D10 Report

Long Term Potentials and Costs of RES

Part I: Potentials, Diffusion and Technological learning

Authors:
Ric Hoefnagels, Martin Junginger, COPERNICUS INSTITUTE / UTRECHT UNIVERSITY
Christian Panzer, Gustav Resch, EEG / TU VIENNA
Anne Held, FRAUNHOFER ISI

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Fraunhofer ISI	Fraunhofer Institute for Systems and Innovation Research (ISI), Germany *(Project coordinator)*
Energy Economics Group	Vienna University of Technology, Institute of Power Systems and Energy Economics, Energy Economics Group (EEG), Austria
ECOFYS	Ecofys b.v. (Ecofys), The Netherlands
DIW BERLIN	DIW Berlin, Department of Energy, Transportation and Environment (DIW), Germany
LEI	Lithuanian Energy Institute (LEI), Lithuania
Universiteit Utrecht	Utrecht University, The Netherlands
Energo Banking	Energy Banking Advisory Ltd., Hungary
KEMA	KEMA, The Netherlands
Università Commerciale Luigi Bocconi	Bocconi University, Italy

RE-Shaping

Shaping an effective and efficient
European renewable energy market

The core objective of the RE-Shaping project is to assist Member State governments in preparing for the implementation of Directive 2009/28/EC and to guide a European policy for RES in the mid- to long term. The past and present success of policies for renewable energies will be evaluated and recommendations derived to improve future RES support schemes.

The core content of this collaborative research activity comprises:

- Developing a comprehensive policy background for RES support instruments.
- Providing the European Commission and Member States with scientifically based and statistically robust indicators to measure the success of currently implemented RES policies.
- Proposing innovative financing schemes for lower costs and better capital availability in RES financing.
- Initiation of National Policy Processes which attempt to stimulate debate and offer key stakeholders a meeting place to set and implement RES targets as well as options to improve the national policies fostering RES market penetration.
- Assessing options to coordinate or even gradually harmonize national RES policy approaches.

Contact details:

<< Project coordinator >>

Mario Ragwitz
Fraunhofer Institute for
Systems and Innovation Research
Breslauer Str. 48
D-76139 Karlsruhe
Germany
Phone: +49(0)721/6809-157
Fax: +49(0)721/6809-272
Email: mario.ragwitz@isi.fraunhofer.de

<< Lead author of this report >>

Ric Hoefnagels
Copernicus Institute – Utrecht University

Budapestlaan 6
3584 CD Utrecht
The Netherlands
Phone: +31(0)30-2537645
Fax: +31(0)30-2537601
Email: r.hoefnagels@uu.nl

This report

provides first findings on the assessment of long-term potentials and cost for renewable energies. With this, we aim to contribute to the creation of a long term vision beyond 2020 for the renewable energy sector.

Authors:
Ric Hoefnagels, Martin Junginger, COPERNICUS INSTITUTE / UTRECHT UNIVERSITY
Christian Panzer, Gustav Resch, EEG / TU VIENNA
Anne Held, FRAUNHOFER ISI

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Table of Contents

Page

Figures

Tables

1 Introduction

Europe requires a long term vision for Renewable Energy Sources (RES) in order to pave the way for a successful and in the mid-term stable RES deployment beyond 2020. This encompasses, on the one hand, an assessment of the mid-term potentials and diffusion constraints for the broad basket of RES options at technology and country level within the EU 27. On the other hand, expected future RES cost are subject of investigation. Consequently, a comprehensive analysis of technological change, in particular with regard to technological learning and corresponding uncertainties is required to support the long term vision of a future renewable energy sector.

This report aims to provide the background information to form the long term vision beyond 2020 for the renewable energy sector. Derived objectives are:

- Refinement and extension of the long term potentials for renewable energy sources in the Green-X database;
- Update and further elaboration of diffusion characteristics of new renewable energy technologies;
- Update and proper model-incorporation of mid-term cost development trajectories of renewable energy technologies including correlations between high energy and raw material prices and RES cost as observed in the past, where a decomposition of key drivers for the historic cost developments (i.e. technological learning versus increasing raw material / energy prices) aims to provide improved explanation of cost developments.

The structure of this report is as follows. The methodology and results for the assessment of mid-term potentials for renewable energy sources in Europe are discussed in chapter 2. Chapter 3 presents the update of technology diffusion characteristics. Chapter 4 deals with a review of current knowledge on technological learning of RES technologies and the methodology and results for incorporating the impact of energy and raw material prices in the learning curves. Chapter 5 presents conclusions related to above described activities.

2 Long term potentials for renewable energy sources in Europe

Nowadays, a broad set of different renewable energy technologies exists. Obviously, for a comprehensive investigation of the future development of RES it is of crucial importance to provide a detailed investigation of the country-specific situation with respect to the potential of the certain RES technologies in general as well as their regional distribution and the corresponding generation cost.

This section depicts first outcomes on the assessment of long term potentials for RES in Europe. Notably, the potential assessment is an ongoing process within the RE-Shaping project and further calibration of the outcomes with respect to infrastructural prerequisites as researched within work package 6 of this project are currently being conducted. Nevertheless, for key technology options (i.e. wind onshore, solar electricity from PV and biomass) the methodology used for the assessment and / or the corresponding preliminary outcomes are discussed.[1]

2.1 Background information

2.1.1 Classification of potential categories

We start with a discussion of the general background and subsequently present the status quo of consolidated data on potentials and cost for RES in Europe as applicable in the Green-X database. These figures indicate what appears to be realisable within the 2030 timeframe.

The possible use of RES depends in particular on the available resources and the associated costs. In this context, the term "available resources" or RES potential has to be clarified. In literature, potentials of various energy resources or technologies are intensively discussed. However, often no common terminology is applied. Below, we present definitions of the various types of potentials as used throughout this report:

- *Theoretical potential:* To derive the theoretical potential, general physical parameters have to be taken into account (e.g. based on the determination of the energy flow resulting from a certain energy resource within the investigated region). It represents the upper limit of what could be produced from a certain energy resource from a theoretical point-of-view, based on current scientific knowledge;

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[1] The potential estimation for wind onshore energy and solar PV electricity conducted within this project is mainly based on (Held, 2011).

- *Technical potential:* If technical boundary conditions (i.e. efficiencies of conversion technologies, overall technical limitations as e.g. the available land area to install wind turbines as well as the availability of raw materials) are considered, the technical potential can be derived. For most resources, the technical potential must be considered in a dynamic context. For example with increased R&D expenditures and learning-by-doing during deployment (see also chapter 4), conversion technologies might be improved and, hence, the technical potential would increase;

- Realisable potential: The realisable potential represents the maximal achievable potential assuming that all existing barriers can be overcome and all driving forces are active. Thereby, general parameters as e.g. market growth rates, planning constraints are taken into account. It is important to mention that this potential term must be seen in a dynamic context – i.e. the realisable potential has to refer to a certain year;

- Realisable potential up to 2030: provides an illustration of the derived realisable potential for the year 2030.

- Mid-term potential: in this report, long-term potentials refer to the 2050 timeframe and consequently what can be realised until then. Obviously, this is closely linked (among other constraining factors) to infrastructural prerequisites.

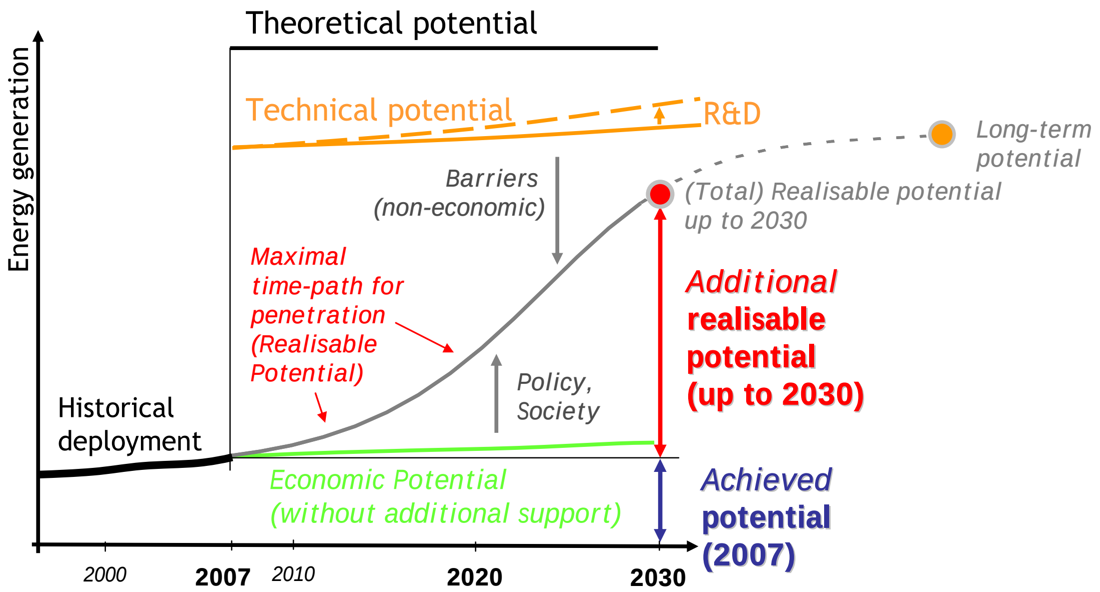

Figure 2-1 Definition of potential terms

Figure 2-1 shows the general concept of the realisable potential up to 2030 as well as in the mid-term (2050), the technical and the theoretical potential in a graphical way.

2.1.2 The starting point: The Green-X database on potentials and cost for RES in Europe

The input database of the Green-X model provides a detailed depiction of the achieved and feasible future deployment of the individual RES technologies in Europe – in particular with regard to costs and penetration in terms of installed capacities or actual & potential generation. Realisable future potentials (up to 2020 / 2030) are included by technology and by country. In addition, data describing the technological progress such as learning rates are available. Both serve as crucial input for the model-based assessment of future RES deployment. Thus, this database served as consistent basis for the assessment of mid-term potentials conducted within this project.

From a historical perspective, the starting point for the assessment of realisable RES potentials in Green-X was geographically the European Union as of 2001 (EU-15), where corresponding data was derived for all Member States (initially in 2001) based on a detailed literature survey and a development of an overall methodology with respect to the assessment of specific resource conditions of several RES options. Next, within the framework of the study "Analysis of the Renewable Energy Sources' evolution up to 2020 (FORRES 2020)" (see Ragwitz et al., 2005) comprehensive revisions and updates have been undertaken, taking into account reviews of national experts etc. Consolidated outcomes of this process were presented in the European Commission's Communication "The share of renewable energy" (European Commission, 2004). Within the scope of the EU research project futures-e again an intensive feedback process at the national and regional level was established. A series of six regional workshops was hosted by the futures-e consortium around the EU within 2008. The active involvement of key stakeholders and their direct feedback on data and scenario outcomes helped to reshape, validate and complement the previously assessed information.

Within the model *Green*-**X**, supply potentials of all main technologies for RES-E, RES-H and RES-T are described in detail.

- RES-E technologies include biogas, biomass, biowaste, onshore wind, offshore wind, small-scale hydropower, large-scale hydropower, solar thermal electricity, photovoltaics, tidal & wave energy, and geothermal electricity
- RES-H technologies include heat from biomass – subdivided into log wood, wood chips, pellets, and district heating -, geothermal heat and solar heat
- RES-T options include traditional biofuels such as biodiesel and bioethanol, advanced biofuels as well as the impact of biofuel imports

The potential supply of energy from each technology is described for each country analysed by means of *dynamic cost-resource curves*. Dynamic cost curves are characterised by the fact that the costs as well as the potential for electricity generation / demand reduction can change each year. The magnitude of these changes is given endogenously in the model, i.e. the difference in the values compared to the previous year depends on the outcome of this year and the (policy) framework conditions set for the simulation year.

Moreover, the availability of biomass is crucial as this energy is faced with high expectations with regard to its future potentials. The total domestic availability of solid biomass by 2030 was assessed at 245 Mtoe/yr. During the previous update as conducted throughout 2009 biomass data has been cross-checked with DG TREN, EEA and the GEMIS database[2]. As biomass may play a role in all sectors, also the allocation of biomass resources is a key issue. Within the Green-X model, the allocation of biomass feedstocks to feasible technologies and sectors is fully internalised into the overall calculation procedure. For each feedstock category, technology options (and their corresponding demands) are ranked based on the feasible revenue streams as applicable for a possible investor under the conditioned scenario-specific energy policy framework, which obviously may change year by year. In other words, the supporting framework may have a significant impact on the resulting biomass allocation and use.

2.1.2.1 Comparison of realisable potentials for RES in the short- to mid-term (2020 versus 2030)

According to the classification of the realisable potential in Figure 2-1 the identified short-term RES potential (2020) is compared in the following part to the assessment on the mid-term potential (2030). The potentials are discussed in relative terms (i) compared to the current (2005) demand and (ii) with respect to the growth rate compared to the 2020 short-term potential.

In France, Sweden and Germany, the contribution of RES to the final energy demand the EU27 is the highest among all Member States. Nevertheless, countries like Denmark, Estonia, Latvia or Sweden provide the most future RES resources up to 2030 expressed as percentage of the total energy demand, see Figure 2-2.

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[2] For example the EEA report "How much bio-energy can Europe produce without harming the environment?" (EEA, 2005) gives 235 Mtoe in 2020 for total biomass under the assumption of significant ecological constraints on biomass use.

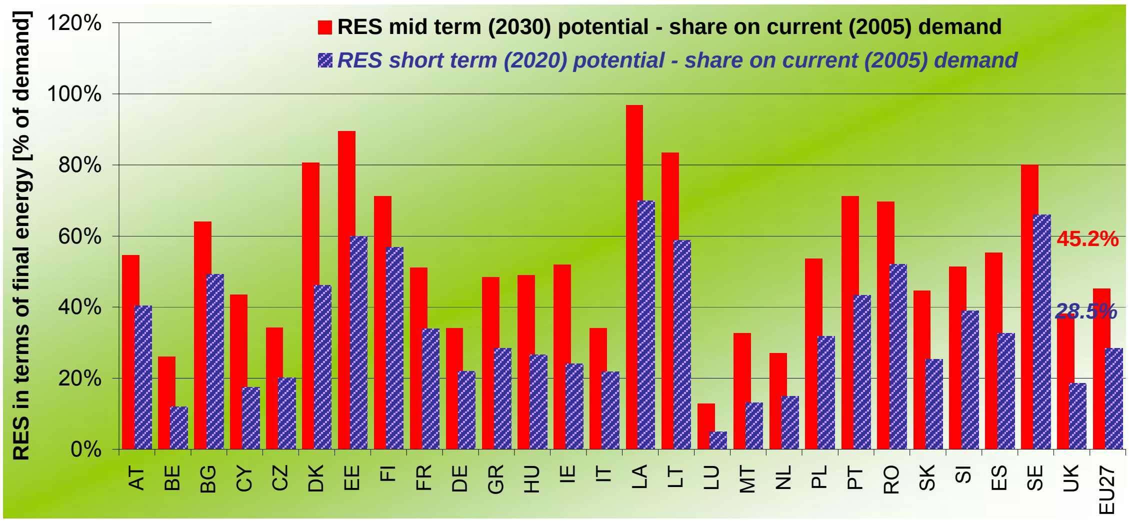

Figure 2-2 Comparison of short-term (2020) and mid-term (2030) realisable potential for RES in terms of (gross) final energy for all EU-27 Member States

In absolute figures, the total realisable mid-term potential of EU-27 countries up to 2030 is 554 Mtoe – an increase of 206 Mtoe compared to the short-term potential of 2020, whereof 352 Mtoe are distributed among the former EU-15 countries. In the EU-15, France contributes most, with a total potential of 85 Mtoe. Among the new Member States, high RES potentials are identified for Poland (32 Mtoe), Romania (19 Mtoe) and Hungary (9 Mtoe).

A comparison of the mid-term (2030) and short-term (2020) RES potential indicates an increase of realisable resources by 59% at EU level, whereas an unequal distribution of the additional potential is given. The strongest increase of 159% occurs in Luxembourg, followed by Malta (149%), Cyprus (148%), Belgium (118%), Ireland (116%) and the UK (105%).

Next, a closer look on the individual energy sectors is taken. As presented in Figure 2-3, the heat sector provides the largest exploitable potential up to 2020 (14.2% of the current final energy demand), followed by the electricity sector (11.1% of the current final energy demand). Figure 2-3 also depicts the feasible contribution of RES up to 2030 for RES in the transport, heat and electricity sector, measured in relative terms as share of current (2005) gross final energy demand. Consequently, in 2030, the largest potential is expected to be applicable for RES in the heat sector, rising from 14.2% (2020) to 22.1% (2030). Of similar magnitude is the increase for RES-electricity, while for biofuels in the transport sector growth perspectives are substantially smaller.

The strong increase of RES-E potentials beyond 2020 is mainly caused by the large additional realisable potential of wind energy, especially offshore wind, and the increased availability of novel technology options such as photovoltaics, tidal and wave energy. In the case of photovoltaics, more than a tripling of the realisable short-term (2020) potential is indicated. For tidal and wave energy as well as solar thermal electricity, even higher increases are assumed. However, wind onshore still provides the largest total potential among all RES-E options. In contrast, the potentials for large-scale hydropower and solid biomass remain almost stable beyond 2020. With respect to the heat similar increases in the period 2020 to 2030 are notable, while potentials for biofuels for transport purposes rise to a smaller extent - see Figure 2-3.

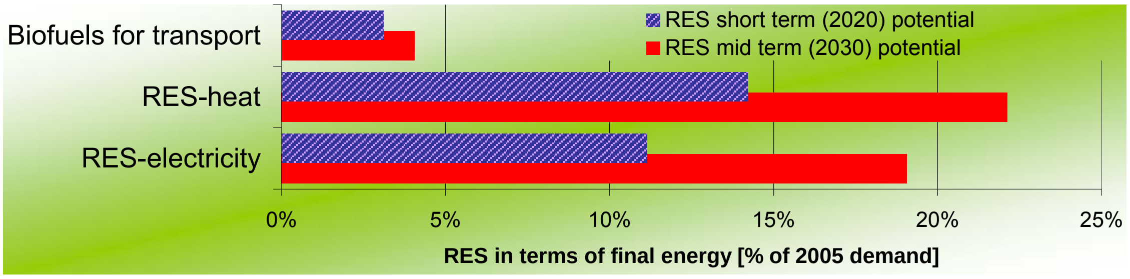

Figure 2-3 Sectoral breakdown of short-term (2020) and mid-term (2030) realisable potential for RES in terms of final energy at EU27 level – expressed in relative terms, as share on current (2005) (gross) final energy demand

2.1.2.2 Realisable mid-term (2030) potentials for RES in Europe

Figure 2-4 aims to illustrate to what extent RES may contribute to meet the energy demand within the European Union (EU-27) up to the year 2030 by considering the specific resource conditions and current technical conversion possibilities[3] as well as realisation constraints in the investigated countries. As explained before, *realisable mid-term potentials* are derived, describing the feasible RES contribution up to 2030. Thus, only the domestic resource base is taken into consideration – except for forestry biomass, where a small proportion of the overall potential refers to imports from abroad.[4]

Subsequently, an overview is given on the overall mid-term potentials in terms of final energy by country, followed by a detailed depiction as done exemplarily for electricity sector.

RES potentials in terms of (gross) final energy[5]

Summing up all RES options applicable at country level, Figure 2-4 depicts the achieved and additional mid-term potential for RES in all EU member states. Note that potentials are expressed in absolute terms. Consequently, large countries (or more precisely those member

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[3] The illustrated short-term potentials describe the feasible amount of e.g. electricity generation from combusting biomass feedstock considering current conversion technologies. Future improvements of the conversion efficiencies (as typically considered in model-based prospective analyses) would lead to an increase of the overall short-term potentials.

[4] Approximately 12.5% of the overall forestry potential or 30% of the additional forestry resources that may be tapped in the considered time horizon refer to such imports from abroad, see also section 2.4.

[5] (Gross) Final energy is hereby expressed in line with the definition as given in the proposal of the Renewable Energy Directive as published by the European Commission on the 23 January 2008.

states possessing large RES potentials) are getting apparent. For example, France, Germany, Italy, Poland, Spain, Sweden and the UK are comparable. To illustrate the situation in a suitable manner for small countries (or countries with a lack of RES options available), Figure 2-5 offers a similar depiction in relative terms, expressing the realisable mid-term potential as share on final energy demand.

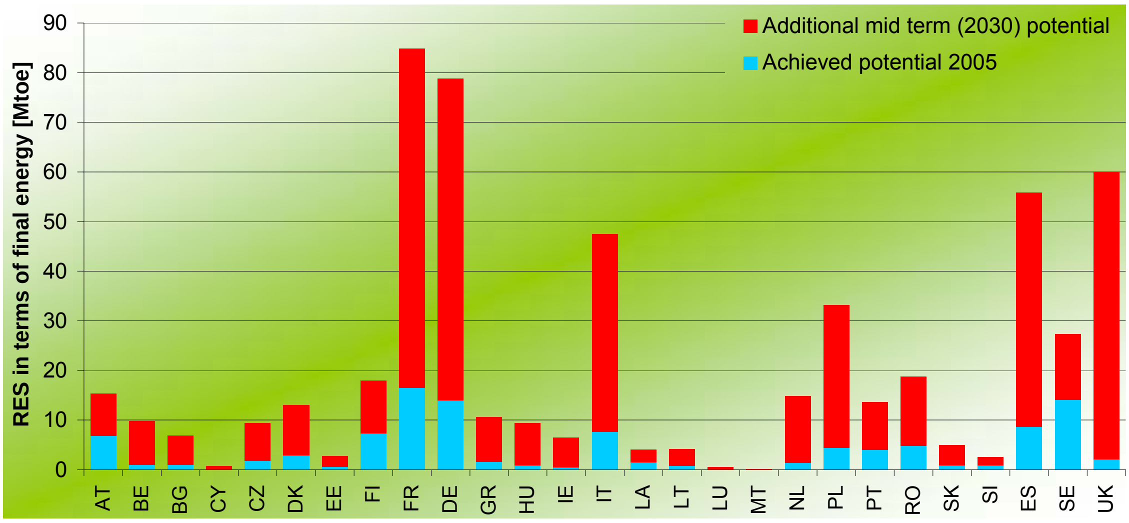

Figure 2-4 Achieved (2005) and additional mid-term (2030) potential for RES in terms of final energy for all EU member states (EU27) – expressed in absolute terms

The overall mid-term potential for RES in the European Union amounts to 554 Mtoe, corresponding to a share of 45.2% compared to the overall current (2005) gross final energy demand.[6]. In general, large differences between the individual countries with regard to the achieved and the feasible future potentials for RES are observable. For example, Sweden, Latvia, Finland and Austria represent countries with a high RES share already at present (2005), whilst Bulgaria and Lithuania offer the highest additional potential compared to their current energy demand. However, in absolute terms both are rather small compared to other large countries (or more precisely to countries with significant realisable future potentials).

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[6] It is worth to mention that biofuel imports from abroad are not considered in this depiction. Assuming imports corresponding to 5% of the current demand for diesel and gasoline (i.e. half of the minimum target of 10% biofuels by 2020) would increase the overall RES potential by 1%.

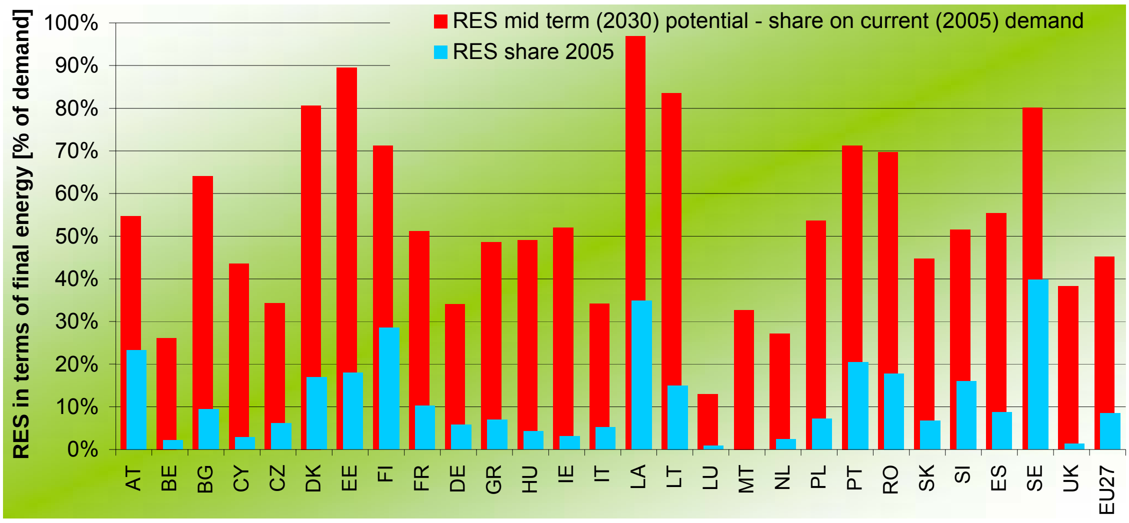

Figure 2-5 Achieved (2005) and total mid-term (2030) potential for RES in terms of final energy for all EU member States (EU27) – expressed in relative terms, as share on (gross) final energy demand

Below, Figure 2-6 relates derived potentials to the expected future energy demand. More precisely, it depicts the total realisable mid-term potentials on a country level [7] (up to 2030) for RES as share on final energy demand in 2005 and in 2030, considering two different demand projections – a baseline and a high energy efficiency scenario taken from PRIMES modelling[8]. The impact of setting accompanying demand side measures to reduce demand growth is becoming apparent: the overall mid-term potential for RES up to 2030 is in size of 45.2% compared to current (2005) gross final energy demand. Even if this would be fully exploited up to 2030, only 37.5% of EU's overall final energy consumption could be covered, if the demand increases as expected under 'business as usual' conditions. In contrast, if a demand stabilisation and later on also a decrease would be achieved as preconditioned in the PRIMES 'high energy efficiency' scenario, RES may contribute to meet almost 48% of total demand in terms of final energy.

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[7] The total realisable mid-term potential comprises the already achieved (as of 2005) as well as the additional realisable potential up to 2030.

[8] In order to ensure maximum consistency with existing EU scenarios and projections, data on current (2005) and expected future energy demand was taken from PRIMES. The used PRIMES scenarios are:

- The European Energy and Transport Trends by 2030 / 2007 / Baseline (NTUA, 2007a)
- The European Energy and Transport Trends by 2030 / 2007 / Efficiency Case (17% demand reduction compared to baseline). (NTUA, 2007b)

Please note that this data (and also the depiction of corresponding RES shares in demand) may deviate from actual statistics.

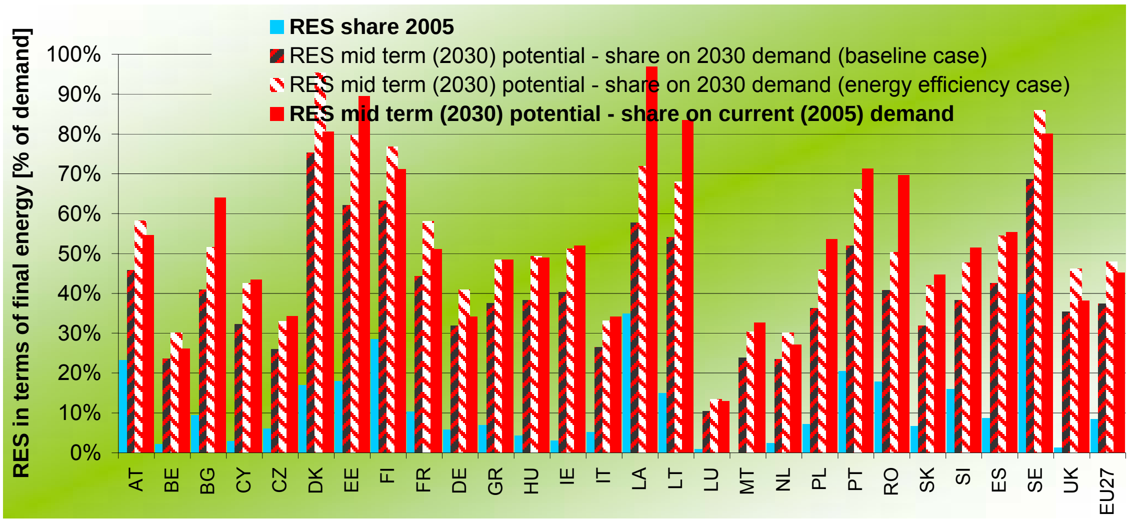

Figure 2-6 The impact of demand growth - Mid-term (2030) potential for RES as share on current (2005) and expected future (2030) (gross) final energy demand.

