas-fired power plants (eventually mothballed) are able to deliver sufficient flexibility. Finally, the cross-border trade of power provides an adequate buffer in case of shortages or oversupply if VRE production is not correlated between neighbouring countries.

2·2 Dutch energy policies

As explained in Section 1.1 of the Introduction, there was no general public awareness of the threats of greenhouse gasses until the 1980s.

In 1987, Norway's Prime Minister Brundtland published, in "Our common future", a list of global environmental challenges that specifically included the threat of climate change. In the Netherlands, it was also the beginning of what former Dutch activist and MP W. Duyvendak, described as 'the first wave'. In the same year, Minister of the Environment E. Nijpels presented the first climate report to parliament, Climate change by CO_2 and other trace gases ("Klimaatverandering door CO_2 en andere sporengassen"), with a subject of climate change as a result of human activities (Duyvendak, 2011). In spite of the support of Prime Minister R. Lubbers, significant resistance came from political parties, notably the liberal-conservatives (VVD), as well from employers' organizations. They feared that Dutch leadership in this domain would lead to a rise in energy costs and a decrease in international competitiveness.

In 1995, Minister of Economic Affairs H. Wijers presented the 3rd Energy Report "Derde Energienota", which for the first time introduced the idea of renewable energy, followed in 1997 with the Report on the Environment and the Economy "Nota milieu en economie" with recommendations for reducing CO_2 emissions in order to mitigate climate change. The recommendations were effectively opposed by a lobby of multinational companies and no tangible measures followed.

A decade later, in 2007, the Netherlands saw a 'second wave' of climate awareness in the wake of Al Gore's film An Inconvenient Truth, supported by his visit and later by that of Bill Clinton. The initiatives of Gore and Clinton induced mayors, CEOs of large companies and board members of public media for the first time to become intensively involved in activities against global warming. For the time being, environmentalism was 'out', but from that moment climate change was 'in' (Duyvendak, 2011). Nevertheless, a political majority was not yet convinced. Minister of the Environment Dr. J. Cramer set the agenda for CO_2 emission reducing legislation and for the subsequent closing of coal-fired power plants. However, without the support of the politically experienced Minister of Economic Affairs M. Van der Hoeven, the intended measures had to be withdrawn. After her resignation, Dr. J. Cramer publicly criticized the former Minister of Economic Affairs for frustrating her sustainability policy (Duyvendak, 2011). Meanwhile, the Copenhagen Accord in 2009 did not meet expectations for a global binding commitment and was therefore not an incentive to change Dutch policies.

As described in the general introduction, in 2013 and under the auspices of the SER (Social and Economic Council of the Netherlands) the "Energieakkoord voor duurzame groei" finally came to the fore, signed by 47 stakeholder organizations. Together with the European commitments, this agreement is the current guideline for Dutch energy policies. It is the intention of the Dutch government to put the Netherlands among the world leaders of energy transition within a short space of time, based on the implementation of this agreement. This can be considered particularly ambitious since the present situation indicates that the Netherlands shares with Malta the last places in the EU ranking of renewable energy sources (Eurostat, 2016). The starting point of the agreement consists of energy consumption savings of on average 1.5 % per year, resulting in 100 petajoules of savings in 2020 (TNO, 2015). Energy savings are indispensable in order to realize a low-CO_2 energy system and are necessary over the full spectrum of the energy supply (Energierapport, 2016).

The signing of the Paris agreement COP21 (in 2015) and its ratification by a qualified majority (in 2016) provided favourable circumstances under which the Dutch government issued the "Energierapport" in January 2016 and the "Energieagenda" in December of the same year.

It must be mentioned that the legal verdict in the "Urgenda" lawsuit in 2015, put more pressure on the government's CO_2 abating agenda, specifically the target of 25 % VRE in 2020. In spite of the contested juridical arguments related to the application of international laws, it had an undeniable influence on both government and public opinion (Urgenda, 2018).

With its Energierapport 2016, the Dutch government has launched an overall vision for the transition to renewable energy with three broad aims:

1. reduction of CO_2 emissions
2. leveraging the economic opportunities which the energy transition offers
3. embedding VRE in environmental planning policies

This report is based on the aforementioned Energieakkoord, as a result of which the status quo and yearly progress will be monitored by the "Commissie borging energieakkoord voor duurzame groei". This commission concluded in December 2016 that the transition targets are within reach and that the representatives of the energy-intensive industries have committed to implement CO_2-reducing processes.

Conforming to the European targets, the challenging goal will ultimately be the reduction of greenhouse gas emissions by 80-95% in 2050, with a reduction of 20% foreseen for 2020 and a decrease of 40% by 2030. To attain this goal, the government expects a significant contribution from the industries via the ETS (Emissions Trading System). However, the EU-ETS is not expected to provide a significant market improvement before 2020, notwithstanding the intended measures, such as the back-loading of auctions to reduce allowances in volumes. The government further proposes energy saving, firing biomass, CO_2-free electricity generation, electricity storage, and CO_2 capture and storage (CCS). These will be robust elements of the energy mix towards 2050, according to the government (Energierapport, 2016).

The Dutch government claims the predicate robust for the description of the directions and intentions of the way to reach the transition to sustainability. They describe an ultimate target (a CO_2-free energy system), but do not indicate how exactly this will be attained. Concrete proposals are missing, let alone quantified flexibility solutions and above all financial commitments apart from SDE+ (Stimulering Duurzame Energieproductie) subventions for generation only. At a minimum, it is clear that the government is uncertain about how future policies have to be formed and which legislation will govern the energy transition.

In order to structure the energy discussion with a new train of thought, the Dutch government follows the approach of the Rli (Council for the Environment and Infrastructure) where energy is a means to an end. It is used for the provision of heat, light, motion and communication. Starting from the functionality of energy, Rli has a different look at the supply, infrastructure and organization of energy (Energierapport, 2016). Rli distinguishes four functionalities of energy and starts its analysis from the total energy demand, also in 2050, with these four fundamental societal needs. In order to fulfil these needs, energy has to perform in the following primary functions (Rli, 2015):

1. low-temperature heat (up to 100 °C), supply of heat in buildings for central heating, hot water
2. high-temperature heat (above 100-120 °C) for the manufacturing of products, high temperature processing heat
3. energy for transport and mobility
4. energy for lighting, electric machinery, information and communication technology

Options to save energy consist principally of insulating buildings, designing sun-oriented buildings, improvement of the energy efficiency of devices and vehicles, avoiding unnecessary transport movements, using more efficient production processes, clustering and integrating industrial installations, and extreme reduction and reuse of (energy-intensive) materials (Energierapport, 2016).

When the 2020 targets of the Energy Agreement are met, more than 30 % of Dutch electricity will be generated from renewable sources. This will be a combination of dispatchable production from biomass co-firing in coal power plants and intermittent production from solar PV and wind. As for the extension of wind capacity, 2,400 MW will be built during the years 2017, 2018 and 2019. For the short term, the Netherlands' largest single offshore wind park Gemini situated 85 km north of the coast, with 600 MW and an output of 2,600 GWh/y, came into use on May 8, 2017. Adding up the Borssele I and II offshore wind parks with a capacity of 700 MW commissioned by the Danish Ørsted power company, together with the Borssele III and IV wind park (700 MW) commissioned by a consortium led by Shell, the conclusion must be drawn that the challenging wind capacity targets of the government are within reach (De Ingenieur, 2017). After 2020, the share of VRE sources in power generation will increase further as additional offshore wind power is built and decentralized and land-based generation grows alongside. The National Energy Outlook (NEV) 2017 estimates that ca. 63 % (80.6 TWh) of the power generated in the Netherlands by 2030 will originate from renewable sources (ECN, 2017b). This means that the production of solar and wind power will at moments substantially exceed the momentary demand for electricity. This will require an enormous step-up in flexibility at system level (TNO, 2015). The implications of this are a prime driver for researching technologies that provide flexibility on the supply and demand side of the power system, a challenge that will be further discussed in Section 2.3.

The Dutch government intends to execute the Energy Agreement, with the aim of achieving (amongst other things) 10,450 MW of installed wind power by 2023. In addition, the Agreement foresees that by approximately 2023, some 5,000 to 7,000 MW of solar photovoltaic panels will have been installed. This will bring the total renewable but intermittent production capacity to over 17,000 MW. This capacity will nearly equal the average peak demand in the Netherlands, so if any other source such as CHP is also running, oversupply will be unavoidable under certain circumstances, especially during the night, with an average maximum demand of only circa 7,000 MW (see Chapter 7).

	Projections (MW)		
	2020	2023	2030
Wind onshore	6,000	6,600	8,000
Wind offshore	3,500	4,450	6,000
Solar PV	5,500	6,250	8,000
Total	15,000	17,300	22,000

Table 2 *– Development of wind and solar PV electric power supply (Frontier Economics, 2015)*

On the basis of the above figures, the projected electricity production from power sources during the years 2018 to 2030 is as shown in Table 3.

Production	**2018**		**2020**		**2023**		**2030**	
	(TWh)		(TWh)		(TWh)		(TWh)	
Total	96.1	100.0%	100.7	100.0%	122.2	100.0%	128.4	100.0%
Natural Gas	32.8	34.2%	27.5	27.3%	28.2	23.1%	13.7	10.7%
Central	12.0	12.5%	10.3	10.2%	13.9	11.4%	7.9	6.1%
Decentral	20.9	21.7%	17.2	17.1%	14.3	11.7%	5.8	4.5%
Coal	29.6	30.8%	27.4	27.2%	29.6	24.3%	22.5	17.6%
Other fossil	3.6	3.7%	3.9	3.8%	4.1	3.4%	4.7	3.7%
Nuclear	4.2	4.4%	4.2	4.2%	4.2	3.5%	4.2	3.2%
Renewable	23.4	24.3%	35.2	35.0%	53.5	43.8%	80.6	62.8%
Wind	12.4	12.9%	19.2	19.0%	34.5	28.3%	58.6	45.7%
Solar	2.7	2.9%	5.0	4.9%	7.7	6.3%	14.2	11.0%
Hydro	0.1	0.1%	0.1	0.1%	0.1	0.1%	0.1	0.1%
Biomass	8.2	8.5%	11.0	10.9%	11.1	9.1%	7.7	6.0%
Other	2.5	2.6%	2.5	2.5%	2.5	2.1%	2.7	2.1%
International trade								
Import balance	20.4		15.4		-5.5		-13.0	
Import	36.3		37.0		33.8		29.6	
Export	15.9		21.6		39.3		42.6	

Table* 3 – *Projections of Dutch electricity production (approved policy) (ECN, 2017b)

Following the detailed projections of Table 3, a histogram representing the same data shows the transition from fossil (black/grey) to renewable (green). It reveals that the reduction of the fossil power production can be qualified as modest.

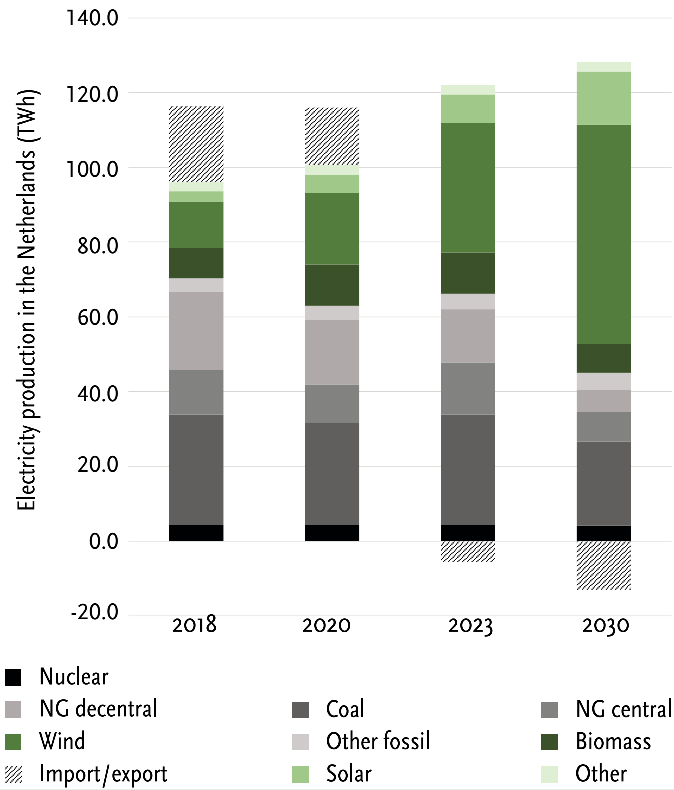


Figure 8 *– Projections of Dutch electricity production (approved policy) (ECN, 2017b)*

The transition to sustainability in electricity production should in the first place be driven by ETS. The Dutch government expects only a marginal reduction of CO_2 emission via ETS before 2030. Therefore, stimulating policy measures – for the generation of electricity by sun and wind – such as SDE+ will need to stay in place in order to reach circa 44 % VRE in 2023. The applicability of the SDE+ system is expected to broaden in the coming decades, ranging from subsidizing sustainable power generation to subventions aimed at CO_2 emission reduction in general (Energieagenda, 2016). These and other measures are intended to be continued and obviously decided by the present and future administrations, whilst the execution is dependent on the political willingness for support and priorities.

2·3 Dutch electricity sector policies and flexibility measures

As Dutch plans for deep penetration of electric renewables continue to take shape, measures will be required to make sustainable energy fit within the future energy system. Multiple simultaneous solutions are likely to be necessary. The government expects sufficient flexibility to become available by stimulating the following:

- cross-border connections
- demand-side management (DSM)
- decentralized storage in the built environment
- decentralized storage in EVs
- thermal backup capacity from coal and gas

Measures for each of these are discussed subsequently in the following subsections.

2·3·1 Cross-border connections

The Dutch government intends to reinforce the coupling of the national electricity grid with the grids of its neighbours. The associated coupling of these national energy markets will contribute to the establishment of a European internal electricity market. This should lead to more efficient price formation in the electricity market and present the market parties with the possibility to trade electricity across national boundaries. In addition to implementing a so-called flow-based market coupling system, TenneT, the TSO, will in the years ahead invest in new interconnectors between the Netherlands and Germany, Belgium, and Denmark, along with an extension of the existing interconnections with Germany (Energierapport, 2016).

In 2016, the total capacity of Dutch interconnections is 5.9 GW. The planned expansion by 2020 will bring the total to 9.1 GW, an increase of 55 %. The following projects, totalling circa 3 GW are foreseen:

- Doetinchem-Wesel: 1.5 GW (connection between the Netherlands and Germany over land)
- COBRAcable: 0.7 GW (sea cable between the Netherlands and Denmark)
- extension of capacity with 0.3 GW (till 0.5 GW) of the connection between Meeden and Diele (Germany)
- mark-up with a maximum of 0.7 GW for the connection between the Netherlands and Belgium (TenneT, 2016c)

The usable capacity depends on the location of the actual producing power units and the allocation of cross-border electricity transport that follows from them, according to the so-called flow-based allocation scheme.

Where in the EU context, the differences in price and volume can be great, in the region there are more possibilities and concrete results can be reached faster. The Netherlands, as a partner within the Benelux region, has good experience with the Pentalateral Energy Forum, in which Germany, France, Austria and Switzerland participate. Since 2005, this forum has played a prominent role in establishing an integration of both the electricity market and the gas market, and a joint approach to supply security. The relation with immediately neighbouring countries deserves special attention. Developments in these neighbouring countries have had a direct impact on the domestic energy supply. In 2014, the Netherlands signed an agreement to intensify the cooperation in the field of energy and also aims to sign an MOU with Belgium in the short term (Energierapport, 2016). It is important to consider that this regards the present situation, in which the intermittency caused by the implementation of VRE sources plays a minor role.

The government emphasizes the benefits of cross-border connections. At present, importing and exporting electricity are viable solutions to adjust for periodical shortages and surpluses in supply. The production parks of North-west European countries currently show completely different characteristics. Germany, for instance, Europe's number one in VRE penetration, is still dependent for more than 50 % on lignite, coal and gas for fossil-fired electricity generation. Belgium presents a completely different electricity production mix, with approximately 20 % VRE and 38% nuclear power, the latter coming from power plants at the end of their life cycle. For its consumption, Belgium is for more than 20 % dependent on imports. Power production of France is historically dominated by nuclear power plants with a share of more than 75 %. Denmark can be characterized as the country with the highest input of VRE by wind turbines, over 50 % (ENTSO-E, 2015). As for the Netherlands, the 2015 VRE penetration is the lowest in Europe (circa 11 % as of 2015) with electricity instead being generated by coal and natural gas, supplemented by imports. One can conclude that the overall picture in north-west Europe today shows a scattered and structurally varied electricity production pattern. However, it is expected that within a decade a completely different electricity supply situation will arise, because it is the intention of each of these countries to substantially increase the role of weather-dependent renewable sources. Consequently, current differences notwithstanding, the growing influence of VRE will lead to a high degree of conformity in the electricity production mix of the above countries.

If the electricity supply is determined to a considerable degree by weather conditions, it is important to take the relevant weather situation into account. The weather circumstances (wind and sun) in the Netherlands are generally correlated with those of its neighbours. Meteorological systems do not stop at borders, especially in relatively small countries. For example, if in a fairly localized area around the English Channel and the adjacent North Sea, there is a weather system of winds of high velocity, it is predictable that wind farms from Dutch, Belgian, British, Danish and German origin will yield high power outputs simultaneously. This will result in synchronous overproduction, especially in times of low demand. The same goes for weather conditions in which large areas of sunshine or overcast dominate part of the continent. Such homogenous weather circumstances will inevitably lead to synchronous over- or undersupply of PV-generated power. Further, the electricity production profiles of the countries in this region after 2020 show a high degree of conformity (Graabak & Korpås, 2016).

In light of the above considerations, it is doubtful whether cross-border interconnections can sufficiently contribute to solving the discrepancy challenge between intermittent supply and indigenous demand.

There is no uncertainty about TenneT's planning; until 2020, the question is not the capacity of the installed cables, but the availability of sufficient power from and/or storage capacity at the linked partner when it is needed. Coupled with this is the need for acceptable price levels for imports as well as exports (see Table 3). According to this prognosis, the Netherlands will have switched from a nett importer to a nett exporter of electricity between 2020 and 2023.

2·3·2 Demand-side management

During recent decades, it has been the policy of electricity suppliers to promote electricity consumption during the night via low pricing. This is an elementary form of load shifting of consumption from peak hours to off-peak hours. The idea behind it is to attempt to even out demand across time, leading to a more efficient use of the power supply. It is a matter of time shifting volumes. In the future, load shifting will be increasingly important, because the superfluous supply of electricity from sun and wind is intermittent and the prices of electricity will become more volatile. The expectation of the electricity system of the future is that ever more parties can and will play a role in the supply of flexibility. As price volatility increases, flexibility of demand will be evermore desirable (Energierapport, 2016).

Demand-side management (DSM for short) is a logical step to facilitate the intelligent use of power generation systems. It can be described as *systemized control of the demand for electricity – within defined limits – in quantity or in time of consumption*. The Dutch government explicitly mentions DSM as one of the instruments for coping with the challenges of the transition to sustainability (Energierapport, 2016).

One of the aspects within the system of DSM is demand response (DR), where users are connected via a two-way central communication system. In this scheme, businesses and consumers are financially incentivized to lower or shift their electricity use at peak times by turning up, turning down or shifting demand in real time.

Existing DR capacities in the Netherlands are in the order of 1,000 MW, according to ENTSO-E (European Network of Transmission System Operators for Electricity). These capacities are mostly load reduction capacities. An additional 200 MW of load shifting capacities are available from heat pumps. In addition to the existing DR capacities, the expectation is that further investment potential will be available in the future: an extension of load reduction potential to 700 MW, mainly arising from industries and emergency generation units, could enter the market in the short term (Frontier Economics, 2015). The rather limited growth of DR capacities as shown in Figure 9 is disproportional to the predicted development of VRE power. Therefore, it is unlikely that DR can play a significant role in fulfilling the future flexibility demand.

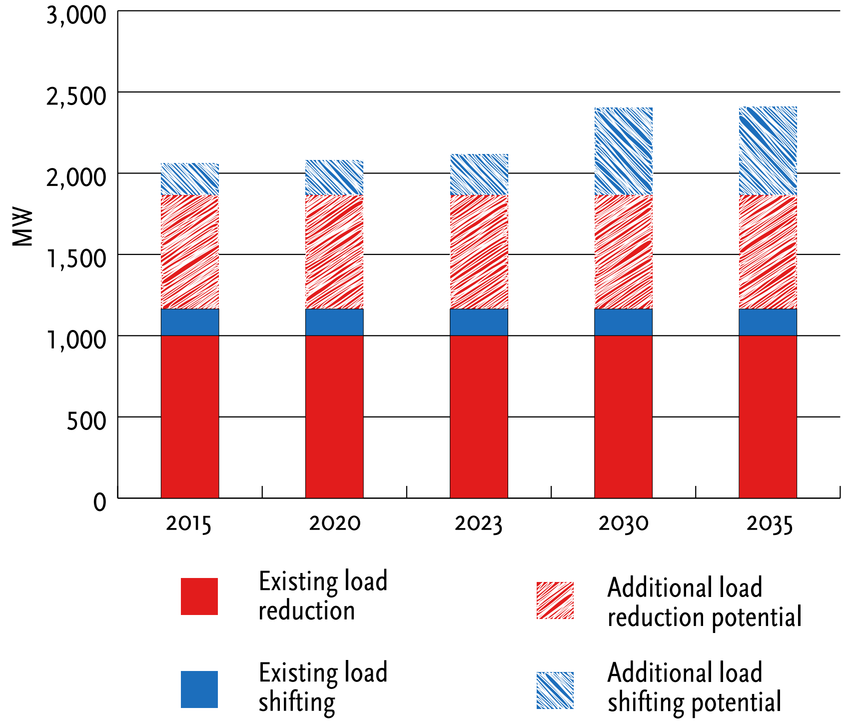


Figure 9 – *Development of demand-side response*) (Frontier Economics, 2015)*

*) Derated capacity according to assumed availability in peak periods (winter period, Monday-Friday from 17:00 to 20:00 h) (Frontier Economics, 2015)

The key to the realization of a demand response approach is the tendency of a growing number of electricity suppliers to settle electricity bills by remote meter reading. With this step, all households are linked to the central communication station. This is a precondition for large-scale demand response. In Europe, this was initiated by the Italian DSO ENEL with the replacement of 30 million conventional meters by smart meters that are remotely accessible. In addition to enabling more efficient administration, these meters are used for capacity limitations during peak hours, for simplifying tariffs or supplier changes, and if necessary for disconnecting non-payers (Sterner & Stadler, 2014).

Considering the fragmented nature of the Dutch electricity supply, based on its present developments, it is doubtful whether a significant number of subscribers can be yielded. Even if the government creates stimulus programs that are attractive to consumers, this will require a lead time of many years, and will probably not be sufficient to meet the total demand for flexibility. According to the European Commission (EC), Europe has a backlog in the area of adjusting demand. It is expected that 10 % of the peak demand is avoidable by shifting in time (TNO, 2015; EC, 2013).

DSM's primary objective is to create greater efficiency in the use of power plants by shifting the consumption load from peak to off-peak hours. The intermittency of VRE electricity constitutes a more complicated challenge for adapting demand to production. DSM endeavours to influence the behaviour of the consumer as well as the wholesale user, in order to optimize the current power capacity. In Section 2.3.3, different models are described, but it is questionable whether a sufficient number of subscribers can be organized in order to play a role in the flexibility process. Financial incentives are required to influence consumer behaviour related to power consumption. Meanwhile, a large majority (86 %) of the Dutch consumers insist on continuous availability of electricity (Motivaction, 2016). Ultimately demand-side participation can only succeed if adequate organizational structures are in place. In spite of some innovative developments, the absence of a homogeneous distribution system (7 DSOs) presents a serious obstacle to the creation of a critical mass which can exercise an influence on the Dutch electricity market.

2.3.3 Decentralized storage: households

Electricity storage in batteries offers consumers the possibility to uncouple the moment of electricity production (from PV) and their consumption. When they install batteries, they can charge during off-peak hours when the price is low, and discharge to the grid in peak hours when the price is high (TNO, 2015). Small-scale prosumers can cluster through local energy initiatives, and by aggregating their production and supply, they can reach a volume which can be of interest for commercial trade and grid applications when supported with storage and proper organization. Alongside local energy collectives, commercial companies may also offer these services. In this regard, an example in Germany is instructive. Germany had, as of 2016, more than 19,000 residential storage systems as a result of a longstanding national subsidy programme that offer loans for installing battery storage systems alongside solar PV panels. The scheme is designed to stimulate the development of battery storage systems for PV. The ministry BMWi reported that the total investment for the installed batteries for consumers amounted to €450 million. Comparing LCOE (Levelized Cost Of Electricity) from solar systems with battery backup against the retail tariff for households, one can conclude that these subsidized systems are approaching economic viability. Without such a subsidy programme in the Netherlands, there has been very little propensity to install batteries in households. Additionally, the netting scheme (i.e. 'salderingsregeling') in the Netherlands counteracts the uptake of household batteries, as kWhs delivered to the grid from household PVs are subtracted from the final electricity bill (regardless of demand and market prices) (Essent, 2018; van Gastel, 2017). Accordingly, the introduction in 2016 of household batteries by energy supplier Eneco was not successful. Only 30 systems were sold during the start-up phase in 2016 (Enexis, 2016), a year later this had increased to only a few hundred household batteries in the Netherlands (van Gastel, 2017). In order to achieve a substantial level of flexibility, thousands or even tens of thousands would have to be installed.

As for DSM, the success of decentralized storage is dependent on influencing consumer behaviour. The German example is instructive for illuminating a path for increased battery-based storage in households. Compared to Germany, with an actual renewable electricity supply of more than 30 %, solar battery-based storage in the Netherlands is in its infancy, due to lower penetration of solar supply and the absence of stimulatory measures. Without incentives by the Dutch government in the form of subsidies like in Germany, a substantial growth of storage in households cannot be expected. There are no signs that the government is going to adapt its policy vis-à-vis the implementation of home batteries, and hence a substantial contribution to flexibility is unlikely.

2.3.4 Decentralized storage: electric vehicles

The transition to electric transport carries high expectations in the Netherlands. An important contribution (to sustainability) is expected from the electrification of vehicles (EVs). The Netherlands are particularly suitable for a rapid transition to electric transport because of the relative short transport distances and the innovation power of Dutch industries. Electric propulsion is particularly suitable for smaller vehicles (cars) and for transport over relative short distances (buses, light goods carrying traffic). Electrically propelled vehicles may even be used for heavy road transport in urban surroundings (Energierapport, 2016).

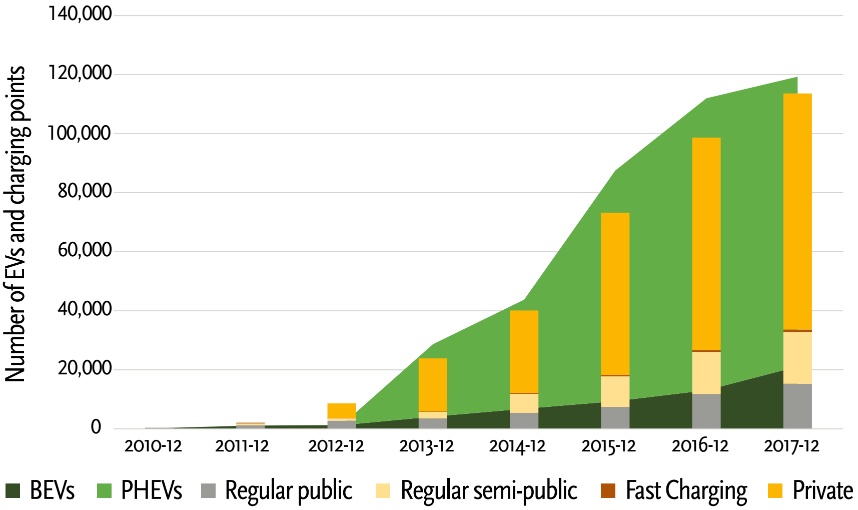


Figure 10 *– EVs and charging points in the Netherlands 2010-2017 (RVO, 2018c)*

The data on the Dutch electric car stock distinguishes between BEVs (Battery Electric Vehicles) and PHEVs (Plug-in Hybrid Electric Vehicles). In December 2017, BEVs accounted for 17.7% of the EV car stock, up from only 11.7% in December 2016 (RVO, 2018c). The growth in EVs depends on the tax measures for car leases. Since 2017, only zero-emission vehicles (i.e. BEVs) are eligible for tax benefits on car leases, resulting in a decrease in PHEVs.

The cost of batteries has fallen over time and with this, the number of EVs sold and loading stations installed in the Netherlands has rapidly increased. The last five years have recorded strong growth of EVs and (semi-)public loading stations. The number of EVs at the end of 2017 constituted 1.5% of the total Dutch motor vehicle fleet (CBS, 2018a; RVO, 2018c).

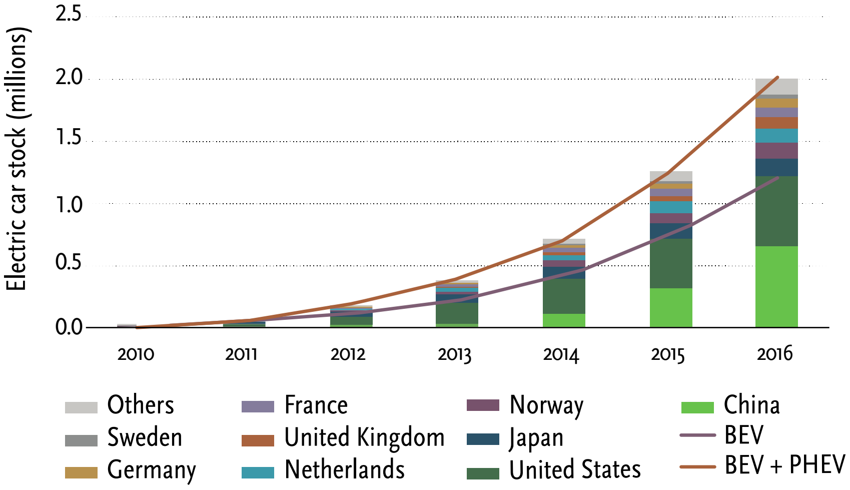


Figure 11 – *Evolution of the global electric car stock, 2010-2016 (IEA, 2017).*

Note: The EV stock shown is primarily estimated on the basis of cumulative sales since 2005. When available, stock numbers from official national statistics have been used, provided good consistency with sales evolutions.

The growth of the EV fleet is determined by many different developments. Key to this is the progress in battery technology in terms of storage density, durability and cost. For EVs, this should translate into an expansion of the electric range and a lowering of charging times.

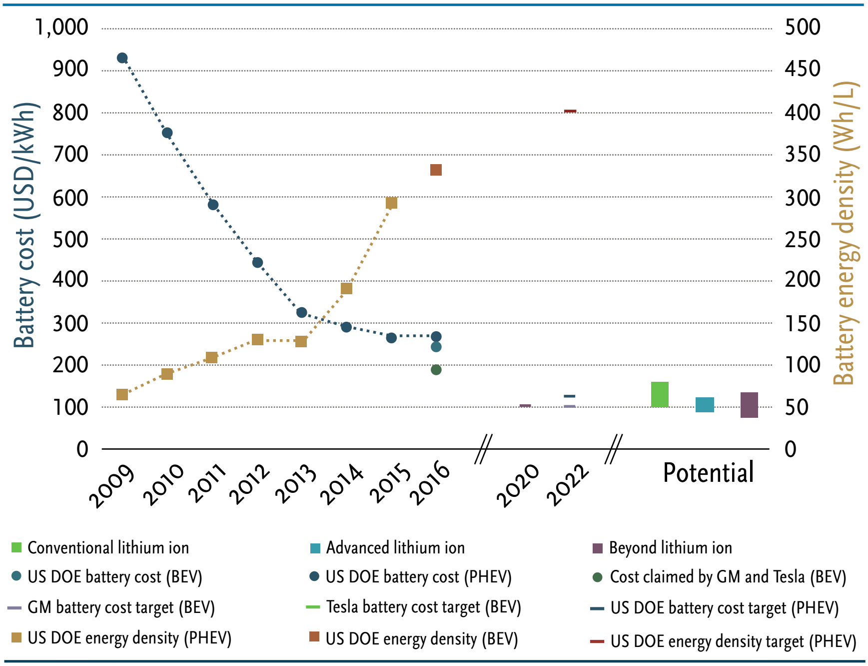


***Figure* 12** – *Evolution of battery energy density and cost (IEA, 2017).*

Notes: USD/kWh = United States dollars per kilowatt-hour; Wh/L = watt-hours per litre. Contrary to the results assessed for 2009-2015, which targeted PHEV batteries, the 2016 estimates of costs and volumetric energy density by the US DOE (costs are to be interpreted as projections for the high-volume production of technologies currently being researched) refer to a battery pack that is designed to deliver a 320-km all-electric range and is, therefore, suitable for BEVs. The latest update of this cost assessment was developed while accounting for an advanced lithium-ion technology (with silicon alloy-composite anode). As this is a technology that is still being researched today, it is currently deemed to have higher costs but also a larger potential for cost reductions compared with conventional lithium-ion technologies.

In addition, EV adoption will also depend on the density of charging stations. For the roll-out of EVs, the government has a decisive role, especially during the introduction phase, through subsidies and/or tax exemptions for EVs and through incentivizing their use, e.g. through parking spaces and charging points. Finally, the car industry will shape the change-over to vehicle electrification in ways that cannot be foreseen. Vehicle electrification has a profoundly disruptive potential for the industry, making traditional market dominance in engine engineering less relevant and thus offering opportunities for new entrants (as witnessed by Tesla).

The Netherlands car stock counts ca. 8.2 million vehicles at the moment, of which 119,332 are EVs (including PHEVs) (CBS, 2018a; RVO, 2018c). The target number of EVs in 2025 is 1,000,000 (Ministerie van EL&I, 2011). The new aspirations in the new Green Deal 2016-2020 are (Green Deal C-198, 2016):

1. By 2025, 50 % of all new cars sold will have an electric powertrain and a plug, and that at least 30 % of these vehicles (15 % of the total) will be fully electric.
2. The aspiration for 2020 is that 10 % of new cars sold will have an electric powertrain and a plug.
3. The aim is to have 75,000 privately driven EVs on the roads by 2020, consisting of 50,000 used cars and 25,000 new vehicles.

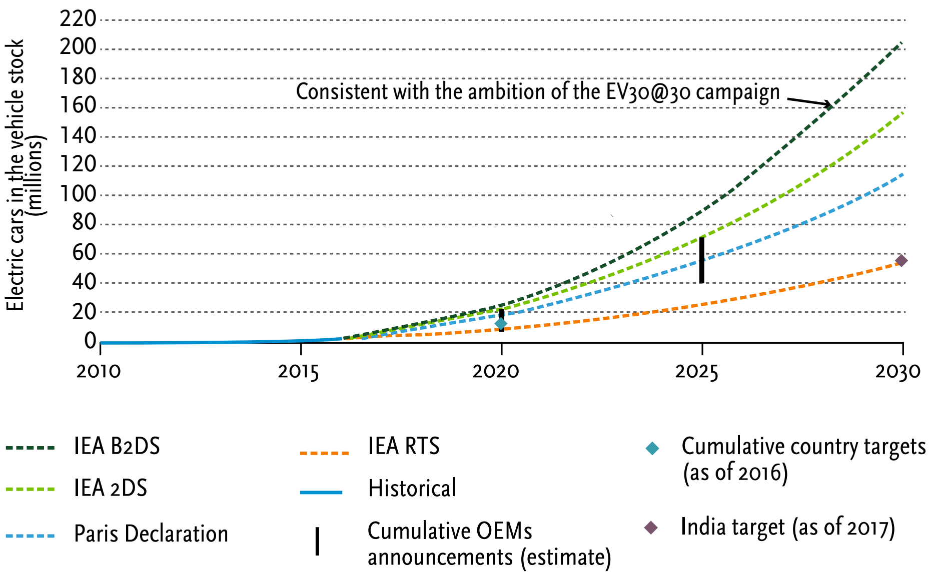


***Figure 13** – Deployment scenarios for the stock of electric cars to 2030 (IEA, 2017).*

Note: Country targets in 2020 reflect the estimations made in EVI (2016a) and updates to date. India's targets reflect a conservative interpretation of the announcement made by the government (PIB India, 2017): 50% of the PLDV stock of the country (in the B2DS) is electrified by 2030. The assessment methodology for OEM announcements included the sales ambitions of major EV manufacturers (IEA,2017). Projections on the stock deployed according to the Paris Declaration are based on UNFCCC (2015a). Projections on the EV uptake were developed with the IEA Mobility Model, March 2017 version (available via IEA).

Vehicle-to-grid (V2G) describes a system in which EVs are connected to the power grid to either return electricity to the grid or adjust their charging rate to the available supply capacity. The Dutch government advocates such additional use of the batteries of EVs as a contribution to the reliability of the electricity supply. The batteries from EVs are able to support the modulation of peaks and lows in electricity production and use over a time frame from one to several days (Energierapport, 2016).

In Utrecht, DSO Stedin launched an innovative trial of public two-way stations where EVs can not only load their batteries but also unload the batteries during high-priced peak times in order to deliver electricity to the grid. A smart IT system protects unloading beyond a certain threshold, for instance 40 % of the battery capacity. Stedin claims numerous benefits from this approach, especially as it can reduce or eliminate the need to extend the distribution grid (Stedin, 2015).

Apart from the degree of penetration of EVs in the vehicle stock, this approach raises the question whether the willingness of individual EV owners to cede control over their batteries to a third party will be sufficient to substantially meet the required capacity.

The predicted growth of the EV fleet, as estimated by the Dutch Ministry of Economic Affairs, will be to around 1 million EVs by 2025. This estimation is dependent on a number of uncertainties, including battery technology development, the density of loading stations, and innovation and pricing policies of the automotive industry. In turn, the industry's challenge lies in R&D with regard to the balance of weight and capacity, and charging and discharging times.

Starting with an estimated 1 million EVs (hybrid and all-electric), we assume that the battery capacity of the higher segment of EVs (which is now 85 kWh for Tesla) will grow to 100 kWh in 2025. Regarding the lower segment, which is proportionally larger, we estimate an average battery capacity around 50 kWh. In theory, this represents a total capacity of 50 GWh. Our second assumption is that the average charging level of the batteries will be 50 % (25 GWh total). Thirdly, we assume that the propensity to accept external controls by the EV owner to be 25 % (IEA, 2014a). In this scenario, the EVs of these participants have 6.25 GWh electricity stored and meanwhile have, in principle, 6.25 GWh storage capacity available. This capacity can only be used if the EVs are connected to the grid. If the number of connected cars were close to 50 %, the available storage capacity would be approximately 3 GWh. Such a scenario is based on fully electric cars. In reality, a major part of the EV fleet consists of hybrid vehicles, which have a considerable lower battery capacity. This could mean that the maximum available storage capacity in this scenario may be in the range of 1.5 GWh.

This considerable storage potential, which is part of the government's projections, can only be realized if the anticipated breakthrough of battery EVs materializes. Competing technologies can have a serious impact on the volume of the EV market. The IEA report of 2015, dedicated to the prospects of hydrogen as a fuel, was rather pessimistic about the propagation of fuel cell-based EVs (FCEVs), in spite of their potential for low carbon emissions, and predicted a ramp-up scenario of 15 to 20 years after the successful introduction of the first 10,000 EVs (IEA, 2015). In Germany, California and Japan, however, concrete steps are underway for the installation of hydrogen stations in the coming years. The German Ministry of Transport and Digital Infrastructure, for instance, has supported hydrogen and fuel cell technology for 10 years through the National Innovation Programme (NIP). Between 2007 and 2016, government and industry have invested a total of 1.4 billion euros in hydrogen and fuel cell projects (NOW GmbH, 2017). The ministry alone has allocated nearly €250 million for hydrogen development for the period from 2016 to 2026 (NOW GmbH, 2017). The government signed an agreement with H2Mobility Germany for installing 400 stations across the country before 2023, an estimated overall investment of €350 million (NOW GmbH, 2017; The Linde Group, 2013). The Governor of California contracted with Shell and Toyota for 100 hydrogen stations before 2024, with a yearly grant of USD 20 million (California ARB, 2017). The Japanese manufacturer Honda has launched the first mass produced automobile powered by hydrogen on the US market (Honda, 2017).

At the Davos World Economic Forum 2017, an incentive to invest 9.5 billion euro in a hydrogen automotive development programme till 2022 was introduced by 13 global companies. Compared to battery-powered EVs, the benefits of a long range and rapid filling are expected to compensate for the higher costs of hydrogen and fuel cells (platinum) (Hydrogen Council, 2017). In addition, the 2017 global market research project by KPMG indicated clearly that the 800 interviewed executives in the automotive industries anticipated that the growth of EVs was waning (KPMG, 2017). The developments in the future transport market will be determined by the degree of substitution of fossil-fuelled vehicles by CO_2-emission-free alternatives. A mix of different types of transport requiring different sources of fuel is likely. The key fact is that FCEVs can only contribute to the (electricity) storage capacity to a limited extend.

The storage capacity of EVs is fully dependent on the pace of their introduction in the market, together with the above-mentioned hydrogen development programmes. The Dutch government has high expectations for the use of EV batteries as a contribution to the grid. Under certain circumstances, the predicted fleet of around 1 million EVs in 2025 could yield, as estimated earlier, a theoretical storage capacity of approximately 1.5 GWh. However, recent figures (12 % BEVs) indicate that the prevalence of PHEVs will lower this theoretical capacity by an uncertain amount.

2.3.5 Thermal backup capacity: coal and gas

In a conventional electricity system, peaks in the electricity demand, which are reasonably predictable, are dealt with by adjustment within the power plant, especially by the input of CCGTs (Combined Cycle Gas Turbines). But coal-fired plants, with a certain time lag, are also able to adjust the power they deliver to the grid. However, if a high percentage of electricity is produced by VRE in the electricity mix, this adds an intermittent supply to a variable demand, so that more flexibility is required. A number of these flexibility measures are described in the previous Sections 2.3.1 to 2.3.4. If the volume of these flexibility measures is insufficient, there is currently no alternative other than backing up via fossil-fuelled power plants. Since the Netherlands has historically possessed abundant natural gas resources, gas-fired power plants dominate the Dutch electricity generation scene.

Gas-fired power plants have 50 % lower CO_2 emissions compared to their coal counterparts. Even with these comparatively lower levels, fossil-fuel backup without carbon capture and storage (CCS) will make the goal of an emission-free or even a close-to-emission-free power sector elusive.

Additionally, because Dutch ports provide cheap coal, coal power plants account for 40-50 % of the Dutch electricity supply mix. In accordance with the national programme of closing ageing coal power plants, their number will be reduced to three. It was agreed in 2007 that these plants will be equipped with CCS, but with the recent official opening of the new facility in Rotterdam (MPP3), the promised

CCS was absent. Apparently, problems with financing and licenses prevented the realization of the prospected CO_2 storage.

The NEA (Dutch Emissions Authority) calculated that CO_2 emissions from these three new plants amounts to approximately 12 Mt/y (million tonnes yearly), which is identical to the emission quantity of the five coal power plants slated for closure (NOS, 2016). This figure does not match the calculated CO_2 capture capacity volume of 1.1 million tonnes per annum of the MPP3 demonstration project (CCS Network, n.d.). It is questionable whether intended demonstration projects in other countries in Europe will be pursued. Therefore, due to uncertainty regarding the introduction of CCS, the reduction of carbon emissions from coal-fired power plants is not realistic.

"While CCS has been applied on a commercial scale in the oil and gas industry, CCS from electricity generation is still an emerging technology that has never been demonstrated on a large scale." And further: "It is therefore not clear, how additional CO_2 capture, compression, transportation and storage could change the operating characteristics of fossil-fuelled plants" (IEA, 2011). In "The global status of CCS – 2016" it is reported that two projects were launched in 2016. The Abu Dhabi CCS project (Phase 1) claims to be world's first commercial steel carbon capture project. It is sponsored by Emirates Steel Industries (ESI), whose two plants will have a nett zero carbon footprint (capacity 0.8 Mt/y). The Tomakomai Japan CCS demonstration project (for three years only) is on the site of a petroleum refinery plant, where CO_2 is captured from off-gas generated at a hydrogen unit in the plant (0.1 Mt/y).

The Global CCS institute claims three major CCS projects in the USA as of 2017. The first is Petra Nova Carbon Capture in Texas, a CCS project with a commercial-scale coal gasification power facility. The second, in Decatur, Illinois, is the world's first large-scale bio-CCS project: a corn-to-ethanol plant (1 Mt/y). The third, in Kemper County, Mississippi, is one of the US flagships of CCS: A lignite power plant of 582 MW with a CO_2 capture capacity of 3 Mt/y, which has been beset with delays and cost increases. The current investment is USD 6.66 billion, whilst the estimate in 2004 was only USD 2.2 billion. These examples show that under the current market conditions without subsidies, especially in the start-up phase, CCS projects are difficult to realize. Nevertheless, according to the Global CCS Institute, there are dozens of projects in the pipeline and/or in the preparation phase worldwide (Global CCS Istitute, 2016).

The question is, in order to decrease CO_2 emissions, whether administration and industry are prepared, at least in the initial phases, to invest in the capital-intensive technology of CCS in the power-generating industries.

The NEV 2017 predicts a VRE supply of ca. 57% for power generated in 2030 (ECN, 2017b), taking the domination from fossil fuel in the Dutch electricity supply, which will be ca. 40% (excl. 3% nuclear) (ECN, 2017b). Frontier Economics (2015) is optimistic about the future electricity system in the Netherlands. "However, as of today, there is substantial flexibility available in the Dutch power market due to the flexible gas-fired power plant capacity, flexibility in CHP plants, and very substantial cross-border interconnections. Therefore, no immediate action is required to increase flexibility in the short and medium term in the Dutch power system" (Frontier Economics, 2015). Frontier Economics, in its role as advisor for the government, considers the existence of gas-fired power plants as a flexibility solution in the short and medium term, neglecting the impact of their CO_2 emissions. Indeed, in the Energy Agreement, clear target figures are defined, but TNO estimates that without adaptations, problems will arise – possibly already before 2030 – with regard to maintaining the system balance for electricity and its related voltage quality. The problem can be solved over time by fitting the electricity system for an efficient absorption of sustainable flexible sources (TNO, 2015).

If the government's measures to provide flexibility as described in this chapter do not meet expectations, the only possibility to guarantee security of supply are gas-fired power plants (with relatively fast ramp-up times) and coal-fired electricity production units. The NEV 2017 predicts that circa 40% of the supply will be fossil-fuelled in 2030. The emissions of coal power plants are high and even gas-fired units produce only 50% less CO_2. The coal power plants hope to find means to abate the carbon emission substantially via CCS. However, this technology is still in a demonstration and development phase. For the time being, no concrete CCS integration programmes are projected yet for coal-fired power plants in the Netherlands. Without CCS, a reduction of CO_2 from coal-fired power plants by the agreed quantity is implausible.

In the case of ROAD (Rotterdam Capture and Storage Demonstration Project), the EU and the Dutch government should double their contributions to facilitate the capital costs of the investment for the already granted amounts of €180 million and €150 million for the EU and NL, respectively, which leads to a total of €660 million. Anticipating a CO_2 capture volume of 1.1 Mt/y, this would lead to a (one-time) capacity storage subsidy of circa €500 million per Mt (CCS Network, n.d.). It is further supposed that the OPEX (including depreciation) will be incorporated in the electricity pricing (€/MWh). In addition to the solution for introducing the application of CCS, this proposal for the policymakers could trigger other CO_2 emission evasion technologies. This new instrument will be included in the existing SDE system for generating power. This could contribute to a future CO_2-free electricity system, with consequences for a storage system such as O-PAC (see Chapter 7).

2·4 Concluding remarks

This chapter reviewed Dutch energy policies. Its main driver is the wish to decarbonize the energy system, starting with the power sector. The effects of the policy instruments to integrate the increasing share of VRE in the grid, while simultaneously reducing CO_2 emissions, are aleatory. This issue is underplayed by the government. The Ministry of Economic Affairs and Climate Policy, for example, states explicitly that storage will not be necessary in the coming 10 to 20 years (Energierapport, 2016). This statement is at odds with the absence of any quantification of the effects of planned measures to increase flexibility, neither is there a micro- and macroeconomic assessment of the viability of these measures.

In view of the ambitious projections of 42.3 TWh VRE supply in 2023 (ECN, 2017b), it is of prime importance to know how to cope with the natural variability of renewable sources. Investments in wind and solar power generation will at some point falter if no attention is paid to their sustainable integration in the grid. Instead, the official option is to provide for fossil-fuelled backup, which is inconsistent with Dutch emission targets. Moreover, the National Energy Outlook 2015 predicts curtailment, which means that production of solar and wind power will have to be switched off at times. This is thought to be necessary from 2024 onwards (ECN, 2015). Curtailment translates into loss of income and will progressively reduce the economic viability of further VRE investments.

The projected measures in the Netherlands focus on the extension of cross-border connections with neighbouring countries (Section 2.3.1). The patterns of demand and supply of wind and sun power, however, exhibit a fair degree of synchronicity across the EU, and especially in Western Europe. Shortages and surpluses largely coincide (Graabak & Korpås, 2016). Interconnections are less efficient than storage.

Dutch energy policies rely for a large part on the use of EV and household batteries for flexibility in the grid. This is shown to be insufficient, unless paired with adequate system solutions.

Questions arise whether the CO_2 reduction targets in the Netherlands can be reached without additional storage and whether this can be provided by the market. Neighbouring countries, such as Germany, with a higher share of VRE, primarily use large-scale energy storage for flexibility (Die Bundesregierung, 2016). This already increases overall efficiency and lowers greenhouse gas emissions. On top of that, they consider PHS an essential instrument for maintaining grid stability and security of supply (DENA, 2015).

Investments in large-scale storage are capital-intensive, require a construction time of 5 to 7 years, and have around 25 years of investment return time. Financial parties are therefore reluctant to invest, especially when future energy policies are uncertain. Another difficulty is the lack of subsidies for storage systems, similar to the existing incentives for the production of electricity from sun and wind (van Leeuwen, 2016). Subsidies are especially necessary when future policies are uncertain, because investors cannot be confident of future returns.

The 'raison d'être' of this thesis, studying a flatland solution, is further underlined by the observation that other storage technologies are currently not adequate for large-scale application in the Netherlands. In the next chapter, various characteristics of storage applications are analysed.

3 Principles and typology of storage

3·1 Introduction

This chapter presents a typology of storage techniques, along with their working principles, capacities and key characteristics. These are analysed for their usefulness for stabilizing the grid, by providing:

- flexibility to balance supply and demand
- backup and reserve with quick start-up / shut-down capabilities
- spinning reserve / black-start capability
- frequency response regulation
- power compensation / voltage support

3·2 History of storage

As already indicated in the introduction of Chapter 1, the underground PHS solution is remarkably underexposed in the literature of storage technology. However, during the last decade, parallel with the rise of VRE in the power mix, there has been a constant stream of academic and non-academic articles discussing different aspects of electrical energy storage. This can be explained by the recognition of the centrality of electricity storage in fulfilling the growing need to equalize the intermittency of power production by sun and wind. This scientific interest in storage is clearly reflected in the number of articles published. As an example, a review by Luo, et al. (2015) of approximately 750 articles showed different perspectives relating to storage, such as hydro power systems, compressed air (CAES), superconducting magnetic energy storage (SMES), and energy management (Luo, et al., 2015). While a multitude of authors have highlighted different aspects of storage, only a few relevant publications warrant mention within the framework of this thesis.

Ibrahim, et al. (2008) characterized and offered an in-depth analysis of power plants, including load levelling and quality control related to storage systems.

Dunn, et al. (2011) discussed electrochemical storage systems, including sodium sulphur, low-cost redox flow, and lithium-ion batteries. Hall & Bain (2008) explored storage systems including batteries, supercapacitors, superconducting magnetic energy storage and flywheels.

Other authors concentrated on the improvement of materials in order to raise the output (W), storage capacity (Wh), and lifetime of batteries (Whittingham, 2008; Liu, et al., 2010).

Energy management is also the subject of many studies, such as the work by Connolly, et al. (2010), focusing on the use of ICT techniques to integrate VRE into various electricity systems.

Díaz-González, et al. (2012) trained their attention on the optimization of wind power in planning operation and control strategies. And more recently, Zhao, et al. (2015) presented solutions and applications for the integration of wind power, analysing planning and optimal (storage) size.

Most of the studies mentioned do not specifically focus on PHS. Since PHS is a technology with high technical maturity and more than a century of application, it is unsurprising that basic research articles refer only to technical optimization and improvement.

Since the subject of this study refers to underground PHS, it is of note that the idea for creating underground basins as the lower part of PHS was proposed more than a century ago.

A recent account of the history, the present state, and future prospects of underground pumped hydro storage came from Pickard (2012). "Although PHS facilities have been built worldwide as a mature and commercially available technology, it is considered that the potential for further major PHS schemes is restricted in the UK" (Pickard, 2012). "Therefore, it is of great importance that suitable EES (Electric Energy Storage) technologies, in addition to PHS, are explored" (Luo, et al., 2015). These thoughts are not unique to the UK. In most of the countries of the EU and worldwide, the search for alternatives has intensified on account of the growth of VRE.

Pickard reveals that Fessenden had already started the discussion about underground pumped hydro in 1910, but there is no evidence that the ideas were acted upon, presumably due to the Great Depression, followed by the Second World War (Pickard, 2012). In 1960, however, Harza broached the idea of employing a disused mine as an underground reservoir (Harza, 1960). At that time, there was a perception that appropriate conventional sites were becoming scarce in the United States, a view that apparently persists to the present day. In 1968, Isaksson, Nilsson and Sjostrand presented a plan for a purpose-built underground reservoir at the World Power Conference in Moscow (Isaksson, et al., 1968). This was followed in 1969 by Sorensen, who published his landmark article "Underground reservoirs: Pumped storage of the future?" and predicted a bright future for U-PHS (Sorensen, 1969).

Continuous research in this field took place on a global scale. In the Netherlands, in the 1980s, a study group, consisting of TH Delft (now Delft University of Technology), Haskoning and Volker Stevin, was established to design a concrete underground pumped storage project in South Limburg (see Chapters 5 and 6).

3·3 Basic operation of electricity storage

As a starting point for analysing storage, a system properties scheme is presented, indicating the different stages in the storage process (Figure 14).

Figure 14 *– Electricity storage system properties scheme*

The storage system properties in Figure 14 are elaborated below:

- **Excess power** can be the result of frequency regulation and avoiding curtailment of wind and solar power.
- **Charging** can be seen as a form of consumption and is characterized by the rate at which electricity can be withdrawn (power) and the time needed to start (ramping rate).
- **Storing phase** adds the time-shifting dimension and is characterized by the amount of electricity the system can store (energy being equal to power multiplied by time) and the self-discharge rate.
- **Discharging** can be considered as a form of power generation and is characterized by the rate at which electricity can be injected (power) and the time needed to start (ramping rate).
- **Supply (reuse)** ends the storage process by delivery to the grid at times when needed.

  Based on: SBC Energy Institute (2013)

3·4 Electricity storage solutions

This chapter will offer profiles of the different storage technologies. In order to contextualize the nature of complex storage technologies, the below classification is introduced.

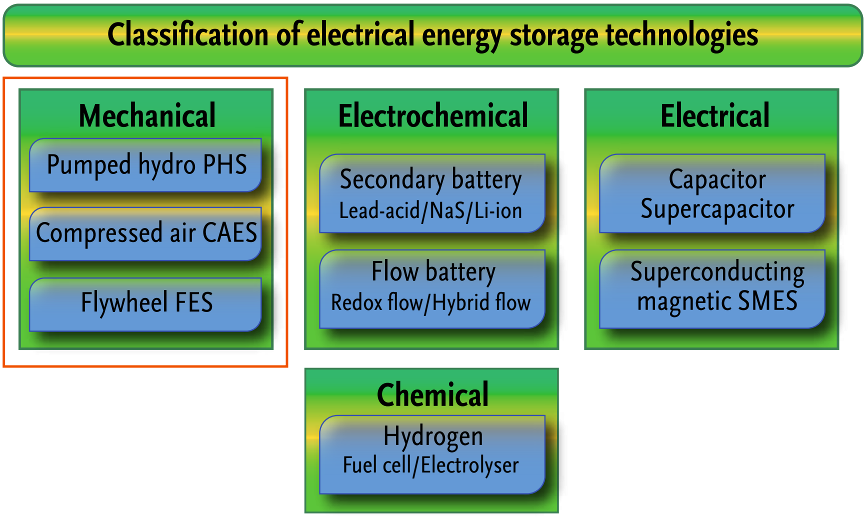


Figure 15 – *Classification of electric energy storage technology (derived from: Luo et al. (2015))*

The upper three boxes of this classification represent the most frequently applied techniques: mechanical, electrochemical and electrical. The three systems in the left box (mechanical storage) are central to this thesis, especially PHS. The large-scale storage capabilities of CAES, and the quick-response properties of FES, are also of particular interest. Direct electrical and electrochemical storage systems are relevant, since they can provide services for flexibility and maintaining frequency and voltage in the grid. Especially capacitors, supercapacitors and SMES, are indispensable for first reserve and quality control. Developments in battery technology are promising in terms of quality, weight, duration and size. The lower part of the storage classification is dedicated to chemical storage technologies. There is no doubt that these applications, most of which are in a research phase, may contribute to resolving future seasonal storage challenges in the long term.

3.4.1 Mechanical storage

Though mechanical storage is one of the most established forms of storage, further developments are of interest, since significant progress has recently been made in optimizing these technologies. In all three applications – PHS, CAES and FES – a growing interest has been observed to meet the demands of flexibility caused by VRE. For mechanical storage, which originated largely in the nineteen-seventies and -eighties, the process of introducing digital control systems has enhanced the efficiency of these systems. Together with the improvement of pump and turbine technology, this has resulted in a higher cycle efficiency and larger capacity for pumped hydro. Likewise, the drawbacks of compressed air have been countered by the development of advanced CAES systems. Finally, flywheel technology has been subject to innovations due to the use of new materials and better control programmes, all of which has resulted in both higher capacities and shorter response times.

Pumped hydro storage (PHS)

"Pumped hydro storage (PHS) projects move water between two reservoirs located at different elevations (i.e. an upper and lower reservoir) to store energy and generate electricity. Generally, when electricity supply outstrips demand (e.g. when VRE output is high at night), excess electric generation capacity is used to pump water from the lower reservoir to the upper reservoir. When electricity demand exceeds the conventional supply, the stored water is released from the upper reservoir to the lower reservoir through a turbine to generate electricity. Pumped storage projects are also capable of providing a range of ancillary services to support the integration of renewable resources and the reliable and efficient functioning of the electric grid" (FERC, 2017). "PHS is an EES technology with a long history, high technical maturity and large energy capacity" (Luo, et al., 2015). Western Europe (WEU) is the cradle of pumped hydro. As early as the end of the 19th century, Switzerland, Austria, and Italy were pioneers of installing hydro power plants. The introduction of a single reversible pump – instead of separate impellers and turbine generators – around the middle of the 20th century, was a breakthrough in the development of this technology. The growth of nuclear power generation favoured the application of PHS as a complement to those baseload plants. Since nuclear power production is less easily modulated than fossil-generated power, it causes superfluous electricity production during off-peak hours, to which PHS offers an effective solution. After this period of growth, different developments, including a significant drop in gas prices, led to decades of stagnation for PHS. Gas turbines are more price-competitive in putting pressure into the market of flexibility; as a result, investments in new PHS were hard to obtain. However, the introduction of VRE has raised the demand for flexibility and hence for storage solutions.

Further detailed descriptions of PHS follow in Chapter 4, including the design of PHS, energy arbitrage, ancillary services, investment costs of PHS plants, and PHS innovations.

CAES / AA-CAES

In recent decades, compressed air energy storage (CAES) has become a large-scale storage alternative to PHS, with power outputs between 100 MW and 1,000 MW. A schematic diagram is presented in Figure 16.

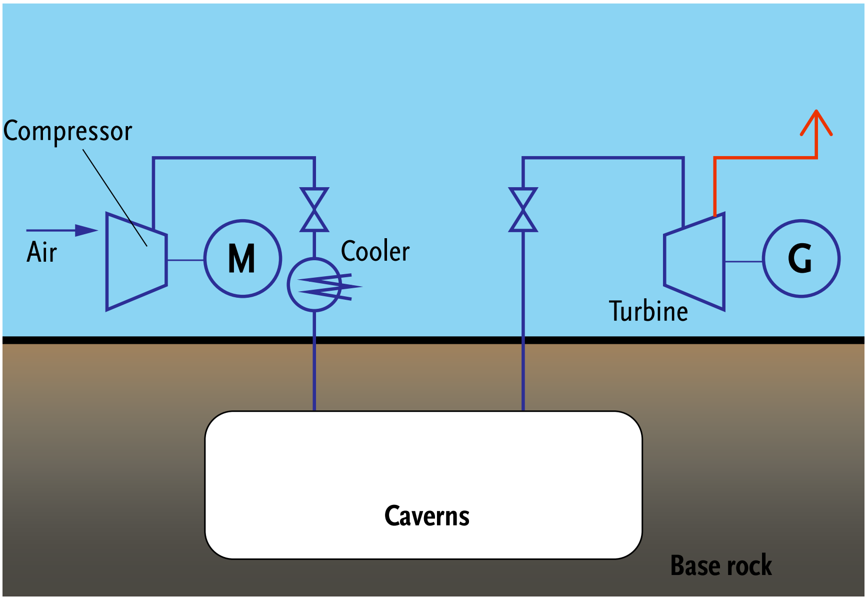


Figure 16 – Diabatic CAES system (IEA, 2009)

CAES allows for a gas turbine power plant that consumes less than 40 % of the fuel used by conventional gas turbines while producing the same amount of electric power. In electricity generation with a conventional gas turbine, about two thirds of the fuel input is used to compress air. In contrast, CAES pre-compresses air using (low cost / off-peak) electricity from the grid, stores it in a reservoir, and utilizes that energy later – along with some gas fuel – to generate electricity upon demand. The compressed air is stored in appropriate underground mines or caverns, typically created in salt rock deposits.

A diabatic CAES system consists of a compressor unit connected to a motor, gas turbine, and underground caverns. When charging, the motor unit consumes power to compress air and store it underground. The adiabatically compressed air is usually cooled via a cooler unit. When discharging, the compressed air is supplied to a combustor in the gas turbine to burn fuel. The combusted gas expands through the turbine, which drives the generator and produces electric power.

The amount of gas required is small enough for a gas turbine working simultaneously with CAES to produce three times more electricity than a gas turbine working on its own, using the same amount of natural gas (Connolly, et al., 2010).

The world's first utility-scale CAES plant was installed in Huntorf, Germany, in 1978. It was initially rated at 290 MW and later upgraded to 321 MW. This plant provides black-start power to nuclear units, backup to local power systems, and load levelling. This system uses two caverns (totalling 310,000 m^3) to provide up to 425 kg/s of compressed air (at a pressure of up to 70 bar) and produces efficiencies up to 55 % (IEA, 2014b). Another commercial CAES plant started operation in McIntosh, USA, in 1991. In 1998, the system was extended with two additional generators and its total capacity is now 226 MW (Barbour, n.d.).

By adding a recuperator to recover the waste heat from the gas-fired expansion process, the efficiency has been improved by 12 %, totalling 54 % (Zakeri & Syri, 2015).

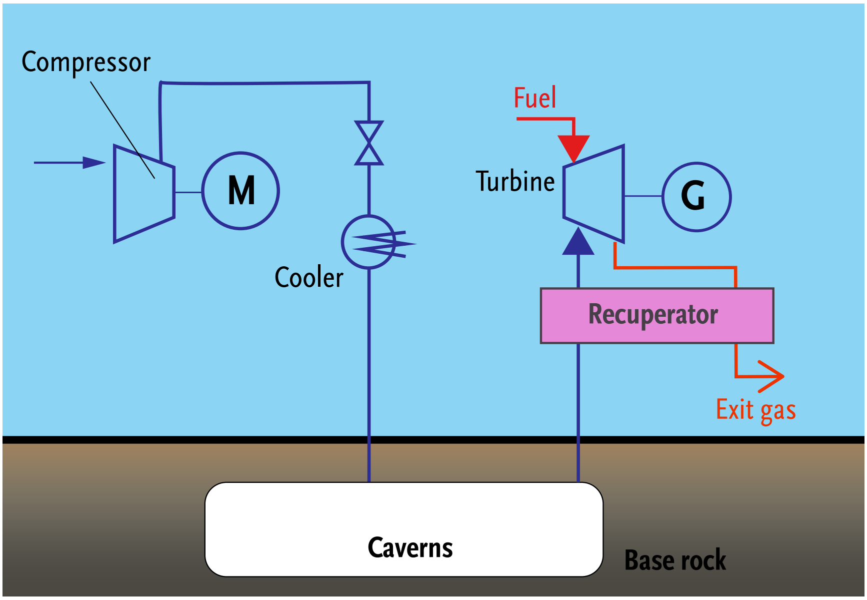


***Figure* 17** – *CAES system with recuperator (IEA, 2009)*

There are a great number of CAES initiatives in the planning phase, but not yet realized. This includes a plant in Norton (USA) in 2000, with an ambitious target of 2,700 MW.

Without any doubt, CAES has a number of inherent advantages, such as more efficient use of fuel. However, there are also a number of drawbacks which hamper propagation:

- low cycle efficiency, varying from 42 to 54% (Zakeri & Syri, 2015)
- scarcity of locations with underground conditions suitable to withstand the pressure
- relatively slow reaction time of around 10 minutes
- the use of fossil fuel causing CO_2 emissions (Connolly, et al., 2010)

In order to mitigate these concerns, the development of a far more complex system was initiated in Germany: advanced adiabatic compressed-air energy storage (AA-CAES). In AA-CAES, the extra heat of air compression is recovered by a thermal storage unit to heat the air during the expansion process, eliminating the supplemental gas-firing procedure. The expected rate of efficiency is approaching 70%.

This process enhancement increases the cost of AA-CAES by 30–40% compared to the conventional counterparts (Zakeri & Syri, 2015).

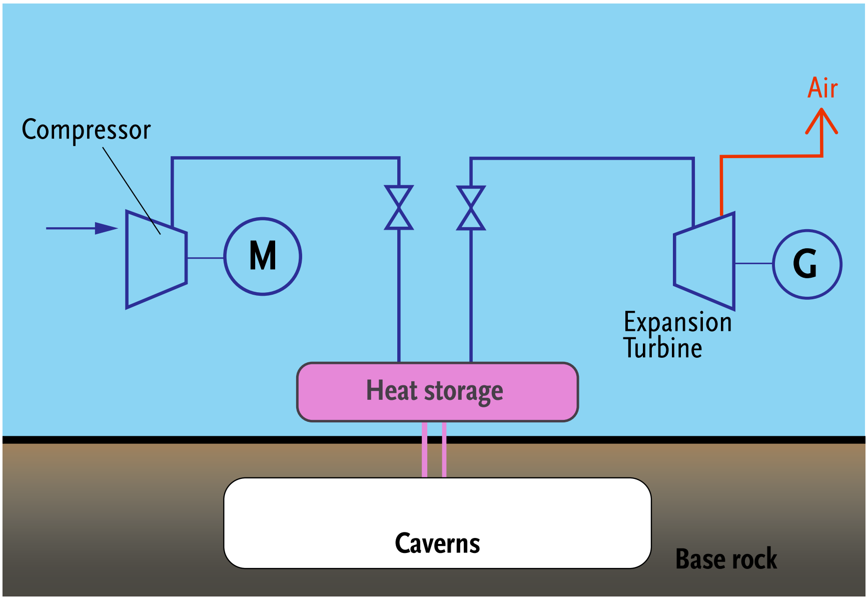


Figure 18 – Advanced adiabatic CAES system (IEA, 2009)

In 2010, an AA-CAES project was introduced under the name of Adele. A project team consisting of RWE-Power AG and, among others, GE Global Research officially started developing the world's first project in Saxony-Anhalt. The German Federal Ministry for Economics subsidized the R&D project, with support from the EU.

The demonstration plant has an objective of 300 MW and 1,000 MWh capacity. One of the greatest challenges is coping with the heavy demands on the equipment, including cyclical stresses, temperatures of over 600 °C, and pressures of up to 100 bar. The core function is compressing the air to 100 bar and feeding it to the heat storage device (RWE, 2010). This is only one example of the R&D complexities in a such a new, multidisciplinary field of application. Unfortunately, the Adele project was terminated in 2012. Due to the rapid structural changes in the energy market, the originators were reluctant to invest further in the necessary research. The rapid deterioration of economic and financial circumstances placed a positive business plan out of reach.

It is quite remarkable that the CAES scheme is prominently featured on the agendas of decarbonizing power generation. Taken into account that diabatic CAES still produces considerable CO_2 emissions, it must be seen as a transition technology on the road to CO_2-free electricity generation. There are currently CAES power plants in the design phase all around the world; 10 plants are being planned in the USA alone. As for Europe, various initiatives are in preparation, but to date, no new CAES projects have been realized (US DOE, 2016; BINE, 2007).

The AA-CAES technology, the aim of which is to produce CO_2-free electricity storage, is in the stage of research and development. Fuelless CAES is an energy storage concept that removes the natural gas combustion from conventional diabatic CAES. There are two main variants: AA-CAES and isothermal CAES. The latter technology is represented by an isothermal prototype of 1.5 MW by SustainX. Its attractiveness is hampered by a high degree of technical challenges, coupled with the need for considerable investment, as the examples of Adele and SustainX demonstrate. Therefore, it is not expected that this technology will contribute substantially to the flexibility of the grid within the coming decade.

Flywheel energy storage (FES)

Though FES does not comply with the large-scale focus of this thesis, attention will be paid to flywheel energy storage (FES) to complete the discussion of mechanical storage systems. As defined by IEA: “Flywheels are mechanical devices that spin at high speeds, storing electricity as rotational energy. This energy is later released by slowing down the flywheel’s rotor, releasing quick bursts of energy (i.e. releases of high power and short duration)” (OECD/IEA, 2014a).

FES is applied in order to maintain power quality, to deliver black-start services and for intermittent balancing. To a limited extent, its services for the TSO consist of power fleet optimization, and in case of limitations of the grid, T&D deferral (SBC Energy Institute, 2013).

FES can be classified into two groups:

1. Low-speed FES: uses steel as flywheel material and rotates below 6,000 rpm. It is typically used for short-term and medium/high-power applications.
2. High speed FES: uses advanced composite materials for the flywheel, such as carbon fibre, which can run up to ≈100,000 rpm.

The main weakness of FES is that flywheel devices suffer from idling losses during the time when the flywheel is on standby. This can lead to relatively high self-discharge, up to ≈20 % of stored capacity per hour (Luo, et al., 2015).

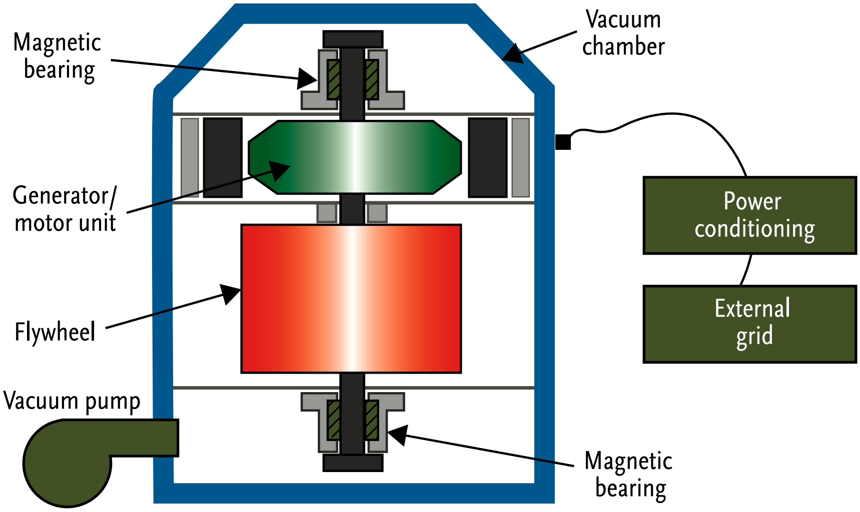


***Figure* 19 – System description of an FES (Luo, et al., 2015)**

A modern FES system is composed of five primary components: a flywheel, a group of bearings, an electrical motor-generator, a power electronic unit, and a vacuum chamber. FES systems use electricity to accelerate or decelerate the flywheel. The stored energy is transferred to or from the flywheel through an integrated motor-generator (Luo, et al., 2015).