Finally, a sectoral breakdown of the realisable RES potentials at European level is given in Figure 2-7. The largest contributor to meet future RES targets represents the heat sector. The overall mid-term potential for RES-heat is 25.1% compared to the current (2005) final energy demand, followed by RES in the electricity sector, which may achieve (in case of a full exploitation) a share of 19% in total final energy demand. The smallest contribution can be expected from biofuels in the transport sector, which offer (considering solely domestic resources) a potential of 4.1% (on current final energy demand).

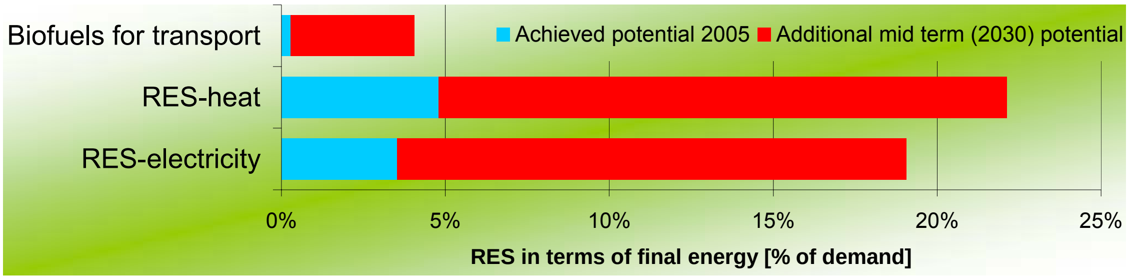

Figure 2-7 Sectoral breakdown of the achieved (2005) and additional mid-term (2030) potential for RES in terms of final energy at EU27 level – expressed in relative terms, as share on current (2005) (gross) final energy demand

Example: RES in the electricity sector

In the power sector, RES-E options such as hydropower or wind energy represent energy sources characterised by a natural volatility. Therefore, in order to provide an accurate depiction of the future development of RES-E, historical data for RES-E is translated into electricity generation potentials[9] – the *achieved potential* at the end of 2005 – taking into account the recent development of this rapidly growing market. The historical record was derived in a comprehensive data-collection – based on (Eurostat, 2007; IEA, 2007) and statistical information gained on national level. In addition, *future* potentials – i.e. the *additional realisable mid-term potentials* up to 2030 – were assessed[10] taking into account the country-specific situation as well as overall realisation constraints.

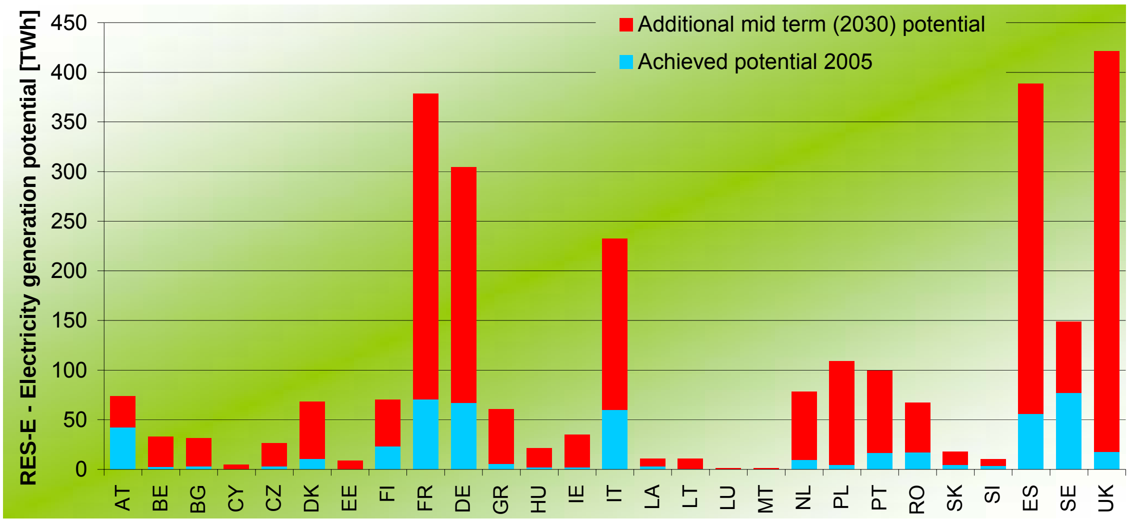

Figure 2-8 Achieved (2005) and additional mid-term potential 2030 for electricity from RES in the EU-27 on country level.

Figure 2-8 depicts the achieved and additional mid-term potential for RES-E in the EU-27 at country level. For EU-27 countries, the already achieved potential for RES-E equals 503 TWh, whereas the additional realisable potential up to 2030 amounts to 2213 TWh (about 67% of current gross electricity consumption). Obviously, large countries such as France, Germany, Spain or UK possess the largest RES-E potentials in absolute terms, where still a huge part is waiting to be exploited. Among the new Member States Poland and Romania offer the largest RES-E potentials in absolute terms.

Consequently, Figure 2-9 relates derived potentials to gross electricity demand. More precisely, it depicts the total realisable mid-term potentials (up to 2030), as well as the achieved potential (2005) for RES-E as share of gross electricity demand in 2005 for all Member States and the EU-27 in total. As applicable from this depiction, significant additional RES potentials

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[9] The *electricity generation potential* with respect to existing plant represents the output potential of all plants installed up to the end of 2005. Of course, figures for actual generation and generation potentials differ in most cases – due to the fact that in contrast to the actual data, potential figures represent, e.g. in case of hydropower, the normal hydrological conditions, and furthermore, not all plants are installed at the beginning of each year.

[10] A brief description of the potential assessment is given e.g. in (Resch et al., 2006).

are becoming apparent for several countries. In this context especially notable are Denmark, Ireland and the United Kingdom, as well as most of the new Member States. If the indicated realisable mid-term potential for RES-E, covering all RES-E options, would be fully exploited up to 2030, 82% of current gross electricity consumption could be covered. For comparison, by 2005 already installed RES-E plants possess the generation potential to meet about 15% of demand.

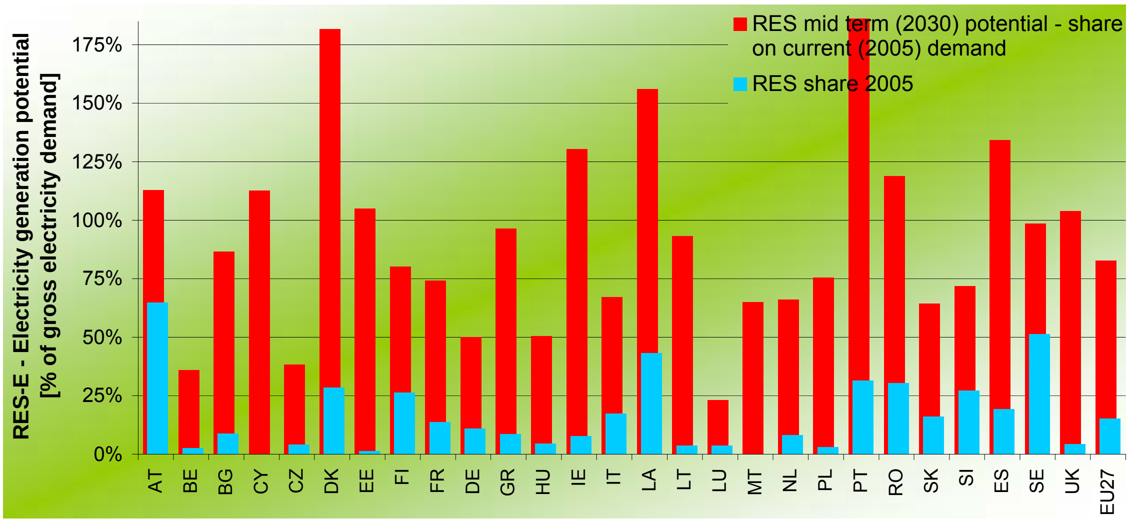

Figure 2-9 Total realisable mid-term potentials (2030) and achieved potential for RES-E in EU-27 countries as share of gross electricity demand (2005).

Additionally, the above-mentioned relations of the total realisable mid-term potential (2030) to the gross electricity demand are addressed in Figure 2-10 with respect to different scenarios on the future development of the electricity demand. A strong impact of the electricity demand development on the share of renewables is noticeable: In a baseline demand scenario (according to PRIMES), a total achievable RES-E share of 61% in the year 2030 would appear feasible, whereas in an efficiency demand scenario, 73% of the electricity demand could be generated by renewables. As already discussed in the previous figure, if the total realisable mid-term potential for RES-E was fully exploited up to 2030, 82% of current gross consumption could be covered, meaning even the efficiency demand scenario takes an increasing electricity demand into account.

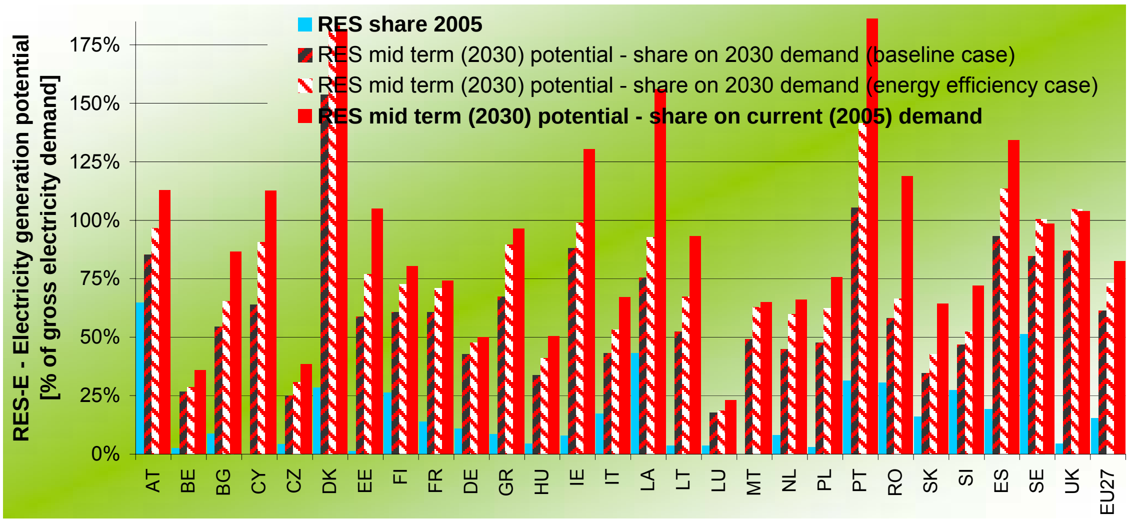

Figure 2-10 Total realisable mid-term potentials (2030) and achieved potential for RES-E in EU-27 countries as share of gross electricity demand (2005 & 2030) in a baseline and an efficiency demand scenario.

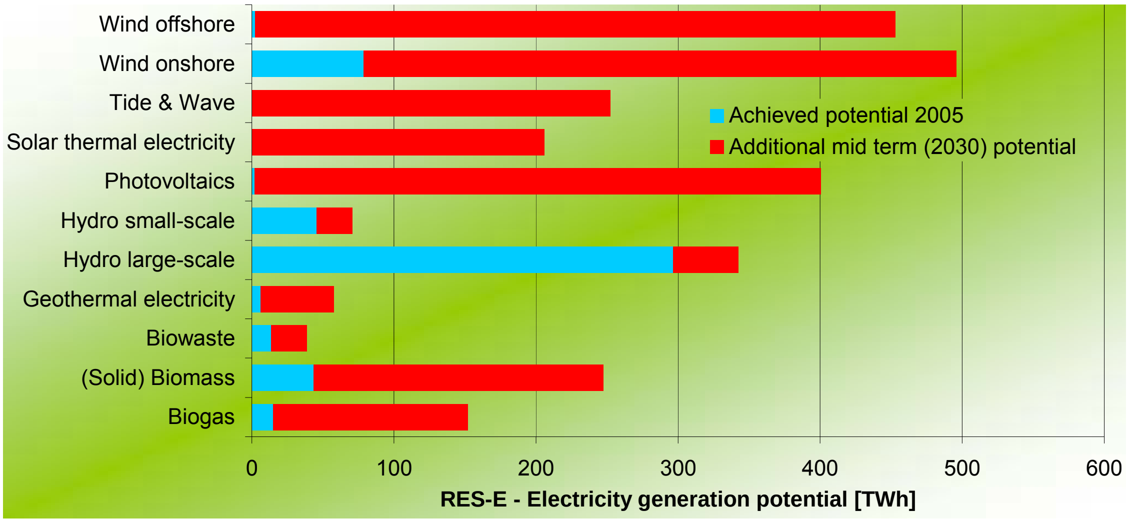

Figure 2-11 Total realisable mid-term potentials (2030) and achieved potential for RES-E in EU-27 countries on technology level.

Figure 2-11 demonstrates both the achieved and the additional realisable mid-term potential up to 2030 on a technology level for the whole EU-27. The figure depicts a high penetration and a small additional realisable potential for hydropower, both small- and large-scale. Wind onshore and solid biomass are both already well developed, but still an enormous additional potential has to be realized to meet future RES-E targets. Moreover, technologies like wind offshore, tide and wave and photovoltaics provide a large additional potential to be exploited up to 2030.

Next, future perspectives are indicated at the country level. As already mentioned, hydropower dominates current RES-E generation in most EU countries, followed by wind, biomass, biogas and biowaste. Figure 2-12 shows the share of different energy sources in the *additional* RES-E mid-term potential up to 2030 for the EU-15. The largest potential is found for wind energy (40%) followed by photovoltaics (17%) and biomass (15% - as aggregate of solid and gaseous biomass as well as biowaste), as well as promising future options such as tidal & wave (13%) or solar thermal energy (11%).

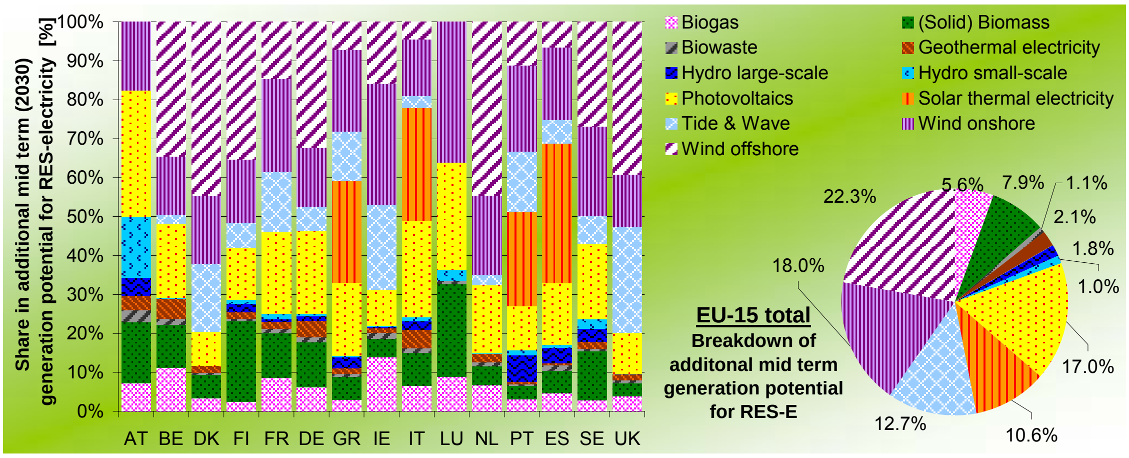

Figure 2-12 RES-E as a share of the additional realisable potential in 2030 for the EU-15 – by country (left) as well as for total EU-15 (right).

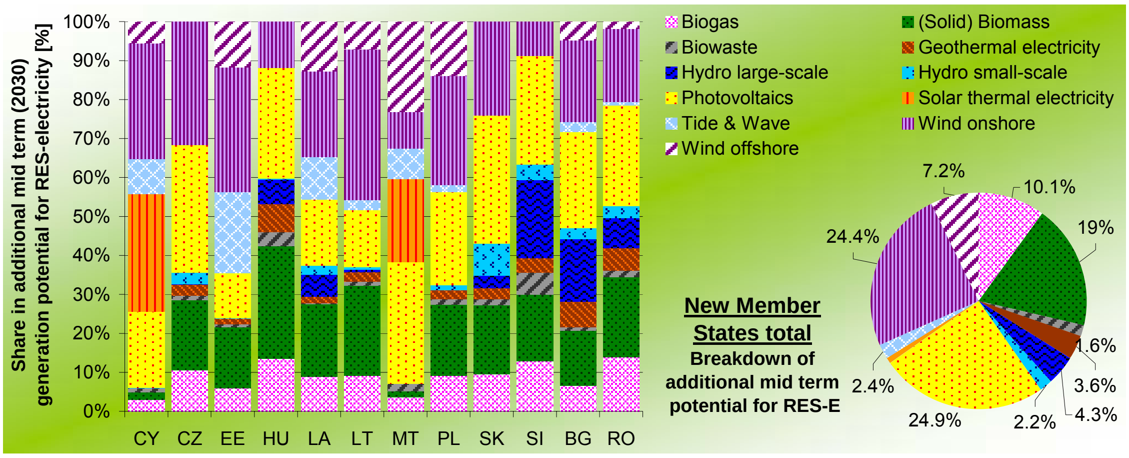

Figure 2-13 RES-E as a share of the additional realisable potential in 2030 for the NMS – by country (left) as well as for total NMS (right).

In the NMS, currently, almost 88% of the renewable electricity is generated by hydro power plants and 10% by solid biomass, mainly co-fired in thermal fossil fuel-based power plants. Only a minor part is provided by novel technologies such as wind energy and biogas. Figure 2-13 provides the 2030 depiction for New Member States (NMS), illustrating the share of different RES-E options in the *additional* mid-term potential up to 2030. In line with the EU-15, the largest potentials for these countries exist in the sectors of wind energy (32%) and photovoltaics (25%) followed by solid biomass (19%). Unlike the situation in the EU-15, the refurbishment and construction of large hydro plants holds significant potentials (4%).

2.2 Assessment of long-term potentials for onshore wind energy in Europe

Wind turbines provide electrical energy by converting the wind's kinetic power partly into a rotation, which in turn drives an electrical generator. As the provided electrical power depends on the cube of the wind speed, local wind regimes represent a crucial influencing factor on the feasible power output of a wind turbine (cf. Kaltschmitt et al. 2003, pp 276). Due to the strong dependence on the wind regime, wind power electricity is characterised by high fluctuations of the electricity output. This poses a crucial challenge for system operation of electricity systems with a high share of wind power (cf. Holttinen et al. 2009, p. 12-27). Wind energy can be produced either by turbines installed onshore or alternatively by turbines installed offshore, generally nearby the shoreline.

2.2.1 Europe's onshore wind power potential – starting point

In this section, existing onshore wind potential studies are compared. With regard to the comparison, it should be taken into account that the regional coverage of the studies available differs slightly. Most of the existing studies calculated the technical onshore wind energy potential on a global level and depicted figures for a zone of Western Europe including the EU15 and Norway, Switzerland and Turkey. Ragwitz et al. (2005) on the other hand estimated the realisable potential up to 2020 focussing on the EU and derived detailed potentials on country level for the EU-MS as of 2006. The estimated potentials are shown according to their availability in Figure 2-14 referring to the EU15 countries. In some cases, also Norway, Switzerland and Turkey are included.

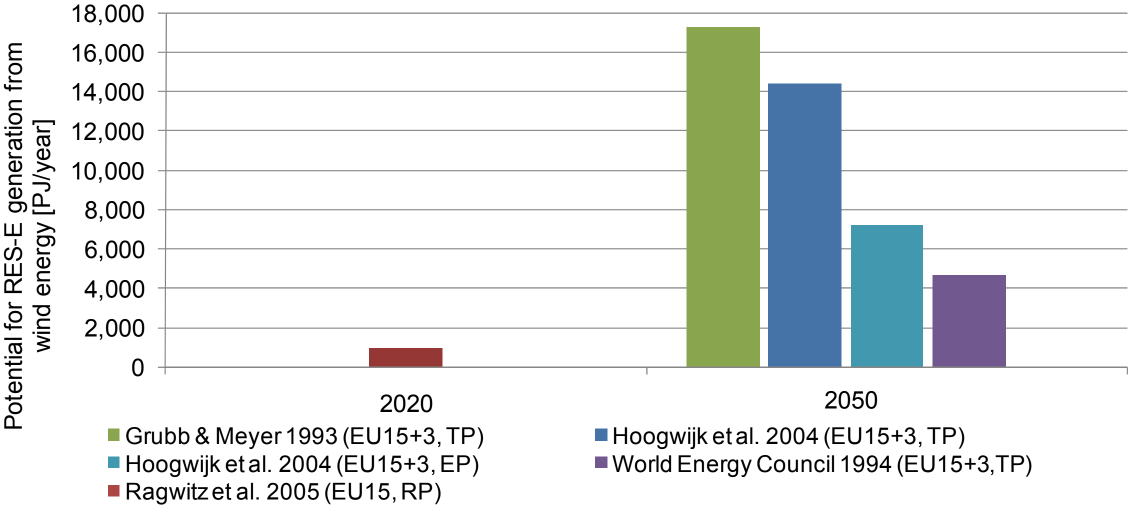

Figure 2-14 Comparison of the onshore wind primary energy potential in Europe. EU15+3 includes Norway, Switzerland and Turkey, TP means 'Technical Potential', EP represents the 'Economic Potential' and includes costs below 0.10 $/kWh and RP stands for 'Realisable Potential'. Source: (Held 2011)

The highest onshore wind potential shown in Figure 2-14 for Western Europe was estimated to be 17,280 PJ/year, using land-use constraints for wind electricity generation (exclusion of cities, forests, inaccessible mountains) as well as social and environmental constraints in order to determine the technical potential based on the theoretical potential (Grubb, Meyer 1993). Only sites with an average wind speed above 6 m/s were included, assuming a conversion efficiency factor of 33 %.

Results from the global potential study carried out by Hoogwijk et al. (2004) indicate a technical onshore wind potential of about 14,400 PJ/year for Western Europe, considering wind speeds exceeding 4 m/s at 10 m. Hoogwijk et al. (2004) took into consideration economic aspects and reported a halved potential when only including sites with electricity generation costs below 0.1 $/kWh.

Based on the assumption that 4 % of the area with a wind speed exceeding 5.1 m/s at 10 m are available for the use of wind energy, the World Energy Council (1994) assessed the technical onshore wind energy potential to be 4,680 PJ/year. A further restriction within this study was that areas with a distance of more than 50 km from the existing grid were excluded.

Not surprisingly, compared to the technical potentials, the realisable potential until 2020 estimated by Ragwitz et al. (2005) shows significantly lower values. Only 964 PJ/year are expected to be realisable realistically until 2020. This can mainly be explained by the assumption of additional barriers such as grid restrictions and planning constraints. Also the constrained annual growth rates limit the available onshore wind energy potential up to 2020.

As electricity generation costs of electricity from wind power plants largely depend on local wind regimes, not only the overall potential but also the corresponding costs of electricity generation have to be considered. The analysed studies aiming to estimate the European wind power potential so far either represented a global assessment, reporting on Europe as a whole (e.g. Grupp & Meyer 1993; World Energy Council 1994; Hoogwijk et al. 2004, Archer et al. 2005), or represent an EU-focussed study not taking into account detailed local wind velocities and land availabilities (Ragwitz et al. 2005). Therefore, a new potential estimation including the derivation of detailed regional cost-resource curves for onshore wind energy in the EU considering a time horizon up to 2050 is realised.

2.2.2 Methodological approach

In this analysis, the realisable potential for onshore wind energy up to the year 2050 is estimated, based on the assumption that dynamic realisation restrictions might be overcome in the long term. Social constraints are considered to some extent. In this way, minimum distances to urban area are taken into account and the capacity density is assumed to be lower than the amount that would be technically feasible. Aspects regarding the integration of wind energy into the electricity system are not considered within this study. The derivation of the onshore wind cost-resource curves is based on (i) the estimation of the wind energy potential, and (ii) on the calculation of the related costs determined in particular by the investment and the local wind regimes. In particular, two main factors influence the available wind energy potential: (i) the local wind regime influencing the energy yield of a turbine, and (ii) the land area available for construction of wind turbines which determines the total available wind capacity potential. A schematic overview of the applied methodology is depicted in Figure 2-15.

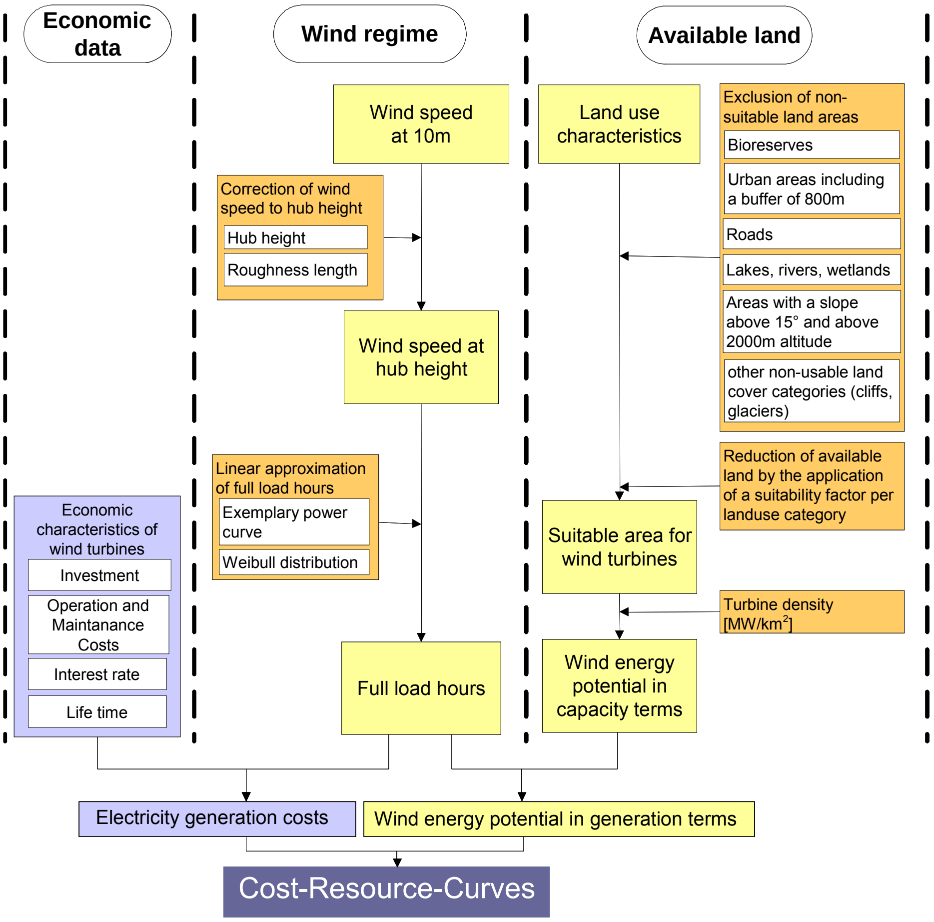

Figure 2-15 Scheme of applied approach for the determination of the cost-resource curves for onshore wind electricity. Source: (Held 2011)

To process the spatial data required for this analysis, the geographical information system (GIS) ArcView provided by ESRI is applied[11]. In a first step, regional wind velocities are transformed into full-load hours, one of the relevant factors determining the economic profitability of wind electricity production[12]. In a second step, the available area for the construction

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[11] More information can be found at: http://www.esri.com/.

[12] The full-load hours represent the ratio between the annual electricity output of a wind turbine and its rated capacity.

of wind-turbines is estimated. Finally, both results are combined in order to determine the feasible electricity output in each region. Subsequently, the determination of the full load hours, the estimation of the available land and the cost calculations are described.

For the calculation of the full-load hours, a wind speed dataset created by the Climate Research Unit belonging to the University of East Anglia was used (cf. New et al. 2002). This wind speed data was derived by means of geo-statistical interpolation using monthly weather measurements reported from 3,950 stations worldwide in the period between 1961 and 1990. The data was interpolated to a geographical resolution of 10' x 10'[13]. Although measurement size varied between the different locations between 2 m and 20° m, the authors recommend assuming a measurement height of 10 m, representing the large majority of known heights. Due to the time-consuming calculation process of the geographical information system, monthly wind speed data was aggregated to annual averages.

As wind speed varies depending on the altitude, the wind speeds were corrected to turbine height according to the barometric formula. The hub height was assumed to be at 80 m within this study. For the wind speed correction to hub height, the roughness length was assumed to amount to 0.0024 m which corresponds to a roughness class of 0.5 according to the definition of Troen et al. (1989). Thereby, one should keep in mind, that this simplified assumption may lead to an underestimation of the wind speeds at hub height in particular in complex and uneven terrains. In addition, the application of the neutral logarithmic wind profile only applies for neutral weather conditions, implying that the effects of thermal stratification are ignored, leading to an error of the wind speed correction to hub height. Focken et al. (2003) observed that the application of the barometric formula tends to underestimate wind speed corrections using exclusively the Barometric formula for stable weather situations at a Dutch measurement station.

The expected energy yield of a wind turbine is determined by the turbine characteristics and the local wind regime. Thereby, the statistical distribution of wind speeds has to be taken into account. Usually, the variations in wind speed are described by means of a Weibull distribution (Hau 2003). Due to the absence of information about wind speed variability in all EU-countries on regional level, a k-factor of 2, representing moderately gusty winds, was assumed as proposed by Seguro (2000) for the approximation of full-load hours. The relation between wind speed (v) and full-load hours (h) is approximated by using a linear regression based on power curves. It should be noted, that this correlation was assumed to be valid for the wind speed interval from 4 m/s to 9 m/s.

Figure 2-16 shows this relation for selected turbine types. Average turbine sizes of newly installed turbines in the five European countries with the largest annual capacity increase of

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[13] The geographical resolution is expressed in angular measurement (arcminutes). The grid cell size in square meters depends on the latitude. One arcminute equals to one sixtieth degree or to about 1.86 km at the equator.

onshore wind plants in 2007 (DE, ES, FR, IT, UK) have increased during the last years and are currently equalling almost 2 MW (EurObserv'ER 2008). Therefore, a 2 MW turbine of Vestas (Vestas V80) was selected as a reference turbine for the linear regression. Following the linear equation h = m*v+b m, m was estimated to be 728 $\frac{s*h}{m*a}$ and b amounted to -2,368 $\frac{h}{a}$ assuming the characteristics of the selected reference turbine[14].

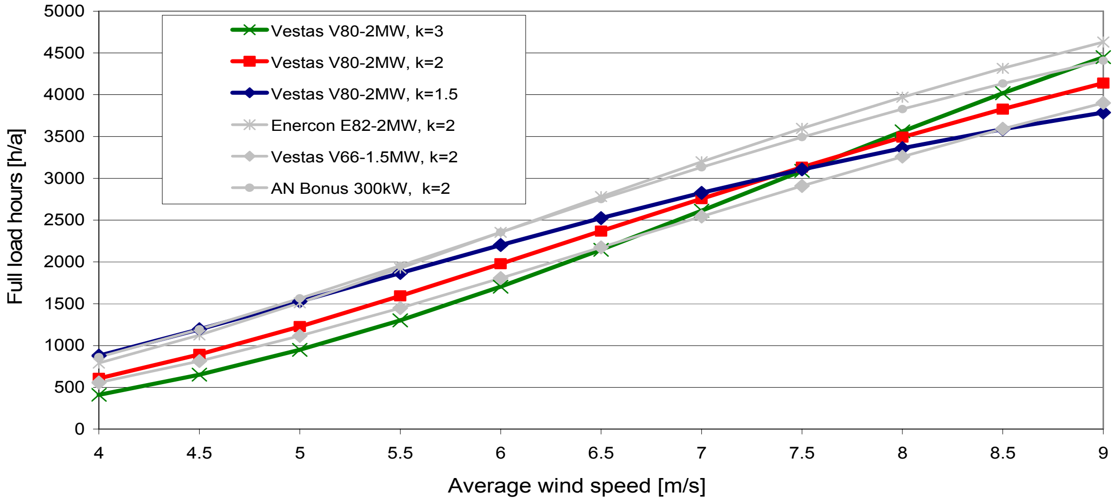

Figure 2-16 Approximation of the relation between full load hours and average wind speeds based on power curves of existing wind turbines. Source: (Held 2011)

The full-load hours were calculated for a range of average annual wind speeds between 4 m/s and 9 m/s on hub height. To avoid that locations with insufficient wind availability are included in the potential calculation, only areas where full-load hours exceed 1,300 h/a were considered. Assuming the described linear correlation of the reference power curve, this lower limit corresponds to an average wind speed of slightly above 5 m/s at hub height. To simplify the calculations, the continuous full-load hours were transformed into discrete intervals of 100 h/a.

The estimation of the available area for the construction of wind turbines is based on the CORINE land-cover database created by the European Environment Agency [EEA] (CORINE land cover 2000)[15]. Existing constraints are considered and used for a reduction of the suitable areas for the construction of wind turbines. The first step was the exclusion of naturally protected areas. Thereby, the protected area management categories I, II and III as declared by the WDPA Consortium (2006) are cut out from the available land area.

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[14] The corresponding Pearson product-moment correlation coefficient amounts to 0.986.

[15] Copyright EEA, Copenhagen, 2007. Data available at http://www.eea.europa.eu. For further information about the data the reader is referred to Nunes de Lima (2005).

Secondly, urban areas and all artificial surfaces as for instance roads were removed from the suitable area as well as natural areas not suitable for the construction of wind turbines including rivers or lakes and other non-usable land cover categories such as cliffs or glaciers. In order to account for the social acceptability of wind turbines, a buffer with a radius of 800 m distance to habitat areas further diminished the available land area.

Mountainous terrain which is difficult to access (areas above 2000 m of altitude and slopes above 15°) were assumed not to be suitable for the construction of wind turbines. The exclusion of these terrains was based on an intersection of the CORINE-data with a geographical dataset containing information about the altitude (SRTM 2004).

In a next step various suitability factors for the remaining available area according to their CORINE-category were assumed in order to account for the fact, that only partial use can be made of the available land, which is already used for other purposes. In this way, suitability factors for sylvan regions were assigned a comparatively low suitability of 10 %, whereas half of the exiting grassland was assumed to be available for the use of wind energy plants. Annex I shows the suitability factors that have been assumed to be available for the construction of wind energy plants for each CORINE land use category.

Since the cost-resource curves and the resulting wind potential depend considerably on the assumed turbine density, we decided to calculate two scenarios. First we assumed a capacity density of 3 MW/km^2 in order to account for social acceptability[16]. Other studies assumed higher turbine densities of 4 MW/km^2 (Hoogwijk et al. 2004) or 9 MW/km^2 (Archer et al. 2005), so this assumption is rather conservative. To show the existing technical potential, we also show an additional scenario for the wind onshore energy potential assuming a turbine density of 10 MW/km^2. This value corresponds to the typical capacity density of wind parks.

Subsequently, the investigated area was combined with the corresponding full-load hours in order to illustrate the combination of available wind power capacity and full-load hours. Losses induced by the aerodynamic interferences of wind turbines in wind parks are not considered within this study. For more information about this effect, the reader is referred to (Hau 2003).

The last step of the derivation of the cost-resource curves requires the calculation of the corresponding electricity generation costs. As wind power generation is strongly capital-intensive, electricity generation costs depend in particular on the amount of the produced electricity output, determined by the full-load hours. Therefore, we determine the electricity generation costs for each potential step based on economic parameters shown in Table 2-1.

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[16] Only for Austria, Bulgaria, Hungary, Malta and Slovenia a capacity density of 5 MW/km^2 is assumed.

Table 2-1 Assumptions for the calculation of the electricity generation costs

	Investment	O&M costs	Turbine size	Lifetime
Technology	*[€/kW$_{el}$]*	*[€/(kW$_{el}$*a)]*	*MW*	*[a]*
Wind onshore	1,380	41	2	20

Source: (Prideaux, Harrison 2009)

Finally, the respective electricity generation costs are assigned to the derived combination of wind power capacity and full-load hours and the complete cost-resource curves are derived.

2.2.3 Resulting onshore wind resources and cost-resource curves

Results (see Table 2-2) show that there is a considerable mid-term realisable potential for the use of onshore wind energy in the EU, amounting to roughly 2 PWh per year. This is based on areas with a wind regime implying more than 1,300 full-load hours per year, and on neglecting existing grid constraints. Contrasting the estimated wind energy potential to the EU's electricity demand of 3.8 PWh by 2030 predicted within the IEA Reference Scenario (International Energy Agency [IEA] 2007), it becomes clear, that wind energy might contribute significantly to European electricity supply on a mid-term horizon. However, one should keep in mind that high penetration rates of wind energy in the electricity system may cause several problems related to the intermittent nature of wind energy and the existing divergence between wind electricity supply and demand for electricity on a high-resolution time scale. The technical potential where a turbine density of 10 MW/ km^2 is assumed shows an even higher potential of more than 3 PWh per year.

Table 2-2 Estimated realisable onshore wind potential up to 2050 in two Scenarios

Country	**Realisable Potential (Capacity density of 3 MW/km^2)**		**Technical potential (Capacity density of 10 MW/km^2)**		**Average full load hours [h/a]**
	Generation potential [GWh]	**Capacity potential [MW]**	**Generation potential [GWh]**	**Capacity potential [MW]**	
Austria	9,780	6,061	19,559	12,123	1,613
Belgium	7,815	4,185	26,049	13,951	1,867
Bulgaria	6,938	4,420	13,876	8,839	1,570
Cyprus	1,470	1,096	4,900	3,652	1,342
Czech Republic	54,327	25,961	181,089	86,538	2,093
Germany	105,906	54,451	353,019	181,502	1,945
Denmark	81,093	25,476	270,309	84,919	3,183
Estonia	35,885	19,800	119,617	66,000	1,812
Spain	189,348	117,884	631,160	392,947	1,606
Finland	24,310	15,553	81,032	51,842	1,563
France	281,421	158,332	938,070	527,772	1,777
Greece	16,288	8,657	36,124	21,391	1,882
Hungary	2,981	2,078	5,962	4,157	1,434
Ireland	127,187	50,205	423,957	167,350	2,533
Italy	26,947	14,725	89,823	49,084	1,830
Latvia	26,297	15,323	87,656	51,078	1,716
Lithuania	8,310	4,896	27,701	16,321	1,697
Luxembourg	1,111	566	3,704	1,886	1,964
Malta	139	71	278	141	1,971
The Netherlands	37,138	16,850	123,793	56,167	2,204
Poland	103,692	65,310	345,640	217,700	1,588
Portugal	58,060	36,459	193,533	121,529	1,592
Romania	13,131	7,640	43,770	25,465	1,719
Sweden	294,264	152,905	980,879	509,682	1,924
Slovenia	520	313	1,041	627	1,660
Slovakia	5,914	3,895	19,715	12,985	1,518
United Kingdom	442,661	178,920	1,475,536	596,399	2,474
EU	**1,962,932**	**992,032**	**6,497,792**	**3,282,049**	**1,979**

Source: Own calculations based on Held (2011)

Observing the spatial distribution of the regional wind regimes in terms of full-load hours in Figure 2-17, one can see that in particular the United Kingdom, Ireland and Denmark possess favourable wind conditions. By contrast, Eastern Mediterranean countries seem to be less favourable for the use of onshore wind energy.

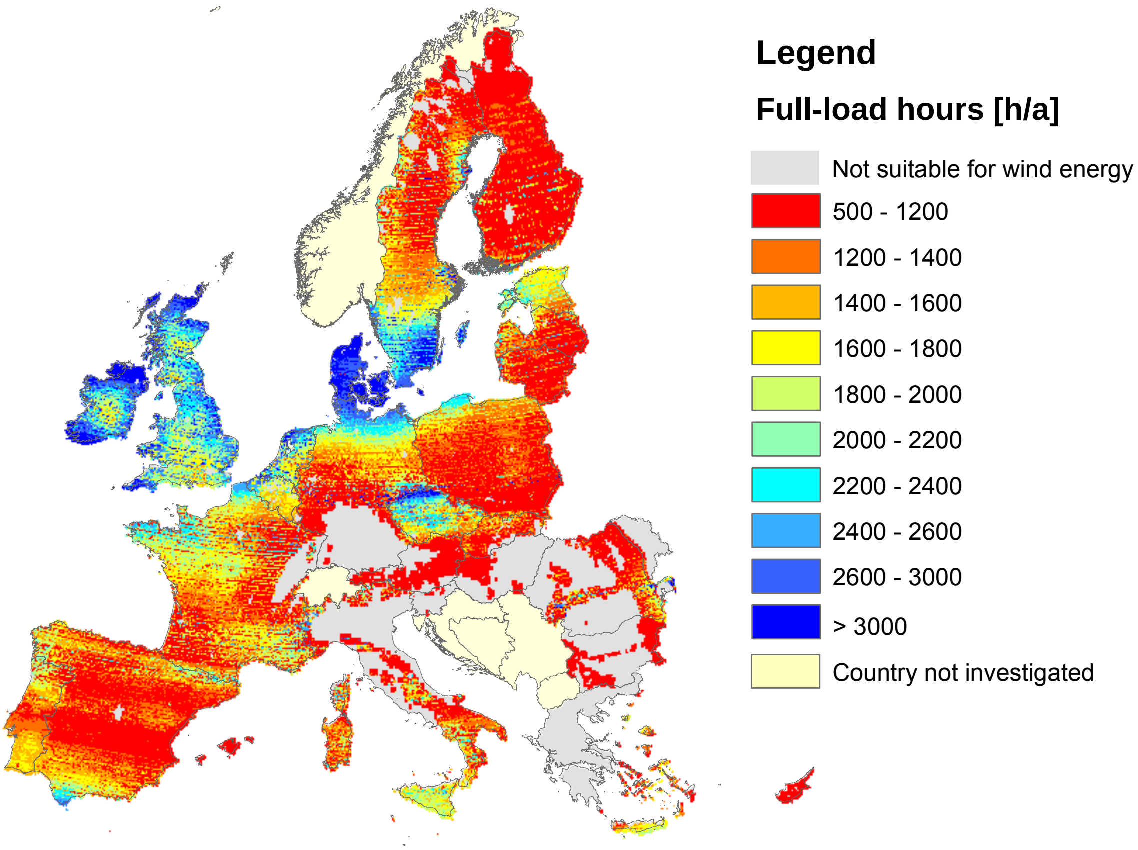

Figure 2-17 Annual full-load hours for onshore wind energy in the EU

Source: (Held 2011)

The corresponding costs of each potential step represented in Figure 2-18 for Western European countries (EU15) show that at present (2009) wind electricity generation costs range between 4 € Cents/kWh and 12 € Cents/kWh corresponding to the lower full-load hour limit of 1300 h/a. Besides favourable wind conditions, the United Kingdom also has a considerable surface area potential. According to the results of this analysis, the total realisable onshore wind potential in the United Kingdom amounts to 446 TWh. Comparing this magnitude to the national electricity demand of 397 TWh in 2007 (Eurostat 2010), the onshore wind energy potential available up to 2050 exceeds current national electricity demand in the United Kingdom. As already stated before, this does not necessarily mean, that total electricity generation could be covered exclusively by wind energy plants due the variable character of the wind electricity output. Further countries with favourable wind resource conditions and a lower area availability are Denmark and Ireland. Looking at the Spanish cost-resource curve, a considerable wind power potential appears to be available, but associated electricity generation costs are on a higher level than in North Sea countries. While the total wind energy generation potential of France and Sweden amounts to a similar magnitude, wind conditions in Sweden seem to be comparatively more favourable.

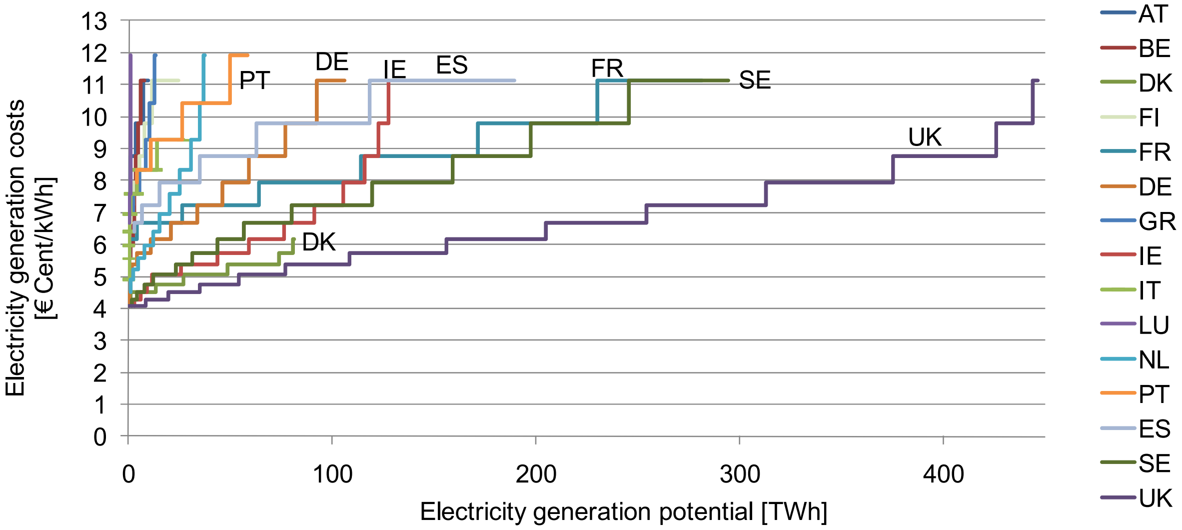

Figure 2-18 Derived cost-resource curves for onshore wind energy in the EU15 with economic data from 2009 based on the realisable wind onshore potential

Source: (Held 2011)

Observing the current cost-resource curves for New Member States (NMS) in Figure 2-19, it becomes clear, that electricity generation costs of onshore wind energy tend to be generally higher than in the EU15. In addition, less land area is available for the construction of wind turbines. Whilst the Czech Republic possesses the most favourable wind conditions in the EU12 (leading to average full-load hours of 2,093 h/a), the largest potential in terms of total generation potential is available in Poland.

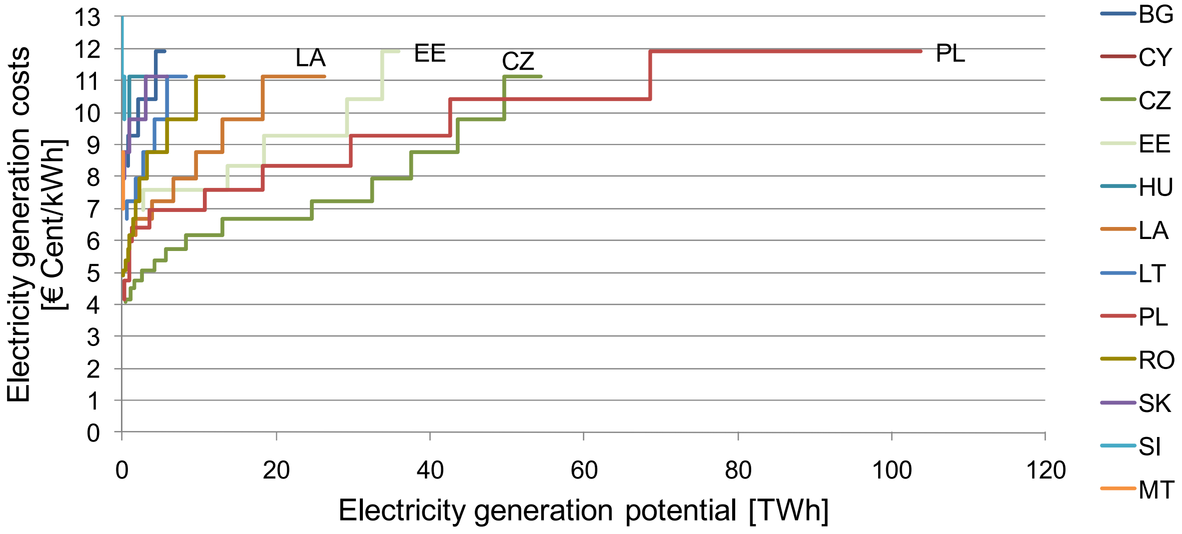

Figure 2-19 Derived cost-resource curves for onshore wind energy in NMS with economic data from 2009 based on the realisable wind onshore potential

Source: (Held 2011)

2.2.4 Discussion of results

In this analysis, the feasible contribution of onshore wind energy up to 2050 has been estimated. Detailed cost-resource curves for onshore wind energy have been derived on a regional level for all EU-MS considering present costs. Due to the strong spatial dependence of the potential and costs of wind power, a geographical information system (GIS) was applied in order to take into account the geographical characteristics of both technologies. Some simplifying assumptions were made to meet the challenges resulting from the broad geographical scope and a high spatial resolution. In this way, the extrapolation of the wind speed from an altitude of 10 m to the assumed hub height of 80 m leads to an error in particular in continental areas, as the assumption of neutral atmospheric stability conditions does not fit perfectly with real weather conditions. The potential estimations are based on average annual wind speeds and thus wind speed variability is assumed to be the same in all EU-MS. A further simplification represents the selection of a single reference turbine. As different turbine types tend to be used for lower wind speeds, the possible power output in lower wind speed zones might be underestimated. Furthermore, one should consider the limitations in spatial accuracy of the used wind speeds given that the dataset is taken from a global wind speed data derived based on geo-statistical interpolation. However, given the wide geographical scope and the time horizon, the above-mentioned limitations appear to be acceptable considering the overall intention to estimate the magnitude of available renewable potential for the EU as a whole and the corresponding electricity generation costs.

2.3 Assessment of long-term potentials for solar PV electricity in Europe

The direct conversion of solar irradiation into electrical energy occurs by means of the photovoltaic effect, in which photons induce the emergence of an electrical potential as a result of a separation of charge carriers in semi-conducting materials. In general a photovoltaic (PV) installation is composed of various modules of solar cells and the balance-of-system (BOS) including typically an inverter (given that the device is connected to the grid), cables and the mounting installation.

Solar cells may be produced using either silicon-based materials (crystalline or amorphous) on the one hand or non-silicon-based materials, such as Cadmium Telluride (CdTe), Copper-Indium-(Gallium)-Selene/Sulphate (CI(G)S) or organic materials on the other hand. Solar cells can e.g. be produced by sawing silicon wafers or alternatively by evaporating thin films of CdTe or silicon (predominantly amorphous). At present, the use of crystalline silicon-based materials dominates the photovoltaic technology. Thus, the market share of global crystalline silicon-based module production capacity is estimated to amount to 82 % in 2009, but the share of thin film based technologies is expected to increase in the future (European Photovoltaic Industry Association [EPIA] 2009, p. 16).

Besides the different types of solar cells, there are different options of mounting a PV installation. Solar PV power plants may either be built on top of roofs, placed directly at ground level, or integrated into buildings. In the latter case, the solar module can be mounted on top of the roof or integrated into the façade. Whilst most of the free-field installations tend to be larger installations of centralised character, building integrated PV installations can be characterised as decentralised installations. PV power plants may be constructed in remote areas without a connection to the electricity grid (off-grid installation) or alternatively in terms of grid connected installations. The potential estimation realised in this thesis is limited to grid-connected PV applications. The electricity output of PV applications is variable depending on the solar irradiance. Compared to the variability of electricity output generated with wind turbines, the supply of solar PV electricity correlates better with the demand for electricity.

2.3.1 Europe’s solar PV potential – starting point

The overall theoretical potential for the use of solar PV energy in Europe is vast. According to Hoogwijk (2004, p. 157) the theoretical potential in terms of solar irradiance reaching the earth amounts to 14,400 EJ/year in Western Europe, including the respective OECD member states in Europe. Comparing the theoretical potential to the current gross final energy consumption of OECD European countries – 48 EJ in 2007 (Eurostat 2010) – it becomes clear, that the theoretical solar PV potential exceeds the current energy demand many times over. Looking at the technically available potential as shown in Figure 2-20, Hoogwijk (2004) places the technical potential of solar PV for OECD Europe at about 15 EJ/year, whilst according to Johansson et a. (1993) the lower limit of total solar potentials amounts to 25 EJ/year.

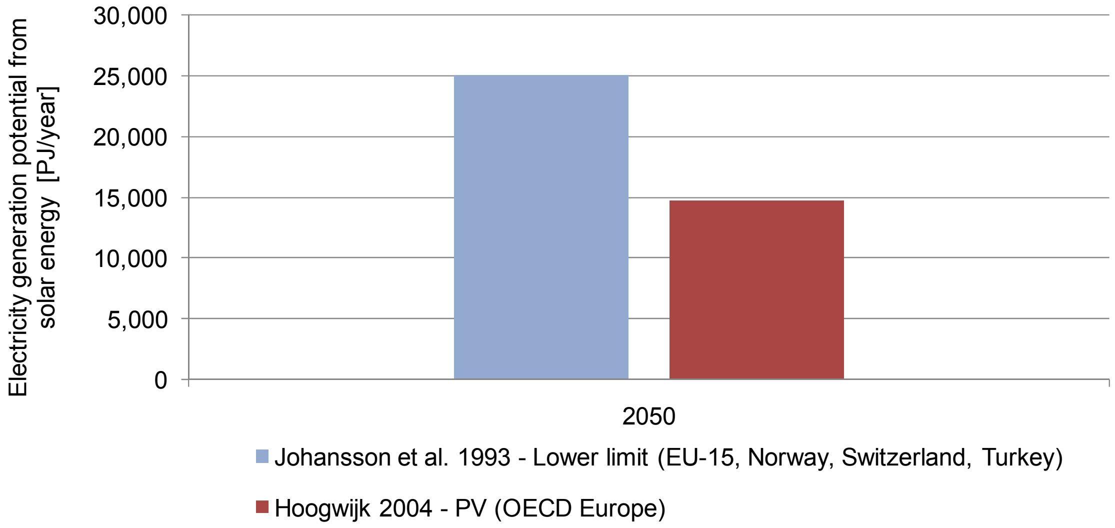

Figure 2-20 Potential estimations for electricity from solar energy

2.3.2 Methodological approach

The electricity generation potential for solar PV mainly depends on the area available for PV installations, the solar irradiation and the conversion efficiency of the modules. Whereas the area available for PV installations determines particularly the amount of solar PV capacity that can be installed, solar irradiation affects the economic feasibility and the potential utilisation of a PV power plant installed. Similar to the weather-related influences of regionally varying wind conditions on the electricity output of wind power plants (see section 2.2.2), solar irradiation may differ considerably between and even within each country. Despite the vast potential available for solar PV electricity generation, the future use of PV technologies depends primarily on its economic performance. Electricity generation costs of PV in Europe still exceed clearly those of other RET, although considerable cost reductions have occurred during the last decade (IEA Photovoltaic Power Systems Program 2009, p. 28-29). Costs are still expected to decrease further in the future. The current economics of PV are characterised by high investments, stemming in particular from the upstream silicon production, and low conversion efficiencies ranging from 8 % - 25 % in production (cf. Kaltschmitt et al. 2003, p. 213). The predominant part of the investment is dominated by the module price.

Given the relevance of the investment for the overall economic performance of electricity from PV power plants, the respective electricity generation costs depend largely on the feasible power output determined by the solar irradiation. For this reason, an own potential estimation was made, taking into account regional solar irradiation data. The detailed description of the methodology follows in the subsequent section.