Figure 20 *– Matrix flywheel system in Hazle Township, Pennsylvania. Source: Convergent Energy + Power flywheels, photo credit: Eugene Hunt.*

Beacon Power's second 20-MW facility in Hazle Township, PA provides an example of FES's application in grid storage. Installed especially for frequency regulation, the plant includes 200 flywheels and has a capacity of 5 MWh (20 MW for 15 minutes) and reached full commercial operation in 2014 (Beacon Power, 2014).

Future flywheels with low speed / high power capacity will need to extend into applications such as regenerative energy and frequency regulation in order to be future-proof (Connolly, et al., 2010).

"The main energy losses of the flywheel are due to windage loss and bearing loss. The latter limits flywheel applications to short-term storage. With the development of high-temperature superconducting materials, superconducting bearing technologies can be applied to flywheels" (IEA, 2009). Flywheels can be categorized as in the deployment phase of the maturity curve. "With commercial applications in UPS systems and individual wind turbines, flywheel systems are at a practical stage of development. To promote their installation, it is important to put larger flywheel systems to practical use. Several efforts are underway to improve their efficiency" (IEA, 2009).

3.4.2 Electrochemical storage

Battery developments

As discussed in Section 1.5, the focus of this thesis is principally on mechanical storage with more than 100 MW power. Nevertheless, battery technology developments, particularly for modular application, are important. These solutions may contribute to storage and will be briefly described below, based on the following observations:

- Huge R&D financial efforts on a global scale have been allocated with the aim of reducing weight and volume, and enlarging power, capacity and lifetime, often through the use of rare materials.
- In most government programmes, household and EV batteries are assigned as capacity for storage to facilitate flexibility of the grid.
- New applications of used battery packs from the automotive sector are being introduced in the grid.
- Specialized large global companies such as AES are dedicated to providing services for levelling the grid through large-scale storage, i.e. 10 MW battery in Vlissingen (NL), with the intention for a roll-out elsewhere in Europe.

“Among the secondary (rechargeable) batteries – lead-acid, NaS and Li-ion – (see Table 4), breakthrough technologies for cost reduction will be required. Even NaS batteries, which have adequate performance characteristics, are more expensive than pumped hydro and CAES. If Li-ion batteries play an important role in the form of electricity storage for electric vehicles (EVs) and plug-in hybrid vehicles, their cost might decrease with volume efficiency. On the other hand, the specifications of Li-ion battery for EVs and power grids are quite different, and current efforts to develop and promote Li-ion batteries for EVs may not be applicable to energy storage use” (IEA, 2009). Recent developments show that the costs of Li-ion batteries have decreased substantially. The Economist (2017) reports a price drop from €1,000 per kWh to a price range of €130 – 200 per kWh, whilst Bloomberg New Energy Finance (2017a) reports a price of €273 per kWh (BNEF, 2017a; The Economist, 2017).

Secondary batteries: NaS, Li-ion and lead-acid

	Lead-acid (LA)	Sodium-sulphur (NaS)	Lithium-ion (Li-ion)
Efficiency %	70 – 90	70 – 90	85 – 95 (1)
Self-discharge % energy/day	0.033 – 0.3	0.05 – 20	0.1 – 0.3
Cycle lifetime cycles	100 – 2,000	2,500 – 4,500	3,000 – 10,000 (2)
Expected lifetime years	3 – 20	5 – 15	7 – 10 (3)
Specific energy Wh/kg	30 – 50	150 – 240	120 – 210 (4)
Specific power W/kg	75 – 300	150 – 230	75 – 300
Energy density Wh/litre	30 – 80	150 – 300	177 – 676 (5)
Other considerations (environment & safety)	Lead is toxic and sulfuric acid is highly corrosive, requiring recycling and neutralization. Air conditioning is required to maintain a stable temperature	Need to be maintained at temperatures of 300 °C to 350 °C, entailing safety issues and preventing suitability to small-scale applications	Lithium is highly reactive and flammable, and therefore requires recycling programmes and safety measures

Table 4 – Secondary batteries (SBC Energy Institute, 2013)

(1) (AES, 2016); (2) (Arteaga, et al., 2017); (3) (Smith, et al., 2017); (4) (EPEC, 2018); (5) (Hesse, et al., 2017)

Sodium-sulphur (NaS) batteries

Among the most widely used secondary batteries is the NaS battery with an installed capacity more than 400 MW worldwide. The Rokkasho-Futamata wind farm (Japan) includes a 34 MW plant with 17 sets of 2 MW batteries with 238 MWh total storage capacity, that is used for load levelling and spinning reserves (SBC Energy Institute, 2013).

The materials required to create a NaS battery are inexpensive and abundant, and 99 % of the battery is recyclable. The NaS battery has the potential to be used on a MW scale by combining modules (Connolly, et al., 2010).

NaS batteries have attained an advanced stage of deployment. With a yearly growth of 75 – 100 MW of installed capacity worldwide, the total volume of the applications of this BES (Battery Electricity Storage) system has crossed the threshold of 1 GW (SBC Energy Institute, 2013).

An area for continued research is reducing the need to operate at temperatures above 270 °C. Maintaining these elevated temperatures is not only energy-consuming, but also creates problems such as thermal management and safety regulations. In addition, due to harsh chemical environments, insulators can be a problem as they slowly become conducting and self-discharge the battery (Connolly, et al., 2010).

Lithium-ion (Li-ion) batteries

An example of the large-scale application of Li-ion batteries is the 32 MW Laurel Mountain West Virginia (USA) plant, commissioned in 2011. Used as backup for a wind farm, it is the largest of its kind, with 15 minutes of storage capacity (SBC Energy Institute, 2013).

Furthermore, in December 2013, Toshiba announced a project to install a 40 MW/20 MWh Li-ion battery project in Tohoku, which will help integrate renewables into the grid. In addition, Li-ion batteries are now applied in hybrid and full electric vehicles (HEVs and EVs), which use large-format cells and packs with capacities of 15 – 20 kWh for HEVs and up to 50 kWh for EVs (Luo, et al., 2015).

Lithium-ion batteries have shown rapid advances, whereas flow batteries may need more time. Small-scale Li-ion battery projects, have increased in popularity during the last few years. They are a favourite method of electricity storage in China, and Japan introduced a three-year subsidy programme (SBC Energy Institute, 2013). Current research focuses for the Li-ion battery include (1) increasing battery power capability with the use of nanoscale materials; (2) enhancing battery-specific energy by developing advanced electrode materials and electrolyte solutions. Several companies have experience using Li-ion batteries in the utility-scale energy market (Luo, et al., 2015).

Sterner and Stadler state that additional research is required to improve the security of Li-ion batteries, specifically in addressing the problem of decomposition caused by temperatures between 150 and 200 °C (Sterner & Stadler, 2014).

Lead-acid (LA) batteries

The world's largest LA battery system was repowered in Puerto Rico in 2005. It can deliver an output of 20 MW for 10 minutes. It is used as a rapid spinning reserve for the island's grid, as well as for frequency and voltage control (Farber-DeAnda, 2005).

Due to the low cost and maturity of the LA battery, it will probably always be useful for specific applications. However, the requirements of new large-scale storage devices would significantly limit the life of a lead-acid battery. Consequently, most research has been directed elsewhere. Therefore, it is unlikely that LA batteries will be competing for future large-scale multi-MW applications (Connolly, et al., 2010).

Flow batteries: redox flow and hybrid flow

"A flow battery stores energy in two soluble redox couples contained in external liquid electrolyte tanks. These electrolytes can be pumped from the tanks to the cell stack which consists of two electrolyte flow compartments separated by ion selective membranes. The operation is based on reduction-oxidation reactions of the electrolyte solutions" (Luo, et al., 2015). One of the most mature flow battery systems is the vanadium redox flow battery (VRB), with a fast response (0.001 s) and a lifetime of 10,000 – 16,000+ cycles. Such systems have efficiencies of up to ≈85 %. At the moment, two projects on VRBs have been funded with a combined cost of £1.2 million in the UK. One is planned to test a 100-kW redox flow battery for utility EES. The other project has been developed in order to store surplus energy from VRE sources. Both projects intend, after successes in small-scale trials, to pursue development on a larger scale (Luo, et al., 2015).

Zinc-bromine (ZnBr) flow batteries belong to the category of hybrid flow batteries. Two aqueous electrolyte solutions based on zinc and bromine elements contain the reactive components and are stored in two external tanks. During the charging/discharging phases, these electrolyte solutions flow through the cell stack, which consists of carbon-plastic composite electrodes in compartments. The firm RedFlow in Australia successfully commercialized a fully functional ZnBr module product, which delivers up to 3 kW of continuous power (5 kW peak) and up to 8 kWh of energy. It claims a maximum nett energy efficiency of up to 80%. In 2011, the Sacramento Municipal Utility District planned to demonstrate a 1 MW ZnBr flow battery system for multi-EES applications (Luo, et al., 2015).

"Unlike conventional batteries, flow batteries rely on two separately stored electrolytes to decouple their power and energy capacities" (SBC Energy Institute, 2013).

Flow batteries constitute an area of very active researching and testing. The hybrid flow technology of VRB, ZnBr, and to a lesser extent PSB (polysulfide bromide battery), are the focus of research, development, and in some case demonstration. Not only in Western Europe, but also in Japan, Australia and the USA, VRB and PSB have great potential due to their unique versatility, specifically regarding their MW power and storage potential. However, they have not yet reached commercial maturity (Connolly, et al., 2010).

3.4.3 Electrical storage

Supercapacitor energy storage (SCES)

"A capacitor is composed of at least two electrical conductors (normally made of metal foils) separated by a thin layer of insulator (normally made of ceramic, glass or a plastic film). When a capacitor is charged, energy is stored in the dielectric material in an electrostatic field" (Luo, et al., 2015).

Supercapacitors (also: electric double-layer capacitors or ultracapacitors) consist of two conductor electrodes, an electrolyte and a porous membrane separator. Supercapacitors have both the characteristics of traditional capacitors and electrochemical batteries, based on their structures. Siemens, of Germany, installed a supercapacitor with a capacitance of 2,600 F and a storage capacity of 5.7 Wh for a metro distribution net application (Luo, et al., 2015).

Supercapacitors are high-power, low-energy devices that are able to react very quickly. Unlike batteries, they can withstand a very high number of cycles (up to 100,000), due to the absence of a chemical reaction. Their efficiency rate is 80 to 95% and they require power electronics to ensure a steady output, because their voltage varies linearly with the charge contained in the system (SBC Energy Institute, 2013).

Current research is concentrated on developing capacitance – the ability to store electrical energy – different electrode materials, such as next-generation nanocarbons, metallic oxides and conducting polymers. This technology has attracted a great deal of attention from the worldwide electricity industry, because it forms an essential element in the storage technology mix. The main developers of advanced supercapacitors include Siemens, SAFT, NESS, ESMA, Maxwell Technologies, ELIT, Power System Co., and Meiden Co. (IEA, 2009).

Superconducting magnetic energy storage (SMES)

An SMES device is made up of a superconducting coil, a power-conditioning system, a refrigerator and a vacuum used to keep the coil at a low temperature. Energy is stored by way of a magnetic field, which is created by the flow of direct current in the coil wire. The wire must be kept at a very low temperature in order to maintain a superconducting state, which allows energy to be stored with practically no losses. Due to the high power capacity and instantaneous discharge rates of SMES, it is ideal for the industrial power quality market. It protects equipment from rapid momentary voltage sags caused by sudden changes in consumer demand levels, lightning strikes or operation switches. However, due to the high energy consumption of the refrigeration system, SMES is unsuitable for daily cycling applications such as peak reduction (Connolly, et al., 2010).

An SMES device is able to react almost instantaneously and has a very high cycling life. Its required maintenance is limited and it can achieve high efficiencies of between 97 and 98 %, with small losses coming from use of AC/DC converters. Due to high refrigeration energy requirements, the complexity of the system, and the high cost of superconductors, SMES are currently at an early demonstration phase and only suitable for short-term storage (Connolly, et al., 2010).

Research priorities for SMES include lowering the high cost of energy (refrigeration) and simplifying the complexity of the system related to magnetic fields. Solutions also have to be found for improvement of the cryogenic processes. The Research Association of SMES, RASMES, in Japan, produced a roadmap for research in the coming decades. From the present day to 2040, the industry has agreed on a three-step programme which should lead to the development and application of 1 GWh-class SMES systems for daily load levelling by 2040 (IEA, 2009).

3.4.4 Chemical storage

Power-to-gas (P2G): hydrogen / synthetic natural gas (SNG)

"Chemical storage is part of the re-electrification pathway, in which electrical power that was used for electrolysis and stored as hydrogen is converted back into electricity. However, development seems to be at standstill, with the number of projects limited and mostly small in scale" (SBC Energy Institute, 2013).

Simplified, the first step is the production of hydrogen (H_2) from water (H_2O) by using the electric power to split off the oxygen (O_2). The next step is combining the hydrogen with carbon dioxide (CO_2) by a high-temperature pressure process generating methane (CH_4) and water. Methanization requires large quantities of CO_2, which may be available as a by-product of production processes of carbon capture (CCS).

The role for P2G in the future Dutch energy system is mainly related to the production and subsequent use of hydrogen (power-to-hydrogen), and only to a lesser extent to the further conversion to synthetic methane (power-to-methane) (ECN, 2014).

IEA states in its "Vision for Deployment to 2050" that hydrogen-based energy storage systems show the greatest potential for achieving acceptable LCOE for seasonal storage applications (OECD/IEA, 2014a). An example of a demonstration plant in Utsira, a Norwegian island, was developed by Statoil and Enercon in 2004. The uninterrupted supply of power on the island is provided by 2 wind turbines, with backup from an electrolyser, hydrogen storage vessels and a 55 kW fuel cell. In spite of it functioning properly, no commercialization has followed as of yet.

Ammonia (NH_3)

A Dutch research programme aims to realize a demonstration project over the next five years, in which abundant power from wind and sun can be stored in the form of ammonia. The chemical process to obtain NH_3 derives from the decomposition of water into hydrogen and oxygen by means of electrolysis, and the subsequent application of the Haber-Bosch process, in which the hydrogen forms a compound (NH_3) with nitrogen. Ammonia poses no great technical storage problems because it is fluid at atmospheric pressure and -35 °C or under 8.5 bar pressure at room temperature. The objective of the demonstration project is to produce industrial quantities of ammonia to be used as fuel, instead of natural gas, for CO_2-free power generation when it is needed. The project aims to provide long-duration storage in order to cope with different seasonal patterns in wind and sun power production. The challenge for research lies on the one side in optimizing the electrolytic production process and on the other side in achieving a significant improvement of the large-scale electricity output. The target is to attain an efficiency rate between 40 and 45 %. It is doubtful whether this technology can play an important role in long-duration storage due to technical feasibility issues.

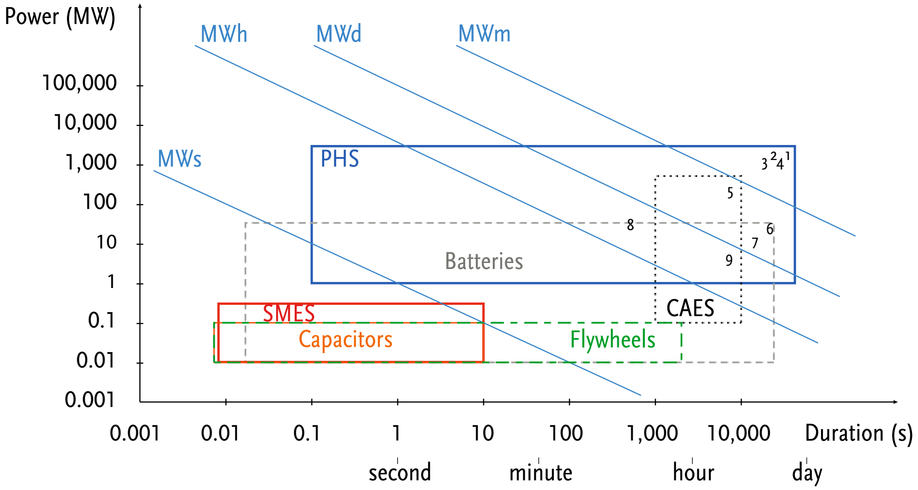
3·5 Characteristics of storage

The properties of a storage system determine the range of applications that it can serve, which are discussed in Section 3.6. In storage, the following key characteristics are presented here with their appropriate units:

Characteristic	Description (Unit)	Section
Power	Watts (W)	3.5.1
Discharge duration	Full power generation (m, h, day, weeks)	3.5.1
Time-to-grid	Response time (ms, s, m, h)	3.5.2
Ramp-up/down time	Change in power output (W per second)	
Self-discharge	Energy losses during storage	3.5.2
Efficiency	Energy out / energy in	3.5.3
Technical lifetime	Typical time of technical life (cycles, years)	3.5.3

3.5.1 Power and discharge duration

As stated repeatedly, this thesis focuses on large-scale storage, which in the literature is generally understood to refer to systems with an output of more than 100 MW. Battery technology is nevertheless included since linking up offers capacities exceeding 34 MW (SBC Energy Institute, 2013). It is a matter of discussion whether the long-duration storage that is under development with research (R&D) and in a demonstration phase (D&D), will play a substantial role in the coming decades. Since the form and the application of these technologies are currently difficult to classify, they are not included in the available schedules.



1. PHS Ludington, USA
2. PHS Dinorwig, GB
3. PHS Vianden, Lux
4. PHS Goldisthal, De
5. CAES Huntdorf, De
6. NaS Rokkasho, Jp
7. Lead-acid Chino, USA
8. NiCd Fairbanks, USA
9. VRB Tomamea, Jp

Figure 21 – Characteristic electricity storage power, capacity and discharge duration. The numbers indicate specific storage plants.

This diagram shows that PHS is able to deliver > 1,000 MW power. The conclusion can be drawn that only PHS and CAES are mature and available for large-scale storage applications. While batteries may be scalable and increasingly mature, a system with a total power output in the gigawatt range has not been installed until now.

This diagram does not claim to be complete, especially in the lower segment with power < 100 MW and capacity < 1,000 MWh. Here, numerous new developments are emerging, especially in the batteries sector.

The different forms of storage were discussed in detail in this chapter. But first several important characteristics related to the key factor of time are subject to further exploration: discharge time, time-to-grid, and technical life time.

3.5.2 Time-to-grid and self-discharge

This refers to: "Response time: is the length of time it takes the storage device to start releasing power" (Connolly, et al., 2010). In case of discontinuity in VRE electricity generation, the power system – in order to maintain an uninterrupted supply of electricity to the grid – must resort to using backup utility power plants.

Type	Technology	Response time	Self-discharge (per day)
Electrical	Supercapacitor	10-20 ms	20-40%
	SMES	< 100 ms	10-15%
Mechanical	PHS	sec-min	very small
	CAES	sec-min	small
	Flywheels	10-20 ms	100%
Electrochemical	NaS battery	10-20 ms	≈20%
	Li-ion battery	10-20 ms	0.1-0.3%
	Flow battery	10-20 ms	0.2%
Chemical	Hydrogen	sec-min	almost zero
	SNG	sec-min	almost zero

Table 5 – Response time for the different energy storage technologies (Deloitte, 2015; Evans, et al., 2012; SBC Energy Institute, 2013)

3.5.3 Lifetime and efficiency

Fundamental characteristics of any storage system are the technical lifetime – expressed in cycles – on the one hand and the rate of efficiency (η = energy_discharged/energy_charged) on the other. If both indicators are high, the system meets optimal requirements (see upper right quadrant).

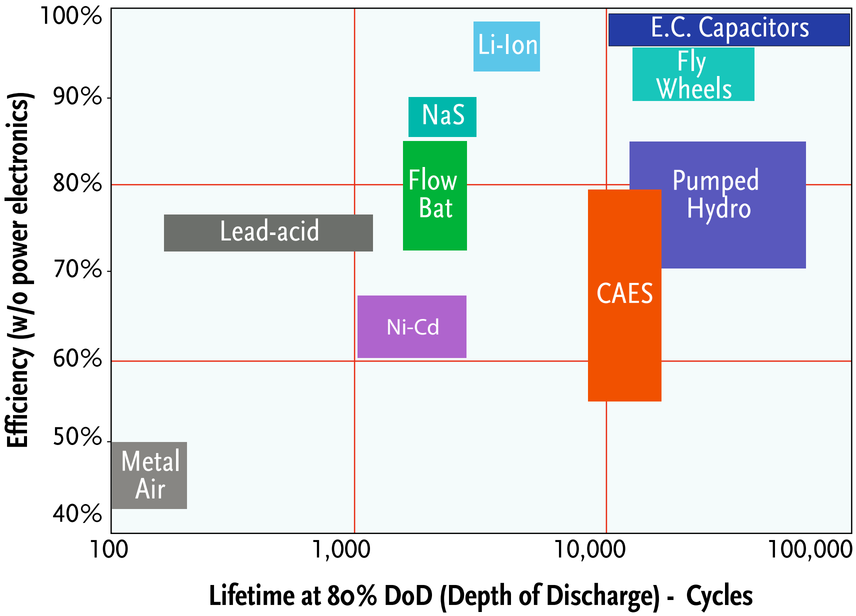


Figure 22 – Lifetime and efficiency (Energy Storage Association, n.d.)

These technical data are important for the analysis and comparison of the costs of the different energy storage systems. On the basis of lifetime / cycles and capital investments, operating and maintenance costs, a realistic model for comparing different forms of storage can be produced. In Sections 3.7 and 7.6, this will be covered more in detail.

3·6 Survey of applicability

“The value of energy storage technologies is found in the services that they provide at different locations in the energy system. These technologies can be used throughout the electricity grid, in dedicated heating and cooling networks, and in distributed system and off-grid applications. Furthermore, they can provide infrastructure support services across supply, transmission and distribution, and demand portions of the energy system” (OECD/IEA, 2014a).

The features of storage technologies required for particular applications are shown in Table 6.

Application	Power (MW)	Discharge duration	Cycles (typical)	Response time
Seasonal storage	500 to 2,000	days to months	1 to 5 per year	day
Diurnal storage	100 to 2,000	8 hours to 24 hours	0.25 to 1 per day	> 1 hour
Load levelling	1 to 2,000	15 minutes to 1 day	1 to 29 per day	< 15 min
Demand shifting and peak reduction	0.001 to 1	minutes to hours	1 to 29 per day	< 15 min
Frequency regulation	1 to 2,000	1 minute to 15 minutes	20 to 40 per day	1 min
Voltage support	1 to 40	1 second to 1 minute	10 to 100 per day	millisecond to second
Spinning / Non-spinning reserve	10 to 2,000	15 minutes to 2 hours	0.5 to 2 per day	< 15 min
Black-start	0.1 to 400	1 hour to 4 hours	< 1 per year	< 1 hour
Transmission and Distribution (T&D) congestion relief	10 to 500	2 hours to 4 hours	0.14 to 1.25 per day	> 1 hour
T&D infrastructure investment deferral	1 to 500	2 hours to 5 hours	0.75 to 1.25 per day	> 1 hour

***Table 6** – Functionality of storage for particular applications (IEA, 2014b)*

"For electricity storage, discharge period, response time and power rating provide a good first indicator on suitability. For thermal storage, storage output temperature and capacity can be used as a starting point in determining suitability for particular applications" (OECD/IEA, 2014a).

Discharge time refers to the duration of the discharge process and can range from microseconds to seasonal storage of weeks and even months.

A sophisticated schedule with the cooperation of IEA and a multitude of institutions, laboratories, and governmental sources from around the world provided the following analysis:

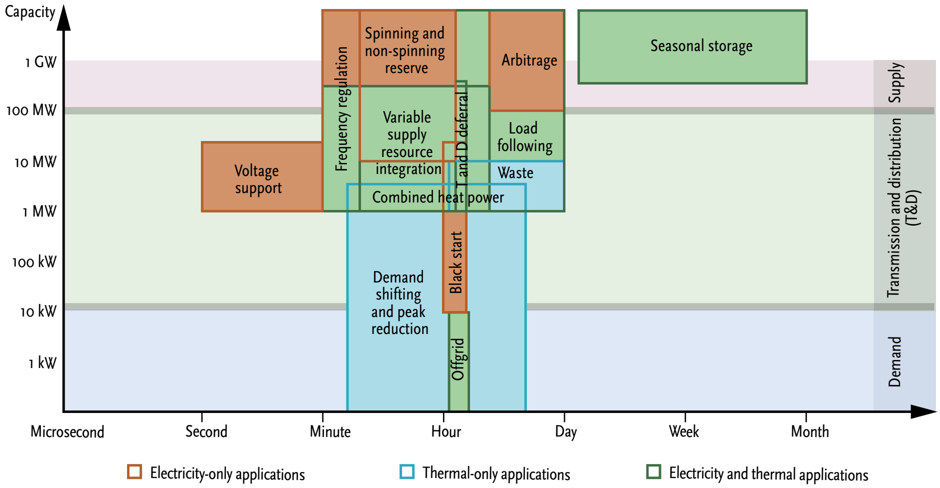


***Figure 23** – Power requirement versus discharge duration for some applications in today's energy system (OECD/IEA, 2014a)*

In terms of functionality, two categories can be distinguished: primary and ancillary. The primary functions are load levelling and frequency regulation, while the ancillary functions include arbitrage, black-start, T&D congestion relief and spinning and non-spinning reserve (IRES Proceedings, 2012).

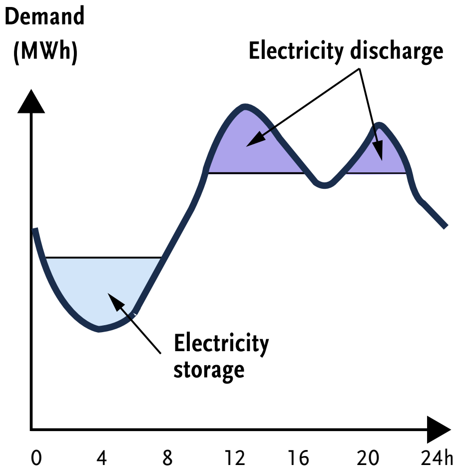


Figure 24 *– Load levelling by means of electricity storage (SBC Energy Institute, 2013)*

Electricity storage is used to level the load on the sources of energy over various timescales. Typically, electricity is stored during periods when demand is low compared to the generating capacity and discharged when peak demand exceeds the generating capacity. Storage helps to reduce the peak/off-peak amplitude of the power generation (daily, weekly and seasonal demand). This can also occur over shorter timescales (hourly) to smooth the load and avoid activating peak plants.

The above figure illustrates a typical situation within a conventional generating mix. However, variable renewables create their own need for storage to balance their intermittency.

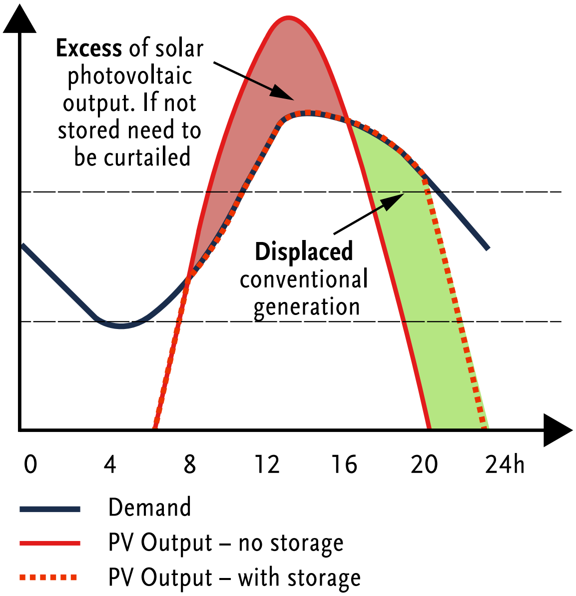


Figure 25 *– Illustrative output of a solar photovoltaic plant with storage (SBC Energy Institute, 2013)*

Load levelling may become essential as wind and solar increase the need for flexibility without themselves contributing significantly to the flexibility of the power system. As VRE comes first in the merit order, they may displace some of the capacity of baseload power plants and affect the utilization rate of peak power plants.

With high VRE penetration, the combination of low demand and high production can result in an excess of energy. Storage can avoid curtailment and, as a result, energy wastage (SBC Energy Institute, 2013).

The above example shows a typical situation in which the solar energy does not match the demand. If electricity generation by wind turbines is added, with its capricious supply patterns, the magnitude of the mismatch may be significantly greater. In relation to the impact on the demand of flexibility, this subject will be analysed further in Chapter 9.

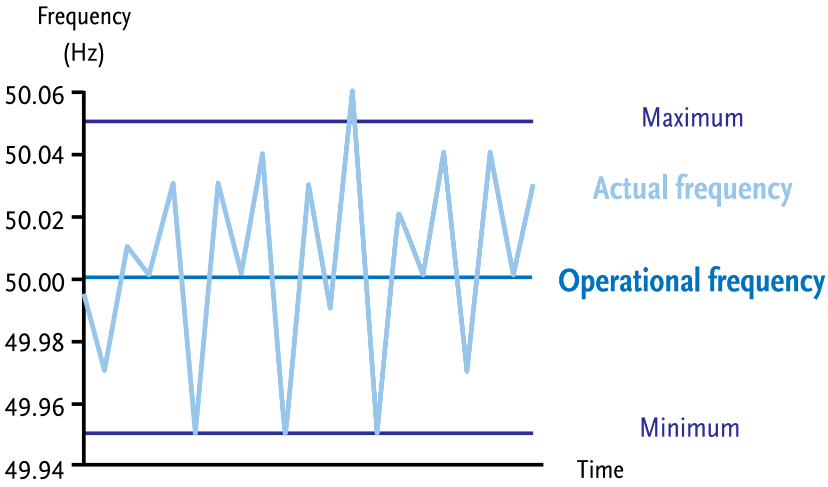


Figure 26 *– Frequency regulation by electricity storage (SBC Energy Institute, 2013)*

The electricity system's frequency and voltage need to be maintained within technical limits to avoid instability and blackouts. This could be achieved by using fast-response electricity storage to inject or withdraw power as an alternative to conventional reserves (frequency response, spinning and non-spinning, and replacement reserves).

3 · 7 Survey status and electricity storage developments 2030–2050

Research in (applied) technologies has the objective of achieving greater efficiency, resulting in lower costs. Ultimately, 'breakthrough' ideas are indispensable for creating general acceptance and support in order to realize the targeted objective.

An example of a 'breakthrough' scenario is proposed by IEA in the Energy Technology Perspectives (ETP) (2014), in which a 2DS (2 °C scenario) serves as a reference case, determining the necessary capacity expansion of power generation technologies by 2050 to meet low-carbon objectives (IEA, 2014b).

"Electricity storage technologies could provide services in a variety of applications across the energy system, from addressing power quality to providing energy arbitrage or seasonal storage" (IEA, 2014b).

An important element in the 'breakthrough' scenario is: "a translation of cost reductions in electricity storage technologies to compete with the least expensive option of providing arbitrage services. This translates to a levelized cost of energy (LCOE) for daily bulk storage of approximately USD 90/MWh. The LCOE includes the cost of the initial technology infrastructure investment, operation and maintenance, and electricity used to charge the storage facilities" (IEA, 2014b).

For PHS, significant reductions in civil engineering costs have already reduced the overall cost. "However, because of the high initial capital investments required for these facilities, potential cost reductions could be found in lowering the cost of capital for new large-scale storage projects" (IEA, 2014b).

Such a scenario is currently realistic since present capital costs are low, a result of historical low interest rates. It is the expectation that this financial situation will continue for the coming decade. This enables the realization of large-scale projects, which were not feasible in the past, since the capital costs amounted to double or triple what they are with current interest rates. Consequently, established, mature technologies are in a privileged position to benefit from these favourable circumstances. In Chapter 7 of this thesis, these and other economic aspects will be discussed in greater detail. In the aggressive ETP 2DS, relatively new storage technologies such as hydrogen have to realize considerable cost reductions and efficiency improvements. According to IEA, it seems unlikely that hydrogen-based power-to-power storage systems will attain the breakthrough cost target (IEA, 2015).

Especially in the case of batteries, technologies such as lead-acid, vanadium redox, and Li-ion would need to realize extreme cost reductions of a factor greater than 10 (OECD/IEA, 2014a).

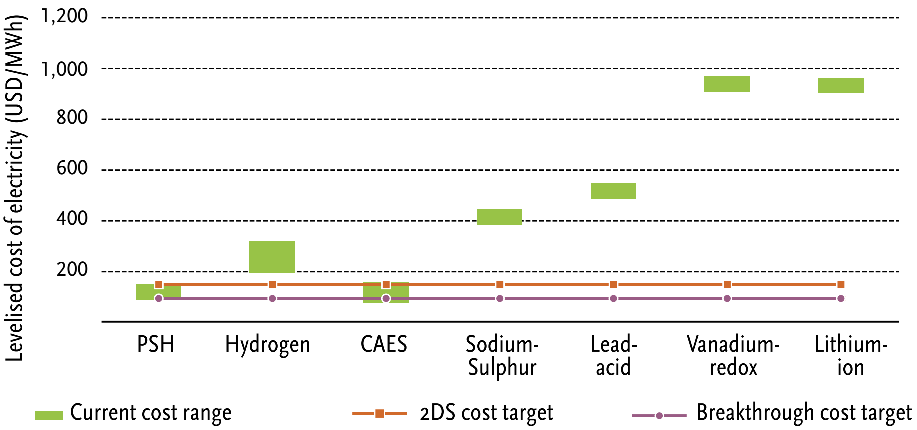


Figure 27 – LCOE in the 'breakthrough' scenario in 2013 and 2050 (OECD/IEA, 2014a)

Given that PHS, CAES and hydrogen already have the lowest LCOE, the question arises whether efforts to realize the targeted storage capacities should be concentrated on these technologies. This implies that policymakers and TSOs should give preference to facilitating the development of these. It is clear that if PHS is the benchmark for daily load levelling, this should be the first option for additional storage capacity.

In order to reach the status of a mature technology, the preceding phases must be passed through: initial research, followed by development, setting up a demonstration project, and deployment, resulting in the application of mature technology. Capital requirements, in function of the specific technological risks, are spread across the total route from research and development up to maturity, and it is a condition sine qua non. SBC Energy Institute presented an instructive graph about the maturity of electricity storage technologies, which are described in Section 3.4.

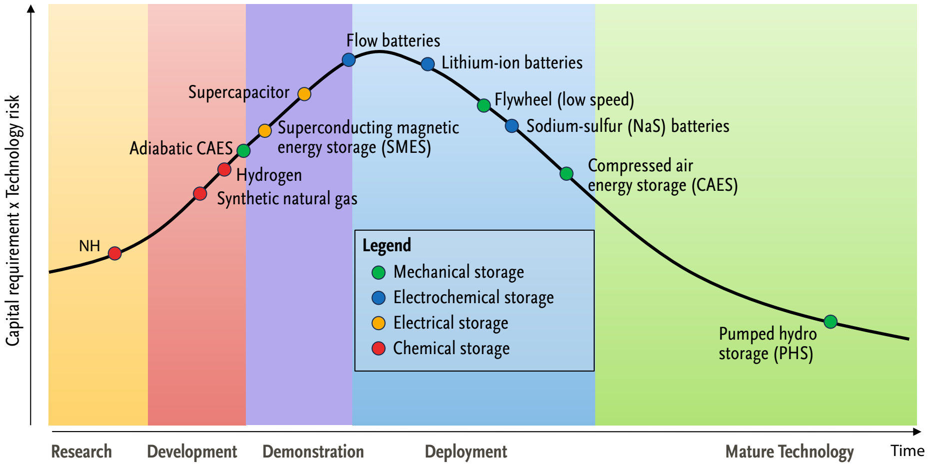


***Figure 28** – Electricity storage technology maturity curve (derived from: SBC Energy Institute (2013))*

With the aid of this classification, the different technologies can be analysed with regard to their relevant phase. However, sharp delimitations are not always possible due to continuing progress in the research and development of a given technology.

Moreover, the cost aspect will play a dominant role since prices of flexibility are subject to the markets. The introduction of all storage systems will be hampered by relatively low current wholesale electricity market prices, which also reflects on ancillary storing services.

This electricity storage technology maturity curve shows that PHS is an undisputed mature technology. Nevertheless, for PHS as well as CAES, specific geographic and other conditions are required for further application. Suitable locations are scarce.

An interesting sidestep beside the presented maturity curve (Figure 28) are the considerations of the Gartner 'Hype Cycle for Emerging Technologies' (2017), where technical developments pass from the 'Peak of Inflated Expectations' via a 'Trough of Disillusionment' and 'Slope of Enlightenment' into a 'Plateau of Productivity'. There are striking similarities between a number of recently proposed projects and Gartner's 'Hype Cycle'. Concepts with towering high expectations on novel electricity storage technologies such as blue hydrogen, adiabatic CAES and underwater spheres, are presently at the top. However, less attention is paid to the further course of the 'Hype Cycle' namely passing the 'Valley of Death' before entering the 'Plateau of Productivity' (Gartner Inc., 2017; Gartner Inc., 2018).

3·8 Concluding remarks

Energy storage is a trade-off between power range, storage capacity, response time and efficiency. Ramp-up times vary from milliseconds to hours, depending on the system, and continuous supply times range from minutes to weeks. Also, large differences exist in power, from 1 kW up to 1 GW and more, whilst providing storage capacity from 1 kWh up to a GWh level.

To supply sufficient power, exactly in tune with demand, TSOs need an arsenal of balancing instruments, including storage, to guarantee the quality of the grid by frequency (within the defined limits) and voltage control. When it comes to multi-day or intraday large-scale energy storage with an output of around 1,000 MW, only PHS and CAES are sufficiently mature. A detailed analysis of PHS is presented in Chapter 4.

4 Pumped hydro storage

4·1 Introduction

PHS is a further development of hydroelectric power generation, with which it still shares many characteristics. The bidirectional water flow is the main difference. In most cases, equipment can be operated in reverse to switch from a generation to a pumping mode. A generator then becomes an electric motor and a turbine a hydraulic pump. However, some PHS plants, particularly those with a very large head (i.e. height difference between upper and lower basin), use different units for the turbine and the hydraulic pump, so that they can be optimized separately (Koritarov, et al., 2013).

Almost all European countries (with the exception of flat countries such as the Netherlands and Denmark) have a large installed capacity of PHS (Table 7).

	PHS Power	Av. Power Consumption	Percentage
Country	**MW** *	**MW (2014)** **	**PHS/Consumption**
Austria	4,808	7,962	60 %
Belgium	1,307	9,247	14 %
Bulgaria	1,052	3,539	30 %
Croatia	282	1,937	15 %
Czech Republic	1,145	6,849	17 %
France	5,894	49,201	12 %
Germany	6,388	60,845	10 %
Ireland	292	2,854	10 %
Italy	7,071	33,219	21 %
Lithuania	900	1,130	80 %
Luxemburg	1,296	708	183 %
Norway	967	14,429	7 %
Poland	1,745	16,210	11 %
Portugal	1,592	5,251	30 %
Serbia	614	3,072	20 %
Slovenia	185	1,484	12 %
Spain	6,889	26,712	26 %
Sweden	350	14,498	2 %
Switzerland	2,687	6,621	41 %
Ukraine	905	16,324	6 %
United Kingdom	2,828	35,274	8 %
Total	49,197	317,366	16 %

Table 7 – *PHS in selected European countries in 2016 compared to their average national power consumption (2014)*

* Yang (2016)
** Wikipedia (2018)

The Netherlands is one of the few countries in Europe without serious hills or mountains. Storage based on conventional PHS is therefore not an option. But a single underground system, as proposed in this thesis, would bring Dutch storage to 1,400 MW, which is 11 % of average power consumption.

The Netherlands is the only country – with the exception of Denmark – within Western Europe having a topography without significant mountainous altitude differences. As a consequence, storage facilities based on the conventional PHS principle are not an option. Even small neighbouring countries such as Belgium and Luxemburg were able to construct pumped hydro storage plants with more than 1,000 MW output based on natural height differences. With the construction of a 1,400 MW U-PHS, as proposed in this thesis, the Netherlands would be represented in the above list with a percentage of approximately 11.

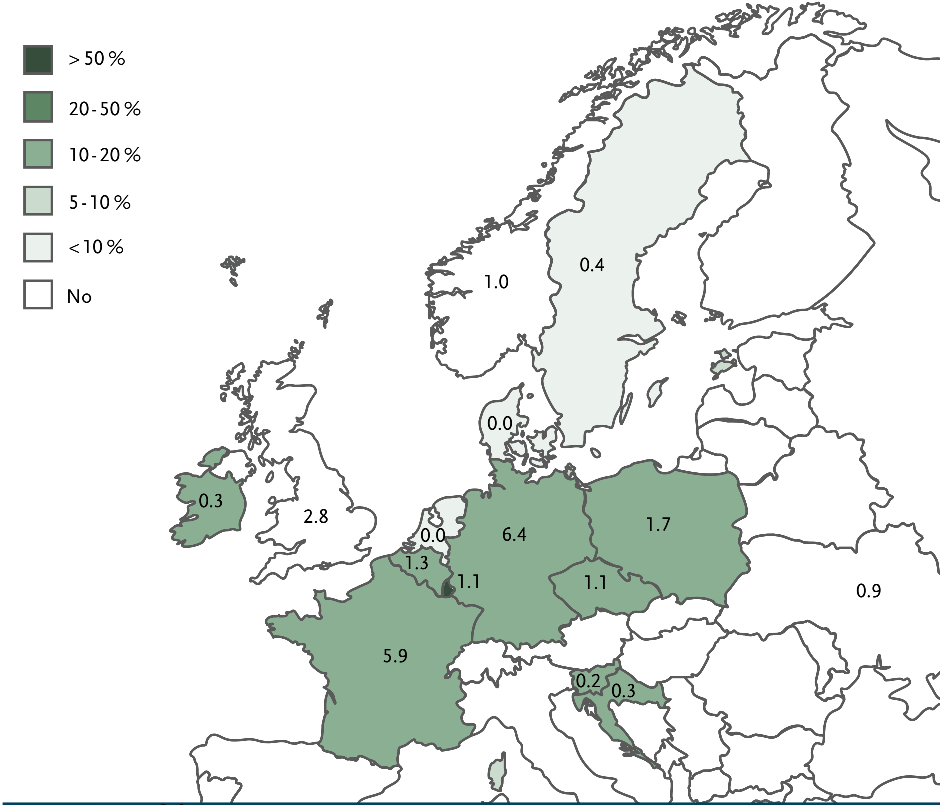


Figure 29 – *PHS in selected European countries in 2016 compared to their average national power consumption (2014)*

The need to decarbonize power generation has increased the interest in PHS around the world. Worldwide, more than 100 new PHS plants with a total power of 74 GW are expected to come into operation by 2020.

Europe is also witnessing a renaissance of PHS – particularly Spain, Switzerland and Austria – with 27 GW of new capacity expected by 2020 (Yang, 2016).

The USA has issued 40 preliminary permits for new PHS. A recent hydro vision plan aims at 6.3 GW of upgrades and 35.5 GW of new capacity before 2020, with the intention to bring the total power to 150 GW by 2050 (US DOE, 2016).

Japan is the current world leader with the highest installed PHS power, more than 24 GW is provided by 27 plants (the smallest being 360 MW) (FEPC, 2016). This storage was originally built to balance nuclear power. Now that an ambitious VRE plan is adopted, power companies develop even more storage, taking advantage of the favourable topographic circumstances.

Lastly, in 2014, the Chinese government announced its plan to drastically increase its 21.5 GW PHS (2015) to 100 GW in 2025 (Yang, 2016).

This shows that "with the mature technology and high volume of commercial development activities, PHS will certainly remain the most dominant energy storage technology in the foreseeable future" (Yang, 2016).

4·2 Theoretical background of pumped hydro storage

4·2·1 Energy and power output

The principle of hydroelectric energy storage is based on gravitational potential energy, created by storing water at a certain height. In physics, the energy used for pumping to an upper reservoir, the stored energy, and the energy that is generated by a specific PHS plant can be calculated with the following formulas:

$E_p = (Q{\cdot}\rho{\cdot}g{\cdot}\Delta h{\cdot}T)/\eta_p$ $\qquad$ $E_s = V{\cdot}\rho{\cdot}g{\cdot}\Delta h$ $\qquad$ $E_t = Q{\cdot}\rho{\cdot}g{\cdot}\Delta h{\cdot}T{\cdot}\eta_t$

Where:

E_s = potential energy stored in upper reservoir (J)
E_p = energy used during pump operation (J)
E_t = energy generated during turbine operation (J)
T = time of operation in pump or turbine mode (s)
Q = flow of water (m^3/s)
V = volume of water (m^3)
ρ = density of water ($\rho \approx 1{,}000\ kg/m^3$)
g = gravitational acceleration ($g \approx 9{,}81\ m/s^2$)
Δh = head (m)
η_p = pump efficiency
η_t = turbine efficiency

The power output of the pump (P_p) and turbine (P_t) can be calculated with:

$$P_p = (Q{\cdot}\rho{\cdot}g{\cdot}\Delta h)/\eta_p \qquad \text{and} \qquad P_t = Q{\cdot}\rho{\cdot}g{\cdot}\Delta h{\cdot}\eta_t$$

These formulas resemble the earlier calculation for energy consumption by the pump and production by the generator closely as energy is power output over the time of operation (i.e. $E = P \cdot T$).

4.2.2 Efficiency

The round-trip efficiency of PHS typically ranges between 70% and 85%. Losses mainly occur in the pumping and turbine stages, both of which are around 92% efficient. Efficiency can be calculated with the formula:

$$\eta_r = \eta_p \cdot \eta_t$$

Where:

η_r = round-trip efficiency
η_p = pump efficiency
η_t = turbine efficiency

The formula can be expanded, to account for the additional losses in transformers, motors, generators and shaft line. Additionally, some losses occur, because on entering the tailrace, the water still retains some residual kinetic energy. However, these efficiency losses are substantially smaller than turbine and pump efficiency losses (Ter-Gazarian, 2011).

4.2.3 Head capacities

The discussed formulas show that one of the determining elements of the pumped hydro system is its hydraulic head, which is the difference between the elevation of the upper basin and the lower basin. The height difference is the prime determinant of hydro power, determining both the power rating and the energy storage. The power capacity (kW) is a function of the flow rate (Q) and the hydraulic head (Δh), whilst the energy stored (kWh) is a function of the reservoir volume (V) and the hydraulic head (Δh).

By planning a conventional pumped hydro plant, the head is dependent on the existing topographic circumstances provided by nature. Also in the case of abandoned mines, both on the surface and in subsurface, the possible heads form a major criterion for the site selection of the PHS plant.

In the case of absence of natural height differences, the creation of an artificial head is necessary, which may be achieved by constructing a lower reservoir underground. Consequently, the geological conditions have to be favourable in order to minimize costly civil engineering works. Two alternatives have the attention of the designing engineers: the low-head variant (Plan Lievense) and the high-head version

(OPAC). Both concepts have different characterizing consequences. The low-head solution in the original version needs vast geographic surfaces of hundreds of square kilometres combined with a huge water volume. The high-head version, on the contrary, uses a limited water volume, combined with the subsequent relatively costly civil engineering works, such as caverns in the deep underground. The head determines the selection of the turbine type for a specific application. Roughly, the following scheme gives an indication:

- Pelton turbines $H = 200$ to 1,800 m
- Francis turbines $H = 30$ to 600 m
- Propeller and Kaplan turbines $H = 3$ to 60 m

In principle, turbines are flow machines, with different diameters, which can be compared with the aid of model rules in hydrodynamics. The performance of geometrically identical machines is proportionally equal, conforming to Newton's similitude principle. Therefore, these machines are useful for modelling studies. In a laboratory environment, the expected output of a turbine can be studied by using a geometrically similar scale model with appropriate hydraulic properties. For large turbines, the demonstration that the output requirements are met (the so-called performance guarantee) is often based exclusively on these model studies.

The following parameters play an important role in the design phase of a turbine:

1. inlet diameter (D) of the runner
2. manometric head (H)
3. volume flow (Q) in m^3/s or in power (P) in kW
4. rotational speed (n) expressed in revolutions per minute (rpm)

These parameters can be scaled from the initial model to the actual geometrically similar turbine by a set of homologous equations. The parameters, which differ in value for every machine type, can be combined in a single formula that suggests the most appropriate turbine type for a given head. This indicator, calculated by the formula, is the specific speed (van Duivendijk, 2014).

The specific speed (n_S) is a dimensioned characteristic of a specific turbine model under specific operational characteristics. The specific speed can be used to determine the type of turbine required for a certain flow and head, or the rotational speed required for a specific model of turbine in a specific operational environment (i.e. given head and power output). The specific speed (n_S) is defined as the speed in revolutions per minute (rpm) at which a geometrically similar turbine would run under 1 unit head to produce 1 unit of power output, and is calculated for turbines with the following formula (Twidell & Weir, 2015):

$$n_S = \frac{P^{0.5} \cdot n}{{H_a}^{1.25}}$$

With P being the power output from the turbine, H_a is the available head at the turbine and n is the runner rotational speed in rpm. The units used for calculation have to be stated as they vary between the USA (e.g. rpm, shaft horsepower, ft) and Europe (e.g. rpm, metric horsepower, m), and a standard for SI units has yet to become common (Twidell & Weir, 2015). Different types of turbines have different typical specific speeds (see below and Figure 47). This knowledge is used to select the best suited turbine for a certain operational situation.

In practice, the specific speed is provided by the turbine manufacturer, which allows for easy turbine selection for the PHS to be designed. The following classification of specific speeds for different turbine types is based on the power in HP (horsepower), rotation in rpm (revolutions per minute), and head in mwc (metres water column) (van Duivendijk, 2014):

Pelton turbines	n_S = 10 to 70
Francis turbines	n_S = 70 to 350
Kaplan turbines	n_S = 300 to 1,000

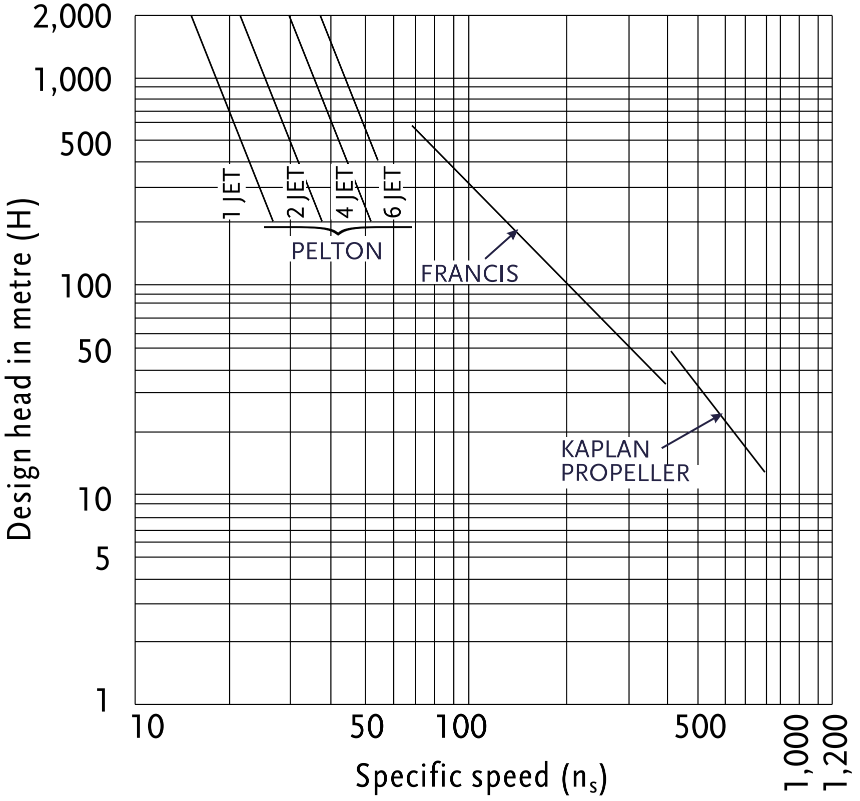


Figure 30 *– Turbine selection chart (derived from: Sangal, et al. (2013))*

Large heads typically correspond with low specific speeds and vice versa. However, this head-dependent relation does not have strict limits. It may be possible that two or more turbine types can operate within the given head range. This means that a different machine with a slightly higher or lower specific speed can also be selected. The choice for a particular machine will have consequences for the turbine power and the level at which the turbine will be located (van Duivendijk, 2014).

The head between the upper and lower reservoir may change, as a result of a dropping water level in the upper, and a rising water level in the lower reservoir. Therefore, different head types can be distinguished for the operation of a turbine:

“The design head is the aimed nett head with the highest peak efficiency. This head should be selected within the permissible operating range of the turbine and approaching as near as possible the weighted average. This design head characterizes the basic capacities of the turbine, and hence of the entire power plant. For Francis and Kaplan turbines, the admissible spread of the head is 65 to 125 % of the design. For fixed-bladed propellers, the range is 90 to 110 % of the design head.

The rated head indicates the nett head at which the turbine produces the generator-rated output in kW or MW at full gate.

The critical head is the nett head at which the full gate output of the turbine produces the permissible overload on the generator (usually 115 % of the generator's power rating). This head will produce the maximum discharge through the turbine" (van Duivendijk, 2014).

Note that the relative difference in head, due to changes in water levels, will be much smaller for high-head systems than for low-head systems.

4.3 Layout and operating principles

PHS stores energy by pumping water with low-cost off-peak electric power from a lower to an upper reservoir. During periods of high demand, the water from the upper reservoir will be released into the lower, running through a turbine connected by a shaft to an electric power generator (see Figure 31).

Two major types of PHS can be distinguished:

1. **The combined, hybrid or pump-back system** uses two reservoirs in tandem on the same river. The pump-back system uses both natural inflow of water and pumped water to generate electricity. These systems have much in common with conventional hydro plants, with the exception that some or all of the turbines are pump-turbine units (Antal, 2014; Koritarov, et al., 2014).
2. **The closed-loop or off-stream system** is based on two reservoirs that are not connected to a natural flow of water (e.g. river). It relies entirely on water that was previously pumped into an upper reservoir as the source of energy. For such system, it may be a challenge to find a source of water for initial filling and refilling of the reservoirs in case of losses. The advantage is that there is minimal interaction with aquatic life in existing ecosystems (Antal, 2014; Koritarov, et al., 2014; Yang, 2016).

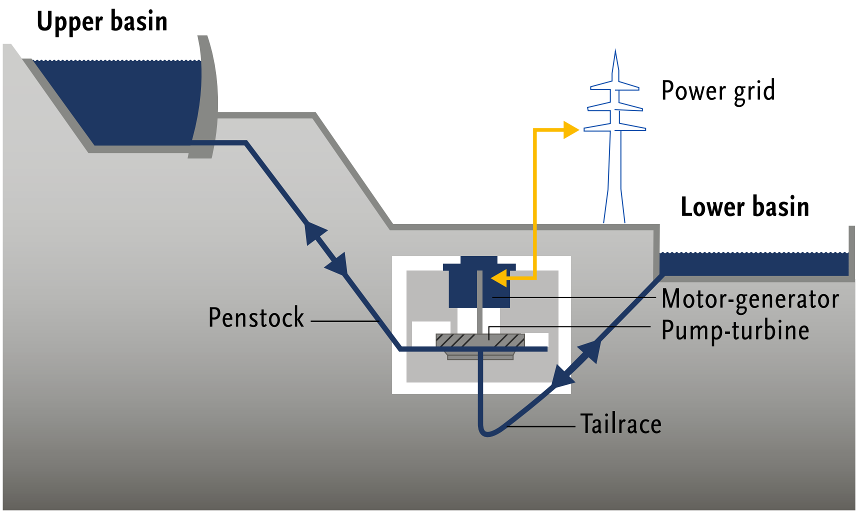


Figure 31 *– Layout of a conventional PHS (typical closed-loop system)*

4.3.1 Pumped hydro storage design

Originally, pumped hydro storage systems adapted the design from the conventional hydroelectric generation (extraction) system and were located in the open air in the vicinity of the lower reservoir. In order to avoid cavitation in pump parts, the hydraulic unit had to be placed at depth, well below the minimum tail water level. The increase of power capacity ratings and pumping heads, together with the higher rotational speed of turbines, required this layout. As a consequence, massive concrete construction works are needed to resist the external water pressure and to counter the hydrostatic uplift, which affects the costs (Ter-Gazarian, 2011).

Developments in civil engineering techniques, such as drilling, blasting, spill removal and rock support, together with the instalment of high-voltage switch gear and ducted busbars, made it cost-effective to design the system subsurface. This includes all elements in the generating, transforming and switching processes. Moreover, this new concept facilitates the location of the power system along the waterways, in this way optimizing the hydrodynamic characteristics of the underground scheme. Initially, the pipelines were usually placed outdoors, but they were ultimately superseded by concrete-lined tunnels, being part of the underground layout. Almost all of the conventional pumped hydro power plants in the open landscape have a considerable great and vital part of the installation (such as machine hall and shafts) in the underground, with the exception of the reservoirs (Ter-Gazarian, 2011).

When designing the layout, the dimension of the machine hall determines the mounting of the pump-turbine and generator by horizontal design, the height of the housing is limited, mainly by the structure of the natural environment, since the rotary axis is also horizontal. In the case of a limited available height, this setting is preferred. Today, this solution is still in use and in some cases of newly built plants with this setup in operation.

Figure 32 – *PHS Vianden with horizontal rotary axes.*
Source: SEO (Société Electrique de l'Our) Archives

Originally the pump-motor and turbine-generator combinations were placed horizontal and separately in the PHS system. Later developments made integration of these functions in a single vertical combined pump-turbine and motor-generator possible. Details will be analysed later in this chapter. The machine hall is the heart of the PHS and is mostly situated subterraneous, since it has to be located below the lower reservoir.

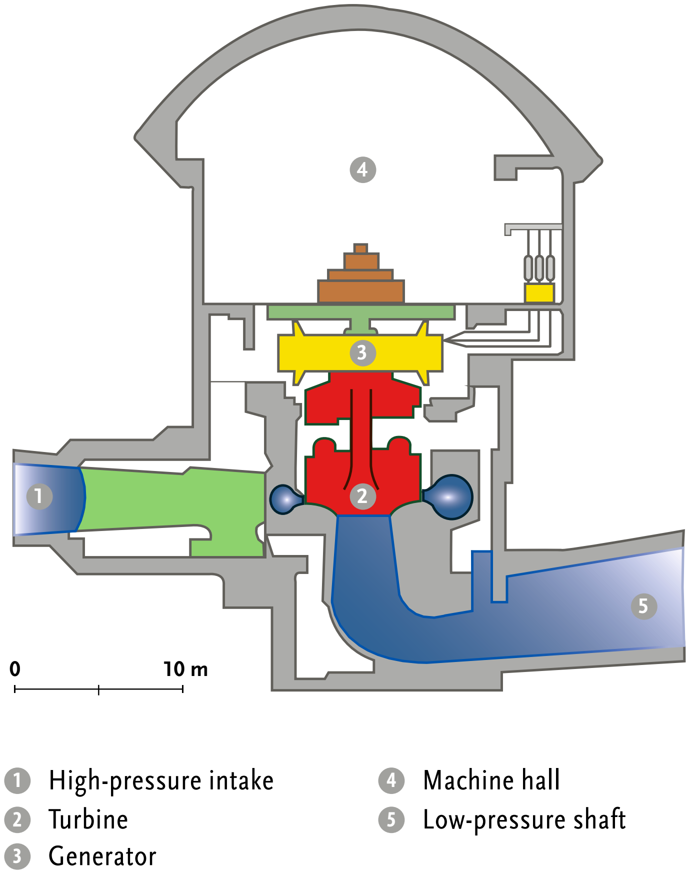


***Figure 33** – Schematic hydro power machine hall layout with vertical axis*

4.3.2 Pumped hydro storage electromechanical typology

Until a century ago, the common PHS practice was a 4-unit system, whereby the turbine-generator and the pump-motor were each mounted on two separate shafts. The principle of separate shaft design is seldomly used these days, due to higher capital costs, which usually outweigh the advantages in efficiency, availability and fast response.

Further developments and change in layout resulted in the preferential 3-unit sets, i.e. ternary pumped storage units, where on a single horizontal or vertical shaft, the separate turbine, pump and generator-motor are arranged. This design was initially adopted widely in

Europe but is currently only used in situations with high hydraulic heads and where the shortest possible start-up and fast switching between pumping and generating are required. The higher efficiency is achieved by optimizing both pump and turbine geometry for the hydraulic head (Koritarov, et al., 2014; Ter-Gazarian, 2011).

During many decades of operation, a few preferences of applications in the pumped hydro technology emerged. In the case of an outdoor station, the horizontal shafts provide easy access for operation and maintenance, but the downside is the expensive excavation related to the submergence of the pump. To remedy this, booster pumps were introduced, but because of the additional complicated operation and less plant availability, this solution is not generally applied. As a consequence, vertically mounted shafts became the most common arrangement for 3-unit sets in outdoor stations. In this layout, the motor-generator is typically mounted above the turbine and pump (Ter-Gazarian, 2011).

Often a disengageable coupling is installed to disconnect the pump while in turbine operation to reduce drag from the pump. This can be performed by a gear-type clutch, which is only operable when the system runs stationary (Ter-Gazarian, 2011; Voith, n.d.). Alternatively, a hydraulic torque converter can be used. Its capability to connect or separate within seconds from the shaft is a major advantage. It transmits torque and/or power from the motor-generator to the pump shaft by being filled with process water. Due to the soft interaction of these processes, the storage pump can start up quickly. Hence, no load surges for the grid occur. This makes the hydraulic torque converter a suitable coupling of the pump for ternary units (Ter-Gazarian, 2011; Voith, n.d.; Höller, 2008).

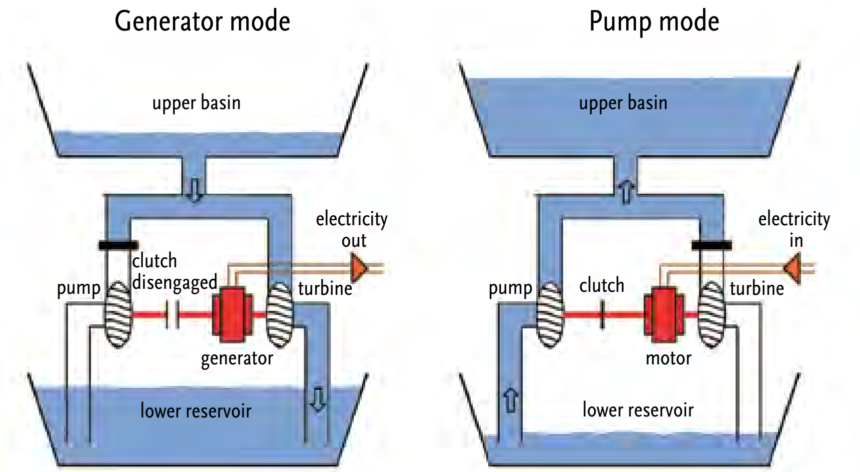
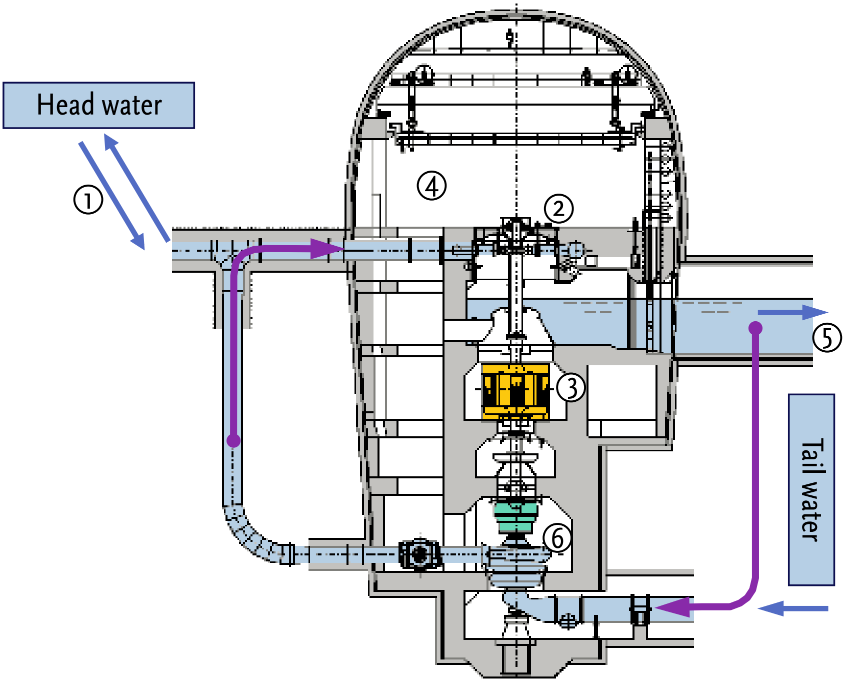


Figure 34 – *Schematic model of ternary PHS in generator/pump mode, with horizontal shaft and use of a clutch (Wikimedia Commons, 2014)*

The ternary unit has a highly flexible operation, because two separate hydraulic machines (i.e. turbine and pump) are mounted to a single shaft, the rotational direction of the motor-generator can be the same in both operational modes (Koritarov, et al., 2014; Voith, n.d.). In this way, the need to reverse the rotation to transition from pumping to generating or vice-versa is eliminated. The hydraulic flow, however, is substantially more complex than it is in a reversible hydro power plant. The ternary unit can use a hydraulic bypass to provide a more flexible operation, especially during the pumping mode. The ternary unit can operate with what is referred to as a 'hydraulic short circuit'. This is shown in Figure 35. "The flow in the penstock is, of course, bidirectional; it goes from the upper to the lower reservoir when the unit is generating electrical power, and in the opposite direction when the unit is absorbing electrical power (i.e. motoring). The flow in the penstock is the nett of the flow to the turbine and flow from the pump. The flow to the tailrace is this same nett flow. One can think of a component of the flow circulating from the turbine to the pump (or vice-versa), which is the hydraulic short circuit referred to above" (Koritarov, et al., 2013).



1 High-pressure shaft	3 Motor-generator	5 Low-pressure shaft
2 Turbine	4 Machine hall	6 Pump

Figure 35 – *Ternary unit demonstrating hydraulic short circuit operation. Source: Voith Hydro GmbH & Co KG*

The hydraulic short circuit operation enables the ternary system to regulate almost the full power range for pumping or generating of the unit (Voith, n.d.), as is explained by the following example from Koritarov, et al. (2014):

"If the plant is in the pumping mode and regulation is needed, both the pump and the turbine operate (i.e. employing the hydraulic short circuit). An example is shown in Figure 36. The flow through the pump and the resulting torque applied to the shaft from the pump correspond to an electrical energy of 150 MW drawn from the power system. However, the turbine guiding vanes are adjusted so that the flow through the turbine and the resulting torque applied to the shaft corresponds to 100 MW of electrical energy supplied to the power system.

The nett result is that 50 MW is drawn from the power system, and the flow pumped up to the reservoir is equivalent to 50 MW." In the ternary system, the turbine and pump guide vanes are the components that enable regulation of the power output or consumption. It should of course be noted that there will be losses in the hydraulic loop, which calls for careful design of the hydraulic system (Koritarov, et al., 2014).

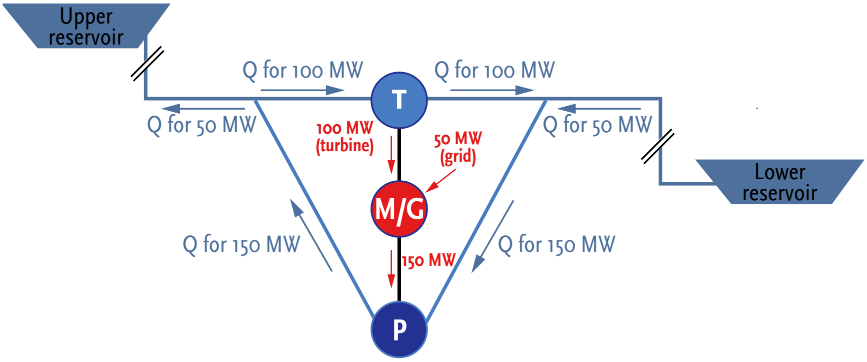


Figure 36 – *Example of a ternary system running in pump mode with regulation by hydraulic short circuit concept. In the example, the motor-generator is placed between the turbine and the pump; this allows for a more compact ternary unit design than a motor-generator that is mounted on top of the shaft above the turbine and pump (Koritarov, et al., 2013)*

The first reversible 2-unit set (see Figure 37) was introduced in 1933 in Baldeney, Germany. Compared to the ternary (3-)unit set, the reversible 2-unit set allows savings up to 30% of PHS investments, by decreasing the number of hydraulic machines, main valves and penstock bifurcations (Ter-Gazarian, 2011). Reversible units have to stop before restarting in the opposite direction, to switch between generator and pump mode (Ter-Gazarian, 2011; Antal, 2014). As a consequence, start-up and transition times between pumping and generating, range from 1.5 to 5 minutes, whereas ternary units may switch between operation modes within 0.5 to 1 minute (Koritarov, et al., 2013). The design of a reversible unit is necessarily a compromise, because the hydraulic machine operates as pump and turbine. The geometrical design of the pump-turbine component is therefore a compromise between the best performance in both operational directions (Koritarov, et al., 2014).

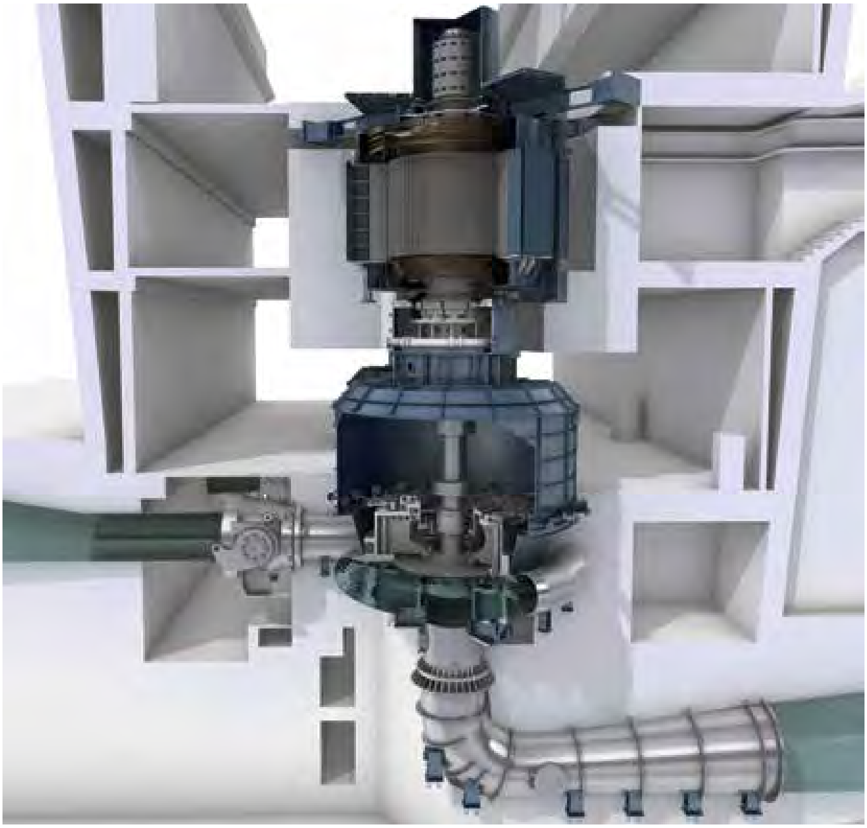


Figure 37 *– Three-dimensional view of a reversible 2-unit set. ©2018, General Electric Company (all worldwide rights reserved)*

Within reversible pumped storage units, there is the distinction between fixed-speed (FS) and adjustable-speed (AS) units. Fixed-speed PHS is an economical way of providing bulk energy storage (Yang, 2016). As a result, FS is the most common technology in PHS, with pump-turbine and motor-generator operating at a fixed speed synchronous to the grid frequency. Currently, in the USA all 40 pumped hydro plants in operation use FS technology, providing 22 GW of installed capacity (Botterud, et al., 2014). However, FS units can only provide limited flexibility in generating mode by adjusting the guide vanes (Antal, 2014). The typical range of flexibility is 70-100 % of the of the maximum rated power output (Antal, 2014). In pump mode, FS pump-turbines operate at a nearly constant rated pump power input, and the discharge varies only with the pumping head (Antal, 2014; Koritarov, et al., 2014).