The relevance of the regional solar irradiance for the economics of PV power plants suggests the use of a GIS, similar to the case of onshore wind energy (see section 2.2.2) for the derivation of cost-resource curves for solar PV. The cost-resource curves are to be derived for different types of plants including installations on free fields, roof-integrated and façade-integrated PV plants (see Figure 2-21).

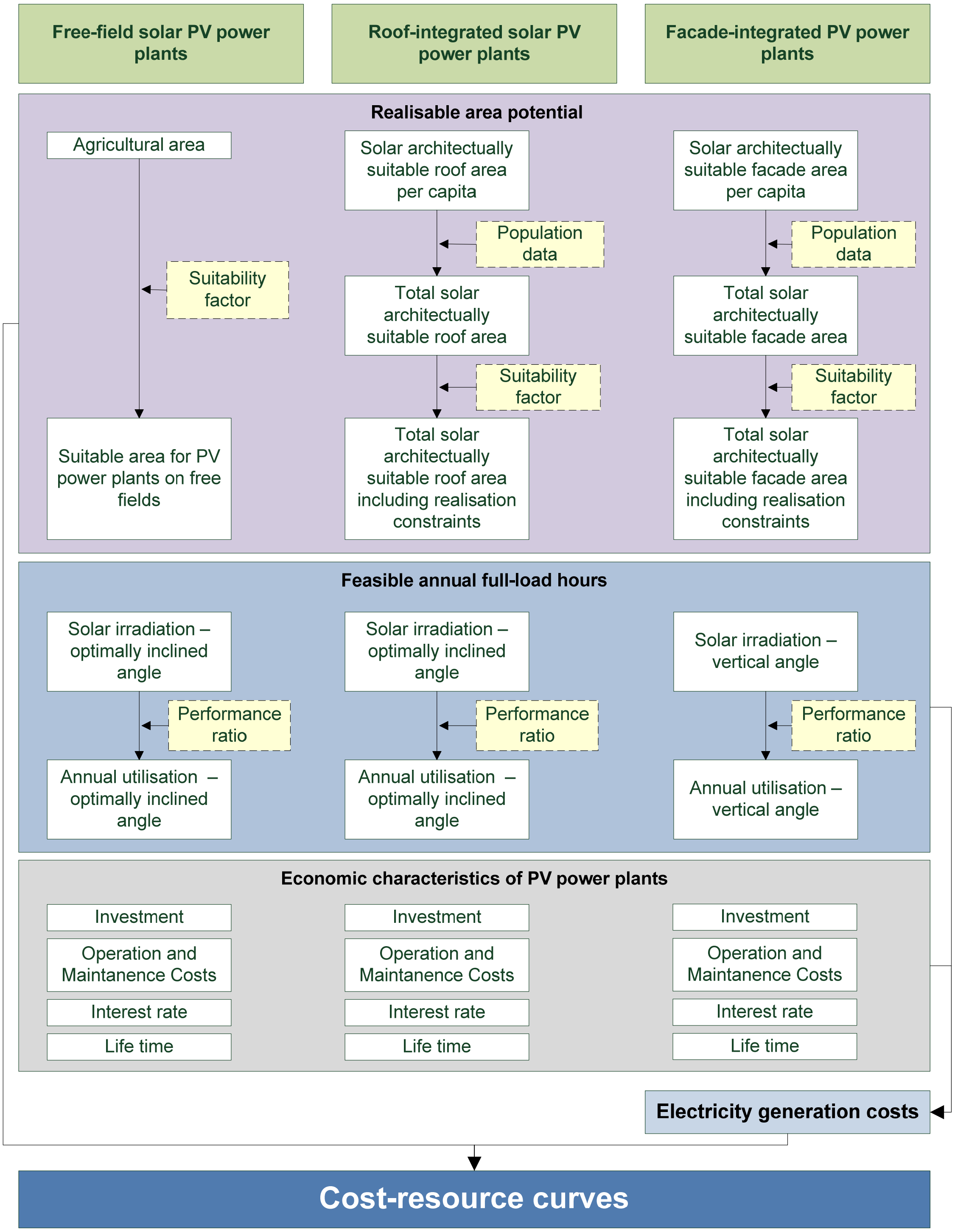

Figure 2-21 Scheme of applied approach for the determination of the cost-resource curves for electricity generation from solar PV power plants. Source: (Held 2011)

As a first step, for all three PV power plant types, the area available for the construction of a PV plant is calculated. By applying a factor, which describes the surface area required for the construction of all three PV plants investigated, the capacity potential is estimated in terms of peak power, corresponding to the rated output of a PV plant at standard test conditions (STC). STC assume an air temperature of 25 C and a solar irradiation of 1000 W/m^2. By applying the peak power and the area requirement for 1 unit of peak power, no additional information on the module efficiency is required. Additional losses occurring in practice are taken into account by use of an indicator reflecting the ratio between the actual power output of the system and the output under STC. This performance ratio (PR) includes deviations from STC such as a higher module temperature or lower solar irradiation, causing a reduction of the actual power output of a PV plant. Likewise, efficiency losses occurring in other components of the PV plant than the module (cables, inverters) are included in the performance ratio.

In a second step, the potential utilisation of PV plants in terms of full-load hours is derived based on spatially explicit solar irradiation data for different angles, depending on the type of the installation. In case of façade-integrated PV installations, the vertical solar irradiation is taken. Free-field PV power plants are assumed to be mounted in an optimally inclined angle to maximise the power output. This angle is generally oriented southwards in the Northern hemisphere, but it may vary from region to region. The optimum angle is mainly determined by the geographical latitude, the proportion of diffuse to direct radiation and potential shadowing effects (Suri et al. 2007). The feasible orientation of roof-integrated modules can diverge depending on the roof type. The architecture predetermines the inclination of a solar PV power plant mounted on pitched roofs, whilst a flexible orientation is possible for mounting the PV installation on flat roofs. In case of pitched roofs, additional losses occur due to deviations from the optimal azimuthal angle or deviations from the optimal angle of inclination. According to Quaschning (2000), losses of pitched roofs induced by deviations from the optimal angle range between 10 % and 15 % (Quaschning 2000, p. 46). Since no reliable information about the share of each roof type in the total roof area is available, the described losses are discarded in this analysis. Therefore, the cost-resource curves analysis is based on solar irradiation data for optimally inclined modules for roof-integrated PV power plants. Thus, the feasible utilisation for roof-integrated PV power plants is overestimated slightly.

In a third step, solar irradiation data is then processed within ArcGIS and the annual potential utilisation in terms of full-load hours is computed for each raster cell. Raster cells are aggregated into discrete full-load hour intervals in order to calculate the share of surface area corresponding to a certain full-load hour interval on country level.

In contrast to the estimation of cost-resource curves for onshore wind energy, no direct overlap of the available area with the corresponding full-load hours is performed. In fact, the available capacity potential is calculated based on the area availability, and then divided up into the discrete full-load hour intervals on country level, that have been investigated by means of the solar irradiation data.

2.3.3 Suitable area for solar PV plants

As the construction of PV power plants on free fields has to compete with other purposes of the surface area, such as urban land use, agriculture or nature conservation, only a minor share of the surface area is in principle available for the construction of PV power plants. In this analysis, the surface area suitable for PV installations is estimated based on the area used for agricultural purposes in each country. Only a certain share of the agricultural area is assumed to be suitable for PV power plants to account for competition with agricultural purposes. Additionally, dynamic realisation constraints such as visual impacts of large-scale PV power plants reduce the suitable area surface for the construction of PV power plants. Given the difficulty to quantify the impact of these factors on the estimation of the surface area suitable for the use of PV, the range of reasonable suitability factors is large, and the determination of the respective suitability factor represents a challenging task. To account for the mentioned restrictions, 0.5 % of the total agricultural area is assumed to be available for centralised PV in this analysis. Compared to another PV potential study realised by Soerensen et al. (1999, p. 92), who proposes to use 1 % of the range land for the construction of PV power plants and 5 % of the marginal land including scrubland and deserts, the estimated suitability factor is in a similar order of magnitude. The total available agricultural area of a country has been taken from Eurostat (2009) for the year 2000. Since the corresponding data for the year 2000 is not available for all countries, the data reported from previous years have been assumed.

Looking at building integrated PV power plants, the estimation of the surface area available depends on the roof and façade area suitable for PV installations. The calculation of the area available for building-integrated PV power plants is based on a study conducted by the International Energy Agency [IEA] (2002). The IEA put the roof area of all building types including agricultural, residential, industrial, commercial and other buildings suitable for PV power plants at 18 m^2 per capita and the respective façade area at 6.5 m^2 per capita. Multiplied with the population data, the overall area suitable for building integrated PV installations on roofs and on façades is computed. One main assumption made in this analysis is, that only half of the roof and façade area estimated by the IEA will be available for potential PV installations by the year 2050. In particular in case of roof-integrated solar PV plants this reduction accounts for the competition with solar heating panels.

Population data is based on a population scenario published by Eurostat (2008), the 'EUROPOP2008 convergence scenario'. In this scenario fertility, mortality and net migration between MS is assumed to converge in the long term. Eurostat estimates the population in the EU25 to increase from 495 million in 2008 to 515 million by 2050. For the calculation of the available roof and facade areas, the population scenario data of the year 2050 is assumed.

2.3.4 Solar radiation

For the estimation of the cost-resource curves, the solar radiation database PVGIS published by the Joint Research Centre 'Institute for Environment and Sustainability' (IES) in Ispra, Italy, is used as main input data. The 'Photovoltaic Geographic Information System' (PVGIS) is based on data processing of meteorological data from 566 measurement stations by means of the solar radiation model r.sun (cf. Suri, Hofierka 2004). Thereof, a raster dataset of global annual irradiation data (kWh/m^2) in Europe is publicly available for different inclination angles of the solar PV modules. The data is provided in terms of mid-term annual averages for the period of 1981 – 1990 with a spatial resolution corresponding to a grid size of 5 arc-minutes[17].

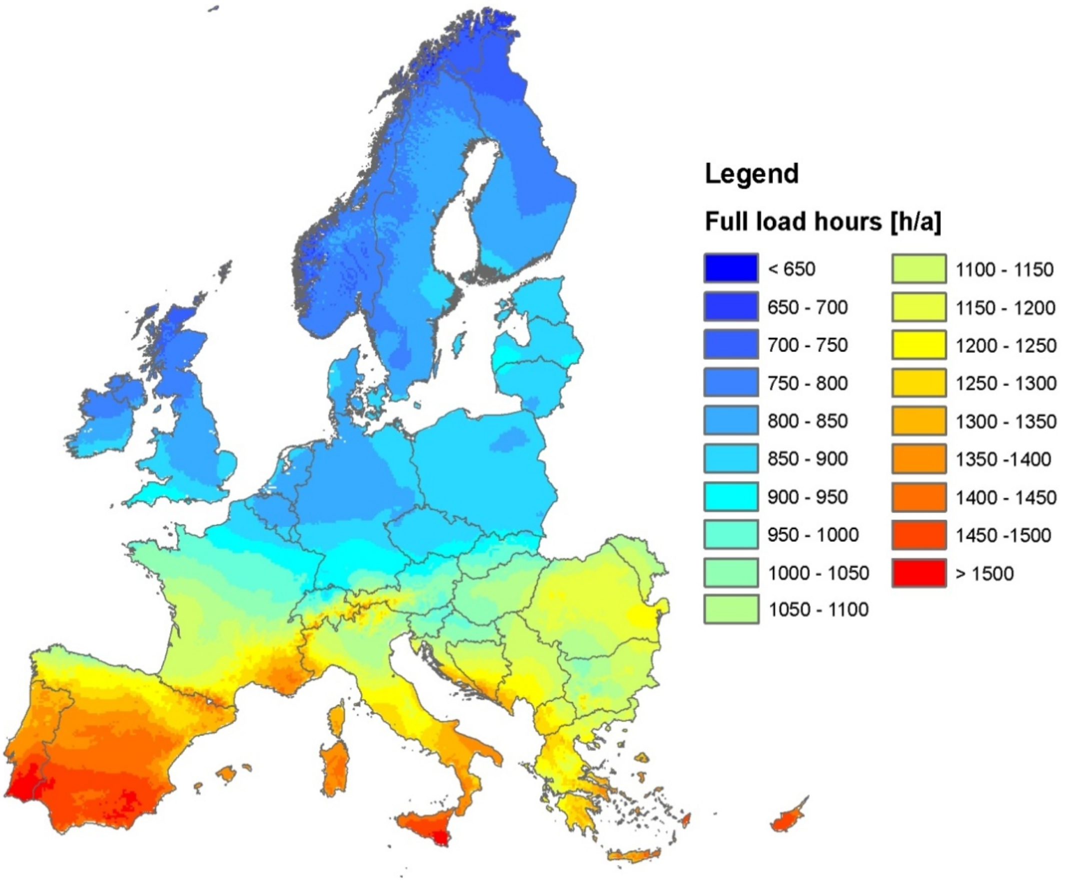

Figure 2-22 Annual full load hours of optimally inclined PV modules

Source: (Held 2011) based on data from Suri et al. (2007) and a performance ratio of 0.75

Looking at the spatially explicit potential utilisation of optimally inclined PV modules in Figure 2-22, full-load hours in Scandinavian countries range from 650 h/a to roughly 800 h/a, whilst full-load hours of up to 1500 h/a can be achieved in Southern Europe; in particular in Western Mediterranean regions including Portugal and Spain as well as in Sicily, Corsica and Crete.

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[17] A grid cell size of 5 arcminutes corresponds to a 9.3-km grid resolution at the equator.

In case of vertically inclined PV modules, the annual utilisation is considerably lower than in case of optimally inclined modules. According to the PVGIS data, annual full-load hours for facade-integrated PV modules range from about 450 h/a in Northern Europe to nearly 1000 h/a in Mediterranean countries. So, the regional annual full-load hours for vertically inclined facade-integrated PV modules differ considerably between Northern and Southern Europe (see Figure 2-23).

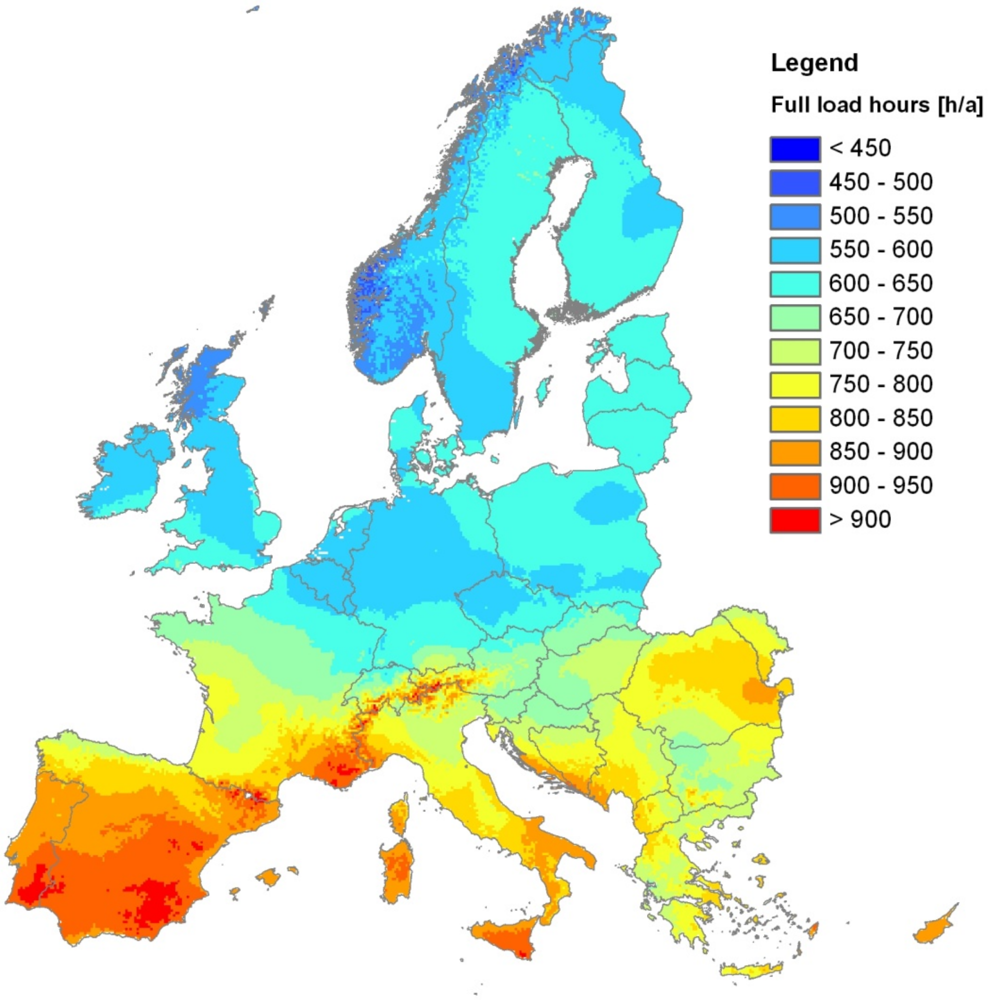

Figure 2-23 Annual full load hours of vertically inclined PV modules

Source: (Held 2011) based on data from Suri (2007) and a performance ratio of 0.75

2.3.5 Resulting solar PV cost-resource curves

As a final step, electricity generation costs are calculated for each of the previously investigated intervals, which are characterised by the combination of the capacity potential and the corresponding electricity generation costs. Electricity generation costs are calculated based on the economic parameters shown in Table 2-3.

Table 2-3 Technical and economic characteristics of solar PV technologies considered for the determination of the cost-resource curves

		Breakdown of investment into components				Assumed techno-economic parameters for cost-resource curve assessment			
		Module	Inverter	Other costs (installation, cables, etc.)	Total investment	Investment	O&M costs	Life-time	Typical plant size
Technology		[€/kW$_p$]	[€/kW$_p$]	[€/kW$_p$]	[€/kW$_p$]	[€/kW$_p$]	[€/(kW$_p$*a)]	[a]	[MW$_p$]
Roof-integrated PV plant	Mono-crystalline silicon	1,910	500	450	2,860	3,000	60	20	0.05
	Poly-crystalline silicon	2,090	500	450	3,040		60	20	0.05
	Amorphous silicon	1,680	500	450	2,630		56	20	0.05
Facade-integrated PV plant (mono- or poly-crystalline silicon)[18]		-	-	-	-	5,500	110	20	0.01
PV plant on free fields (amorphous silicon)		1,680	400	400	2,480	2,600	52	20	1

Source: (Held 2011) based on information from Bundesverband Solarwirtschaft e.V. [BSW-Solar] (2009); Kreutzmann (2009); Rutschmann & Siemer (2009)

According to the potential estimation, the resulting total potential for electricity generation with PV modules amounts to 1,760 TWh per year (see Figure 2-24). Comparing the available PV potential with the EU's annual gross electricity demand in 2007 of 3,338 TWh, it becomes clear that PV electricity might contribute significantly to the EU's electricity supply. The dominating share of the total PV potential consists in non-building integrated PV power plants (due to the surface area availability), corresponding to a total potential of 1,108 TWh per year or 63 % of the total solar PV potential. At the same time, the cost-resource curve of free-field PV power plants features the lowest electricity generation costs of all three investigated plant types starting from 186 €/MWh to 411 €/MWh. The corresponding electricity generation costs correspond to full-load hours between 700 h/a in Northern Europe and 1,500 h/a in Southern Europe. Looking at the roof-integrated solar PV plants, it turns out, that the overall potential amounts to 455 TWh per year. Due to higher initial investment requirements, electricity generation costs are higher compared to free-field plants ranging from 214 €/MWh to 474 €/MWh. The PV potential of facade-integrated plants is placed at 111 TWh per year, accounting only for roughly 7 % of the total PV potential in the EU27. In addition,

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[18] Investment for facade-integrated PV power plants was reduced by 1,500 €/kW$_p$ in order to account for the substitution cost of the facade-material.

electricity generation costs for facade-integrated PV installations are by far the highest, ranging between 609 €/MWh and 1,218 €/MWh.

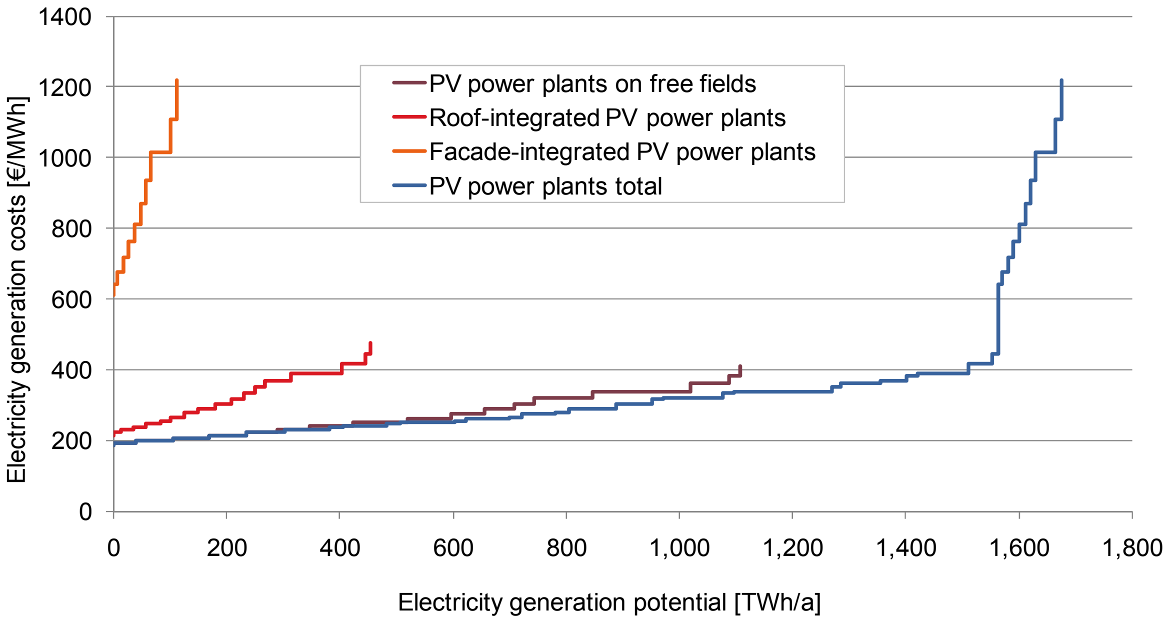

Figure 2-24 Derived cost-resource curves for solar PV technologies in the EU27 in 2009

Source: (Held 2011)

2.3.6 Summary and discussion of results

In this subsection, cost-resource curves for solar PV technologies have been estimated based on spatially explicit irradiation data. Three types of PV installations have been integrated into the analysis including plants mounted on free fields, plants mounted on the top of a roof and plants integrated into the building facade. The available surface area for all three types has been estimated based on a simplified approach. The estimation of the land area feasible for the installation of free field PV plants based on the total agricultural land and a suitability factor is characterised by high uncertainties. In particular the determination of the suitability factor is not exempt from a certain degree of arbitrariness. It should be kept in mind that the overall PV potential for free-field plants in capacity terms is highly sensitive to the suitable surface area. With regard to the assessment of the area suitable for building-integrated PV power plants, the applied data is based on average calculations assuming facade and roof area per inhabitant. In this way, country specific differences in living space per inhabitant are not taken into account. Furthermore, potential future changes in residential areas have not been taken into account. With regard to the composition of the roof types, the share of flat and pitched roofs in the roof area suitable for the construction of PV power plants was not considered as a result of lacking information on this issue.

Irradiation data, available for different inclination angles of the PV modules, has been used to create utilisation intervals on MS level. An important advantage of the applied radiation data consists in the high spatial resolution of 5 arc-minutes corresponding to a grid size of approximately 9.3 km * 9.3 km. In addition, irradiation data for different inclination angles, accounting for shadowing effects of the local terrain could be resorted to. Losses resulting from deviations from the optimal inclination angle in case of roof-integrated PV installations have been neglected. This simplification causes a slight overestimation of the feasible utilisation for roof-integrated PV power plants. In addition, it should be taken into account that differences in local conditions influencing e.g. the performance ratio differently throughout the EU have been neglected. This leads to an underestimation of the PV potential in Northern parts of Europe and to a slight overestimation in Southern Europe, where higher module temperature involve certain efficiency losses that may range up to 5%.

Instead of a direct map overlay of the geo-referenced data including the estimated area suitable for PV power plants and the respective radiation data, discrete utilisation intervals built for each country have been used to split up the estimated capacity potential. Thus, the fact that urban areas are not evenly distributed across a country is not accounted for in this analysis. Accordingly, this simplification reduces the accuracy of the results. Likewise, it is probable that in case of free field solar PV plants, a higher share of the agricultural surface area is dedicated to PV power plants in Southern parts of a country with more favourable weather conditions than areas with a less favourable solar regime. As a consequence the resulting costs of the cost-resource curves tend to be overestimated. Finally, neither grid integration issues have been considered for the derivation of the cost-resource curves nor improvements of the conversion efficiencies in the long run.

2.4 Potential of biomass for energy in the EU27

This section covers an assessment of available biomass for bioenergy production and costs in the EU27 between 2005 and 2030 and a long-term outlook beyond 2040. The 2009 COWI consortium (COWI 2009) conducted a review of the assumptions in Green-X on the cost and availability of biomass for bioenergy in the EU-27 including imports of biomass and biofuels to 2020. For the domestic potential in the EU-27, COWI concludes that the estimated potentials in Green-X are relatively conservative. However it was also noted that other studies were criticized for being too optimistic. Different from COWI, this study compares the potential on a country level. Furthermore, medium and long term assumptions beyond 2020 were reviewed.

Green-X includes assumptions on actual production, import and use of biomass for bioenergy which is defined as “implementation-economic potential” (COWI 2009), but will be referred to as “Green-X potential” in this section. Figure 2-25 shows the current Green-X potential for bioenergy in the EU-27 per feedstock type in the model. The total potential increases from 6.7 EJ in 2005 to 10.8 EJ in 2030 with the share of forestry products (FP) reducing from 37% in 2005 to 28% in 2030 and the share of dedicated energy crops (AP) increasing from 22% in 2005 to 33% in 2030. Mainly second generation energy crops (maize, whole plant, SRC, miscanthus and switchgrass) show the highest growth in potential between 2005 and 2030. A detailed discussion of these assumptions per resource type is provided in the following sections.