The main difference between AS and FS technology is the use of a doubly fed induction machine (DFIM), using a multistage alternating/direct/alternating current (AC/DC/AC) solid-state convertor and a three-phase sinusoidal rotor, which results in a motor-generator that operates asynchronous to the grid (Antal, 2014; Botterud, et al., 2014; Koritarov, et al., 2014; Voith, n.d.). With AS, the frequency of the rotor voltage and current can be adjusted to control the rotational speed of the rotor and pump-turbine (Antal, 2014; Koritarov, et al., 2014). This provides the possibility to adjust the rotational speed of the pump-turbine to the most optimal design speed and power over a large head range (Koritarov, et al., 2014). This, in turn, increases the operational efficiency of AS units over a hydraulic head range and power input/output range (Antal, 2014; Botterud, et al., 2014).

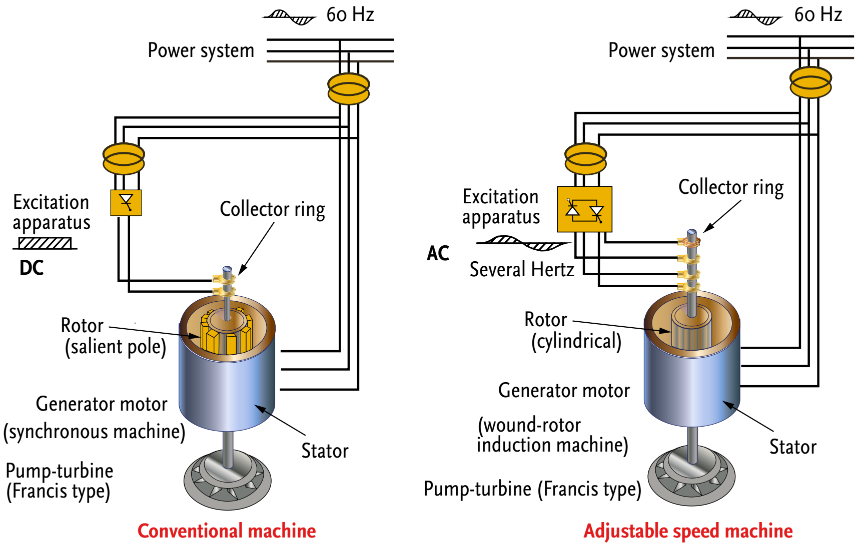


Figure 38 – *A simple schematic side-by-side comparison of a fixed-speed (called conventional) and adjustable-speed machine with DFIM (Botterud, et al., 2014)*

Adjustable-speed (AS) units have been preferred in recent years, due to their increased efficiency and ability to adjust their power consumption during the pumping mode (Antal, 2014). The flexibility of AS enables it to provide load-following and control reserve services, capabilities that are valuable to the power system when frequency deviations and short-term electricity disbalances occur. These additional flexibility benefits from AS units outweigh the higher capital investment costs compared with FS. Since 1990, more than 20 AS units have been operational globally, with Japan leading the implementation of AS technology (Yang, 2016; Botterud, et al., 2014). The increased flexibility of AS technology is also more suitable than FS to counterbalance the intermittency effect inherent to the increased penetration of VRE sources, such as wind and solar (Botterud, et al., 2014).

The pumped hydro plant consists, as a rule, of multiple power units. After discussing several types of pump-turbine technologies, the question arises which combination, taking into account the needs of the grid, and which types are optimal for the current structure of electricity supply. Ideally, the FS unit, being the most economically attractive one, should form the basis of a power plant. Based on the total storage capacity demand, the number and type of selected units has to be determined. The specific capacity of power units for large-scale storage is commonly between 100 and 500 MW, with an average capacity of 200 to 250 MW. The total capacity of the PHS plant typically ranges between 500 and 2,000 MW, with an average around 1,000 MW.

The Goldisthal PHS in Germany is an example of a PHS with different types of units. It is also the first European large-scale PHS with AS motor-generator technology. Construction started 1997 and the PHS was put into operation in 2004 (Botterud, et al., 2014). The total pumping and generating capacity of approximately 1,060 MW is provided by four 265 MW reversible Francis pump-turbines, of which two use FS synchronous motor-generators and the other two are based on asynchronous AS motor-generators. This design was based on several factors: the demand for flexible pumping, black-start capability with the synchronous motor generators, and the uncertainty surrounding the novel AS asynchronous motor-generator technology (Botterud, et al., 2014). This shows that careful selection and combination of different types of units is necessary to fit in with the desired grid applications for the PHS system.

As seen, the range of head to be handled by a turbine will be determined by stream flow analyses and the installed capacity derived from the power-generating capacity of the proposed plant. The selection process will be followed by choosing an optimum turbine type and series, the number of generating units, the runner diameter, rotational speed and runner axis elevation. Knowing the total layout of the power station, the number of units can be decided, depending on the load requirements of that particular area. The capacity of the plant should be optimized, taking into account low initial costs and efficient operation. Furthermore, attention must be paid to the feature of adapting the turbine for times of lean seasons. Finally, the availability of transport, shipping facilities and access to the plant has to be secured (Sangal, et al., 2013).

4.3.3 Turbine technology

The turbine is a mechanical unit consisting of a water inlet with guide vanes or nozzle with flow needle, runner and shaft, which – once assembled – converts momentum and pressure in a water flow into a rotational mechanical movement. The water is directed to the runner by either a nozzle that creates a high-speed water jet, or a set of guide vanes that create swirl in the high-pressure water flow. The runner is constructed in such a way that it converts the hydraulic energy into mechanical power by redirecting the fluid flow. The runner is equipped with cups or blades that interact with the moving water and cause the runner to rotate. Lastly, the mechanical movement of the runner is transferred by the shaft to the generator (Sangal, et al., 2013).

With respect to the choice of turbine types, the hydraulic properties are principally determined by the geometry of the fans, each geometry having its own specific character with an appropriate range of head. For the selection of a turbine type for a specific application, the hydraulic head has to be determined first. Turbines are classified into two main categories – impulse turbines and reaction turbines – which will be discussed below. Figures 39–41 show a schematic of these different types of turbines.

Impulse turbines (Pelton)

The operation of impulse turbines is described as follows: “Pressurized water from the penstock is converted to high-speed water jets that transfer the kinetic energy of the water jet(s) by impacting the turbine blades or cups causing rotation. The pressure drop in the water flow occurs at the nozzle and the runner operates at atmospheric pressure. Examples of impulse turbines include the Pelton wheel, Turgo wheel, and cross-flow (Banki-Michell) turbines. Impulse turbines generally operate best with medium or high head” (Sangal, et al., 2013).

Around the 1870s, the modern impulse turbine was developed by Lester Pelton, based on the principle of a split bucket with a central edge. Those double elliptic buckets are attached to a wheel, together with a notch for the jet and a needle control for the nozzle. The nozzle(s) is/are adjusted so that the water jet hits the moving cups perpendicularly at the optimum relative speed for maximum momentum transfer (Twidell & Weir, 2015). Pelton turbines have been used from circa 1900 onwards and are still the most commonly used impulse turbines. The original Pelton turbine was of a horizontal type (see Figure 39), but the Pelton turbine can also be used with the axle in a vertical configuration (Brekke, 2014).

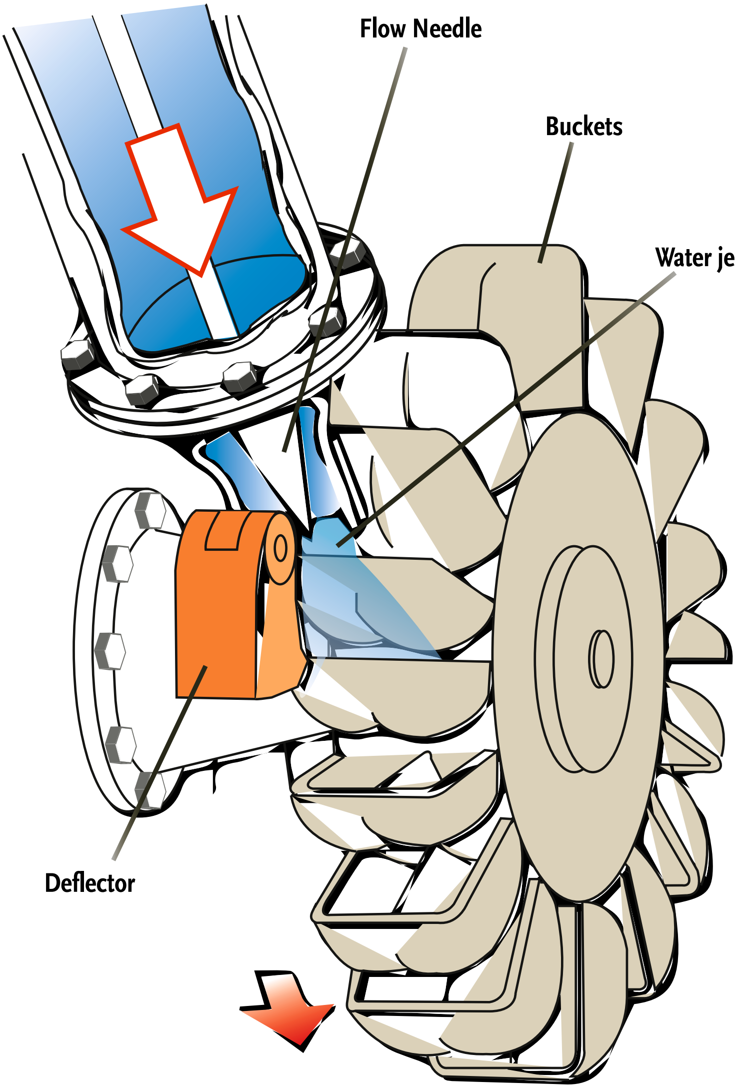


Figure 39 – Schematic of a Pelton turbine (OSU, 2018)

Reaction turbines (Francis and Kaplan)

The operation of reaction turbines is based on a different principle than that of impulse turbines and can be described as follows: "Reaction turbines operate under pressure in an internal flow regime. Water passes the water inlet and then through spiral casings or guide vanes to introduce swirl into the flow. The flow is then redirected by the runner blades. The angular momentum of the water forces rotation in the runner. In contrast to impulse turbines, the water pressure drops after passing the runner. Examples of reaction turbines include propeller (e.g. Kaplan), Francis, screw and hydro kinetic turbines (used for low-head range less than 5 m). Reaction turbines often have complex blade geometries and housings, which make them more difficult to manufacture" (Sangal, et al., 2013).

James B. Francis and his collaborators developed and tested the first reaction type turbine in 1848 in Lowell, Massachusetts, USA. The concept was based on an inward-flow direction turbine combined with radial and axial flows. Until the present day, they are commonly used and the standard operation spread is between 30 and 600 m. The main parts of a Francis turbine are the casing, also called volute casing (around the runner of the turbine), the guide vanes that convert the pressure energy of the fluid into momentum energy, the runner blades – the heart of any turbine – where the fluid strikes the blades and the tangential force of the impact causes the shaft of the turbine to rotate, and the draft tube that connects the runner exit to the tail race, minimizing the loss of kinetic energy. Figure 40 shows a three-dimensional schematic of a Francis-type turbine.

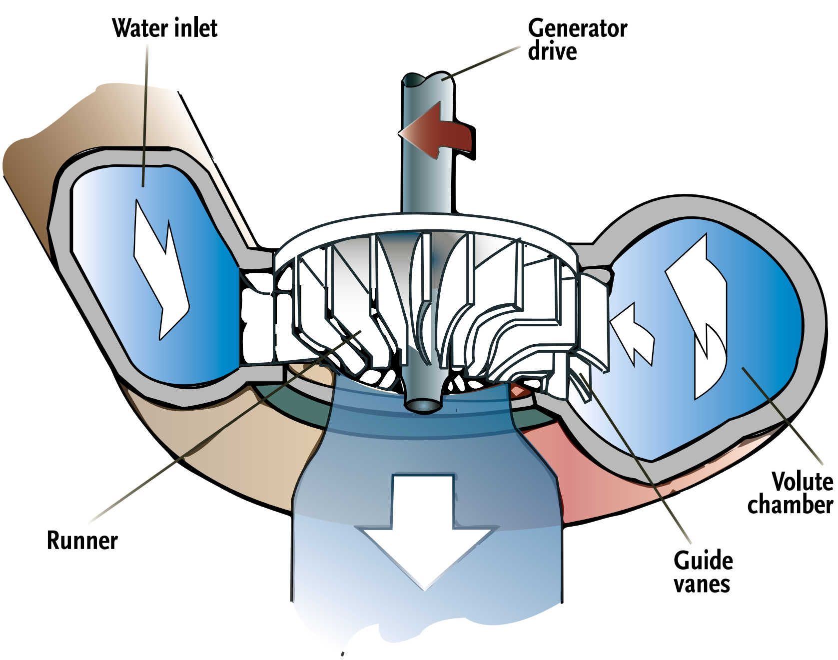


Figure 40 – *Schematic of a Francis turbine (OSU, 2018)*

The Kaplan turbine is a specific propeller reaction turbine, a family named after the shape of the turbine runner (Twidell & Weir, 2015). The propeller turbine has several different types, e.g. bulb, straflo, tube and Kaplan turbine (US DOE, n.d.; Brekke, 2014). The propeller turbine generally has a runner with three to six blades that are constantly in contact with the water flow. The specific Kaplan turbine has high adjustability, because both the guide vanes and the blades of the runner are adjustable (US DOE, n.d.). This adjustability makes it possible to optimize operation for a large variation of hydraulic heads, as each setting of the blades giving the turbine a new efficiency curve. However, Kaplan and propeller turbines are generally only applied in high-flow, low-head (i.e. typically below 60 m) applications (Twidell & Weir, 2015; Brekke, 2014). Due to the higher degree of complexity, the costs of Kaplan turbines is typically higher than of Pelton and Francis turbines that achieve similar or better efficiencies at high-head operation. As a result, Pelton and Francis turbines are often preferred for high-head applications (Brekke, 2014). Figure 41 is a schematic overview of a Kaplan turbine.

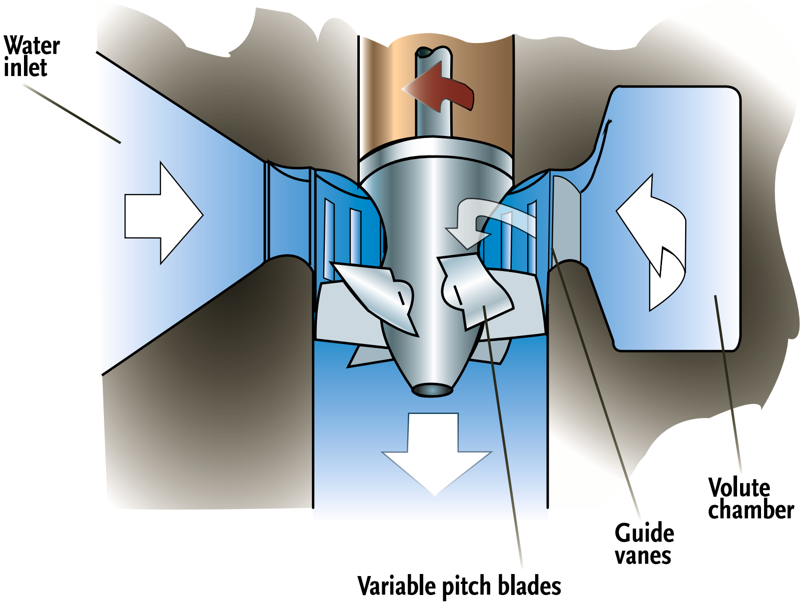


***Figure 41** – Schematic of a Kaplan turbine (OSU, 2018)*

The benefit of reaction turbines is the substantial pressure change when the water moves through the turbine casing, sealed off from the atmosphere. In the system, a pressure may occur that is even lower than the vapour pressure of water, forming bubbles of vapour. The water can suddenly reach atmospheric pressure again further downstream, which results in bursting of the bubbles and a powerful inflow of liquid water. The inflow of water into the bursting bubbles can cause substantial damage to mechanical components. This process is called cavitation. If the hydraulic head or flow changes away from the turbine optimum, cavitation effects may increase (Twidell & Weir, 2015). A decrease in efficiency may also be observed if water does not strike the turbine blades at the optimal angle. Kaplan turbines have an advantage here over Francis turbines, as turbine blades can be adjusted to change the hydraulic pressure to reduce cavitation at varying flow and head (Brekke, 2014).

The transition from the traditional fossil-fuelled electricity sources with predictable production and consumption patterns to VRE, has consequences for PHS plants. The classic operating mode of PHS units of pumping principally during the night to generate electricity at peak times, has drastically changed. In the past, the turbine-pump cycles switched once a day in a diurnal pattern. With the rise of variable sources such as wind and sun, PHS plant management has to adapt to this fluctuating supply of electricity. As a consequence, the pumps and turbines have to be switched on and off several times a day. In some cases, even as many as ten times (Botterud, et al., 2014).

This new power regime can cause turbine failure in high-head Francis turbines of all makes. Therefore, all manufacturers were involved to solve the risen challenges. The changing water current caused by many production starts and stops results in an oscillating pressure on the steel turbine blades. Resonance may cause damage to the turbine, i.e. when the frequency of the oscillation approaches the fundamental frequency of the steel runner (NTNU, 2015).

Though the industries have excellent research teams, it was apparent that only joint teams with universities were able to plan and execute the basic research that was needed to understand and find the proper solutions. The NTNU (Norwegian University of Science and Technology), in collaboration with the LTU (Luleå University of Technology) of Sweden are partners in the Francis-99 project to lead the fundamental scientific research. The Francis-99 project started in 2014 with the first workshop, followed by the second in 2016. A third workshop is planned for 2018. In the meantime, status reports have been published, such as “Simulation of the Francis-99 Hydro Turbine During Steady and Transient Operation” (Dewan, et al., 2017). The project will be followed by a new 4-year research project, initiated by Statkraft and supervised by the NTNU. The NVKS (Norwegian Hydropower Center) has a laboratory available for applied research on a scale model. Usually, businesses are interested in more practical research, but in this case the industry is taking part in basic research (NTNU, 2015).

4.4 Basic and ancillary services

Although arbitrage is the major characteristic of PHS, and hence already mentioned in Section 3.6, Table 6, the technical complexity of ancillary services requires an extensive description. The financial consequences, i.e. possible revenues related to ancillary services and arbitrage, will be discussed separately in Section 7.3.

Ancillary services can be described as those functions that are indispensable as a contribution to the stability of the grid. It is a primary defined task of the TSOs, whilst their balancing function consists of maintaining quantitative and qualitative control over the power supply. Before the massive introduction of VRE, this presented a minor challenge, since the producing power plants could easily respond to the reasonably predictable demand of the market. Due to the aforementioned higher penetration degrees of VRE, combined with a highly fragmented and decentralized electricity generation, the instability of the grid forms a realistic threat (González, et al., 2014). As a try-out, commercial battery backup, such as in Vlissingen (10 MW), was launched. To demonstrate the seriousness of the problem, TenneT is ready to experiment on a small scale with the input of (200) EV batteries via the digital blockchain system. The question remains whether all these measures will be sufficient to meet the significant demand for flexibility (TenneT, 2017f).

Finally, in Germany, with a 30 % VRE penetration, the storage problem is manifest and there is a desperate search for storage solutions. With the absence of sufficient storage capacity, the paradox emerged that instead of the intended 2 % reduction of carbon emissions, an increase of 2 % was noted in 2016 as a result of the backup from fossil-fuelled (lignite) power plants.

DENA (Deutsche Energie-Agentur) in Germany highlighted the contribution of PHS to grid stability and security of supply, as summarized below (DENA, 2015):

Growing need for flexibility and services in the power system: the changing role of PHS

The possibilities of PHS for the creation of power flexibility and system services are essential for a changing VRE-based electricity model. Traditionally, the PHS plants provided intertemporal arbitrage, which means that in times of low electricity prices or low residual load, the upper storage basin will be filled using excess electricity and emptied for electricity generation when needed in times of high prices. In addition, PHS provided system services for maintaining security of delivery for TSOs. The unique technical propensities for balancing purposes, such as blind-start and hydraulic short circuit features, make PHS extremely appropriate for future requirements with the implementation of VRE. In the case of serious disturbances in electricity supply, PHS can also provide black-start capacities in order to re-establish the required power on the grid. In de following subtitles the multifunctional role of pumped hydro and its future potential will be analysed.

Significant contribution to flexibility: reaction to production gradients

For TSOs, PHS offers the only relevant large-scale flexibility option, based on fast power capacity changes. The volatility of the supply and demand of electricity leads to a continuously changing pattern. The change of electricity generation per time unit describes the production gradient. The ability to deliver a continuous balance between demand and supply can be assured by a maximum degree of production change speed for the power plants, including dispatchable consumers. A high degree of production change speed can be delivered by the latest generation of highly flexible pumped hydro plants using variable speeds, which are capable of delivering many hundreds of MW within a few seconds.

Grid stability: PHS as crucial supplier for frequency regulation and inertial reserve

The frequency regulation and, as a result, the short-term stability of the electricity supply will be secured by the TSOs, by levelling out the differences between electricity production and demand. An operational grid frequency of 50 Hz has to be maintained with a tolerance of +/- 0.2 Hz. The TSOs achieve frequency regulation with the input of inertial response as well as the regulation capacities known as FCR (Frequency Containment Reserve), FRR (Frequency Restoration Reserve), and RR (Replacement Reserve). FCR, FRR and RR were formerly named primary, secondary and tertiary reserve, respectively (E-Bridge, 2014). The different ranges of operation are shown in Figure 42.

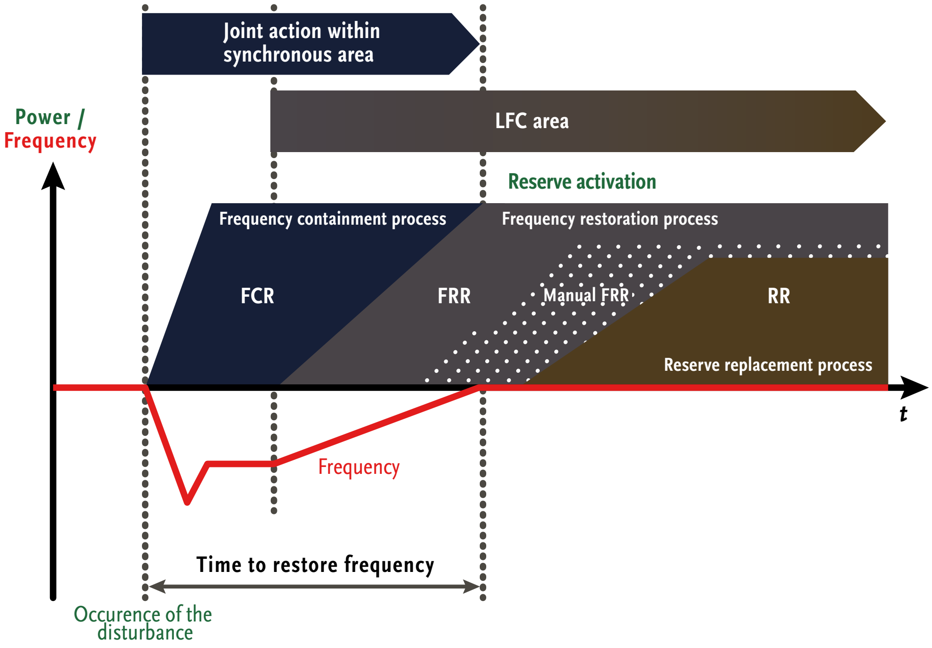


Figure 42 – Reserves and their mode of operation (E-Bridge, 2014)

With the growth of VRE, the inertia control in the grid will become more challenging as solar PV does not have any rotational inertia and a wind turbine's rotational inertia is often hidden behind regulating equipment for varying turbine speeds. Recent research discusses the technologies that may enable variable-speed wind turbines and solar PV to provide inertial control by adding complex control systems (Dreidy, et al., 2017; Shang, et al., 2017). The alternative is to combine VREs with storage for the provision of inertial control (Dreidy, et al., 2017). The advantage of O-PAC for the power system is that synchronous hydro units (i.e. FS and ternary) can contribute substantially to the inertial control of the grid without any adjustment to control electronics (Koritarov, et al., 2014).

The ability of PHS to react to steep production gradients prequalify the pumped hydro plants for intervention in all three regulation markets and hence deliver an essential contribution to grid stability. The characteristics of pumped hydro plants consists therein that they can provide from standstill both positive and negative power regulation. Moreover, state-of-the-art PHS plants that are equipped with the so-called hydraulic short circuit feature (simultaneous pump and turbine operation), can always deliver a negative regulation reserve, independent of the storage volume. As soon as a PHS is in operation, the rotating masses of the generators or motors contribute to the inertial reserve (Koritarov, et al., 2014).

Avoidance of grid bottlenecks: re-dispatch / T&D congestion relief

As a major difference with conventional power plants, PHS offers the technical ability of absorbing electricity from the grid and is able to take the excess VRE supply. This additional take-up of electricity from the grid also facilitates a smooth integration of VRE. Another difference with existing power plants is its versatility: conventional power plants have two possibilities for dispatch, increasing or decreasing the capacity. PHS, on the other hand, has four dispatching modes: on top of increasing or decreasing the capacity, PHS can deliver positive and negative re-dispatch, by increasing or decreasing the pump/turbine capacity. These multiple options facilitate in principle scalable products for avoiding power bottlenecks for TSOs, surpassing the initial characteristics of the traditional PHS. Based on the satisfactory suitability for the delivery of blind- and short-circuit capacities, PHS is specifically predestined for frequency-related re-dispatch.

Local voltage control: strategic geographical distribution of PHS

By analogy with grid frequency balancing, the security of supply by maintaining voltage control in all nodes (i.e. the feed-in/feed-out points) has to be kept continually between specific local or regional limits. Voltage control is not only the result of supply and demand but is also dependent on the blind capacity offered or used by the different regional grid nodes. Most of the pumped hydro plants are equipped with synchronous generators, which are appropriate for blind-capacity regulation and increase significantly the regional available short-circuit capacity. PHS is able to act as an inductive or capacitive user, i.e. taking blind capacity off the grid, as well as delivering it to the grid. The capability of a gliding exchange between generator and pumping mode puts PHS in the position to flexibly adjust the blind capability at any chosen process point. The synchronous generators of the PHS power plant can also operate during phase shifting and idling without output enables pure blind capacity to be received or delivered. In this situation, it forms an additional contribution to the inertial reserve.

Central role with grid recovery: black-start capability

In spite of the described measures for frequency regulation, voltage control and further system services, which the TSOs permanently survey, it is not completely excluded that a large-scale collapse may occur due to technical failure or calamities. In this case, all TSOs are automatically separated from the grid. In order to proceed to a coordinated rebuilding of the grid, fast-starting and secure dispatchable power generating units must be available that can operate without an external power supply (black-start capability). Pumped hydro plants with FS units and ternary units can provide black-start capabilities, provided they have a mechanical start-up facility. These units have a minimum start-up time from a stand-still situation to full operation without any external power supply. Contrary to ternary and FS units, AS units often have electronic regulation equipment that requires external power supply for start-up. If an on-site power supply is not available, the AS unit will not be able to provide black-start capacity. The only precondition for PHS is that the upper basin contains a minimum of water.

As soon as the grid frequency and voltage capacity are returned to within the tolerance limits, a considerable number of consumers will switch on the electricity in an uncontrolled manner, which will again cause great disturbances. But also in this case, pumped hydro plants are fully designed to meet this kind of levelling problems (DENA, 2015).

4.5 Developments in pumped hydro storage

In general, pumped hydro storage plants can reach their full power load in a few minutes, with reaction times ranging in seconds. In recent years, variable-speed pump-turbines have been developed with the ability to pump asynchronously to the grid, providing faster power adjustment.

This type of large-scale electricity storage constitutes the first option for expert engineers. It is the result of a century of proven advantages of conventional pumped hydro technology, such as a high degree of efficiency, long-life reliability, multi-applicability, low maintenance costs etc. However, the preconditions for the application of this kind of technique, such as geological and geographical qualities along with a lack of suitable differences in height, hamper wide-spread use of PHS solutions. Consequently, research for alternative PHS applications started. As a result, derivative concepts on land, on sea, subsurface solutions etc. are being proposed. Recent developments in PHS are summarized in Table 8.

On-surface	
Extension/retrofit PHS	Vianden, Coo, Linthal, etc
Abandoned (day) mines	coal/silver/gold
Sea/land plant	Japan
Innovative land or sea concepts	low-head
Subsurface	
Innovative U-PHS	O-PAC
Abandoned mines	coal/copper
Innovative under water	spheres/ Lake Constance

Table 8 *– Recent developments in PHS-systems*

Extensions and retrofits

Given the fact that suitable locations for PHS are scarce, due to numerous obstacles, the growing demand for flexibility induces the existing pumped hydro power plants to enlarge and/or retrofit their present installations. In the first instance, these plants study the possibilities for constructing additional volume in upper and lower basins. Upgrading or adding pump turbine units can also be considered in order to increase power. The enlargement of the basins can cause major problems related to lack of acceptance by environmental opposition, as shown in Atdorf (Germany). But in all cases, there is a general trend towards maximization of output by retrofitting obsolete equipment and/or implementing electronic upgrades for dynamic regulation. Below are some examples of PHS upgrades or extensions in the EU to show the diversity of recent projects.

In 2014, the PHS in Vianden (Luxembourg) was enlarged for the fourth time after its commissioning in 1976. Another 200 MW of turbine power was added, as well as 500,000 m^3 of water volume in the upper reservoir. To realize the additional machine hall, 180,000 m^3 of rock was excavated (Zanter, 2013). Being partially owned by RWE, it operates separately from the domestic supply mainly on the German market.

The PHS in Coo-Trois-Ponts (Belgium) started operation in 1972 and was enlarged in 1979. The underground excavations for the machine hall and shafts amount to 275,000 m^3. Currently, feasibility studies are being carried out to increase the turbine power with 600 MW (to 1,764 MW) and to add an upper basin of 5 million m^3 (Electrabel, 2015).

In 2016, Axpo completed an expansion of its Linthal PHS with 1,000 MW on top of the existing capacity of 520 MW. This expansion was accomplished by increasing the capacity of the upper reservoir by the construction of a new dam and installing four 250 MW reversible Francis pump-turbine units in an underground machine hall. This resulted in the largest PHS plant in Switzerland and it is in the top 5 PHS plants in Europe (Axpo, 2018; Harris, 2016).

FMHL Power Plant (Forces Montrices Hongrin-Leman, Switzerland), with an original capacity of 240 MW, has recently been upgraded with two additional 120 MW turbines. The PHS plant has been in operation since May 2017, with a total capacity of 480 MW. The investment amounted to USD 329 million (i.e. €266 million, assuming an exchange rate of 0.809 USD/€) (Harris, 2017).

Kopswerk I, Vorarlberg/Bregenz, Austria was built during the 1960s and was developed during decades of extension plans. Kopswerk II was at last executed and forms part of a complex set of power plants and water management solutions in the mountains of Tirol. With a 450 MW pump and a 525 MW Pelton turbine capacity divided over three ternary unit configurations with a hydraulic torque converter, it is one of the most sophisticated PHS plants of the last decade. The head is over 800 m and the machine hall is located entirely underground. The total costs for the Kopswerk II project were €400 million after its commissioning in 2009 (US DOE, 2013; Vorarlberger Illwerke AG, 2016; Botterud, et al., 2014).

In Cruachan, Scottish Power completed a feasibility study in 2016 to expand the existing 440 MW PHS plant with a capacity increase of 400 to 600 MW. The company is planning to invest €338 to €451 million to complete the project. Scottish Power, owned by the Spanish Iberdrola Energy Group (10,000 MW of PHS plants worldwide), together with the Scottish Minister Salmond sees opportunities to smoothen the electricity supply of Scotland, which is increasingly dependent on highly volatile wind (ScottishPower, 2016).

The Dinorwig (UK) power station, which came into operation in 1984, is able to start up from 0 to 1,320 MW in 12 seconds (when running in condense mode). Its six 300 MW pump-turbines provide a fast response to short-term rapid changes in power demand or sudden loss of power stations. Recently, an advanced governor system was installed; it must be noted that the upgrade did not include upgrading any hydraulics or mechanical aspects of the governor, merely the electronic control system. The aim of the upgrade was to provide the PHS with an up-to-date governor control and speed monitoring system, as the old hardware and software were outdated and had little support. The upgrade was successfully tested for one of the six units, after which all units received the upgrade (Jones & Yohe, 2013).

There are also substantial ongoing efforts in improving and retrofitting older governor systems, increasing operational flexibility and efficiency rates (Yang, 2016; Botterud, et al., 2014). A large part (about 35 GW) of the European PHS fleet is currently older than 30 years, constructed during the 1960s, 1970s and 1980s (see Figure 43), with the purpose of shifting excess nuclear energy from off-peak to peak hours (Antal, 2014). Due to the era in which these PHSs were build, the design of most PHSs in Europe and the US are based on fixed-speed pump-turbine units (Antal, 2014; Botterud, et al., 2014).

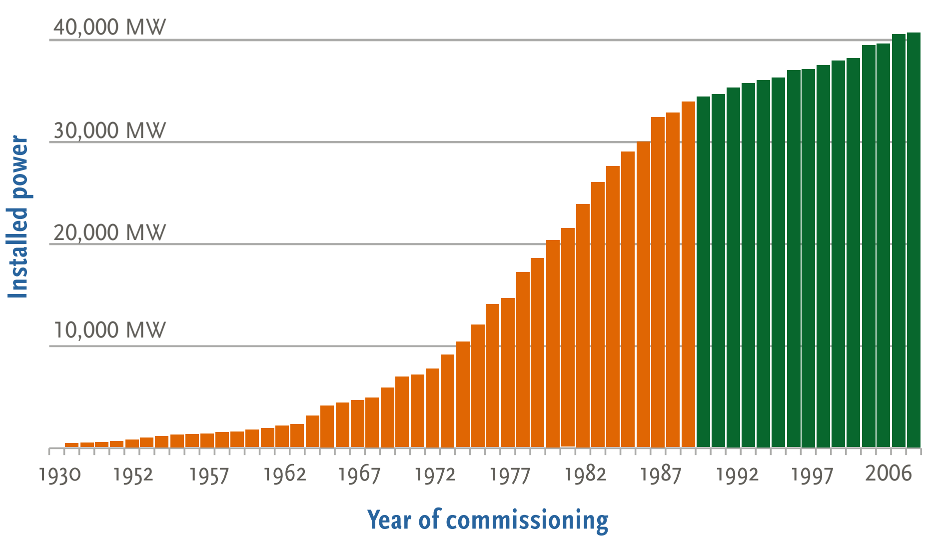


***Figure 43** – Installed European PHS capacity; orange bars indicate installed capacity of 30 years and older (eStorage, 2016b)*

In this context, it must be mentioned that a study by eStorage researched the benefit of upgrading old PHS systems from fixed-speed (FS) to adjustable-speed (AS) systems. The report showed considerable cost savings for the European power system, ranging from €448–€635 million per year in 2020 and up to €929–€1,271 million per year by 2050. The resulting benefit comes from increased efficiency and greater flexibility, due to the possibility for regulation in pump mode (eStorage, 2016a).

On-surface: abandoned (day) mines projects

To save on investments, there have been proposals for using old mines for PHS. It may seem advantageous, but often this is not the case.

Example 1: Tipperary (abandoned silver mine), Ireland, 360 MW. This PHS will be built in an open-cast mining site, according to an announcement by Ireland's Minister for the Environment in January 2016, after a development period of 5 years. The construction of the hydroelectric project with a price tag of €600 million is expected to be built by a joint venture of Strabag, Andritz Hydro and Road Bridge. Construction of the scheme includes a new 2.5 million m³ second reservoir. After the 2-year planning process has been completed, construction will take another 4 years. The expectation is justified that with the financial support of Irish government and an experienced group of companies with technically advanced equipment, a realistic transformation from mine to PHS could be realized (DHPLG, 2016).

Example 2: Kidston pumped storage (former goldmine) in Georgetown, Australia, 250 MW. The Kidston mine used to be the largest open-cut gold mine in Australia and has been out of operation since 2001. Genex Power, a public electricity provider, is currently developing an innovative clean-energy project located in Northern Queensland, which will consist of three renewable electricity generating projects. Phase one comprises a solar project of 50 MW, which is under construction and will soon be in operation, with an expected output of 145,000 MWh electricity per year. The project plans include another, larger solar park (phase two) of 270 MW, with a projected production of 783,000 MWh per year. The solar parks are designed to act as a source for the planned Kidston pumped hydro storage project with a capacity of 250 MW. These elements together form an innovative energy hub. Detailed feasibility studies are being executed and it is expected that the construction of the pumped storage project will start after 2018.The abandoned goldmine has two deep holes carved into the rock, which may act as the upper and lower reservoirs for a PHS. The process water volume is estimated to be 5 million m^3. The head between the two basins is approximately 200 m, and they will be connected by a 190 m long surface excavation. The construction budget includes costs for the excavation and installation of an underground power house of 94 m long, 21 m wide and 46 m high. For the intake and tailrace, there are 3 tunnels each, with a 4.4 m diameter. To connect the surface with the machine hall, a 6.5 m wide vertical shaft has to be constructed. A switchyard/transformer platform forms part of the external connection to the HV grid. Considering these extensive constructing works and the addition of technical equipment, it is questionable whether these can be covered by the planned budget of AUD 300 million (250 million euro). If compared with the investment of 600 million euro for the planned Irish silver mine (360 MW), there is a discrepancy of 100 % (Genex Power, 2015; Kraemer, 2016).

Example 3: Glenmuckloch Pumped Storage Hydro (former surface coal mine) in Kirkconnel, Scotland, 400 MW. The Scottish government granted a planning permission for the construction of a large-scale pumped hydro storage plant in the former Glenmuckloch surface coal mine. The disused open-cast coal pit is projected as the lower reservoir for the hydro plant, while on an adjacent higher ridge, the upper reservoir will be constructed. The intention is to install a wind park alongside this reservoir. The head between the reservoirs is estimated to be 200 m, and the water volume amounts to approximately 3.3 million m^3. A high-pressure pipeline will connect the upper reservoir with the machine hall situated below and a tailrace to the lower reservoir in the former pit. The project requires an investment of around 300 million pounds (255 million euro).

In Energy Matters, Euan Mearns presented an in-depth analysis of the Glenmuckloch pumped hydro scheme, in which some vital statistics were calculated. Lacking official information, calculations were made to quantify the storage capacity based on the data presented. This resulted in a storage capacity of 1.8 GWh (4.5 hours of power production). Based on a UK wind production analysis, the observation is made that a business model with a daily storing surplus is not realistic under these circumstances (BNEF, 2017a; Mearns, 2016). Of course, if the Scottish government is interested in an electricity balancing system, it could be prepared to grant substantial financial support.

On-surface sea/land plant: shoreline PHS

This prototype of a conventional application of natural height differences based on the frequent occurrence of mountainous coastal shorelines along the sea, is an important innovative step. One of the additional complications in this project is corrosion caused by the use of (salty) seawater. Below is the example of the Yanbaru pilot plant in Okinawa (Japan), coping with the effects of aggressive seawater on machinery, i.e. pumps and turbines. As a consequence, newly designed gaskets etc. had to be implemented in all moving vulnerable machine parts, so that eventually the fascine works resulted in a new type of sea-proof pumps and turbines. Fibre-reinforced plastic tubes were adopted instead of steel tubes for the penstock and the tailrace in order to avoid corrosion and adhesion of barnacles (Fujihara, et al., 1998). It is evident that maintenance must be executed with a considerably higher frequency than for PHS systems on land, resulting in higher costs.

Worldwide, there is a growing interest in solutions with seawater, hence the authorities in Japan recognized the great importance of this development and honoured the project with a substantial grant. The 30 MW pilot PHS cost ¥3.2 billion (€24.2 million at exchange rate of 0.00757 ¥/€), and was decommissioned in 2016, not for technical reasons but due to limited economic potential in the region (Japan Update, 2016).

Figure 44 – *Yanbaru, Okinawa, seawater PHS. The octagon-shaped upper dam is located 500 m away from the seashore at an elevation of 136 m*

According to Iberdrola's CEO, I. Galan, utilities could consider building more innovative pumped storage stations on high seaside cliffs, such as on the British south coast (de Clercq, 2015).

Low-head solutions: on land

The great advantages of PHS as a storage solution for regions without favourable geological conditions i.e. flat and windy areas, is underlined by Sterner & Stadler (2014).

In this category, there are numerous development plans all over the world. The Dutch engineering group Lievense was at the origin of one of these project concepts, located in the Markermeer lake, which was presented in 1981. The design of the project included the construction of a 12 m high surrounding dike in the Markermeer lake, topped by 400 wind turbines of 1 to 1.5 MW each. It concerned a flatland PHS solution with all the associated beneficial qualities of the system. In a later revised alternative Lievense plan, the original circular dike height of 12 m with a diameter of 20 km was changed to a dike of 80 m height and a reduced cross-section of 5 km. The reasons why this project never saw the light of day was that, in addition to the financial aspects (huge investments, insufficient feasibility), the realistic danger of a dike breach would cause a real tsunami on the IJsselmeer lake (Wassink, 2008).

As we look to the basic equation $E = V \cdot \rho \cdot g \cdot \Delta h$, it is evident, that with an aimed energy storage E (energy), there is a linear relation between V (volume of water) and height (Δh) (as ρ and g are constants for the density of water and gravity). This implies that in proportion to the height reduction, the volume of water has to increase in order to obtain the same storage capacity. So, if the natural difference in height is failing, the required areal surface has to increase accordingly. In the case of a considerable storage capacity, this will extend to a surface between 20 and 100 km^2.

It was not surprising that the huge demand for surface land was not accepted, neither by the public, nor by politicians. Because of fierce opposition, the plans had to be cancelled.

Low-head solutions: on sea

***Figure* 45** – *Energy island (1). Source: DNV GL and Rudolf Das*

The ‘energy island’ on the sea is based on the former ‘plan Lievense’. It concerns a PHS plant where the North Sea functions as the upper basin and the lower reservoir is surrounded by a special dike made of a sheetpile wall, in which the machine hall, with the pump-turbines and motor-generators are located. The water level of the lower reservoir lies tens of metres below sea level. In the case of an accidental collapse of the dike, the water will fill the lower basin, with limited damage. For an exact selection of the location, in addition to a number of other conditions, the presence of a homogeneous clay layer of tens of metres thick is required in order to prevent leakage of water into the lower basin from under the basin. Only in a limited area of the North Sea, such geological conditions exist, where there is what is called ‘Boomse klei’.

***Figure 46** – Energy island (2). Source: DNV GL and Rudolf Das*

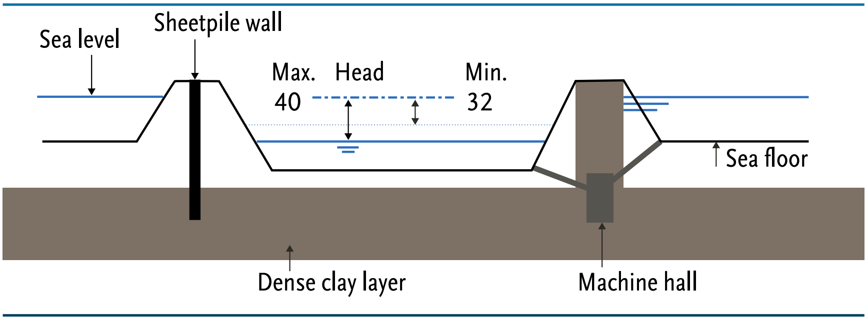


***Figure 47** – PHS on sea (de Haan, 2009)*

Because of the varying fall height during pumping or turbine cycles, the potential pump capacity varies substantially and there is also a considerable variation in turbine capacity. For the energy island, two alternatives have been worked out:

Power (MW)	Storage capacity (GWh)	Head (m)	Surface island (km^2)	Construction costs in 2007 (billion €)
1,500	20	32 - 40	40	2.45
2,250	30	32 - 40	60	3.40

A specific complicating factor is the presence of one of the world's busiest navigation routes. And last but not least, there is environmental opposition related to endangered wildlife on sea.

Similar concepts have been worked out in Belgium and Germany. The Belgian project was called the 'energy atoll' concept in the North Sea (Tommelein, 2015). The German concept was initiated by M. Popp, to address the need for electricity storage due to the fact that the VRE percentage is expected to reach 50% before 2020 (Sterner & Stadler, 2014).

Subsurface: abandoned mines

Germany has the greatest potential for using underground mines for pumped storage applications. There are more than 100,000 mining structures available, with a small number phasing-out. The Ruhr region alone has been the area of intensive coal mining activities, with a network of tunnels from more than 120 mines (Alvarado Montero, et al., 2016).

The German Ministry for the Environment, together with Clausthal University of Technology, identified 104 underground mining structures that were considered as either suitable or suitable to a limited extent (Meyer, 2013). From an economic point of view, it is fully understandable that the enormous investments in the past could – with a positive outcome of the investigations – form the basis of future reuse as underground hydro storage capacity, but Sterner and Stadler have doubts about the economic feasibility, due to the impossibility to secure reliable calculations for the required additional constructing work (Sterner & Stadler, 2014).

As pumped storage has proven to be an effective solution in the quest for balancing capacities of the grid, the network of tunnels of the Prosper Haniel mines have been the subject of a detailed study. The first inventory delivered an infrastructure of approximately 600,000 m^3 at a depth of between 600 and 1,000 m. An analysis is made of the hydraulic aspects under different operational conditions, i.e. cycles of pumping and turbine modus. The propagation and hydraulic efficiency was also tested, resulting in the consideration that the installed capacity may vary between 200 MW and 350 MW during at least 4 hours. The mines network consists of 7 layers, of which level 6 offers the most promising storage opportunity, with 22 km of tunnel length and a volume of 25,000 m^3 per km, i.e. a yield of 550,000 m^3. However, the potential capacity can be negatively influenced by the future level of ground water. An alternative solution would be the construction of new tunnels above ground water level. This extension, in the form of a closed ring of approximately 15.5 km, will have considerable effects on the economic feasibility of the reuse of this mine. Additionally, extending the calculated capacity up to 1,000,000 m^3 at the foot of the colliery's mine shaft with a depth of approximately 1,200 m will lead to a maximum of 5 hours of power supply (Parkin, 2017).

One of the conclusions of the study group was: "Despite of the non-permanent conditions in which coal mine infrastructure is typically foreseen, their adaption to a long-term facility has fewer uncertainties while compared to new underground infrastructure". Our conclusion is, as long as the costs for the adaption and necessary new tunnelling are undefined, there can be no outlook for a positive business case. Of course, if governmental considerations are determined to make reuse of mines a social and/or political issue, and only in case of huge subsidies, this storage alternative can see the light of day. To gain general support, a public poll was organized in 2013, which resulted in a positive report. The State Chancellery of North Rhine-Westphalia awarded further subventions by Minister Remmel in 2016.

The search for a potential use of former mines is not limited to Germany, since activities have started in many countries all over the world to identify and explore the possibilities of abandoned underground mines.

Subsurface: innovative U-PHS

At the basis of subsurface thinking for lower reservoir solutions for electricity storage, there was and is the perception of scarcity of sites suitable for conventional PHSs, which persists to the present day (Pickard, 2012). Moreover, the fact is that former proposals started with the idea of reusing of old coal mines, empty ore mines or abandoned quarries. It started in 1960 with Harza, who had the idea of employing a disused mine as a lower reservoir. In the Netherlands, 10 years after the closure of the last coal mines in the seventies, the same discussion about using deserted mines as underground reservoirs took place.

From a technical point of view, a specially designed tailor-made underground infrastructure in a controlled environment is preferable, because state-of-the-art mining engineering, hydro- and pumping technology are the best references for a feasible project. In this way, all elements can be scrutinized and calculated in order to minimize all kind of risks. This new approach creates the conditions for a realistic project based on a combination of known technologies.

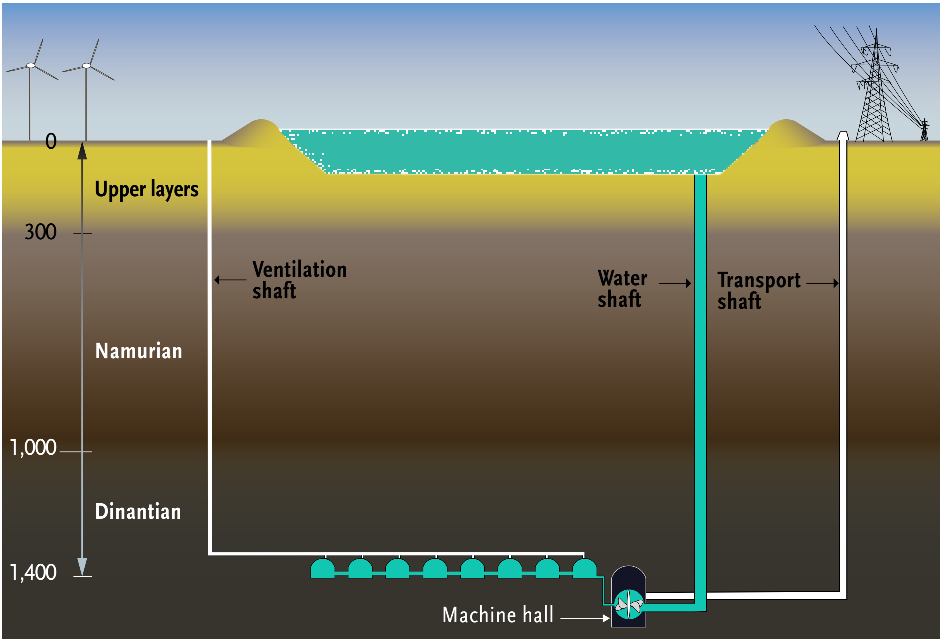


Figure 48 – *O-PAC cross-section*

O-PAC (Ondergrondse Pomp Accumulatie Centrale) is an example of the described engineering philosophy. This underground pumped hydro storage plant (U-PHS) is similar to a conventional PHS, a storage system that is based on the conversion of potential energy in electrical energy and vice versa. During the turbine cycle, electricity is generated whilst in the pumping mode electricity is stored. In a subsurface PHS, the machine halls and the storage basin are situated deep underground. The connection on the surface with the subterranean infrastructure consists of a single water shaft and two transportation shafts, one of which also functions as a ventilation shaft.

Thanks to the underground design, combined with an optimal head, the required surface area is very limited. Therefore, applicability is not limited to areas where geographical differences in height are lacking but is also possible in locations (for instance in densely populated areas) where insufficient space is available for a conventional PHS. For a specific choice of location, it is crucial for the subterranean infrastructure (the machine halls and the subsurface storage basin) that sufficient suitable homogeneous hard rock layers are available at the planned depth. In the case of the O-PAC project, this was confirmed by means of drilling up to a depth of circa 1,700 m. A U-PHS has an important additional advantage, namely that the head during pump and turbine cycles stays almost constant. Depending on the technical possibilities, plans will always opt for a maximum underground depth location (head) in order to minimize the space required. This counts for both the surface and underground reservoir, consequently reducing the construction costs significantly.

Many conventional PHS plants already function satisfactorily with subterranean machine halls, shafts and penstocks. For a U-PHS, the only addition is a lower reservoir in the form of underground caverns.

Part Two of this thesis is dedicated entirely to the details of a worked-out O-PAC project. Chapters 5 to 8 will cover different aspects of the plan, including geology, design and engineering, underground constructions, turbine and pump technology etc.

Innovative under water: concrete spheres

The StEnSea (Storing Energy at Sea) PHS in the form of a concrete sphere was tested at the end of 2016. The research team of Fraunhofer Institute for Wind Energy and Energy System Technology tested the prototype in Lake Constance (Germany). Hollow spheres on the bottom of the lake serve as the lower reservoir. The principle is similar to that of a conventional PHS. Electricity is stored by pumping the sphere empty. By releasing high-pressure water back into the sphere via a turbine, electricity can be delivered back to the grid. According to the StEnSea project management, the test fulfilled the expectations (BINE, 2017). However, the challenge will be upscaling this 1:10 scale model to a diameter of 30 m. At the intended depth of approximately 750 m, the external pressure will dictate the thickness of the wall of the sphere, which has to correspond with its weight to stand securely on the bottom without anchoring. The project management is aiming at investigating more suitable locations. The estimated investment costs for a storage park based on StEnSea are €1,500 to €2,000 per kW installed capacity. The design of the storage system allows for 4 h of full capacity delivery when the system is fully charged, resulting in an energy volume cost of €375 to €500 per kWh (Puchta, 2017).

4.6 Project investment costs of PHS plants

PHS requires a high head between reservoirs or very large reservoirs to increase its relatively low energy density (1 cubic metre of water at a height of 100 m has only 0.27 kWh of potential energy). This reduces the number of naturally suitable sites and may result in a large environmental footprint. As discussed in Section 4.5, solutions are being investigated to avoid these issues (e.g. artificial reservoirs underground or in the sea) (SBC Energy Institute, 2013). However, PHS has been successful on many locations worldwide, the project investment costs of large (> 500 MW) PHS plants built after 1980 are discussed here. A full list of PHS plants worldwide is provided in Appendix II.

The investment costs of some PHS plants in various European countries are presented in Table 9. It shows that the investment for PHS differs substantially between regions.

PHS name	Country	Comm. year	Power (MW)	Energy storage (MWh)	Power investment (€/kW)	Storage investment (€/kWh)
Dinorwig	UK	1984	1,728	8,640	1,126	225
Kops II	Austria	2009	525	2,340	900	202
Goldisthal	Germany	2004	1,060	8,480	880	110
Aguayo II	Spain	2017	1,014	3,700	604	68
Nant de Drance	Switzerland	2017	900	28,953	1,843	57
La Muela 2	Spain	2013	852	24,500	1,518	53
Linthal 2015	Switzerland	2017	1,000	42,442	1,832	43

Table 9 – *Calculated investment costs related to power and energy storage for PHS plants in Europe*

The calculation is based on the investment in civil engineering works, machinery, accessory installations. The total investment is divided by the installed capacity and the operable storage volume, which yields the specific installed power and specific energy storage investment, respectively.

The conclusion must be drawn that the topography determines the minimal investments required for the creation of the volume of the reservoirs and hence affects the capital costs per kWh. With regard to favourable topographic situations, it is clear that large-volume reservoirs have a lower investment per kWh. In some cases, this may result in high investment costs for the installed power (€/kW).

The La Muela 2 plant in Spain is an example of a PHS expansion of 852 MW to the original La Muela PHS. The project consisted of excavating an underground penstock, machine hall and tailrace. The existing La Muela 1 reservoirs were also used for the Muela 2 project, thus avoiding additional construction costs for reservoirs. The total specific investment for the Muela 2 project was €1,518 per kW and €53 per kWh. The two Swiss projects show the construction costs for recently built PHS stations. The Linthal 2015 project had a specific investment of €1,832 per kW and €43 per kWh. The project included the 3-year construction of a dam that increased the storage volume of an existing reservoir from 9 million m^3 to 25 million m^3 and the excavation of the machine hall, transformer hall, headrace, penstock and tailrace. The second Swiss project is the Nant de Drance PHS, which also includes an expansion of the reservoir by raising the height of the Vieux-Emosson dam by 20 m, and the construction of underground waterways and a machine hall.

The above examples show that PHS plants often have their machine halls and water shafts situated underground or in the mountain. This requires large excavations and underground tunnelling, whereas other PHS projects may require less civil engineering works. As a result, the investment costs for individual PHS plants differ substantially. This is shown in Figure 49, which presents the specific investment costs for PHS plants worldwide in €/kW and €/kWh. These investment costs show the project-specific investment and do not include adjustability in the PHS design at the presented investment costs (e.g. energy storage capacity cannot simply be expanded by paying an additional amount of euros per kWh, similarly for installed power; thus, actual additional investment costs may differ from the specific investment costs presented here). It illustrates that the actual investment depends to a great extent on all circumstances for which the PHS will be designed, e.g. the geographical availability of large lakes in mountainous areas typically results in low investments relating to energy storage (€/kWh), and the PHS layout will influence the investment relating to the installed power (€/kW).

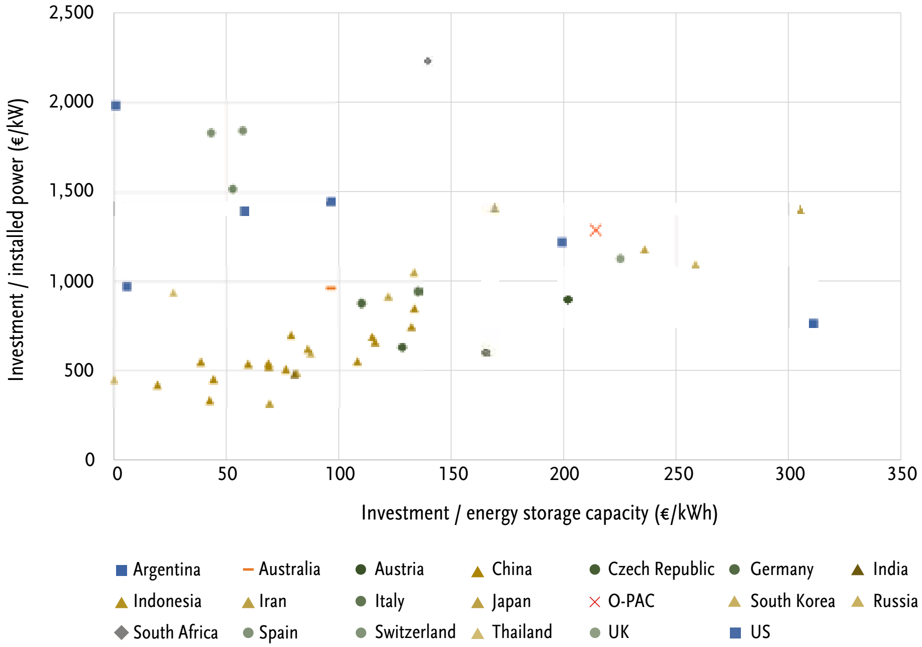


Figure 49 – *Specific capital costs of PHS plants worldwide (Sources: US DOE Energy Storage Database (2016) complemented with several online sources). The PHS plants are categorized per country and the shape of the symbols represents the continent. The prices are presented in € in 2018, and as most cost figures are reported in USD, these were corrected for inflation from the PHS year of commissioning and then converted to euro with a conversion factor €0,809 per USD.*

Furthermore, the investment costs for PHS plants show significant differences between regions, as presented in Table 10. The worldwide PHS specific investment costs show that the average investment in PHS power is €924 per kW, at an average energy storage investment of €111 per kWh.

	Power investment costs (€/kW)	Storage capacity investment costs (€/kWh)
Europe	1,156	134
USA	720	68
Japan	1,292	271
China	576	79

Table 10 *– Average costs of PHS plants in different regions*

4·7 Concluding remarks

PHS has recently seen a revival both in Europe and worldwide, with its mature technology and its 99 % share in storage power. Geological, environmental and political constraints are obstacles to its necessary further growth.

The best and easiest places have already been taken and some countries (such as the Netherlands) have no suitable locations at all. Therefore, an innovative alternative is presented in Part Two: underground pumped hydro storage (U-PHS).

PART 2

PART TWO – An innovative contribution to a sustainable solution: underground pumped hydro storage

The O-PAC project is the subject of Part Two. **Chapter 5** analyses how geology determines the location of underground caverns and the machine hall. **Chapter 6** describes in more detail the design and construction of the power plant. In **Chapter 7**, a cost-benefit analysis is presented, based on empirical figures. **Chapter 8** covers the environmental, social and cultural impact of the project. **Chapter 9** describes the role of O-PAC in the Dutch grid. **Chapter 10** highlights key discussion points and presents final conclusions.

5 O-PAC study

5·1 Introduction

The underground pumped hydro storage project described in this monograph has a long history. As early as 1983, Dutch Parliament (Tweede Kamer) asked the Ministry of Economic Affairs (EZ) to start a feasibility study of large-scale energy storage. This was the starting point for two independent groups of engineers.

The 'plan Lievense' group presented a large pumped hydro project (Pomp Accumulatie Centrale, PAC) with a low head (a small height difference between upper and lower water levels). At the same time, the OPAC (Ondergrondse Pomp Accumulatie Centrale, Dutch for U-PHS) group worked out a subterranean PHS project based on a high head. The OPAC project initially consisted of TH Delft (now Delft University of Technology), Haskoning and Volker Stevin (Aveco). Because of the specialist knowledge required for tunnelling and cavern construction, engineers from Germany (including Müller+Hereth Ingenieurbüro für Tunnel- und Felsbau, Deilmann-Haniel, Heitkamp Ingenieur- und Kraftwerksbau) joined the study group and have continued to contribute their expertise to the present day.

During these studies, drill core samples were taken on the projected site in South Limburg. Analysis by the RGD (Rijks Geologische Dienst, then the national geologic service) and the Laboratory of Engineering Geology at Delft University of Technology showed that rock layers at a depth of 1,400 m are well suited for the construction of a machine hall and caverns. An underground variant of PHS seemed viable at this particular location. Subsequently, all relevant aspects of civil engineering, electrical mechanics, mining techniques, geology, environmental impact and finance were studied.

In 1983, the Ministry of Economic Affairs appointed the then energy development agency NEOM (Nederlandse Energie Ontwikkelings Maatschappij) as co-ordinator of both study projects. NEOM commissioned Motor Columbus, a Swiss advisory engineering group, to make a comparison of the two proposed systems (PAC and OPAC), which led to a preference for OPAC.

In spite of these efforts, the Dutch government decided in 1989 to refrain from investing in either proposal. One reason to suspend all storage plans was the sheer size of both projects, with investments between 2 and 3 billion Dutch guilders. At the same time, plans for additional nuclear power plants were put on ice. These plans were initially a rationale for large-scale storage – nuclear plants are best operated continuously. A broad public consultation from 1981 to 1984 did not lead to a consensus about the necessity of new nuclear plants in the Netherlands, contrary to neighbouring countries. The subsequent Chernobyl disaster (1986) made the government abandon its nuclear plans (Verbong & Geels, 2007). This provided the second reason – apart from the environmental discussion around 'plan Lievense' – because it resulted in a lack of urgency to build such a capital-intensive installation.

Some twenty years later, Royal Haskoning, together with Sogecom, resumed the studies under the name of O-PAC group. The hyphen in its acronym distinguishes this resumption from its predecessor OPAC. In 2008, Dutch Parliament adopted the Hessels & co motion (full motion available in Appendix III) with the recommendation for TenneT to participate in a private project to build a large-scale energy storage to balance the increasing share of renewable and decentralized power production (Rijksoverheid, 2008). These concerns were also the reason for O-PAC to take up the project again. With the support of the Province of Limburg in 2009, O-PAC updated the existing plans and presented a business case, including investments, a financial plan, estimated revenues, an assessment of regional economic effects on employment and a project plan. In order to reconfirm the feasibility of O-PAC in Southern Limburg, the Province of Limburg commissioned TNO/Geostructures in 2011 to study a possible location at Graetheide (Kramers, et al., 2011).

The main reason for reviving OPAC was the observation of significantly increased climate awareness, the urgent need for reducing CO_2 emissions, resulting in a transition to renewable power generation. The intermittency of these renewable sources requires much more flexibility in the power system and thus more storage capacity.

5·2 Mining history of South Limburg

South Limburg, situated in the southern-most part of the Netherlands, has been a site of coal mining since the twelfth century, with the first extraction by monks through open pit mining. Coal mining continued via private enterprise until 1901, when the Dutch government claimed the exclusive right by law, while private mines which were already in operation kept their right to continue. The importance of coal mining for the economy was first demonstrated when importing coal was not possible due to isolation caused by the neutrality in World War I. Similarly, during and after World War II, the production of coal for domestic use was the only available source of energy. Especially during the years after the war, the reconstruction of a destroyed country demanded great efforts to maximize coal production. Then in the 1960s, the world price for coal collapsed. In spite of the implementation of efficiency measures, it turned out to be impossible for the Dutch mining industry to remain profitable. Coal production in all Western countries had to be subsidized in order to preserve employment (Messing, 1988).

The discovery and exploitation of vast natural gas reserves in the north of the Netherlands in the sixties, had an immediate effect on the position of the coal mines. Natural gas was promoted for domestic use by the government and later became the dominant fuel in electricity production, up to 80 % in the mid-1970s (Verbong & Geels, 2007).

Besides reducing the need for coal as an energy source, these reserves put the government in a favourable position to mitigate the financial consequences of the termination of mining activities. In contrast with neighbouring coal-producing countries, the Netherlands had an economic lead. These reasons led to the Dutch government's decision to close all mines in South Limburg. The decision resulted in the loss of employment for 75,000 workers, and enormous socio-economic and cultural effects. Nonetheless, in December 1965, the Minister of Economic Affairs Joop den Uyl announced the definitive closure of all mines. Part of the announcement was the promise that closure would be accompanied by compensatory employment. The last mine, Oranje Nassau I, shut its doors on 31 December 1974 (Messing, 1988).

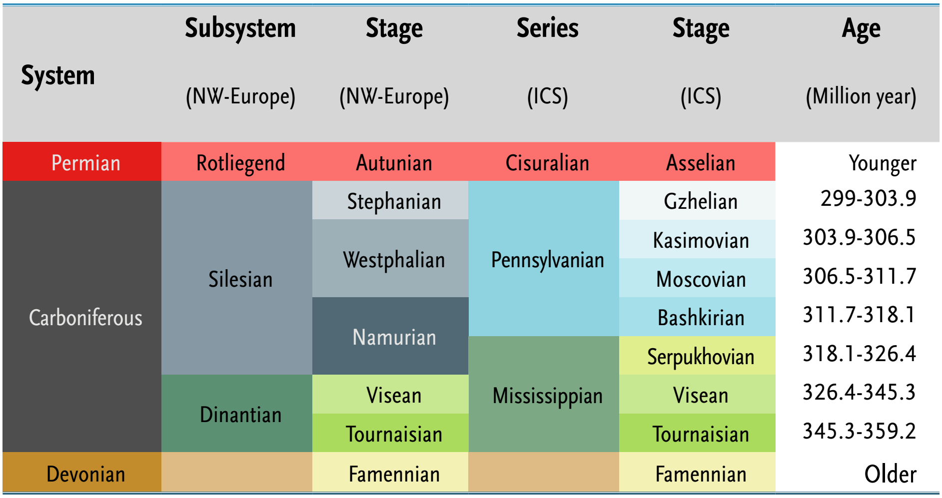
Several years later, the question was raised in parliament and government circles whether the closed mines could be used as underground reservoirs for a hydro power storage plant. Confronted with this question, the TH Delft (now Delft University of Technology) mining Professors P.Th. Velzenboer and P. Van Leeuwen came to the conclusion in 1980 that the abandoned mines in Limburg were unfit to function as a lower basin for an underground hydro power plant. ”The old mines cannot be reopened for an underground storage plant use as most of the underground areas have caved in, and the formations have been disturbed to such a degree that these are no longer reliable” (de Haan, 2011). The observed deterioration of the historic coal mines was to be expected, as resource mining is a typical extractive industry that builds subsurface structures with stability until the fossil resource is depleted. However, it is worth noting that in Germany, in the Ruhr region which neighbours the Netherlands, efforts are currently being made to reuse abandoned mines as lower reservoirs for PHS (see also Section 4.5).

This contrasts with the construction of O-PAC and PHS, which will create a long-lived and sustainable subterranean infrastructure for water storage. The disturbance of the coal formations induced the researching engineers to concentrate on rock layers well below the coal layers (the South Limburg coal mines operated at a maximum depth of 900 m).

For a U-PHS, the underground situation and geologic structure is of determining importance when selecting the location. The stability of the rock layers has a direct relation with the investment costs of the subterranean infrastructure. This aspect is discussed in the section below.

5·3 Geological conditions

The stratigraphy of rock layers is an important part of geology, in which the sequence of successive layers (stratification) is studied, enabling the dating and characterization of those layers. Based on these data, the different rock layers can be categorized in various ways, such as sedimentary environment, property of layers (lithostratigraphy, petrophysics), and in relation to periods, groups, formations and members. Names such as Dinantian, Namurian are used to denote formations in the subsurface. For this study, the Carboniferous and Devonian are relevant (Kramers, et al., 2011). See Figure 50.



System	Subsystem (NW-Europe)	Stage (NW-Europe)	Series (ICS)	Stage (ICS)	Age (Million year)
Permian	Rotliegend	Autunian	Cisuralian	Asselian	Younger
Carboniferous	Silesian	Stephanian	Pennsylvanian	Gzhelian	299-303.9
		Westphalian		Kasimovian	303.9-306.5
				Moscovian	306.5-311.7
		Namurian		Bashkirian	311.7-318.1
			Mississippian	Serpukhovian	318.1-326.4
	Dinantian	Visean		Visean	326.4-345.3
		Tournaisian		Tournaisian	345.3-359.2
Devonian		Famennian		Famennian	Older

Figure 50 *– Subdivisions of the Carboniferous system in Europe compared with the official ICS stages (Kramers, et al., 2011)*

The investigation on the feasibility of an underground pumped hydro system (O-PAC) centralizes on the availability of the required rock quality at a designated depth. This will be elaborated in 5.3.2. Numerous studies covering the geological and geotechnical influences on the geometry and volume of the subterranean excavations, form part of the research in support of O-PAC. Further, the required supportive construction aimed at long-term stability of the caverns and tunnels is an important aspect, as outlined in Section 6.2.

A possible target area (see Section 5.4) is situated in the centre of South Limburg around the village of Geverik. To identify the main structures of the subsurface, a 2D seismic investigation was executed in 1985. Because of a lack of sufficient reliable information about the stratification, it appeared necessary to conduct a core drilling. In 1986, this drilling was carried out near Geverik and resulted in a complete set of samples up to a maximum depth of 1,687 m. This yielded detailed information and has been analysed by a number of geologists, as will be described below.

Based on these outcomes, the preliminary conclusion can be drawn that in a limited area at a depth of around 1,400 m, there is a homogenous structure of good-quality rock which may be suitable to host an underground pumped hydro power installation. “The Dinantian limestones met in the Geverik borehole seem to be favourable for underground openings. In spite of its cyclic sedimentation, extremely high rock strength has been found" (Müller & Hereth, 1987a).

5.3.1 Core drilling results

The drilling took place near Geverik, north of Maastricht-Aachen Airport, alongside the A2 motorway, and was cored from 400 m to the bottom (1,687 m).

Figure* 51 – *Samples from core drilling

Here follows a brief description of the findings from Geverik borehole 1 from the top down: from the surface to a depth of 125 m, a layer of unconsolidated Tertiary and Quaternary sand, clay and silt was encountered. From 125 m onward, there are sediments of Palaeocene chalk down to 176 m. Next, down to 236 m, a Cretaceous claystone layer is found. At a depth of 324.5 m, the bottom of the Palaeozoic erosion surface is located, with silty, glauconitic and partly unconsolidated characteristics (Müller & Hereth, 1987a).

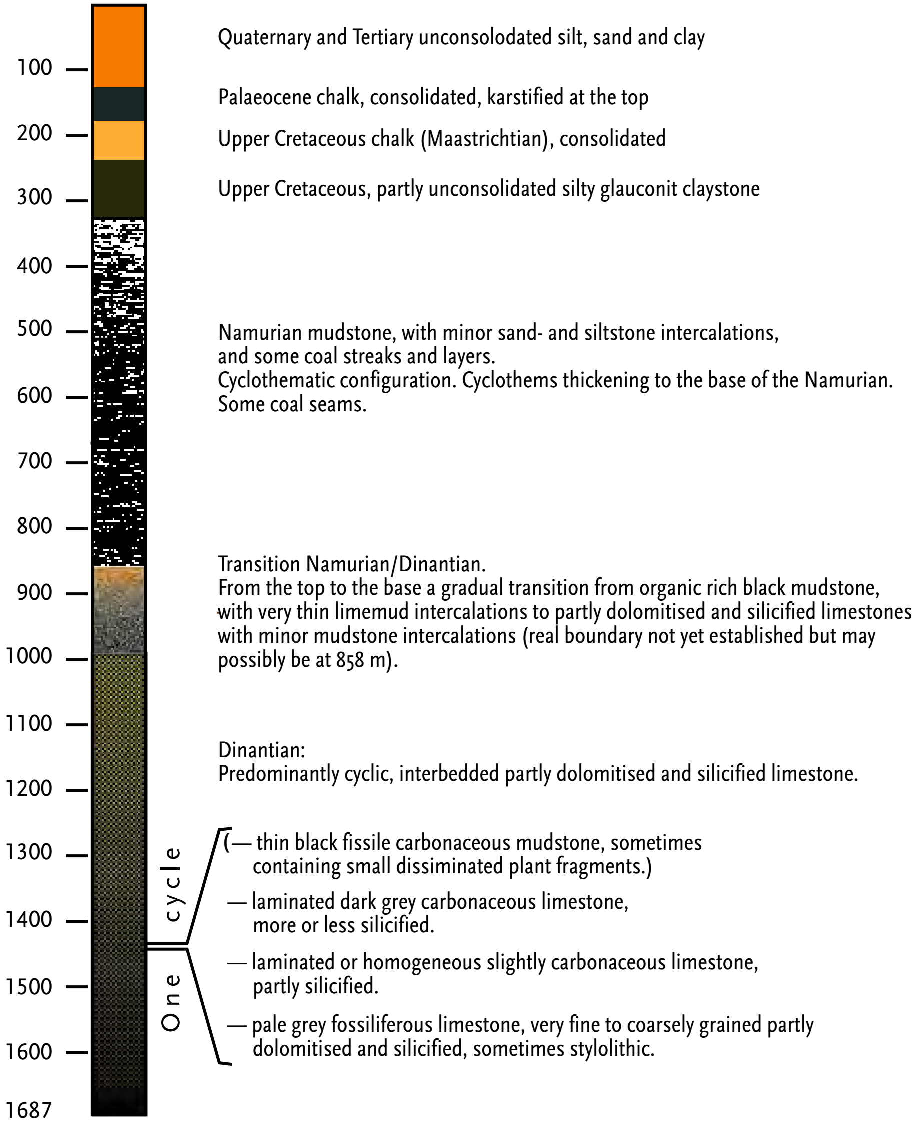
From 400 metres down to the base of the borehole, extensive research was executed, co-ordinated by the engineers of OPAC study group, especially KVS (Aveco) and Haskoning, by the following specialists:

- RGD, (Rijks Geologische Dienst, Geologisch Bureau Heerlen, 1984-1985)
- Schlumberger Log Services BV (1986)
- Delft University of Technology, (Laboratory of Engineering Geology, Prof. D.G. Price, 1987)
- BCO (Bergschot Centrum voor Onderzoek, 1987)
- KEMA (Keuring van Elektrotechnische Materialen te Arnhem, 1987)

Detailed follow-up work by Mathes-Schmidt (2000) was based on micro-paleontological microfacies, sedimentological and diagenetic investigations, in order to unravel the geodynamical and paleogeographical implications for the Lower Carboniferous (Visean) time interval, which contains the carbonate rocks that are most relevant for the O-PAC project (Kramers, et al., 2011).

RGD Heerlen		Own data	
Depth	Stratigraphy		Depth/ foraminifers, conodonts
917.81 m 954.45 m	Nm	Nm	917.53 m 942.20 m Warnantella
992.00 m 1108.28 m	V3c	Nm? (Cf7?) V3c	980.00 m
1133.93 m 1266.30 m	V3c	(Cf6δ)	1226.00 m
1279.00 m 1305.12 m	V3bγ – V3c		1297.00 m
1306.53 m 1416.00 m	V3bγ-δ	V3c (Cf6δ) -Transition V3b/V3c- V3b	1306.54 m P. symmutabus, P. homopunctatus, G. bilineatus bilineatus, G. girtyi girtyi, G. girtyi intermedius 1357.75 m G. bilineatus bilineatus 1334.00 m first Asteroarchaediscus
1421.12 m 1559.40 m	ob. V3bβ – V3bγ	V3b (Cf6γ)	1460.60 m Cribrospira panderi 1505.31 m Paragnathodus homopunctatus 1506.00 m Howchinia 1542.15 m Koskinobigenerina 1545.55 m Vissariotaxis
		V3b (Cf6β – γ)	1566.30 m Cribrostomum
1563.22 m 1669.18 m	V3bα – V3bβ	V3a – V3b (Cf6α – β)	1659.50 m bilam. Palaeotextulariidae
1672.09 m 1683.70 m	V3a – V3bα		1687.20 m End depth

Table 11 – *Biostratigraphy of the Geverik1 well based on foraminifers and conodonts (after Mathes-Schmidt (2000)). The indication for V is Visean, for Nm Namurian and a – c for different stages in stratigraphy (Kramers, et al., 2011)*



Quaternary and Tertiary unconsolodated silt, sand and clay

Palaeocene chalk, consolidated, karstified at the top

Upper Cretaceous chalk (Maastrichtian), consolidated

Upper Cretaceous, partly unconsolidated silty glauconit claystone

Namurian mudstone, with minor sand- and siltstone intercalations, and some coal streaks and layers.
Cyclothematic configuration. Cyclothems thickening to the base of the Namurian.
Some coal seams.

Transition Namurian/Dinantian.
From the top to the base a gradual transition from organic rich black mudstone, with very thin limemud intercalations to partly dolomitised and silicified limestones with minor mudstone intercalations (real boundary not yet established but may possibly be at 858 m).

Dinantian:
Predominantly cyclic, interbedded partly dolomitised and silicified limestone.

(— thin black fissile carbonaceous mudstone, sometimes containing small dissiminated plant fragments.)
— laminated dark grey carbonaceous limestone, more or less silicified.
— laminated or homogeneous slightly carbonaceous limestone, partly silicified.
— pale grey fossiliferous limestone, very fine to coarsely grained partly dolomitised and silicified, sometimes stylolithic.

Figure 52 – Core drilling at Geverik 1 (Müller & Hereth, 1987a)

Below the top layers described above, lies the Namurian layer, which consists of cyclothematic mudstone with minor sand- and siltstone intercalations. Coal seams have been found at the depth of 439, 566, 670 and 672 m. No sharp boundary was noticeable in the transition zone between 858.0 and 988.5 m to the Dinantian layers.

Dinantian layers can be characterized by cyclic sedimentation; from the bottom, the cycle starts with fossiliferous pale grey limestone, and transitions to carbonaceous limestone with grades into black fossiliferous mudstone at the top. “Between 1,345 and 1,380 m, Schlumberger logs show a very homogenous area with almost no clay and only 10 % SiO_2” (Müller & Hereth, 1987a).

The Geverik 1 well shows no sequence boundaries or major cycle boundaries internally at the transition zone into the Namurian black shales. These boundaries are associated with significant karstification in areas further to the west and south of the target area (Kramers, et al., 2011).

Transition zone	**Change from a regressive character to a more transgressive environment**
Depth interval (m)	**Lithology**
858 - 915	No clear sedimentary trends. From 858 m, fast and large increase in carbon content. Chalk content in the shales increases. Permeability very small, porosity of max. 10 % in broken zone.
915 – 991	Strong increase in chalk content from top to basis. Layering to basis and clear silicification with a layered character occurs in this tract.
Dinantian (Visean)	
Depth interval (m)	**Lithology**
992 – 1193	‘Fining upward’ cycle characterized by an increase in silicification and carbon content from basis to top. Stratification of mudstone and packstone. In the base, shale is practically absent and gradation of grainstones occurs.
	1130 – 1193 m moderately to strongly influenced by cracks.
1193 – 1265	Unit strongly influenced by cracks. Mainly pack-wackestone.
	Fault zone on 1265 – 1275 m.
1275 – 1325	Weak, megashale ‘fining upward’ trend.
	Silicification and secondary dolomitization vary from weak to moderate.
1325 – 1381	Uniform limestone, coarse granular packstone that gradates to mudstone. Little silicification and dolomitization.
1381 – 1547	1381 – 1508 m is a large ‘coarsening up’ series. Carbon-shale content reduces from basis to top. 1508 – 1547 m a homogenous series of pack- and grainstone, with light crystallization and dolomitization. 1539 – 1547 m Coarsening up cycle of pack-grainstone. Light silicification and light dolomitization.
1547 – 1588	1547 – 1572 m ‘coarsening up’ of pack-grainstone and some mudstone. 1572 – 1588 m fining up pack-wackestones. Carbon and shale content increase gradually to the top. Light dolomitization and silicification.
1588 – 1632	‘Fining up’ of pack- and mudstone. Shale and carbon content increase from basis to top.
1631 – 1687	‘Coarsening up’ limestone cycle. 1632 – 1644 m pack-/grain- to mudstone with concretionary silicification and dolomitization. 1644 – 1687 m homogenous packstone and fine-grained wacke- to mudstone. Irregular silicification and secondary dolomitization.

***Table* 12 –** *Summary of the lithography of the report “Investigation results of core drilling at Geverik 1” (Kramers, et al., 2011)*

5.3.2 Suitability of the subsurface

The results of the geological engineering research, supported by the outcomes of the core drilling analyses, confirm the suitability of the underground in South Limburg for a U-PHS. Especially the Dinantian layers between approximately 1,000 and 1,700 m depth are promising and offer a stable rock formation to host U-PHS. Within Dinantian layers, preferred formations can be distinguished: the outer band zone between 1,305 m and 1,579 m depth and the inner band zone which measures 1,350 to 1,450 m depth. See Figure 53.

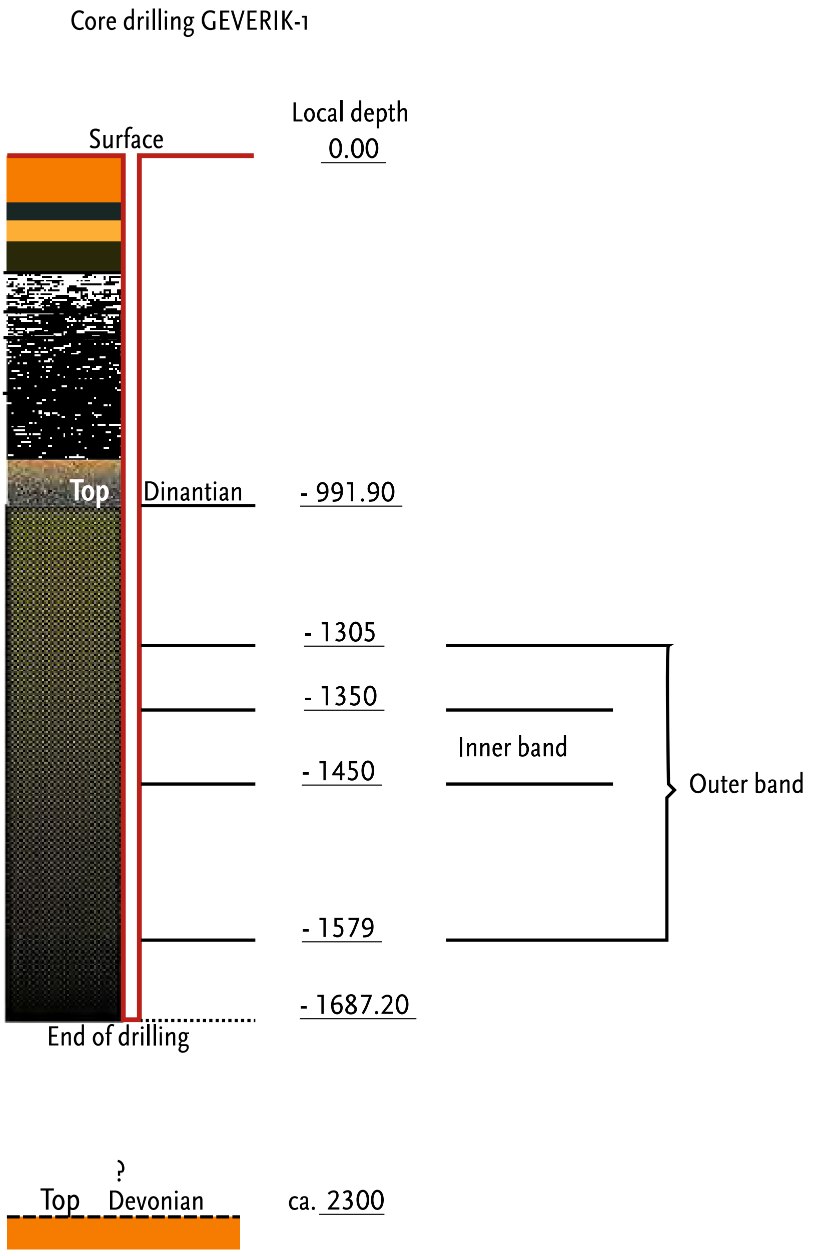


Figure 53 – Preferred formations in Dinantian (NEOM, 1987)

These two selected sections from the core drilling column are important for the design and construction of the hydro power plant. They correspond to a preferred formation in which the lower reservoir will be located and more specifically in this zone the machine hall will be constructed. In the subsequent discussion of the design of the O-PAC project, these preferred formations (which are horizontally long and vertically relatively narrow) will be described as outer (band) zone and inner (band) zone for the reservoir and machine hall locations, respectively. The outer zone (band) measures 275 m in the drilling column of Geverik 1, which corresponds with a horizontal N-S width of the preferred zone of 750 m, which is only 20 % of the available 3.8 km project width. The inner zone is based on a column length of 100 m and hence a horizontal width of approximately 275 m to locate the machine hall system in the preferred zone. However, the outer zone is determining for the location selection, because it is easier to shift the machine hall complex than the cavern system of the lower reservoir. Finally, based on the 20-degree slope angle of the rock layers and 5-10 % seismic uncertainty, the deviation of the formation bounds in the horizontal plane at 1,400 m depth is at the most 200 to 400 m.

Nevertheless, the homogeneity of these layers is not known in all places. Therefore, it is necessary to conduct further site-specific research to be able to quantify faults and other geostructural threats in order to select the proper underground conditions for the exact location of the U-PHS.

Maximum horizontal neotectonic stress in this area in the deeper underground is NW-SE oriented. The seismic profiles show a strike with a flat, locally faulted layering in the south and an increasing N-E dip in the north. Several faults have been noticed, and while they do not reach the surface, some do cut through the overburden. See Figures 54-57.

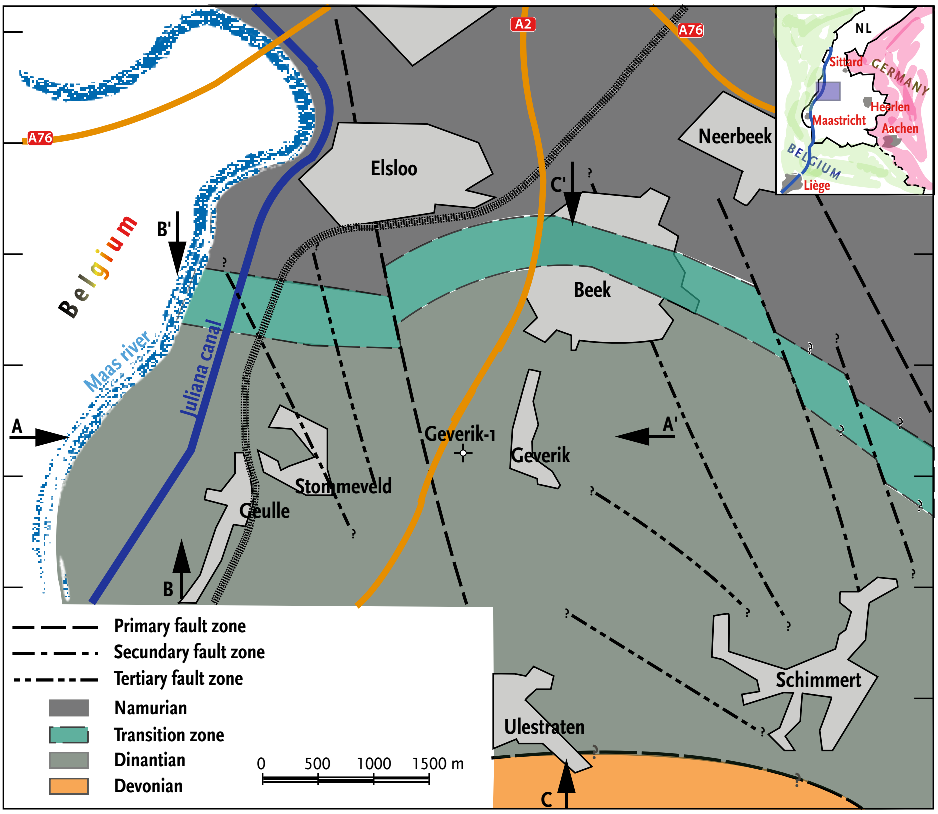


Figure 54 – *Site map illustrating geological conditions at -1,400 m. The seismic profiles for the locations indicated with the letters A-A', B-B' and C-C' are presented below in figures 55, 56 and 57, respectively (Müller & Hereth, 1987a)*

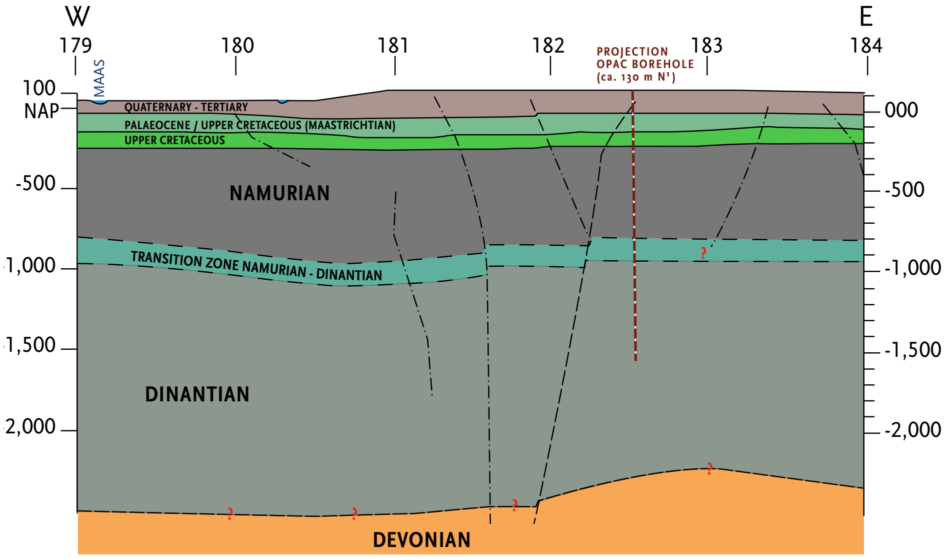


Figure 55 *– Seismic profile (326 500), section A-A' (Müller & Hereth, 1987a)*

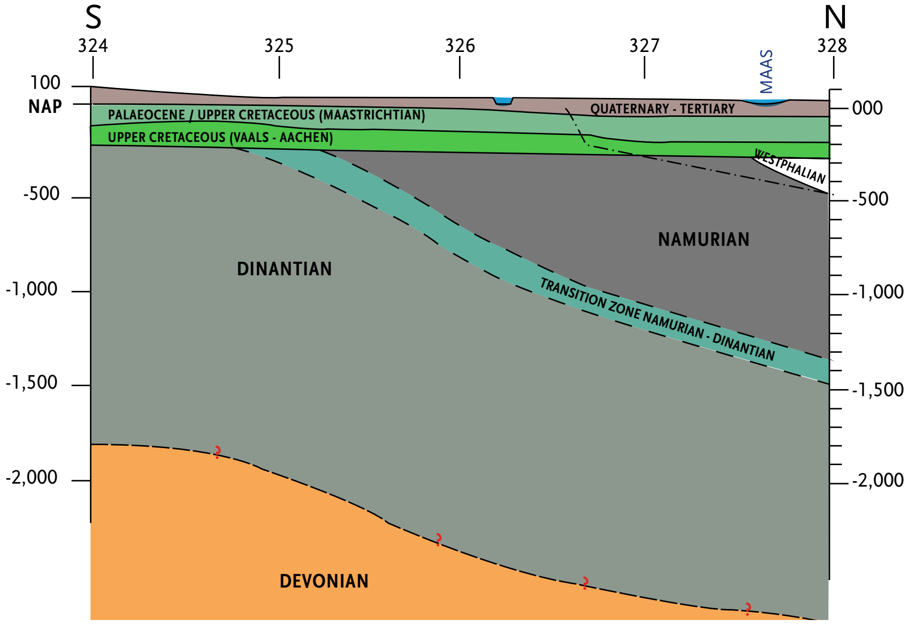


Figure 56 *– Seismic profile (180 000), section B-B' (Müller & Hereth, 1987a)*

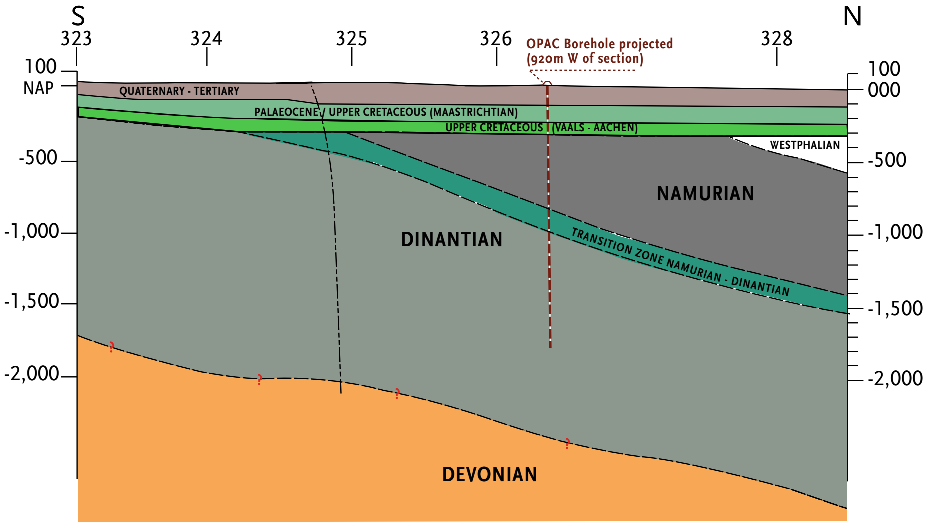


Figure 57 *– Seismic profile (183 500), section C-C' (Müller & Hereth, 1987a)*

Using the existing vintage seismic data, a 3D geological model was constructed for the O-PAC project (Petrel model). For the southern part, the seismic interpretation of the O-PAC study (RGD, 1987) is used, whilst for the northern part the data are from TNO's public database. See Figure 58.

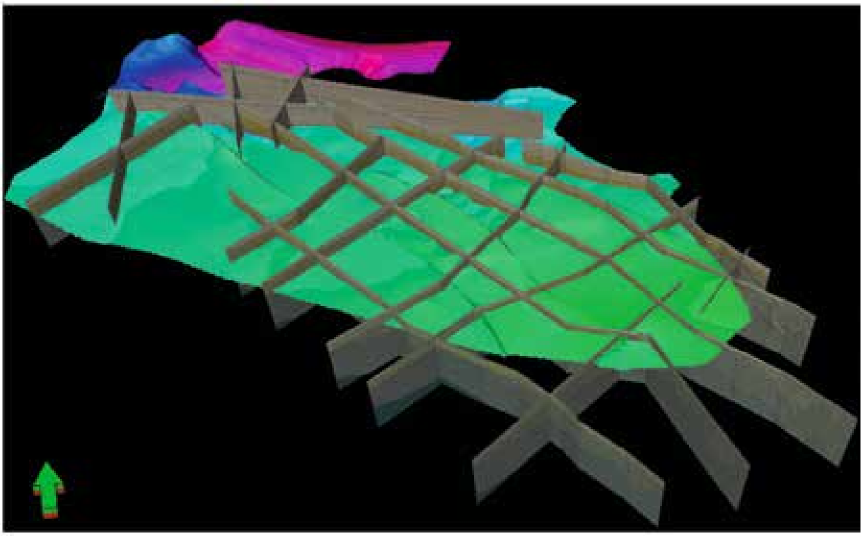


***Figure 58** – Petrel model of the top Dinantian (Kramers, et al., 2011)*

It must be taken into consideration that the area is active neotectonically. The 'Feldbiss' fault near Sittard registers nearly annual weak earthquakes of the magnitude of 4 MSK (Medvedev-Sponheuer-Karnik scale).

Though the general area of South Limburg is seismically active, the O-PAC site appears to lie outside the area of large active faults. However, identification of minor active faulting and hitherto undetected fault structures can only be done by additional 3D seismic investigation or core drilling.

The probability of an earthquake with a magnitude of 5 is one in 5,000 years (KNMI, 1985). In 1992 an earthquake of the magnitude of 5.5 (Richter scale) was registered near Roermond (Kramers, et al., 2011). Müller & Hereth (1987a) emphasize that "for the underground openings earthquake risks are very small, compared to the risks on the surface. This is the reason why the indicated earthquake activity has no significant influence on the stability of the OPAC underground openings."

Summarizing all data of the geological and geotechnical research and drilling results, the conclusion can be drawn that the optimal O-PAC version of 1,400 MW, 8.4 GWh and 1,400 m depth is feasible in the underground of the designated area of South Limburg.

Though the underground circumstances for O-PAC are generally favourable, additional 3D seismic research and borings should be carried out locally at designated measuring points.

5·4 Location selection in the target area

After the conclusion that the former mines were not adequate to function as an underground reservoir for a U-PHS and the positive core drilling results, it was apparent that a suitable location could be found in South Limburg to host an underground power plant. Further considerations concerned logistic aspects, such as accessibility, the presence of water, etc. The presence in this area of both the river Meuse and the Juliana Canal considerably improves the feasibility of the project.

In order to prevent subsidence of the surface, a sufficiently thick rock layer must be present. The risk of subsidence is small when the cavern is situated in the middle of a 700 m thick homogenous rock layer at more than 1,000 m depth.

It is an advantage if the upper reservoir is situated well above the lower reservoir. However, there is a certain horizontal distance between the two basins that can be covered. There are examples of PHSs in which the distance between the two reservoirs is considerable. This factor can enlarge the scope of the search area for the upper reservoir. The location of the upper reservoir may be relatively flexible with respect to the lower subterranean reservoir.

The remarks below refer to the location selection for the lower reservoir:

- The intended location will be clearly situated outside the area of the former mining activities.
- The underground tunnels and caverns should stay clear of tectonic faults.
- No karstification should be present in the relevant rock layers.
- The excavation works aim to create durable caverns as water reservoirs and therefore must be situated in homogenous rock layers.

5·5 Geothermic conditions

Temperature estimates within the OPAC project are based on the drilling results. The figure below shows the geothermal temperature of 2.2 °C/100 m (between 375 and 1,085 m), and ca. 2.9 °C/100 m (between 1,085 and 1,495 m). The OPAC study group concluded that at a depth of 1,400 m the rock temperature is expected to be around 44 °C.

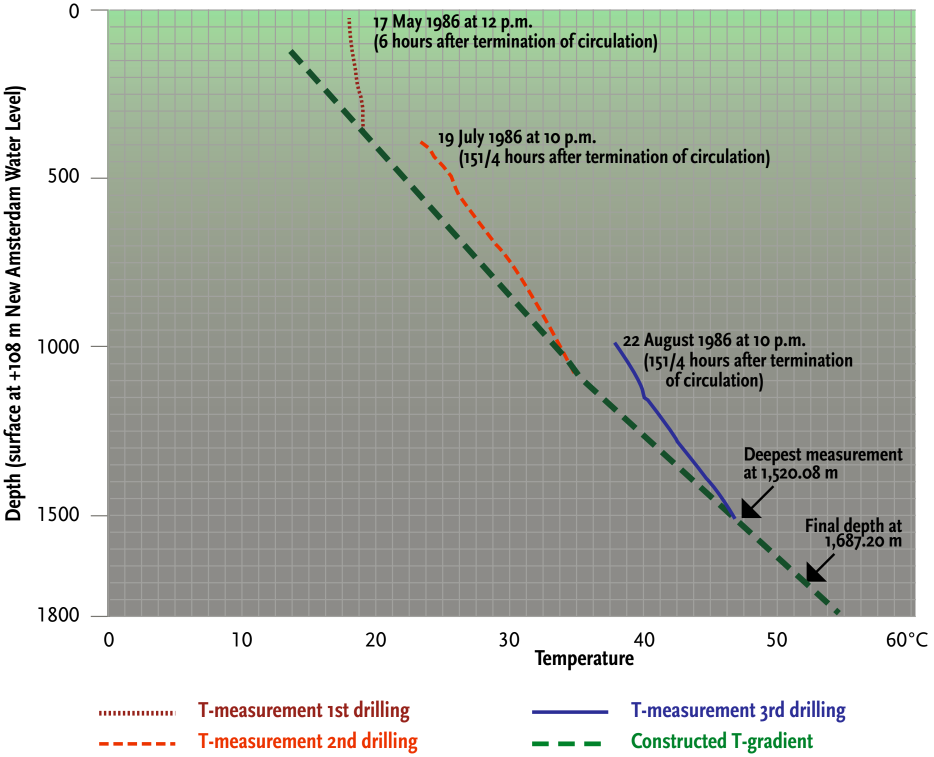


Figure 59 – Geothermal gradient at the OPAC project site (RGD, 1987)

As a consequence, the geothermic influence during the construction phase at the projected depth requires adequate refreshing/ventilation. In order to meet the current regulations, ventilation has to be designed in accordance with the number of employees involved on the site, and must be capable of lowering the air temperature to 28 °C.

The water in the caverns will be warmed up by the surrounding rock mass. The average warming-up time will be approximately 20 hours, as this is the expected maximum time the water resides in the lower reservoir. The dimensions of the caverns dictate the volume-surface ratio. Whilst the rock mass temperature underground at the -1,400 m level is approximately 44 °C, the process water temperature is estimated to stay be well below 30 °C.

During operation, the basic temperature gradient is still valid, the major difference being that only a very limited number of electromechanical technicians are working in an air-conditioned environment. Moreover, the command/control room where the operation and handling will be carried out, is positioned above the ground.

Although the heat conductivity of the rocks is low, a significant cooling of the limestone surrounding the cavities during operation is not expected, particularly since the processed water has an elevated temperature caused by thermal energy losses of the turbines (Müller & Hereth, 1987a).

5.5.1 Influence on process water

O-PAC is a closed-loop system, so apart from the amount of water, a number of other processes, such as evaporation, inflow of formation water, and subsequent salinization are also relevant.

Water inflow, calculated on the basis of the bore results of Geverik 1 in 1986, appears to be of minor importance. In addition, the samples of the Namurian mudstone have a very low permeability. Calculating from these parameters, the resulting water flow is projected to amount to around 0.6 $l/m^2 \cdot d$ (Müller & Hereth, 1987a). Relative to the power plant's total process water of 2.4 million m^3, this is a very small amount.

The process water in the upper reservoir must stay within certain parameters with regard to environmental consequences. In addition to the previously mentioned increase in water temperature by thermal energy losses from the turbines, the heating of the process water by contacting the rock walls of the underground reservoir must also be taken into consideration. The process water, because it is mixed with salty formation water and thickened by the difference between evaporation and supplementation, will salinate to a certain degree. As a starting point, Dutch law (Wet Verontreiniging Oppervlaktewater) states that the temperature of the process water has to stay below 30 °C to avoid the development of hazardous germs to public health.

The thermal discharge in different supplementation flows can be summarized as follows (N = supplementation flow x evaporation):

N = 1	N = 10	N = 100	N = 1,000
Q = 50 l/s	Q = ± 500 l/s	Q = ± 3,000 l/s	Q = ± 20,000 l/s
No thermal discharge	Thermal discharge ca. 10 MW	Thermal discharge ca. 50 MW	Thermal discharge ca. 100 MW

The released quantity of salt dissolved in water amounts to between 4 and 40 tonnes per day. A discharge flow of 200 m³/sec of the river Meuse, together with the salinity of 50 mg/l (= 864 t/d) already present, leads to an increase of the concentration of 0.45 to 4.5 % (NEOM, 1987). As can be concluded, the discharge of salt into the Meuse signifies only a small increase of the existing concentration, which depends on the water level in the river.

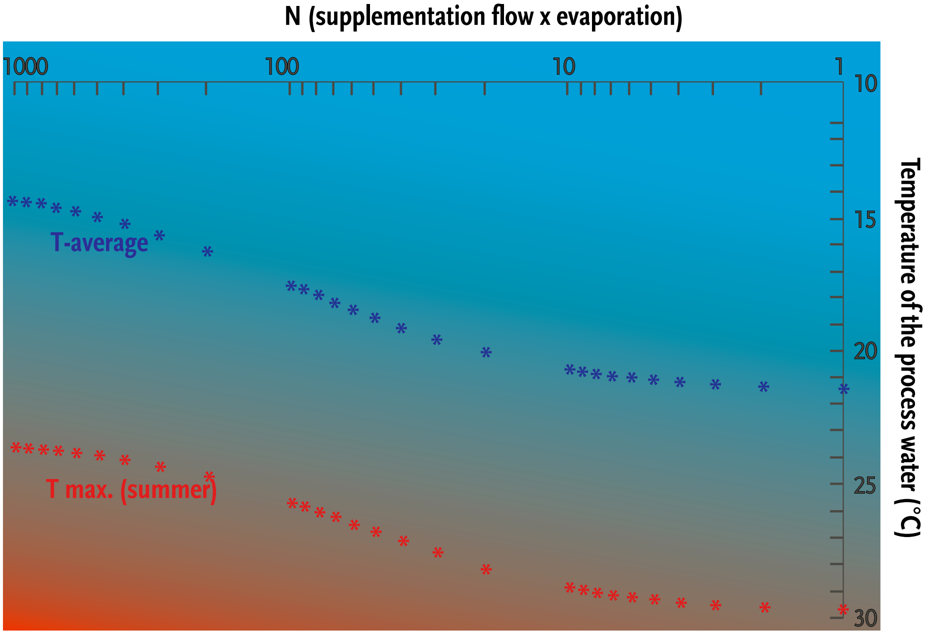


Figure 60 – Temperature gradient based on supplementation and evaporation (NEOM, 1987)

5·6 Concluding remarks

Abandoned coal mines in South Limburg were found to be unsuitable for containing a reservoir for a U-PHS plant, due to cave-ins and structural instability.

However, analysis of drill cores showed that rock masses beneath it are suitable, but additional characterization of the subsurface at the designated location is needed before a final decision on the project can be taken. In order to eliminate the risk of open fractures in the subsurface, it is strongly recommended that a 3D seismic study be carried out and drill cores be taken.

The geothermal heat at the designated underground location is well below the admissible thresholds, despite the considerable depth. The temperature can be controlled sufficiently to allow personnel to work at this depth, both during construction and operation.

The optimal conditions of the underground are present in the area around Geverik, while the river Meuse and the Juliana Canal provide for fresh water intake and efficient transport during construction.

6 Design and construction of O-PAC

6·1 Introduction

The design and construction of OPAC has been studied since 1980. Optimization at the time led to a functional design based on:

- the most efficient storage capacity and volume
- the optimal depth and location, as determined by geologic conditions
- the ideal layout of the underground reservoir, using the structural possibilities of the rock layers involved
- the most effective pump-turbine combination

In coordination with SEP (cooperative electricity producers, the predecessor of TenneT), different storage sizes, varying between 400 MW and 2,000 MW, and storage capacities (5 GWh – 20 GWh) were compared. The following characteristics were found to be optimal for the situation at the time:

storage capacity:	8.4	GWh
pump/generator capacity	1,400	MW
depth/head	1,400	m

From design to final construction, the schematic process follows Figure 61.

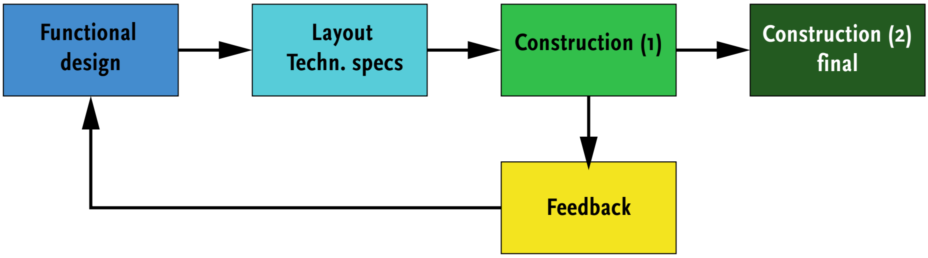


Figure 61 – Iterative design and construction process

This chapter describes the construction of U-PHS. First the layout of the underground machine hall is considered (6.2.1). Then the design and construction of the subterranean reservoirs is discussed (6.2.2). Subsequently, the construction of the shafts, which connect the underground structures with the surface, is explored (6.2.3). The selection of the electrical and mechanical equipment is considered in Section 6.3.

This is followed by an analysis of the horizontal and vertical transport of excavated rock, goods and persons (6.4). The construction of the upper reservoir, the only surface part of U-PHS, and its environmental embedding is discussed after that (6.5).

The careful planning and monitoring of all safety aspects during both construction and operation are covered next (6.6). This chapter closes with a discussion of the conditions under which U-PHS is feasible in other locations (6.7).

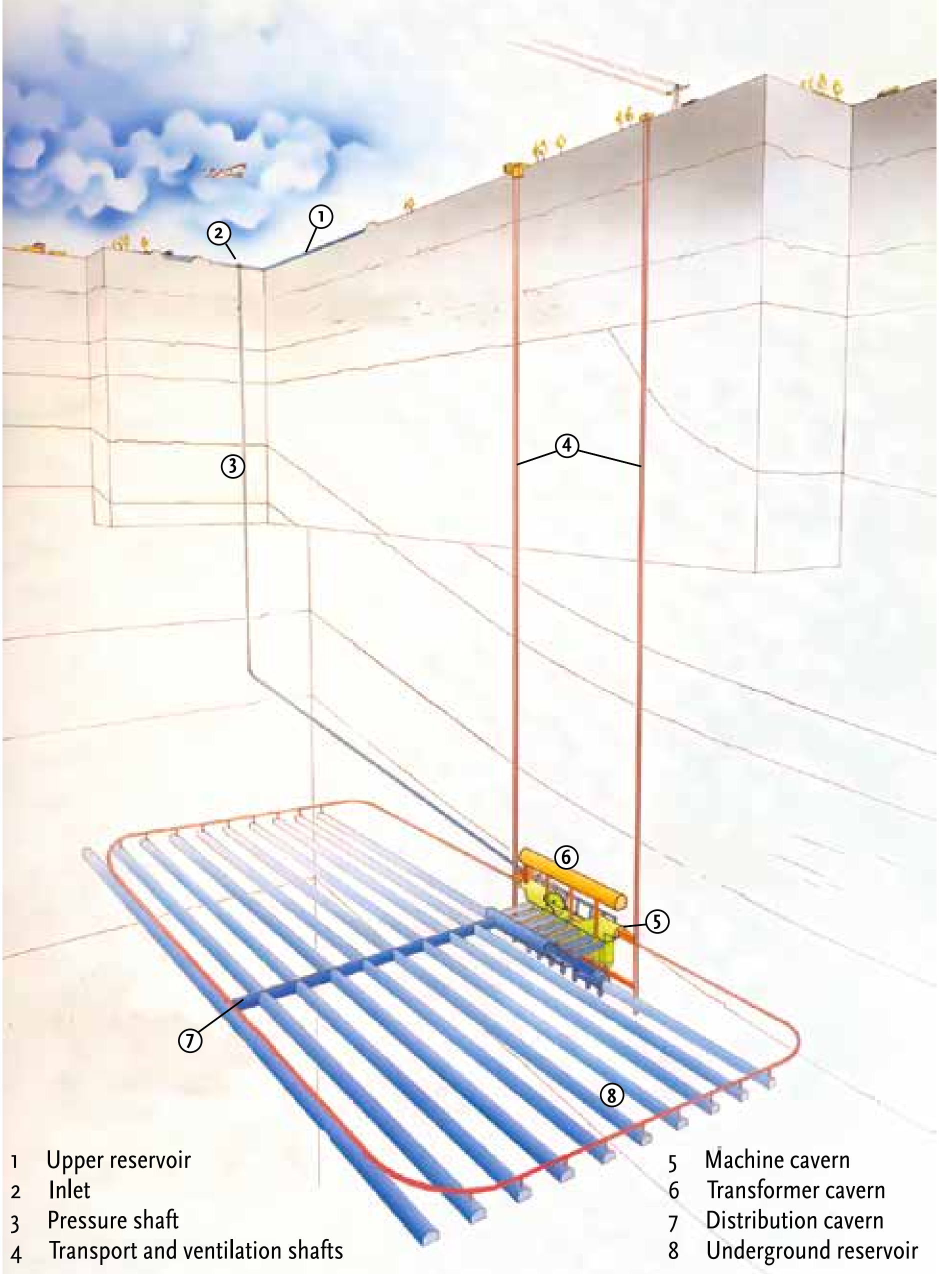


***Figure 62** – Schematic view of OPAC (NEOM, 1987)*

6·2 Principles of underground construction methods

In order to give insight into the differences between the subterranean construction methods and the more familiar on-surface building systems, the philosophy of cavern design in underground rock layers will be discussed first. In contrast to the design of on-surface structures, where (pre)fabricated support structures of steel, wood and concrete are used, underground building can be characterized as building with nature itself.

The European Committee for Standardization (CEN) describes how to design geotechnical constructions. These standards, informally known as Eurocode 7, were published under EN 1997, and approved by the member states in 2010.

The Austrian Society of Engineers and Architects defines NATM (the New Austrian Tunnelling Method) as: *"A method where the surrounding rock or soil formations of a tunnel are integrated into an overall ring-like support structure. Thus the supporting formations will themselves be part of this supporting structure"*. The NATM, also known as sequential excavation method (SEM), first received attention in the 1960s, based on the work done by Ladislaus von Rabcewicz, Leopold Müller and Franz Pacher between 1957 and 1965 in Austria. "Their work with the New Austrian Tunnelling Method should, however, not be underestimated. They introduced an important step in the development of modern tunnelling. Together with new understanding from the young field of rock mechanics in combination with the development in support technology, a movement was created, which enormously enriched tunnelling" (Maidl, et al., 2013).

"This sequential method caused widespread astonishment among engineers and constructors at the outset, but the conscientious work in Austria during the 1960s ended up consolidating this approach as a gold standard in the industry" (Putzmeister, n.d.).

"Unlike the classical methods such as the Belgian or German approaches, where the tunnel is immediately supported without allowing it to deform naturally, NATM allows the deformation of the rock mass before stabilizing the tunnel, which reduces the amount of additional support materials required" (Putzmeister, n.d.).

Compared to the new Italian tunnelling method ADECCO-RS (Analysis of COntrolled DEformation in Rocks and Soils) developed by Lunardi and Pelizza in 1980, preference is given to NATM (Maidl, et al., 2013).

The advantages of the Italian method, which has a specific relevant application in friable and soft rock, are not present in the hard rock mass of Dinantian.

The following seven elements serve as guiding principles for the construction of O-PAC, based on Rabcewicz & von Golser (1973):

Rock mass classification – Rock masses range from very hard to very soft, and this process determines the minimum support measures required and avoids economic waste that comes from excessive support measures. Support system designs exist for all main rock classes. These serve as the guidelines for tunnel reinforcement.

Exploitation of the strength of native rock mass – This relies on the inherent strength of the surrounding rock mass being conserved as the main component of tunnel support. Primary support is directed to enable the rock to support itself.

Shotcrete protection – Loosening and excessive rock deformation must be minimized. This is achieved by applying a thin layer of shotcrete immediately after face advance.

Flexible support – The primary lining is thin and reflects recent strata conditions. Active rather than passive support is used, and the tunnel is strengthened by a flexible combination of rock bolts, wire mesh and steel ribs, rather than by a thicker concrete lining.

Closing of the invert – Especially crucial in soft ground, the rapid closing of the invert (the bottom portion of the tunnel) is important, as it creates a load-bearing ring, and offers the advantage of engaging the inherent strength of the rock mass surrounding the tunnel.

Measurement and monitoring – Potential deformations of the excavation must be carefully monitored. NATM requires the installation of sophisticated measurement instrumentation. These instruments are embedded in the lining, ground, and boreholes. In the event of observed movements, additional supports are installed only when needed, with a resultant overall economy to the total cost of the project.

Contractual arrangements – Since NATM is based on monitoring measurements, changes in support and construction method are possible, but only if the contractual system allows them.

By way of creating a self-supporting rock mass ring around them (NATM), the caverns can be realized through careful excavation (Müller & Hereth, 1987a; Müller & Hereth, 1987c), with relatively minor building efforts (lining), provided that the support structure is installed at the right time and in the proper way (see 6.2.2) (Müller & Hereth, 1987c).

The core function of the lining is not to bear all the pressure, but rather to keep the rocks together, so that the rock mass itself is able to bear the pressure. Consequently, the level of tension concentrations in the cavern walls is a very important consideration. These edge tensions dictate the form and design of the caverns and tunnels, as does the quality of the rock layers.

Based on these considerations, the construction process of this supporting structure necessitates the following steps (NEOM, 1987):

- the choice of the desired cross-section and the excavation sequence of the caverns
- the orientation of underground cavern groups
- the determination of the tension concentrations
- the determination of the lining in relation to the rock quality

In view of the complexity of the O-PAC project, where a major part of the construction is based on mining technology, it is crucial to establish an uninterrupted flow of excavated rocks to the surface. As the period of excavations will be approximately 3 years, all measures relating to this process must be scrutinized for optimal efficiency. A simplified construction scheme describes the main steps:

1. Drilling and blasting of rock mass	5. Discharged or unloaded from the lift cart
2. Rocks are scooped up by excavators	6. Transported by conveyor belt or truck
3. Transported to the lift by dump trucks	7. Dumped to a depot
4. Vertically lifted to the surface	8. Transported by boat

6.2.1 Design and layout of the machine hall

The heart of the pumped hydro power plant is the machine hall, where the pumps/turbines are installed. The solid rock formation facilitates the construction of a large underground vault measuring 71.5 m in height by 20 m in width and 128 m in length (Figure 65), based on the NATM constructing method (see 6.2). The enormous vertical dimension is necessary to house the 7 pump-turbines, where the pump, turbine and generator are each integrated from bottom to top, along a vertical axis, (see vertical cross-section, Figure 64) as will be explained in 6.3. Directly adjacent to the machine hall, a separate transformer hall is situated with a volume of 30,400 m^3.

The machine hall is not only the centre of the electromechanical equipment, but also a connecting hub for the valves. For proper water handling, the layout includes an additional collector cavern (68,200 m^3) and a distribution cavern for joining the storage caverns (78,500 m^3). The valves are also part of the water circuit and are connected to the pump-turbines in the machine hall (volume of the valve chambers: 50,400 m^3).

Related to the machine hall, the total volume of the excavated caverns is:

machine hall / power house	148,300 m^3
transformer cavern	30,400 m^3
collector cavern	68,200 m^3
distribution cavern	78,500 m^3
valve chambers	50,400 m^3
total	375,800 m^3

Figure 63 *– Underground machine hall. Source: Illwerke VKW*

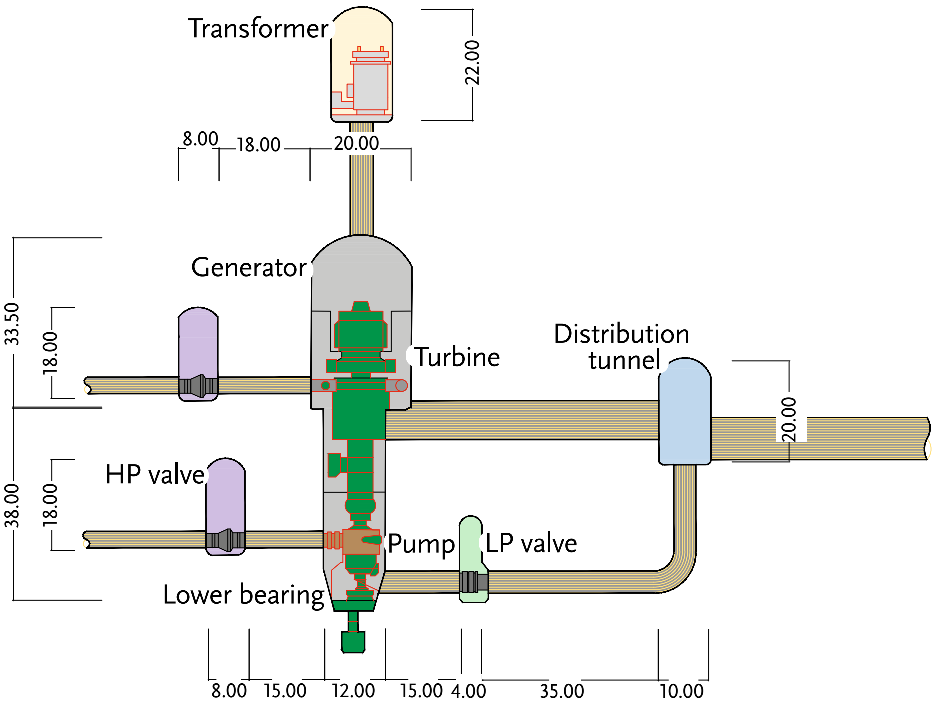


Figure 64 – *Cross-section of the machine hall (Müller & Hereth, 1987c)*

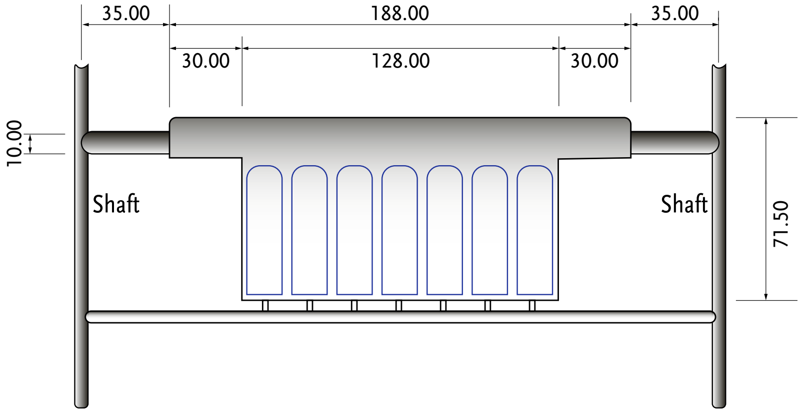


Figure 65 – *Longitudinal section of the machine hall (Müller & Hereth, 1987c)*

6.2.2 Design and layout of the underground reservoir: caverns

During the last decade, significant progress has been made in mining technology through automating drilling and blasting. "In tunnelling, drilling equipment is a means to the end of blasting, which is intended to loosen the rock to the correct profile and without excessive damage to the surrounding rock" (Maidl, et al., 2013). The high-performance drilling machinery in modern drill and blast tunnelling can be mounted on wheel tracks or rails, matching the cross-sectional size and shape of the tunnels. Worldwide, numerous specialist companies are developing and manufacturing automatic equipment for mining and tunnelling purposes (Mining Technology, 2018). Automatic rigs for drilling and blasting with 3 or more simultaneous drills are the industry standard. This significantly reduces the labour cost expenses. Moreover, the accompanying reduction in construction time also results in a considerable cost decrease.

According to NATM, the cavern excavation method by drilling and blasting is preferred over construction with tunnel boring machines (TBMs), because of the high degree of flexibility that the former allows in response to possible local differences in rock quality. The risk of mechanical failure of TBMs is another reason.

The function of the underground caverns is to serve as a lower reservoir, comparable with its open-air counterpart in a conventional PHS. The layout at a greater depth creates the advantage of a higher head, which consequently allows a drastic reduction in the volume of process water. From an economic viewpoint, this solution is attractive, because it requires substantially less rock excavation. The result is that the costs, and therefore investments, for a U-PHS are relatively favourable, compared with a PHS with two large open basins.

The cavern system consists of caverns with 200 m^2 surface per section, with a length of 12 km. The cavern system is divided in two subsystems by a middle distribution cavern. This main cavern collects/distributes to and from the two cavern systems of 8 caverns measuring 750 m length each (a total of 6 km), with a total volume of 2.4 million m^3. See Figure 68 for cavern layout.

Conforming to the NATM excavation procedure, three different profiles of cavern reservoir cross-sections can be selected, depending on the geological structure. After recent consultation with design engineers and construction firms who were recently involved in the construction of the Gotthard Tunnel, mutual confirmation was obtained that the techniques described below are still the industry standard. Moreover, there are no known alternative methods (excluding TBMs) that could replace the proposed proven technology (NATM).

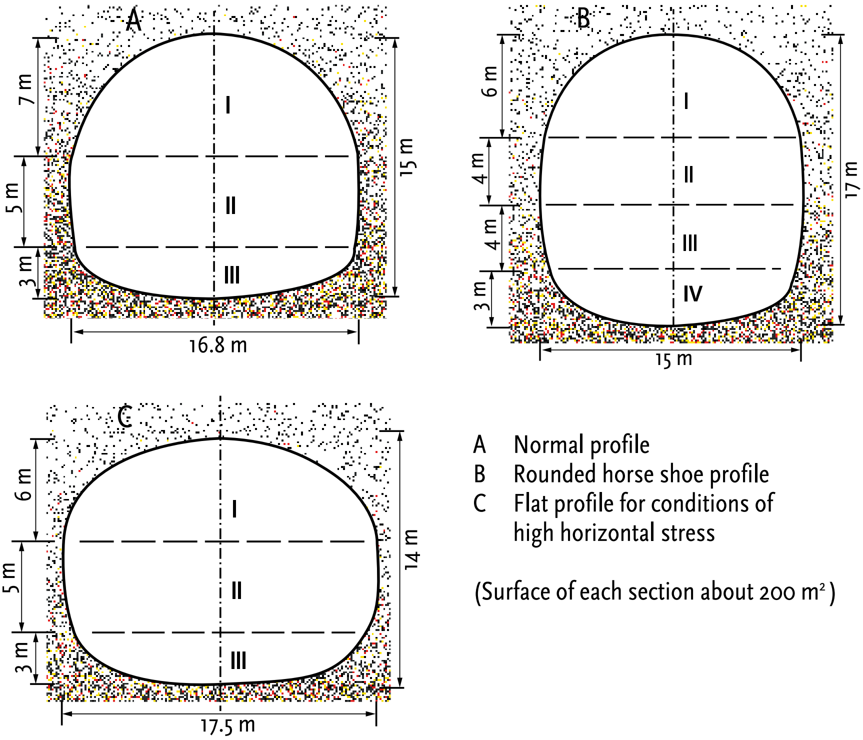


Figure 66 *– Different shapes of cavern reservoir cross-sections (Müller & Hereth, 1987a)*

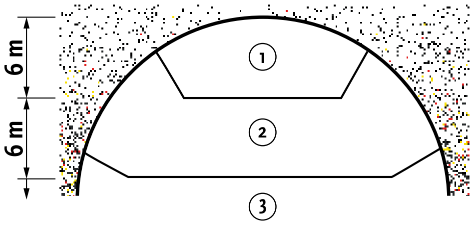


Figure 67 *– Excavation scheme (Müller & Hereth, 1987c)*

General practice (NATM) in cavern construction technology is to start excavating from the ceiling down, and for security reasons, to reinforce the top segment I, followed by segments II, III, and eventually IV (see Figure 66). The different shapes are dependent on the surrounding rock stress conditions (Müller & Hereth, 1987a).

More specifically, after securing the lining by appropriate rock bolts, wire mesh and shotcrete, the next step in the process can be executed, which is detailed under 2 (Figure 67 – Excavation scheme). This step implies the excavation of the benches, together with the appropriate securing measures. From here on, further excavation to the invert (bottom) can be completed.

The rock mass classification is of paramount importance, because it serves as a guideline for tunnel/cavern reinforcement, having both substantial construction and financial consequences.

In order to explore the area where the caverns are proposed, after the excavation of the first shaft, a fan-shaped exploration system will be constructed. These horizontal tunnels would measure 0.96 m in diameter and are designed to investigate the exact geological situation (Deilmann-Haniel GmbH, 1987). During the construction phase, they play an important role in providing measurements for the monitoring system, as well as for safety aspects (see 6.6).

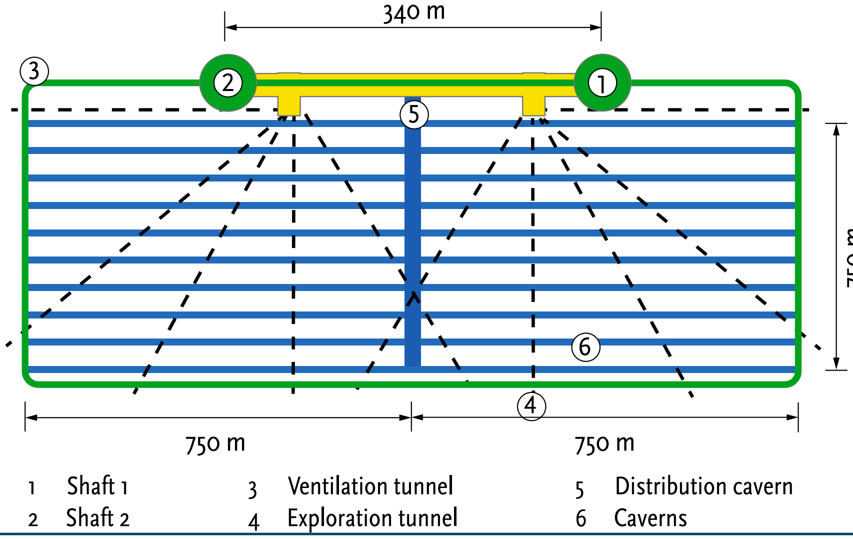
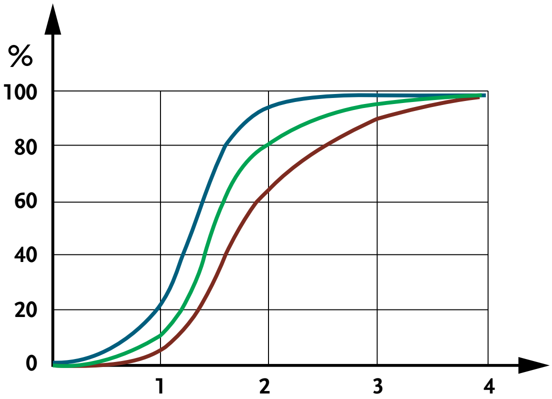


Figure 68 – Fan-shaped exploration system

As stated above, the estimates of the rock classes in the underground layers of South Limburg need to be as accurate as possible, taking into account the results of the exploration tunnels. Based on the rock analysis of Delft University of Technology laboratories by Prof. Price, the following distribution of rock classes have been defined.



Class C	1	2	3	4	Σ %
Optimistic	20	75	4	1	100
Realistic	10	70	15	5	100
Pessimistic	5	60	25	10	100

Figure 69 *– Estimated distribution of rock classes in the Dinantian in South Limburg (Müller & Hereth, 1987b)*

It is important to select the proper lining technique for optimal adaptation to varying rock qualities. Consequently, a classification system has been set up to describe specific technologies for different excavated rock surfaces. In this context, it is relevant to discuss the 4 different classes of lining. An estimated realistic distribution model comprising 4 classes is presented in Figure 69. The different lining support constructions can influence the costs of investment positively or negatively. To explain these significant differences, it is crucial to understand the various lining classes with different rock bolting and other support systems.

Class	Lining	Rated distribution
C1	4 m length of rounds drilling and blasting. In crown, to secure: – galvanized steel wire mesh with 1.5 m long rock bolts, in a lattice of 1.3 x 1.5 m	10 %
C2	4 m length of rounds with 2-4 hours stress redistribution after round. In crown, to secure: – 5-7 cm shotcrete – locally 1.5-2 m long rock bolts at difficult points Subsequently in crown: – systematic rock bolting, 3 m long, centre to centre 2 m – steel wire mesh fixed with 1.5 m bolts	70 %
C3	2.5 - 3.5 m length of rounds with 2-4 hours stress redistribution. In crown and benches, to secure: – 5-7 cm shotcrete – locally rock bolts at difficult points Subsequently in crown and benches: – systematic rock bolting, 5 m long, centre to centre 2 m – steel wire mesh fixed with bolts – 10 cm shotcrete after decreasing transformations (convergence), at approximately 30 - 50 m after work area	15 %
C4	1 - 2 m length of rounds drilling and blasting, otherwise mill. In crown and benches, to secure: – 5-7 cm shotcrete – locally rock bolts at difficult points Subsequently on all sides: – systematic rock bolting, 10 m long, centre to centre 1 m – steel wire mesh and further concrete layers up to 30 cm thickness	5 %

Table 13 – *Lining of the lower reservoir as a function of rock class; practical classes of lining and lengths of rounds drilling and blasting for caverns (NEOM, 1987)*

6.2.3 Design and layout shafts: wet shafts, dry shafts

An optimization study for the selected OPAC version (1,400 MW, 1,400 m depth, 8.4 GWh capacity) to determine the number of shafts, resulted in a minimum of three shafts: two dry shafts for transport, ventilation etc. and one wet shaft to facilitate the process water.

Shaft 1, a dry shaft with a diameter of 7 m, will be utilized for excavated rock transport with double skip containers, an emergency elevator, pressurized air tubes, waste water pipes and cabling.

Shaft 2, a dry shaft with an 8 m diameter, is equipped for large material transport with high load container hoisting equipment with a counterweight and a maximum capacity of 20 tonnes. A backup elevator would be present too. Further cabling for energy, tubes and other auxiliary installations are located in this shaft.

Shaft 3, the wet shaft, is the high-pressure water shaft, and with a diameter of 6 to 7 m, it is the major system element in the closed-loop water circuit of the U-PHS (Figure 71).

For construction of the shafts, the freezing method, in which a circular zone around the shaft is frozen, was considered but rejected, as this technology requires more time and is more costly than conventional drilling methods.

The wet shaft construction deserves special care due to the high-pressure water mass used to power the turbines in the machine hall. Therefore, special concrete ring elements have to be prefabricated, equipped with a steel outside coat, which will function both as an outside mould and later as a water seal. From the depot on the site, these concrete ring elements will be transported to the traverse crane, which is situated on top of the shaft opening. Since the rings are to be installed floating on drill sludge, the first element is provided with a steel bottom, which is designed to be easily removed later (NEOM, 1987). During shaft construction, another element will be successively placed on top of the previously installed concrete ring. For OPAC, a special water shaft system was designed with drainage openings in the seams and connected with dowels. After carefully guiding the element into its proper place, the steel covering will be welded and the joint between the rings will be filled with mortar. These welded elements will result ultimately in a tube with an outer diameter of 7 m, which will be lowered into the shafts and then filled with bentonite. The tube will be supported by the hydrostatic pressure of the filling fluid at the bottom, assisted by the gantry crane. After reaching the designated depth with the entire prefabricated pipe, the finishing of the interior of the shaft can commence with large-scale grouting.

The method of drilling for excavating shafts is used more frequently in the industry than the freezing technology, and this technique will now be described in greater detail (NEOM, 1987).

In order to reach the designated diameter of the drilling hole – 7.40 m to 9.20 m, depending on the type of shaft – the drilling process takes place stepwise. The concept is to start with a drill head of successively Ø 1.80 m, Ø 4.00 m and then Ø 7.40 m or Ø 9.20 m. The first drilling with a diameter of 1.80 m is the so-called 'pilot drilling', which has to be carefully executed in order to maintain maximum precision in the vertical orientation; this is decisive for the drilling accuracy of the entire shaft. In the pre-shaft operation for the guidance of the bottom hole assembly (BHA), a temporary guidance construction must be installed in the form of a tube (NEOM, 1987).

When the pilot hole is finished, the following step will be drilling with a 4 m diameter, when a part of the 1.80 m BHA will be fixed under the 4 m bore head, to ensure guidance in the already present pilot hole. If possible, the 4-metre drilling can be performed as a first drilling (pilot hole). The described method could be repeated with the following steps. The drill head of Ø 7.40 – 9.20 m is equipped with cutting rolls or chisels, which can be pneumatically expanded to extend the borehole locally to Ø 10 m for the eventual shaft foundation.

The drill grit will be transported by circulating drilling fluid via drill tubes and the drill head, using the air-lift principle to raise it up to the rinsing basin on the surface. Here, the drill grit sinks to the bottom of the basin and will eventually be dredged from the bottom and removed. The drilling fluid will be refreshed and returned to the drilling station. Based on the actual geotechnical data, it can be assumed that bentonite rinsing, with possible addition of polymers, will be applied. After completing the drilling cycles of shaft 1, the drilling installation will be relocated to shaft 2.

It is necessary to protect the turbines from damage by eventual loose rock or concrete particles between the underground reservoir and the penstock. Therefore, a rock trap will be installed, allowing only stone particles smaller than 0.25 mm to pass.

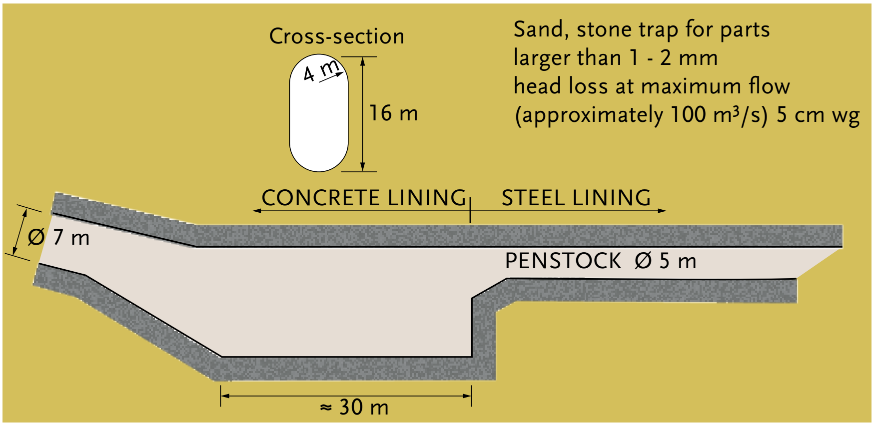


Figure 70 – *Rock trap for penstock (NEOM, 1987)*

Shaft	**Function**	
	Temporary	Permanent
Shaft 1	TRANSPORT SHAFT Ventilation, intake Transport of: – people – heavy parts – building materials (down)	OPERATIONAL SHAFT Ventilation, intake Transport of: – people – heavy parts
Shaft 2	ROCK SHAFT Ventilation, exhaust Escape shaft Transport of excavated rock (up)	CABLE SHAFT Ventilation, exhaust Electric cables Escape shaft

Table 14 – *Functions of the dry shafts (NEOM, 1987)*

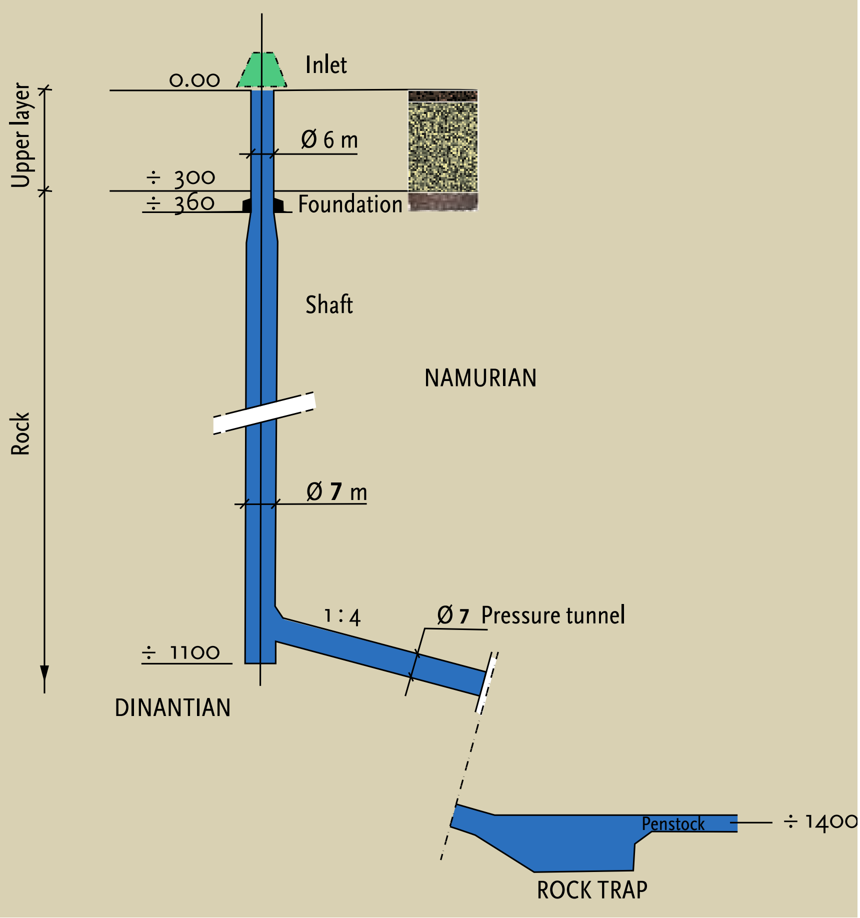


***Figure* 71** – *Water shaft and pressure tunnel (NEOM, 1987)*

The water shaft forms a key system element in the closed-loop water circuit of the PHS and is ideally located directly below the upper reservoir. The vertical part ends at a depth of 1,100 metre, while a sloped high-pressure tunnel connects the shaft with the underground machine hall. The internal diameter in the upper layers measures 6 m, and then increases to 7 m from 375 metres of depth onward in order to compensate for the losses caused by bending of the shaft and the installation of a rock trap (see Figure 71).

6·3 Selection of pump-turbines

Pump-turbine technology (see also Chapter 4) has undergone impressive progress during the last decades. One of the developments has been the tuning of the head capacities of the pump-turbines. Until the 1980s, pumping capacity did not exceed a head barrier of 700 m. During the first studies of OPAC, a two-stage solution had to be considered because of the limited head capacity. The consequences were very high costs, as an additional machine hall had to be constructed at a mezzanine level of 700 m depth, in order to reach the caverns at 1,400 m depth. Presently, head capacities of more than 1,000 m are possible. A depth of 1,400 m still presents a challenge, but one that leading pump-turbine manufacturers are able to meet.

Taking into account the limited diameter of the shafts and hoisting capacity, the original studies showed that 200 MW units were the optimal size for the OPAC project. This resulted in an initial OPAC design with 7 ternary FS units, providing a power of 1,400 MW. As the grid will have more VRE in the future, the system will have to be designed for highly flexible operation and frequent, rapid switching between operating modes.

As stated in Chapter 4, the design and selection of the pump and turbine units will have to be optimized to suit grid demands. This implies that the capabilities and especially the ancillary services which TSOs require, have to be reflected in the design of O-PAC.

The most recent specification of the design proposes the application of 5 reversible multistage pump-turbines, combined with 2 Pelton turbines. The multistage FS reversible pump-turbines constitute the backbone of the power generation, delivering 1,000 MW (5 x 200 MW). The reversible units have limited balancing characteristics and hence are inadequate for power adjustment, due to their fixed-speed operation. However, the Pelton turbines provide versatility and are able to deliver balancing capabilities from 10 MW to full power (2 x 200 MW). This enables the plant to deliver from 10 MW to 1,400 MW when generating. Moreover, each pump-turbine can be started separately in pump mode with the aid of the Pelton turbine. The second Pelton turbine functions as a backup. The power uptake can only be regulated by the number of active pumping units (Haskoning, 2009).

The only downside of this pump-turbine selection is that the pumping mode takes approximately 30 % more time than for discharge to the lower reservoir. However, within the 24h cycle, this should not affect the effectiveness of the O-PAC pumped hydro power plant.