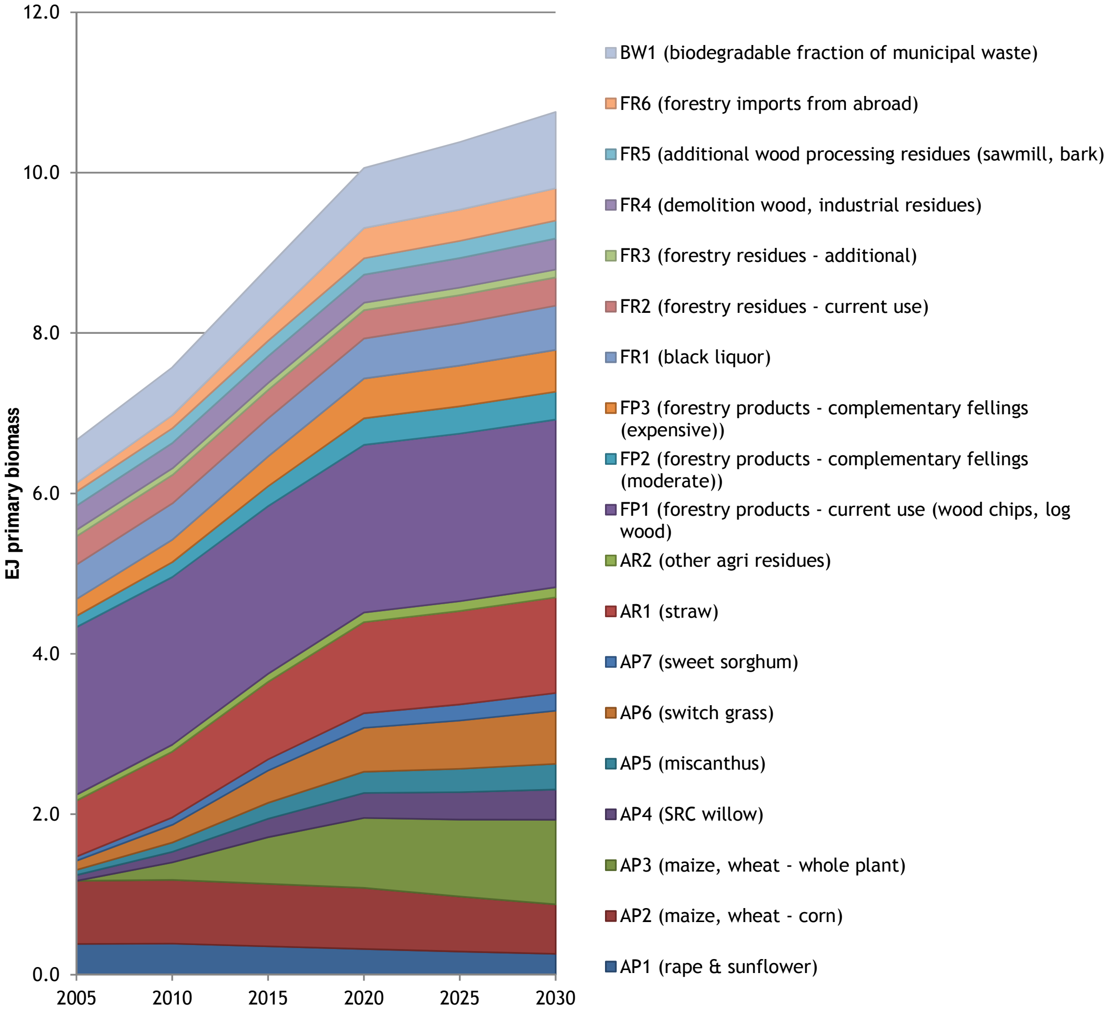

Figure 2-25 Implementation-economic potential of all bioenergy sources in Green-X

2.4.1 Energy crops

2.4.1.1 EU-27 potential

Based on the recently conducted biomass resource assessment for bioenergy in context of the Biomass Energy Europe (BEE) project, Rettenmaier et al. (2010) compared several studies that estimated the potential for energy crops within Europe. As these studies cover different regions within Europe ranging from the EU20 to EU27+3 countries, the potentials were, amongst others, calibrated for the EU27 based on for example the relative share of country specific potentials. Figure 2-26 shows the calibrated results of the projected biomass potentials for the EU-27. For reason of comparison, the Green-X potential for energy crops (AP) was added to the results from Rettenmaier et al. (2010).

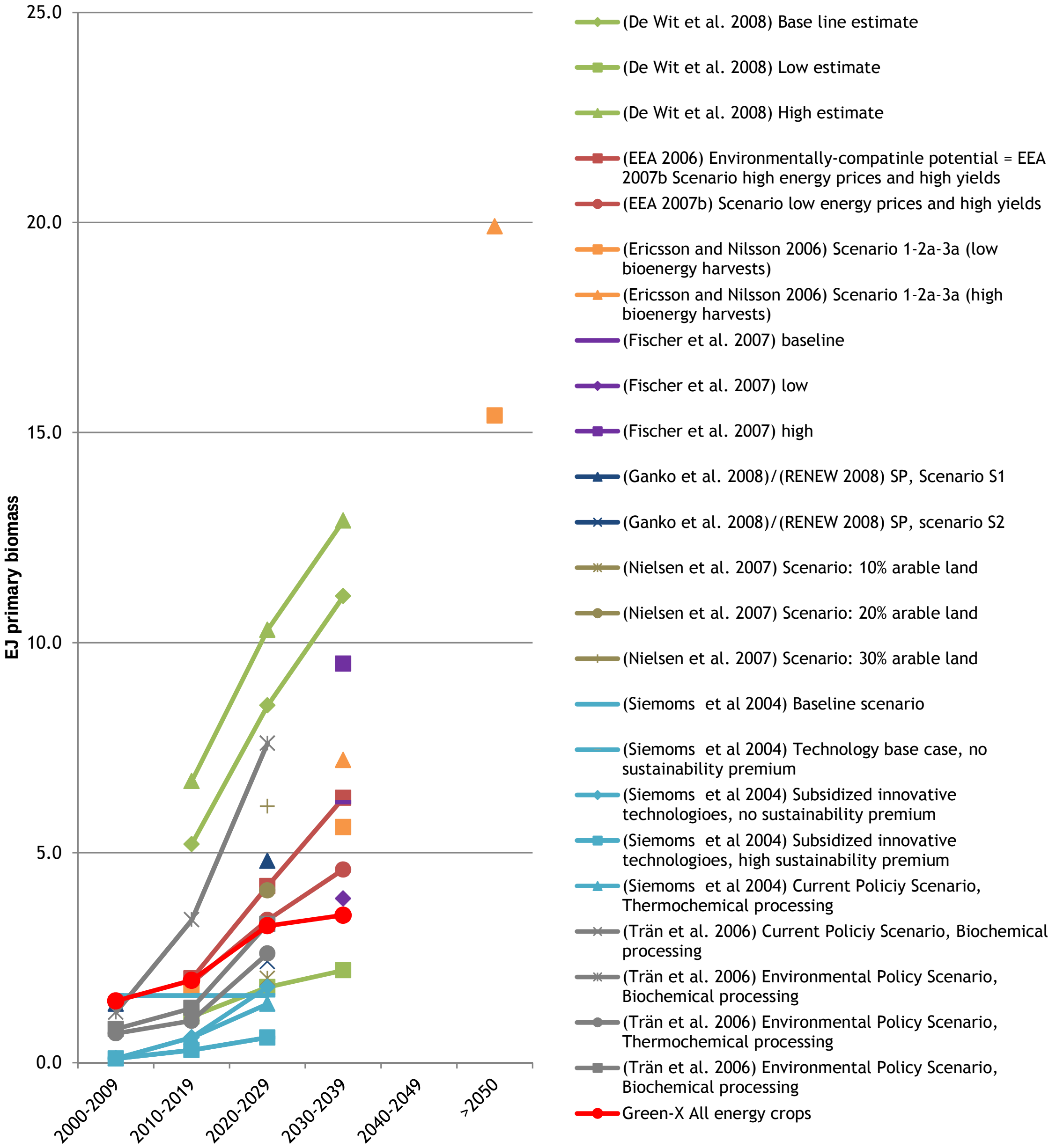

Figure 2-26 Total energy crops calibrated for the EU27 (Rettenmaier en al 2010) with the energy crop potentials from Green-X added[19] and projections from (Siemons, Vis et al. 2004; EEA 2006; Ericsson and Nilsson 2006; Thrän, M. Weber et al. 2006; Fischer, Hizsnyik et al. 2007; Nielsen, Oleskowicz-Popiel et al. 2007; EEA 2007b; Gańko, Kunikowski et al. 2008; Wit, Faaij et al. 2008).

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[19] Note that the results of Figure 2-27 differ from the results of De Wit et al. (2008) in Figure 2-27, because crops produced on pasture land are excluded in Figure 2-27.

Until 2020, the potentials in Green-X for energy crops are in range with the projections from the EEA Low energy high yields scenario (EEA 2007b) and the Environmental Policy Biochemical Processing scenario from Thrän et al. (2006) (3.3 to 3.4 EJ in 2020). Other studies and scenarios show a wide range in the projections for 2020 (0.6 to 10.3 EJ) . For 2030, despite partly substitution of first generation energy crops by second generation energy corps in Green-X (Figure 2-25), there is little increase (8%) in the potential for energy crops relative to 2020. The biomass resource assessment studies depicted in Figure 2-25 that include results for 2020 and 2030 show much higher increased potentials between 2020 and 2030 ranging from 22% (Low estimate de Wit et al. (2008)) to 50% (EEA 2006). It appears therefore that the trend in biomass potentials in Green-X between 2020 and 2030 is conservative. It should be noted though that some of these resource assessment studies have been criticized for being too optimistic. The EEA (2006), for example, for its degree on liberalization in trade of agriculture and de Wit et al. (2008) for being too optimistic on productivity increases in new EU member states (COWI 2009).

Most of the studies on EU potentials include potential estimates up to 2030 likely due to the horizon of energy and climate policies (Rettenmaier, Schorb et al. 2010).For long term potentials beyond 2030, only Ericsson and Nilsson (2006) provide projections for 2050. According to Ericsson and Nilsson, the potential for energy crops increases with over 175% between 2030 and 2050 for both scenarios. It should be noted however that these results are based on simple statistical methods without particular crop types (Rettenmaier, Schorb et al. 2010).

2.4.1.2 Energy crop potential per country

To compare the biomass supply potentials on a country level, similar to COWI (COWI 2009), the cost-supply curves of biomass of the REFUEL project and the studies that underlie the results of this project (de Wit and Faaij 2009; Fischer, Prieler et al. 2009a; Fischer, Prieler et al. 2009b) were used. Figure 2-27 depicts the potential of dedicated energy crops in the EU27 for Green-X (columns) and REFUEL (markers). The markers for REFUEL show the potential for the same crop mix as assumed in Green-X[20] produced on available arable land. The crop mix in Green-X is depicted in Figure 2-25. The negative error bars show the range if only low yield energy crops (oil crops) are produced on available land. The positive error bars show the potential if only high yield (grassy crops) are produced on available land. Results of REFUEL are based on the base scenario and exclude potentials of cultivation of lignocellulosic crops on pasture land (2009).

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[20] To harmonize the crop production mix between Green-X (fixed shares) and REFUEL (variable crop shares), the MS Excel solver was used to estimate the maximum total biomass production with the REFUEL database with the Green-X crop shares per country.

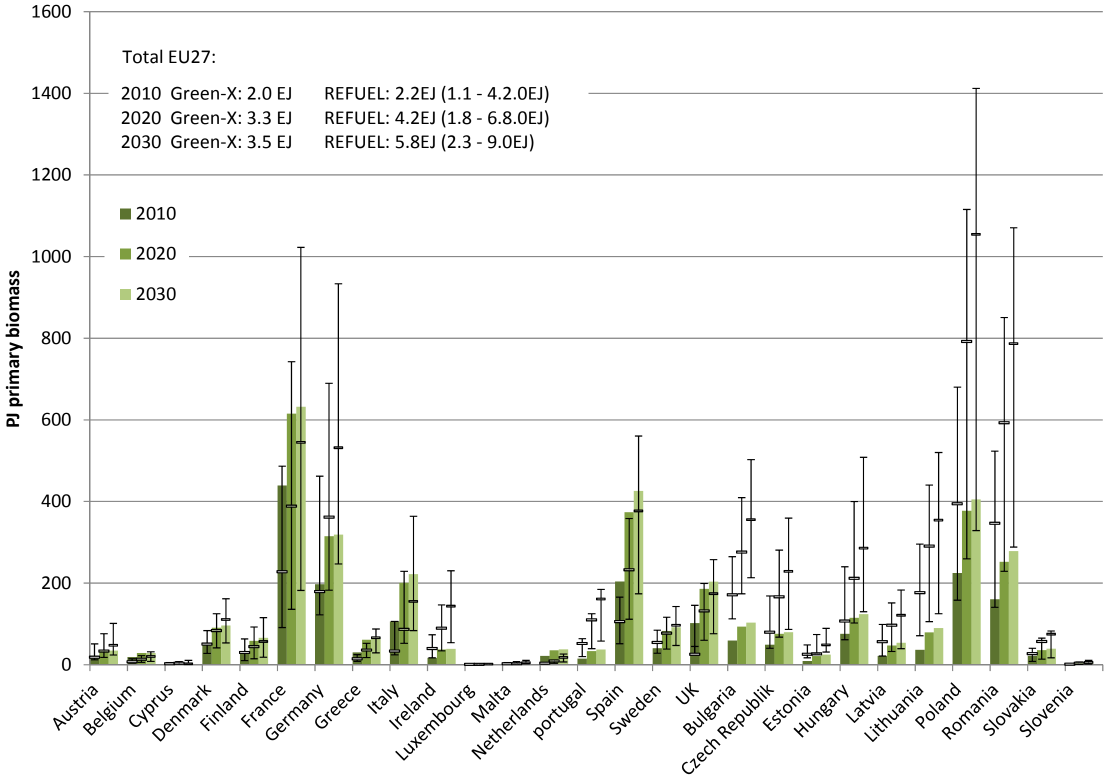

Figure 2-27 Supply potential of dedicated energy crops in the EU27 for Green-X (columns) and REFUEL (markers) for the same crop type production mix

The comparison of Green-X potentials and REFUEL potentials of dedicated energy crops shows that the higher estimated potentials in 2030 in REFUEL (5.8 EJ) compared to Green-X (3.5 EJ) are mainly due to differences in Central and Eastern European Countries (CEEC[21]). In France, Spain, Italy and the UK, the estimated potentials are more conservative in REFUEL compared to Green-X. In REFUEL, the estimated potential for energy crops in CEEC increases from 1.4 EJ in 2010 to 3.3 EJ in 2030 (57% of the EU27 potential). In Green-X, the potential in CEEC countries increases from 0.7 EJ in 2010 to 1.2 EJ in 2030 (34% of the EU27 potential).

2.4.1.3 Costs of energy crops

The costs for biomass production depend on the cost per hectare including land, labor, capital and fertilizers which differ per country and region. The costs of bioenergy crops in Green-X are estimated on country level per crop type. To compare the cost of bioenergy crops in Green-X with REFUEL, cost supply curves were made for the EU-27 using the Green-X database and the REFUEL NUTS-2 level database for the same region. In order to compare the

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[21] Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia.

costs more consistently, similar crop type shares were assumed in REFUEL[20]. Figure 2-28 shows the cost-supply curves of energy crop cultivation in the EU27 for REFUEL (left) and Green-X (right).

Both in Green-X and REFUEL, lignocellulosic energy crops (grassy crops and SRC) are the cheapest whereas oil crops (rapeseed and sunflower) are the most expensive. The main differences between REFUEL and Green-X are:

- The cost for biomass in REFUEL is significantly lower compared to Green-X, partly due to the relatively high potential in CEEC countries with lower production cost due to land and labor prices in these regions;
- In REFUEL, the cost of, especially lignocellulosic crops, is assumed to decrease in time due to accumulated experience (learning) whereas in Green-X, the cost increase over time in relation with increasing trends in fossil fuel prices.

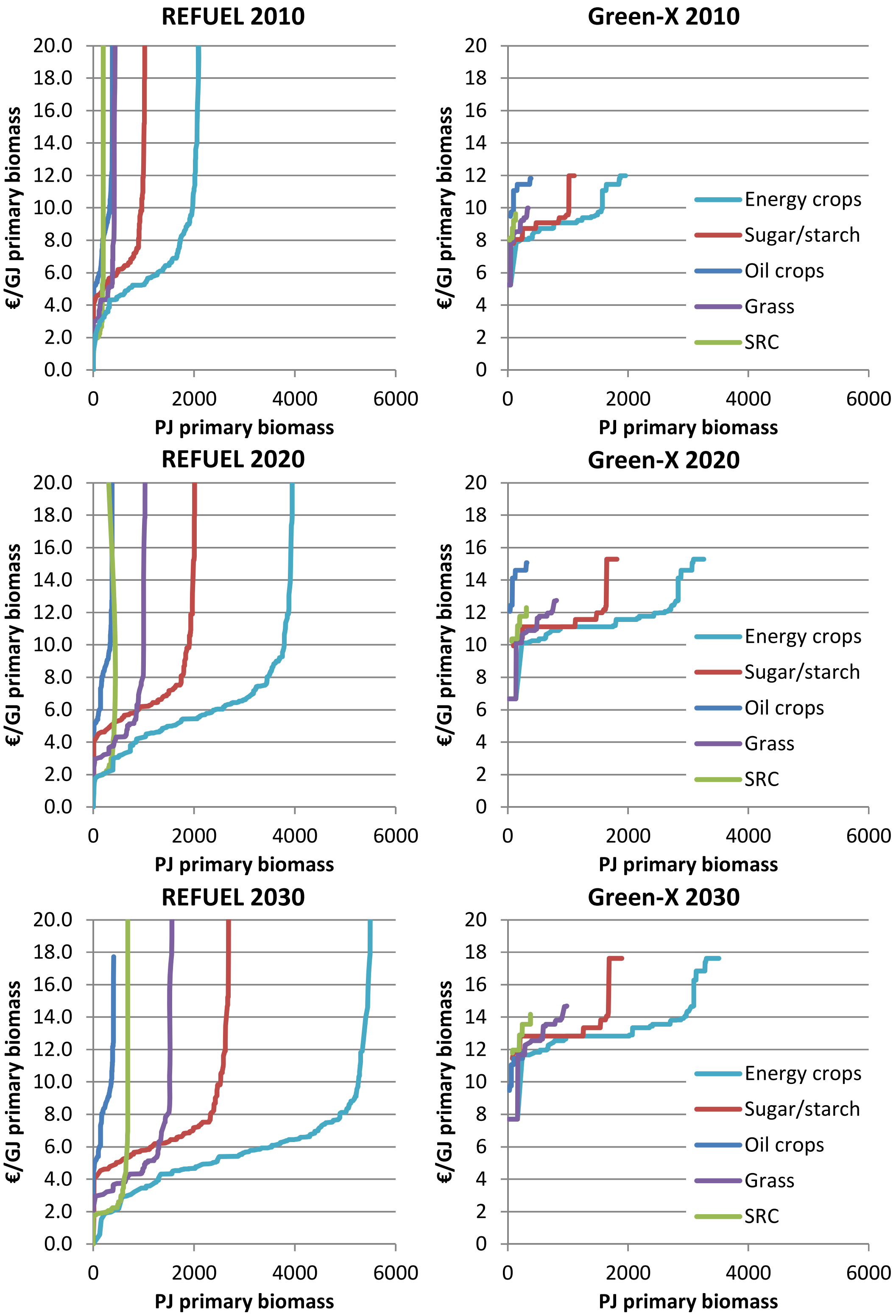

Figure 2-28 Farm gate cost-supply curves for bioenergy crops in the EU27 in Refuel and Green-X for the same crop type production mix.

2.4.2 Biomass from forestry, agricultural residues and waste

Fehler! Verweisquelle konnte nicht gefunden werden. shows the cost-supply curves of biomass from forestry products (current used log wood and wood chips and complementary fellings), forestry residues, secondary forest residues (demolition wood, black liquor and wood processing residues) agricultural residues (mainly straw) and the organic fraction of waste in Green-X. The total supply increases from 5.4 EJ in 2010 to 6.8 EJ in 2030 of which 67% (2030) to 72% (2010) are forestry products & residues and 17 (2010) to 19% (2030) are agricultural residues. Waste has a negative value (-1.1 €/GJ in 2010, -1.4 €/GJ in 2030).

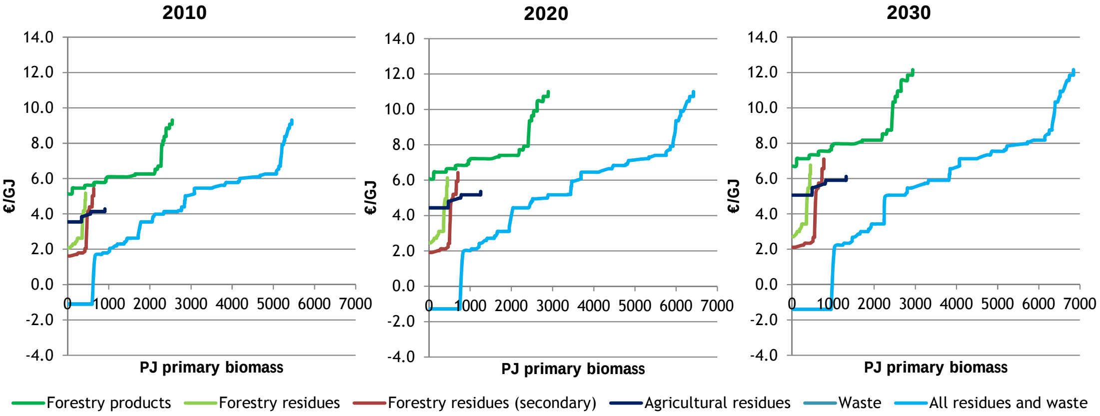

Figure 2-29 Cost-supply curves of forestry products (primary and secondary), agricultural residues and waste in Green-X. The waste curve is not visible, as it completely overlaps with the first horizontal line of the overall supply curve.

From all forestry products and forestry residues in Green-X, forestry products current use is the largest category with a share of 55% in 2005 to 46% in 2030 (Figure 2-25). This category includes the current use of all forestry products for decentralized and domestic heat production. Because this category is heterogeneous, it is not possible to compare the potentials in Green-X with other resource assessment studies per feedstock type. Nevertheless, it is possible to compare the total amounts of primary and secondary products from forestry on an aggregated basis. For the Biomass Energy Europe (BEE) project, Rettenmaier et al. (2010) compared several studies on the forest biomass potential for energy purposes in Europe with different geographical scopes and time frames. The differences in geographical scope were calibrated to the geographical coverage of the EU27 by taking the area included in the selected studies multiplied with the potential forest area in the EU27. The calibrated results of this study are depicted in **Fehler! Verweisquelle konnte nicht gefunden werden.** for primary and secondary forestry products and residues. To compare these results to Green-X, the primary forestry products in Green-X (FP1: forestry products - current use (wood chips, log wood), FP2: forestry products - complementary fellings (moderate), FP3: forestry products - complementary fellings (expensive), FR2: forestry residues - current use, FR3: forestry residues – additional and secondary forestry products and residues (FR1: black liquor, FR5: additional wood processing residues (sawmill, bark) were added to these results. The Green-X demolition wood category was excluded.

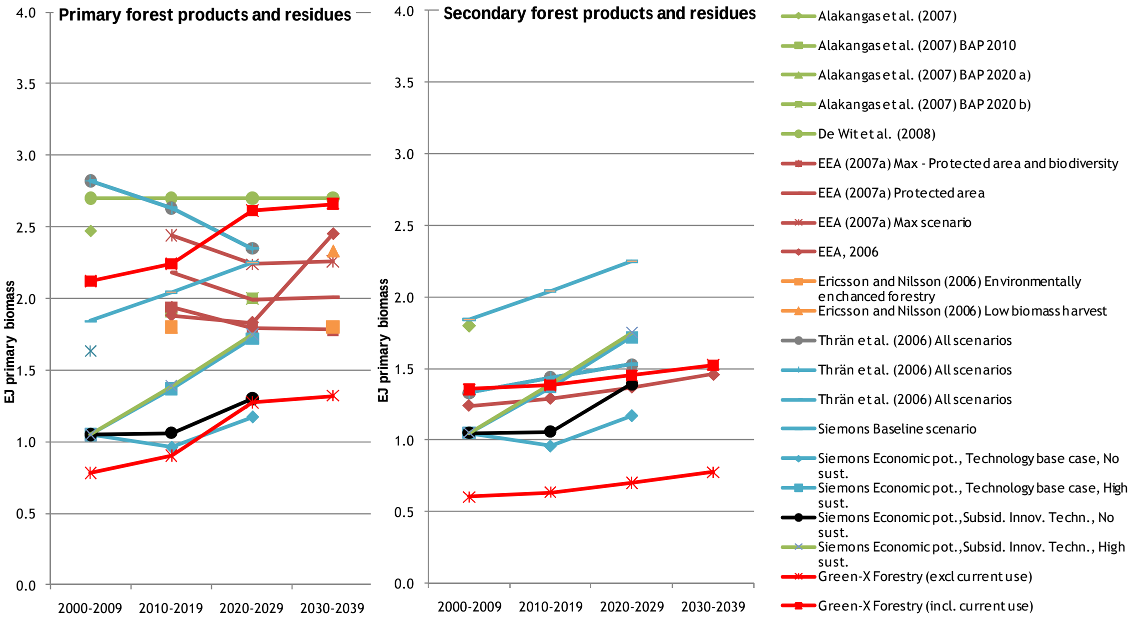

Figure 2-30 Total forestry potential (calibrated for the EU27) of stemwood and primary forestry residues (left) and secondary forestry residues (right) from Rettenmaier et al. (2010) with projections from (Siemons, Vis et al. 2004; EEA 2006; Ericsson and Nilsson 2006; Thrän, M. Weber et al. 2006; Alakangas, Heikkinen et al. 2007; EEA 2007a; Wit, Faaij et al. 2008) and forestry products and residues in Green-X excluding demolition wood and EUwood (Increasing demand allocated to materials scenario, IPCC A1) (Mantau, Saal et al. 2010).

The comparison of these forestry resource assessment studies show very different results for primary and secondary forestry products and residues between the studies depicted. For primary forestry products and residues, Green-X is close to the most optimistic estimates, specifically with regard to long-term prospects. For secondary forestry products and residues, Green-X is in range with the average estimates if the current decentralised use of forestry residues is taken into account. The differences are mainly the result of wood categories included and a result of different potential types (technical, economical, sustainable), approaches (demand or supply driven) and future scenario assumptions including demands from non-energy uses. The total potential of primary and secondary products and residues from forestry ranges from 1.2 EJ (EEA 2006) to 4.3 EJ (Alakangas, Heikkinen et al. 2007) for the current situation (2000-2009). The total potential in Green-X (primary and secondary forestry products and residues) increases from 3.5 EJ in 2005 to 4.2 EJ in 2030, the highest from the combined results of Figure 2-29 for 2030.

A potential explanation for the high potentials of primary forestry products and residues in Green-X could be the use for small-scale heating in households as well as in industry. The results for Green-X are therefore shown with and without this category. Many studies such as the EEA (EEA 2007a) did not consider the use of forestry biomass for small scale heating in households in their assessment because the affected volumes of wood are usually not included in the harvested statistics. In Green-X, the current use of forestry products for small scale heating forms a significant share of the total potential of forestry products. Wide ranges are found in the total potential of small-scale heat generation from biomass due to the uncertainty and lack of data. Mantau, Saal et al. (2010) estimated the total production of heat in traditional wood stoves by private households based on the Joint Wood Energy Enquiry of the UNECE/FAO Forestry and Timber section for 13 available countries in the EU-27 for the EU-wood study. For the other member states, an indicator was used (forest area (ha)/rural population). If the results are compared to Held, Ragwitz et al. (2010), based on similar results to Green-X, it appears that there is a large difference in the production of heat from households. Held, Ragwitz et al. estimated 2320 PJ final heat to be produced in decentralized and 320 PJ final heat in centralized systems in 2008. EUwood estimates 1480 PJ primary biomass to be used by households for the EU-27. It is noted in the EUwood study that the use of biomass from households is very uncertain.

Another important factor is the allocation of biomass to material users such as wood panel industries and pulp and paper mills. Mantau, Saal et al. (2010) estimated for the EUwood study that, if the demand for materials remains constant, the future potential of primary forestry products available for energy use could increase in the medium mobilization scenario (**Fehler! Verweisquelle konnte nicht gefunden werden.**) from 1.56 EJ to 2.5 EJ in 2030 and from 2.7 EJ to 3.6 EJ if high mobilization is assumed.

3 Technology diffusion characteristics

In several countries, financial support appears to be sufficiently high to stimulate deployment of RES technologies, but in practice, actual deployment lacks however far behind expectations. This is a consequence of several deficits not directly linked to the financial support offered which in literature are frequently named “non-economic /non-cost barriers”. These barriers refer to administrative deficiencies (e.g. a high level of bureaucracy), diminishing spatial planning, problems associated with grid access, possibly missing local acceptance, or even the non-existence of proper market structures.

In the Green-X model, dynamic diffusion constraints are used to describe the impact of such non-economic barriers. Details on the applied modelling approach are explained subsequently.

3.1 Modelling the impact of non-economic barriers on the feasible technology diffusion

Within the Green-X model, dynamic diffusion constraints are used to describe the impact of such non-economic barriers. They represent the key element to derive the feasible dynamic potential for a certain year from the overall remaining additional realisable mid- / long-term potential for a specific RES technology at country level. The application of such a constraint in the model calculations results in a technology penetration following an “S-curve” pattern – obviously, only if financial incentives are set sufficiently high to allow for a positive investment decision.