Multistage pump-turbines			
Speed (rpm)		600	
No. of stages		6	
Runner diameter (mm)		2,200	
Turbine mode		Pumping mode	
Nett head (m)	Output (MW)	Lift (m)	Flow (m^3/s)
1,380	204	1,420	13

Pelton turbine	
Speed (rpm)	600
No. of jets	4
Runner diameter (mm)	2,450
Turbine mode	
Nett head (m)	Output (MW)
1,345	204

Table 15 – *Specification of the 5 multistage pump-turbines and two Pelton turbines*

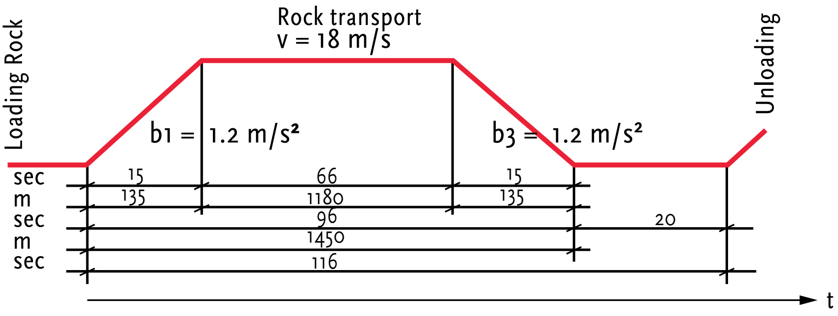
6·4 Transport; vertical and horizontal

For horizontal transport in underground locations, such as tunnels, rail transport is generally preferred for long distances. However, in the case of the limited distances of the caverns, transportation by front loaders on rubber wheels is a better option (Deilmann-Haniel GmbH, 1987). This is especially true in view of the recent arrival of electrically driven equipment as an alternative to fully diesel-fuelled shovel equipment. This new generation of front loaders is powered by an electric motor that receives its electricity from a small diesel generator. This provides a considerable improvement by reducing emissions (up to 49 %), which in turn decreases the required ventilation capacity. In order to clear the boulder and rubble coming from the drilling and blasting processes, continuous removal by a sufficient number of electric bulldozers must be secured. The use of dump trucks could also be efficient, since they have more than triple the load capacity of front loaders. The maximum distance to the skips of the elevator in the transport shaft is around 700 m, with an average distance of approximately 300 m.

After loading into the skips and hoisting via the transport shaft, the excavated rock will be directed from the shaft head to the final destination, requiring the use of a temporary depot for storage. From this distribution centre (depot) next to the shaft head, three transfer directions will be possible for further transportation (NEOM, 1987):

- directly to the upper basin by a conveyor belt
- by inland shipping on river transport boats
- to a temporary depot for interim storage prior to the final transfer to the upper basin or to inland shipping destinations

The primary challenge during the construction period will be the transport of rock excavated from the 1,400 m level to the surface. The time-critical aspect is the vertical transport. Therefore, high speed elevators are foreseen (65 km/h). The two dry shafts are primarily designated to fulfil this function, which will switch to permanent use after finishing the construction works and the subsequent alteration. The following scheme gives an indication of the hoisting capacity of shaft 2 (rock shaft). In order to reduce the construction period, it would be advisable to double the capacity with the installation of a second Koepe hoisting device. This would result in an excavation time of the underground reservoir of about 2.5 years (NEOM, 1987).



# Hoists per hour 3600/116	31.03 hoists per hour
Shaft capacity	559 t/hour
Operational time	20 hours/d
Daily production	11,180 t/d
Weekly production	78,260 t/w

Figure 72 *– Key figures of the vertical transport system and shaft hoist system (NEOM, 1987)*

	one unit	two units
# Hoists per hour	31.03	62.06
Shaft capacity (tonnes/hour)	559	1,118
Operational time (hours/day)	20	20
Daily production (tonnes)	11,180	22,360
Weekly production (tonnes)	78,260	156,520

Table 16 *– Double-skip Koepe installation*

6·5 Upper reservoir

The position of the upper reservoir is dependent primarily of the location of the lower reservoir. Within an approximately 5 km radius of the Geverik drilling site, there are ample locations suitable for the upper basin, (this will be further detailed by 3D seismic tests). The design is dependent on the surface layers, especially the clay layers. Excavated limestone can be effectively reused for the foundation of the encircling dike and as a ballast layer under the upper reservoir.

Figure 73 – Graphic render of the upper reservoir

This upper reservoir has a total surface – including the dikes – of approximately 50 ha, and its dimensions yield 2.4 million m^3 process water. The upper reservoir will be excavated to the maximum depth possible at the site. This reduces the required surface area and thereby the impact on the environment and landscape. In the optimal version of O-PAC, the following figures concerning rock material are relevant (NEOM, 1987):

· available rock	2.8 million m^3 solid
· from excavation	4.8 million m^3 loose
· weight	7.4 million t
· porosity of the aggregate	40%.
· specific gravity	2.65 t/m^3

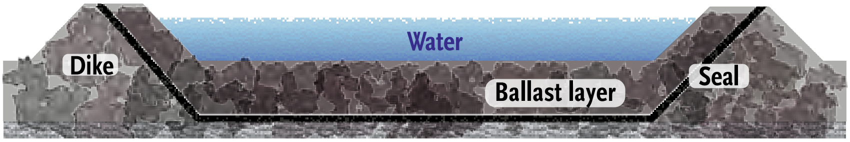


Figure 74 *– Cross-section of the upper reservoir, with ballast layer of excavated rock under basin and dikes*

The specific location and geotechnical properties of the surface define the possible depth of the upper reservoir. Starting from a maximum available depth of around 13 m, the upper basin could absorb 2.92 million m^3 or 60 % of the rock excavation (NEOM, 1987). This layer of excavated rock functions as a counterweight (ballast) against seepage of groundwater. Excavation of the upper reservoir, which would be situated near the river Meuse, would generate large quantities of gravel and cobbles, which is useful for construction industries, and can thus provide substantial revenues. By avoiding supplemental transport costs, this solution also contributes significantly to cost savings.

6·6 Health, safety and environmental aspects

Since this project has all the features associated with mining activities, from the beginning of the design all preventive measures must be taken for the protection of personnel and the environment, both during the construction phase and operation of the power plant.

This will be based on modern health safety and environment (HSE) management principles (Shooks, et al., 2014) and be fully compliant with European legislation. Below, we discuss some aspects of HSE with regard to construction and operation.

An important aspect is that the underground civil engineering works described under 6.2.2 – especially the classes of lining – also serve to prevent rock fall. It is essential that the chance of falling rocks is minimized. Therefore, even stable rock walls, which geotechnically do not need reinforcement, will nonetheless be covered by shotcrete and/or steel wire mesh that is affixed to the rock.

In choosing the appropriate class of lining, it is clear that greater security is more desirable, resulting in more support construction than strictly necessary from a rock-mechanics perspective. In the event of unexpected appearances of rockburst, experience with deep mines (2,000 – 3,000 m) shows that even thin layers of shotcrete, combined with adequate rock bolting, could prevent rockburst (Müller & Hereth, 1987b).

Taking account of the relatively long distances underground and the need for communication with ground-level operations, an effective communication system is indispensable (Deilmann-Haniel GmbH, 1987).

In addition, adequate lighting of operation nodes is not only important for efficiency reasons but will also contribute to the general safety for workers. Especially cross-roads, depots and vital construction site surroundings must be illuminated (Deilmann-Haniel GmbH, 1987).

Above the entire cavern structure, a system of galleries with small diameters has been designed, which will be excavated after completion of the shafts. During the permanent operation, the underground caverns will be aerated by a ventilation tunnel. Further, these tunnels have important roles during construction for surveys and as escape routes (NEOM, 1987).

This system has the character of a test gallery and allows for the following functions (Müller & Hereth, 1987b):

- to investigate the geological conditions in detail
- to investigate rock properties and stress situations
- to investigate groundwater conditions
- to dewater the area, if necessary
- to improve the geomechanical situation by grouting or injections, if necessary
- to optimize all details of the construction process (orientation of the reservoir system, excavation method, support system)
- to clear all conditions for exact price-setting for subcontractors

From a safety point of view, this gallery presents an essential possibility for monitoring and controlling emergency situations.

Moreover, hazardous materials and substances have to be continuously monitored by measuring equipment, therefore the installation and monitoring of a security system equipped with sufficient cameras will be necessary.

Lastly, it is worth noting that a specific study on safety and risks was executed in 1985 (Ingen-Housz, 1985). Though this research deals in detail with a number of aspects, due to the focus on an OPAC version with a 20 GWh capacity (2,000 MW power), its conclusions are not fully applicable. Before the construction of the current O-PAC version, it will be necessary to update the safety aspects to present-day regulations, based on modern HSE management principles (Shooks, et al., 2014) and recent European legislation.

6·7 Reflection on site-specific aspects

While this monograph focusses on the particulars of implementing U-PHS in South Limburg, many of the issues discussed can be generalized for future U-PHS projects elsewhere. Before considering the implementation of a large-scale underground pumped hydro storage system in another region of the world, the following market-oriented conditions should be present:

1. Large quantities of non-dispatchable electricity generating sources must be available.
2. It is preferred that the location of the storage plant is in near proximity to densely populated areas or intensive electricity-consuming industries.
3. There must be, in the case of insufficient DR measures, a great demand for grid-scale storage.

The following technical and geological conditions and circumstances are a condition sine qua non:

1. The underground geotechnical conditions, i.e. solid homogeneous rock formations at a suitable depth, must be available.
2. The preferred location of the lower basin is situated at a depth of between ca. 1,000 and 1,400 m depth. A greater depth is technically feasible but would require two-stage pumping. A depth from 500 m until 1,000 m is possible but is less volume-efficient.
3. For the upper reservoir, there are no specific requirements; an industrial site of approximately 50 ha will be sufficient.
4. The presence of a river/lake or canal is an advantage for irregular water supply. Moreover, during the construction period, it permits the transport of surplus excavated rock.
5. The ability to make an efficient connection with the HV grid.

This subject will be further elaborated in Appendix I, covering the site-specific conditions in order to employ the U-PHS, the flatland storage method, elsewhere in the world and specifically Denmark.

7 Cost-benefit analysis

7·1 Introduction

The Netherlands is currently in the first phase of the transition towards sustainable power generation, while the markets are not yet balanced. It is expected that from 2035 onwards, exclusively non-subsidized electricity will dominate the market, in a mix of VRE and conventional (ECN, 2017b). This expectation is based on the recently reported construction of the North Sea wind parks at lots I and II by Nuon, via its subsidiary Chinook C.V. (Rijksoverheid, 2018; RVO, 2018d) and the tender allocation to Ørsted for the construction of two wind parks at OWP West and Borkum Riffgrund West 2 (Postma, 2017), both without requiring government subsidies. Additionally, there were 4,500 projects that required SDE+ subsidies during the registration period in spring 2018. These requests totalled an amount of only €5.3 billion out of the €6 billion available (RVO, 2018b). SDE+ also has a maximum duration of 15 years, depending on the type of renewable electricity production (RVO, n.d.). This means that the development in VRE technology and the learning-curve effect with growing scales may result in new renewable electricity projects without subsidies, as already observed for wind parks. All SDE+ agreements from before 2020 will have expired by 2035. The need for SDE+ may also diminish in the near future, as the last registration period saw fewer requests than the total subsidy that was available.

Phasing-out of the majority of conventional (coal and gas) power plants and increasing fuel and CO_2 prices will result in an upsurge of electricity prices when dispatchable power is required. The electricity price from dispatchable power generators is estimated to return to levels similar to those before the introduction of VRE. This provides a growing revenue opportunity from energy arbitrage for O-PAC.

However, the business case for O-PAC will be a challenging one during the start-up years after commissioning in 2025. In the beginning of the operation, initial revenues are estimated to cover the operational costs, the direct capital costs, and only partly the depreciation of investment. After 2030, the increase of VRE penetration will facilitate progressive earnings that provide an opportunity for further depreciations. These circumstances will lead to a positive cost-benefit analysis (CBA).

Additionally, major benefits in the public interest (e.g. security of supply) are not compensated, nor are non-paid grid services (e.g. inertia control). These factors are not included in the CBA but are elaborated upon in Chapter 8.

After summarizing the market outlook (7.2), future electricity price projection is presented. Data from projections is used to draw up a revenue model (7.3), leading to a calculation of the total expected revenues (7.3.4). After identifying the benefits, the cost calculation of the investment is of primary importance. For a project as complex as O-PAC, realistic and reliable calculations for estimating the construction costs (7.4.1) are especially important. Alongside construction costs, operational and maintenance costs (O&M, 7.4.3) constitute the basis for the investments required. The structure of these investments is discussed in 7.5. The Chapter concludes with a calculation of the levelized cost of storage (LCOS) in 7.6.

7·2 Summarized market prognoses

The pivotal part of a CBA are the market conditions during operation. For O-PAC this is expected to be after 2025, at the earliest. In 7.2.1, the current market pricing mechanism will be explained. Price forming in relation to fuel costs and CO_2 emission permits, determine future projections. Volatility and especially extreme price differences raise the possible revenues from arbitrage. Control reserve auctions and future development of these trade platforms are discussed in 7.2.2. It is important that this section is understood in the context of the future structure of the Dutch electricity supply, which was discussed in Chapter 2 (Tables 2 and 3).

7·2·1 Electricity price

The Dutch, German and Nordic electricity markets rely on an auction mechanism in which producers bid for an electricity price linked to an amount of electricity supply. This bid is then matched to the demand bids (Nord Pool, 2018a). The electricity price is determined by the uniform pricing principle, i.e. the margina accepted bid sets the market price for a timeslot (Holmberg, 2017; NECG, 2014). In this market design, producers typically bid their SRMC (Short-Run Marginal Costs) for electricity production, though strategic bidding is allowed and occasionally occurs (Holmberg, 2017). SRMC only includes the variable operation costs for electricity production, i.e. fuel, CO_2 permits and variable O&M (NECG, 2014). Therefore, the electricity price is affected mainly by fuel consumption and CO_2 permits, both of which are expected to become more expensive in the future (ECN, 2017b; Energy Brainpool, 2017). This results in an increasing electricity price in projections by Energy Brainpool (2017), presented in Figure 75.

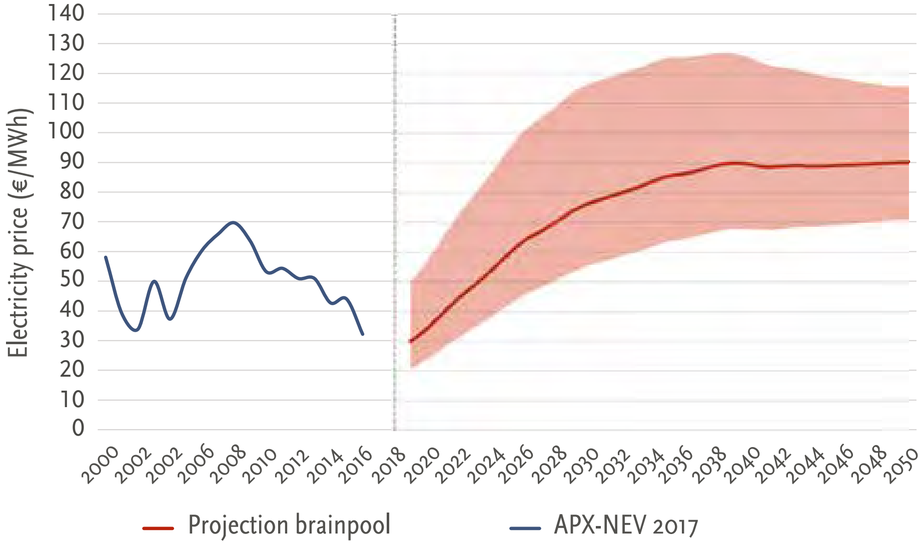


Figure 75 – *Historical average annual electricity prices from the Dutch (APX) day-ahead market combined with electricity price projections from Energy Brainpool for EU-28. Data from: Energy Brainpool (2017) and ECN (2017b)*

The results of price projections from Energy Brainpool (2017), show a substantial rise of the price of electricity in the future. This is affected by more expensive fuel and CO_2 prices, which will stimulate a transition to renewable energy sources. The difference between SRMC for fossil-generated electricity and VRE-based electricity is large. The theoretical SRMC for VRE is €0 per MWh, as wind and solar resources are freely available. While the SRMC for fossil-fuelled power plants goes up in the future, in line with increasing future fuel and CO_2 prices. This is expected to result in a market in which price extremes will occur.

This volatility in electricity prices is more important for O-PAC than the annual average price, as price volatility is the basic principle for performing arbitrage. Energy Brainpool (2017) made projections for electricity price extremes, i.e. prices of €0 per MWh or less and prices higher than €100 per MWh. Their results are presented in Figure 76, which shows that extreme volatility is expected to become more common in the near future.

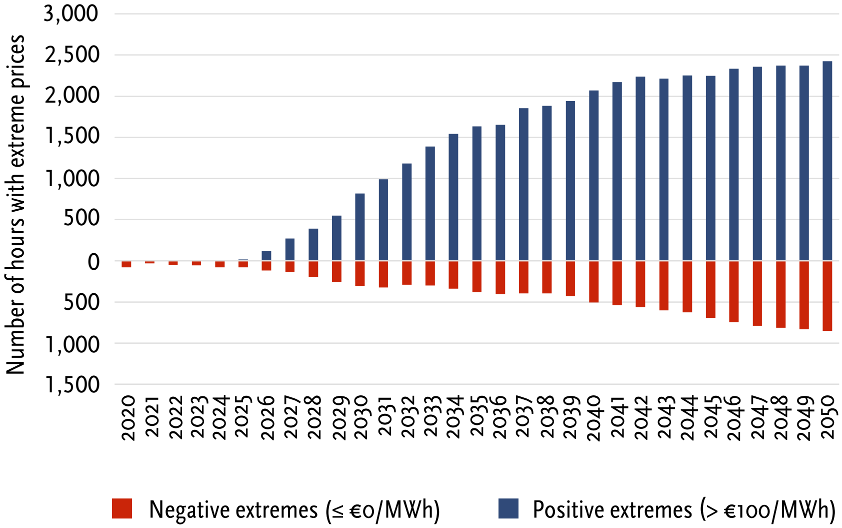


Figure 76 *– Projections on the number of hours with occurrences of extreme electricity prices. Extreme prices are defined as ≤ €0/MWh and > €100/MWh (Energy Brainpool, 2017)*

Both the average electricity price and the expected growth in price volatility provide possibilities for energy arbitrage with O-PAC. Estimates of revenues from energy arbitrage are further discussed and calculated in Section 7.3. Although the calculation approach used in Section 7.3 is not directly based on price extremes (Figure 76), it indicates that the revenue from arbitrage could be substantial after 2025 and increase in the subsequent years.

7.2.2 Frequency control reserve price

The frequency control reserves consist of FCR (Frequency Containment Reserves), aFRR (automatic Frequency Restoration Reserves) and mFRR (manual Frequency Restoration Reserves). The FCR market is already being internationalized, unlike the other control reserves, which are currently national. Below is an overview of the auction mechanisms for different control reserves, tender results, remuneration and future aims. The future of these markets is mainly impacted by the electricity balancing guideline (EBGL), which has already resulted in considerable efforts towards the development of EU-wide markets for control reserves (TenneT, 2017b).

Frequency containment reserves (FCR)

The TSO in the Netherlands, and also in neighbouring countries, uses a tender for the procurement of FCR power. At the FCR auction, balancing service providers (BSPs) place bids for symmetric (up- and down-regulation) blocks of power for a contract period of one week, at a certain price in the FCR auction. The TSO selects bids based on a merit order after closure of the weekly tender. The remuneration for accepted bids is based on a pay-as-bid principle for the reserve power provided (€/MW · week). There is no payment for the activated energy (€/MWh). This means that strategic bidding is necessary, as there is no uniform pricing like there is in the day-ahead and intraday electricity markets (E-Bridge, 2014).

The FCR market is currently being transformed into an international auction, facilitated by the website regelleistung.net. For this international auction, the results are publicly available and presented in Figure 77. From this figure, one can see that the international FCR market has grown in volume, from 600 MW in 2011 to 1,400 MW in 2018. In the Netherlands, there is also a national auction, through which roughly 30 % of the Dutch FCR capacity is contracted (ENTSO-E, 2018c).

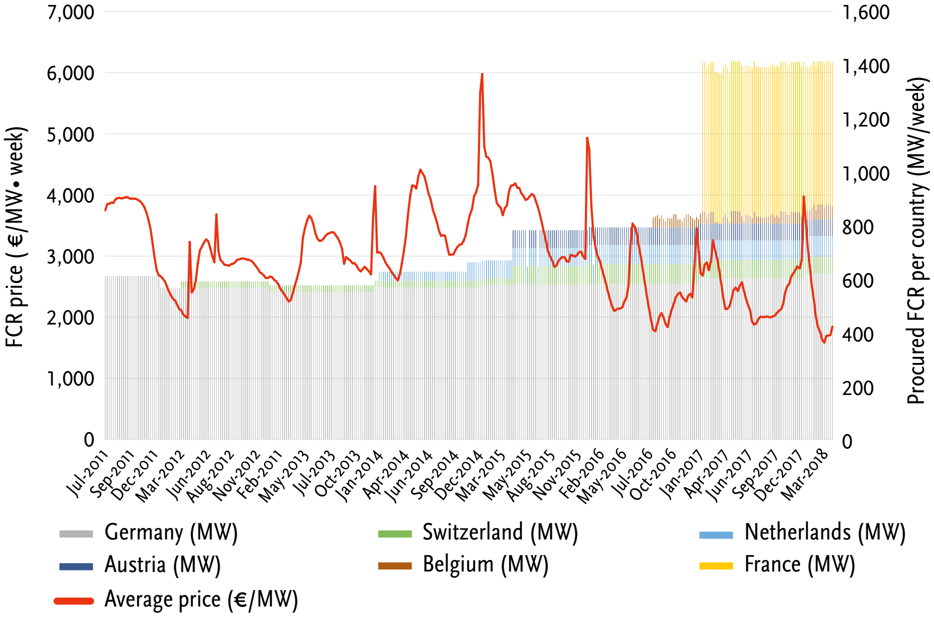


***Figure 77** – Average weekly FCR market price and procured volume per country in the international reserve market. The graph also shows when countries joined the international reserve tender (Regelleistung.net, 2018)*

The average weekly price for FCR dropped from around €3,650/MW · week in 2015 to €2,450/MW · week in 2017 (Regelleistung.net, 2018). From Figure 77, it can be concluded that the price in 2017 is a return to the FCR prices that were observed before 2015. The FCR prices for the Dutch national FCR auction differ only slightly from the international market; in 2017 the average price was around €2,500/MW · week (ENTSO-E, 2018c).

Automatic frequency restoration reserves (aFRR)

aFRR was formerly known as 'regulating power' in the Netherlands (TenneT, 2016b). TenneT selects aFRR bids based on economic optimization to obtain the lowest average price for balancing (E-Bridge, 2014). Therefore, smaller bids may be selected at a higher price, to obtain the smallest capacity overshoot at the lowest total costs for the aFRR capacity required. The BSPs are remunerated according to a pay-as-bid price for the power set available during the contracted period (€/MW). BSPs are consequently obligated to bid at least their contracted power in the daily aFRR market during the contracted period, and in these bids an electricity price (€/MWh) is included (TenneT, 2016b). The actual activation is based on a merit order of the daily bids (€/MWh). These bids are limited to the day-ahead market price + €1,000 per MWh for up-regulation and the day-ahead market price – €1,000 per MWh for down-regulation with a minimum of – €999.99 per MWh for each PTU (Program Time Unit) (TenneT, 2016b). A PTU is 15 minutes long and for each PTU the electricity price for all activated reserves is set by the most expensive activated reserve bid, i.e. uniform pricing (E-Bridge, 2014).

In case of up-regulation, the aFRR up-price is paid by TSO to the BSP (TenneT, 2018b). For down-regulation, the BSP has to pay the down-regulation price to the TSO, so when the price for regulating down is negative, this effectively means that the TSO pays the BSP to regulate power output down (TenneT, 2018b). This is schematically explained in Table 17.

	Bidding price > 0	Bidding price < 0
Power regulation up	TSO pays BSP	BSP pays TSO
Power regulation down	BSP pays TSO	TSO pays BSP

Table 17 *– Payment direction for aFRR and mFRR (TenneT, 2017d)*

In the Netherlands, the average monthly price for reserved power was found to be around €7,000 per MW (ENTSO-E, 2018c). The energy price depends, as explained, on bids from BSPs and the marginal activated reserve bid during each PTU.

aFRR was originally contracted in annual contracts between BSPs and the TSO. This has changed recently to a system in which 50% of the aFRR capacity is contracted in annual contracts and 50% is contracted in quarterly contracts (TenneT, 2016a). Even more recently, the contracting procedure for aFRR was further revised. From January 2018, the TSO started contracting aFRR in weekly, monthly and quarterly agreements with BSPs (TenneT, 2017a).

In the future, aFRR may be contracted internationally, as is the aim of the PICASSO project (Platform for the International Coordination of

Automated frequency restoration and Stable System Operation). The project originates from the work of the Austrian, Belgian, Dutch and German TSOs to design, implement and operate a common platform for trading aFRR in the EXPLORE project (ENTSO-E, n.d.2; ENTSO-E, 2017a). The first phase in the project encompasses the design and implementation of an aFRR auction platform. The project is currently in the design phase; a first (end 2017) and second (June 2018) public consultation on TSOs' design proposals should lead to the implementation of an international aFRR target platform in the summer of 2018 (ENTSO-E, 2017a).

Manual frequency restoration reserves (mFRR)

In the Netherlands, mFRR consists of two products; mFRRsa (known as reserve power) and mFRRda (known as incident reserve) (TenneT, 2017c). For the first (mFRRsa) there is no power contracted, so scheduled activation is used (hence the 'sa' suffix). This means that TenneT sends out a request for an amount of balancing energy that has to be provided in a certain PTU. This is in contrast to mFRRda, where capacity is contracted and direct activation (hence the 'da' suffix) on the TSO's demand is possible (E-Bridge, 2014). In practice, mFRR is hardly used in the Netherlands, because aFRR resources are used almost to depletion prior to switching to mFRR (E-Bridge, 2014). TenneT estimates that the activation of mFRRda is limited to once a month, with activation for only short periods of time (less than one hour) (TenneT, n.d.2).

mFRRda is contracted in both up- and down-regulating directions (TenneT, 2017c). Providers receive a pay-as-bid reward for the power made available (€/MW), if their bid is accepted (E-Bridge, 2014). The price for mFRRda in 2017 was around €900 per MW per month for up-regulation and €1,800 per MW per month for down-regulation (ENTSO-E, 2018c). It should be noted that mFRRda was contracted in quarterly and half-year agreements in 2017 (ENTSO-E, 2018c). There is also remuneration for the electricity delivered, a minimum of €200 per MWh is guaranteed, with a possible addition to this price based on the APX day-ahead market price for the hour of activation (TenneT, 2017c).

The future of mFRR capacity is, as the other control reserves, developing towards an international market between interconnected EU countries. This started with the cooperation of nineteen European TSOs who signed an MOU to consolidate a single, shared view on how to implement a European wide platform for trading the mFRR. This project is called MARI (Manually Activated Reserves Initiative) and is a reaction to European guidelines that require the introduction of European platforms to coordinate the exchange of all types of control reserves (TenneT, 2017b). As TSOs were early in starting the process of discussing a common mFRR market, it is expected to come online between 2020 and 2022, easily meeting the set deadline (ENTSO-E, 2017b; TenneT, 2017b).

7.3 Revenue model for O-PAC

The revenue for O-PAC is not clear-cut, as it depends on several factors. First among these is the average electricity price and its volatility, which is affected by both fuel prices, CO_2 price and the generator park (i.e. the price setting marginal generator). Second is the frequency reserve market where O-PAC can obtain additional revenue. Third is the potential for turnover from the provision of additional ancillary services. As it is evident that O-PAC will operate in a market with high uncertainties, a combination of revenue opportunities may be necessary to provide a viable revenue model to generate a profit.

7.3.1 Energy arbitrage

Energy arbitrage can only generate profits when differences in electricity price are large enough to cover electricity losses in storage, capital depreciation, interest, and annual operation and maintenance costs (discussed further in Sections 7.4 and 7.5). The first step in estimating the possible revenue from arbitrage is the selection of projections on future fuel and CO_2 prices, used to calculate the SRMC (Short Run Marginal Cost) for conventional power plants. The growth of VRE in the market and its associated SRMC of €0 per MWh is the starting point. It can be argued that the SRMC for VRE is currently negative, as these producers receive the exploitation based SDE+ (Stimulation of Sustainable Energy Production), where reward depends on the actual production of electricity (Mortelmans, 2018; RVO, 2018a). The development of the electricity price for conventional generators is much less predictable, as this is affected directly by the fuel price and the CO_2 EUA (EU emission Allowance) price. A lesser known factor that may affect the price is the future scarcity of installed dispatchable generators, which may create a monopoly. This can result in the occurrence of supply bids in the market with a scarcity rent, i.e. electricity price bids considerably higher than the actual SRMC of the supplier. This has already been observed as price peaks at the Dutch APX in 2006, when electricity supply was low compared to demand (Rooijers, et al., 2014).

In conclusion, it can be assumed that future prices will increase when VRE is not able to meet the demand. At the same time, oversupply of VRE production at other times will result in free electricity or even negative electricity market prices, thus increasing volatility (this is presented in the price extremes chart in Figure 76).

A quantitative model was developed to estimate revenue from energy arbitrage. Note that the residual load is used in the calculation model, which is the load that remains after the supply from VRE is subtracted from the total load (as explained in detail in Section 9.2.4). The calculation model is explained stepwise below:

1. The hourly load curve for 2015 in the Netherlands was assumed to be representative of future loads, based on the structural consistency in the load profile over time.
2. The residual load was calculated on the basis of wind and solar production. Wind and solar production was calculated on the basis of KNMI data (KNMI, 2017b; KNMI, 2017a) and on installed solar and wind power from the NEV 2017 (ECN, 2017b).
3. The hours with the lowest residual load were selected for pumping with O-PAC and the hours with the highest residual load were selected for generating electricity with O-PAC. The ratio of pumping to generating hours was corrected with a roundtrip efficiency of 80 %. The operating hours for O-PAC were economically optimized in step 8, by varying the hours of operation and selecting the number of operating hours with the highest revenue from arbitrage.
4. The residual load was adjusted for the impact of pumping/generating with O-PAC and additionally for possible activation of upward demand response (DR up) during each hour. This was done by adding O-PAC pump power and DR up power to the residual load during low residual load hours, thus increasing the residual load (and consequently the electricity price, as explained in point 5). For high residual loads, the O-PAC generator and the activated downward demand response (DR down) power were subtracted from the residual load, lowering it and consequently the electricity price. This includes the maximum price levelling impact caused by O-PAC and DR.

5. The remaining load (after subtraction of DR and O-PAC power from the residual load) that resulted after step 4, was assumed to be met by conventional generators and therefore matched with the generator type that was price setting (i.e. the marginal generator's SRMC sets the electricity price during that hour), based on cumulative installed power. During hours with a residual load of less than 0 MW, the price was set at €-25/MWh. Hours with a residual load less than the total must-run output were assumed to have a price of €0/MWh and hours in which not all demand could be met with conventional capacity were assumed to have a VoLL (Value of Lost Load) price of €200/MWh (see Section 7.3.2, which discusses a case with imbalance prices).
6. SRMCs for generators were calculated with projected coal, gas and CO_2 prices from Energy Brainpool (2017). Operational characteristics for generators were based on various sources (EIA, 2016; ECN, 2007; Ray, 2016) and future installed conventional power was based on NEV 2017 (ECN, 2017b).
7. This was used to calculate the total cost for pumping during the hours with low electricity prices and total revenue from generating during hours with high prices. The final step was to calculate the nett revenue from these price differences.
8. To assess the number of hours of operation that would be most profitable in each year, a sensitivity analysis was performed on the hours of operation (in increments of 100 hours).

The results from this model are presented in Table 18 below:

	2025	**2030**	**2035**
Revenue from generating (m€/year)	73.9	157.0	191.5
Pumping costs (m€/year)	12.7	-29.1	-34.5
Nett revenue arbitrage (m€)	**61.2**	**186.1**	**226.0**
Avg generating price (€/MWh)	82.4	93.4	122.2
Avg pumping price (€/MWh)	11.3	-13.9	-17.6
Hours generating (hours)	640	1200	1120
Total production (TWh)	0.90	1.68	1.57

***Table 18** – Results from the quantitative calculation model for energy arbitrage revenue*

From these results, it can be concluded that the possible revenue for energy arbitrage is limited in the near future (2025). This is the result of a substantial increase in CO_2 prices, which in turn causes the price of coal-fired capacity to grow towards the prices for gas-fired capacity, which is impacted less by CO_2 prices. At the same time, there is still a limited number of hours with VRE oversupply, which is easily adjusted by both O-PAC and DR. Additionally, the lack of nuclear power plants in the Netherlands provides less opportunity for energy arbitrage in 2025. However, performing arbitrage between baseload nuclear power and peak demand is not O-PAC's priority, as the project has the objective of providing flexibility and thus facilitating VRE uptake in the power system.

Later, in 2030 and 2035, there is a major opportunity for revenue from energy arbitrage, which is caused by a much larger VRE generator capacity and a much smaller conventional generator park. The former results in prices of ≤ €0 per MWh (i.e. free or even rewarded pumping) and the latter results in high prices (€100-200 per MWh) due to the limited capacity of expensive generators and some hours with loss of load in 2035.

From these observations, it can be concluded that there is little opportunity for energy arbitrage between different conventional generators. Therefore, it is most probable that future energy arbitrage will be between VRE prices and fossil power prices, instead of between baseload prices and peak-load prices, as originally performed in energy arbitrage.

There are of course limitations to this model; nevertheless, the approach that is used is more detailed than assuming operation for a certain amount of time between average peak-load and average baseload prices. The inherent assumption in the model is that O-PAC can benefit during all these hours with extreme electricity prices (both low prices and high prices), which may not be the case in real-world operation. The important element of the model approach is the variability included and the impact of wind and solar resources on the residual load, based on real measurements instead of estimates. As a result, it can be seen that the opportunity for energy arbitrage is relatively small in 2025 but increases in following years. This represents a realistically increasing revenue for O-PAC, hand in hand with the growth of VRE power.

7.3.2 Control reserve

As discussed in Section 7.2.2, all control reserve markets are developing towards international auctions between nations within the European interconnected electricity grid. This will become reality before O-PAC can be operational, as most of the FCR is already traded internationally and the PICASSO and MARI projects are planned to start their operational phases in the early 2020s. The future for both aFRR and mFRR is currently hard to predict, because the final design for the international trade platform, product requirements and reserve payment methods are not yet known. For FCR, the international platform at regelleistung.net provides insight in previous tender results (presented in Figure 77). The total trade volume is also shown and calculated to be around 1,400 MW per week during the first quarter of 2018. Table 19 shows recent figures on the control reserve market volume in the countries where O-PAC can operate. It can be concluded that the control reserve market will not be limited to a single national grid and will thus be much larger at the time that O-PAC's construction can be completed.

	Belgium	Germany	The Netherlands
FCR	81 MW	620 MW	111 MW[1]
aFRR	139 MW	1,906 MW[2]	300 MW
mFRR	830 MW	1,319 MW[3]	350 MW

***Table 19** – Market volume for control reserves in Belgium, Germany and the Netherlands (Elia, 2018; Regelleistung.net, 2018; ENTSO-E, 2018c; E-Bridge, 2014)*

[1] 77 MW is procured at the international auction and 34 MW at a national auction
[2] 1,906 MW up-regulation and 1,835 MW down-regulation
[3] 1,319 MW is up-regulation and 1,716 MW down-regulation

The market for control reserves is particularly important in 2025 when revenue from energy arbitrage may be limited. If it is assumed that prices for control reserves stay constant in relation to former years, the following estimate on income from reserves can be made. The assumption is made that on average 400 MW of power will be bid successfully in the reserve markets. The results are presented in Table 20.

	Power (MW)	Price (€/MW)	Total (m€/year)
	Low – mid – high		Low – mid – high
FCR	80 – 100 – 120	€2,452/ MW per week	10.2 – 12.8 – 15.3
aFRR	125 – 150 – 175	€7,000/ MW per month	10.5 – 12.6 – 14.7
mFRR	125 – 150 – 175	€1,800/ MW per month	2.7 – 3.2 – 3.8
Total	330 – 400 – 470		23.4 – 28.6 – 33.8

***Table 20** – Estimated annual revenue from control reserves*

The revenue that can be obtained from both FCR and aFRR, is high compared to mFRR. This could help O-PAC increase its total revenue during the earlier years after commissioning, while energy arbitrage may be sufficiently large to generate profits in later years.

In addition to power reservation remuneration, the provision of both aFRR and mFRR also has the potential of payment for delivered electricity (see Section 7.2.2). This opportunity should not be completely disregarded, as mFRR prices caused by imbalances can be very high, despite the fact that they are reported as incidental (NOS, 2018). Therefore, it is impossible to estimate the revenue from electricity generated for aFRR and mFRR. An indication of the opportunity is presented by a recent example of grid imbalance (April 30, 2018), when the price ranged from €235.60 – €401.20 per MWh for four and a half hours (TenneT, 2018b). O-PAC is well suited to provide reserves during such circumstances, while according to TenneT, there is only a minor impact on normal operation of a generator when it participates in mFRR provision (TenneT, n.d.2).

7.3.3 Additional ancillary services

In addition to control reserves, revenue may be generated by other ancillary services. For these services, it is impossible to estimate the actual revenue, as they are contracted between the TSO and the ancillary service provider, and therefore not publicly available (Ecofys, 2014). Three types of remunerated ancillary services are discussed: re-dispatch, black-start capability and reactive power.

Re-dispatch

Re-dispatch is the adjustment of the active power output by producers on instruction of the TSO. This ancillary service is used to address (1) grid congestion, (2) overloading of operational resources in the grid due to power flows, and (3) prevention of exceeding the approved voltage range. The highly developed grid and large conventional generator park in the Netherlands makes congestion a rarity, resulting in almost no demand for re-dispatch by the TSO. However, contracts can be drawn up for re-dispatch between TSO and providers for the locations that may face grid congestion. The remuneration for re-dispatch can be a predetermined fee aligned to the spot price or based on a formula that takes variables such as fuel prices into account (Ecofys, 2014).

In Germany, there is high demand for re-dispatch, especially in the north where high feed-in of wind power forces conventional power stations to reduce generation as grid upgrades lag behind the rapid growth of renewables (Appunn, 2016; Transnet BW GmbH, 2018). This causes high costs for re-dispatch from VRE prioritization; in 2016 re-dispatch costs totalled €219 million (S&P Global, 2017). However, grid congestion may also cause additional costs due to the feed-in tariff that has to be paid for VRE production, even when it is curtailed. In 2016, this amounted to €643 million (see Figure 78 for further figures from earlier years).

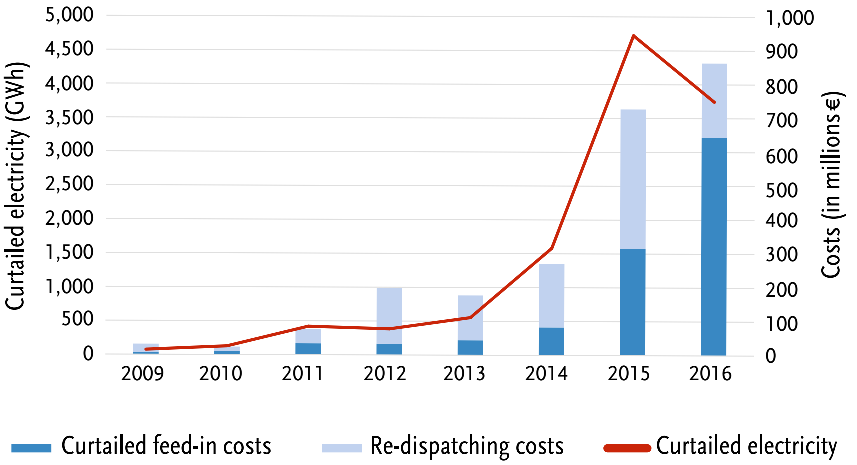


***Figure 78** – Costs for curtailment and re-dispatching in Germany (Bundesnetzagentur, 2018)*

The O-PAC storage plant can provide re-dispatch when grid congestion occurs, by storing locally generated VRE to prevent congestion further in the grid. However, the regional grid status and amount of local VRE will be determinants in the demand for re-dispatch. The current aim of the government for new wind parks and the nationally installed wind capacity are both concentrated in coastal regions and offshore (Windstats, n.d.). The opportunity for re-dispatch prevention is therefore larger in these regions than in Limburg. Nevertheless, O-PAC may resolve grid congestion that occurs in the interconnected EU-wide grid (this is further explained by its regional location in Section 9.2.1).

Black-start

Black-start capability supports an important ancillary service, which is to bring the grid back into operation after an outage (Ecofys, 2014). It is contracted in yearly tenders by the TSO in the Netherlands. Providers of the service can offer black-start for the period of a year or longer and are remunerated with a fixed fee that is settled bilaterally with the TSO.

The market for black-start capacity is small and providers must be geographically spread out, because of the requirement for local availability of black-start. Currently, most black-start is provided by gas turbines and hydro plants (Ecofys, 2014). Tender results and bilateral contracts for black-start are not publicly available, making it impossible to estimate the revenue from black-start for O-PAC. The energy storage plant can easily be designed to have the ability to provide black-start to the grid (as was discussed in Section 4.4).

Reactive power

The electricity grid not only requires frequency control for reliable operation, it also needs to be kept at a stable voltage. As active power is transmitted over transmission lines, reactive power rises along the lines, resulting in a voltage drop, thus limiting the lines' capacity to transmit active power. To mitigate these effects, reactive power has to be provided at the end nodes. This makes the provision of reactive power highly dependent on local needs. The local dependency for reactive power provision makes the development of a national reactive power market impossible, which also causes providers of reactive power to be monopolists for this service (Ecofys, 2014). Bilateral contracts between the TSO and provider are drawn up after a yearly tender organized by TenneT (TenneT, 2017e). In these contracts, the remuneration is agreed upon in either a fixed annual fee or a variable hourly fee (Ecofys, 2014). In spite of its precise design, O-PAC may provide reactive power to the grid, as common PHS units (i.e. FS, AS and ternary) can provide reactive power (Koritarov, et al., 2014). The only limiting factor is the regional demand for this ancillary service. Estimating revenue from reactive power is impossible, as the contracts are not publicly available and total costs for reactive power are not published by TenneT.

7.3.4 Total revenues for O-PAC

From the analysis in Sections 7.3.1 – 7.3.3, it can be concluded that there is a wide range of possibilities for generating revenue with O-PAC. The ancillary services that do not have publicly available market results (7.3.3) are not included in the total revenue calculation but may provide the opportunity to supplement revenues from arbitrage or control reserve. The best strategy for generating income may differ in time, so the years 2025, 2030 and 2035 will be discussed separately. The revenue calculation for arbitrage was only performed for these three years, because the NEV uses these years in projections (ECN, 2017b). In Figure 79, a linear growth in arbitrage revenue is assumed for energy arbitrage income, while two modes of operation are compared: (1) O-PAC uses full power (1,400 MW) to perform energy arbitrage only and (2) O-PAC commits 1,000 MW for arbitrage and 400 MW for control reserves. Figure 79 shows that between 2025 and 2030, the maximum income is generated in operation mode 'arbitrage and reserves' instead of 'arbitrage only'.

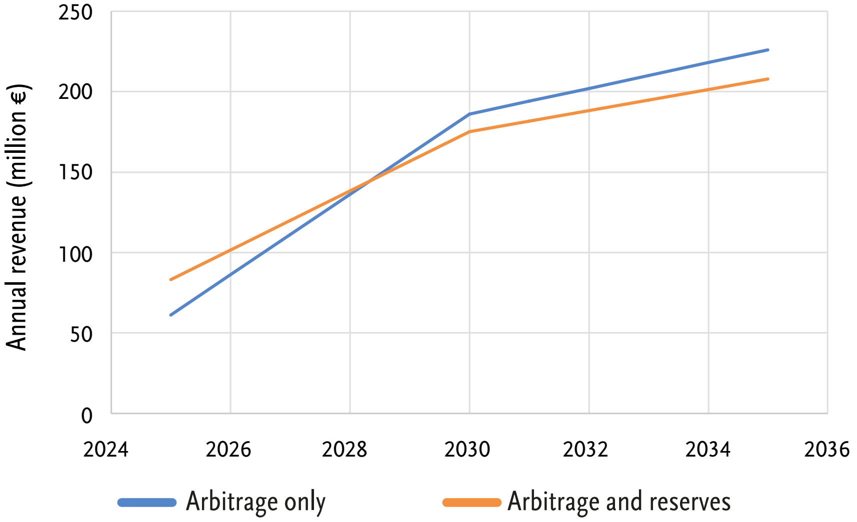


Figure 79 *– Annual revenue calculation and comparison between modes of operation; 'arbitrage only' and 'arbitrage and reserves'*

The total calculated revenue for the years 2025, 2030 and 2035 is summarized in Table 21 and further explained below as addition to Figure 79:

Year	2025	2030	2035
Total revenue	€83.2 million	€186.1 million	€226 million
Power reserved for: • control reserves • energy arbitrage	 400 MW 1,000 MW	 0 MW 1,400 MW	 0 MW 1,400 MW

Table 21 *– The total estimated annual revenue, with an optimal combination between arbitrage and control reserves*

In 2025, the amount of VRE will be limited, compared to later years, with peak prices that are relatively low due to lower fuel and CO_2 prices relative to those projected for 2030 and 2035. This relatively non volatile market results in revenue from arbitrage that totals €61.2 million per year. In that scenario, it would be advisable to allocate part of the capacity to participation in control reserve markets and other types of ancillary services. It is therefore assumed that 1,000 MW is allocated to energy arbitrage, while the remaining 400 MW is used for control reserves only. This results in an arbitrage revenue of €54.6 million for producing 0.8 TWh of electricity. The estimated revenue for control reserves (€28.6 million) combined with arbitrage, results in a total revenue of €83.2 million in 2025. This is expected to cover the annual fixed costs during the lead time of O-PAC. These costs consist of annual capital costs and O&M costs, as discussed in Sections 7.4 and 7.5.

The total revenue possible from arbitrage is substantially higher in 2030 and 2035, at €186.1 and €226 million, respectively. This is caused by the significant expected amount of installed power for wind and solar and the projected rise in electricity prices. The choice of capacity deployment should then be made on the basis of the highest revenue obtainable on either the electricity or the reserve markets. If the assumption is made to allocate 1,000 MW power to arbitrage, the annual income would be €147 and €179 million for 2030 and 2035, respectively, at the optimal number of operating hours. In a market with a high penetration of VRE, the market for arbitrage alone seems more lucrative for O-PAC than participating in both arbitrage and control reserves, as with the observed current prices and consequently estimated revenue for control reserves, the total revenue will be lower than with arbitrage alone. A combination of arbitrage and reserve provision may still be preferable if prices for control reserves were to increase considerably in the future. An in-depth future projection for the control reserve market was not performed here.

7·4 O-PAC costs overview

At the initiative of the parliamentary commission on storage and energy (COE, Commissie Opslag en Energie), the minister of Economic Affairs (EZ) ordered NEOM to start an OPAC study group in 1983. At the same time, a similar assignment was commissioned to the Lievense group for an alternative low-head PHS project. To contextualize these studies, it is important to realize that they were executed in an era of public utilities. Electricity supply was considered a societal task and investment decisions were taken by public provincial or municipal authorities. As a consequence, the considerations and the calculations were performed with a conservative attitude, which resulted in thorough detailed and realistic estimates for the investment costs. In 1985, the cost estimate for the basic version amounted to 2,315 million Dutch guilders (€1,147 million), excluding the costs for engineering, grid connection and unforeseen. The public electricity facilities had a cooperation of power generating utilities from 1949 on, called SEP (Samenwerkende Elektriciteitsproducenten).

The introduction of the new law on power supply (Elektriciteitswet 1998) was the result of the political trend of privatization. The electricity-generating utilities became private companies and the responsible coordination tasks of the electricity grid was entrusted to a state-owned private company in 1998 under the name TenneT Transmission System Operator B.V.. This led to a TSO that was not involved in the investment in new generators, as this part of the market was separated from grid operation. Presently, large-scale investments that provide grid balancing and ancillary services, such as O-PAC, are not actively pursued or supported by the TSO.

7·4·1 Estimated construction costs

For this present CBA, actualized data were collected by the O-PAC Development Group, using the optimal size for the U-PHS as researched by study groups in the past as a starting point. The estimates originated from specialized engineering and construction firms involved in the studies from the beginning. These companies and consultants are presently active in the studies for and construction of underground tunnels and power plants. These calculations gain credibility on the basis of the results of core drilling for analyses of the underground in relation to the construction of caverns and tunnels, as the construction costs are impacted by the quality of the hosting rock formations. As a consequence, around 50 % of the investments are to be allocated for underground civil engineering works. The total construction costs for the O-PAC amounts to approximately €1,800 million, excluding the costs for development and grid connection and interest during construction. A specification of the different items is presented in Table 22.

O-PAC construction	million €
Shafts	247
Shaft installations	101
Subterranean spaces (e.g. cooling and ventilation)	82
Civil engineering works	709
Machinery	324
Electrical installations	52
Above-ground construction	37
Unforeseen construction costs (15%)	233
Total	1,785

Table 22 *– Construction cost breakdown for O-PAC*

Lastly, it must be mentioned that in this O-PAC business case, three different study groups separately provided estimates of the investments needed for the construction of the underground pumped hydro plant with identical specifications in South Limburg. Moreover, these studies took place in a time frame of three decades.

For a project the size of O-PAC, it would be logical to perform a probabilistic analysis on the construction costs. However, as the probabilistic approach elaborates upon empirical data from earlier similar projects (Vrijling & Theunissen, 2015), this would be a challenging and complex study, as a comparable project to O-PAC has never been executed. Nevertheless, there are projects and sectors that show similarities to

O-PAC and their empirical data may form a starting point for probabilistic research on the construction costs:

1. The tunnelling sector that, similar to O-PAC, aims at constructing durable caverns/tunnels in hard rock formations.
2. The mining sector that, similar to O-PAC, uses vertical shaft constructions in its excavation processes. Additionally, the logistical challenge of the excavation itself and transport of mined materials to the surface may be regarded as comparable.
3. Earlier PHS projects that show similarity to O-PAC with regard to the construction of tunnels and machine halls underground. Here the challenge is in creating tunnels with an adequate water flow (e.g. fluid physics, roughness of tunnel sides, etc.) and the construction of machine halls and the installation of power-unit machinery (e.g. motor-generator and pump-turbine) and power handling (e.g. transformers).
4. The construction of the upper reservoir for O-PAC seems similar to constructions in water management, particularly in dike construction. This is a practice that is well developed in the Netherlands.

Overall, the complexity of analysing these sectors exceeds the scope of this multidisciplinary monograph. Instead, this simple note on possible starting points for an actual probabilistic research is provided on the basis of similar sectors and projects that were identified during the study. Prior to the actual construction, a probabilistic analysis should be performed by the project team.

The lack of probabilistic analyses is partially compensated by the relatively high unforeseen provision of 15 %, as presented in Table 22.

7.4.2 Capital costs

The capital costs are based on the WACC (Weighted Average Cost of Capital) calculation, which is used as the discount rate in the annualization of the total investment. The WACC is the average cost for financing of a company/project from investment by both shareholders (equity) and debt. The following formula is used as O-PAC is assumed to be financed with both debt and equity:

$$WACC = \left(\frac{E}{E + D} \cdot R_e \right) + \left(\frac{D}{E + D} \cdot R_d \right)$$

Where:
E = value of equity
D = value of debt
R_e = rate of return of equity
R_d = interest on debt

Based on one third equity financing and two thirds debt financing, with the cost of equity at 5% and a cost of debt of 3%, the WACC results in 3.67%. To express the investment as annual capital cost in current-day prices, the total investment is multiplied by the annuity (or capital recovery factor) factor a:

$$a = \frac{r}{1 - (1 + r)^{-L}}$$

Where:
r = the discount rate (here assumed to be the WACC)
L = the economic or technical lifetime of the investment (here technical lifetime is assumed, i.e. 50 years)

The annuity factor is calculated to be 4.39% when the discount rate (here WACC) is 3.67%, resulting in an annual capital cost of €78.40 million. However, the discount rate could also be set at 2% for the O-PAC project, because of the societal, environmental and grid-wide benefits that it can provide. This is in line with the statement that "some economists argue that with problems with a long timeframe, like the problem of climate change, discount rates as low as 2 % should be used" (Blok, 2009). Using the social discount rate of 2 % results in total capital cost of €56.80 million per year.

7.4.3 Operation and maintenance costs

As with the construction of any PHS, many technical disciplines are involved and therefore operating and maintenance (O&M) servicing also requires a team of skilled engineers. Though the O&M of U-PHS is a substantial task, communities of specialists across the world (hydro mechanical, electrotechnical) operate hundreds of pumped hydro power plants on a daily base. These experienced technical engineers handle and operate the pumping/turbine process of intaking and delivering high volumes of electricity to the grid. Many authors, like Zakeri & Syri (2015), have dealt with the cost aspect of the operational handling and maintenance (OPEX) of PHS-systems. Their estimates vary between 1 % and 3 % of the investment per year. This variation is dependent on the nature of the structure and dimensions of the different power plants. It must be realized that in the case of conventional pumped hydro power plants, huge dams deserve special care as they must attend to excessive varying high water pressure. Also, the size and structure of the different PHS plants explain the relatively large variation in maintenance team and costs. Because of the economy of scale, larger PHS plants require lower percentages for O&M, whilst the < 500 MW plants tend to the higher 3 % of the investment.

For O-PAC, the detailed calculations lead to an OPEX level of 1.1 % of the total investment, which accounts for €19.8 million a year. It is common practice that O-PAC engineers involved in the installation of the equipment during the construction phase, will also be responsible for proper handling during the operational phase. Especially during the start-up phase, it must be considered that manufacturer's warranty on installations and equipment will reduce the annual O&M expenses. Consequently, the calculated budget for O&M will only be required after the start-up phase, which lasts 5 years. Therefore, an annual growing maintenance schedule would be appropriate, starting in 2025 with a budget of €9.8 million, with an annual growth of €2 million. This builds up to €19.8 million in 2030, which is the average annual O&M cost from then onward.

7.5 Investment

As the present business cycle shows a steady positive trend and the structural finance markets are optimistic, pension and investment funds are looking for attractive long-term investment opportunities. Abundant cash reserves, combined with structural long-term low interest rates, mean that large projects > €100 million participation are currently in high demand. However, the present historically low interest scenario does not signify that the financing of a large-scale energy project would be easily secured. Even with a positive CBA and cash flow, it will not be funded automatically. The challenge is that the positive cash flow begins only after a relatively long preparation and construction period, when operation and earnings start. Moreover, like all starting enterprises, maximum revenues cannot be attained instantly during the initial phase. This phenomenon was already identified by the EU. Precisely for large-scale projects with a long-term horizon, such as O-PAC, a specific fund has been created under the name of EFSI (European Fund for Strategic Investments). Moreover, a participation of more neighbouring member states (Belgium and Germany) would improve the chances of securing funding from the EFSI regulation for this O-PAC project.

7.5.1 Investment structure

The structure of the electricity market can be characterized as a regulated free market in which the government determines the playing field. Within the limits of this system, market parties can pursue their business interests through the market mechanism of supply and demand. Under these conditions, it would be logical to setup an investment structure in the form of a PPP (Public-Private Partnership). This can be concretized in an equal share of equity participation. Consequently, the capitalization can be structured as follows.

In order to create a stable and reliable financing formula, an equity share of one third of the necessary investments is established, amounting to €600 million. Applying the PPP structure, this signifies €300 million invested by the public sector and €300 million by private partners. The shareholders from the public sector could be diverse, including not only the central government, but also provincial and the municipal authorities. Since the successful sale of their shares in generating companies, abundant capital is available for reinvestment in green power projects. Besides, large pension funds are already showing an interest in secure investments in renewable energy.

In the private sector, there has been a noticeable trend recently of investing in renewable energy. Large multinational companies striving for CO_2 emission reduction have also started to invest in green projects, possibly out of the easily understandable self-interest of creating a positive public image. The traditional fossil-fuelled electricity generating industry, after difficult transition years, has no other option than switching to renewables. Finally, the traditional oil suppliers from the Middle East are aware of the necessity to invest in the green energy of the future.

7.5.2 Project financing

As dealt with in Section 7.5.1, the summarizing of the capitalization is as follows:

	million
PPP equity	€600
Investment by third parties (in bonds)	€1,200
Total investment	€1,800

Long-term debt in the form of bonds is preferred, in order to create a stable financial structure. These 20-year bonds are to be placed directly with pension funds or in the market by an international bank consortium, with a yield between 2% and 3% interest. The growing public appetite for solid green projects will enhance the outlook for participation in O-PAC as a socially acceptable, environmentally friendly project.

7.6 Levelized cost of storage

The levelized cost of storage (LCOS) is the calculation of annual cost for capital, fuel and O&M, divided by the amount of annual electricity production/storage. This metric is commonly used as key economic parameter to compare power plants and renewables (WEC, 2016). The LCOS is called levelized cost of electricity (LCOE) when it represents generating power plants. In renewable power plants, the LCOE is particularly significant as it is a cost indicator that can be used to identify revenue deficits that are de-risked by policy mechanisms, e.g. SDE+ (WEC, 2016). This makes it a recognizable parameter, despite the limitations it may have for assessing storage.

Firstly, the LCOS is somewhat arbitrary, as the amount of energy stored and discharged from a storage plant can vary depending on its type of application, which is not simply generating electricity like renewable and fossil power plants (WEC, 2016). The second limitation of LCOS is that it does not capture the full value that storage can obtain from providing flexibility and its value for the power system as a whole (as further explained in Chapters 8 and 9). Therefore, WEC (2016) calls for analysis on a case-by-case basis for electricity storage, where the focus should not be on costs alone, but rather on the value of storage.

Nevertheless, the levelized costs of storage have been calculated for O-PAC. Particular attention must be paid to the input and calculation method for LCOS, as these must be similar to those of other reports and research on storage technologies to allow a fair comparison. Therefore, the method and input used are explained in detail:

The formula for calculating the LCOS (€/MWh) is:

$$LCOS = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_t}{(1+i)^t}}$$

I_0 = investment costs (€)
A_t = annual total costs in year t (€)
M_t = electricity produced in each year t (MWh)
n = technical lifetime (years)
t = year of technical lifetime (1, ..., n)
i = discount rate or interest rate (WACC) (%)

If the annual costs (A_t) and the annual electricity production (M_t) are assumed to be constant over time, the formula for LCOS can be written in a simplified way as:

$$LCOS = \frac{\alpha \cdot I_0 + A_t}{M_t}$$

Here the annual costs (A_t) consist of O&M alone. The 'α' is the annuity factor used for calculating annual capital cost from the initial investment (I), which is determined by the discount rate and lifetime (as explained in Section 7.4.2). The input for LCOS calculation is presented in Table 23.

Description	Value	Unit
Annuity factor (α)	4.39	%
Investment (I_0)	1,785	million €
Annual total costs (A_t)	19.8	million €
Annual electricity production (M_{el})	2	TWh

***Table 23** – Input for LCOS calculation*

The LCOS for O-PAC is €49.10 per MWh, calculated from the input in Table 23. To show how much impact variables can have, the LCOS is plotted against the annual electricity production (Figure 80), while the other variables are kept fixed.

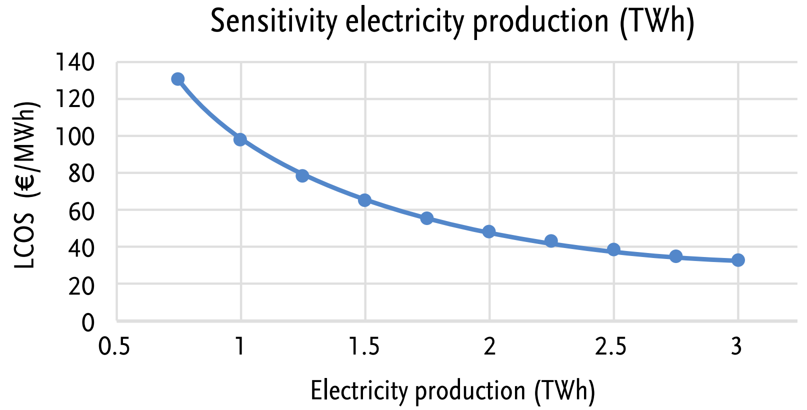


***Figure 80** – LCOS sensitivity to the annual electricity production of O-PAC*

Figure 80 shows that the outcome of the LCOS is very sensitive to the assumptions made for the actual operation of the storage plant. Higher electricity production results in lower LCOS, while there is a substantial increase in LCOS when less electricity is produced. As the LCOS calculation does not include valuation of the electricity produced and the associated flexibility that it may have provided in the grid, this makes the LCOS approach less suitable as a basis for investment decisions.

There is also no sophisticated estimate for the actual number of hours that energy storage could operate to perform arbitrage in the electricity markets. Consequently, estimates for the total electricity production value can differ substantially between publications. This sensitivity to input variables makes the LCOS only suitable to a limited extent for comparing different storage technologies, especially between different publications.

7·7 Remarks and conclusions

In concluding the CBA for O-PAC, the first and primary remark is that the transition to a nearly decarbonized energy system in 2050, will encompass a multitude of uncertainties with regard to interpretation and timing. As a consequence, various forecast studies have been published by Dutch and international research institutes. Only general trends are recognizable and reliable facts and figures are extremely rare. It is a challenge to cope with the numerous changing conditions (e.g. legislation, economy, market internationalization etc.) in the development of the transition. Nevertheless, setting up a reliable prognosis is a necessity.

As explained, the cost estimate has been repeatedly tested and audited by specialized engineers and construction firms, which has provided a sound insight in the total costs. With regard to the magnitude of the project, the €1.8 billion construction costs are in line with similarly large civil engineering projects.

Also, the revenue model is adaptable to changing market developments, thus presenting a realistic picture of possible revenues. Specific services, such as arbitrage and control reserves, were estimated for the years 2025–2035. The total revenue is estimated to cover the fixed annual costs in 2025. In subsequent years, the growth in revenue partially covers the depreciation of the investment and additional dividend payout to shareholders. From 2030 onwards, the business case for O-PAC seems profitable, based on substantial depreciation.

The outcome of this cost-benefit analysis justifies pre-investment in further research and project development (1-2% over the total investment), before reaching a final investment decision (FID).

Societal benefits that are not compensated, also constitute significant benefits of the project. Chief among these is the function of stabilizing the electricity supply for industry and consumers. This is further explained in Chapter 8.

8 Socio-economic effects

Art by Eldon Dedini (© The New Yorker Collection/The Cartoon Bank)

8·1 Introduction

"The pyramids would never have been built, if the pharaohs had compared the costs with the benefits" (Vrijling & Verlaan, 2013). In "The accidental cathedral, thoughts on rebuilding the energy system", G.J. Kramer (2011) visualizes the impact of the introduction of VRE as an 'industrialization of the countryside', following D. MacKay (2009) in his unsurpassed work "Sustainable energy — without the hot air".

Kramer's metaphorical cathedral of rebuilding the energy system will not infringe on the idyllic countryside, since O-PAC will be constructed underground.

Objectively considered, O-PAC (or any other energy project) does not belong in the category of the Pyramids of Giza or the Notre Dame de Paris. Nonetheless, it is undeniable that such an enormous underground energy project as O-PAC will invite comparisons with the defining projects of other eras. In spite of its indisputable social and economic advantages, such comparisons may not always be charitable.

The economic advantages of O-PAC were considered in the CBA in Chapter 7.

This chapter will explore the advantages for external stakeholders and society beyond those directly captured in revenue. Unlike the aesthetic and cultural contributions of pyramids or cathedrals, these macro- and socio-economic effects are not always clear-cut or easily recognized, let alone precisely estimated.

We use the method of concentric analyses to identify the relevant interrelations (Vrijling & Verlaan, 2013), which is introduced in Section 8.2. In Section 8.3, we present the macroeconomic effects based on an update of the analysis of employment and regional structure effects, by J.A.H. Maks and M.J. Oude Wansink of Maastricht University (2009). Section 8.4 considers the wider societal benefits and in Section 8.5, aspects of innovation originating from the construction of O-PAC are discussed.

8·2 Concentric analyses approach

In economics, the immaterial benefits and costs are disregarded as external effects. This demands the introduction of alternative approaches, as presented in the following concentric system of a CBA model.

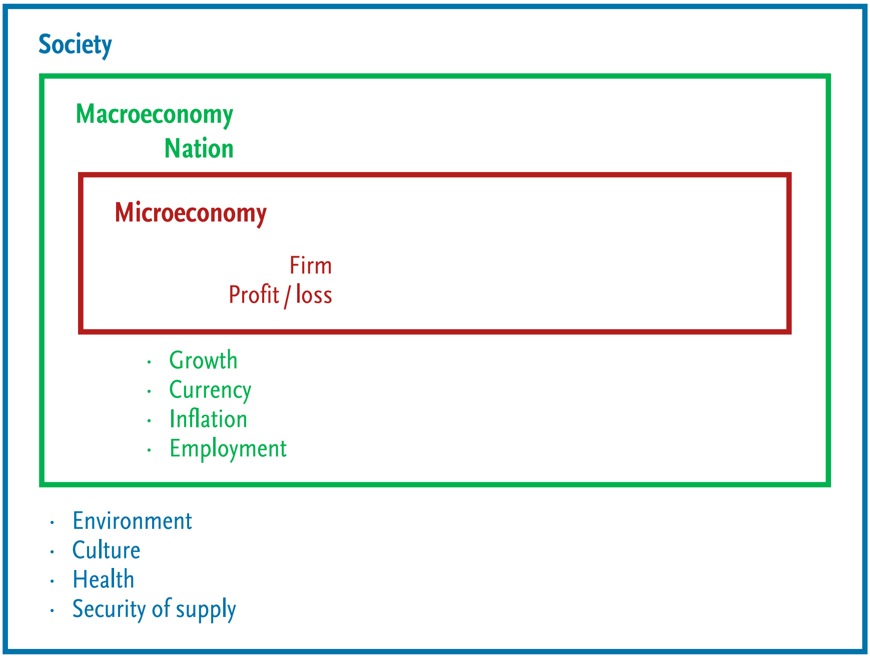


Figure 81 *– The concentric system of cost-benefit analyses (Derived from: Vrijling & Verlaan (2013))*

This concentric model can be interpreted by starting inside with the microeconomy (i.e. the O-PAC investment analysis in Chapter 7) and moving outward to the outer square of political science. Though O-PAC has a calculated microeconomic analysis with an outlook from 2025 onwards, the project may also lead to macroeconomic benefits that are not directly rewarded to the investors. The second square represents the macroeconomic effects caused by O-PAC and encompasses the effects of economic growth, employment etc. In the outer square, the (inter)national political aspects are presented, including effects on the environment (CO_2 emissions), culture and health.

In the next section (8.3), special attention will be given to the macroeconomic effects during the construction and afterwards. We will also consider the structural composition and geographical distribution of employment effects. In 8.4, the societal benefits of O-PAC will be discussed.

8·3 Macroeconomic effects

8·3·1 Employment effects: direct/indirect

Research on the impact of the construction and operation of O-PAC was carried out by J. Maks of the Maastricht University, School of Business and Economics (2009), based on an input–output model (Miller & Blair, 2009).

It is common practice to utilize input–output modelling in order to quantify the various effects of projects vis-à-vis the socio-economic environment. The foundation of this theory was laid by Nobel Prize-winning economist W. Leontief in the 1930s and is widely recognized as a method for analysing the interdependencies between different branches of the economy. Miller & Blair (2009) formulated a brief definition: “In its most basic form, an input–output model consists of a system of linear equations, each one of which describes the distribution of an industry’s product throughout the economy”.

In addition to the findings of the Maastricht University study, it is useful to introduce recent data. Based on data provided by specialist underground construction firms, a sizable decrease of employment figures related to the construction is projected, compared with those from the study of a decade ago.

An interesting aspect of the employment involved in O-PAC is an analysis about the differences in educational level of the workforce, both during the construction period and afterwards during the operational phase. In the massive excavation period, it is not surprising that more than 80 % of the workers are low-to-medium-skilled. However, during the operational phase, a turnaround is noticeable to more than 80 % higher- and medium-educated employees.

The central question is whether the employment is just a matter of job replacement and not of job creation. In this context, it should be noted that in times of high business activity, this concern is more relevant than during a recession. As high business activity will result in high employment, job replacement could occur as the available workforce is limited. This is less important during a recession, when higher unemployment results in a larger available workforce. Also, it must be taken in account that the construction time (approx. 6 years) is likely to span much of a complete economic business cycle. It is justified to average the two employment extremes of the business cycle in order to obtain a realistic estimate of the actual job creation.

The structural employment situation in the region is also important, especially in the job market for less educated individuals in search of employment. Especially the South Limburg region suffered the loss of employment for many tens of thousands of employees during the last decades of the 19th century, caused by the closure of all coal mines (see 5.2). In spite of regional restructuring programmes, such as PNL (Perspectives Note Limburg), the structural employment figure stayed well below the national average. Moreover, the influx of young labour stagnated, so that the region has to cope with an ageing of the labour force. In these specific circumstances, a major employment injection by O-PAC could provide a unique opportunity of a synchronized phasing-out of a great part of the labour force during the construction period.

Reconsidered, the results of the updated figures for the yearly direct employment – of both civil engineering excavation works and electro-mechanical installations – account for 900 to 1,000 employees yearly, hence 5,400 to 6,000 man-years during the construction period (6 years). From then on, the input–output modelling can be proportionally adapted, taking account of the progress in technology and its accompanying effects on employment in the time after the initial modelling.

8.3.2 Investment effects

As far as the total investment of approximately €1.8 billion is concerned, it was already stated in 7.4.1 that no significant changes in relation to former investment calculations were necessary, largely due to technological innovation.

Over a construction period of 6 years, this investment represents an annual average expenditure of €300 million. These investments will be decomposed in specific industrial sectors in order to calculate the effects of intermediary (regional) consumption and added value. Consumption effects (intermediary – regional) have an influence on the turnover value and employment in a specific industry sector. The increase of intermediary consumption is the result of the total purchasing value of all the goods and service procured by the company that will be used during the production process (Maks & Oude Wansink, 2009). Analogous to this are the added-value effects resulting in additional spending in that sector. Lastly, the effects of domestic consumption will be computed with the specific multiplier of the different sectors in the relevant region of impact (see also 8.3.3). The macro- and micro-economic effects of spending can be presented as follows:

	within the company leading to:	**leading to:**	**in the economy leading to:**
investment/ spending ⟶	higher intermediary consumption ⟶	multiplier effect ⟶	higher turnover and employment (consumption effect)
investment/ spending ⟶	higher added value ⟶	multiplier effect ⟶	higher turnover and employment (added-value effect)
		result:	increased turnover and employment

Table 24 – Economic effects of spending (Maks & Oude Wansink, 2009)

Employment effects emanating from the investments (6 years) and the operation of O-PAC (50 years) with a capital-intensive scenario (labour years):

· direct effect	35,500
· indirect effect of intermediary consumption	11,400
· added-value effect	19,200
· total effects	66,100

The total employment effects from the investment and the operation of O-PAC account for circa 66,000 man-years. Approximately 55 % of the total employment effects is the result of 50 years of operation. The balance of 45 % of the total employment is related to the investment in O-PAC.

8.3.3 Geographical distribution of effects

As a major energy project with an investment of €1.8 billion, O-PAC would have an impact across the EU-15 countries. Situated in South Limburg, close to the borders with Germany and Belgium (max. 10-20 km distance), the so-called Euregion Meuse-Rhine (3.9 million inhabitants) is the centre of this impact. The significance of the establishment of the O-PAC power plant is not only in the interest of the Netherlands, but also of the broader region. The economic effects of the investments will also end up in the neighbouring territories. The attribution of the investment effects will be distributed as follows:

Euregion	58 %	of investments
rest of NL	12 %	of investments
EU-15	30 %	of investments

The construction and civil engineering works account for the lion's share and are locally and Euregionally concentrated. A share of 30 % is related to machinery and electromechanical equipment originating from EU-15 countries. Approximately 12 % for business services, consulting etc. come from the rest of the Netherlands. The following table (25) provides more detail.

	Branches of activity			
	Electro-mechanical	Construction industry	Transport	Business services
Above-ground infrastructure		Euregion		Euregion
Machines	EU-15		EU-15 / rest of NL	
Shaft installations	EU-15	Euregion		EU-15
Geologic investigations				rest of NL
Underground works		Euregion	Euregion	
Grid connection	rest of NL	Euregion		
Preparation/development				rest of NL

***Table 25** – Geographic distribution of the investments in O-PAC*

The geographic distribution of O&M (Operation and Maintenance) of the power plant will be largely attributed to the Euregion. It is more complicated to determine the allocation of other revenues, such as interest payments to financial institutions etc.

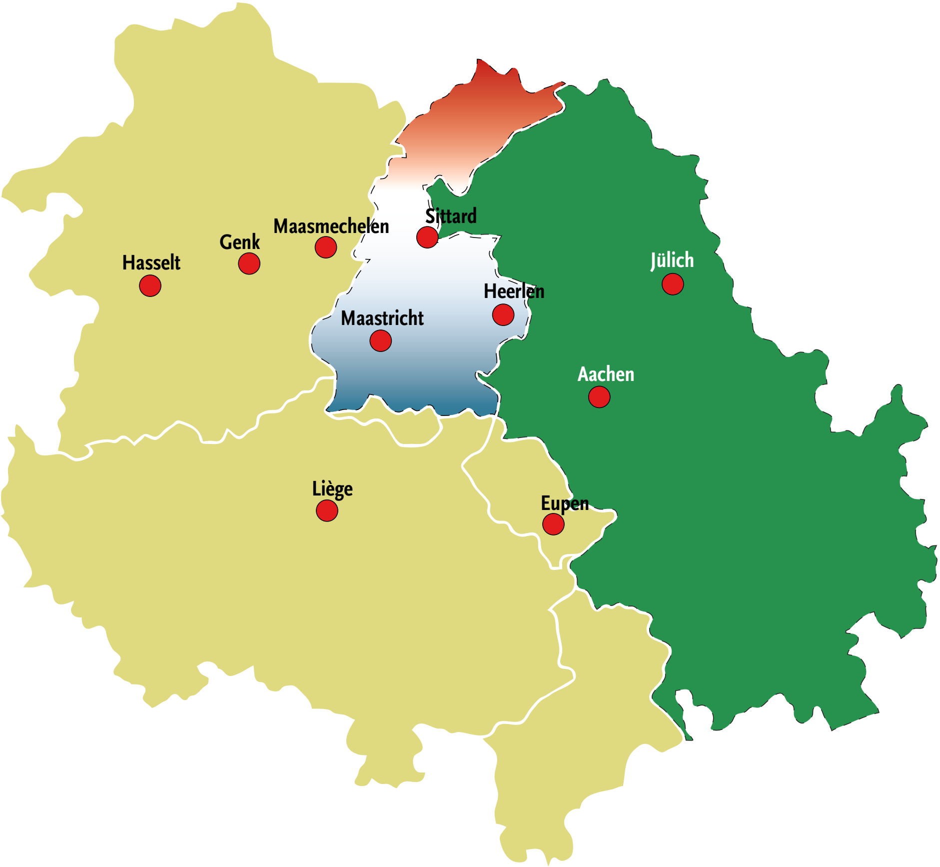


Figure 82 – *Euregion Meuse-Rhine, main area of economic impact*

8·4 Societal benefits

Here the societal benefits are discussed in connection with the European Commission's (EC) aim for "secure, sustainable, competitive, affordable energy for every European” (EC, 2015a). In the new energy strategy, the adjectives ‘competitive’ and ‘affordable’ are often used interchangeably (EC, n.d.1), probably as a result of overlap between the approaches envisioned to achieve these aims. The energy strategy is obviously not limited to electrical energy alone, but in the following subchapters the focus will be on electrical energy, as O-PAC will operate in this sector.

8.4.1 Security of supply

There are some key figures for the EU energy system related to the security of supply (EC, n.d.2):

- The EU imports more than half of all the energy it consumes. Its import dependency is particularly high for crude oil (90 %) and natural gas (69 %), while the import of solid fuels (42 %) and nuclear (40 %) are lower. The total import bill is more than €1 billion per day.
- Many countries are reliant on a single supplier. Some rely entirely on Russia for their natural gas. This leaves them vulnerable to supply disruption, caused by political or commercial disputes or infrastructural failure. This was observed in the 2009 gas dispute between Russia and Ukraine, which left many EU countries with severe shortages.

These primary energy sources are related to electricity supply, as most countries still depend for a large part on fossil fuels for their electricity production. In the current fossil-based electricity system, the storage of energy is in the fuel stock, including natural gas reserves (Gasrotonde) etc., which adds to the security of supply. An example is the available infrastructure for large-scale storage and distribution of liquid natural gas, coal, and crude oil in the port of Rotterdam, which contains a considerable amount of energy at any moment (Port of Rotterdam Authority, 2016).

The EU ambition of sustainable energy consumption in all economic sectors drives the electrification of transport, industrial processes, heating and cooking, which currently rely heavily on fossil fuels as a primary energy source (EC, 2017). This means that these fossil fuels for electricity generation are planned to phase out and conventional fuel storage capacity will eventually become irrelevant. In renewable energy production, solar PV- and wind turbine-generated electricity seem to have the largest potential, as the National Energy Outlook (ECN, 2017b), EIA Annual Energy Outlook (EIA, 2018) and the IEA World Energy Outlook (IEA, 2017b) all expect a large future contribution of renewable energy from these technologies. The primary driver (i.e. wind flow and solar irradiance) of these electricity-generating technologies is impossible to store. As a result, the future security of supply will depend less on political stability or trade relations, and increasingly on meteorological availability of these resources or the storage of renewably produced electricity.

The O-PAC system, along with other storage technologies, can help increase the security of supply by decoupling the production time and the moment of renewable electricity consumption. This enables a security buffer for renewable energy to bridge inter- and intra-daily variability in the supply of wind and solar resources. The buffering capacity of O-PAC is limited to this timeframe by the reservoir volume (MWh) related to the installed turbine and pump power (MW). In a different configuration, the O-PAC system may even provide a security buffer for longer timeframes (see Section 6.1). Moreover, an additional social benefit of O-PAC is its ability to provide local/regional security of electricity supply in case of grid transmission failure.

Energy security in the future power system will not be limited to the availability of resources (i.e. wind and solar). The security of the electricity supply will also depend on the proper functioning of the electricity grid, a task performed by the TSO and achieved by ancillary services from electricity generators (as discussed in Section 4.4). The paid ancillary services were discussed with regard to revenue opportunities in Chapter 7. However, there are also services that are provided for free, because of abundant availability in the current Dutch power system (e.g. inertia control) (Ecofys, 2014).

The discussed societal energy security benefits that storage, and O-PAC in particular, can provide are not remunerated, but they may contribute to commercial viability when remunerated. This was recognized during the 2015 *EU round table on the role of energy storage in the energy system of the future*, where it was concluded that "... energy security is a public good and the market mechanisms are not providing incentives in the current energy system. In the future, the security of supply needs to be valued by the markets" (EC, 2015b). This called for a review of current regulations, as the grid services from energy storage are expected to be important in the future power system, while reward for these services is not adequately covered by the market (EC, 2015b). The latest EC document on energy storage emphasizes the energy security benefits that it can provide and calls for a reward for services provided (EC, 2017).

8.4.2 Supporting sustainable energy

The sustainability targets for a low-carbon economy set by the European Commission are well known: 40% greenhouse gas (GHG) emission reduction relative to 1990, 27% renewable energy and 30% improvement of energy efficiency by 2030 (EC, 2015b; EC, 2017), with a final target of reducing GHG emissions by 80-95% in 2050 (EC, n.d.1). The targets require large VRE penetration, which in turn requires storage. The EC recognizes the benefits of energy storage with regard to the observed and projected growth in solar- and wind-generated electricity, namely (EC, 2017):

- effective operation of the grid
- fast ramp-up and ramp-down in case of rapid power drops or surges
- linking various grid elements for a cost-effective balancing of VRE over various timeframes

These storage characteristics support the installation of a larger share of VRE power, thereby creating a more sustainable grid and enabling production of more renewable energy for society. The technological application of flexibility that facilitates the uptake of VRE is explained by load shifting and ancillary grid services. Chapter 4 explained how the PHS design relates to the ability to provide ancillary services. The O-PAC design requires careful consideration with regard to targets for renewables, because the conventional daily storage cycle will not be the operational reality for storage in a high-VRE future power system (EC, 2017).

PHS projects typically have a large capacity that is added to the grid, as would O-PAC. This may be regarded as an advantage to the power system, in which dispatchable capacity may become scarce. Koritarov, et al. (2014) discuss the ‘duck chart’ where there is a substantial dip in the residual load profile around midday, as a result of high solar power generation. During the late afternoon, the availability of solar capacity decreases rapidly, which drastically increases the need for fast ramping dispatchable capacity. In such occasions, storage may act as a double capacity compared to conventional generators. For example, an O-PAC system with 1,400 MW in pumping mode during high solar production can switch to generating 1,400 MW in several minutes; this effectively has a nett impact on the load curve of 2,800 MW, which is a much larger impact than a similarly sized (1,400 MW) conventional generator (Koritarov, et al., 2014; Ecofys, 2014).

An additional benefit of O-PAC is its role in the optimization of fossil generator dispatch, which results in more efficient use of fossil fuels and therefore leads to lower emissions. So, in its early stage of operation, storage of VRE and optimization of fossil generators both contribute to sustainability targets. When VRE power increases, O-PAC will be able to store more renewables and redeliver them to the grid when VRE supply is low, eliminating the need for fossil-fuelled generators as backup.

8.4.3 Potential CO_2 emission reduction

The potential for CO_2 emission reduction facilitated by O-PAC overlaps with its support for sustainable energy. This section provides insight by a simple calculation of the potential CO_2 reduction.

CO_2 emissions related to electricity production depend on the heat rate (i.e. fuel input (MJ) per kWh electricity produced) specific to a type generator and fuel consumption. The CO_2 emission associated with electricity production from gas are in the range of 0.38-0.66 kg CO_2/kWh_e, while coal has higher specific emissions in the range of 0.74-1.0 kg CO_2/kWh_e (Ray, 2016; ECN, 2007; EIA, 2016).

O-PAC can generate 2 TWh annually, based on 250 full operational cycles of 8 GWh. With this amount of energy, O-PAC can offset 1.48 million tonnes of CO_2, by substituting for a combined cycle coal power plant. For replacing a gas combined cycle power plant, this represents 0.77 million tonnes of CO_2 emission reduction. This calculation assumes a power system with a fully developed VRE share. It is expected that VRE supply will not be sufficiently large during the lead time, which initially results in a smaller amount of CO_2 reduction than presented. Considering the long lifetime of O-PAC, the initially smaller CO_2 reduction is negligible. As mentioned, O-PAC can additionally contribute to the optimization and more efficient dispatch of the initially operational fossil generator park, thereby reducing CO_2 emission during the transition toward a high penetration of VRE.

This benefit would not necessarily be remunerated to the operator of O-PAC, as emitting CO_2 is priced in EU ETS (Emissions Trading System), while there is no arrangement for a reward on mitigation of emissions. This means that the reduction in CO_2 emissions from O-PAC should be regarded as a benefit that is provided to society for free. However, if it is assumed that O-PAC is added to the generator portfolio of an electricity producer, the system could be used to minimize the producers' total CO_2 emissions and thereby CO_2 permitting costs. This would result in reduced costs for the producers' total generator park, proportional to the amount of electricity sold, a benefit that is directly attributable to O-PAC.

In conclusion, an operator with only O-PAC as an asset would not receive remuneration from facilitating CO_2 emission reductions, instead providing it as an unpaid societal benefit. In contrast, not only societal, but also monetary benefits may be obtained, in the form of reduced emission costs when O-PAC is combined in the generator park of an electricity producer. This shows the discrepancy between pricing emissions and the lack of reward for the reduction of emissions, which results in a reduced incentive for external stakeholders to invest in stand-alone VRE storage plants.

8.4.4 Facilitating affordable energy

The European Commission aims to provide affordable energy for all Europeans, without compromising the above sustainability targets. This demands a simple discussion on the effects that storage may have on the total power system costs and the effects on electricity prices. The EC recently formulated that "Energy storage could simultaneously reduce the volatility of the electricity prices, reduce the cost of the electricity system and facilitate a higher share of variable RES in the energy system" (EC, 2017). The definition used for the 'cost of the electricity system' refers to the total cost of the electricity system from generation to consumer, including operational and capital cost for the entire system (EC, 2017).

Energy arbitrage was explained in detail in Chapter 7 and can also be regarded as load shifting or levelling. It is obvious that, while being an important source of income, the process also reduces the possible revenue for the storage owner(s). The benefits for electricity consumers, however, are high, as volatility and unexpected price extremes are prevented by arbitrage. This energy storage function adds value for society and the economy, while rewards for the storage provider only decrease with greater energy storage. The benefits for the power system have been explained by the flexibility and ancillary services that can be provided by storage. This results in a reduction of the total electricity generation cost, as reported by the European Commission (EC, 2017) and also found in modelling the California power system by Koritarov, et al. (2014).

8·5 Innovation effects: spin-off

At present, there is an unmistakeable trend towards direct subsidies and financing programmes for research and high-tech solutions. The most active areas of financing include areas such as IT solutions, power-to-gas and chemicals. As already demonstrated in Section 3.7, Figure 28 (electrical storage technology maturity curve), most of these technologies are between the R&D and demonstration phase and not yet nearing deployment. It is justifiable to dedicate substantial means to cope with future technical challenges. At the same time, it should be stressed that new applications and uses of existing technologies are even more valuable. After all, the results from these approaches are far more certain. Failure to consider and adapt already available technology can prove even more damaging than failure to invest in new approaches.

The innovative character of an underground pumped hydro storage plant is generally apparent from the range of different disciplines that are necessarily involved (see Figure 3). However, there are only two main drivers behind this innovative project, namely pumped storage technology, and mining techniques, such as tunnelling methods. Though a multitude of concepts and projects were presented during the last century, (starting with a U-PHS patent by A. Fessenden (1917)), but no project has seen the light of day. Should O-PAC be realized, it would be world’s first.

This project definitely responds to the notion of “Durchsetzung neuer Kombinationen”, or “carry through of new combinations” from J. Schumpeter. As explained with his quote, "For centuries, a new possibility can lead a fruitless existence in the shadows, although it is known in fairly wide circles, without any particular effect on the outside. The leader personality snatches it away from this shadow existence. And it happens in all fields in a way which is closely analogous to the manner that new ideas get pushed through in the economy. It never happens as a response to present or revealed needs. The issue is always to obtrude the new, which until recently had been mocked or rejected or had just remained unnoticed. Its acceptance is always a case of compulsion being exercised on a reluctant mass, which is not really interested in the new, and often does not even know what it is all about" (Backhaus, 2003).

The first and most important spin-off lies in the intrinsically innovative qualities of the project itself, which is the first realization of an operational underground pumped hydro storage in the world. Beyond this, during the design and construction phases, new innovative techniques and services can be developed. These derivative functions have a substantial potential for generating spin-offs.

The O-PAC study group, in cooperation with Royal Haskoning engineering consultants, elaborated on the opportunities for endogenous spin-offs from developing new techniques during the construction and operation of the underground hydro storage plant (Maks & Oude Wansink, 2009), as presented by the following examples:

- The construction of O-PAC, including development, know-how and experience by way of joint ventures, can lead to new local enterprises.
- The application of spraying composite (based on the local resins industry) can be implemented in new firms that are active in restoration of tunnels and underground structures.
- Electromechanical experience with underground air conditioning and ventilation systems can be the input for start-ups.
- Mechanical experience in hoisting equipment and elevators with large height differences could be validated.
- As services spin-off, the safety strategy implementation of underground projects could offer specialization opportunities.
- During the construction, geotechnical subterranean investigation can lead to innovative new methods.
- Finally, as a direct spin-off the local reuse of heat from process water could be used for district heating.

8·6 Conclusions

The concentric system of cost-benefit analysis offers insight into the significant positive impacts that go beyond any direct benefit to of the firm, in this case the O-PAC power plant. The macroeconomic and societal effects on a national and international scale are often underestimated. O-PAC reinforces South Limburg's position as an electricity hub in Europe. This could attract various related industries.

The investment and interrelated employment aspects are significant for the labour market and economic development, with direct employment effects of 35,500 man-years and indirect employments effects of 30,600 man-years.

Geographically, the Euregion Meuse-Rhine is a densely populated compact area in three countries and is valuable from a European perspective, not only economically, but also socially and culturally.

The societal benefits from O-PAC are in line with the EU aims for the energy transition towards 'secure, sustainable, competitive and affordable electricity'. The installation of O-PAC will result in a reduction of the total electricity system costs and prevention of a highly volatile electricity prices. From the societal point of view, the CO_2 emission reductions that can be obtained by substituting fossil-fuel generated electricity is important. However, policy constraints are still in place, as the recognition of the role of storage in the energy transition has only recently received attention.

Lastly, a complex multi-industrial project such as O-PAC offers a multitude of opportunities, as specified in developing spin-off companies.

9 Large-scale storage in the future electricity grid

9·1 Introduction

Before the introduction of VRE electricity, grid performance was balanced through flexible supply from thermal power generators. By 2030, the projected growth of intermittent sources (e.g. wind and sun) to 70 % will create a drastically different situation (NEV 2017 reports 62.8 % see Section 2.2, Table 3) (van der Walle, 2018). This new electricity production landscape will be further complicated by the fact that the traditional (fossil) centralized power generation, will not only be replaced by decentralized electricity production originating from wind and PV parks, but also from a multitude of prosumers (households). In this new reality, it will be a challenge to maintain a stable, reliable and uninterrupted power supply.

Future developments on the supply side of the power system are discussed in Section 9.2, where the effects of this additional power on the residual load will be analysed. Building on this, Section 9.3 discusses possible solutions for meeting residual load, namely DR, double structuring, interconnection, smart grids, large-scale storage and power-to-gas. The challenges of VRE in the future power system are illustrated in Section 9.4 by a case study of the German power system. Section 9.5 considers recent developments specific to large-scale energy storage in the Netherlands.

9·2 Supply side of the Dutch power system

9·2·1 Electricity grid

The Netherlands, with its densely populated and confined spatial dimensions, has one of the world's most efficient electricity infrastructures, colloquially known as the 'copperplate'. The Dutch grid is state-owned and since privatization in 1998, the responsibility has been in the hands of TenneT. In order to serve the market, there are 7 DSOs active in a (regulated) free-market model, physically connecting consumers and industries to the grid (see Figure 83).

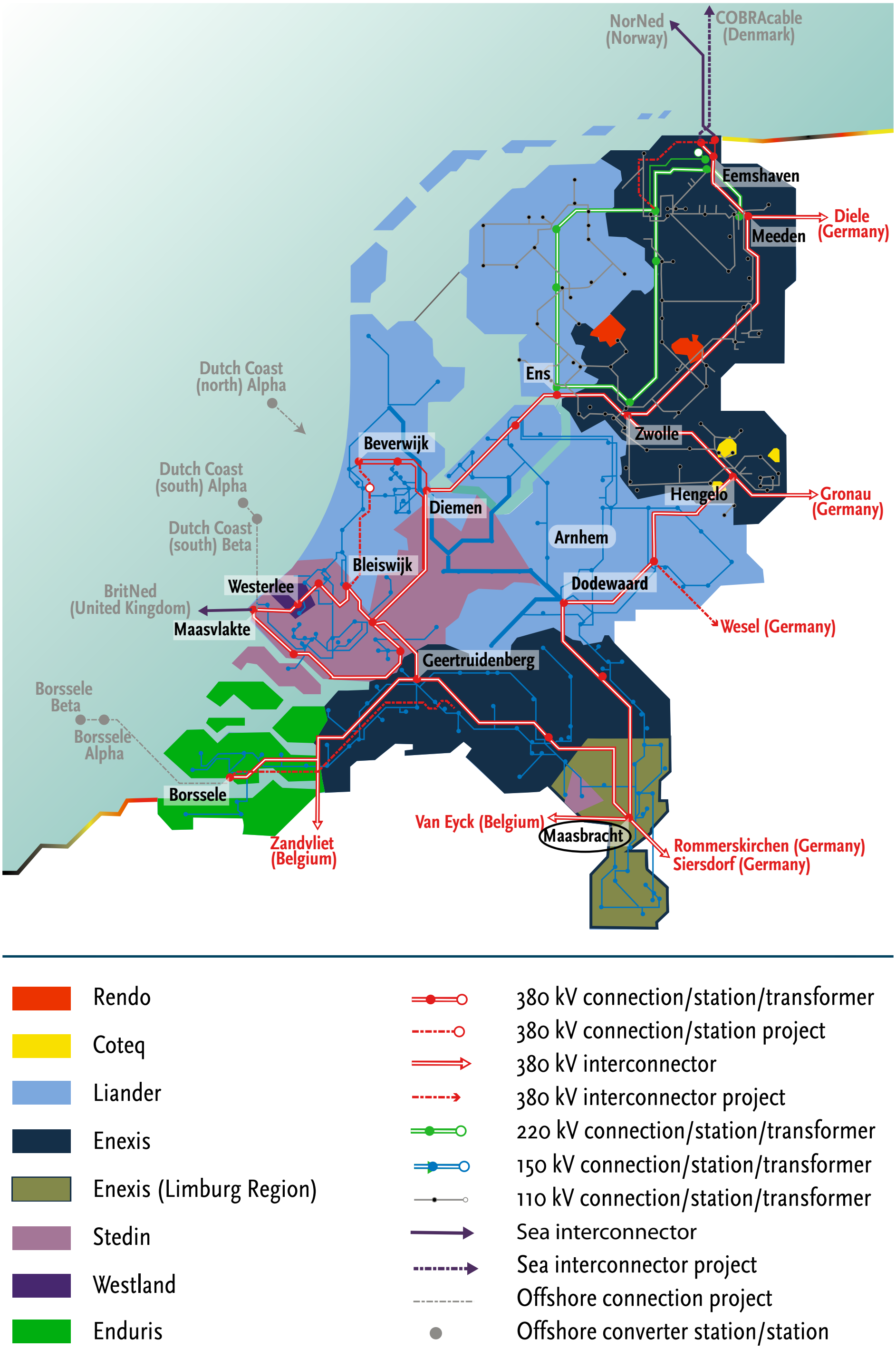


Figure 83 *– DSOs and grid overview in the Netherlands (TenneT, n.d.1; Energieleveranciers.nl, 2018)*

The backbone of the electricity supply is the network of domestic HVAC (High-Voltage Alternating Current) connections, running at 380 kV, 220 kV, 150 kV and 110 kV power capacities. This national system is linked with surrounding countries: there are four interconnections to Germany and two to Belgium. Additionally, overseas cables link the grid with Denmark (COBRAcable), Norway (NorNed) and Great Britain (BritNed). Cables with wind parks in the North Sea, Borssele Alpha and Beta, Dutch Coast North (Alpha and Beta) and Dutch Coast South (Alpha and Beta) complete the picture.

TenneT is the TSO in the Netherlands and also in a large part of Germany, where it introduced HVDC (High-Voltage Direct Current) transmissions between the North Sea offshore wind parks and the mainland. After completion, the BorWin 3 and DolWin 6 platforms will convert and transmit 4.7 GW of electrical power to shore. This novel technology will be important for the future development of transmission in the Netherlands (Siemens, 2017).

On the national grid chart, it is remarkable that only one HV node exists to connect the Netherlands to its two neighbours, Germany and Belgium. Located in Maasbracht, this 380 kV link plays a dominant role in the Netherlands' connectivity. Moreover, during the last decades, it was also an important link with the Claus gas-fired power plant (1,275 MW). Since this unit is no longer operational, it presents a unique opportunity for the TSO to link O-PAC (1,400 MW) to the national grid. It could be advantageous both for TenneT and for the electricity plant O-PAC in the region.

In the location planning of O-PAC, a 380 kV underground connection of approximately 30 km is anticipated. Alternatives could be to connect to the 150 kV station in Kerensheide (Chemelot) or the 150 kV station situated in Neerbeek, both at 5 km distance. The above-mentioned 3-country node (Maasbracht) has an excellent strategic position in relation to the neighbouring German Ruhr area with cities including Cologne, Düsseldorf, Aachen as well as the Belgian cities Brussels, Liège and Hasselt. These highly industrialized regions will be confronted with the demand for decarbonization in the near future and hence the need for greater electrification of processes. Within this region, O-PAC could play an important role as a buffer to support the industries and to enable regional storage of VRE surpluses produced by North Sea wind parks.

9.2.2 Installed power in the future

The National Energy Outlook 2017 provides projections for 2025, 2030 and 2035 for the installed power of generators in the Netherlands, based on current policies, announced projects and environmental targets (ECN, 2017b).

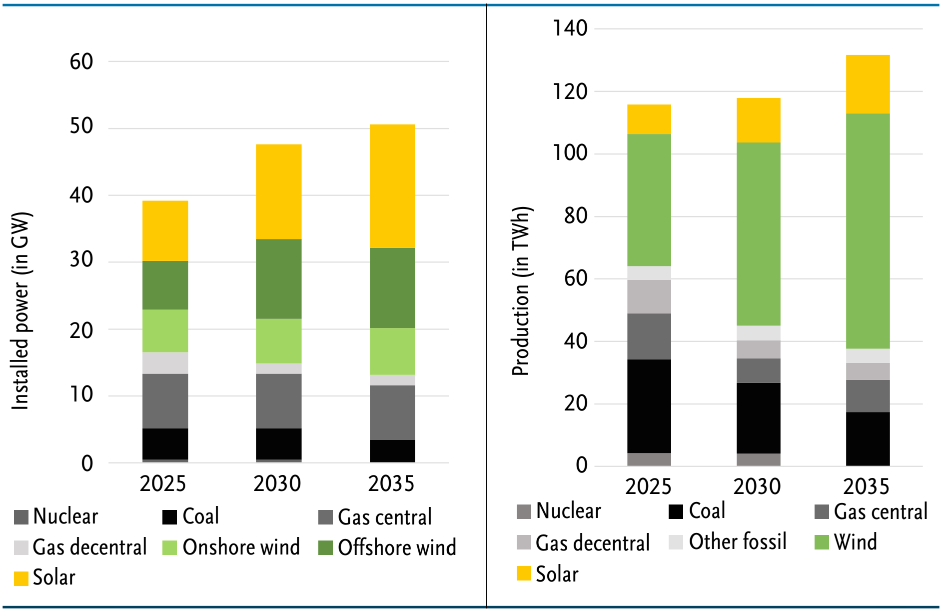


Figure 84 – *The projected installed power (GW) and the projected electricity production per energy source (TWh). Only defined sources are included, the category 'others' is not included, i.e. biomass, hydro, waste incineration etc. (ECN, 2017b)*

Figure 84 shows a substantial future increase in renewable solar and wind power, while conventional fossil-based generators will be decommissioned or mothballed. Electricity production shows a similar trend, with an increasing amount of electricity production from wind and solar.

9.2.3 Capacity factor: history and projection

The capacity factor (CF) is defined as the annual electricity production from a generator divided by the theoretical maximum annual production (full power output (P_{max}) for 8,760 hours). The following formula shows the calculation of the capacity factor:

$$CF = \frac{Electricity\ production\ (MWh)}{P_{max}\,(MW) \cdot 8760(h))}$$

Baseload power plants are designed for a high capacity factor and rely on achieving this to maintain business viability. Lower capacity factors are typical of peak load generators, which require fewer operational hours to be economically viable. For wind and solar generators, the capacity factor depends on the amount of available wind or solar irradiance and may differ from year to year. An example is the Gemini wind park in the Netherlands with 600 MW of installed power, which is expected to produce 2.6 TWh annually, corresponding to a capacity factor of 49.5 % (Gemini, n.d.). Figure 85 presents the historical and projected capacity factors for wind and solar generators, calculated on the basis of data for installed power and electricity production data.

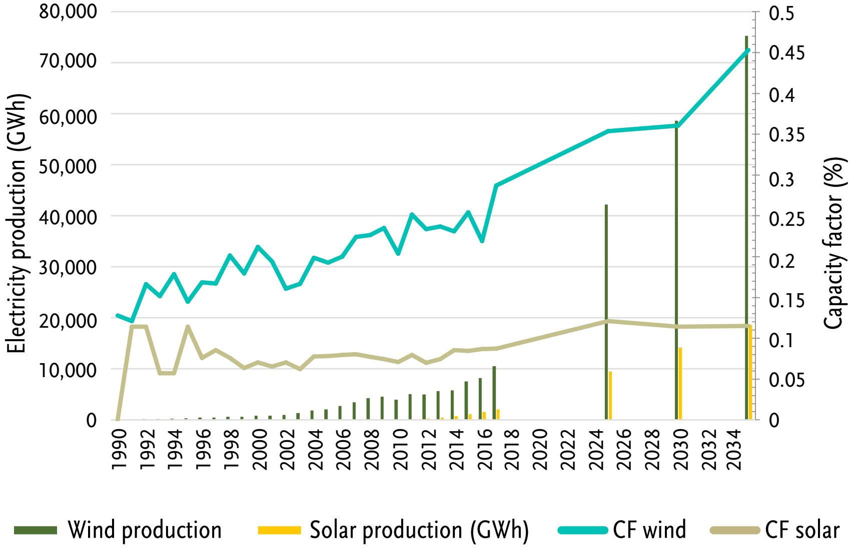


Figure 85 – *The production from wind and solar per year is presented by the bars, the capacity factor is presented by the green line for wind and yellow line for solar (based on data from Statistics Netherlands (CBS, 2018b) and projections from the NEV 2017 (ECN, 2017b))*

In Figure 85, the historical CF for solar PV is around 8 %, while the CF for wind is substantially higher and has increased from around 18 % to 25 % in recent years. Development in CF is to be expected as technologies may become more efficient in generating power over a wider range of wind speeds or intensities of solar irradiance. However, the large increase projected in the CF for wind power is unlikely, as Figure 84 shows no substantial increase in installed wind power capacity from 2030 to 2035, while the expected wind production increases substantially from 2030 to 2035. This increase in CF could be possible as new offshore wind parks can already achieve a high CF (e.g. Gemini projections). However, it is not expected that the CF of existing wind parks will increase substantially during these years. Moreover, growth of installed wind power is likely to reduce system-wide CF, as moments where wind power production exceeds demand will be more common and lead to curtailment more often. This phenomenon does not seem to be included in the estimates of VRE production in the NEV. Consequently, the projections for wind production in 2035 assumed in the NEV 2017 seem optimistic, compared to the historical capacity factors and without many new wind power installations between 2030-2035 to enable such growth in CF.

It is interesting to compare the figures for Germany, where the capacity factor in 2014 was 9.9 % for solar and 16.3 % for wind. Only a small deviation for solar capacity is noticeable, but there is a considerable difference in the wind capacity factor. One of the reasons may be curtailment (Sinn, 2017).

9.2.4 Residual load

The residual load is the load that remains beyond the cumulative production from 'must-run' and from wind and solar generators. A system that aims for almost fully renewable electricity cannot rely on conventional 'must-run', because it is too inflexible to support high VRE penetration and it is inescapably based on fossil fuel as in the case of gas-fired combined heat and power (CHP). Therefore, the residual load for a renewable-based future is regarded here as the load that remains after subtracting the power output from wind and solar generators:

$$\text{Residual load (MW)} = \text{System load (MW)} - \text{Wind and Solar power output (MW)}$$

If this formula is applied to load, wind speed and solar irradiance data for one year, the following residual load distribution curves can be calculated. The results are presented in Figure 86.

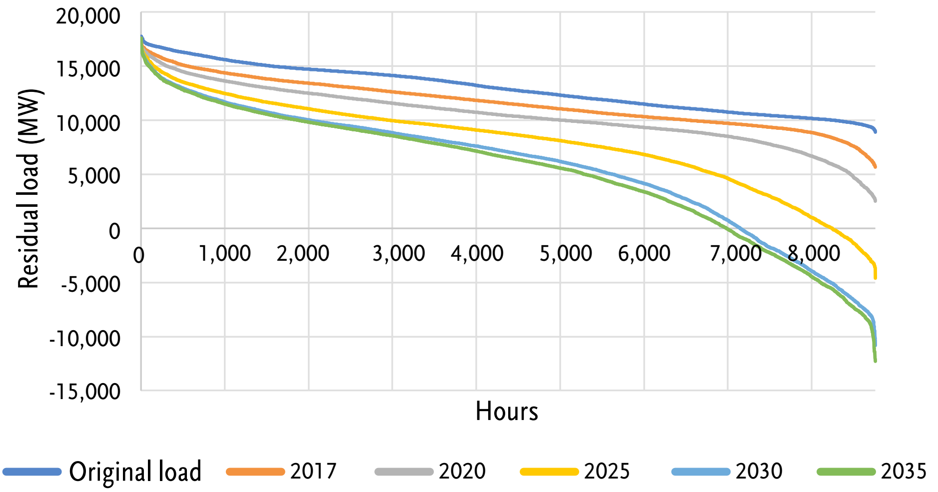


Figure 86 *– The load distribution curve and residual load distribution curves for 2017, 2020, 2025, 2030 and 2035. Projections based on a load profile, wind speed and solar irradiance data from 2015, combined with NEV 2017 data on projected VRE growth (ENTSO-E, 2016; ECN, 2017b; KNMI, 2017b; KNMI, 2017a)*

The residual load distribution curves show that there is always residual load to be met by dispatchable generators in 2017 and 2020. Between 2020 and 2025, though, the VRE installed power is expected to grow to such proportions that during some hours the residual load will become negative, so curtailment of VRE, storage of electricity or ramping-up demand will be inevitable. It should be noted that curtailment is likely to occur before residual load is negative, as some generators may have to stay online for ancillary services. The occurrence of negative residual load only grows in the subsequent years, while there will also be a demand for dispatchable capacity, as the residual load will stay positive most of the time. In 2035, there are still 1,907 hours during which the residual load is larger than 10,000 MW and more than 7,000 hours with a positive residual load. This means that meeting all load with VRE seems impossible without installed power that can be dispatched, as there may be occasions when there is little to no wind and solar power available.

On the other hand, there are roughly 1,760 hours of negative residual load that may be curtailed, unless demand is ramped up. This counteracts the expected increase in wind power capacity factor for 2035, mentioned in Section 9.2.3. As wind power is curtailed, the annual actual electricity production may be less than the possible production of an individual wind park. This in turn would decrease the capacity factor of installed wind power in the entire power system. Eventually the amount of curtailment is likely to grow due to the negative residual load that is itself a consequence of more installed VRE power.

In Chapter 2, the concept of demand response (DR) was discussed, where it was expected that about 700 MW of load shifting and 1,700 MW of load reduction capacity will be available in 2035 (Frontier Economics, 2015). This DR load shifting capacity (e.g. EVs, heat pumps, etc.) is inadequate in the face of the negative residual load shown in Figure 86. Besides, the total DR load reduction capacity, which is expected to be larger, will be insufficiently large to meet all demand during positive residual load. This shows that DR may contribute to 'shaving off' residual load extremes, but its scale is unlikely to be sufficiently large to meet the entire residual load. An additional limitation of DR is the need for electricity somewhere in the near future, as the use of electricity can often only be delayed for a limited time. Alternatively, load reduction is likely to result in loss of economic activity or reliance on emergency power backup (Frontier Economics, 2015), which could be a fossil-powered backup generator or decentralized storage (e.g. battery).

9.3 Solutions for supply-demand matching

From Section 9.2.4, it can be concluded that a positive residual load cannot be provided entirely by DR. We will therefore consider five additional solutions that are possible, separately or in a combination:

1. Power is delivered by dispatchable fossil- or biofuel-based power plants.
2. Power is imported/exported during positive and negative residual loads, respectively.
3. Smart grids may provide better matching between production and consumption.
4. Power is stored during negative residual load and redelivered during positive loads.
5. Use of power-to-gas, which is the conversion of excess power into hydrogen and/or into hydrocarbons.

9.3.1 Conventional power plants

Power delivered by conventional fossil power plants, or biofuel-based variants, provides a viable solution in meeting the positive residual load. The drawback is that fossil fuels should be avoided in the transition to emission-free energy, while biofuels are not expected to grow substantially as an energy source in the future electricity grid (ECN, 2017b). Additionally, negative residual load cannot be used by conventional power plants.

9.3.2 Interconnection

Interconnection with the neighbouring countries is one of the spearheads of the Dutch energy policy. Expansion and intensification of power via cables will play a dominant role in the future electricity supply (se also 2.3.1). This approach has been of crucial importance for the stability of the power system in the past and will continue to be so for years to come. Especially during the recent years, Germany provided the Netherlands with electricity from the superfluous electricity generated by wind and solar parks in Germany.

Recently, on April 30, 2018, the Dutch TSO TenneT declared an emergency situation because of depleted system reserves (TenneT, 2018a). This forced the TSO to procure several hundred MWs of reserve power from neighbouring countries. According to TenneT, this calamity is exceptionally rare, as it is expected to occur at most once in two years. Obviously, TenneT had insufficient means to balance the power system after unexpected high demand combined with lower than projected VRE production (NOS, 2018). It is our opinion that such situation will not be incidental in the future, because the Netherlands, with a current VRE penetration of 10 %, is only at the beginning of the electricity transition.

A possible solution lies in imports via interconnectors during positive residual load and exports during negative residual load. In considering this approach, losses in transmission lines should be considered as well as the generator mix in neighbouring countries.

Electricity-conducting lines experience losses in the form of heat when current flows against resistance. DC lines have in-line losses of about 5 % over a distance of 1,000 km, while losses for AC lines can be as great as 20 % over the same distance (van Werven & van Oostvoorn, 2006). For long distances, DC lines are therefore preferred as resistive losses become less large than all the losses associated with AC lines (United Nations, 2006). At a line length of 600 km, high-voltage DC is less expensive to build and operate than AC transmission lines (United Nations, 2006). Additional benefits are the possibility to connect two electrical systems without the challenges of synchronous AC operation between the two systems and the lack of capacitance losses for coaxial undersea cables (United Nations, 2006).

After 2023, when the planned extensions of wind and PV parks are completed, the VRE share in the energy mix will yield approximately 12,000 MW of wind energy and 7,000 MW of PV electricity, totalling more than 19,000 MW. Together with the fossil-fuelled power plants, more than 38,000 MW of capacity will be available. Especially during times with much wind and sun, electricity production will exceed domestic demand. After 2023, the surrounding countries themselves will also have expanded their VRE electricity generation substantially.

As mentioned in Chapter 2, there is correlation between wind speed for wind turbines and day-night cycles for solar power in the interconnected Northern European area (Graabak & Korpås, 2016; Mehrens, et al., 2016; Mulder, 2014). Combined with the fact that Germany has already reached historic heights for nett electricity exports (Fraunhofer ISE, 2018) and the Netherlands is expected to become a nett exporter of electricity (between 2020 and 2023) (ECN, 2017b), this raises the question whether it will be possible to export negative residual load to neighbouring countries. As other countries also increase their installed VRE power, produced VRE electricity will therefore need to be transmitted over large distances to reach regions with different climate regimes, e.g. from Northern Europe to Southern Europe (Graabak & Korpås, 2016). At these distances, losses in the transmission infrastructure will become more important and a comparison with local storage should be considered.

9.3.3 Smart grids in the future power system

The national climate change and energy policy objectives require a massive transformation not only in low-carbon electricity generation, but also in upgrading the existing infrastructure. The increasing amount of renewable electricity will force the building of new lines and stations, but above all of a smarter system by introducing information and communication technology (ICT) (JRC, 2011).

ICT integration is transforming the power system from a merely physical platform for one-way transactions of electricity supply for passive consumers, into a market platform for the transactions of electricity supply and services among several heterogeneous grid users (JRC, 2011). Siderius & Dijkstra (2006) define smart grids as: "A rich transactional environment, a market platform, a network connecting producers and consumers who contract and negotiate their mutual exchange of value (product service) for value (payment). A smart grid is a transactive grid."

The basis of any smart grid system is the nationwide introduction of smart metering in household and industries. The second essential element is the installation of a communication system, supported by adequate ICT and controlled DSM (demand-side management) design and implementation. Based on these principles, a system is able to exercise the DR (demand response) function, which can play an important role in balancing the supply and demand of electricity by the system operator DSO.

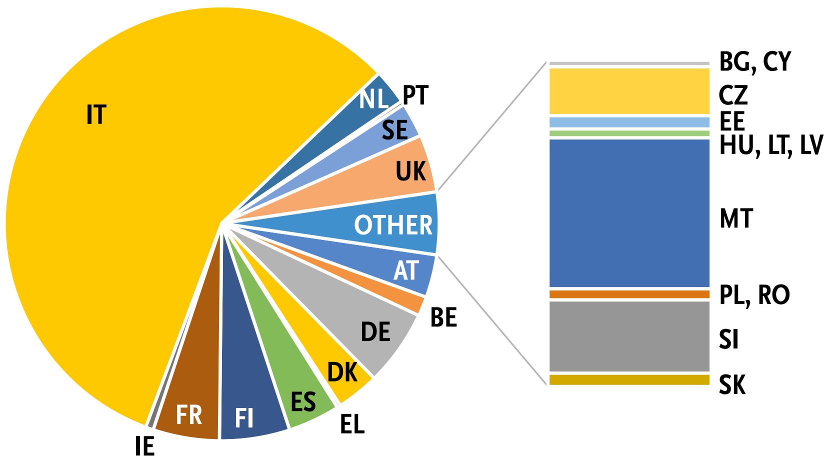


Figure 87 – *Distribution of investments between EU15 and EU12 countries (JRC, 2011)*

A decade ago, Italy was the first country in the world with a nationwide roll-out of smart metering (Sterner & Stadler, 2014). This country was the forerunner with the installation of 30 million smart meters (see also 2.3.2), which, together with the ICT systems, amounted to a €2 billion investment, as shown in Figure 87. The Italian case, moreover, had an unintended side effect of cashing unpaid bills for electricity amounting to roughly €500 million.

If the situation related to the introduction of smart meters and current smart grid penetration are compared, the conclusion can be drawn that smart grid development is likely to experience considerable growth.

At present, there are more than 950 smart grid R&D and demonstration projects identified in the EU, with a total investment of €5 billion. There is a great diversity between different states, with Germany holding the lead, followed by Denmark and the UK (JRC, 2017). Five domains can be discerned:

- SNM, or smart network management (34 %), which focuses on increasing operational flexibility by grid-monitoring and control capabilities.
- DSM, with the objective to shift consumption to another time (demand response) without affecting functionality.
- DG&S, which introduces new ICT solutions to integrate distributed generation and energy storage, in order to boost system reliability and security.
- E-mobility, focusing on the smart introduction of EVs and PHEVs into the grid.
- L _ RES (large-scale renewable energy sources) integration into the HV (high-voltage) distribution network, such as offshore networks for wind power integration.

The following graph presents the investments in smart grids in the different domains per country.

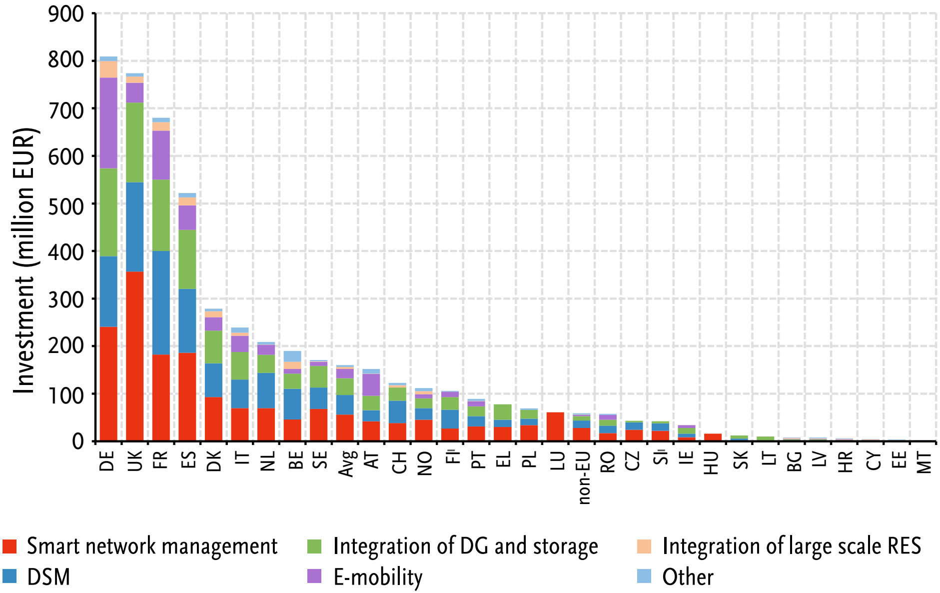


***Figure 88** – Distribution of investment per smart grid domain and country (JRC, 2017)*

As for the Netherlands, the investments in smart grids are represented in the middle group. The introduction of smart meters remains a challenge, as described in 2.3.2. Since 2015, however, a vast majority of consumers have accepted smart metering and distant meter reading, with only 3 % refusing. As of 2017, 3 million consumers had a smart meter installed, which is 20 % (Netbeheer Nederland, 2018). Until 2020, the smart meters are to be installed for free, but deployment is on a voluntary basis. The legal situation and regulatory measures, in this case the infringement of the privacy of the consumers, was the subject of fierce debates in the Dutch Parliament. The initial law with compulsory installations (2008) of smart meters had to be changed by Minister Van der Hoeven on the order of the Senate into voluntary participation. It took three years, from 2008 to 2011, before Minister Verhagen could pass the law through the Parliament. These regulations were necessary in order to comply with the European guideline of 80 % smart grid penetration by 2020 (EC, 2018).

If the Netherlands, conforming to the ambitions of the Rutte III government, wants to play a leading role in the European renewable electricity systems, a considerable challenge lies ahead. The central question will be whether the currently proposed measures will be sufficient to attain this goal, and in turn the viability of CO_2 emissions targets at stake (a reduction of 49 % in 2030, relative to 1990). After years of inadequate climate policies, the recent Ministry of Economic Affairs and Climate Policy (EZK) made an attempt at leadership through a 'polder' solution, where all possible stakeholders are invited to contribute to various solutions. This proposal was concretized in the form of 'tables' representing five sectors: (1) built environment, (2) electricity, (3) industries, (4) mobility, (5) agriculture and use of land, alongside one 'coordination table'. The latter table has the task the of executing measures that are selected and monitoring their results. The storage of electricity, however, either centralized or decentralized in households and industries, does not play a significant role, though its necessity in combination with a sun- and wind-generated electricity supply is demonstrated in the surrounding countries.

Recently, a report was published by Rli (Council for the Environment and Infrastructure), titled "Stroomvoorziening onder digitale spanning" (in English: Electricity supply under digital tension) (Rli, 2018). This report showed that the reliability of the electricity supply is under pressure due to the increasing digitalization of the system necessary to integrate the decentralized sources such as wind and PV, together with growing electrification (heat pumps etc.), storage systems (batteries) and smart meters. As complexity increases, novel threats can occur due to the behaviour of pre-programmed self-regulating systems, not to mention malicious cyber threats. It is advised that the dangers can be reduced through European cooperation, since energy and ICT facilities are internationally linked.

As has been repeatedly suggested in this monograph, these developments demonstrate clearly that it is not reasonable to rely uniquely on different decentralized balancing sources. Only a large-scale centralized flexible storage facility is able to deliver a balance in all different scenarios.

9.3.4 Large-scale electricity storage

Electricity storage is the only option that provides the opportunity to ramp-up demand (i.e. charging) during negative residual load and later provide dispatchable power during positive residual load (i.e. discharging). Chapter 3 elaborated on the differences in the operation and applications of a range of storage technologies. The focus here is on large-scale (> 500 MW of power with several GWh of energy storage capacity) and the viability of stationary storage technology for the Netherlands at that size with regard to global resource production, scarcity of raw material supplies and technology maturity.

From Chapter 3, several storage technologies could be considered, based on size and storage duration:

1. PHS: the limitation here is that the Netherlands does not have the geographical elevation differences for conventional PHS.
2. CAES: this storage solution uses natural gas in its generation cycle. The new iterations of CAES, AA-CAES and isothermal CAES are still immature.
3. Li-ion batteries: this shows potential, as prices have decreased and relatively large (up to 100 MW) Li-battery systems have been commissioned recently (Spector, 2017). However, scaling up batteries to > 500 MW is unrealistic with regard to the worldwide Li-ion cell production capacity and expected growth in demand for Li-ion cells for EV production worldwide (BNEF, 2017b).
4. Flow batteries: while still a commercially immature technology, it does, however, show potential with regard to power and energy size.

It is clear that sustainable large-scale storage will therefore be challenging in the Netherlands. As mentioned, O-PAC provides the solution for implementing the world's largest and most mature energy storage technology (i.e. PHS) in the Netherlands.

Pumped storage plants are considered as most prominent and promising buffering schemes, alongside demand management and grid expansion to other countries, which includes Norway's hydro plant capacities. According to the European Commission (AS) pumped storage technology "offers a new era of smarter energy management", which could be instrumental in moving on to green energy and fight climate change (DNV-GL, 2015; EC, 2016).

9.3.5 Power-to-gas

As already discussed under chemical storage in 3.4.4, power-to-gas could provide a solution for long-term (seasonal) storage, but it is still in the developmental phase. ECN (2014b) researched the role of power-to-gas, specifically in the context of the future Dutch energy system. Their main conclusions are summarized below:

1. Power-to-gas can contribute to deep CO_2 reduction for the entire energy system (electricity and other types of energy), as most renewable energy production will come from solar PV and wind turbines. Power-to-gas enables the use of renewable electricity in parts of the energy system that are difficult to electrify through a different energy carrier (e.g. hydrogen, synthetic ammonia and methane). In this respect, power-to-gas may play an important role in the distant future, because it will compete with technologies that are surrounded with uncertainties, such as CCS and energy from biomass.
2. The use of electrolysers, similar to the options mentioned earlier, adds flexibility to the grid. However, without low and even negative electricity prices, a positive business case for power-to-gas cannot be created due to the capital intensity and the inherent efficiency losses of the technology.
3. The study shows that power-to-hydrogen is the most viable of the range of power-to-gas solutions. Power-to-methane should only be considered when all CO_2 storage options have been depleted or when there is much societal resistance against carbon storage. Before using the methanation route, distributing CO_2 in the form of methane will make it even more expensive to capture than utilization of CCS.
4. While power-to-gas cannot be considered as a cost-effective option in the short to medium term, its potential grows further in the future. Nevertheless, there may already be niche applications for the technology on a local scale, where limitations in the electricity grid may cause frequent oversupply of renewable electricity. Combined with local demand for hydrogen, this can create a more positive situation for power-to-gas.

It can be concluded from the ECN study results that power-to-gas (mainly hydrogen) may be inevitable on the road to an energy system in which CO_2 emissions are reduced by 80-95 %. The mentioned options earlier (e.g. energy storage, DR etc.) are economically much more attractive in the short and medium term than power-to-gas and they also operate specifically in the electricity system in which the first challenges from VRE will occur.

9.4 Case study: German paradox

On the German showcase of VRE introduction, H.W. Sinn (2017) describes the impact of their impressive growth of VRE, combined with the closing and phasing-out of nuclear power plants in: "Buffering volatility: A study on the limits of Germany's energy revolution". He demonstrates unmistakably that fossil backup will inevitably play an indispensable role for the coming decade. The continuous growth of solar and wind electricity, together with the intended closure of coal, lignite and gas generating sources, will enhance volatility, causing still more storage tensions.

Although the present German buffering strategy functions, it is also expensive, as it requires a double generation outlay and hence double fixed costs. As a result, it harms the profitability of conventional power plants, whilst reducing their hours of operation. This not only leads to unprofitability but even threatens the very existence of the formerly healthy electricity-generating companies. The consequence of the double structure, apart from ecological aversions, is that only temporary backup services can be delivered, based on the limited lifetime of the plants. Investments in new power plants are considered impossible under the present regime, also because of the fact that green power feed-in is receiving priority according to merit order.

"The German Energiewende and its climate paradox" (Graichen & Redl, 2014) deals with an interesting phenomenon. In spite of the increasing input of renewables, greenhouse gas emissions rose in recent years. The phasing-out of nuclear plants is not the reason, in itself, since the lost capacity has been fully offset by the supply of renewables. The paradox in reality is caused by the fuel switch from gas to coal out of economic reasons. The challenge for the coming years in Germany will be the restructuring strategy for the reforming and phasing-out of the coal sector.

The EU's eStorage project study showed convincingly that aside from efficiency improvements by upgrading pump-turbines of existing PHS plants, only a limited number of geographically suitable locations are available. For Germany, only one suggested location is available with a capacity of 5 GWh (JRC, 2013), which limits the German potential. As for the other EU member states, a limited number of suitable sites are proposed.

H.W. Sinn provided an in-depth analysis of different trains of thought in modelling how the German VRE electricity could be connected with the vast Norwegian hydro capacity. He concluded that without the constructing of second dams in the fjords, there would be insufficient pumped hydro available in a closed-loop system, especially when working with environmental constraints. The effect of DR measures was also part of the considerations, leading to a conclusion that, though it renders a positive contribution, it will only be a limited part of the solution.

Finally, it must be underlined that PHS has traditionally been focused on diurnal storage and, though suitable for more variable operation, it is generally not intended for seasonal storage. Within the Netherlands, a number of studies and initiatives can be identified with seasonal storage as their subject. In this light, it is interesting to take account of H.W. Sinn's analysis of hydrogen (H_2) and methane (CH_4), since seasonal buffering by batteries is not applicable. Germany has a dense methane distribution network and sufficient storage capacity of 267 TWh, which is more than enough to cope with the volatility of German supply and demand. However, the available technologies for converting electricity to methane and back are inefficient and costly (Sinn, 2017). Another bottleneck comes from the substantial production of waste heat in the summer, when the largest surplus of renewable solar energy is available for methane production. Using methane production from electricity and recuperation in a gas power plant causes losses between 66-80 %. Methane generated in this way costs a multiple of the market price. For instance, one kWh of Russian natural gas cost 2.42 eurocents in 2016, whilst the cost of converted methane is about 25 eurocents/kWh, a tenfold amount (Sinn, 2017). These observations are food for thought when designing the future storage strategy for the Netherlands.

9.5 Large-scale storage in the Netherlands

The transition to a CO_2-free power system will be a process that spans decades. The introduction of VRE is taking place at a pace that exceeds expectations. However, there are numerous uncertainties linked to the timing and execution of the necessary steps. Political and economic factors will play a decisive role in the time frame of attaining the targets. These processes require decisions about closing and phasing-out of fossil generation units, for which the consent of the operators is indispensable.

The FME (Federation of the mechanical and electrotechnical enterprises) founded a coordination group of stakeholders in energy storage. Under the name of Energy Storage NL, this platform counts more than 50 members from the industry, consulting, government, investors, employed activities and studies. In particular, they presented a national plan for energy storage called “Nationaal Actieplan Energieopslag” in 2016 to (a member of) the Dutch Parliament (Energy Storage NL, 2016). In this study, a general overview of the different storage techniques was introduced, along with an indication of key bottlenecks and a number of response measures and proposals. In particular, three impediments to the dissemination of (large-scale) storage projects were suggested:

1. The current laws and regulations upset a level playing field for storage. An example is the double levying of energy tax.
2. High costs, including investments and future uncertainties for businesses and additional relative unfamiliarity with the opportunities of storage lead to system underinvestment. Because of the resultant lack of storage capacity, more CO_2 emissions occur than necessary.
3. Moreover, curtailment causes a substantial loss of energy, which has to be compensated by energy from fossil sources.

In 2017, FME and the association of the Dutch engineers (NL Ingenieurs) produced a vision document called "Grootschalige energieopslag" (large-scale energy storage) with 10 points of action for stimulating large-scale storage (Energy Storage NL, 2017). A number of these recommendations are specifically relevant for the O-PAC project:

- Large-scale projects related to the efficient use of VRE, such as O-PAC, require construction periods of 5 to 7 years, so decisions have to be taken many years in advance. Moreover, this particular project was the subject of decades of investigation on behalf of the Ministry of Economic Affairs (Section 5.1). The accompanying challenge is the lack of urgency in times of superfluous electricity supply, necessitating foresight and a long-term vision.
- O-PAC has to participate in a free-market system where the reward for societal benefits is not evident. This makes it challenging to reach a positive CBA from an investor's perspective. In order to concretize large-scale electricity storage, societal benefits (e.g. CO_2 emission reduction) must be compensated by adequate regulations.
- O-PAC can contribute to curtailment prevention during VRE surpluses. This reduces the loss of economically valuable electricity that would otherwise have to be generated by fossil power plants, with accompanying CO_2 emissions.
- O-PAC intends to develop hybrid business models in cooperation with large wind and solar PV parks, with the aim to create synergies for both VRE parks and storage plants.

The above-mentioned vision document formulated a number of recommendations aimed at policy constraints, which are also relevant for O-PAC:

- Innovation policies should focus on large-scale electricity storage, with heavy-duty demands for long lifespan reliability.
- Policies are needed for stimulating the propensity to invest, since financial markets only invest if sufficient security is offered.
- Restrictive laws and regulations should be removed. Various disturbing barriers in the laws and regulations (e.g. the double levying of energy tax and surcharging of grid tariffs) are identified that prevent a level playing field.

- New technological solutions (e.g. O-PAC) should be supported in the transition, as they often experience the 'valley of death' phenomenon, which is the uncertainty phase between the introduction and acceptance by the financial markets. This phase could be bridged by stimulating regulations.

9·6 Conclusions

Higher capacity factors can be achieved for VRE sources when storage is included in the power system, eventually leading to a higher return on investment. It may also result in lower spatial requirements for wind and solar parks.

Balancing the electricity grid will become more challenging in the future power system, in which high VRE will provide challenges for power production predictions. The result will be reliance on DR, interconnection and electricity storage.

Explicitly, maintaining conventional fossil plants as backup will be inescapable during the coming decade(s).

The Dutch energy transition to VRE should benefit from the lessons that can be learned from the 'Energiewende paradox' experienced by VRE frontrunner Germany.

There is a discrepancy between the free-market remuneration for electricity storage and the societal benefits it may provide. Additionally, policies do not stimulate investment in storage and may even provide constraints for a successful business case. This provides a challenge for all stakeholders involved in the process of creating a renewable-based power system.

10 Conclusions and discussion

To conclude, this thesis comes full circle by answering the main questions of Chapter 1, namely:

Which technologies and policy measures offer the potential to meet the demand for flexibility and what is their impact on sustainability? (Section 1.2, Question 1).

This question frames the subsequent discussion and the central hypothesis that U-PHS is probably the most promising of these technologies. In answering this question, we review the scope of technologies other than U-PHS in order to establish the basis for comparison with U-PHS, and this comprises the second key question of the thesis (Section 1.2, Question 2). As U-PHS is largely absent from energy system outlooks and policy considerations, this section in essence reviews the current thinking on the mitigation of future intermittency.

Dutch policy (Section 2.3) foresees a considerable role for decentralized storage in the batteries of electric vehicles (EVs) to provide future balancing. This is a realistic option to enhance flexibility, provided the necessary infrastructure is in place (Section 2.3.4). Nonetheless, it is difficult to guess how fast the EV fleet will grow and hence how much battery capacity will be available. There are other clean vehicle technologies that compete with battery-powered EVs and might account for a considerable portion of the total car fleet. Moreover, the availability of battery capacity is also a matter of consumer behaviour and a propensity to adapt. Consequently, there are no reliable forecasts for the contribution of EVs to flexibility. But even if this turns out to be important, it is not a sustainable way to provide for energy storage. Batteries use rare and costly raw materials and have a relative short lifetime of less than 10 years.

Household batteries are currently limited by a lack of installed capacity and the growth of household battery capacity will be negligible without subsidies. Furthermore, the infrastructure for a smart contribution to provide flexibility for the electricity grid is still under development in the Netherlands (Section 2.3.3).

Dutch policies are also directed at demand-side management (DSM) and demand response (DR). By building intelligence into the grid, demand can be controlled, for example by remotely switching off large loads such as freezers for a limited time to balance peak demand. Yet there is great uncertainty about the acceptance by consumers and industries, as well as whether this approach can be applied at an adequate scale to contribute to the necessary flexibility.

Distributed battery storage and demand-side management have in common that their availability for grid control is subject to the primary service they provide, allowing capacity to be made available. This means that the degree of control is inevitably limited and by extension, so is their contribution to the security of supply.

The role of interconnections is expected to be limited by the synchronous occurrence of high VRE production between the interconnected countries. This solution will be further limited when the electricity mixes of these countries conform to a greater extent than they currently do (i.e. higher VRE power in all grids) (Section 2.3.1).

This means that on cloudy and windless days, net managers could often be out of options to balance the grid in a sustainable way. Inevitably, they will need to reach for backup power from fossil-fuelled power plants. This will most likely result in CO_2 emissions, as CCS on stand-by power is economically unattractive. Fossil backup thus compromises our ability to reach reduction targets (Section 2.3.5). Moreover, reliance on backup power rather than storage leaves more power curtailed during periods of renewable oversupply. Still, some dependence on fossil-fuelled backup power will continue during the coming decades.

As foreseen in some outlooks (Gigler & Weeda, 2018), hydrogen produced by electrolysis during periods of renewable oversupply may eventually be used as backup fuel. However, its low cycle efficiency makes it costly and ineffective for diurnal storage and limits its relevance for relatively rare events (seasonal storage) while U-PHS is superior for diurnal storage.

The identified measures all contribute to the flexibility of the electricity grid within their respective limitations. The greatest challenge is to create a system in which supply can be sufficiently controlled without the emission of CO_2. Here, the solution of energy storage is proposed as the best alternative for dispatchable conventional generator capacity. Within the above-mentioned mix of flexibility measures, energy storage is identified as an indispensable component to facilitate the transition to an emission-free energy system.

How do the characteristics of different storage systems compare to the alternative of U-PHS, both in terms of environmental sustainability and economic considerations? (Section 1.2, Question 2).

Across storage technologies, there is wide variety of storage characteristics, including capacity, time-to-grid, charge and discharge times, number of cycles, efficiency ratio, useful life, etc. (Section 3.5). As discussed in Section 3.7, it can be concluded that PHS is an affordable option for large-scale electricity storage from an economical viewpoint. The only large-power and large-capacity solution is pumped hydro storage (PHS). Yet its social acceptance in view of its impact on the landscape puts serious limitations on its deployment, as the slow progress of recent PHS projects demonstrates. It is increasingly difficult to integrate large water reservoirs in an environmentally and socially acceptable manner.

There have been plans for large-scale PHS with a low head (height difference) in the IJsselmeer, a closed-off inland sea in the Netherlands. This has similar backdrops. It is hard to integrate a basin of more than 40 km^2 in a densely populated country with a fragile environment. Moreover, the risk of a breach in the 12-metre-high dikes so close to Amsterdam is unacceptable. Similar plans in the North Sea are hampered by unfavourable geological conditions, interference with maritime transport and – again – environmental concerns.

This is where U-PHS excels, with its largely subterranean constructions which do not disrupt the landscape. While the upper (surface) reservoir can be kept to a limited size, due to the high head.

Compressed air energy storage (CAES) is virtually the only other technology for large-scale storage. It is mature enough for effective balancing. Yet, this is not a CO_2-neutral technology, as natural gas is used to co-propel a turbine. It is therefore a transitional technology, which may aid the energy transition, but should be abandoned once the energy system is almost CO_2-free. Advanced variants of this technology, which wouldn´t need additional fuel, are in an early stage of development and may have some role in a more distant future.

The O-PAC project offers a storage scale and especially an installed power capacity that is unparalleled by competitive storage technologies applicable to the Netherlands. The additional benefit is its substantial flexibility in operation and provision of ancillary services that can be observed in other European countries that have conventional PHS, thanks to a more favourable topography than the Netherlands. In comparison, O-PAC has an economical advantage in its limited environmental (spatial) impact that requires little compensation of disruption of the landscape. This results in an economical and mature energy storage solution that is applied already worldwide in its conventional form of PHS. Developments in mining technology and the maturity of PHS technology support its viability in providing large-scale storage and flexibility to the Dutch power system.

Under what conditions is an (optimized) U-PHS in the Netherlands technically, economically and financially feasible? (Section 1.2, Question 3).

A U-PHS project is an innovative approach that could be linked to Schumpeter's statement as a "Durchsetzung neuer Kombinationen". As with many innovations, it is a novel combination of existing technologies, applied in a new context. Therefore, U-PHS has a sound basis in proven technology, state-of-the-art civil engineering and mining techniques and mature electrical and electromechanical technology. It is in fact quite similar to 'surface' PHS. There too, it is common practice to build machine halls and sometimes reservoirs underground, with – in one case – 3,000 metres of rock above it. There is therefore no doubt that U-PHS is technically feasible (Chapters 4 and 6). South Limburg has a suitable location for a launching project. Its favourable geology is demonstrated from drilling samples (Section 5.3).

Nevertheless, the exact location for the lower reservoir must be further determined and researched for fractures. It is therefore recommended to perform 3D seismic research and core drilling analysis for the underground target site.

U-PHS is a long-term solution which requires considerable investments, for which financing will be a major challenge. Still, analysis shows that it may be operated profitably (Section 7.3.4), given cooperation from both private- and public-sector stakeholders. National and international institutional investors have already shown a keen interest in participating in future assets provided by O-PAC. U-PHS is therefore financially and economically feasible (Chapter 7).

What are the restrictions and obstacles to be addressed to realize a U-PHS? (Section 1.2, Question 4).

The main restriction for the technology is the local geology. But the rock at a depth of 1,400 metres in the studied area in South Limburg is favourable. For the technology to be applied elsewhere, the subsurface would need to be studied thoroughly. The depth and quality of suitable rock layers are the main determinant for the costs of subterranean works, and therefore the profitability of U-PHS.

The relatively long construction time of O-PAC is beyond the scope of some investors and will make it difficult to find public support, all the more so as current conditions do not create a sense of urgency. Awareness is increasing, but by the time bottlenecks become apparent, it will be too late to build large-scale facilities for balancing the grid. It will be a painstaking task to fulfil all administrative and legal requirements to acquire the necessary permits and licenses. Numerous laws and regulations are involved. To this end, it would be helpful if the 'Crisis- en herstelwet' (Crisis and Recovery Act) were to be applied, to simplify the process of obtaining permits.

O-PAC will take up electricity during oversupply, for which grid fees are charged. When power is redelivered to the grid during shortages, the grid fees are charged again. This restricts energy storage economically as grid fees are charged twice, which should be avoided.

Surpluses and shortages of renewable electricity production will occur frequently and it is our expectation that the planned CO_2-free balancing technologies and measures will not be sufficient, and will demonstrate a considerable discrepancy, inescapably leading to the use of a fossil-fuelled backup, which will be counterproductive to the agreed CO_2 emission reduction targets (Section 1.2, central hypothesis).

In the short term, the Dutch power system is deceptively stable and secure. It will take at least three to five years before variable renewable energy (VRE) in the Netherlands reaches the current level of neighbouring countries. Moreover, trade through cross-border interconnectors allows for effective balancing, as the electricity generation mixes on either side of the border presently have different structures.

This will change around 2023-2025, when the Dutch share of VRE is projected to exceed 30% and will have caught up with that of neighbouring countries. This will make cross-border differences smaller.

Because of its unique flat geography, the Netherlands lacks options to apply conventional pumped hydro storage, which is the dominant storage technology worldwide. The continued use of fossil fuels as a backup will be necessary. This will make it more difficult to reach the agreed CO_2 emission targets.

The question arises whether the proposed measures and set of technologies under mainstream consideration, such as interconnection, demand response and EVs, will deliver sufficient flexibility for balancing a VRE-dominated grid.

The PBL (Netherlands Environmental Assessment Agency), together with the ECN, issued a report in October 2017 with the prediction that only half of the CO_2 reduction (49 % in 2030) will be attained. The recommendation reads as follows: “Three measures are needed, which are collectively able to significantly reduce emissions which are: The closure of coal-fuelled power plants, enforcing a minimum CO_2 price for the electricity sector and broadening the scope of the SDE+ regulation” (PBL, 2017).

Based on the work of this thesis, we suggest that the use of subterranean water reservoirs for underground pumped hydro storage offers a useful and necessary complement to the suite of technologies needed to address the storage problem. The South Limburg underground is a suitable launching site for large-scale underground pumped hydro storage. Its technology is proven, its economics are sound and its funding is within reach. O-PAC can bring solace for the lack of flexibility in the Dutch grid in a project that will be a breakthrough example in electricity storage for the rest of the world.

The Netherlands have a historically huge storage capacity for energy resources in the form of oil, coal and natural gas reserves. This made the Netherlands an important energy buffer for Europe. In its newly intended role to become an important electricity hub, such indispensable buffering capacity is not yet incorporated in the Dutch infrastructure. The proposed storage system could therefore play an important role in both the transition towards sustainable electricity and establishing the Netherlands as a main European energy hub.

Summary

Summary

PART ONE discusses the intermittency of wind and solar electricity, a main challenge in the transition to a low-CO_2 power supply. It opens with **Chapter 2**, which deals with the present and future Dutch power system and Dutch energy policies. The Netherlands have become greatly dependent on natural gas after the discovery of huge natural gas fields in Groningen and gas findings under the North Sea. In 2015, gas had a share of 41.7 % in power generation. With strategic coal depots in the ports of Rotterdam, Amsterdam and Antwerp, low-priced coal is the second pillar of the power generation, with a share of 35.9 %. This means that fossil fuels supply around 80 % of Dutch power, complemented by 4 % nuclear power (with one plant in Borssele), and 7.9 % variable renewable energy (VRE), mainly from sun and wind.

In its "*Energierapport, transitie naar duurzaam*" (Energy report, transition towards sustainable, 2016), the Dutch government set out three targets for the transition to renewable energy:

1. a reduction of CO_2 emissions
2. the use of opportunities that arise from the energy transition
3. facilitation of variable renewable energy (VRE) in planning and construction regulations

Under the current national energy agreement from 2013, a total of 3,500 MW of wind power will be added offshore in the period until 2023, in addition to the currently installed 1,000 MW. Of these, the Gemini Offshore Wind Park is the first of the new series of offshore wind farms in the Netherlands, and has been fully operational since 8 May 2017, with 600 MW of power and an estimated annual production of 2,600 GWh. This will be followed by the Dutch wind farms Borssele I and II (together 752 MW), which are being built by the Danish Ørsted power company and Borssele III and IV (also 731.5 MW), to be realized by a consortium led by Shell. The tender for a 740 MW wind farm at sites I and II of the plot Dutch Coast (South), was recently awarded to Chinook, a subsidiary company of

Nuon. Sites III and IV are expected to be tendered in the 4th quarter of 2018. This shows that wind power is growing rapidly in the Netherlands. For the subsequent period (2024-2030), the target is an additional 7,000 MW, totalling 11,500 MW in 2030 (RVO, 2018d).

Onshore wind also has impressive growth targets. The total installed wind power in 2023 (both onshore and offshore) is planned to be 10,450 MW. On top of that, an installed power of 5,000 to 7,000 MW of photovoltaic (PV) power is to be expected. The total installed VRE power is projected to be over 17,000 MW in 2023. This is slightly more than the current daily average demand during peak hours in the Netherlands. As some other power sources, such as combined heat and power (CHP), cannot be switched off, oversupply is unavoidable. Especially at night, with an average demand of only around 7,000 MW, oversupply and curtailment of VRE will occur frequently.

Balancing the power grid is still a matter of routine, with an electricity system that is based on a predictable and controllable supply, which can be tuned to match demand. Yet this will change substantially, certainly when the targets of 63% of VRE (set in the *National Energy Outlook 2017*) are to be reached.

The Dutch government expects to get the required flexibility from:

- cross-border connections with neighbouring countries
- demand-side management (DSM), especially demand response (DR)
- storage in batteries placed in households
- storage in batteries of electric vehicles (EVs)
- backup by fossil (coal and gas), biomass and waste power generation

The main policy measure is the expansion of high-voltage connections with neighbouring countries. In 2016, Dutch interconnections amounted to 5.9 GW, which is projected to increase to 9.1 GW in 2020. Cross-border electricity trade is thought to offer flexibility, as the electricity mix on either side of the border differs. Problems arise when electricity systems grow more similar with the introduction of variable renewable energy. Especially after 2020, there will be a high degree of conformity in the generator mix of neighbouring countries of the Netherlands. As weather conditions are correlated in Western Europe, electricity from sun and wind will be produced synchronously. Therefore, frequent surpluses and shortages will occur quasi-simultaneously, so that import and export cannot balance these at every moment.