According to general diffusion theory, penetration of a market by any new commodity typically follows an “S-curve” pattern. The evolution is characterised by a growth, which is nearly exponential at the start and linear at half penetration before it saturates at the maximum penetration level. With regards to the technical estimate of the logistic curve, a novel method has been employed by a simple transformation of the logistic curve from a temporal evolution of the market penetration of a technology to a linear relation between annual penetration and growth rates. This novel procedure for estimating the precise shape of the logistic curve is more robust against uncertainties in the historic data that may if only growth rates are used lead to an over- or underestimation of future technology deployment. Furthermore, this method allows the determination of the independent parameters of the logistic function by means of simple linear regression instead of nonlinear fits, involving the problem of local minima, etc.

Analytically, the initial function, as resulting from an econometric assessment, has a similar form to equation (1). However, for model implementation, a polynomial function is used, see equation (2). This translation facilitates the derivation of the additional market potential for the year n if the market constraint is not binding, i.e. other applicable limitations provide stronger restrictions. As absolute growth rate is very low in the case of an immature market, a minimum level of the yearly realisable additional market potential has to be guaranteed – as indicated by equation (3).

$$X_n = \frac{a}{\left\{1 + b * e^{\left[-c*(\text{year}\,n - \text{start year} + 1)\right]}\right\}} \tag{1}$$

$$\Delta P_{Mne} = P_{\text{stat long-term}} * \left[A * X_n^{\,2} + B * X_n + C\right] * \left[\chi_{M\min} + \frac{\chi_{M\max} - \chi_{M\min}}{4} * b_M\right] \tag{2}$$

$$\Delta P_{Mn} = \text{Max}\left[\Delta P_{M\,\min};\ \Delta P_{M\,ne}\right] \tag{3}$$

where:

$\Delta P_{M\,n}$	realisable potential (year n, country level)
$\Delta P_{M\,\min}$.......	lower boundary (minimum) for realisable potential (year n, country level)
$\Delta P_{M\,ne}$........	realisable potential econometric analysis (year n, country level)
$P_{\text{stat long-term}}$ ..	static long-term potential (country level)
a............	econometric factor, technology specific
b............	econometric factor, technology specific
c............	econometric factor, technology specific
A	quadratic factor yield from the econometric analysis
B	linear factor yield from the econometric analysis
C	constant factor yield from the econometric analysis (as default 0, considering market saturation in the long-term)
X_n...........	calculated factor - expressing the dynamic achieved long-term potential as percentage figure: In more detail … $X_n = \frac{\text{dynamic achieved potential (year n, country level)}}{\text{total long - term potential (country level)}}$; X_n [0, 1]
$\chi_{M\,\max}$	absolute amount of market restriction assuming very low barriers; $\chi_{M\,\max}$ [0, 1]; to minimise parameter setting $\chi_{M\,\max} = 1$
$\chi_{M\,\min}$	absolute amount of market restriction assuming very high barriers; $\chi_{M\,\min}$ [0, $\chi_{M\,\max}$]
b_M	barrier level market / administrative constraint assessment (level 0 - 4) [22]; i.e. the country-specific parameter to describe the impact of non-economic barriers

For parameter setting, the econometric assessment of past deployment of the individual RES technologies at country level represents the starting point, whereby factors A, B and C refer to the "best practice" situation as identified via a cross-country comparison.[23] [24]

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[22] A value of 0 would mean the strongest limitation (i.e. no diffusion, except minimum level), while 4 would mean the strongest feasible diffusion (according to "best practice" observations).

Note, if alternatively the level number '5' is chosen, the default approach would be replaced by a simplified mechanism: In this case, the yearly realisable potential is defined as share of the dynamic additional realisable mid-term potential on band level. Hence, it is possible to chose separately how much of the remaining potential can be exploited each year.

[23] For the "best practice" country, the applied market barrier b_M equals 4 – see notes as given in the corresponding description. Consequently, the comparison to this "ideal" case delivers the barrier level b_M for other countries.

Within the scenario work, two different variants of settings with respect to the non-economic barriers of individual RES technologies have been applied:

- **High non-economic barriers / low diffusion ("BAU settings")**

  This case aims to reflect the current situation (BAU conditions) where non-economic barriers are of relevance for most RES technologies. The applied technology-specific parameters have been derived by an econometric assessment of past deployment of the individual RES technologies within the assessed country.

- **Mitigated non-economic barriers / high diffusion ("Best practice")**

  This case represents the other extreme where the assumption is taken that non-economic barriers will be mitigated in time.[25] This more optimistic view is applied in the policy assessment referring to the ambitious target of 20% RES by 2020. Applied technology-specific settings refer to the "best practice" situation as identified by a cross-country comparison. Accordingly, an enhanced RES deployment can be expected – if financial support is also provided in an adequate manner.

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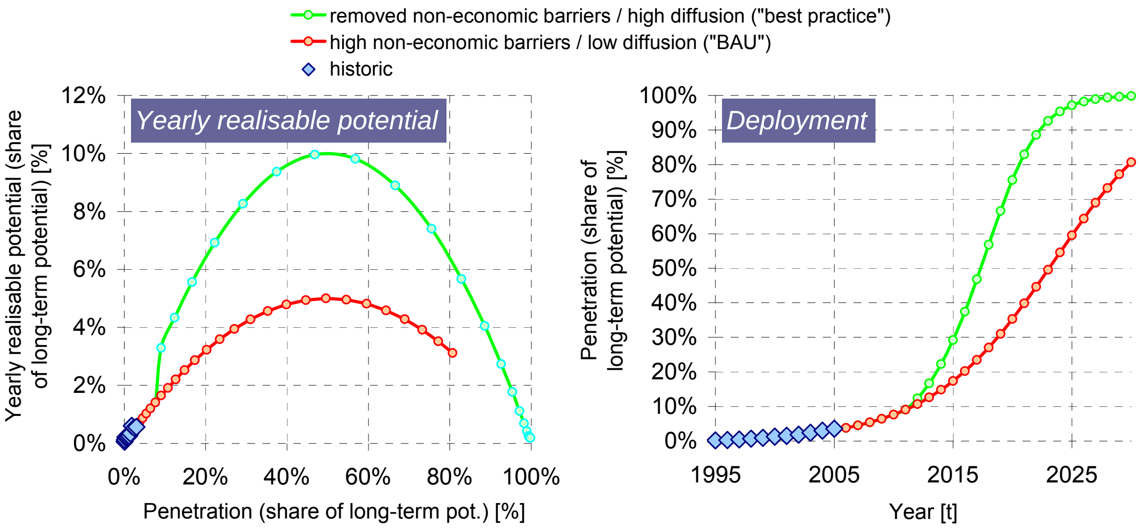
[24] Novel technologies in an early stage of development have no historic record regarding non-economic barriers. For these technologies, the level of non-economic barriers is estimated based on those of comparable technologies.

[25] More precisely, a rapid removal of non-economic barriers is preconditioned which allows an accelerated RES technology diffusion. Thereby, the assumption is taken that this process will be launched in 2011.



Note: Key parameter have been set in this schematic depiction as follows: A = (-B) = -0.4; b_M was varied from 2 (high barriers / low diffusion) to 4 (removed barriers / high diffusion)

Figure 3-1 Schematic depiction of the impact of non-economic barriers on the feasible diffusion at technology and country level: Yearly realisable potential (left) and corresponding resulting feasible deployment (right) in dependence of the barrier level

Figure 3-1 illustrates the applied approach: On the right-hand side the resulting yearly realisable potential in dependence of applied barrier level and on the left-hand side related deployment – in case that no other (financial) constraint would exist – are depicted, illustrating schematically applied variants with respect to non-economic barriers as used in the follow-up scenario assessment.

3.2 Illustration of the derived approach – scenarios on the future RES deployment w/o mitigation of non-economic barriers

Next, selected outcomes of a model-based scenario elaboration in line with 20% RES by 2020 are discussed, done by application of the Green-X model. We focus hereby on the illustration of the derived approach for modelling technology diffusion, in particular for the impact of non-economic barriers. This is demonstrated in the context of identifying recommendations towards an achievement of the Member State’s 2020 RES commitments in an effective and efficient manner – i.e. illustrating the impact of individual measures to move from a business-as-usual to a strengthened national policy path in line with the 2020 RES commitment.

3.2.1 Example: Towards an effective and efficient 2020 RES target fulfillment – from BAU to strengthened national support

With currently implemented RES support – i.e. according to our scenario definition named as business-as-usual (BAU) case – it can be expected that the majority of EU countries would fail to trigger the required investments in new RES technologies as needed for 2020 RES target fulfilment. Subsequently, we present the impact of individual measures to move from BAU to a policy path where all Member States would meet their RES commitments. Thereby, special attention is paid to illustrate the impact of a mitigation of non-economic barriers. To model this, the previously discussed approach of modelling technology diffusion was applied.

Figure 3-2 illustrates the future deployment in relative terms for both RES-E (left) and RES in total (right) in the EU-27 in the period 2011 to 2020 for the BAU case – incl. a sensitivity variant of mitigated non-economic barriers - and the case of “strengthened national support (in line with 20% RES by 2020). More precisely, this graph illustrates the RES-E share in gross electricity demand (left) and the share of RES (in total) in gross final energy demand (right). Complementary to this, Figure 3-3 shows the corresponding development of yearly consumer expenditures due to the underlying conditioned RES support for the identical scenario selection. Similar to above, results are presented for both RES-E (left) and RES in total (right) in the EU-27 for the forthcoming years up to 2020.

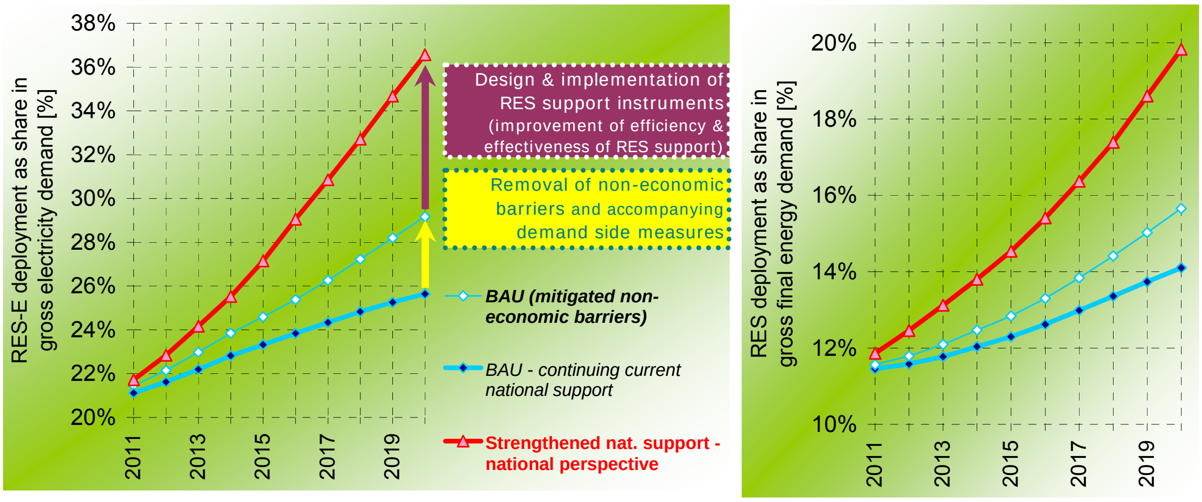


Figure 3-2: RES-E (left) and RES (right) deployment (expressed as share in gross electricity demand (left) / gross final energy demand (right)) in the period 2011 to 2020 in the EU-27 according to the BAU case (incl. a sensitivity variant of <u>mitigated non-economic barriers</u>) and the case of “strengthened national policies – national perspective”

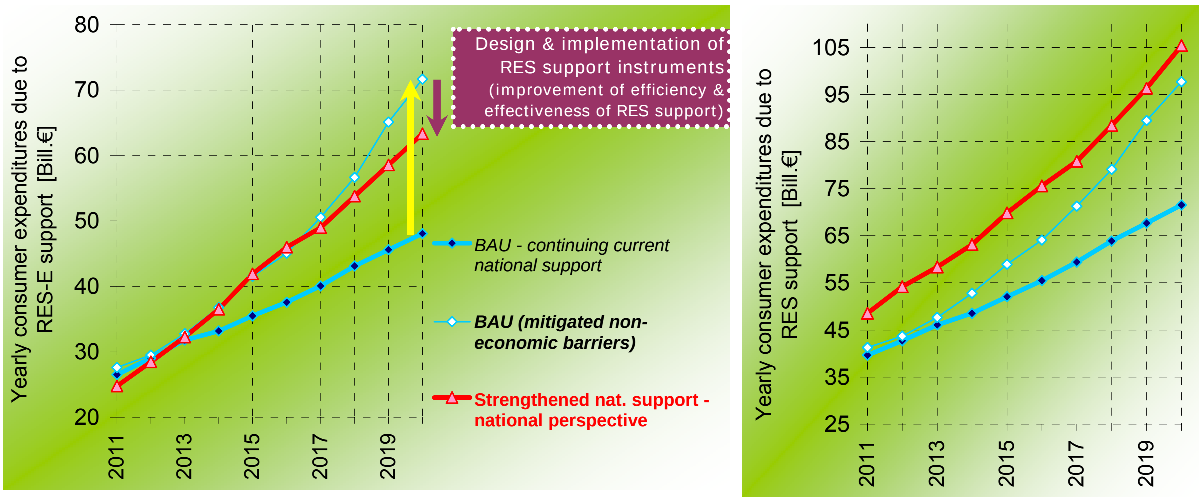


Figure 3-3: Yearly consumer expenditures due to RES-E (left) and RES (right) support (expressed as share in gross electricity demand (left) / gross final energy demand (right)) in the period 2011 to 2020 in the EU-27 according to the BAU case (incl. a sensitivity variant of mitigated non-economic barriers) and the case of "strengthened national policies – national perspective"

As applicable in Figure 3-2, an accelerated expansion of RES-E as well as RES in total can be expected with effective and efficient RES support in place (as derived for all "strengthened national support" variants) while under BAU conditions a rather constant but moderate deployment is projected for the period up to 2020. Analyzing the above illustrated sensitivity variants of the BAU case indicates the impact of the individual key measures to move from a BAU to an enhanced RES deployment in line with 20% RES by 2020:

- **Mitigation of non-economic RES barriers:** Retaining current financial RES support but supplemented by a mitigation of non-economic deficits that limit technology diffusion would allow for a 2020 RES-E share of 29.2% (compared to 25.6% as default). The corresponding figure for RES in total is 15.7% (instead of 14.1% as default). A significant impact can be also observed for the corresponding yearly consumer expenditures due to RES(-E) support. Required expenditures by 2020 would increase substantially under the assumed retention of current support conditions (without any further adaptation) - i.e. rising from about 48 to 72 billion € in 2020 for RES-E solely, while expenditures for RES in total increase from 72 to 98 billion €. This indicates the need to align support conditions to the expected / observed market development, as otherwise specifically novel RES technologies would achieve significant over-support in case of future mass deployment;
- **Design and implementation of RES support instruments:** The detailed policy design has a significant impact on the RES deployment and corresponding expenditures, specifically for the electricity sector. This can be seen from the comparison of the "strengthened national policy" case with the BAU variant where similar framework

conditions are applied (i.e. removed (non-economic) barriers). For RES-E the direct improvement of the efficiency and effectiveness of the underlying support instruments causes an increase of the RES-E share from 29.2% (BAU with removed barriers) to 36.6% ("strengthened national support"). For RES in total the impact on deployment is of similar magnitude – i.e. an increase of the RES share of gross final energy demand from 15.7% to 19.8% is observable. With respect to support expenditures, the consequences are more significant for the electricity sector as then the required burden can be decreased substantially (while the deployment follows an opposite trend). More precisely, yearly expenditures in 2020 would decline from 72 to 63 billion € for RES-E, while for RES in total a comparatively less significant increase is observable (i.e. from 98 to 105 billion € in 2020) that matches well with the increased deployment.

The above discussed example aims to illustrate the application of the derived novel approach for modelling technology diffusion characteristics within Green-X. For further details on the briefly sketched policy scenario assessment we refer to the forthcoming corresponding RE-Shaping scenario report.

4 Long term cost developments –technological change

This chapter covers the analysis of technological change, in particular with regard to technological learning, the assessment of learning rates of RES technologies available in literature and forecasting studies and the identification of trade-offs between high energy prices and raw material cost developments. In recent years, energy and raw material prices have shown to have a significant impact on the cost development of RES technologies. Therefore, possibilities for model incorporation to address for these factors have been elaborated.

4.1 Technological learning

For many (energy) technologies, a log-linear relation was found between the accumulated experience and the technical (e.g. efficiency) and economic performance (e.g. investment costs). This empirical observed phenomenon can be expressed by formula 4-2 or in logarithmic form rewritten as formula 4-2. The rate at which cost decline for each doubling of cumulative production is expressed by the progress ratio (PR). A progress ratio of 90% results in a learning Rate (LR) (4-4) of 10% and similar cost reduction per doubling of cumulative production (IEA 2000; Junginger, Sark et al. 2010).

$$C_{Cum} = C_0 Cum^m \tag{4-1}$$

$$\log C_{Cum} = log C_0 + m log Cum \tag{4-2}$$

$$PR = 2^m \tag{4-3}$$

$$LR = 1 - PR \tag{4-4}$$

Where:

- C_{Cum} = cost per unit
- C_0 = cost of the first unit produced
- Cum = cumulative (unit) production
- m = experience parameter
- PR = progress ratio

The historic development of the investment costs of three RES technologies (on- and offshore wind, PV) and two fossil fuel power systems (natural gas combined cycle and pulverized coal plants) plotted against the cumulative installed capacity on a double logarithmic scale in Figure 4-1. All technologies included show a log-linear decreasing trend with strong reductions in investment costs. The strongest decline was found for PV, that decreased from several hundred €/Wp in the 1960s to 4-5 €/Wp at present. From 2002 onwards, a discontinuation of the decreasing learning trends was observed for these technologies and costs even started to increase. The drivers that underlie these negative learning trends are, amongst others, increased commodity and energy prices, overheated markets, and shortages of skilled labour and production capacities that leveled out learning effects. These effects and are discussed in detail in the following subsections.

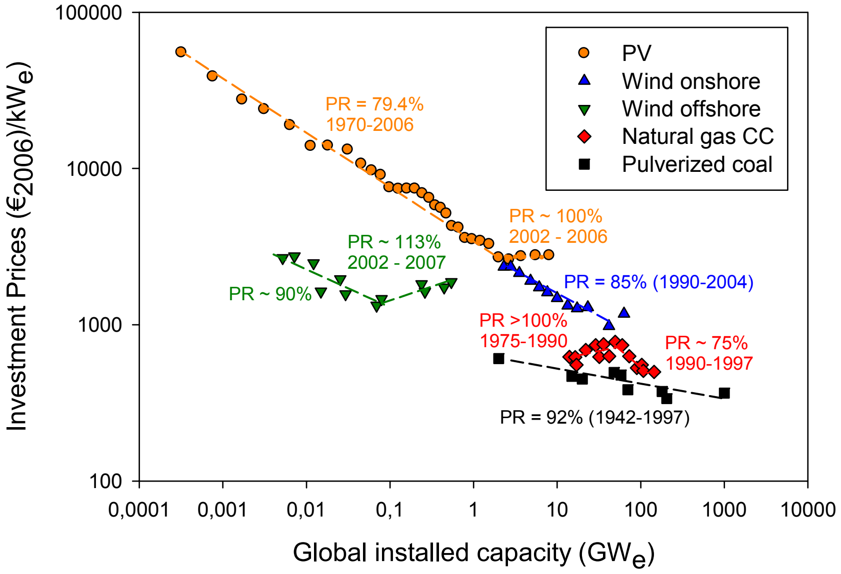


Figure 4-1 Comparison of experience curves for energy conversion technologies, based on historical data (Junginger, Sark et al. 2010)

4.2 Technological learning of renewable energy technologies

A state-of-the-art overview of technological learning in the energy sector, including a wide range of renewable energy technologies, was recently published in Junginger et al. (2010). The results of this section are therefore mainly based on the available RES technologies in Junginger et al. (2010). The technologies included in the assessment are: on- and offshore wind, photovoltaics (PV), concentrated solar power (CSP) and energy from biomass (electricity and fuels).

4.2.1 Onshore wind

Onshore wind has developed from small scale (10 – 30 kW) units during market introduction in the 1970s to a mature technology with units currently up to 5 MWe. The effect of technological learning on the investment cost and electricity production cost of wind turbines has been studied extensively. Table 4-1 provides an overview of the learning rates of onshore wind turbines published in literature after 2002. A complete overview of studies (15) is provided in Junginger et al. (2010).

The progress ratio found for onshore wind ranges from 81 to 101% depending on the selected parameters such as time frame, production or installation region (e.g. at country level or global) and electricity generation costs or investment costs. As shown in figure 14, the investment cost of onshore wind turbines have more than halved over the last 20 years. After, 2004 however, the investment costs increased again from 980 €/kW in 2004 to 1380 €/kW in 2008. After 2008, the cost stabilized, but may increase again in the coming years (Junginger, Lako et al. 2010). The learning rates applied in Green-X are in range with Extool (Neij et al. 2003). These might be underestimated as they are derived from a selected region. A recent study on global wind development (Nemet 2009) shows a progress ratio of 89% for the period 1981 to 2004, however the progress ratio varies significantly if other time periods are selected (PR = 83 – 97%).

Table 4-1 Overview of progress ratios for onshore wind in Green-X and published in literature (Junginger, Lako et al. 2010)

Reference	PR	Time frame	Price data region	Capacity
Investment costs				
Range found in literature	81-101%			
Green-X	91%	2010-2020	Global	Global
	94%	>2020	Global	Global
Neij et al. 2003	92-94%	1981-2000	DK, ES, DE, SW	Produced per country
	89-96%	1981-2000	DK, ES, DE, SW	Installed per country
Junginger et al. 2005	81-85%	1990-2001	Price data from UK and ES	Global
	91-101%[1]	1991-2001	Germany	Germany
Taylor et al. 2006	85%	1982-2000	California	Global
Nemet 2009	89%[2]	1981-2004	Global	Global
Levelized electricity costs				
Neij et al. 2003	83%	1982-2000	Denmark	Denmark
Taylor et al. 2006	85.50%	1981-2002	California	California

1) 1991-1996 (phase I, PR = 91%) 1996 - 2001 (Phase II, PR = 101%).
2) 83-97%, depending on period of time.

4.2.2 Offshore wind

Offshore wind developed as a near shore derivative from onshore wind turbines to a dedicated technology optimized for offshore conditions. Because the experience with offshore wind turbines is relatively short, empirical trends of cost developments are also limited. According to Lako et al. (2010), the development of offshore wind can be divided into two phases. Phase 1 (1991 -2000) defines the period when offshore wind parks were mainly built to gain experience with the technology. The cumulative capacity in this period did not exceed 100 MWe. In phase 2, after 2001, large parks were started to be built mainly in Europe, but also the US and Asia initiated projects on offshore wind. In 2012, over 10 GWe of cumulative capacity is expected to be installed in Europe alone. Other regions might add another 0.7 GWe (Lako, Junginger et al. 2010).

Three studies are available including experience curves of offshore wind (Table 4-2). Lako (2002) differentiates between the turbine section (rotor, nacelle and towers), the offshore construction and the grid connection for offshore wind parks. The study is focused on state-of-the-art systems in the demonstration phase. Junginger et al. (2004) also uses a sub-system approach, but assumes progress ratios of the turbines section analogue to onshore wind turbines. Development of the grid connection costs are based on submarine high voltage direct current (HVDC) cables whereas the foundation costs are based on steel price reductions of 1-2%/yr. Note that these developments have changed over recent years with increasing commodity prices (mainly steel). The installation costs were derived from the installation time of an offshore wind park in Denmark. Isles (2006) found a disconnection between prices and cost of wind turbine manufactures due to lack of competition. The study was based on 22 wind farms of which 19 were in operation built between 1991 and 2006. For the whole time period, Isles found a progress ratio of 97%, but for a two phase experience curve, a progress ratio of 90% was found for 1991 – 2001 and 113% for 2002 – 2007.

The progress ratio for offshore wind in Green-X to 2020 (PR=91) is close to the progress ratio found by Isles (2006) for phase 1 of the development of offshore wind. However, more recent development of the cost of these technologies emphasize the need for incorporating effects other than learning that can have a substantial influence and result negative experience curves (PR=113%) (Figure 4-1). These include, amongst others, the effect of raw material prices, such as steel, on the cost of wind turbines.

Table 4-2 Overview of progress ratios for offshore wind in Green-X and published in literature (Lako, Junginger et al. 2010)

Reference	PR	Time frame	Price data region	Capacity
Range found in literature	81-113%			
Green-X	91%	2010-2020	Global	Global
	94%	>2020	Global	Global
Lako 2002 (reference)			?	?
Rotor and nacelle	90%	1991-2007		
Balance of plant	95-97.5%	1991-2007		
Junginger et al. 2004			Price data from UK and ES	Global
Turbine	81-85%[1]			
Foundation	1-2% per yr[2]			
Grid connection	62-71%[3]			
Installation	77-95%[4]			
Isles 2006			?	?
One-phase case	97%	1991-2007		
Two-phase case	90%	1991-2000		
	113%	2001-2007		

1) Based onshore and offshore wind in the UK and Spain (Junginger et al. 2005).

2) Cost reductions of 1-2% per year based on the assumption that steel prices show a similar decline. Since 2004 however, steel prices have increased.

3) PR for HVDC cable = 62%, PR for HVDC converter station = 71%

4) Marginal turbine installation time PR = 77%

4.2.3 Photovoltaic solar energy

Photovoltaic solar energy (PV) include systems that directly convert (sun)light into electricity of which the most PV systems are based on silicon (95%). Large interest for PV started after the oil crisis in the 1973s when PV was regarded as a potential alternative to fossil fuels. Nevertheless, the cumulative experience of PV cells was still below 100 MWp in the mid 1980s. Rapid growth of PV modules started in 1999 with high annual growth percentages of 30% in 1999 to 87% in 2008 (Sark, Nemet et al. 2010). Due to the efficiency improvements, reduced silicon consumption and reduced cost of silicon, improved crystal growing methods and economies of scale of production facilities (Nemet 2006), the cost of PV per Wp dropped by a factor 20 between 1976 and 2002 (Yu, van Sark et al. 2010). After 2002, the cost of PV modules more or lest stabilized due to increased prices of silicon and silver as observed by Yu et al. (2010) (Figure 4-1).

Cost development trends of PV solar energy have been studied extensively resulting in a range of publications. Sark et al. (2010) provide an overview of 20 experience curves published on PV between 1972 and 2009. Table 4-3 depicts the experience curves that were published after 2002 and the progress ratios used in Green-X model. The progress ratios found in these studies ranges from 65% for the EU between 1980 and 1995 (IEA, 2000) to 94.7% for Germany for 1990 to 2003 (Staffhorst, 2006). Sark et al. (2010) conclude that the progress ratio of PV systems can vary substantially with ranges found in literature between 53 and 94.7% depending on the data source and time frame studied.

Table 4-3 Overview of progress ratios for photovoltaics in Green-X and published in literature (Sark, Nemet et al. 2010)

Reference	PR	Time frame	Price data region	Capacity
Range found in literature	53-94.7%			
Green-X				
	80%	2006-2010	Global	Global
	83%	2011-2020	Global	Global
	85%	2021>	Global	Global
Nemet (2006)	74-83%		Global	Global
			Global	Global
Nemet (2009)	79%	1976-2006	Global	Global
Swanson (2006)	81%	1975-2005	Global	Global
Schaeffer et al. 2004a[1]				
	80%±0.4	1976-2001	Global	Global
	77%±1.5	1987-2001	Global	Global
Sark et al. (2008)	79.4% ± 0.3	1976-2006	Global	Global
Staffhorst (2006)	94.70%	1990-2003	Germany	Germany

1) Also national results for the Netherlands and Germany are available

4.2.4 Concentrated Solar Thermal Electricity

Concentrated Solar Power (CSP) units have been operational since the 1980s with capacities up to 355 MW, but further capacity growth stagnated up to recent years when new units where built in Spain followed by Germany and the US. The cumulative experience of CSP plants is therefore still relatively low compared to other RES technologies such as PV. Nevertheless, some experience curve studies are published on CSP (Sark and Lako 2010). Enermodal (1999) used the SEGS units built in California (SEGS I to SEGS IX) to derive an experience curve. For these units, a progress ratio of 88% was found, consistent with Green-X. For future units, Enermodal (1999) estimates that the progress ratio will be between 85 and 92%. For Spanish plants, a progress ratio of 80% was found. Alternatively, DLR (2003) applied a subsystem approach for CSP plants in the ATHENE model with different progress ratios for the collectors, the storage systems and the power generator.

Table 4-4 Overview of progress ratios for concentrated solar thermal enegry in Green-X and published in literature (Sark and Lako 2010)

Reference	PR	Time frame	Price data region	Capacity
Green-X				
	82%	<2010	Global	Global
	88%	>2010	Global	Global
Enermodal, 1999				
	88%	1984-1990	California	California
	85-92%	Future units		
ATHENE model				
Collectors	90%			
Storage systems	88%			
Power generator	94%			
Neij et al. 2008	80%		Spain	Spain

4.2.5 Bioenergy

Although bioenergy is the largest source of renewable energy, experience curve studies on fuels, electricity and heat from biomass are limited. There are several reasons that underlie the complexity to derive experience curves from these systems (Junginger, de Visser et al. 2006; Faaij and Junginger 2010):

- There is a wide range of bioenergy systems available which also vary in scale;
- Bioenergy systems require fuel which adds a cost component to the learning system and can also influence investment and O&M costs. E.g., if fuel prices increase, it might trigger investments in more efficient technologies to reduce overall production costs;
- Technological learning also results in improved conversion efficiencies;
- Bioenergy systems are usually adapted and optimized to local circumstances.

4.2.5.1 Bioelectricty

Table 4-5 provides an overview of studies conducted on technological learning in bioelectricity systems. For CHP and biogas, Junginger et al. (2005; Junginger, de Visser et al. 2006) conducted research on experience curves in CHP and biogas plants in Sweden and Finland and Denmark respectively. Furthermore, the IEA presents a progress ratio of 85% for biomass electricity plants for the EU-ATLAS project. It is however unclear if this is based on empirical evidence and if so, what the data source were used.

The assumptions on technological learning for bioelectricity systems in Green-X differ for small scale CHP and electricity (PR=90% after 2010) and large scale electricity, CHP and waste (PR=95% after 2010). For the additional costs of co-firing in coal fired power plants, no learning was assumed in Green-X which is consistent with the expected development of the additional cost of co-firing (IEA 2008).

Table 4-5 Overview of experience curves for biomass electricity in Green-X and published in literature (Faaij and Junginger 2010).

Reference	PR	Time frame	Price data region	Capacity
Green-X				
Biomass/biogas smalls scale (electricity and CHP)	92.5%	<2010	Global	Global
	90%	>2010	Global	Global
Biomass/biogas large scale (electricity and CHP)	97.5%	<2010	Global	Global
	95%	>2010	Global	Global
Waste (electricity and CHP)	97.5%	<2010	Global	Global
	95%	>2010	Global	Global
Biomass co-firing	0%			
Junginger et al., 2005				
Logistic chain forest wood chips	85-88%	1975-2003	Sweden/Finland	Sweden/Finland
CHP (€/kWe)	75-91%	1983-202	Sweden	Sweden
Junginger et al., 2006				
Biogas (m3 biogas/day)	88%	1984-1998		
Biogas electricity	85-100%	1984-2001	Denmark	Denmark
Electricity from biomass CHP	91-92%	1990-2002	Sweden	Sweden
IEA, 2000				
Electricity from biomass	85%	?	EU?	EU?

4.2.5.2 Biofuels

Biofuels include a wide variety of feedstock sources such as sugar and starch crops, oil seeds and lignocellulosic biomass and various conversion systems to create biofuel (ethanol, pure plant oil, fatty acid methyl ester (FAME) or BtL-diesel). Apart from the wide variety of biofuel production system options available, also the cost and performance of these systems are also location and size specific. Crop yields for example depend on climate, soil conditions, and agricultural management. It is therefore infeasible to create general experience curves on biofuels. Nevertheless, Table 4-6 provides an overview on studies conducted on technological learning in biofuel production including sugar cane, corn ethanol and rapeseed-diesel and the assumed progress ratios in Green-X for 1st and 2nd generation biofuels.

For 2nd generation biofuels, there is not sufficient empirical data available to create experience curves due to the limited amount of installations that are deployed up to now. Alternatively, expert judgments are used to project the costs of lignocellulosic ethanol and BtL-diesel up to 2015 when the technology is expected to be commercially available. From 2015 onwards, a progress ratio of 90% is assumed for both biofuel production systems.

For the REFUEL project (2008), de Wit et al. (de Wit, Junginger et al. 2009) developed an alternative approach to address for technological learning of advanced biofuels with a multi-factor learning curve approach. This learning model includes a scale dependent and a scale independent learning factor. The scale dependent factor is bounded by a minimum time before the capacity of a single plant can double (3-5 years) and a maximum market share of a single plant (5%). The scale-independent progress ratio was assumed to be 98-99%.

Table 4-6 Overview of progress ratios for 1st and 2nd generation biofuels in Green-X and published in literature (Faaij and Junginger 2010)

Reference	PR	Time frame	Price data region	Capacity
1st Generation biofuels				
Green-X				
Biodiesel/bioethanol	97.5%	<2010	Global	Global
	95.0%	>2010	Global	Global
Van den Wall Bake et al., 2009				
Sugar cane cultivation (tonne sugar cane)	68(±3)%	1975-2003	Brazil	Brazil
Sugar cane ethanol plant (investment+O&M)	81(±2)%	1975-2003	Brazil	Brazil
Ethanol from sugar cane (final energy)	80(±2)%	1975-2003		
Goldemberg et al., 2004				
Ethanol from sugar cane (final energy)	93/71%	1980-1985	Brazil	Brazil
Hettinga et al., 2009				
Corn cultivation	55(±0.02)%	1975-2005	USA	USA
Corn ethanol plant (investment+O&M)	87(±1)%	1975-2005	USA	USA
Corn ethanol	82(±1)%	1975-2005	USA	USA
Berghout 2008				
Rapeseed cultivation (seed)	80.4(±1)%	1993-2007	Germany	Germany
Biodiesel plant (investments)	97.6(±1)%	1993-2007	Germany	Germany
Rapeseed biodiesel (final energy)	97.7±1)%	1993-2007	Germany	Germany
2nd Generation biofuels				
Green-X				
Lignocellulosic ethanol/BtL	Expert judgment	<2015	Global	Global
	90%	>2015	Global	Global

4.2.6 Summary of the review

As shown in the previous sections, a number of studies have been published recently, providing new insights on technological learning for renewable energy technologies. Based on this overview, we conclude that the learning rates as employed by Green-X (see Annex II) are within the ranges found in (recent) literature. However, it has also become clear that technological learning experience curves sensitive to changes in variables (e.g. time frame, region size), and that especially input prices (i.e. material) prices can have a substantial effect on experience curves, which has previously not been taken into account. Therefore, in the following section, an advanced methodological approach is developed how to include the effect of the main input materials for wind onshore and offshore, photovoltaic solar energy and biomass plants.

Another notable aspect is that most learning systems for renewable energy technologies tend to be global, i.e. technological learning takes places with global installed capacity. As Green-X is a European model, and can only endogenously take into account the cumulative capacity used in Europe, this is another factor which may introduce uncertainties in the final results.

4.3 Impact of key parameter on the mid-term cost development of renewable energy technologies

In recent years, the prices for renewable energy technologies, such as photovoltaics, onshore and offshore wind turbines and other technologies, have stabilized or even increased in real terms. This was caused by a variety of factors, among them the increasing demand for raw materials (such as steel, concrete, silicon, plastics) and higher production costs due to increased coal, oil and natural gas prices. Also, a strongly increasing demand for renewable power technologies may have caused prices to stabilize, but this effect is not further analyzed in this report.

In this subtask, first, a historical decomposition of key drivers for the historic cost developments (i.e. technological learning versus increasing raw material / energy prices) aims to provide clarification for the past observed price trends. As a second step, for each RES technology considered, an analysis is carried out how the production cost structure depends on these input factors, and - depending on scenarios for the costs of raw material and energy prices – whether they may (partially) offset the effects of further technological learning and associated production costs reductions. In this context, new modeling approaches considering these parameters are discussed, first results are presented and some preliminary conclusions regarding the new modeling approach are drawn.

4.3.1 Motivation and background information

Following the current trend of ambitious RES targets within the European Union as well as abroad, the detailed design of well-tailored support schemes deserves key attention. To improve design criteria towards more effectiveness and efficiency, in the recent past, several studies have been published where conducted scenarios have been discussed in detail. In this context, a key parameter for such estimations, and in specific for the *Green-X* model, is the future development of investment costs for RES technologies. Historically, many energy models based the determination of investment costs for the technologies assessed on the status quo and expected technological improvements following learning curve trajectories (see also sections 4.1-4.2). Recent observations have shown that investment costs of most RES technologies have not closely followed the learning curve trajectory. Some deviations may be put in close correlation to other market situations. For example, Yu et al (2010) discuss crucial parameter of technological learning for photovoltaic technology. Principally, they identify three different periods in the historic PV module price development; see Figure 4-2.

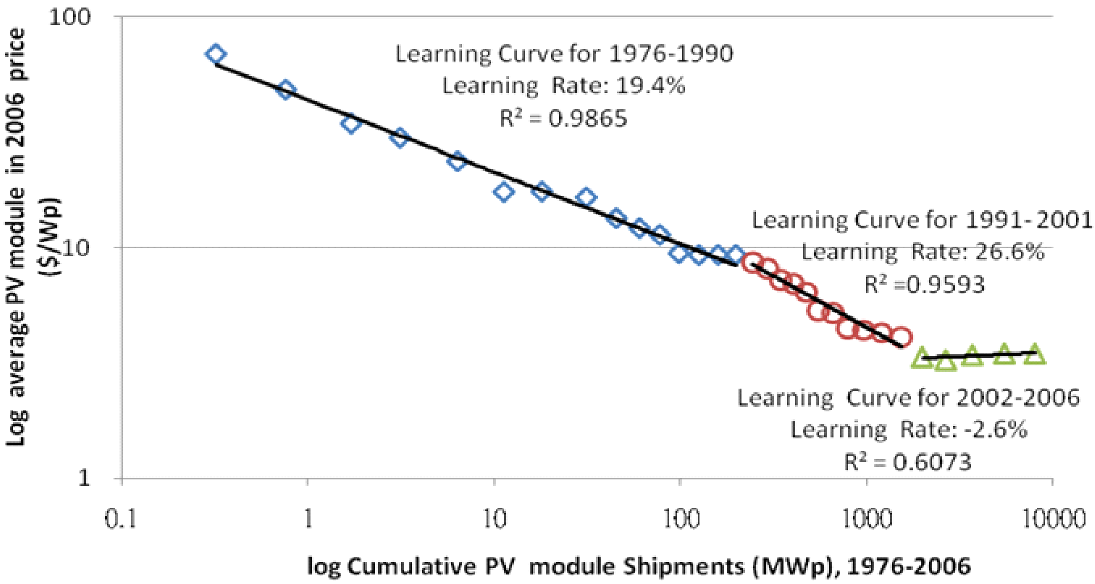


Figure 4-2 Technological learning rate for the Photovoltaic modules in the time period from 1976-2006 (Source: Yu et all, 2010)

As indicated by Figure 4-2, the determination of learning curves appears to be sensitive to the observed time period on the one hand, and to the identification of the cost of the initial unit on the other hand. This opposes the general concept of technological learning based on cumulative production, which implicitly predicts that only one learning rate may exist for a certain technology. This conflicting observation represents the motivation for further research in the thematic context. Among others, Yu et al. (2010) identified the impact of raw material and energy prices on energy technology costs in addition to technological learning. With respect to the example of Figure 4-2, relevant price decrease of silicon have been noted in the nineties whereas, due to several reasons, strong price increases of silicon are observable from 2004 to 2006, leading in turn to an overall (slight) increase of PV module prices throughout that period.

However, it is the aim of this work to improve future investment cost estimations of RES technologies serving as input for scenarios conducted by the Green-X model. Since this model is constrained to the (renewable) energy sector, other than energy-related parameter cannot be considered endogenously, although they may also possess an important impact on investment costs. In this respect, market power of manufacturers is not neglected in the dynamic future cost estimations for RES technologies presented next.[26] The subsequent analyses endogenously derive raw material prices based on the future development of energy prices. This

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[26] This issue raises the topic of costs versus prices of raw materials which are representing the main commodities for the construction of RES technologies. Raw material costs are mostly not available and their future development is difficult to predict. Moreover, they are generally also depending on energy prices.

shall finally contribute to the systematic shaping of more efficient and effective support schemes for the various RES technologies, within the model but obviously also within the real world context.

4.3.2 Input data

The assessment of the impact of energy and raw material prices on investment cost for RES technologies is discussed in this report for on – and offshore wind energy, photovoltaics and biomass. As key raw materials for the construction of wind turbines, PV modules and biomass plants, we identified crude steel, concrete and silicon. As a further step, also corresponding energy-related drivers were identified, aiming to describe historic trends of observable raw material prices. As far as available, time series of historic investment costs of the selected RES technologies were collected for the whole period – i.e. from the start of commercial use until the present day. Additionally, literature-based data has been gathered for technological learning rates and the related cumulative installations. Finally, time series for raw material prices were needed to determine the correlation between investment costs and raw material prices.

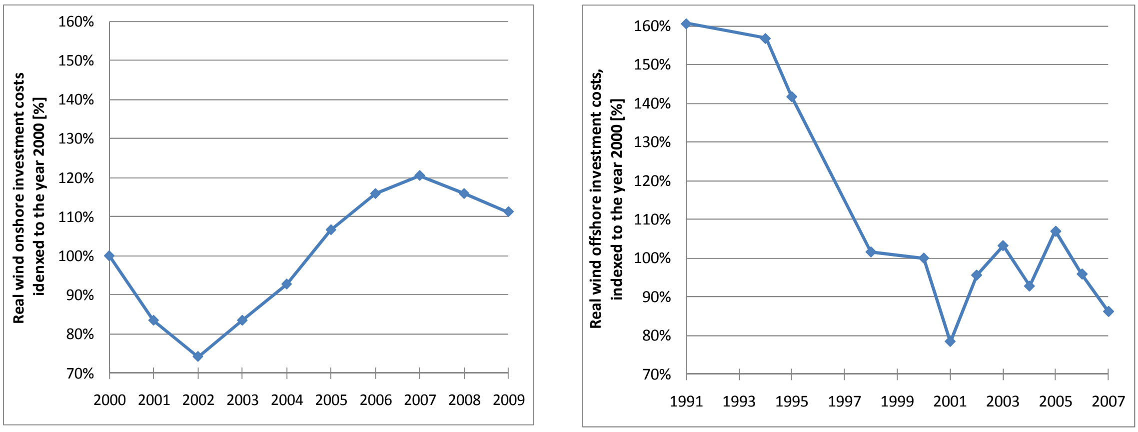

Figure 4-3 Real investment costs of wind onshore energy (left side) and wind offshore energy (right side) in times of volatile energy prices. Figures are indexed to the year 2000 (Source: EWEA, 2009, Junginger et al, 2004)

Firstly, historic investment cost of wind energy converters, as yearly averages, are depicted in Figure 4-3, whereas these figures are corrected for inflation and indexed to the year 2000 in order to allow for comparison. However, both technologies are largely developed in parallel since main components of both plant types show a high level of similarity. Additional cost for the offshore technology can be devoted to additional features required for offshore use. Offshore wind energy converters show an overall steeper cost decline in early years due to strong technological learning of their additional components. Nevertheless, both historic investment cost records are characterized by a volatile development in recent years, when energy and raw material markets showed also a significant volatility[27].

Next, a closer look is taken at photovoltaic and bioenergy technologies. Photovoltaics (PV) are mostly characterized by crystal silicon modules since hardly any information on thin film modules is available in public literature. Regarding bioenergy, we focus on the thermal conversion of solid biomass to electricity. Although several different plant types exist, especially different in scale, they all show a similar trend in material use and consequently in investment cost development. Notably, also conventional gas power plants show similar trends which allow drawing some qualitative conclusions for the conventional sector as well.

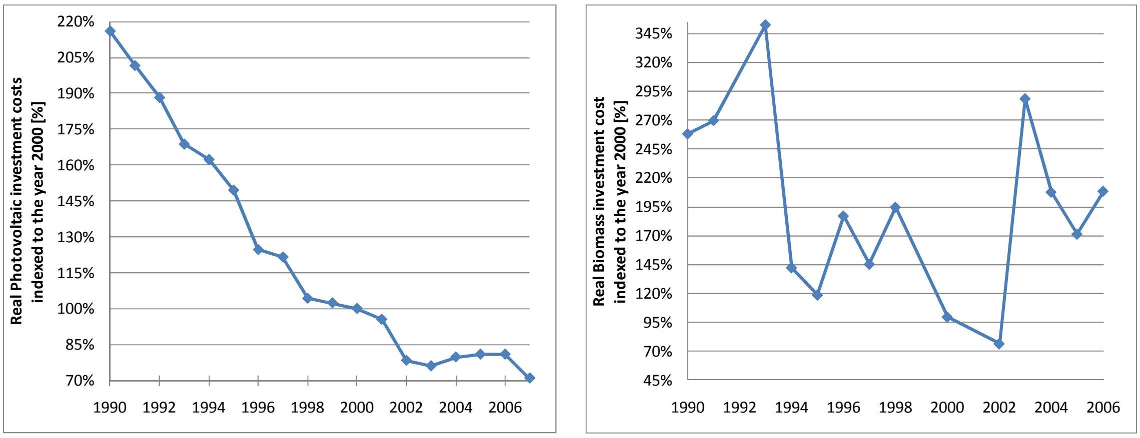

Figure 4-4 Real investment costs of photovoltaic energy (left side) and biomass energy (right side – different scale!). Figures are indexed to the year 2000 (Source: Yu et al, 2010; Junginger et al, 2004)

In principle, photovoltaic is characterized by a strong decline of module prices[28] in an early stage of deployment- see Figure 4-4. However, this trend stopped or even turned into a slight increase of module prices in 2003 which lasted only for a few years and turned downwards in the past two years. Several aspects were responsible for that development, and only one was the volatile silicon price.

In contrast, the situation is more difficult with respect to biomass. Two parameters appear important beside the learning effect: the scale and the type of the plant. On the one hand, co-firing plants only require small additional investments, and hence less additional raw material. On the other hand, the specific investment costs of bioenergy plants vary strongly de-

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[27] Additional, offshore wind farms have been built in deeper waters and further form shore in order to exploit new potentials has also added to increasing investment costs.

[28] The figure only reflects the prices of Photovoltaic modules, but their real production costs

pending on the scale[29] of a plant. However, generally only small technological progress can be identified for biomass energy plants, since the applied technology is comparatively similar to conventional thermal power plants, which have been built for decades and in large numbers.

A closer look at the main technical components of the selected RET discussed above indicates that crude steel and concrete, in particular cement, dominate the raw materials used composition. In the case of photovoltaic the silicon price and respectively the silicon intensity which differs by cell type holds a significant impact on the overall module price. Moreover, materials as copper, aluminum or glass are of relevance as well, but are currently not considered in this study.

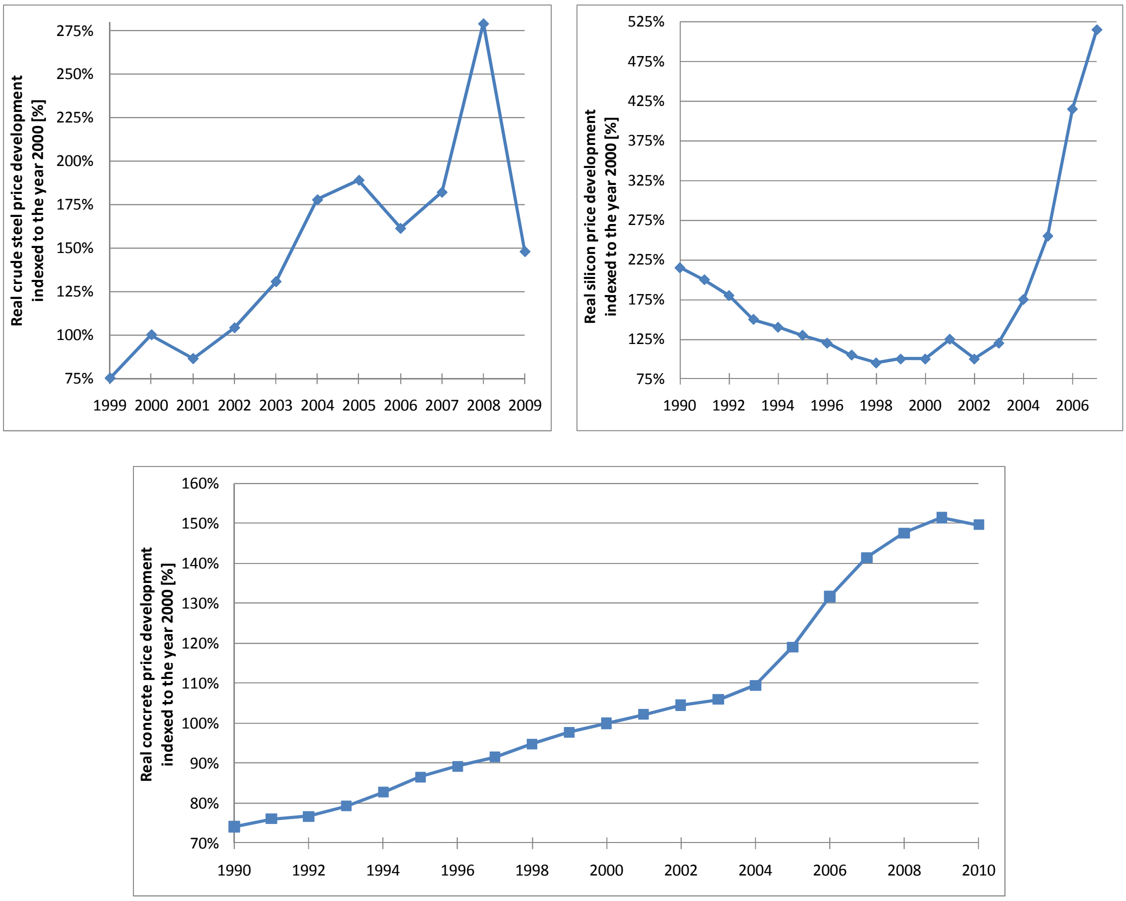

Figure 4-5 Real crude steel price development (upper left side), real silicon price development (upper right side – different scale!) and real concrete price development in times of volatile energy prices.

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[29] Compared to RES technologies discussed previously, biomass energy plants have historically been built mostly in large-scale capacities whereas more novel plants were installed rather small to mid-scale. Thus, small-scale plants show higher specific investment costs. Consequently, Figure 4-4 (right side) shows a very volatile development.

Figures are indexed to the year 2000 (Source: Steel Business Briefing, 2010; Yu et al, 2010; BLS data 2010)

Figure 4-5 above presents the selected raw material prices indexed to the year 2000. Remarkable is the similar trend for all three commodities in the period 2002 to 2008. However, while crude steel and silicon prices constantly decreased prior to the year 2000, concrete prices already followed a moderate increase before 2000. Since all three raw materials are very energy intensive in production, a major driver, among others, was the fast growing global economy, and consequently growing energy demand and prices, which all collapsed in 2008.

As various steel products exist (flat steel, long steel, stainless steel, etc.), this study focuses on price developments of flat steel products on a European market, since manly flat steel products are used in power engineering. Moreover, the energy intensity of steel production depends on the type of steel making process. The two dominant types are the Basic Oxygen Furnace (BOF) and the Electric Arc Furnace (EAF). The latter builds on steel scrap usage[30] and therefore reduces the demand for coking coal.

In contrast to the steel price development, the silicon price was not directly influenced by growing energy prices, but more by strategic pricing based on a production shortage of silicon itself. Until 2004, most silicon used in the photovoltaic industry was a waste product of the electronic industry, but with an increasing demand for photovoltaic, a shortage of silicon production occurred. New solar-grade (i.e. high purity) silicon manufactures entered the market, which caused a relaxation on the market and, consequently, a decrease of silicon prices after 2008. The shift from former electronic-grade silicon to the nowadays common solar-grad silicon usage reduced the energy intensity of PV cell manufacturing significantly. Regardless, this development was accompanied by increasing electricity prices, which are the main driver for silicon production, and consequently partly compensated the effect of reduced silicon production costs due to technological development[31].

Compared to the steel and silicon price development, concrete prices increased continuously, although a stronger increase beyond 2004 followed by a peak in the second quarter of 2008 is noted as well. Similar to silicon production, cement production – a key component of concrete - is a very energy intensive process and therefore linked to the biomass energy price and coal price development, that is used for the heat supply.

All considered raw materials are either carbon intensive in production or at least very energy intensive, and, consequently, are depending on the energy generation portfolio at the pro-

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[30] Although the EAF technology shows promising future perspectives due to the reduced coking coal demand, the EAF technology will continue to a rather limited extent since steel scrap as main input is only limited available

[31] The shift from electronic grade to solar grade silicon production, reduced the energy intensity and holds therefore an impact on the silicon production costs

duction location. Therefore, a strong linkage between the price for coal and partly natural gas to raw material prices is apparent. Within this report, the future development of these energy carriers is exogenously provided by the PRIMES modeling scenarios – i.e. the assumptions on their global development as applied for the latest baseline (NTUA, 2009) and reference scenario (NTUA, 2010).

4.3.3 Methodology

This report addresses the impact of energy and raw material prices on investment costs of renewable energy technologies. In particular, scenarios are conducted based on empiric evidence of correlations between raw material prices and investment costs as assessed for several RES technologies.

4.3.3.1 General concept

The **general concept** to assess the impact of energy and raw material prices on investment costs of RES technologies comprises the following steps:

1. **Identification of the correlation between energy and raw material prices:** The impact of energy prices on raw material prices needs to be identified to calculate raw material costs as a function of energy prices, but neglecting market impacts that usually define the raw material prices.
2. **Data adjustment:** to explicitly separate the effect of technological learning and raw material price impacts, a data adjustment of historic data on investment costs for RES technologies is carried out
3. **Econometric assessment:** an econometric assessment can be conducted, in which the impact of dynamic raw material price changes on RES technology investment costs will be determined
4. **Impact assessment:** As a final step, a quantitative assessment of the impact of energy prices and raw material prices on the future development of investment costs for RES technologies is conducted.

Following these steps, we start in the subsequent section with the discussion of the correlation between energy prices and raw material prices / costs.

4.3.3.2 Identification of the correlation between energy and raw material prices

Modeling of raw material prices goes well beyond the scope of the *Green-X* model. Therefore, this report only takes into account the impact of energy price on raw material prices. In this context, the economic data for raw materials as used in this study are classified as production cost rather than market price. Other drivers, such as demand increases, supply bottlenecks, political (fiscal) interests or transport issues are neglected.

Only the steel-, concrete- and silicon price are considered in this study. Their future development was calibrated within the econometric assessment based on empiric data. Consequently, the data gathering process of both raw material and energy prices was of key importance for the overall project result. Furthermore, regression analyses are conducted, depicting the relation between material and energy prices as well as future expectation of different trends are considered. Regarding future energy prices, exogenous assumptions on the development of crude oil, natural gas and coal prices are taken from the latest PRIMES baseline scenario (see NTUA, 2009). Electricity wholesale price are an endogenous result of *Green-X* (which is however obviously linked to the fossil fuel price development).