In this period after 2020, the Netherlands will acquire an overcapacity, which will change it from nett importer to a nett exporter. The question arises whether neighbouring countries will buy our surpluses when they themselves have surpluses for the same reasons. It is therefore uncertain if the investments in cross-border links will provide a return.

Demand-side management (DSM) is another Dutch policy aimed at balancing the grid. This involves a change in behaviour of consumers and industries, so that they shift their power use to off-peak hours. Financial incentives are thought to bring about this change, for which smart metering and – more in general – ICT technology needs to be in place. ENTSO-E estimates that this so-called demand response (DR) may be as large as 1,000 MW. An extra 700 MW of load reduction would be within short-term reach with a targeted programme, and another 200 MW in the longer run.

These numbers are based on far-reaching assumptions on consumer behaviour and the adaptability of industries. A large majority of the Dutch consumers (86 %) demands electricity to be continuously available. Moreover, the absence of a homogeneous distribution system (with seven DSOs) presents a serious challenge for influencing the market. It is therefore unlikely that DSM can contribute considerably to flexibility.

Similar reservations hold with regard to storage in household batteries. In Germany, national subsidy programmes have resulted in more than 19,000 residential storage systems (2016). As the costs are otherwise forbiddingly high, only subsidy programmes will entice consumers to install household batteries. At present, there are no signs that the Dutch government is willing to do this.

Storage in batteries of EVs is thought to be another option. In a vehicle-to-grid system, EVs store surplus energy and return it during peak hours. Dutch policies estimate a fleet of 1 million EVs in 2025. This will provide a storage capacity of 1.5 GWh. However, in 2017, EVs had only a 1.5 % share of the Dutch motor vehicle fleet. Future growth of this fleet is dependent on the progress of battery technology in terms of storage density, durability and costs. Also, there must be a match between the number of EVs and charging points, in order to use car batteries for balancing the grid.

The question is also whether battery-powered EVs, with their inherent limitations, will survive in the fierce competition between clean car technologies. Hydrogen-fuelled cars are another option. In Germany, California and Japan, many hydrogen filling stations have already been planned for the coming years, in spite of the pessimistic prognoses of IEA. The German federal government has signed a contract with H_2 Mobility Germany to install 400 stations across Germany before 2023. California contracted Shell and Toyota for 100 stations towards 2024. Hydrogen cars use fuel cells and have only a negligible storage capacity for electricity. The introduction of a large number of fuel-cell EVs will go at the expense of battery-powered EVs and thus significantly reduce the storage potential in EVs.

If these options provide insufficient flexibility, there is no alternative than firing up fossil-fuelled power plants, with their inevitable CO_2 emissions. Power from gas has a 50 % lower emission than the power from coal. Yet carbon capture and storage (CCS) could neutralize these emissions from fossil fuels. This is still a challenging technology and its high costs (especially for gas-fired power) will probably require it to be subsidized. Germany, with its high share of VRE, does not see this as viable option and focuses on large-scale power storage instead.

Chapter 3 describes the principles and characteristics of storage. A classification scheme is presented with four main electrical storage technologies: mechanical, electrochemical, electrical and chemical. Systems differ in how they take up surplus power, store it and inject it back into the power grid. They also differ in storage times. There is seasonal storage of months, diurnal storage of 1 or 2 days and also much shorter. This corresponds to different applications for storage, such as load levelling, frequency regulation and voltage support, spinning and non-spinning reserve, and black-start capability.

Batteries are an important storage technology. There are huge R&D efforts in reducing weight and volume, enlarging power, capacity and useful life. Some governments promote batteries for households and EVs, so that these can also serve to provide flexibility to the grid.

Different types of chemical battery technologies are compared, such as NaS, Li-ion and lead-acid. Flow-type batteries such as redox and hybrid flow are also described.

Other technologies, such as power-to-gas, which produce hydrogen or methane, are analysed for their ability to absorb power surpluses. Capacitor and supercapacitor electrical storage (SCES) are attractive for their short ramp-up times, although only a small amount of energy can be stored. Superconducting magnets (SMES) are a means to control power quality for the industrial market.

There are only few very large capacity storage technologies, apart from pumped hydro storage and its underground variant. Storage with compressed air (Compressed Air Energy Storage (CAES) and advanced adiabatic CAES) is one candidate, yet its development is still at an early stage. Large-scale application is not within sight. Even worse, Adele, a promising CAES pilot in Germany, has been discontinued.

Little wonder that 99 % of worldwide storage is realized with pumped hydro storage (PHS). Extension to the underground has been considered earlier. As early as 1910, Reginald Fessenden drew the first design for underground pumped hydro storage, for which he registered a patent in 1917. R.D. Harza proposed to use an abandoned mine in 1960. At the World Power Conference in Moscow in 1968, G. Isaksson, et al. presented a plan for constructing an underground reservoir. In 1969, Sorenson predicted a bright future for this technique with his publication: “Underground reservoirs: pumped storage for the future?”

Chapter 4 analyses the central technology of this thesis: pumped hydro storage (PHS). All European countries, with the exception of the Netherlands and Denmark, rely on large-scale PHS for balancing their nets. They have a total power available of around 50 GW. It is expected that 100 new PHS plants will be commissioned by 2020, adding another 74 GW, with 27 GW in Spain, Switzerland and Austria alone.

Elsewhere, growth of PHS is impressive too. The USA has issued 40 preliminary permits for 35.5 GW in new plants and 6.3 GW through extension of existing plants, to be realized before 2020. An additional 150 GW towards 2050 is being planned. Japan, the current world leader with 27 plants supplying 24 GW in total, is developing an ambitious extension plan. The Chinese government announced an increase of its present 21.5 GW (2015) to 100 GW by 2025. Pumped hydro storage will therefore continue to dominate the storage market.

Pumped hydro storage is based on storing energy as gravitational potential energy. Low-cost (or surplus) power is used to pump water up into a reservoir at elevated heights. During periods of high demand and high prices, water is released, passing through a turbine connected to a power generator. Its round-trip efficiency varies between 70 and 85%. Losses occur mainly in the pumping and turbining stages, each with around 92% efficiency.

Two types of PHS exist. A combined, hybrid pump back system uses a lower lying river in combination with a higher reservoir. Closed-loop or off-stream systems are not connected to a river and have two reservoirs at different heights, circulating water between them in a closed system. One of the determining elements of a PHS system is the difference in height between the water levels of the upper and lower reservoirs. This is its so-called hydraulic head. In a conventional pumped hydro plant, the head is determined by local geography.

A conventional PHS consists of an upper and a lower basin, a machine hall, high- and low-pressure water shafts (called penstock and tailrace), a transformer room and a connection to the grid. The technology for PHS is based on conventional hydroelectric generation, extracting energy from the drop of a river. This explains the design and operating principles of PHS. Most conventional pumped storage hydro plants have their installations largely subsurface, as developments in civil engineering, such as drilling, blasting, spill removal and rock support, made it cost-effective to do so. Therefore, often only their reservoirs are visible.

Originally, the pump and its electric motor was a separate installation, independent from the turbine with its generator. Already in the 1930s, 2-unit systems came in use, in which the turbine-generator can be operated in reverse as a pump and electric motor. As an electric motor is basically an inverse generator, and a turbine an inverse pump, these functions can be combined. The mounting of this 2-unit device depends on the layout of the machine hall. When height is limited, a horizontal rotary axis is used, such as in Vianden (Luxembourg). In the absence of such constraints, the axis is usually vertical.

A further development is the ternary storage unit, with three instead of two units. In this design, there are distinct hydraulic units for the pump and turbine, which allows for a better optimization for both tasks. They share a combined electric motor-generator. Because both hydraulic units (turbine and pump) are mounted on a single axis, it is possible to operate them simultaneously in a so-called 'hydraulic short circuit' mode, in which almost the full power range is available during pumping or generating. Moreover, a ternary unit need not change its rotational direction when switching between pumping and generation, so that it can respond quickly to changing demands. Ternary units are less common. Most PHS plants operate with reversible 2-unit sets, which are 30 % cheaper to build.

Reversible units come in fixed-speed (FS) and adjustable-speed (AS) varieties. FS is dominant and provides an economical way to operate bulk storage. In recent years, as the growth of VRE increased the need for flexibility, AS units have become popular, because their power uptake during pumping can be controlled. The first large-scale European AS was installed in Pumpspeicherwerk Goldisthal in Germany and commissioned in 2004. Its pumping and generating capacity of 1,060 MW is provided by four 265 MW reversible Francis units, of which two with FS synchronous motor-generators and the other two with asynchronous AS units.

AS costs more than FS. In spite of this, its flexibility makes AS the preferred choice for new plants. Globally, more than 20 AS units have come in operation since 1990, with Japan in the lead. A recent study by eStorage showed that upgrading from FS to AS could bring considerable savings in the European power system. It could save €448 to €635 million a year in 2020 and up to €929 to €1,271 million a year in 2050.

The turbine is a vital part of a hydropower plant. It consists of a stator or nozzle, a runner, and shafts. The stator or nozzle creates a high-speed jet through an orifice or creates swirl through a set of vanes. This jet or water flow is directed to the runner. The runner has cups or blades which transform the energy in the water flow into rotation. Thus, hydraulic energy is converted into mechanical energy. The shaft of the turbine transfers this rotation to the generator.

Turbines come in two types: impulse turbines (Pelton) and reaction turbines (Francis and others). The impulse turbine was developed by Lester A. Pelton around 1870, based on the principle of a split bucket with a central edge. Double elliptic buckets are attached to a wheel, together with a notch for the jet and a needle control for the nozzle. The original Pelton turbine was a horizontal construction, but it can also be built vertically. They are used for hydraulic heads between 200 and 1,800 m and rotate with a specific speed of 10 to 70 rpm.

The reaction turbine developed by James B. Francis in 1848, is based on an inward-flow turbine combined with radial and axial flows. Until today, they are widely used. They are adequate for hydraulic heads between 30 and 600 m. Its lower head, compared to the Pelton turbine, corresponds with a higher rotation rate, ranging from 70 to 350 rpm. A Francis turbine consists of a spiral casing (volute casing) around the runner of the turbine, guide vanes that convert the pressure of water into a mechanical momentum, runner blades, where the water hits the blades, and the draft tube, which connects the runner output to the tail.

Until recently, PHS plants pumped at night and generated power in peak hours during the day. This diurnal arbitrage provides most of their revenue. However, PHS is increasingly used to balance fast changes in power production. It contributes to grid stability by helping frequency regulation and providing inertial services. PHS can also re-dispatch energy and provide transmission congestion relief to help resolve bottlenecks and congestion in the grid. In the case of a blackout of the grid, PHS is usually the only power supply that can ramp-up without the aid of an external power supply, and thus provide grid managers with a black-start capability. All these ancillary services demand flexibility, which PHS can offer.

In order to provide these ancillary services, operation of PHS needs to change. Pumps and turbines need to be switched on and off several times (up to ten times) a day. Rapid changes in water flow may cause oscillating pressure changes on the turbine blades. As these resonances may cause damage, this is an active field of research. The last developments in PHS technology include the variable-speed pump-turbines with the ability to generate synchronously with the grid frequency and pumping asynchronously. This allows faster power adjustment. In the Francis-99 project, specialists from industries teamed up with universities in Norway and Sweden to redesign a Francis turbine for highly variable use and make the design available in the public domain. The project was initiated by Statkraft in 2014 and extended in 2018 with a new 4-year research programme under the direction of the Norwegian Hydropower Center (NVKS).

As suitable locations for PHS are scarce, different studies assessed alternative ways to build water reservoirs. Abandoned mines (subsurface and open pit) are being considered as reservoirs. Pumped hydro storage with the sea as a lower reservoir is now a proven technology. The Yanbaru pilot plant in Okinawa, completed in 1999, pioneered the first sea-water pumped storage power plant, with corrosion-proof machinery and plastic tubes instead of steel tubes.

The Netherlands is almost flat and lacks locations with a natural hydraulic head. The only way to use PHS, is to create an artificial head. This was the subject of several studies. A 1981 study, known as 'plan Lievense', proposed to use part of the IJsselmeer, a closed-off inland sea, to create a low hydraulic head. Combined with a large surface, this would provide adequate capacity. Neighbouring countries considered similar projects, such as the German design of an circular wall storage project. This integrates PHS storage, PV panels and leisure and housing facilities. Belgium considered an oval dam in the North Sea to provide a reservoir. None of these projects were carried out, presumably due to the relative high investment and maintenance costs because of the corrosive and otherwise harsh maritime environments.

Another approach has been studied by the OPAC group since the early 1980s, with representatives from the TH Delft (now Delft University of Technology), Haskoning, and Koninklijke Volker Stevin. This group explored the construction of an underground water reservoir. A recently formed O-PAC development group (note the hyphen in its name, which distinguishes it from its forerunner), came to the conclusion that investments in U-PHS are quite similar to those in conventional PHS plants, taking into account the environmental measures required to integrate a reservoir into the landscape. The O-PAC project is analysed in more detail in **PART TWO**.

PART TWO gives an in-depth analysis of the O-PAC project. It starts with a geological survey in **Chapter 5**. In the early 1980s, Dutch Parliament solicited a study to assess whether the South Limburg mines, abandoned in 1974, could serve as pumped hydro storage. The outcome of this study by the mining department of the TH Delft (now Delft University of Technology) was negative. The former mines were judged to be unsuitable as water reservoirs.

Nevertheless, test drilling at the time revealed a homogeneous rock layer at 1,000 m depth. This rock layer turned out to be suitable for an underground construction. Especially the Dinantian rock layers between 1,000 and 1,700 m depth are promising. Further geological studies, using seismic profiles to locate faults and other geostructural defects in this rock layer, showed that only a relative small area around the initial drilling location could be used. This demonstrated that the selection of a location requires extensive research. Appropriate locations are preferably searched for in the direct neighbourhood of the river Meuse and its canalizations, as this allows for an upper basin with limited environmental impact.

Chapter 6 describes the design of U-PHS. A specialized team of engineers from Germany and the Netherlands, experienced in underground construction works, was involved in drawing up a functional design, optimized for:

- power and storage capacity
- depth, given the geological conditions
- geostructural layout of the underground reservoir
- most effective pump-turbine techniques

Different options were considered, with system powers ranging from 400 MW to 2,000 MW and capacities from 5 GWh to 20 GWh. The optimal configuration, based on TSO input, turned out to be:

·	storage capacity	8.4	GWh
·	pump/generator power	1,400	MW
·	depth (head)	1,400	m

Due to the high head, the turbines need to be of the Pelton type and the reversible pump-turbines need to be multistage. The original functional design foresees a pool of seven units. Five multistage reversible pump-turbines (FS) provide the backbone of power generation, delivering a maximum of 1,000 MW. Two Pelton turbines (AS) add versatility, with a power ranging from 10 MW to their full 2 x 200 MW.

The NATM (New Austrian Tunnelling Method) is identified as the preferred construction technology for the underground caverns. This technique integrates the surrounding rock formations into an overall ring-like support structure. A self-supporting rock mass around the caverns is created as careful excavation proceeds. This method can be carried out with relative minor building efforts.

The design consists of two groups of eight caverns with a distribution cavern in its centre. Each of the caverns is 750 m long, thus providing a total length of 12 km. With 200 m^2 cross-section of caverns, a total of 2.4 million m^3 needs to be excavated. Three different profiles of cavern reservoir cross-sections are presented, each for a different geological structure.

The largest cavern is the machine hall. It houses the pump-turbines and the electromechanical equipment. It is also the connecting hub for the valves and water ducts. The homogeneous rock formation at the designated location allows for the construction of an underground vault of 71.5 m high, 20 m wide and 128 m long. This is enough to house seven pump-turbines and auxiliary installations. A separate transformer hall is situated adjacent to the machine hall. For proper water handling a collector and a distribution cavern will be connected to the cavern storage system. The total volume of the excavations for the lower reservoir is 2.4 million m^3, with an additional approximately 250 thousand m^3 for machine halls. This is of the same order of magnitude as the excavations for the A2 motorway tunnel in Maastricht.

A wet shaft connects the underground and surface reservoirs with a high-pressure duct. This is constructed by stacking prefabricated concrete rings until the desired depth is reached. The duct contains a rock trap, blocking all stone particles larger than 0.25 mm.

A major challenge for the construction work is evidently the transport of rocks excavated from the 1,400 m deep level to the surface. The design foresees two dry shafts of 7 or 8 m diameter to serve for the transport of excavated rock and materials. Vertical transport is the determining factor for the construction time. Therefore, high-speed (65 km/h) elevators with double-skip Koepe installations are projected, with a capacity of 20 tonnes each. This would enable an excavation time of approximately 2.5-3 years, within a framework of 5-6 years for the entire construction.

Horizontal transport between the underground locations is facilitated by electrically driven front-loaders on rubber wheels because of the relative short distances (up to around 750 m). These electric vehicles require less air ventilation than equipment with combustion engines.

All measures relating to the construction must be carefully planned for optimal efficiency: (1) drilling and blasting, (2) excavators loading into (3) dump trucks, (4) discharging into (5) a vertical lift, (6) discharging/unloading, (7) transport by conveyor belts or trucks, (8) dumping to depot, and (9) transport by boat.

Safety during construction and operation is essential. Therefore, all rock walls will be reinforced, even if there is no geotechnical need to do so. A separate ventilation tunnel will air the caverns and allows for surveillance and emergency escapes, both during construction and operation.

To determine the exact locations and shapes of the caverns, exploratory drilling with a diameter of 0.96 m is required. It is essential to identify the different rock mass classes, in order to determine the lining techniques. This in turn determines investment costs.

The upper reservoir should be located more or less above the lower reservoir. It will have a gross surface of approximately 50 ha, including the surrounding dikes. It needs to contain 2.4 million m^3 of process water and must be sealed off with on top a layer of excavated rocks to prevent ground water pressure from raising the reservoir. Excavated rocks will also be used in the dikes, so that a total of approximately 2.92 million m^3 of excavated rocks will be reused.

From a point of view of grid connectivity, the Maasbracht area is an excellent location for this project. It is the only high-voltage node in the Dutch national grid with a connection to two neighbouring countries. This node served among others the Claus gas-fired power plant, which is now decommissioned. It provides a unique position to connect O-PAC to the grid.

The O-PAC project, once realized, will be the world's first underground PHS plant. To assess the potential of the technique for other regions, a number of market considerations have been elaborated in **Appendix I** as well as a potential location: Denmark.

Chapter 7 deals with the cost-benefit analysis (CBA) of the O-PAC project. This is the pivotal part of this monograph, as this is where the project's feasibility becomes clear.

In the Netherlands, power is traded through an auction mechanism with bidding procedures to match supply and demand. The average price of electricity is expected to rise substantially in this market, because of increasing fossil-fuel and CO_2 permit prices. The volatility of this market is also expected to increase, as the increased share of VRE decreases predictability of supply. Especially after 2025, it will at times be difficult to balance the net, which will lead to large price jumps. These price differences offer ample opportunities for arbitrage, which is the main source of revenue for O-PAC.

The analyses show that the first 5 years (2025-2030) of O-PAC will be challenging, as revenues initially only cover capital costs, operations, and maintenance. After this start-up phase, price movements in the electricity market will provide more and better opportunities for arbitrage, leading to a sharp increase in revenues. This enables depreciation write-offs and shareholder dividend payout.

The total possible annual revenues are calculated to increase as follows:

2025	€83 million
2030	€186 million
2035	€226 million

In 2025, the opportunities for arbitrage are still limited and therefore the capacity is partially used for arbitrage and partially for the provision of control reserves. Other revenues may come from the remuneration for additional ancillary services to the grid. Additional ancillary services are contracted between TSO and service providers and are therefore not published. So, they cannot be estimated here.

The budget for construction was already drawn up by a specialized German engineering groups in the 1980s. Their figures were recently updated. Construction will cost €1,800 million, including all excavation costs, electromechanical equipment, pumps, turbines, ground-level installations, etc. These numbers have been reviewed by engineering companies that recently participated in the construction of the Gotthard Base Tunnel.

Annual costs for operations and maintenance are low, only 1.1% of investment costs, because the project involves technology that has been proven over many years.

Investments can best be structured as a public-private partnership (PPP), with a sound one third (€600 million) of private equity. It is proposed that the remaining €1,200 million is placed in the market through a bond participation issued by a bank consortium. It would be helpful if O-PAC were supported by EU investment facilities, i.e. the European Fund for Strategic Investments (EFSI), which is explicitly meant for large-scale long-term infrastructural projects.

Chapter 8 analyses the macroeconomic effects and societal benefits of a U-PHS system in the Netherlands.

Investments and employment are assessed in a multicriteria analysis. It turns out that the direct and indirect effects on employment are considerable. The six-year construction phase provides work for 900 to 1,000 employees, amounting to a total of 5,400 to 6,000 man-years. These figures were derived from a study by Maastricht University. The effects on the local and regional economy were prognosticated with an input-output model. During the operational period of 50 years, the project will provide a total of 66,100 man-years, assuming an annual average investment of around €300 million during 6 years. More than half (58 %) of this employment is in the Euregion Meuse-Rhine, 12 % in the rest of the Netherlands, and 30 % in the EU.

The societal benefits from O-PAC are discussed in the light of EU targets for energy transition. With its ability to store electricity, the security of supply can be better ensured in a grid where volatility will be considerable. Additionally, support for the integration of VRE is facilitated by the flexible operation that is possible with O-PAC. This also provides the opportunity for reducing emissions, by storing surplus VRE production and redelivering it to the grid when there is a lack of supply. The final EU target is achieved by the levelling of electricity market prices, which provides affordability and predictability for electricity costs. Overall, this supports a secure, sustainable and affordable electricity supply for all Europeans.

A number of potential spin-offs are identified by Royal Haskoning, based on their experience in civil engineering, such as the further development of spraying composites (based on the local resin industry), which can be implemented in new firms.

Chapter 9 assesses the significance of U-PHS in the more distant future. The Netherlands currently has one of the best electricity grids and gas distribution systems in the world. The significant international connections of these infrastructures contribute considerably to a reliable and stable energy supply.

The Netherlands has identified chemical technology as the principal solution for large-scale storage. The idea is to use surplus energy to produce hydrogen or ammonia. Yet these techniques are in an early stage of research. In particular the current low efficiency of these techniques (30-40 %) will make it difficult to become cost-effective.

Power supply will become more variable as more VRE enters the grid. The share of VRE in the total installed power is predicted (in NEV 2017) to increase from 57 % (2025), to 68 % (2030) and 73 % (2035). The share of fossil-fuelled power will decline from 40 % (2025), to 30 % (2030) and 26 % (2035). These figures do not reflect their share in the power supply, as variability of wind and sun reduces the contribution of these renewables (the ratio of average power supplied and installed power is called the capacity factor). Fossil-fuelled power will thus have a substantially higher share in the power supply than its share in installed power suggests.

The German author H.W. Sinn points out that the German VRE had a capacity factor of 9.9 % for solar and 16.3 % for wind energy in 2014. In that year, German VRE had a share of 40 % in installed power, but an additional ca. 15 % fossil-fuelled power was needed as backup.

Dutch policies intend to reduce imbalances caused by VRE through decentralized storage in household batteries and EV batteries. A condition for this to work is the extension of the low-voltage grid, which also needs to be made smart enough to provide for this balance. This will be a major challenge for the coming decade, since seven different DSOs are involved and the necessary ICT technology still needs to be installed. Simultaneously, solar and wind power will increase considerably, which puts even higher requirements on balancing. It is therefore questionable whether decentralized storage will provide enough balancing.

Chapter 10 summarizes the circumstances, characteristics and conditions under which O-PAC is a viable large-scale underground storage system within the total mix of flexibility measures for the Dutch grid, from a point of view of technology, economy and sustainability.

It is questionable whether the measures proposed by the Dutch government can provide the necessary flexibility to integrate the increasing share of VRE in the grid and simultaneously reach its CO_2 reduction targets, which confirms the central hypothesis in Chapter 1.

This conclusion is also shared by the Netherlands Environmental Assessment Agency (PBL) and the then Energy Research Centre of the Netherlands (ECN) in a report with the recommendation to close all coal-fired power plants, enforcing a minimum CO_2 price and enlarging the scope of Dutch energy subsidies in the SDE+ programme.

Samenvatting

Samenvatting

Deel 1 behandelt de variabiliteit van wind- en zonne-energie, een belangrijke uitdaging in de transitie naar een duurzamere en CO_2-arme energievoorziening. Dit deel opent met **hoofdstuk 2**, dat zowel het huidige als toekomstige Nederlandse energiesysteem en energiebeleid behandelt. Nederland is sterk afhankelijk geworden van aardgas na de ontdekking van grote aardgasvelden in Groningen en onder de Noordzee. In 2015 had gas een aandeel van 41,7 % in de elektriciteitsopwekking. Met strategische steenkooldepots in de havens van Rotterdam, Amsterdam en Antwerpen is goedkope steenkool een tweede pijler van elektriciteitsopwekking, met een aandeel van 35,9 %. Dit betekent dat fossiele brandstoffen ongeveer 80 % van de Nederlandse elektriciteit leveren, aangevuld met 4 % kernenergie (met één centrale in Borssele) en 7,9 % variabele hernieuwbare energie (VRE), hoofdzakelijk van zon en wind.

In het *"Energierapport, transitie naar duurzaam"* (2016) stelt de Nederlandse overheid drie doelen voor de transitie naar hernieuwbare energie:

1. reductie van CO_2-emissies
2. gebruik van kansen die voortkomen uit de energietransitie
3. faciliteren van variabele hernieuwbare energie in planningsprocedures en bouwvoorschriften

Volgens het huidige Energieakkoord uit 2013 zal in de periode tot 2023 in totaal 3.500 MW windenergie worden toegevoegd aan de huidige 1.000 MW. Het Gemini Offshore Windpark is het eerste van een nieuwe serie offshore windparken die daaraan gaat bijdragen. Het is sinds 8 mei 2017 volledig operationeel met een vermogen van 600 MW en een geschatte jaarlijkse productie van 2.600 GWh. Dit wordt gevolgd door de windparken Borssele I en II (samen 752 MW) die worden gebouwd door het Deense energiebedrijf Ørsted en Borssele III en IV (eveneens 731,5 MW), die worden gerealiseerd door een consortium onder leiding van Shell. Een windpark van 740 MW op de locaties I en II van het perceel Nederlandse Kust (Zuid) werd onlangs aanbesteed aan Chinook, een dochteronderneming van Nuon. Naar verwachting worden de locaties III en IV aanbesteed in het vierde kwartaal van 2018. Windenergie groeit dus snel in Nederland. Voor de volgende periode (2024-2030) is het doel om 7.000 MW extra te realiseren, wat het totaal brengt op 11.500 MW in 2030 (RVO, 2018d).

Ook onshore wind heeft indrukwekkende groeidoelstellingen. Het totaal aan geïnstalleerde windenergie (zowel onshore als offshore) moet in 2023 op 10.450 MW uitkomen. Daarnaast moet fotovoltaïsche (PV) elektriciteit groeien tot een geïnstalleerde vermogen van 5.000 tot 7.000 MW. Het totaal geïnstalleerd VRE-vermogen zal naar verwachting meer dan 17.000 MW bedragen in 2023. Dit is iets meer dan de huidige dagelijkse gemiddelde vraag tijdens de piekuren in Nederland. Omdat sommige andere elektriciteitsbronnen zoals warmtekrachtkoppeling (CHP) niet kunnen worden uitgeschakeld, is een overschot onvermijdelijk. Vooral 's nachts, met een gemiddeld verbruik van slechts 7.000 MW, zullen overaanbod en afschakelen van VRE vaak voorkomen.

Met een elektriciteitssysteem dat gebaseerd is op voorspelbare en regelbare centrales, die kunnen worden afgestemd op de vraag, is het in balans houden van het elektriciteitsnet nu nog een kwestie van routine. Maar dat zal aanzienlijk veranderen, zeker wanneer het doel van 63 % VRE (vastgelegd in de *Nationale Energieverkenning 2017*) bereikt moet worden.

De Nederlandse regering verwacht de benodigde flexibiliteit te verkrijgen uit:

- grensoverschrijdende verbindingen met buurlanden
- vraagbeheersing (demand-side management, DSM), met name vraagrespons (demand response, DR)
- opslag in accu's in huishoudens
- opslag in accu's van elektrische voertuigen (EV's)
- back-up door elektriciteitscentrales gestookt met fossiele brandstoffen (kolen/gas), biomassa en afval

Het grootste effect verwacht de regering van de uitbreiding van hoogspanningsverbindingen met buurlanden. In 2016 bedroeg deze interconnectie 5,9 GW, wat moet toenemen tot 9,1 GW in 2020. De veronderstelling daarbij is dat grensoverschrijdende elektriciteitshandel flexibiliteit biedt, omdat de elektriciteitsmix aan weerszijden van de grens verschilt. Problemen ontstaan wanneer elektriciteitssystemen meer op elkaar gaan lijken door de introductie van variabele hernieuwbare energie. Na 2020 zal de energiemix in de buurlanden nagenoeg gelijk zijn aan de Nederlandse. Omdat de weersomstandigheden in West-Europa gecorreleerd zijn, zal ongeveer op hetzelfde moment elektriciteit uit zon en wind worden geproduceerd. Daarom zullen vaak bijna gelijktijdig overschotten en tekorten optreden, die dus niet steeds gebalanceerd kunnen worden met import of export.

Nederland krijgt in deze periode na 2020 een overcapaciteit, waardoor het netto-exporteur in plaats van netto-importeur wordt. De vraag is of buurlanden onze overschotten zullen kopen als ze zelf om dezelfde reden overschotten hebben. Het is daarom onzeker of de investeringen in grensoverschrijdende netwerken een rendement opleveren.

Vraagbeheersing (DSM) is een andere Nederlands strategie om het elektriciteitsnet in balans te houden. Consumenten en industrieën moeten verleid worden om hun energieverbruik te verschuiven naar de daluren. Financiële prikkels kunnen zo'n gedragsverandering teweegbrengen. Daarvoor zijn slimme meters en – meer in het algemeen – ICT-technologie nodig. ENTSO-E schat dat deze verschuiving, de zogenaamde vraagrespons (DR), wel 1.000 MW kan zijn. Met een gericht programma zou daarbovenop een extra respons van 700 MW op korte termijn en nog eens 200 MW op langere termijn haalbaar zijn.

Deze cijfers zijn gebaseerd op verregaande aannames over het gedrag van consumenten en het aanpassingsvermogen van de industrie. Een grote meerderheid van de Nederlandse consumenten (86 %) wil dat elektriciteit continu beschikbaar is. Bovendien vormt de afwezigheid van een homogeen distributiesysteem (met zeven DSO's) een serieuze uitdaging voor het beïnvloeden van de markt. Het is daarom onwaarschijnlijk dat DSM een aanzienlijke bijdrage zal leveren aan flexibiliteit.

Soortgelijke bezwaren gelden voor de opslag in accu's in huishoudens. In Duitsland hebben nationale subsidieprogramma's meer dan 19.000 residentiële opslagsystemen opgeleverd (2016). Door de onoverkomelijk hoge kosten kunnen consumenten alleen met subsidieprogramma's gemotiveerd worden om thuis accu's te installeren.

Op dit moment zijn er geen tekenen dat de Nederlandse overheid bereid is om dit te doen.

Een andere optie is opslag in accu's van elektrische auto´s (EV's). In een vehicle-to-grid-systeem slaan EV's overtollige energie op en retourneren deze tijdens piekuren. Nederland gaat uit van een wagenpark van 1 miljoen EV's in 2025. Dit zal een opslagcapaciteit van 1,5 GWh bieden. In 2017 was nog maar 1,5 % van de Nederlandse motorvoertuigen elektrisch. De toekomstige groei van EV's is afhankelijk van de voortgang in accutechnologie zodat opslagdichtheid, duurzaamheid en kosten verbeterd worden. Daarnaast moet er ook een match zijn tussen het aantal EV's en het aantal oplaadpunten om autoaccu's te kunnen gebruiken om het net in balans te houden.

De vraag is ook of de huidige accugebaseerde EV's, met hun inherente beperkingen, zullen overleven in de felle concurrentiestrijd met andere schone autotechnologieën. Een andere optie is de waterstofauto. In Duitsland, Californië en Japan zijn er al veel waterstoftankstations gepland voor de komende jaren, ondanks de pessimistische prognoses van het IEA. De Duitse federale overheid heeft een contract getekend met H_2 Mobility Germany om voor 2023 in totaal 400 stations in heel Duitsland te installeren. Californië heeft een contract met Shell en Toyota afgesloten om 100 stations te realiseren voor 2024. Waterstofauto's gebruiken brandstofcellen en hebben geen grote accu's nodig. Als brandstofcel-EV's een succes worden, gaat dit ten koste van accugebaseerde EV's, waardoor het opslagpotentieel in EV's aanzienlijk vermindert.

Als deze opties onvoldoende flexibiliteit bieden, is er geen ander alternatief dan het gebruik van elektriciteitscentrales die op fossiele brandstoffen werken, met hun onvermijdelijke CO_2-uitstoot. Gas heeft een 50 % lagere emissie dan steenkool. Maar CO_2-afvang en -opslag (CCS) zou emissies van zowel kolen als gas kunnen neutraliseren. Dit is echter nog steeds een lastige technologie en de hoge kosten (met name bij gasgestookte centrales) zullen waarschijnlijk moeten worden gesubsidieerd. Duitsland, met zijn grote aandeel aan VRE, ziet dit niet als een haalbare optie en richt zich in plaats daarvan op grootschalige energieopslag.

Hoofdstuk 3 beschrijft de principes en de kenmerken van verschillende technieken om elektriciteit op te slaan. Er wordt een classificatieschema gepresenteerd met vier belangrijke technologieën: mechanisch, elektrochemisch, elektrisch en chemisch. Systemen verschillen in hoe ze een elektriciteitsoverschot opnemen, opslaan en retourneren aan het elektriciteitsnet. Ze verschillen ook in de duur van de opslag. Er zijn technieken voor seizoensopslag van maanden, dagelijkse opslag van een of twee dagen en systemen voor kortere opslag. Deze karakteristieken maken ze geschikt voor verschillende toepassingen, zoals load-leveling, frequentieregeling en spanningsondersteuning, spinning en non-spinning reserve en black-start-capaciteit.

Accu's zijn een belangrijke vorm van opslag. Er wordt veel onderzoek en ontwikkelingswerk gedaan om het gewicht en het volume van accu's te verminderen, en het vermogen, de capaciteit en de gebruiksduur te vergroten. Sommige overheden promoten accu's in huishoudens en EV's, zodat ze ook ingezet kunnen worden voor flexibiliteit van het net. Verschillende soorten chemische accutechnologieën worden vergeleken, zoals NaS, Li-ion en loodzuur. Ook worden er flow-type accu's zoals redox en hybride flow beschreven.

Andere technologieën zoals power-to-gas, waarmee waterstof of methaan wordt geproduceerd, worden geanalyseerd op hun vermogen om een energieoverschot op te nemen. Condensator en supercondensator elektrische opslag (SCES) zijn aantrekkelijk vanwege hun korte opstarttijden, maar ze kunnen maar weinig energie opslaan. Supergeleidende magneten (SMES) zijn een middel om de energiekwaliteit voor de industriële markt te reguleren.

Behalve pompaccumulatiecentrales en de ondergrondse variant daarvan zijn er maar weinig opslagtechnieken met zeer grote capaciteit. Opslag door lucht samen te persen (Compressed Air Energy Storage, CAES, en geavanceerde adiabatische CAES) is een kandidaat, maar de ontwikkeling ervan bevindt zich nog in een vroeg stadium. Grootschalige toepassing is niet op korte termijn mogelijk. Sterker nog, Adele, een veelbelovende CAES-pilot in Duitsland, is stopgezet.

Het is daarom geen wonder dat 99% van de wereldwijde opslag wordt gerealiseerd met pompaccumulatiecentrales (PHS). Een ondergrondse variant daarvan werd al eerder overwogen. Al in 1910 tekende Reginald Fessenden een eerste ontwerp voor een ondergrondse PHS, waarvoor hij in 1917 een octrooi heeft aangevraagd. R.D. Harza stelde in 1960 voor om een verlaten mijn te gebruiken. Op de World Power Conference in Moskou in 1968 presenteerden G. Isaksson, et al. een plan voor de aanleg van een ondergronds reservoir. In 1969 voorspelde K. Sorenson een mooie toekomst voor deze techniek met zijn publicatie: "Underground reservoirs: pumped storage for the future?"

Hoofdstuk 4 analyseert de centrale techniek van dit proefschrift: pompaccumulatiecentrales (PHS). Alle Europese landen, met uitzondering van Nederland en Denemarken, zetten grootschalige PHS in voor het balanceren van hun netwerken. Ze hebben een totaal vermogen van ongeveer 50 GW beschikbaar. Naar verwachting zullen in 2020 totaal 100 nieuwe PHS-centrales in gebruik zijn genomen, waardoor nog eens 74 GW aan het vermogen wordt toegevoegd, met alleen al 27 GW in Spanje, Zwitserland en Oostenrijk.

Ook elders is de groei van PHS indrukwekkend. De VS heeft 40 voorlopige vergunningen afgegeven voor projecten die voor 2020 moeten worden gerealiseerd, met 35,5 GW in nieuwe centrales en 6,3 GW door uitbreiding van bestaande centrales. Er zijn plannen voor nog eens 150 GW in de periode tot 2050. Japan, de huidige wereldleider met 27 centrales die in totaal 24 GW leveren, ontwikkelt een ambitieus uitbreidingsplan. De Chinese overheid heeft aangekondigd de huidige 21,5 GW (2015) te vergroten tot 100 GW in 2025. Pompaccumulatiecentrales zullen daarom de markt voor energieopslag blijven domineren.

PHS is gebaseerd op het opslaan van energie als gravitationele potentiële energie. Goedkope of overtollige stroom wordt gebruikt om water op te pompen naar een hooggelegen reservoir. Als er een grote vraag is en de prijs hoog, wordt het water geretourneerd via een turbine die verbonden is met een generator. De efficiëntie van een complete cyclus varieert tussen 70 en 85 %. Verliezen komen vooral voor in de pomp- en turbinefases, elk met een efficiëntie van ongeveer 92 %.

Er zijn twee soorten PHS. Een gecombineerd, hybride pompsysteem dat een lager gelegen rivier gebruikt in combinatie met een hoger reservoir. Closed loop- of off-stream-systemen zijn niet aangesloten op een rivier en hebben twee reservoirs op verschillende hoogtes, waardoor het water in een gesloten systeem circuleert. Een belangrijke karakteristiek van een PHS-systeem is het hoogteverschil tussen de waterniveaus van de bovenste en onderste reservoirs. Dit is de valhoogte. In een conventionele waterkrachtcentrale is de lokale geografie bepalend voor de valhoogte.

Een conventionele PHS bestaat uit een hoog en een laag bassin, een machinekamer, hoge- en lagedrukleidingen (ook wel penstock en tailrace genoemd), een transformatorruimte en een aansluiting op het elektriciteitsnet. De techniek van PHS-systemen is gebaseerd op die van conventionele waterkrachtcentrales en halen energie uit het verval van een rivier. Dit verklaart het ontwerp en de beheersprincipes van PHS. De meeste conventionele centrales hebben hun installaties grotendeels onder het oppervlak, omdat ontwikkelingen in de civiele techniek zoals boren, springen, gesteentetransport en rotsversterking het kosteneffectief maakten om dit te doen. Daarom zijn vaak alleen hun reservoirs zichtbaar.

Oorspronkelijk waren er voor pompen en elektriciteit opwekken aparte installaties. Al in de jaren dertig van de vorige eeuw werden twee-unit-systemen in gebruik genomen, waarbij de turbinegenerator in omgekeerde richting gebruikt kan worden als een elektrische pomp. Deze functies kunnen worden gecombineerd omdat een elektromotor in feite een omgekeerde generator is en een turbine een omgekeerde pomp. De wijze van monteren van deze gecombineerde installatie hangt af van de indeling van de machinekamer. Wanneer de hoogte beperkt is, wordt een horizontale rotatieas gebruikt, zoals in Vianden (Luxemburg). Zonder deze beperkingen is de as meestal verticaal.

Een verdere ontwikkeling is de ternaire opslagunit, met drie in plaats van twee units. In dit ontwerp zijn er verschillende hydraulische units voor de pomp en de turbine, waardoor een betere optimalisatie voor beide taken mogelijk is. Ze delen een gecombineerde elektromotor-generator. Omdat beide hydraulische eenheden (turbine en pomp) op een enkele as zijn gemonteerd, is het mogelijk om ze tegelijkertijd in een zogenaamde 'hydraulische kortsluiting'-modus te bedienen, waardoor de installatie geregeld kan worden over bijna het volledige vermogensbereik. Een ander voordeel is dat een ternaire unit zijn draairichting niet hoeft te veranderen bij het schakelen tussen pompen en genereren, zodat de installatie snel kan reageren op veranderende eisen. Ternaire units worden minder vaak gebruikt. De meeste PHS-centrales werken met omkeerbare installaties van twee units, die 30 % goedkoper kunnen worden gebouwd.

Er zijn omkeerbare units met vaste snelheden (FS) en aanpasbare snelheden (AS). FS wordt het meest gebruikt en maakt het economisch bedrijven van grootschalige opslag mogelijk. Omdat de afgelopen jaren de behoefte aan flexibiliteit toenam door de groei van VRE, zijn AS-units populairder geworden omdat hun pompvermogen kan worden geregeld. De eerste grootschalige Europese AS is vanaf 2004 in gebruik in Pumpspeicherwerk Goldisthal in Duitsland. De pomp- en opwekkingscapaciteit van 1.060 MW wordt daar geleverd door vier 265 MW omkeerbare Francis-units, waarvan twee met FS-synchrone motorgeneratoren en twee met asynchrone AS units.

AS kost meer dan FS. Desondanks wordt in nieuwe installaties vaak voor AS gekozen vanwege de flexibiliteit. Wereldwijd zijn meer dan 20 AS-units operationeel sinds 1990, met Japan als koploper. Een recent onderzoek door eStorage heeft aangetoond dat een upgrade van FS naar AS aanzienlijke besparingen in het Europese elektriciteitssysteem kan opleveren. Het kan in 2020 € 448 tot 635 miljoen per jaar besparen en in 2050 € 929 tot 1.271 miljoen per jaar.

De turbine is een vitaal onderdeel van een waterkrachtcentrale. Deze bestaat uit een stator of een mondstuk, een runner en assen. Een mondstuk creëert een hogesnelheidstraal door een opening. De andere optie, een stator, maakt een werveling met een reeks schoepen. Deze straal of waterstroom wordt naar de runner geleid. De runner heeft bekers of bladen die de energie van de waterstroom omzetten in rotatie. Zo wordt hydraulische energie omgezet in mechanische energie. De as van de turbine draagt die rotatie over aan de generator.

Turbines zijn er in twee soorten, impulsturbines (Pelton) en reactieturbines (Francis en anderen). De impulsturbine is rond 1870 ontwikkeld door Lester A. Pelton en is gebaseerd op het principe van een gespleten emmer met een centrale rand. Dubbele elliptische emmers zijn aan een wiel bevestigd, samen met een inkeping voor de jet en een naald om het mondstuk te regelen. De oorspronkelijke Pelton-turbine was een horizontale constructie, maar de turbine kan ook verticaal worden gebouwd. Ze worden gebruikt voor valhoogtes tussen 200 en 1.800 m en roteren met 10 tot 70 omwentelingen per minuut (specifieke toerental).

De reactieturbine, die in 1884 is ontwikkeld door James B. Francis, is gebaseerd op een waterstroom door de turbine, waarbij de combinatie van radiale en axiale stromingen de turbine in beweging zet. Deze turbines worden nog steeds wereldwijd gebruikt. Ze zijn geschikt voor valhoogtes tussen 30 en 600 m. De lagere valhoogte, in vergelijking met de Pelton-turbine, correspondeert met een hoger toerental (rpm) van 70 tot 350. Een Francis-turbine bestaat uit een spiraalvormig omhulsel (volute casing) rond de runner van de turbine, leischoepen die de druk van het water omzetten in een mechanisch moment, de runner-bladen, waar het water de bladen raakt en een uitlaatbuis, die de runner met de uitstroomopening verbindt.

Tot voor kort pompten PHS-centrales ’s nachts water omhoog en produceerden ze overdag tijdens piekuren elektriciteit. Deze dagelijkse arbitrage levert het merendeel van hun inkomsten op. PHS wordt echter in toenemende mate gebruikt om snellere veranderingen in energieproductie te balanceren. PHS draagt bij aan de stabiliteit van het netwerk door frequentieregulering en inertie. PHS kan ook energie herverdelen en transmissie-problemen oplossen door knelpunten en congestie in het elektriciteitsnetwerk te ontlasten. In het geval van een black-out van het netwerk, is PHS vaak goed geschikt om het net opnieuw te helpen opstarten zonder de hulp van externe stroomvoorziening. Dit biedt netwerkbeheerders een black-start-capaciteit.

De toename van VRE in het net vereist een flexibiliteit aan de leveringskant die PHS kan bieden. Daarvoor is wel een andere regeling van PHS nodig. Pompen en turbines moeten verschillende keren (tot tien keer) per dag worden in- en uitgeschakeld. Snelle veranderingen in de waterstroom kunnen oscillerende drukveranderingen op de turbinebladen veroorzaken. Omdat deze resonanties schade kunnen veroorzaken is dit een actief onderzoeksgebied. Een van de laatste ontwikkelingen in PHS-technologie is een variabele-snelheid-pompturbine en de mogelijkheid om synchroon met de netwerkfrequentie te genereren en asynchroon te pompen. Dit zorgt voor een snellere aanpassing van het vermogen. In het project Francis-99 werkten specialisten uit de industrie samen met universiteiten in Noorwegen en Zweden om een Francis-turbine te herontwerpen voor zeer variabel gebruik en het ontwerp vrij beschikbaar te maken. Het project is in 2014 gestart door Statkraft en in 2018 verlengd met een nieuw vierjarig onderzoeksprogramma onder leiding van het Norwegian Hydropower Center (NVKS).

Omdat geschikte locaties voor PHS schaars zijn, zijn er verschillende studies naar alternatieve manieren om waterreservoirs te bouwen. Zo wordt overwogen om verlaten mijnen (ondergronds en dagbouw) als benedenreservoir te gebruiken. Het gebruik van de zee als lager reservoir is inmiddels een bewezen techniek. De Yanbaru pilot-centrale in Okinawa, voltooid in 1999, was pionier in gebruik van zeewater met corrosie-bestendige machines en plastic buizen in plaats van stalen buizen.

Nederland is bijna helemaal vlak en mist locaties met een natuurlijke valhoogte. De enige manier om PHS te gebruiken is het maken van een kunstmatig hoogteverschil. Dit was het onderwerp van verschillende studies. Een plan uit 1981, bekend als ‘Plan Lievense’, stelde voor een deel van het IJsselmeer te gebruiken om een gering hoogteverschil te creëren. Gecombineerd met een groot oppervlak zou dit voldoende capaciteit kunnen geven. Buurlanden overwogen soortgelijke projecten zoals het Duitse ontwerp van een eiland met cirkelvormig meer, die PHS-opslag, PV-panelen en vrijetijds- en woonfaciliteiten integreert. België onderzocht een ovalen dam in de Noordzee als een reservoir. Al deze projecten werden niet uitgevoerd, vermoedelijk vanwege de relatief hoge investerings- en onderhoudskosten door de corrosieve en anderszins barre maritieme omgeving.

Een andere aanpak wordt sinds het begin van de jaren tachtig bestudeerd door de OPAC-groep, waarin de toenmalige TH Delft, Haskoning en Koninklijke Volker Stevin samenwerkten. Deze groep onderzocht de constructie van een ondergronds waterreservoir. Een recent gevormde O-PAC ontwikkelingsgroep (let op het koppelteken in de naam, dat het onderscheidt van zijn voorganger) kwam tot de conclusie dat investeringen in U-PHS vergelijkbaar zijn met die in conventionele PHS-centrales, zeker als je daarin de milieumaatregelen betrekt die nodig zijn om een reservoir in het landschap te integreren. Het O-PAC-project wordt gedetailleerder geanalyseerd in Deel 2.

Deel 2 geeft een diepgaande analyse van het O-PAC-project. Het begint met een geologisch onderzoek in **hoofdstuk 5**. Begin jaren tachtig vroeg het Nederlandse parlement om te onderzoeken of de Zuid-Limburgse mijnen, die sinds 1974 verlaten zijn, konden dienen voor PHS. Het resultaat van deze studie, die werd uitgevoerd door de mijnafdeling van de toenmalige Technische Hogeschool Delft (nu TU Delft) was negatief. De voormalige mijnen werden ongeschikt bevonden als waterreservoir.

Toch toonde een testboring op dat moment een homogene rotslaag aan op 1.000 m diepte. Deze rotslaag bleek wel geschikt voor ondergrondse constructies. Vooral de rotslagen uit het Dinantien, 1.000 tot 1.700 m diep, zijn veelbelovend. Verdere geologische studies, waarbij seismische profielen werden gebruikt om fouten en andere geostructurele defecten in deze rotslaag te lokaliseren, toonden aan dat slechts een relatief klein gebied rondom de oorspronkelijke boorlocatie kon worden gebruikt. Dit laat zien dat voor de selectie van een locatie uitgebreid onderzoek nodig is. Geschikte locaties worden bij voorkeur gezocht in de directe omgeving van de Maas en nabijgelegen kanalen, aangezien dit een bovengronds bassin met beperkte milieu-impact mogelijk maakt.

Hoofdstuk 6 beschrijft het ontwerp van U-PHS. Een gespecialiseerd team van ingenieurs uit Duitsland en Nederland, ervaren in ondergrondse constructiewerken, was betrokken bij het opstellen van een functioneel ontwerp, geoptimaliseerd voor:

- vermogen en opslagcapaciteit
- diepte, rekening houdend met de lokale geologie
- geostructurele lay-out van het ondergrondse reservoir
- meest effectieve pomp-turbine technieken

Er werden verschillende opties overwogen, met vermogens variërend van 400 MW tot 2.000 MW en capaciteiten van 5 GWh tot 20 GWh. De optimale configuratie op basis van gegevens van de TSO bleek te zijn:

opslagcapaciteit	8,4 GWh
pomp/generatorvermogen	1.400 MW
diepte (valhoogte)	1.400 m

Vanwege de grote valhoogte is in het ontwerp gekozen voor Pelton-turbines en omkeerbare meertraps pomp-turbines. Het originele functionele ontwerp bevat zeven units. Vijf meertraps omkeerbare pomp-turbines (FS) vormen de ruggengraat van de energieopwekking en leveren maximaal 1.000 MW. Twee AS-Pelton-turbines voegen daar een regelbaar vermogen aan toe van 10 MW tot maximaal 2 x 200 MW.

In het ontwerp wordt gekozen voor de New Austrian Tunnelling Method (NATM) voor het maken van de ondergrondse cavernes. Deze techniek integreert de omringende rotsformaties in een algehele ring-achtige ondersteuningsstructuur. Tijdens het behoedzaam uitgraven van de cavernes wordt de rotsmassa rondom zelfdragend gemaakt. Deze methode kan worden uitgevoerd met relatief kleine bouwinspanningen.

Het ontwerp bestaat uit twee groepen van acht cavernes met een centrale distributiecaverne. De cavernes zijn elk 750 m lang en hebben daarmee een totale lengte van 12 km. Met 200 m^2 doorsnede van de cavernes moet in totaal 2,4 miljoen m^3 worden uitgegraven. Er worden drie verschillende profielen voor de cavernes gepresenteerd, elk passend bij een andere geologische structuur.

De grootste caverne is de machinekamer. Deze herbergt de pomp-turbines en de elektromechanische apparatuur. Het is ook de verbindende hub voor de kleppen en waterkanalen. De homogene rotsformatie op de onderzochte locatie maakt een ondergronds gewelf mogelijk van 71,5 m hoog, 20 m breed en 128 m lang. Dit is voldoende om de elektro- en hydromechanica en hulpinstallaties in onder te brengen. Naast de machinekamer bevindt zich een aparte transformatorhal. Voor de benodigde waterhuishouding zijn een collector en een distributiecaverne verbonden met de reservoirs. In totaal moet 2,4 miljoen m^3 voor het onderste reservoir worden uitgegraven en voor de machinekamers nog eens 250 duizend m^3. Dit is dezelfde orde van grootte als de ontgravingen voor de A2-snelwegtunnel in Maastricht.

Een natte schacht met een hogedrukleiding verbindt de ondergrondse en bovengrondse reservoirs. Deze schacht wordt geconstrueerd door geprefabriceerde betonnen ringen op elkaar te stapelen totdat de gewenste diepte is bereikt. Het kanaal bevat een steenvanger die alle deeltjes groter dan 0,25 mm afvangt.

Een belangrijke uitdaging bij de constructie is het transport van uitgegraven gesteente vanuit 1.400 m diepte naar het maaiveld. Verticaal transport is de bepalende factor voor de bouwtijd. Het ontwerp voorziet daarom in twee droge schachten met een diameter van 7 of 8 m voor het transport. Daarin bewegen hogesnelheidsliften (65 km/uur) met een dubbele kooi Koepe-installatie, met een capaciteit van elk 20 ton. Daarmee zouden de graafwerkzaamheden ongeveer 2,5-3 jaar duren en de totale constructieperiode uitkomen op 5-6 jaar.

Het horizontale transport ondergronds op relatieve korte afstanden (tot ongeveer 750 m) wordt verzorgd door elektrisch aangedreven voorladers op rubberen wielen. Deze elektrische voertuigen vereisen minder ventilatie dan voertuigen met verbrandingsmotoren.

De bouwlogistiek moet zorgvuldig worden gepland voor optimale efficiëntie: (1) boren en springen, (2) graafmachines die laden in (3) kiepwagens, die (4) ontladen bij (5) een verticale lift, die op het maaiveld (6) ontladen wordt, met vervolgens (7) transport door vrachtwagens of transportbanden, (8) storten in een depot en (9) transport per boot.

Veiligheid tijdens constructie en gebruik is essentieel. Daarom zullen alle rotswanden worden versterkt, zelfs als er geen geotechnische noodzaak voor is. Een aparte ventilatietunnel zal de cavernes ventileren en maakt bewaking en evacuatie mogelijk, zowel tijdens de bouw als tijdens het gebruik.

Om de exacte locaties en vormen van de cavernes te bepalen, is het nodig om verkennend te boren met een diameter van 0,96 m. Het is essentieel om de 'gesteenteklassen' te identificeren, omdat dit de bekledingstechnieken bepaalt en daarmee ook de hoogte van de investeringen.

Het bovenste reservoir moet min of meer recht boven het onderste reservoir worden aangelegd. Het heeft een bruto oppervlak van ongeveer 50 hectare, inclusief de omliggende dijken. Het moet 2,4 miljoen m^3 proceswater bevatten en wordt afgedicht met daarop een laag stenen afkomstig uit het ondergrondse werk om opstuwing door grondwater te voorkomen. Deze afdichting voorkomt dat het grondwater omhoog komt in het reservoir. Uitgegraven stenen worden ook in de dijken gebruikt, zodat in totaal ongeveer 2,92 miljoen m^3 ontgraven gesteente wordt hergebruikt.

Vanuit het oogpunt van verbindingen met het elektriciteitsnet is het gebied rond Maasbracht een uitstekende locatie voor dit project. Het is het enige hoogspanningsknooppunt in Nederland met een verbinding tussen twee buurlanden. Dit knooppunt heeft onder andere gediend als aansluiting voor de Clauscentrale, een gasgestookte elektriciteitscentrale die buiten bedrijf is gesteld. Het is een unieke positie om O-PAC met het netwerk te verbinden.

Wanneer O-PAC eenmaal is gerealiseerd, zal het de eerste ondergrondse PHS-fabriek ter wereld zijn. Om het potentieel van de techniek voor andere regio's te beoordelen, zijn een aantal marktoverwegingen uitgewerkt in **Appendix I** en een potentiële locatie: Denemarken.

Hoofdstuk 7 behandelt de kosten-batenanalyse (CBA) van het O-PAC project. Dit is het belangrijkste onderdeel van deze monografie, omdat hiermee de haalbaarheid van het project duidelijk wordt.

In Nederland wordt energie verhandeld via een veilingmechanisme met biedprocedures om vraag en aanbod bij elkaar te brengen. De verwachting is dat de gemiddelde elektriciteitsprijs op deze markt aanzienlijk zal stijgen vanwege de stijgende prijzen voor fossiele brandstoffen en CO_2-heffingen. Ook wordt verwacht dat de volatiliteit van deze markt zal toenemen, omdat het groeiende aandeel van VRE het aanbod minder voorspelbaar maakt. Vooral na 2025 zal het op sommige momenten moeilijk zijn om het netwerk in balans te houden, wat zal leiden tot grote prijssprongen. Deze prijsverschillen bieden goede mogelijkheden voor arbitrage, de belangrijkste bron van inkomsten voor O-PAC.

De analyses tonen aan dat de eerste 5 jaar (2025-2030) van O-PAC uitdagend zullen zijn, omdat de opbrengsten aanvankelijk alleen kapitaalkosten, bedrijfskosten en onderhoud dekken. Na deze opstartfase zullen prijsbewegingen op de elektriciteitsmarkt meer en betere arbitragemogelijkheden bieden, wat leidt tot een sterke toename van de inkomsten. Dit maakt afschrijvingen en uitbetaling van dividend aan aandeelhouders mogelijk.

De totale mogelijke inkomsten zijn als volgt berekend:

- 2025 € 83 miljoen
- 2030 € 186 miljoen
- 2035 € 226 miljoen

In 2025 zijn de arbitragemogelijkheden nog steeds beperkt en daarom wordt de capaciteit gedeeltelijk gebruikt voor arbitrage en gedeeltelijk als regel- en reservevermogen. Andere inkomsten kunnen komen uit vergoedingen voor aanvullende ondersteunende diensten aan het netwerk. Deze diensten worden tussen de TSO en aanbieder van het vermogen gecontracteerd en worden daarom niet gepubliceerd. Ze kunnen daarom hier ook niet geschat worden.

Het budget voor de bouw is al in de jaren tachtig opgesteld door een gespecialiseerd Duits ingenieursbureau. Deze cijfers zijn onlangs bijgewerkt. De bouw zal € 1.800 miljoen kosten, inclusief alle ontgravingen, elektromechanische apparatuur, pompen, turbines, installaties bovengronds, etc. Deze cijfers zijn beoordeeld door technische bedrijven die onlangs hebben deelgenomen aan de bouw van de Gotthard-basistunnel.

De jaarlijkse kosten voor exploitatie en onderhoud zijn laag: slechts 1,1% van de investeringskosten. Dit kan omdat het technieken betreft die zich gedurende vele jaren hebben bewezen.

Investeringen kunnen het best worden gestructureerd als een publiek-private samenwerking (PPS) met een solide éénderde (€ 600 miljoen) privaatvermogen. Voorgesteld wordt om de resterende € 1.200 miljoen op de markt te plaatsen via een obligatieparticipatie uitgegeven door een bankenconsortium. Het zou nuttig zijn als O-PAC kan worden ondersteund door EU-investeringsfaciliteiten, met name het Europees Fonds voor Strategische Investeringen (EFSI), dat expliciet is bedoeld voor grootschalige langetermijninfrastructuurprojecten.

Hoofdstuk 8 analyseert de macro-economische effecten en maatschappelijke waarde van een U-PHS-systeem in Nederland.

Investeringen en effecten op de werkgelegenheid zijn beoordeeld in een multicriteria-analyse. Het blijkt dat de directe en indirecte effecten op de werkgelegenheid aanzienlijk zijn. De bouwfase van zes jaar biedt werk aan 900 tot 1.000 werknemers, een totaal van 5.400 tot 6.000 mensjaren. Deze cijfers zijn afgeleid van een onderzoek van de Universiteit Maastricht. De effecten op de lokale en regionale economie zijn voorspeld met een input-output model. Tijdens de operationele periode van 50 jaar zal het project een totaal van 66.100 mensjaren opleveren, uitgaande van een jaarlijkse gemiddelde investering van ongeveer € 300 miljoen gedurende 6 jaar. Meer dan de helft (58 %) van deze werkgelegenheid bevindt zich in de Euregio Maas-Rijn, 12 % in de rest van Nederland en 30 % in de EU.

De maatschappelijke voordelen van O-PAC worden besproken in het licht van de EU-doelstellingen voor de energietransitie. Met de mogelijkheid om energie op te slaan, kan de leveringszekerheid beter worden gewaarborgd in een netwerk met sterke volatiliteit. Daarnaast wordt een verdere integratie van VRE mogelijk door de flexibiliteit die O-PAC kan leveren. Dit biedt de mogelijkheid om CO_2-uitstoot te verminderen door overproductie van VRE op te slaan en opnieuw aan het netwerk te leveren wanneer er een tekort is. De uiteindelijke EU-doelstelling wordt bereikt met een stabielere en lagere prijs voor elektriciteit. Kortom, O-PAC bevordert een betrouwbare, duurzame en betaalbare elektriciteitsvoorziening voor alle Europeanen.

Ook heeft Royal Haskoning een aantal potentiële spin-offs geïdentificeerd op basis van ervaring in civiele techniek. Dit is onder andere de verdere ontwikkeling van het spuiten van composieten. De lokale kunststofindustrie biedt een basis om dit in spin-offs te realiseren.

Hoofdstuk 9 analyseert de betekenis van U-PHS in een wat verder gelegen toekomst. Nederland heeft momenteel een van de beste elektriciteitsnetten en gasdistributiesystemen ter wereld. De belangrijke internationale verbindingen van deze infrastructuren dragen aanzienlijk bij aan een betrouwbare en stabiele energievoorziening.

Nederland heeft chemische technologie aangewezen als de belangrijkste oplossing voor grootschalige energieopslag. Het idee is met overtollige energie waterstof of ammoniak te produceren. Maar deze technieken bevinden zich nog in een vroeg stadium van onderzoek.

Vooral de huidige lage efficiëntie van deze technieken (30-40 %) maakt het moeilijk om ze kosteneffectief te maken.

Het aanbod aan elektriciteit zal meer variëren, omdat er meer VRE in het elektriciteitsnet wordt opgenomen. Het wordt voorspeld (in de NEV 2017) dat het aandeel van VRE in het totale geïnstalleerde vermogen stijgt van 57 % (2025) naar 68 % (2030) en 73 % (2035). Het aandeel van elektriciteit van fossiele brandstoffen daalt van 40 % (2025) tot 30 % (2030) en 26 % (2035). Deze cijfers betreffen het geïnstalleerde vermogen, wat niet het aandeel in de geproduceerde energie weerspiegelt, omdat de variabiliteit van wind en zon de bijdrage van deze hernieuwbare energiebronnen vermindert (de verhouding tussen gemiddeld geleverd vermogen en geïnstalleerd vermogen wordt capaciteitsfactor genoemd). Energie van fossiele brandstoffen heeft dus een aanzienlijk groter aandeel in de elektriciteitsvoorziening dan het aandeel in geïnstalleerd vermogen suggereert.

De Duitse auteur H.W. Sinn berekent voor Duitsland in 2014 een capaciteitsfactor van 9,9 % voor zonne-energie en 16,3 % voor windenergie. Duitse VRE had in dat jaar een aandeel van 40 % in geïnstalleerd vermogen, maar er was een extra (ca. 15 %) voorziening van fossiele brandstoffen nodig als back-up.

In het Nederlandse beleid moet de onbalans die VRE oplevert verminderd worden door gedecentraliseerde opslag in accu’s, geplaatst in huishoudens en EV’s. Een voorwaarde om dit te laten slagen is de uitbreiding van het laagspanningsnet, dat ook slim genoeg moet worden gemaakt om voor deze balans te zorgen. Dit zal een grote uitdaging zijn in het komende decennium, omdat er zeven verschillende DSO’s bij betrokken zijn en de nodige ICT-technologie nog moet worden geïnstalleerd. Tegelijkertijd zullen wind- en zonne-energie nog aanzienlijk toenemen, wat nog hogere eisen stelt aan het balanceren. Het is daarom de vraag of decentrale opslag voldoende oplossing biedt.

Hoofdstuk 10 vat de omstandigheden, kenmerken en voorwaarden samen waaronder O-PAC als grootschalig ondergronds opslagsysteem een zinvolle bijdrage levert binnen de totale mix van flexibiliteitsmaatregelen voor het Nederlandse net, bezien vanuit de optiek van techniek, economie en duurzaamheid.

Het is de vraag of de maatregelen voorgesteld door de Nederlandse regering de noodzakelijke flexibiliteit opleveren om het groeiend aandeel van VRE te integreren in het elektriciteitsnet en tegelijk haar doelen voor CO_2-reductie te halen, wat de centrale hypothese uit hoofdstuk 1 bevestigt.

Deze conclusie wordt ook gedeeld door het Planbureau voor de Leefomgeving (PBL) en het toenmalige Energieonderzoek Centrum Nederland (ECN) in een rapport met de aanbeveling om alle kolencentrales te sluiten, een minimum prijs voor CO_2 vast te stellen en de SDE+ subsidieregeling voor energie uit te breiden.

References

References

AES, 2016. Advancion Energy Storage, 4300 Wilson Boulevard, Suite 1100, Arlington, VA 22203: AES Energy Storage, LLC.

Alvarado Montero, R., Niemann, A. & Wortberg, T., 2016. Underground pumped-hydroelectricity using existing coal mining infrastructure, s.l.: E-proceedings of the 36th IAHR World Congress.

Antal, B., 2014. Pumped Storage Hydropower: A Technical Review, Boulder: B.S., University of Colorado.

Appunn, K., 2016. Re-dispatch costs in the German power grid. [Online] Available at: *https://www.cleanenergywire.org/factsheets/re-dispatch-costs-german-power-grid*
[Accessed 29 March 2018].

Arteaga, J., Zareipour, H. & Thangadurai, V., 2017. Overview of Lithium-Ion Grid-Scale energy storage systems. Curr Sustainable Renewable Energy Rep.

Axpo, 2018. PSW Limmern. [Online]
Available at: *http://www.axpo.com/axpo/ch/en/landing-pages/psw-limmern.html*
[Accessed 13 March 2018].

Backhaus, J., 2003. Joseph Alois Schumpeter: Entrepreneurship, Style and Vision. Dordrecht: Kluwer Academic Publishers.

Barbour, E., n.d.. Compressed Air Energy Storage (CAES). [Online]
Available at: *http://energystoragesense.com/compressed-air-energy-storage/*
[Accessed 19 March 2018].

Beacon Power, 2014. 20 MW Flywheel Energy Storage Plant, s.l.: Beacon Power.

BINE, 2007. Compressed air energy storage power plants, FIZ Karlsruhe: BINE Projektinfo 05/07.

BINE, 2017. Concrete sphere for the sea successfully stores electricity, s.l.: BINE Information Service.

Blok, K., 2009. Introduction to energy analysis. Amsterdam, The Netherlands: Techne Press.

BNEF, 2017a. Pumped Hydro - the ‘unsung hero’ of energy storage?, s.l.: Bloomberg New Energy Finance.

BNEF, 2017b. Lithium-ion Battery Costs and Market, s.l.: Bloomberg New Energy Finance.

Botterud, A., Levin, T. & Koritarov, V., 2014. Pumped Storage Hydropower: Benefits for Grid Reliability and Integration of Variable Renewable Energy, s.l.: Argonne National Laboratory.

Brekke, H., 2014. Hydraulic Turbines – Design, Erection and Operation, s.l.: NTNU.

Bundesnetzagentur, 2018. Monitoringberichte. [Online] Available at: *https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/DatenaustauschundMonitoring/Monitoring/Monitoringberichte/Monitoring_Berichte_node.html* [Accessed 19 May 2018].

California ARB, 2017. California's Hydrogen Transportation Initiatives. California Air Resources Board. [Online] Available at: *https://www.arb.ca.gov/msprog/zevprog/hydrogen/hydrogen.htm* [Accessed 22 February 2018].

CBS, 2017. CBS Statline, Elektriciteit en warmte; productie en inzet naar energiedrager. [Online] Available at: *https://opendata.cbs.nl/statline/#/CBS/nl/dataset/80030ned/table?ts=1519204730774* [Accessed 21 February 2018].

CBS, 2018a. CBS Statline, Personenauto's; voertuigkenmerken, regio's, 1 januari, Den Haag: Centraal Bureau voor de Statistiek.

CBS, 2018b. Hernieuwbare elektriciteit; productie en vermogen. [Online] Available at: *https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82610NED/table?ts=1520423350877* [Accessed 3 May 2018].

CCS Network, n.d.. ROAD project Rotterdam. [Online] Available at: *http://ccsnetwork.eu/projects/road-project-rotterdam*

Connolly, D., Lund, H., Mathiesen, B. & Leahy, M., 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy, Issue 87, pp. 1059-1082.

CPH Post Online, 2018. Government wants to build massive wind energy park. [Online]
Available at: *http://cphpost.dk/news/government-wants-to-build-massive-wind-energy-park.html*
[Accessed 14 July 2018].

Danish Energy Agency, 2017. Danish experiences from Offshore Wind Development, s.l.: Danish Energy Agency, part of the Ministry of Energy, Utilities and Climate in Denmark.

Danish Energy Agency, 2018. Overview of the energy sector. [Online]
Available at: *https://ens.dk/en/our-services/statistics-data-key-figures-and-energy-maps/overview-energy-sector*
[Accessed 12 July 2018].

de Clercq, G., 2015. Hydro dams best for massive power storage. [Online]
Available at: *https://www.reuters.com/article/iberdrola-storage/hydro-dams-best-for-massivepower-storage-iberdrolas-galan-idUSL8N1453B620151216_*
[Accessed 14 March 2018].

de Haan, J., 2009. Vergelijkende beschrijving van systemen voor elektriciteitsopslag, s.l.: O-PAC Business Case 2009.

de Haan, J., 2011. Existing coal mines, Nijmegen: ir. J.F. de Haan, former president of Royal Haskoning.

De Ingenieur, 2017. Windpark in gebruik genomen. [Online]
Available at: *https://www.deingenieur.nl/artikel/gemini-windpark-in-gebruik-genomen*
[Accessed 26 May 2018].

Deilmann-Haniel GmbH, 1987. OPAC Kavernenmethode, Dortmund: Deilmann-Haniel GmbH.

Deloitte, 2015. Energy Storage: Tracking the technologies that will transform the power sector, New York: Delloite.

DENA, 2015. Der Beitrag von Pumpspeicherwerken zur Netzstabilität und zur Versorgungssicherheit – die wachsende Bedeutung von Pumpspeicherwerken für die Energiewende, Berlin: Deutsche Energie-Agentur.

Department for Business, Energy & Industrial Strategy, 2016. Digest of UK energy statistics 2016, Londen: Department for Business, Energy & Industrial Strategy.

Destatis, 2018. Bruttostromerzeugung in Deutschland 2013 bis 2015. [Online] Available at: *www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/Energie/Erzeugung/Tabellen/Bruttostromer zeugung.html* [Accessed 19 March 2018].

Dewan, Y., Custer, C. & Ivashchenko, A., 2017. Simulation of the Francis-99 Hydro Turbine During Steady and Transient Operation, s.l.: OP Conf. Series: Journal of Physics: Conf. Series 782 (2017) 012001.

DHPLG, 2016. 650m euro Silvermines Hydro Electric Power Station project launched by Environment Minister Alan Kelly. [Online] Available at: *http://www.housing.gov.ie/corporate/other/650m-euro-silvermineshydro-electric-power-station-project-launched-environment* [Accessed 19 March 2018].

Díaz-González, F., Sumper, A., Gomis-Bellmunt, O. & Villafáfila-Robles, R., 2012. A review of energy storage technologies for wind power applications. Renewable and Sustainable Energy Reviews, Issue 16, pp. 2154-2171.

Die Bundesregierung, 2016. Neue Speicher für ein stabiles Stromnetz entwickeln. [Online] Available at: *https://www.bundesregierung.de/Webs/Breg/DE/Themen/Energiewende/EnergieTransportieren/neueSpeicher/_node.html* [Accessed 26 May 2018].

DNV-GL, 2015. Routekaart Energieopslag 2030, Arnhem: DNV-GL.

Dreidy, M., Mokhlis, H. & Mekhilef, S., 2017. Inertia response and frequency control techniques for renewable energy sources: A review. Renewable and Sustainable Energy Reviews, Issue 69, pp. 144-155.

Dunn, B., H., K. & Tarascon, J., 2011. Electrical energy storage for the grid: a battery of choices. Science, Issue 334, pp. 928-935.

Duyvendak, W., 2011. Het groene optimisme: het drama van 25 jaar klimaatpolitiek. s.l.:Uitgeverij Bert Bakker.

E-Bridge, 2014. Potential cross-border balancing cooperation between the Belgian, Dutch and German electricity Transmission System Operators, Bonn, Germany: Institut für Elektrische Anlagen und Energiewirtschaft.

EC, 2013. Incorporating demand side flexibility, in particular demand response, in electricity markets, Brussels: European Commission.

EC, 2015a. Energy Union: secure, sustainable, competitive, affordable energy for every European. [Online] Available at: *europa.eu/rapid/press-release_IP-15-4497_en.pdf*

EC, 2015b. Strategic contribution of energy storage to energy security and internal energy market - High level roundtable, Brussels: European Commission.

EC, 2016. Variable speed Pumped Storage Hydro Plants offer a new era of smarter energy management. [Online]
Available at: *https://cordis.europa.eu/news/rcn/125319_en.html*
[Accessed 4 May 2018].

EC, 2017. Energy storage - the role of electricity, Brussels: European Commission.

EC, 2018. Smart grids and meters. [Online]
Available at: *ec.europa.eu/energy/en/topics/markets-and-consumers/smart-grids-and-meters*
[Accessed 4 May 2018].

EC, n.d.1. Energy Strategy and Energy Union. [Online]
Available at: *https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union*
[Accessed 19 April 2018].

EC, n.d.2. Energy Security Strategy. [Online]
Available at: *https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/energy-security-strategy*

ECN, 2007. Vragen over nieuwe kolencentrales in Nederland, s.l.: Energieonderzoek Centrum Nederland.

ECN, 2014a. Exploring the role for power-to-gas in the future Dutch energy system. Final report of the TKI power-to-gas system analysis project, Petten: Energieonderzoek Centrum Nederland.

ECN, 2014b. The role of power-to-gas in the future Dutch energy system, Petten: Energieonderzoek Centrum Nederland.

ECN, 2015. Nationale energieverkenning 2015, Petten: Energieonderzoek Centrum Nederland.

ECN, 2016. Nationale Energieverkenning 2016, Petten: Energieonderzoek Centrum Nederland.

ECN, 2017a. FLEXNET. [Online]
Available at: *https://www.ecn.nl/flexnet/*
[Accessed 28 May 2018].

ECN, 2017b. Nationale Energieverkenning 2017, Petten: Energieonderzoek Centrum Nederland.

Ecofys, 2014. Energy Storage Opportunities and Challenges - A West Coast Perspective White Paper, Utrecht: Ecofys.

EIA, 2016. Average Tested Heat Rates by Prime Mover and Energy Source, 2007-2016. [Online]
Available at: *https://www.eia.gov/electricity/annual/html/epa_08_02.html*
[Accessed 18 April 2018].

EIA, 2018. Annual Energy Outlook 2018, Washington, DC 20585: U.S. Energy Information Administration.

Electrabel, 2015. Welcome to Coo Seminar SPF, s.l.: GDF Suez.

Elia, 2018. Ancillary Services: Volumes & Prices. [Online]
Available at: *http://www.elia.be/en/suppliers/purchasing-categories/energy-purchases/Ancillary-services/Ancillary-Services-Volumes-Prices*

Energieagenda, 2016. Energieagenda – Naar een CO_2 arme energievoorziening, Den Haag: Ministerie van Economische Zaken.

Energieleveranciers.nl, 2018. Overzicht netbeheerders elektriciteit. [Online]
Available at: *https://www.energieleveranciers.nl/netbeheerders/elektriciteit*
[Accessed 24 May 2018].

Energierapport, 2016. Energierapport, transitie naar duurzaam, Den Haag: Ministerie van Economische Zaken.

Energinet, 2018. energinet.dk. [Online]
Available at: *https://en.energinet.dk/*
[Accessed 12 July 2018].

Energy Brainpool, 2017. Trends in the development of electricity prices - EU Energy Outlook 2050. [Online]
Available at: *https://blog.energybrainpool.com/en/trends-in-the-development-of-electricity-prices-eu-energy-outlook-2050/*

Energy Storage Association, n.d.. [Online]
Available at: *http://energystorage.org/*
[Accessed 28 May 2018].

Energy Storage NL, 2016. Nationaal Actieplan Energieopslag overhandigd aan de politiek. [Online]
Available at: *https://www.energystoragenl.nl/nationaal-actieplan-energieopslag-overhandigd-aan-de-politiek/1178*
[Accessed 4 May 2018].

Energy Storage NL, 2017. Visiedocument Grootschalige Energieopslag, Zoetermeer: FME, NL ingenieurs.

Enexis, 2016. Verkoop van de thuisaccu in Nederland valt tegen. [Online]
Available at: *https://www.zelfenergieproduceren.nl/nieuws/verkoop-thuisaccu-nederland-valt/*
[Accessed 19 March 2018].

ENTSO-E, 2015. Detailed monthly production 2015, Brussels: European Network of Transmission System Operators for Electricity.

ENTSO-E, 2016. Consumption Data. [Online]
Available at: *https://www.entsoe.eu/data/data-portal/consumption/Pages/default.aspx*
[Accessed 25 January 2017].

ENTSO-E, 2017a. Consultation on the design of the platform for automatic Frequency Restoration Reserve (aFRR) of PICASSO region, s.l.: ENTSO-E.

ENTSO-E, 2017b. MARI Project in a Nutshell and Accession Conditions. [Online]
Available at: *https://docstore.entsoe.eu/Documents/MC%20documents/balancing_ancillary/2017-06-07/170607_Manual_Activation_Reserve_Initiative.pdf*
[Accessed 11 May 2018].

ENTSO-E, 2018a. Installed Capacity per Production Type. [Online]
Available at: *https://transparency.entsoe.eu/generation/r2/installedGenerationCapacityAggregation/show?name=&defaultValue=false&viewType=TABLE&areaType=BZN&atch=false&dateTime.dateTime=01.01.2017+00:00|UTC|YEAR&dateTime.endDateTime=01.01.2019+00:00|UTC|YEAR&area.values*
[Accessed 12 July 2018].

ENTSO-E, 2018b. www.entsoe.eu. [Online]
Available at: *https://www.entsoe.eu/data/power-stats/monthly-domestic/*
[Accessed 14 July 2018].

ENTSO-E, 2018c. transparency.entsoe.eu. [Online]
Available at: *https://transparency.entsoe.eu/*

ENTSO-E, n.d.1. ENTSO-E Transmission System Map. [Online]
Available at: *https://www.entsoe.eu/data/map/*
[Accessed 14 July 2018].

ENTSO-E, n.d.2. PICASSO. [Online]
Available at: *https://electricity.network-codes.eu/network_codes/eb/picasso/*
[Accessed 14 May 2018].

EPEC, 2018. Battery cell comparison. [Online]
Available at: *http://www.epectec.com/batteries/cell-comparison.html*
[Accessed 12 April 2018].

Essent, 2018. De salderingsregel zonnepanelen voor en na 2020. [Online]
Available at: *https://www.essent.nl/content/particulier/kennisbank/zonnepanelen/salderingsregelingzonnepanelen.html*
[Accessed 9 April 2018].

eStorage, 2016a. Potential, Economic and Environmental value of large-scale energy storage in Europe, Brussels: prepared for the European Commission – Directorate General for Research.

eStorage, 2016b. eStorage project update, Brussels: eStorage.

eStorage, 2016c. Project Final Report, Publishable Summary, s.l.: eStorage.

Eurostat, 2016. Energy balance sheets – 2014 data. In: Statistical books Eurostat 2016 edition. s.l.:s.n.

Evans, A., Strezov, V. & Evans, T., 2012. Assessment of utility energy storage options for increased renewable energy penetration. Renewable and Sustainable Energy Reviews, Issue 16, pp. 4141-4147.

Farber-DeAnda, M., 2005. Puerto Rico's 20 MW battery energy storage - The world's largest lead acid battery system Is repowered, Proceeding Workshop on electricity storage, California energy commission: U.S. Department of Energy.

FEPC, 2016. Electricity review Japan, Tokyo: The Federation of Electric Power Companies of Japan.

FERC, 2017. Pumped Storage Projects, Washington: Federal Energy Regulatory Commission.

Fessenden, R., 1917. System of storing power. USA/ Massachusets, Patent No. Patent No. US1247520 A.

Fraunhofer ISE, 2018. Annual electricity generation in Germany. [Online]
Available at: *https://www.energy-charts.de/energy.htm?source=all-sources&period=annual&year=all*
[Accessed 3 May 2018].

Frontier Economics, 2015. Scenarios for the Dutch electricity supply system, London: Frontier Economics Ltd.

Fujihara, T., Imano, H. & Oshima, K., 1998. Development of Pump Turbine for Seawater Pumped-Storage Power Plant. Hitachi Review, 47(5), pp. 199-202.

Gartner Inc., 2017. Top Trends in the Gartner Hype Cycle for Emerging Technologies, 2017. [Online]
Available at: *https://www.gartner.com/smarterwithgartner/top-trends-in-the-gartner-hype-cycle-for-emerging-technologies-2017/*
[Accessed 12 April 2018].

Gartner Inc., 2018. Gartner Hype Cycle. [Online]
Available at: *https://www.gartner.com/technology/research/methodologies/hype-cycle.jsp*
[Accessed 12 April 2018].

Gemini, n.d.. geminiwindpark.nl. [Online]
Available at: *http://geminiwindpark.nl/feiten--cijfers.html*
[Accessed 3 May 2018].

Genex Power, 2015. Genex power limited – renewable energy on tap. [Online]
Available at: *www.genexpower.com.au/*
[Accessed 19 March 2018].

Gigler, J. & Weeda, M., 2018. Contouren van een Routekaart Waterstof, Amersfoort: TKI Nieuw Gas Topsector Energie.

Global CCS Istitute, 2016. The Global Status of CCS 2016 Summary Report, Melbourne: Global CCS Istitute.

González, P., Villar, J., Díaz, C. & Campos, A., 2014. Joint energy and reserve markets: Current implementations and modeling trends. Electric Power Systems Research, Issue 109, pp. 101-111.

Graabak, I. & Korpås, M., 2016. Variability Characteristics of European Wind and Solar Power Resources - A Review. Energies, 9(449), pp. 1-31.

Graichen, P. & Redl, C., 2014. The German Energiewende and its Climate Paradox, Berlin: Agora Energiewende.

Green Deal C-198, 2016. Electric Transport Green Deal 2016-2020, Den Haag: Rijksoverheid, RVO, Green Deal.

Hall, P. & Bain, E., 2008. Energy-storage technologies and electricity generation. Energy Policy, Issue 36, pp. 4352-4355.

Harris, M., 2016. Switzerland's 1,000-MW Linthal pumped-storage plant connected to the grid. [Online]
Available at: *http://www.hydroworld.com/articles/2016/01/switzerland-s-1-000-mw-linthal-pumped-storageplant-connected-to-grid.html*
[Accessed 13 March 2018].

Harris, M., 2017. Expansion of Switzerland's 480-MW FMHL Pumped Storage Plant Complete. [Online]
Available at: *http://www.renewableenergyworld.com/articles/2017/05/expansion-of-switzerland-s-480-mw-fmhlpumped-storage-plant-complete.html*
[Accessed 13 March 2018].

Harza, R., 1960. Hydro and pumped storage for peaking. Power Engineering, 10(64), pp. 79-82.

Haskoning, 2009. Actualisatie investeringsraming van de ondergrondse energieopslag centrale (OPAC), Amersfoort: Royal Haskoning Nederland BV.

Hesse, H., Schimpe, M., Kucevic, D. & Jossen, A., 2017. Lithium-Ion battery storage of the grid – A review of stationary battery storage system design tailored for applications in modern power grids. Energies, 10(12).

Höller, H., 2008. Hydrodynamics in Drive Technology, s.l.: Voith.

Holmberg, P., 2017. Strategic bidding in electricity markets. [Online] Available at: *https://www.eurandom.tue.nl/wp-content/uploads/2017/12/Slides-Tutorials-Holmberg_Dec-12-2017.pdf* [Accessed 10 May 2018].

Honda, 2017. Introducing the Clarity series. [Online] Available at: *https://automobiles.honda.com/clarity* [Accessed 19 March 2018].

Hydrogen Council, 2017. How hydrogen empowers the energy transition, s.l.: Hydrogen Council.

Ibrahim, H., Ilincaa, A. & Perron, J., 2008. Energy storage systems—Characteristics and comparisons. Renewable and Sustainable Energy Reviews, Issue 12, pp. 1221-1250.

IEA, 2009. Prospects for large-scale energy storage in decarbonised power grids, Paris: International Energy Agency.

IEA, 2011. Harnessing variable renewable - A guide to the balancing challenge, Paris: International Energy Agency.

IEA, 2014b. Energy Technology Perspectives 2014 - Harnessing Electrcity's Potential, Paris: International Energy Agency.

IEA, 2015. Technology Roadmap - Hydrogen and Fuel Cells, Paris: International Energy Agency.

IEA, 2017a. Global EV Outlook 2017, Paris: International Energy Agency.

IEA, 2017b. World Energy Outlook 2017. [Online] Available at: *https://www.iea.org/weo2017/*

Ingen-Housz, B., 1985. Veiligheid en risico. Deelrapport in het kader van rapportage fase I. OPAC studie 1985-1986, s.l.: OPAC-groep KVS.

IRENA, 2015. Renewables and Electricity Storage, A technology roadmap for Remap 2030, Abu Dhabi: International Renewable Energy Agency.

IRES Proceedings, 2012. Conference Presentations and Materials of the 7th International Renewable Energy Storage IRES 2012, Berlin: EUROSOLAR, WCRE.

Isaksson, G., Nilsson, D. & Sjostrand, T., 1968. Pumped storage power plants with underground lower reservoirs. Moscow, Seventh World Power Conference, Section 2, Paper 160.

Japan Update, 2016. Experimental power plant in Kunigami dismantled. [Online]
Available at: *http://www.japanupdate.com/2016/07/experimental-power-plant-in-kunigamidismantled/*
[Accessed 14 March 2018].

Jones, T. & Yohe, G., 2013. Improved governor response at the Dinorwig power station, s.l.: American Governor Company, Ivyland, Pennsylvania USA and First Hydro Company, Dinorwig, Wales UK.

JRC, 2011. Smart Grid projects in Europe: lessons learned and current developments, Petten: Joint Research Centre.

JRC, 2013. Assessment of the European potential for pumped hydropower energy storage, Petten, The Netherlands: Joint Research Centre, Institute for Energy and Transport.

JRC, 2017. Smart grid projects outlook 2017: Facts, figures and trends in Europe, Petten: Joint Research Centre.

KNAW, 2011. Quality assessment in the design and engineering disciplines - A systematic framework, Amsterdam: Royal Netherlands Academy of Arts and Sciences.

KNMI, 1985. Aardbevingseffecten, s.l.: Koninklijk Nederlands Meteorologisch Instituut.

KNMI, 2017a. Uurgegevens van het weer in Nederland - Download. [Online]
Available at: *http://projects.knmi.nl/klimatologie/uurgegevens/selectie.cgi*
[Accessed 29 March 2017].

KNMI, 2017b. Uurgegevens van Noordzee stations. [Online]
Available at: *http://www.knmi.nl/nederland-nu/klimatologie/uurgegevens_Noordzee*
[Accessed 3 April 2017].

Koritarov, V. et al., 2013. Modeling Ternary Pumped Storage Units, s.l.: Argonne National Laboratory.

Koritarov, V. et al., 2014. Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the United States, s.l.: Argonne National Laboratory.

KPMG, 2017. Global automotive executive survey 2017, s.l.: KPMG.

Kraemer, S., 2016. Gold mine recycled as Australia's largest pumped hydro storage. [Online]
Available at: *https://cleantechnica.com/2016/06/16/gold-mine-recycled-asaustralias-largest-pumped-hydro-storage/_*
[Accessed 19 March 2018].

Kramer, G., 2011. The Accidental Cathedral; Thoughts on rebuilding the energy system, Leiden: Leiden University.

Kramers, L. et al., 2011. Studie naar Haalbaarheid van OPAC op de locatie Graetheide en nabije omgeving, s.l.: TNO.

Liu, C., Li, F., Ma, L. & Cheng, H., 2010. Advanced materials for energy storage. Advanced Materials, Issue 22, pp. 26-62.

Luo, X., Wang, J., Dooner, M. & Clarke, J., 2015. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy, Issue 137, pp. 511-536.

MacKay, D., 2009. Sustainable energy - without the hot air. Cambridge, England: UIT Cambridge Ltd..

Maidl, B., Thewes, M. & Maidl, U., 2013. Handbook of Tunnel Engineering. Volume I: Structures and methods. Berlin: Wilhelm Ernst & Sohn.

Maks, J. & Oude Wansink, M., 2009. Economische impact van de Ondergrondse Pomp Accumulatie Centrale (OPAC) in Limburg, Maastricht: Maastricht University / OWP Research.

Mathes-Schmidt, M., 2000. Mikrofazies, Sedimentationsgeschehen un paläogeographischen Entwicklung im Verlauf des oberen Viseums im Untergrund der Niederrheinischen Buch und des Campine-Beckens, Aachen: RWTH.

Meadows, D., Meadows, D., Randers, J. & Behrens, W., 1972. The limits to growth. 5th ed. New York: Universe Books.

Mearns, E., 2016. The Glenmuckloch Pumped Storage Hydro Scheme. [Online]
Available at: *https://cleantechnica.com/2016/06/16/gold-mine-recycled-asaustralias-largest-pumped-hydro-storage/_*
[Accessed 19 March 2018].

Mehrens, A., Hahmann, A., Larsen, X. & von Bremen, L., 2016. Correlation and coherence of mesoscale wind speeds over the sea. Quarterly Journal of the Royal Meteorological Society, Issue 142, pp. 3186-3194.

Messing, F., 1988. Geschiedenis van de mijnsluiting in Limburg. s.l.:Noordhoff Uitgevers B.V. .

Meyer, F., 2013. Storing wind energy underground, Jülich, Germany: Research Centre Jülich.

Miller, R. & Blair, P., 2009. Input-Output Analysis. 2nd ed. Cambridge, UK: Cambridge University Press.

Mining Technology, 2018. Suppliers/Drilling And Blasting. [Online] Available at: *www.miningtechnology.com/contractors/drilling* [Accessed 21 March 2018].

Ministerie van EL&I, 2011. Elektrisch Rijden in de versnelling - Plan van Aanpak 2011-2015, s.l.: RVO.nl.

Mortelmans, K., 2018. Wiebes heeft overschot in SDE+ kas. [Online] Available at: *https://www.fluxenergie.nl/wiebes-heeft-overschot-in-sde-kas/* [Accessed 18 May 2018].

Motivaction, 2016. Energievoorziening 2015-2050: publieksonderzoek naar draagvlak voor verduurzaming van energie, Den Haag: Rijksoverheid.

Mulder, F., 2014. Implications of diurnal and seasonal variations in renewable energy generation for large scale energy storage. Journal of Renewable and Sustainable Energy, Issue 6.

Müller, L. & Hereth, A., 1987a. Feasibility study to the OPAC project - Part A: Introduction, geological and geotechnical evaluation, Ainring: Ingenieurbüro für Tunnel- und Felsbau GmbH.

Müller, L. & Hereth, A., 1987b. Feasibility study to the OPAC project. Part B: Reservoir system excavation and support for tunnel and cavern system. , Ainring: Ingenieurbüro für Tunnel- und Felsbau GmbH.

Müller, L. & Hereth, A., 1987c. Feasibility study to the OPAC project. Part C: Statische Untersuchungen zum Bereich Krafthaus, Ainring: Ingenieurbüro für Tunnel- und Felsbau GmbH.

NECG, 2014. #2 - Nuclear Power & Short-Run Marginal Cost. [Online] Available at: *https://nuclear-economics.com/nuclear-power-short-run-marginal-cost/* [Accessed 19 April 2018].

NEOM, 1987. OPAC Prolongatiestudie, hoofdrapport. , s.l.: Author organisations: TU Delft, Haskoning Koninklijk ingenieurs en architectenbureau, Koninklijke Volker Stevin.

Netbeheer Nederland, 2018. Slimme Meter. [Online] Available at: *https://www.netbeheernederland.nl/consumenteninformatie/slimmemeter* [Accessed 4 May 2018].

Nord Pool, 2018a. Price calculation. [Online] Available at: *https://www.nordpoolgroup.com/TAS/Day-ahead-trading/Price-calculation/* [Accessed 10 May 2018].

Nordic CCS Competence Centre, n.d.. Geology and stratigraphy - Denmark. [Online]
Available at: *https://data.geus.dk/nordiccs/geology.xhtml*
[Accessed 14 July 2018].

NOS, 2016. Ondanks klimaatakkoord nieuwe kolencentrale, nog zonder CO_2-afvang. [Online]
Available at: *https://nos.nl/artikel/2100426-ondanksklimaatakkoord-nieuwe-kolencentrale-nog-zonder-co2-afvang.html*
[Accessed 19 March 2018].

NOS, 2018. Netbeheerder moest groot inkopen om stroomtekort op te vangen. [Online]
Available at: *https://nos.nl/artikel/2229787-netbeheerder-moest-groot-inkopen-om-stroomtekort-op-te-vangen.html*
[Accessed 4 May 2018].

NOW GmbH, 2017. Electric Mobility with Hydrogen and Fuel Cells, Berlin: National Organization Hydrogen and Fuel Cell Technology.

NTNU, 2015. Preventing hydropower turbine failure. [Online]
Available at: *https://phys.org/news/2015-05-hydropower-turbinefailure.html*
[Accessed 10 March 2018].

OECD/IEA, 2014a. Technology Roadmap - Energy Storage, Paris: International Energy Agency.

OSU, 2018. Types of turbines. [Online]
Available at: *http://rivers.bee.oregonstate.edu/turbine-sizing*
[Accessed 9 March 2018].

Parkin, B., 2017. German Coal Mine to Be Reborn as Giant Pumped Storage Hydro Facility. [Online]
Available at: *http://www.renewableenergyworld.com/articles/2017/03/german-coal-mine-to-be-reborn-as-giantpumped-storage-hydro-facility.html*
[Accessed 19 March 2018].

PBL, 2017. Analyse regeerakkoord Rutte III: Effecten op Klimaat en Energie, Den Haag: Planbureau voor de Leefomgeving.

Pickard, W., 2012. The history, present state, and future prospects of underground pumped hydro for massive energy storage. Proceedings of the IEEE, Issue 100, pp. 473-483.

Port of Rotterdam Authority, 2016. Over 120 Industrial Companies. One Powerful Cluster. Make it happen., Wilhelminakade 909, 3072 AP, Rotterdam: Port of Rotterdam Authority.

Postma, R., 2017. Eerste windparken zonder subsidie. [Online]
Available at: *https://www.nrc.nl/nieuws/2017/04/18/eerste-windparken-zonder-subsidie-8260661-a1554856*
[Accessed 4 June 2018].

Puchta, M., 2017. Offshore Pumped Hydro Storage – Project STENSEA, TIP-SNET Central Region Workshop, Aachen: Fraunhofer IWES.

Putzmeister, n.d.. The New Austrian Tunneling Method (NATM) & shotcrete: growing side by side. [Online]
Available at: *http://bestsupportunderground.com/natm-shotcrete/?lang=en*
[Accessed 8 May 2018].

Rabcewicz, L. & von Golser, J., 1973. Principles of dimensioning the supporting system for the “New Austrian Tunneling Method”. Water Power, Volume 3, pp. 88-93.

Ray, R., 2016. Power Plant Performance in 2015. [Online]
Available at: *https://www.power-eng.com/articles/print/volume-120/issue-12/features/power-plant-performance-in-2015.html*
[Accessed 22 April 2018].

Regelleistung.net, 2018. Tender overview - Search for tender. [Online]
Available at: *https://www.regelleistung.net/ext/tender/*
[Accessed 2018 March 2018].

Reve, 2014. Denmark’s Offshore Wind Power among Best in World, with More Growth by 2020. [Online]
Available at: *https://www.evwind.es/2014/10/31/denmarks-offshore-wind-power-among-best-in-world-with-more-growth-by-2020/48438*
[Accessed 12 July 2018].

RGD, 1987. Onderzoeksresultaten van boring Geverik-1 (OPAC-studie Zuid Limburg), s.l.: Rijks Geologische Dienst.

Rijksoverheid, 2008. Energierapport 2008. [Online]
Available at: *http://www.rijksbegroting.nl/algemeen/gerefereerd/1/2/4/kst124652.html*
[Accessed 8 May 2018].

Rijksoverheid, 2018. Nuon krijgt vergunning voor windpark zonder subsidie. [Online]
Available at: *https://www.rijksoverheid.nl/actueel/nieuws/2018/03/19/nuon-krijgt-vergunning-voor-windpark-zonder-subsidie*
[Accessed 4 June 2018].

Rli, 2015. Rijk zonder CO_2 – Naar een duurzame energievoorziening in 2050, Den Haag: Raad voor de Leefomgeving en Infrastructuur.

Rli, 2018. Stroomvoorziening onder digitale spanning, Den Haag: Raad voor de leefomgeving en infrastructuur.

Rooijers, F., Hers, S., Afman, M. & Kampman, B., 2014. Investeringen in conventioneel vermogen, Delft: CE Delft.

RVO, 2018a. SDE+ voorjaar 2018 gepubliceerd. [Online] Available at: *https://www.rvo.nl/actueel/nieuws/sde-voorjaar-2018-gepubliceerd* [Accessed 18 May 2018].

RVO, 2018b. Ruim 4.500 aanvragen voor SDE+ voorjaar 2018. [Online] Available at: *https://www.rvo.nl/actueel/nieuws/ruim-4500-aanvragen-voor-sde-voorjaar-2018* [Accessed 4 June 2018].

RVO, 2018c. Electric passenger cars and charging points in the Netherlands analysis of 2017, Den Haag: Rijksdienst voor Ondernemend Nederland.

RVO, 2018d. SDE+ Offshore Wind Energy. [Online] Available at: *https://english.rvo.nl/subsidies-programmes/sde/sde-offshore-wind-energy* [Accessed 13 June 2018].

RVO, n.d.. Berekening Stimulering Duurzame Energieproductie. [Online] Available at: *https://www.rvo.nl/subsidies-regelingen/stimulering-duurzame-energieproductie/aanvragen-sde/berekening-sde* [Accessed 4 June 2018].

RWE, 2010. ADELE – Adiabatic compressed-air energy storage for electricity supply, Essen/Köln: RWE Power AG.

S&P Global, 2017. German power grid redispatch measures, costs down by quarter in 2016. [Online] Available at: *https://www.platts.com/latest-news/electric-power/london/german-power-grid-redispatch-measures-costs-down-26745793* [Accessed 29 March 2018].

Sangal, S., Garg, A. & Kumar, D., 2013. Review of Optimal Selection of Turbines for Hydroelectric Projects. International Journal of Emerging Technology and Advanced Engineering, 3(3), pp. 424-430.

SBC Energy Institute, 2013. Electricity Storage Factbook series – Leading the energy transition, s.l.: Schlumberger Business Consulting.

ScottishPower, 2016. ScottishPower concludes feasibility study for Cruachan expansion. [Online] Available at: *https://www.scottishpower.com/news/pages/scottishpower_concludes_feasibility_study_for_cruac han_expansion.aspx* [Accessed 13 March 2018].

SER, 2013. Energieakkoord voor duurzame groei, s.l.: Sociaal Economische Raad.

Shang, L., Hu, J., Yuan, X. & Chi, Y., 2017. Understanding Inertial Response of Variable-Speed Wind Turbines by Defined Internal Potential Vector. Energies, 10(22).

Shooks, M., Johansson, B., Andersson, E. & Lööw, J., 2014. Safety and Health in European Mining. A report on safety and health, statistics, tools and laws, produced for the I2Mine (Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future) project, Luleå: Luleå University of Technology.

Siderius, H. & Dijkstra, A., 2006. Smart Metering for Households: Cost and Benefits for the Netherlands, s.l.: s.n.

Siemens, 2017. Siemens receives major order from TenneT for DolWin6 offshore grid connection. [Online] Available at: *https://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2017/energymanagement/pr2017070370emen.htm&content[]=EM* [Accessed 11 May 2018].

Sinn, H., 2017. Buffering volatility: A study on the limits of Germany's energy revolution. European Economic Review, Issue 99, pp. 130-150.

Smith, K., Saxon, A., Keyser, M. & Lundstrom, B., 2017. Life prediction mode for grid-connected Li-ion battery energy storage system, Presented at the 2017 American Control Conference, Seattle, Washington: National Renewable Energy Laboratory.

Sorensen, K., 1969. Underground reservoirs: pumped storage of the future. Civil Engineering, 3(39).

Spector, J., 2017. Tesla Fulfilled Its 100-day Australia Battery Bet. What's That Mean for the Industry. [Online] Available at: *https://www.greentechmedia.com/articles/read/tesla-fulfills-australia-battery-bet-whats-that-mean-industry#gs.qe9pBn8* [Accessed 3 May 2018].

Stedin, 2015. Wereldprimeur Utrecht: laadpaal maakt opslag zonne-energie mogelijk. [Online] Available at: *https://www.stedin.net/over-stedin/pers-en-media/persberichten/wereldprimeur-utrecht-laadpaal-maakt-opslag-zonneenergie-mogelijk* [Accessed 26 May 2018].

Sterner, M. & Stadler, I., 2014. Energiespeicher – Bedarf, Technologien, Integration. Heidelberg: Springer-Verlag Berlin .

TenneT, 2016a. Oproep voor de levering van Regelvermogen (aFRR) in 2017. [Online] Available at: *https://www.tennet.eu/nl/nieuws/nieuws/oproep-voor-de-levering-van-regelvermogen-afrr-in-2017/*

TenneT, 2016b. Product information aFRR (Regulating power), Arnhem: TenneT.

TenneT, 2016c. Internationale verbindingen van TenneT compenseren daling binnenlands productievermogen. [Online] Available at: *http://www.tennet.eu/nl/nieuws/nieuws/internationale-verbindingen-van-tennet-compenserendaling-binnenlands-productievermogen/*

TenneT, 2017a. Wijzigingen in regel- en noodvermogen TenneT 2018. [Online] Available at: *http://www.utilities.nl/wijzigingen-regel-en-noodvermogen-tennet-2018/*

TenneT, 2017b. MARI-Project: 19 European TSOs agree to further cooperation on mFRR-platform. [Online] Available at: *https://www.tennet.eu/news/detail/mari-project-19-european-tsos-agree-to-further-cooperation-on-mfrr-platform/* [Accessed 11 May 2018].

TenneT, 2017c. Product information mFRRda (incident reserve), Arnhem: TenneT.

TenneT, 2017d. Uitvoeringsregels met betrekking to Net- en Systeemcode, Arnhem: TenneT TSO B.V..

TenneT, 2017e. TenneT is voornemens om te starten met het proces voor de inkoop van blindvermogen voor 2018. [Online] Available at: *https://www.tennet.eu/nl/nieuws/nieuws/tennet-is-voornemens-om-te-starten-met-het-proces-voor-de-inkoop-van-blindvermogen-voor-2018/* [Accessed 30 March 2018].

TenneT, 2017f. TenneT opent de balanceringsmarkt voor batterijen via blockchain. [Online] Available at: *https://www.tennet.eu/nl/nieuws/nieuws/tennet-opent-de-balanceringsmarkt-voor-batterijen-viablockchain/* [Accessed 19 March 2018].

TenneT, 2018a. Bedrijfstoestand: ALERT. [Online] Available at: *http://www.tennet.org/bsmailfax/20180430_112319_Afroep_bedrijfstoestand_ALERT___EMERGENCY.html* [Accessed 4 May 2018].

TenneT, 2018b. Verrekenprijzen. [Online]
Available at: *http://www.tennet.org/bedrijfsvoering/Systeemgegevens_afhandeling/verrekenprijzen/index.aspx*
[Accessed 18 May 2018].

TenneT, n.d.1. Gridmap Netherlands NL. [Online]
Available at: *https://www.tennet.eu/fileadmin/user_upload/Company/Publications/Gridmaps/NL/Gridmap_Netherlands_NL.pdf*
[Accessed 24 May 2018].

TenneT, n.d.2. Noodvermogen (Brochure), Arnhem: TenneT TSO B.V..

Ter-Gazarian, 2011. Energy Storage for Power Systems. 2nd ed. London, UK: The Institution of Engineering and Technology.

The Economist, 2017. After electric cars, what more will it take for batteries to change the face of energy?, s.l.: The Economist.

The Linde Group, 2013. Leading industrial companies agree on an action plan for the construction of a hydrogen refuelling network in Germany. [Online]
Available at: *https://www.thelinde-group.com/en/news_and_media/press_releases/news_20130930.html*
[Accessed 22 February 2018].

The Local, 2018. Danish government proposes giant 800MW wind farm. [Online]
Available at: *https://www.thelocal.dk/20180426/denmark-proposed-giant-800mw-wind-farm*
[Accessed 14 July 2018].

TNO, 2015. Naar een toekomstbestendig energiesysteem: Flexibiliteit met waarde, Den Haag: Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek.

Tommelein, B., 2015. Positieve adviezen voor energie-atol. [Online]
Available at: *http://www.tommelein.com/positieve-adviezen-voor-energie-atol/*
[Accessed 19 March 2018].

Transnet BW GmbH, 2018. Redispatch. [Online]
Available at: *https://www.transnetbw.com/en/energy-market/ancillary-services/redispatch*
[Accessed 29 March 2018].

Twidell, J. & Weir, T., 2015. Renewable energy resources, Chapter 6: Hydropower (p202-221). 3rd ed. 711 Third Avenue, New York, NY 10017: Routledge.

United Nations, 1992. United Nations framework convention on climate change, s.l.: s.n.

United Nations, 2006. Multi Dimensional Issues in International Electric Power Grid Interconnections, New York: United Nations.

United Nations, 2015. Framework convention on climate change, Paris: UN Climate Summit, Conference of Parties, twenty first session.

Urgenda, 2018. Climate Case Explained. [Online] Available at: *http://www.urgenda.nl/en/themas/climate-case/climate-case-explained/* [Accessed 28 May 2018].

US DOE, 2013. Kops II pumped storage power station. [Online] Available at: *http://www.energystorageexchange.org/projects/553* [Accessed 13 March 2018].

US DOE, 2016a. DOE Global energy database. [Online] Available at: *http://www.energystorageexchange.org/projects/data_visualization* [Accessed 20 February 2018].

US DOE, 2016b. Hydropower Vision - Executive Summary, s.l.: United States Department Of Energy.

US DOE, n.d.. Types of Hydropower Turbines. [Online] Available at: *https://www.energy.gov/eere/water/types-hydropower-turbines_* [Accessed 9 March 2018].

van der Walle, E., 2018. Wie de balans verstoort moet dokken. [Online] Available at: *https://www.nrc.nl/nieuws/2018/05/04/wie-de-balans-verstoort-moet-dokken-a1601958* [Accessed 7 May 2018].

van Duivendijk, J., 2014. Water power engineering. April 2014 ed. Delft: Faculty CiTG, Lecture notes CT5304.

van Gastel, E., 2017. Energieopslag wint fors terrein. Smart Storage magazine, Volume 4, p. 3.

van Leeuwen, M., 2016. Gemiste kans voor opslag in geplande wet energietransitie, Amsterdam: Energeia.

van Werven, M. & van Oostvoorn, F., 2006. Barriers and drivers of new interconnections between EU and non-EU electricity systems, Petten: Energy research Centre of the Netherlands (ECN).

Verbong, G. & Geels, F., 2007. The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960-2004). Energy Policy, Issue 35, pp. 1025-1037.

Vestergaard, J., Brandstrup, L. & Goddard, R., 2004. A Brief History of the Wind Turbine Industries in Denmark and the United States. Academy of International Business (Southeast USA Chapter) Conference Proceedings, pp. 322-327.

Voith, n.d.. Pumped storage machines – Reversible pump turbines, Ternary sets and Motor-generators, Alexanderstrasse 11, 89522 Heidenheim, Germany: Voith Hydro Holding GmbH & Co. KG.

Vorarlberger Illwerke AG , 2016. Kopswerk II. [Online]
Available at: *https://www.illwerke.at/kopswerk-2.htm*
[Accessed 13 March 2018].

Vrijling, J. & Theunissen, R., 2015. Is probabilistisch ramen een wetenschap?. COSTandVALUE, pp. 36-39.

Vrijling, J. & Verlaan, J., 2013. Financial Engineering; collegedictaat 2300, Delft: Technische Universiteit Delft.

Wassink, J., 2008. Plan Lievense eigenlijk bedoeld voor kernenergie. Delta. TU Delft, 40(6).

WEC, 2016. E-storage: Shifting from cost to value wind and solar applications, London, Cornhill: World Energy Council.

Whittingham, M., 2008. Materials challenges facing electrical energy storage. MRS Bulletin , Issue 33, pp. 411-419.

Wikimedia Commons, 2014. File: Prinzip Pumpspeicherkraftwerk.svg. [Online]
Available at: *https://commons.wikimedia.org/wiki/File:Prinzip_Pumpspeicherkraftwerk.svg*
[Accessed 19 March 2018].

Wikipedia, 2018. List of countries by electricity consumption. [Online]
Available at: *https://en.wikipedia.org/wiki/List_of_countries_by_electricity_consumption*
[Accessed 19 March 2018].

Windstats, n.d.. Statistieken. [Online]
Available at: *https://windstats.nl/statistieken/*
[Accessed 29 March 2018].

Worldometers, 2018. Denmark population. [Online]
Available at: *http://www.worldometers.info/world-population/denmark-population/*
[Accessed 23 July 2018].

Yang, C., 2016. Pumped Hydroelectric Storage. In: T. Letcher, ed. Storing energy. Amsterdam: Elsevier, pp. 25-38.

Zafirakis, D., Chalvatzis, K., Baiocchi, G. & Daskalakis, G., 2016. The value of arbitrage for energy storage: Evidence from European electricity markets. Applied Energy, Issue 184, pp. 971-986.

Zakeri, B. & Syri, S., 2015. Electrical energy storage systems: A comparative life cycle cost analysis. Renewable and Sustainable Energy Reviews, Issue 42, pp. 569-596.

Zanter, F., 2013. Erweiterung Pumpspeicherkraftwerk Vianden, Neubau M11, RWTH Aachen 2013: WASA, Wasser als Energieträger, 10. und 11. Januar 2013, Internationales Wasserbau-Symposium.

Zhao, H. et al., 2015. Review of energy storage system for wind power integration support. Applied Energy , Issue 137, pp. 545-553.

Curriculum vitae

Curriculum vitae

Dr Johannes Marie Hubert Huynen, born on 18 July 1932 in Valkenburg, the Netherlands, is married and has 5 children. He grew up in a business family that had to cope with the crisis of the thirties, followed by the German occupation during World War II. During his school years, he witnessed the destabilization in the war years and eventually the liberation by the American forces.

After finishing primary and secondary education, he enrolled in the Hotelschool The Hague, from which he graduated in 1950. His working experience eventually brought him to Hilton International New York in 1956, where he specialized in convention management.

Back in the Netherlands, he founded the event and congress centre Eurohal in Valkenburg in 1961.

In spite of his duties as an entrepreneur, he started studying economics at Hogeschool Tilburg (now Tilburg University) in 1967. He graduated with distinction from the LUC (Limburgs Universitair Centrum, Hasselt) in 1972 with a licentiate in Economics (equivalent to master's degree).

The doctor's degree in social sciences was conferred on him in 1973 by the Rijksuniversiteit Utrecht (now Utrecht University) for his thesis Trends in Trade Fairs. Professor Sj. Groenman, rector, and Professor J.A. Geertman (Tilburg University) were his supervisors.

In the same year, the Eurohal moved from Valkenburg to Maastricht as a start-up for what later became the exhibition and congress centre MECC Maastricht, which he founded in 1985. He also initiated the world's largest art fair TEFAF. From 1985, his interest turned to technology and specifically to the electromechanical company ACEC (Ateliers de Constructions Électriques de Charleroi), which was, among other things, a manufacturer of hydro power equipment. He was vice president of ACEC until 1989. In this function, he was a partner in the OPAC project. In 2006, he re-opened the OPAC files, anticipating the growing need to make our energy supply sustainable.

During the last decades, he founded and led several international enterprises in various fields, from ICT to biotechnology. Despite being of pensionable age, he prefers to keep working on multidisciplinary innovative projects, together with other generations. He is a promoter of the cross-border cooperation between the universities of Maastricht, Aachen, Liège and Hasselt.

He is Officer in the Order of Orange-Nassau, Knight of the Legion of Honour of the French Republic and was awarded the Honorary Gold Medal of the City of Maastricht.

Abbreviations

2DS	2 °C scenario (climate scenario from IEA)
3D	three-dimensional
AA-CAES	advanced adiabatic compressed air energy storage
AC	alternating current
AC/DC	alternating current/ direct current
ADECCO-RS	analysis of controlled deformation in rocks and soils
aFRR	automatic frequency restoration reserve
AS	adjustable speed
AUD	Australian dollar
BES	battery energy storage
BEV(s)	battery electric vehicle(s)
BHA	bottom hole assembly
BRPs	balance responsible parties
BSP	balancing service provider
CAES	compressed air energy storage
CBA	cost-benefit analysis
CCGT(s)	combined cycle gas turbine(s)
CCS	carbon capture and storage
CEO(s)	chief executive officer(s)
CF	capacity factor
CHP	combined heat and power
CO_2	carbon dioxide
COP21	21st conference of the parties
D&D	development and demonstration
DC	direct current
DFIM	doubly fed induction machine
DG&S	distributed generation and storage
DoD	depth of discharge
DR	demand response
Dr	doctor *(equivalent to the PhD title)*
DSM	demand-side management
DSO(s)	distribution system operator(s)
e.g.	exempli gratia
EES	electric energy storage

ETP	energy technology perspectives
EU ETS	the European Union emissions trading system
EUA	EU emission allowance
EV(s)	electric vehicle(s)
EXPLORE	European x-border project for long term real-time balancing electricity market design
FCEV(s)	fuel cell electric vehicle(s)
FCR	frequency containment reserve
FES	flywheel energy storage
FID	final investment decision
FLES	flatland electricity storage
FLEXNET	flexibility of the power system in the Netherlands
FRR	frequency restoration reserve
FS	fixed speed
GHG	greenhouse gas
H_2	hydrogen
H_2O	water *(chemical name: dihydrogen monoxide)*
ha	hectare
HEV(s)	hybrid electric vehicle(s)
HP	horsepower
HVAC	high-voltage alternating current
Hz	hertz
i.e.	id est
ICT	information and communications technology
Ir	engineer *(from Dutch: ingenieur)*
IT	information technology
LA	lead-acid
LCOE	levelized cost of electricity
LCOS	levelized cost of storage
Li-ion	lithium-ion
MARI	manually activated reserves initiative
mFRR	manual frequency restoration reserve
mFRRda	manual frequency restoration reserve direct activated
mFRRsa	manual frequency restoration reserve schedule activated

MOU	memorandum of understanding
MP	Member of Parliament
MSK	Medvedev-Sponheuer-Karnik scale
Mt	megatonne (is equal to 1 million metric ton)
mwc	metres water column
n.d.	no date
NaS	sodium-sulphur
NATM	new Austrian tunnelling method
NDCs	nationally determined contributions
NEOM	Netherlands energy development agency *(abbr. from Dutch: Nederlandse energie ontwikkelings maatschappij)*
NEV	national energy outlook *(abbr. from Dutch: nationale energieverkenning)*
NH_3	ammonia *(chemical name: nitrogen trihydride)*
NiCd	nickel-cadmium
NIP	national innovation programme
NW	north western
O&M	operation and maintenance
OPAC	ondergrondse pomp accumulatie centrale (project group with collaboration between Delft University of Technology, Haskoning and Koninklijke Volker Stevin)
O-PAC	underground pump accumulation plant *(abbr. from Dutch: ondergrondse pomp accumulatie centrale)*
OPEX	operational expenditure
P2G	power-to-gas
PAC	pomp accumulatie centrale (low-head PHS solution developed simultaneously with OPAC)
PHEV(s)	plugin hybrid electric vehicle(s)
PHS	pumped hydro storage
PICASSO	platform for the international coordination of automated frequency restoration and stable system operation
PNL	perspectives note Limburg
PPP	public-private partnership
PSB	polysulfide bromide battery
PV	photovoltaic
R&D	research and development
rpm	revolutions per minute
RR	replacement reserve
SCES	super capacitor energy storage

SDE+	stimulation renewable energy production *(abbr. from Dutch: stimulering duurzame energieproductie)*
SEM	sequential excavation method
SiO_2	silicon dioxide
SMES	superconducting magnetic energy storage
SNG	synthetic natural gas
SNM	smart network management
SRMC	short-run marginal costs
StEnSea	storing energy at sea
T&D	transmission and distribution
TBM(s)	tunnel boring machine(s)
TSO(s)	transmission system operator(s)
U-PHS	underground pumped hydro storage
UPS	uninterrupted power supply
USD	United States dollar
V2G	vehicle-to-grid
VRB	vanadium redox flow battery
VRE	variable renewable electricity
WACC	weighted average cost of capital
WEU	Western Europe
ZnBr	zinc-bromine

Appendices

Appendix I – Identification of potential locations for U-PHS: Denmark

As commonly known, pumped hydro storage (PHS) is the largest and most mature type of electricity storage. This type of storage is highly limited in its worldwide application by the requirement for natural height differences. In this context, underground pumped hydro storage (U-PHS) is introduced as a solution because it can facilitate flatland electricity storage (FLES). There are a number of important criteria for U-PHS to make a location suitable for its installation. These criteria can be divided into aboveground and subsurface. For the subsurface, the following is of importance:

1. the presence of a sufficiently thick and strong rock layer that allows cost-efficient construction of the facility
2. the layer must be homogenous, without strong fracturing and karstification
3. located at a depth between 1,000 and 1,500 metres

The subsurface criteria limit the possible sites for an underground reservoir, while the surface criteria address the need for electricity storage at a location where infrastructural costs can be limited. The surface criteria for a suitable location are as follows:

1. availability of renewable energy sources, i.e. large solar and wind capacity
2. the availability of demand, e.g. metropolitan areas
3. near a high-voltage electricity grid node

Of the above criteria, the most important are the need for storage and the stability of suitable rock at a suitable depth. Without these, the construction or need for storage on a scale like U-PHS will not be possible or beneficial to the power system. The following chapter presents a brief analysis on the potential in Denmark as an example in Europe.

Denmark shows potential for U-PHS for a limited number of areas with the geologic characteristics that seem suitable for underground storage, as will be detailed further below.

Subterranean criteria

Geology

The geology of Denmark is characterized by the centrally located Norwegian-Danish Basin, where the sedimentary succession is up to 10 km thick. This basin is bounded to the north and north-east by the Fennoscandian Border Zone (Sorgenfrei-Tornquist Zone and Skagerrak-Kattegat Platform) and to the north-west/south-east by the basement high, the Ringkøbing-Fyn High. With 1-2 km, the sediment layers on these highs are relatively thin, and stronger basement rocks are close to the surface. The North German Basin is located south of the basement high, which has sediment layers that have a similar thickness to the Danish Basin (Nordic CCS Competence Centre, n.d.).

The geological map in Figure 1 shows that potential sites for U-PHS are limited in central Denmark, due to thick sedimentary layers and major salt tectonics. However, the most northern, the extreme eastern and the southern parts of Denmark may have suitable locations for U-PHS, because sediments are thin and pre-Zechstein layers can be found at relatively shallow depths. At these locations, there could be homogenous rock available at a suitable depth between 1,000 to 1,500 metres.

Nevertheless, core drillings and 3D seismic research will be required to determine in detail if the subsurface criteria are met, and detailed geological research is needed to ensure that the structural stability is sufficient for creating a subterranean water reservoir at an initially suitable location.

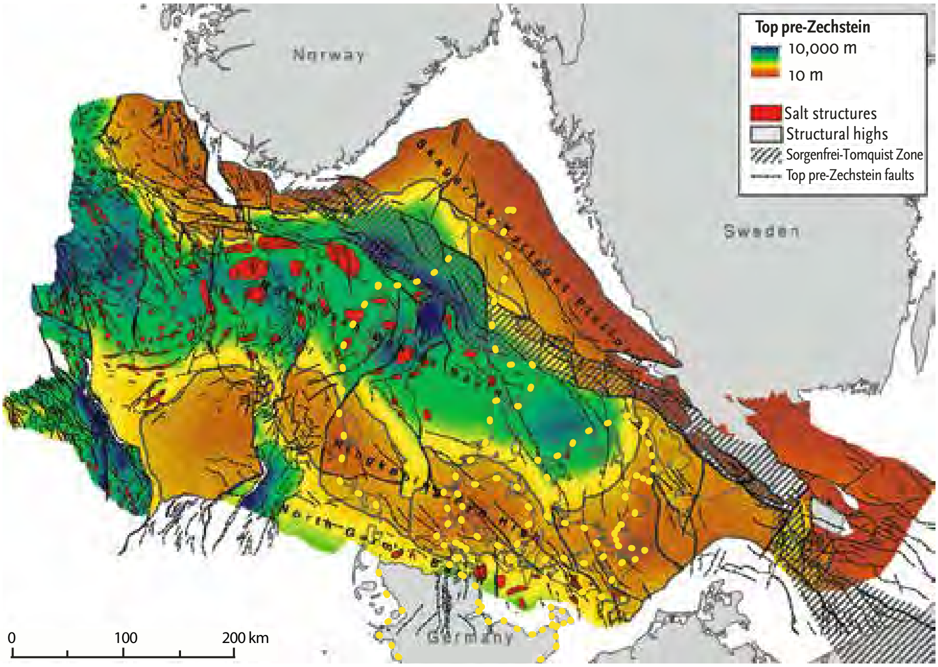


Figure 1 – Map with the major structural elements and depth to the top of the pre-Zechstein in Denmark (Nordic CCS Competence Centre (n.d.), via URL: https://data.geus.dk/nordiccs/geology.xhtml)

Surface criteria

VRE resources in the Danish power system

Denmark is a country that pioneered in the development of wind power; its first wind turbine was built in 1891. This interest in wind power was driven by a lack of domestic natural energy sources such as fossil fuels and water falls for hydropower (Vestergaard, et al., 2004). Already in the late 1970s, the first grid-connected wind turbines contributed to electricity production in Denmark. The development of wind capacity in Denmark is presented in Figure 2. These achievements are especially spectacular when keeping in mind that Denmark is only a small EU country with 5.8 million inhabitants (Worldometers, 2018).

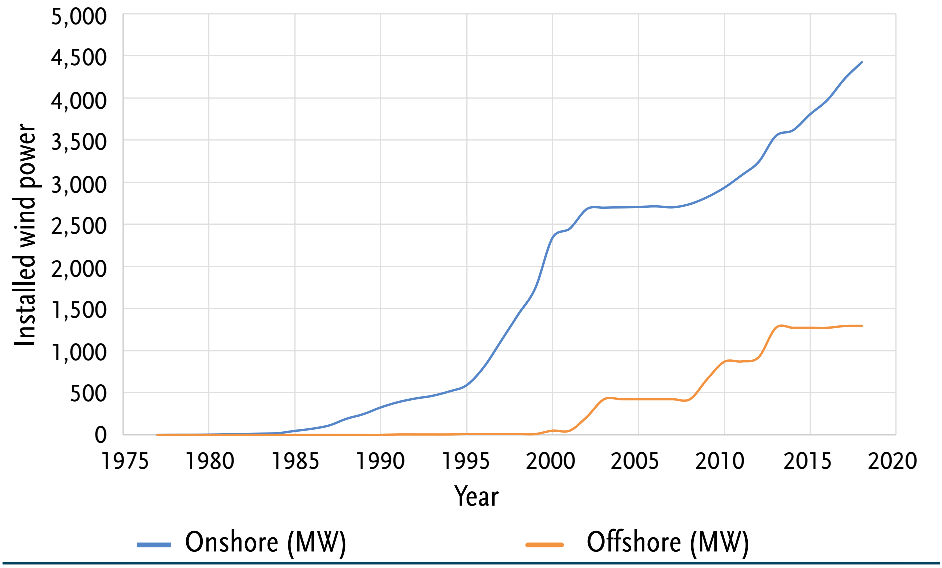


Figure 2 *– Growth of installed onshore and offshore wind power in Denmark based on data from the Danish Energy Agency (2018)*

The most recent figures available from the Danish Energy Agency (2018) show an onshore capacity of 4,423 MW and an offshore capacity of 1,294 MW, totalling 5,717 MW. Installed wind power is substantially larger than solar power in Denmark. The total amount of installed solar power was limited to 601 MW, according to the data for Denmark in 2017, based on data available on ENTSO-E (2018a). The total production from wind turbines was 14.8 TWh in 2017, while the contribution of solar power was only 0.8 TWh (ENTSO-E, 2018b). In 2017, 43.24 % of the total consumption was produced by wind turbines, while 50.12 % of domestic electricity production was from wind power. This makes Denmark a frontrunner and one of the world leaders in wind power.

The exchange balance for Denmark is noteworthy, as 15.3 TWh of electricity was imported and 10,6 TWh was exported in 2017, resulting in a nett import of almost 5 TWh (ENTSO-E, 2018b). This exchange balance shows that domestic storage of electricity could be beneficial for the Danish power system, especially when considering the Danish future growth in offshore wind power capacity: The Horns Rev 3 wind farm with a rated capacity of 406.7 MW is expected to be commissioned in 2020 and two more nearshore projects (totalling 350 MW) are expected to be commissioned in 2019 (Danish Energy Agency, 2017). Additionally, Kriegers Flak is expected to be commissioned in 2021, which will be Denmark's largest wind farm with 600 MW of power output (Danish Energy Agency, 2017). For the more distant future, there are governmental plans for installing even more wind power. In 2021, a tender will be put out for an offshore wind farm of 800 MW, to be constructed between 2024 and 2027 (The Local, 2018; CPH Post Online, 2018).

The sites for offshore wind farms are presented in Figure 3. This figure is still relevant since only about 23 MW of new offshore wind power capacity has been installed since 2013 (Danish Energy Agency, 2018).

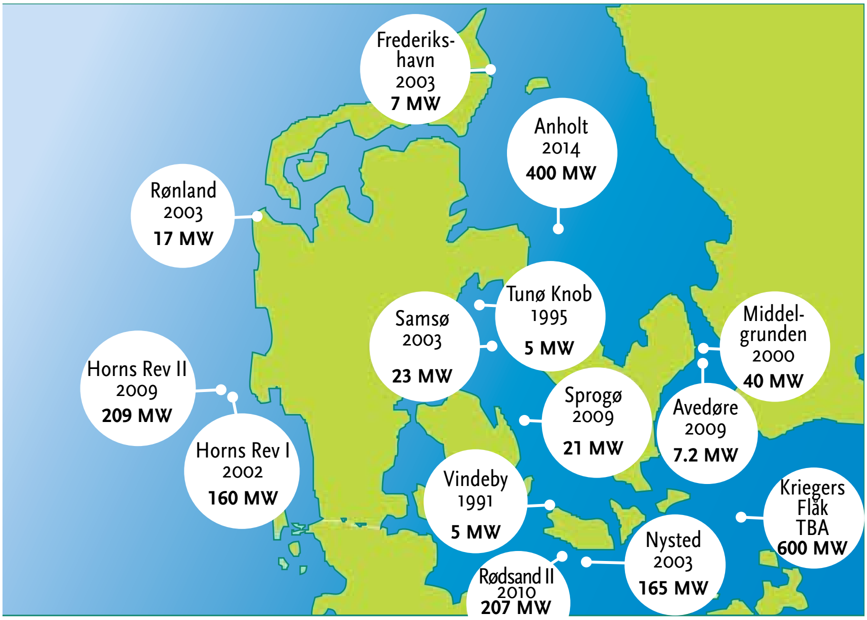


Figure 3 – *Map with offshore Danish wind farms (Reve (2014) via URL: https://www.evwind.es/2014/10/31/denmarks-offshore-wind-power-among-best-in-world-with-more-growth-by-2020/48438). Horns Rev 3 will be located north of the earlier Horns wind farms, Rev 1 and 2*

Populated areas

The population in Denmark is mainly concentrated around the main cities: with the main city of Aalborg in the north and also some population concentrated around Frederikshavn. To the south-west, the population is concentrated around the city of Esbjerg. In the centre of the country, the population is concentrated around the cities of Aarhus and Odense, and to a lesser extent around the city of Vejle. To the east, the population is largely in Copenhagen and Roskilde.

A suitable subterranean location around these areas would be preferable as high-voltage grid connections are available (compare Figure 4 with Figure 5).

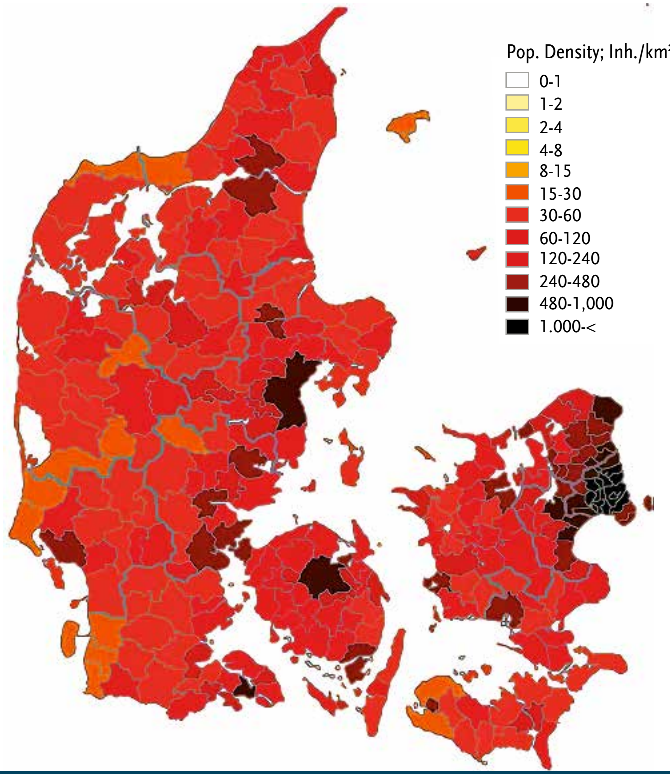


Figure 4 – *Chart with the population density in Denmark (via URL: https://nl.pinterest.com/pin/312015080425420409/)*

Grid connections

The Danish grid is, similarly to the Dutch grid, highly interconnected with neighbouring countries, as can be seen in Figure 5. The high-voltage alternating current (HVAC) domestic grid covers most of the country and does not seem to be a limiting factor for connecting a U-PHS in the Danish power system.

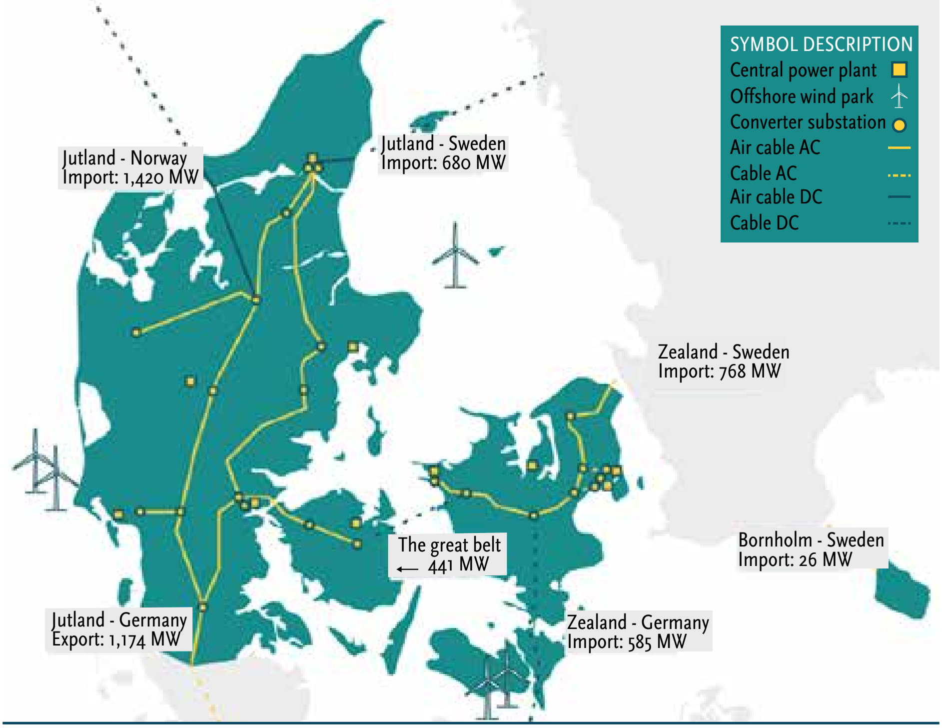


Figure 5 – *Danish high-voltage grid map, from energinet.dk (2018), via URL https://en.energinet.dk/. A more detailed electricity grid map is available from ENTSO-E, named the "ENTSO-E Transmission System Map" (ENTSO-E, n.d.1)*

Conclusions

Summarizing the findings in this short survey for potential sites for U-PHS in Denmark, it can be concluded that in the extreme north, the area around Frederikshavn and potentially Aalborg may be suitable, because of the shallow depth of potentially suitable basement rocks. In the east, the area around Copenhagen and Roskilde seems suitable, because south of this area a large offshore wind farm (Kriegers Flak) is under construction and the geology may have suitable rock formations. In the south, the area around Esbjerg seems the most suitable, as there is a large availability of wind power (Horns Rev wind farms) and the basement high may exhibit potentially stable rock formations at a suitable depth.

The grid in Denmark seems to be highly suitable for connecting U-PHS in the power system, while the population density is limited throughout Denmark. However, the areas identified for U-PHS are typically near the larger cities in Denmark, which have an electricity demand and probably an increasing demand for storage as a fully VRE-based electricity system comes ever closer.

In conclusion, Denmark presents the optimal preconditions for exploring an underground FLES (Flatland Electricity Storage) system, based on mature engineering research for balancing the grid, and at the same time significantly reducing the dependence on interconnections with other countries.

Appendix II – Table of PHS plants larger than 500 MW

Based on the US DOE global energy storage database (US DOE, 2016a)

Name/location pumped hydro storage plant	Rating (in MW)	Country	Commissioning date
Fengning	3,600	China	1-12-2021
Kannagawa	2,820	Japan	1-1-2020
Jixi (绩溪抽水蓄能电站)	1,800	China	1-12-2018
Upper Cisokan	1,040	Indonesia	1-1-2018
Sardar Sarovar	1,450	India	17-9-2017
Linthal 2015 (Linth-Limmern Expansion)	1,000	Switzerland	31-3-2017
Liyang	1,500	China	13-1-2017
Nant de Drance	900	Switzerland	1-1-2017
Aguayo II	1,014	Spain	1-1-2017
Tehri	1,000	India	31-12-2016
Venda Nova III	736	Portugal	31-12-2016
Frades II	778	Portugal	31-12-2016
Ingula	1,332	South Africa	1-12-2016
Hongping	2,400	China	1-12-2016
Dniester	2,268	Ukraine	21-12-2015
Qingyuan	1,280	China	1-12-2015
Xianju (仙居)	1,500	China	1-1-2015
Zagorsk PSP-2	840	Russia	1-12-2014
Hohhot	1,224	China	20-11-2014
Kazunogawa	1,600	Japan	9-6-2014
Alqueva	520	Portugal	31-12-2013
Xianyou	1,200	China	20-12-2013
La Muela 2	852	Spain	14-10-2013
Siah Bishe	1,040	Iran	1-1-2013

Pushihe	1,200	China	29-9-2012
Baoquan	1,200	China	15-12-2011
Yecheon	800	Korea, South	1-12-2011
Xiangshuijian (响水涧抽水蓄能电站)	1,000	China	14-8-2011
Omarugawa	1,200	Japan	1-7-2011
Huizhou	2,448	China	15-6-2011
Heimifeng	1,200	China	1-10-2010
Bailianhe	1,200	China	21-11-2009
Xilongchi	1,200	China	16-10-2009
Kops II	525	Austria	1-5-2009
Zhanghewan	1,000	China	1-2-2009
Yixing	1,000	China	1-12-2008
Purulia	900	India	1-2-2008
Langyashan (琅琊山抽水蓄能电站)	600	China	1-12-2007
Tai'an	1,000	China	20-12-2006
Yangyang	1,000	Korea, South	12-9-2006
Cheongsong	600	Korea, South	1-9-2006
Tongbai	1,224	China	1-1-2006
Baishan (白山)	1,800	China	1-11-2005
Goldisthal	1,060	Germany	20-10-2004
Caliraya-Botocan-Kalayaan (CBK)	709	Philippines	1-5-2004
Zagorsk PSP-1	1,200	Russia	5-11-2003
Lam Ta Khong	500	Thailand	1-1-2002
Sancheong	700	Korea, South	28-9-2001
Tianhuangping	1,836	China	25-12-2000
Kruonis	900	Lithuania	19-12-2000
Guangzhou	2,400	China	1-6-2000
Okutataragi	1,932	Japan	1-6-1998
Shisanling (Ming Tombs)	800	China	1-6-1997
Dlouhé Stráně	650	Czech Rep.	20-6-1996
Matanogawa	1,200	Japan	1-4-1996
Okikuyotsu (Okukiyotsu) No. 2	600	Japan	1-1-1996
Okumino	1,500	Japan	1-11-1995

Muju	600	Korea, South	28-2-1995
Rocky Mountain	1,095	United States	1-1-1995
Chaira	788	Bulgaria	1-1-1995
Shiobara	900	Japan	1-1-1994
Mingtan Dam	1,600	Taiwan	1-1-1994
Srinagarind	720	Thailand	1-1-1991
Domenico Cimarosa (Presenzano)	1,000	Italy	1-1-1991
Anapo (Solarino)	600	Italy	1-1-1991
Bad Creek	1,065	United States	1-1-1991
La Muela 1	635	Spain	1-1-1989
Imaichi	1,050	Japan	1-7-1988
Tenzan	600	Japan	1-1-1987
Grand'Maison Dam PHS	1,820	France	1-1-1987
Tamahara	1,200	Japan	1-7-1986
Rio Grande-Cerro Pelado	750	Argentina	14-2-1986
Saurdal	640	Norway	1-1-1986
Super Bissorte	748	France	1-1-1986
Bath County	2,100	United States	1-12-1985
Nagarjuna Sagar	700	India	1-12-1985
Samrangjin	600	Korea, South	1-11-1985
Minghu	1,008	Taiwan	1-8-1985
Richard B. Russell	600	United States	1-1-1985
Edolo	1,000	Italy	1-1-1985
Helms	1,212	United States	30-6-1984
Dinorwig	1,728	UK	1-1-1984
Hongawa (Motokawa)	615	Japan	1-1-1984
Wivenhoe	500	Australia	1-1-1984
Żarnowiec	716	Poland	1-1-1983
Montézic	910	France	1-12-1982
Bajina Basta	614	Serbia	23-9-1982
Okikuyotsu (Okukiyotsu)	1,000	Japan	1-1-1982
Tanbara	1,200	Japan	1-1-1982
Drakensberg	1,000	South Africa	1-5-1981
Okuyahagi No. 2	780	Japan	1-2-1981
Srisailam	1,670	India	1-1-1981

Čierny Váh	735	Slovakia	1-1-1981
Chiotas plant (Entracque power plant)	1,184	Italy	1-1-1981
Shin-Takasegawa	1,280	Japan	1-5-1980
Okuyoshino	1,206	Japan	1-1-1980
Malta Main Stage	730	Austria	1-1-1979
Porabka-Zar	500	Poland	1-1-1979
Markersbach	1,050	Germany	1-1-1979
Coo-Trois-Ponts	1,164	Belgium	1-1-1979
Fairfield	511	United States	1-12-1978
Raccoon Mountain	1,652	United States	1-1-1978
Nabara	620	Japan	1-1-1976
Revin	800	France	1-1-1976
Wehr	910	Germany	1-1-1976
Ohira	500	Japan	1-1-1975
Bear Swamp	600	United States	1-1-1974
Jocassee	710	United States	19-12-1973
Blenheim-Gilboa	1,160	United States	1-7-1973
Numappara	675	Japan	1-6-1973
Ludington	1,872	United States	1-1-1973
San Fiorano	568	Italy	1-1-1973
Roncovalgrande (Lago Delio)	1,000	Italy	1-1-1973
Tumut 3	1,500	Australia	1-1-1973
Castaic	1,247	United States	1-1-1973
Northfield Mountain	1,168	United States	1-1-1972
Kyivska (Kijev)	603	Ukraine	1-1-1972
Shin Toyone	1,125	Japan	1-1-1972
Villarino (Almendra)	810	Spain	1-1-1970
Azumi, Inekoki Dam	623	Japan	1-1-1969
Edward Hyatt (Oroville)	819	United States	1-1-1967
Smith Mountain PHS	560	United States	7-3-1966
Muddy Run	1,070	United States	1-1-1966
Vianden	1,096	Luxembourg	17-4-1964
Aldeadávila	718	Spain	1-1-1962
Grimsel 3	600	Switzerland	
Lago Bianco	1,000	Switzerland	

Appendix III – Motion Hessels c.s.

Energierapport 2008

31 510

MOTIE VAN HET LID HESSELS C.S.

Voorgesteld tijdens het Notaoverleg van 17 november 2008

De Kamer,

gehoord de beraadslaging,

overwegende, dat een verregaande toename van duurzame en decentrale opwekking van elektriciteit zal leiden tot een groot beroep op de balanceringscapaciteit van het elektriciteitsnet;

overwegende, dat opname van een grootschalige elektriciteitsbuffer in de hoofdinfrastructuur een belangrijk aandeel zou kunnen hebben binnen de benodigde balanceringscapaciteit;

overwegende, dat deelname door netbeheerder TenneT in een dergelijke grootschalige elektriciteitsbuffer in lijn zou zijn met de taakopdracht van TenneT om het net te balanceren, waarbij TenneT maximaal de elders te besparen kosten voor balanshandhaving kan inbrengen;

spreekt uit dat het wenselijk is dat – indien een dergelijke grootschalige elektriciteitsbuffer binnen een privaat project gerealiseerd wordt – deze buffer opgenomen wordt in het landelijk elektriciteitsnet;

verzoekt de regering te bevorderen dat netbeheerder TenneT omwille van de balancering van het net zal participeren binnen een project om een grootschalige elektriciteitsbuffer aan te leggen,

en gaat over tot de orde van de dag.

Hessels, Samsom, Wiegman-van Meppelen Scheppink

KST124652
0809tkkst31510-5
ISSN 0921 - 7371
Sdu Uitgevers
's-Gravenhage 2008

Motie Hessel c.s. translated to English

MOTION FOR A RESOLUTION TABLED BY MP HESSELS AND OTHER MEMBERS

during the consultation of 17 November 2008 about the Energy Policy Memorandum.

The House, having heard the deliberations, being aware that

a far-reaching increase in sustainable and decentralized generation of electricity will lead to a large demand for balancing capacity of the electricity grid;

the inclusion of a large-scale power buffer in the main infrastructure could have a considerable share in the required balancing capacity;

participation by grid manager TenneT in such a large-scale electricity buffer would be in line with TenneT's task to balance the grid, with TenneT being able to contribute to the balancing with a maximum of costs saved elsewhere;

states that it is desirable that – if such a large-scale electricity buffer is realized within a private project – this buffer is included in the national electricity grid;

calls on the government to promote that grid operator TenneT will participate in a project to build a large-scale electricity buffer for the sake of balancing the grid,

and will proceed with the order of the day.

Hessels
Samsom
Wiegman-van Meppelen Scheppink