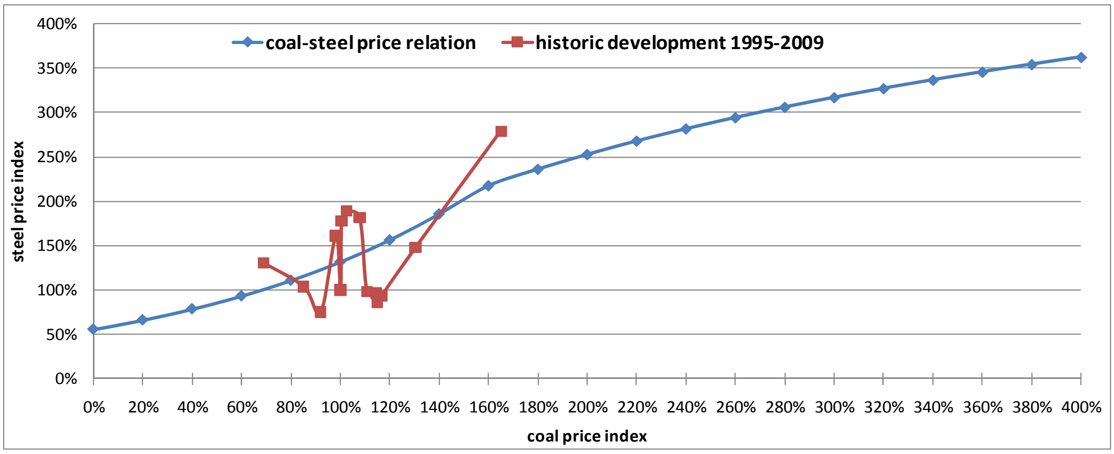

Figure 4-6 Implemented relation between the coal and steel price development (based on Eq. (1), and empiric evidence of the years 1995 to 2009

Figure 4-6 depicts the calculated relation between the relative coal price and the relative steel cost, based on empiric evidence. Below, Eq(1) describes this relation in mathematical formulas:

$$\begin{aligned} \forall p_{coal} \leq 1.575 &\Rightarrow c_{steel} = 0.5567 * e^{0.86 * p_{coal}} \\ \forall p_{coal} > 1.575 &\Rightarrow c_{steel} = 1.5811 * \ln(p_{coal}) + 1.4308 \end{aligned} \qquad \text{Eq(1)}$$

whereas p_{coal} represents the relative coal price and c_{steel} the relative steel costs. The coefficients of Eq(1) are determined by best fit analysis of the historical observed data.

Generally, regardless of the type of steel making process, coking coal is the largest contributor in the cost of steel production. However, with respect to prices, coke prices increased significantly in 2009 (due to production shortages) whereas coal prices had already started to decrease again. Since this assessment focuses on commodity costs – neglecting such events - the coal price is more convenient to derive a relationship between energy prices and steel costs. Moreover, a constant increase of steel costs with increasing coal prices is according to experts unlikely due to expectable production type changes and associated material input changes. Figure 4-6 also indicates that above a 160% of the steel price from 2000, its increase slows down compared to the increase in coal costs, which is conform the assumption that more energy-efficient steel-making is then assumed.

Next, silicon is addressed. Silicon prices are mainly determined by electricity prices, and also by the amount of electricity required to produce one kilogram of silicon. Electricity consumption in silicon production decreased significantly in early years of the observation period (starting in 1976) and electricity prices only increased slightly in this period. However, until the first years of the new millennium, silicon used in the photovoltaic industry was only a waste product of the silicon production of the electronic industry. With the increasing demand for photovoltaic modules, new silicon production facilities were built, and a different grade of silicon was developed – the solar grade[32]. As shown by Figure 4-7 and Eq(2) below, silicon prices followed the electricity costs rather well. An exception is the year 2004, when prices increased strongly due to a high demand and a resulting shortage in silicon production.

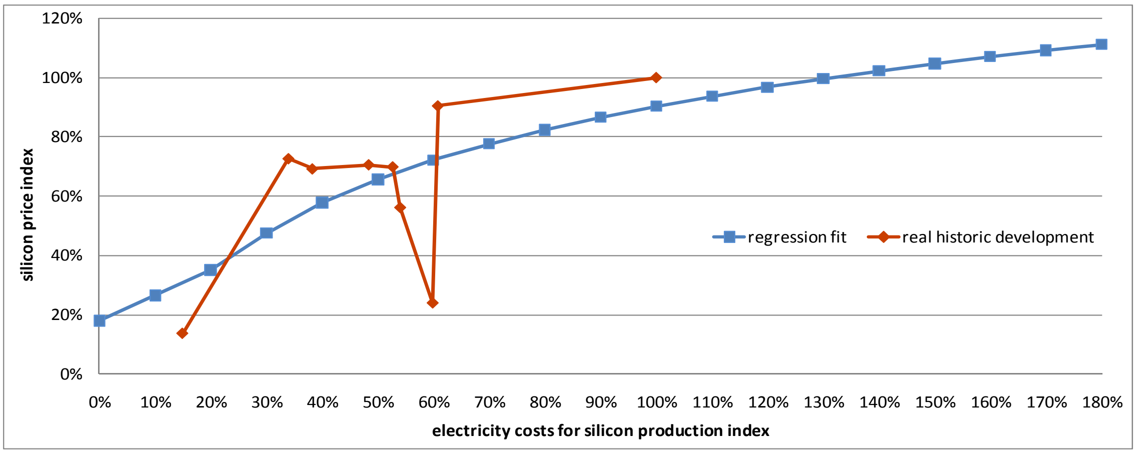

Figure 4-7 Implemented relation between the energy costs of silicon prodcution and the silicon price development as well as the empiric evidence of silicon price development of the years 1976 to 2007

$$\begin{aligned} &\forall p_{energy} < 0.224 \Rightarrow c_{silicon} = 0.8538 * p_{energy} + 0.18 \\ &\forall p_{energy} \geq 0.224 \Rightarrow c_{silicon} = 0.3553 * \ln(p_{energy}) + 0.903 \end{aligned} \qquad \text{Eq(2)}$$

Formula Eq(2) describes the relation between the energy costs p_{energy} for silicon production and the related silicon costs $c_{silicon}$, in accordance with the general approach where no other than energy related drivers for commodity costs are considered. Consequently, some deviations between historical observations and calculated data appear. Nevertheless, the approach allows endogenous forecasts of the development of silicon costs until 2030, which obviously has an impact on the development of investment costs for PV modules. However, the introduction of the logarithmic function in formula Eq (2) of the energy costs indicate some qualit-

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[32] Before that only electronic grade silicon was used, showing a higher degree of purity and consequently characterized by a higher electricity consumption in the production chain.

ative saturation of the silicon price with increasing energy costs due to other impact factors, i.e. a decreasing demand for silicon in the case of increasing energy costs.

Finally, concrete prices influence investment costs of RET to some extent, whereas especially cement production, as a very energy intensive process, bridges the relation to energy costs. Generally, cement production is characterized by high electricity consumption as well as high process heat demand. Depending on the site, this energy is provided by natural gas, coke or biomass energy but mostly a combination of these energy carriers. In this study, biomass energy prices and coke prices are considered as drivers of the endogenously calculated concrete costs.

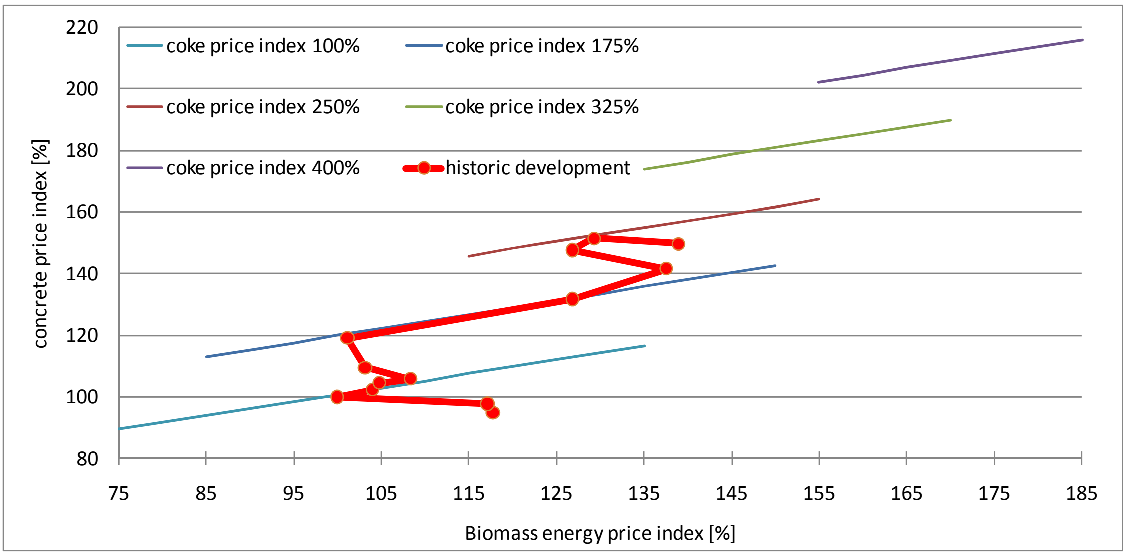

Figure 4-8 Illustration of the regression analysis of the concrete price index as combination of biomass energy prices and coke prices. As well as historic observations between 1995 and 2010

Figure 4-8 depicts the result of the two parameter regression analysis of the concrete price. Depending on historic biomass energy prices (forestry products) and coke prices, concrete costs are derived according to the formula Eq(3) wherein $c_{concrete}$ represents the costs of concrete, p_{coke} the coke price and $p_{biomass}$ the biomass energy price.

$$c_{concrete} = 29.845 + 0.255 * p_{coke} + 0.453 * p_{biomass} \qquad \text{Eq(3)}$$

Although, historic biomass energy prices[33] and coke price showed similar trends, in absolute terms, coke prices increased much stronger. The combination of these two parameter results in a much better fit than if only considering one of the two energy commodities for the regression analysis. Thus, Figure 4-8 is a discrete function of the continuous two parameter analysis and only presents possible points of the regression curve for concrete costs.

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[33] This study currently assumes forestry biomass prices as energy prices, but this needs to be improved since mostly biomass energy in form of sewage sludge or bone meal are used

4.3.3.3 Data adjustment

Modeling the impact of the commodity costs for the manufacturing of RET as discussed above requires a new approach to estimate future cost developments of RET. In this context, the multi-factor learning curve has been implemented with basically two factors, the impact of the commodity costs (steel, silicon and concrete costs) as well as the default technological learning approach based on cumulative production. Depending on the specific energy technology, the most important materials are considered in the model, see Eq (4).

$$c(x_t) = c(x_0) \cdot \left(\frac{x_t}{x_0} \right)^m \cdot \prod \left(\frac{CP_0}{CP_t} \right)^{LCP} \qquad \text{Eq(4)}$$

In Eq (4), the product of the first two terms describes the default learning characteristics as already discussed previously. Summing up, the learning index *m* is used to describe the relative cost reduction – i.e. *($1-2^m$)* – for each doubling of the cumulative production. The value *(2^m)* is called the progress ratio *(PR)* of cost reduction. Progress ratios or their pendant, the learning rates *(LR)* – i.e. *LR=1-PR* – are used to express the progress of cost reduction for different technologies. More important with respect to this assessment, the last term indicates the positive or negative impact (*LCP)* of dynamic raw material prices on investment costs of RES technologies, depending on the raw material price C_{P0}/C_{Pt}. Since this approach only pursues to measure the impact of commodity prices that have a high share of the total investment costs, other materials (such as copper, glass or aluminum) are neglected in this study. It might be argued that an overestimation of the impact of considered raw material prices on investment costs for RES technologies could occur. However, due to the fact that for the future development of raw material prices only the energy price driven part of the raw material prices – the raw material costs – are taken into account, such an overestimation appears unlikely - especially, because raw material costs represent the minimum future price development[34] of the single commodity. Therefore, the calculated impact of a commodity on RET investment cost is at least as strong as presented. Nevertheless, capital costs of RES technologies are determined not only by this minimum impact of commodity costs on RET investment costs which could be amplified of (partly) compensated by other influences, as mentioned above.

Another study (Yu et al, 2010) introduced an extra term, modeling the impact of the sum of other parameters. However, the study by Yu et al. aimed to prove the historic development and consequently determined the other commodities as the difference between the impact of selected commodities plus the learning effect to the real historic observation. Therefore, that approach would not allow future forecasts up to 2030, and hence appears not suitable for this assessment.

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[34] This approach assumes that no manufacturer will sell his commodity below the production costs.

To determine the impact factor LCP of commodity costs on investment costs of RES technologies, a regression model is established and calibrated according to historic observations.. Hence, the outcomes only reflect the impact of the commodity costs and technological learning effects, but do not necessarily meet the real historic investment costs, as we neglect other(e.g. market driven) price effects as mentioned above.

However, this assessment builds on constant, exogenous technological learning rates, which are derived from historic observations of the development of investment costs for RES technologies or refer to the existing *Green-X* database. Allowing for applying exogenous – not regression based – technological learning rates for RES technologies requires to select a time period where no other influence than technological learning took place. We assume that such a time period was between 1975 and 2003 - see Figure 4-9, when the CEPC Index (Chemical Engineering Plant Cost Index)[35] developed in the same range as the steel price. Such an exogenous definition of the learning rate[36] is also necessary in this assessment, since not all required data is available for each technology right from its initial market entrance.

Moreover, the regression analysis – to identify the impact factor LCP - is applied to historic commodity prices and the investment costs of RES technologies[37]. Thus, it needs to be corrected for the technological learning rate in prior. This learning correction is a necessary precondition to determine the “pure” / undisturbed impact factor LCP of the commodity prices on investment costs, without taking into account other technological improvements of the RES technology within the selected time period.

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[35] Originally, the CEPC Index represents the historic development of costs in the chemical engineering sector. In most components, it is similar to the power sector. Therefore, the CEPCI is a suitable parameter for this assessment.

[36] Since a technological learning rate is defined for the period of introducing a new technology until now. Interpreted strictly, it cannot change over time. Therefore, the period for determining a learning rate must be comparatively long and, additionally, it appears to be sensitive to the selected starting point.

[37] Commodity prices as well as investment cost of RES technologies are expressed in real terms – i.e. in €$_{2006}$.

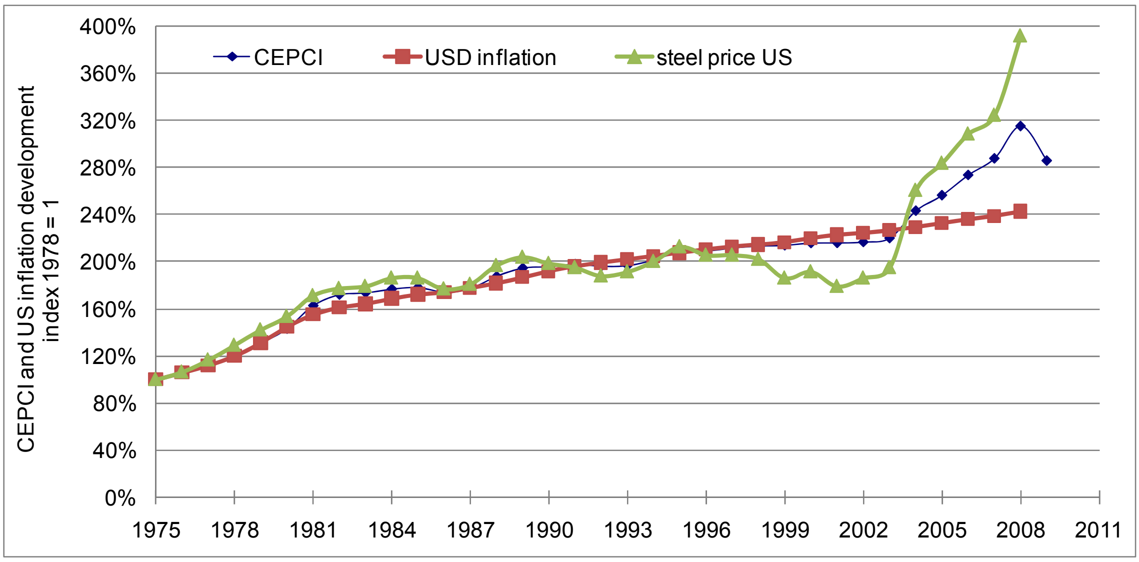

Figure 4-9 Historic development of the CEPC index (Chemical Engineering Plant Cost Index), ths US inflaction and the steel price in nominal terms from 1975 to 2009

Figure 4-9 shows that in the period between 1975 and 2003, hardly any influence of commodity prices was noticed on engineering components. Therefore, on the one hand, this confirms that default technological learning rates appear appropriate and that the technological learning effect can be identified without consideration of the regression analysis. On the other hand, it indicates that a pure correction for technological learning of the development of investment costs for RES technologies within this period is appropriate as data preparation for the regression analysis identifying the LCP factor. Summing up, conducting a multi regression analysis for determining both - the commodity price impact and the technological learning rate in this selected time period endogenously would return the same result for the learning rate as if defined without consideration of the commodity price impact. However, since technological learning rates are by definition constant over time, they can be defined independently from the regression analysis. Furthermore, investment costs for RES technologies are corrected for the learning effect for the time period of volatile commodity prices and hence the pure impact factor, LCP, of each commodity can be identified. Thus, Figure 4-9 in combination with footnote 36 confirms that from 1975 to 2003, a technological learning rate can be defined without considering raw material prices, and the impact of raw material prices can be derived from the learning corrected RET investment cost in the period beyond 2003. Combining these two impact parameters in Eq(4) allows estimating RET investment costs.

4.3.3.4 Econometric assessment

Next, the regression analyses for the selected RES technologies are discussed in further detail. Firstly, Figure 4-10 indicates the model regression curve of the relation between the relative wind investment costs compared to the relative steel costs. Additionally, the historic relation between wind onshore investment costs and the steel price in the period 1999 to 2009 is depicted.

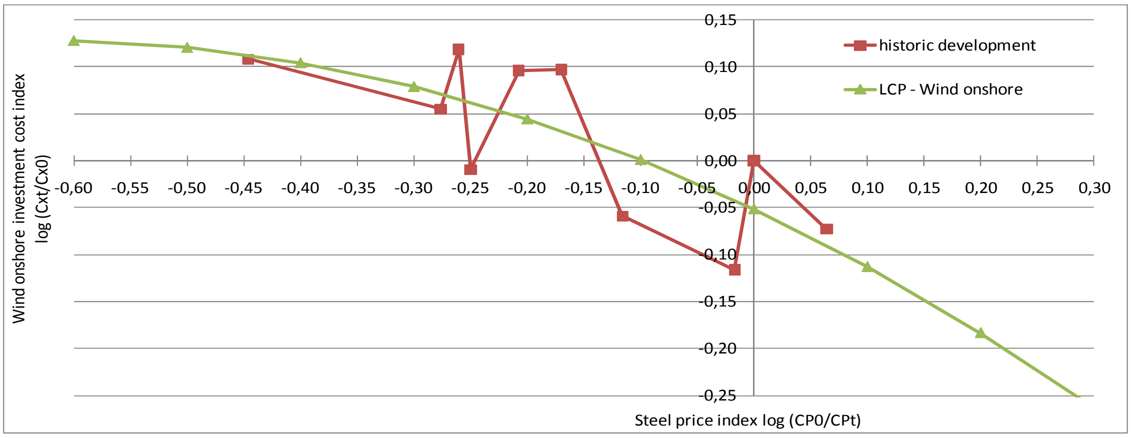

Figure 4-10 Impact factor LCP for the steel price impact on wind onshore investment costs as well as historic observations between 1999 and 2009

In the recent past, most values of $\log\left(\frac{CP0}{CPt}\right)$ (x-axis) are below zero, caused by an almost constant increase of the steel price throughout this time period. Again, a plausible relation according to formula Eq(4) between steel costs and wind investment cost developments results in a negative sign for the logarithmic change of the steel price and in a positive sign for the relative wind investment costs, and vice versa. A detailed look at the regression curve points out that an increasing steel price only increases the wind investment costs to a certain extent, whereas decreasing steel prices have a stronger impact on wind investment costs. This can be explained by the fact that in times of high steel prices, different kinds of steel alloys are used or even some material substitutions of alternative components take place. In mathematical formulas, the impact factor, $LCP_{WI\text{-}ON}$, of the steel costs on wind onshore investment costs is described according to formula Eq(5):

$$LCP_{WI-ON} = \frac{\log\left(\frac{INV_{WI-ON\,(t)}}{INV_{WI-ON\,(0)}}\right)}{\log\left(\frac{c_{steel\,(0)}}{c_{steel\,(t)}}\right)} \qquad \text{Eq(5)}$$

In formula Eq(5), $INV_{WI\text{-}ON(t)}$ represents the investment cost of wind onshore at present (time t) whereas $INV_{WI\text{-}ON(0)}$ indicates the investment cost at the beginning of the observation. The same notification is applied for the steel costs c_{steel}. The investment costs at time t are in advance corrected for the technological learning effect (as explained above).

In contrast to above, a slightly different situation occurs for wind offshore energy. Principally, the approach applied is based on the assumption that the only major differences compared to wind onshore are the type of foundation (consisting mainly of concrete) and the offshore grid infrastructure (including the transformer platform). Therefore, investment costs of wind offshore energy technology are divided into two components, one representing the wind turbine, and the other with the above-listed additional features regarding wind offshore. However, modeling the impact of commodity costs on the extra components of a wind offshore plant requires extending the approach to two commodity costs, steel costs and concrete costs. Consequently, the same methodology as discussed above is applied, but in order to determine the impact factor $LCP_{WI\text{-}OFF}$, the regression analysis is extended to a two parameter regression[38]. This results in two impact parameters, one for steel (LCP_{steel}) and one for concrete ($LCP_{Concrete}$), plus an additional constant term. The cumulated impact of the two commodity costs on wind offshore investment costs without considering technological learning is explained by formula Eq(6):

$$c_{WI-OFF} = 64.405 * \left(\frac{c_{steel(0)}}{c_{steel(t)}}\right)^{-0.179} * \left(\frac{c_{concrete(0)}}{c_{concrete(t)}}\right)^{0.277} \qquad \text{Eq(6)}$$

To calculate the overall development of wind onshore investment costs, formula Eq(6) needs to be inserted into the last term of formula Eq(4). However, in formula Eq(6), $C_{WI\text{-}OFF}$ represents the extra component costs of wind offshore compared to wind onshore technologies without taking into account the technological learning effects. The constant term is only a result of the multi-parameter regression analysis. The overall wind offshore technology costs can be derived by combining Eq(6) and Eq(4) plus adding the component costs of the calculated wind onshore investment costs for the specific years. While doing so, it appeared that generally, the impact of steel costs is much stronger than from concrete costs.

A similar approach as for wind onshore technology is applied for photovoltaic technology. According to Schumacher et al. (2010), the most important raw material for a PV plant is silicon, whereas others as glass, aluminum or steel play only a minor role. However, since PV is a less mature technology than wind energy, the data preparation for the regression analysis (and especially the correction for historic learning effect) gains key importance. Additionally, high silicon prices were noticed from 2004 onwards[39], which distort the determination of the impact parameter $LCP_{silicon}$ to a certain extent. This needs to be taken into account for model calibration.

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[38] The regression analysis is conducted with Excel, which requires linearizing the parameters before running the regression, for which a logarithmic function is used.

[39] Due to a significant increase of the demand for silicon accompanied by production shortages as discussed previously.

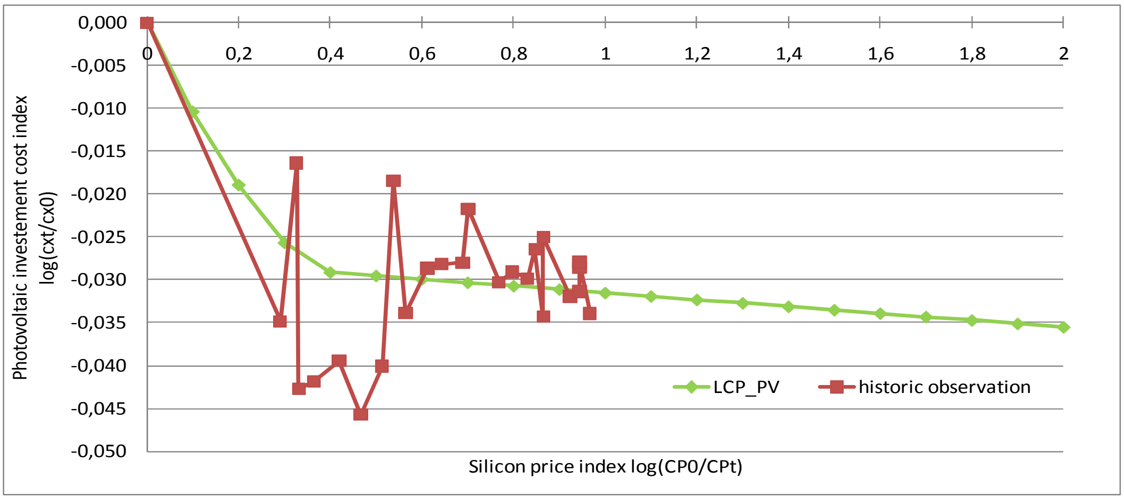

Figure 4-11 Impact factor LCP for the silicon price impact on Photovoltaic investment costs as well as historic observations between 1976 and 2007

Above, Figure 4-11 depicts the relation between the relative development of investment costs for PV and the relative development of the silicon costs in logarithmic scale. Additionally, the historic evidence of the dependence of PV investment cost on silicon prices is illustrated. Some strong deviations are apparent in the historic record due to the previously discussed difference between silicon costs and prices. However, the impact factor $LCP_{silicon}$ holds a negative sign at each point, meaning a positive correlation between the silicon costs and the investment cost for PV. The corresponding mathematical relation is expressed in Eq(7):

$$LCP_{SILICON} = \frac{\log\left(\frac{INV_{PV\,(t)}}{INV_{PV\,(0)}}\right)}{\log\left(\frac{c_{silicon\,(0)}}{c_{silicon\,(t)}}\right)} \qquad \text{Eq(7)}$$

Since the regression is calibrated using data of a long time period, early relations between investment costs and silicon prices are considered as well as more recent relations. In this context, it is obvious that with decreasing photovoltaic investment costs, the influence of silicon costs decreases due to a more efficient usage of the raw material – see Figure 4-11. Finally, inserting the impact factor $LCP_{silicon}$ from Eq(7) into the formula Eq(4) allows to assess also the future development of investment costs for photovoltaic in dependence of both learning and energy / raw material prices.

In order to complete the depiction of the different methodological approaches for the RES technologies assessed, biomass energy is addressed next. Schumacher et al. (2010) concluded that independent from the type of biomass plants, steel and concrete prices hold the most significant impact on their investment costs. This fact requires a multi parameter regression analysis, as presented for wind offshore energy, whereas the mathematical relation of the biomass investment costs is presented in Eq(8):

$$c_{BM} = 42.901 * \left(\frac{c_{steel(0)}}{c_{steel(t)}}\right)^{0.507} * \left(\frac{c_{concrete(0)}}{c_{concrete(t)}}\right)^{-0.29} \qquad \text{Eq(8)}$$

The same method of determination of the coefficients as well as notification as explained above are used here, whereas c_{BM} represents the investment costs of biomass energy, influenced by the concrete and steel price, but without the consideration of technological learning – which is anyhow limited in the advanced biomass technology sector. Unfortunately, the regression analysis delivers only limited satisfying results, since the steel costs obviously shows a negative correlation to the investment costs – see formula Eq(8). There are two main reasons for this. Firstly, available data is very limited on historic biomass energy investment costs and, secondly, these investment costs depend strongly on the scale of the plant[40]. A possible remedy is to consider similar technologies, respectively energy technologies using the same components, at least to a large extent. In this context, conventional gas fired power plants are a good approximation for the estimation of steel and concrete price impacts. Applying the methodology to historic gas power investments (see King et al. 2008) results in a relation according to formula Eq(9) below:

$$c_{NG} = 7{,}697.9 * \left(\frac{c_{steel(0)}}{c_{steel(t)}}\right)^{-0.406} * \left(\frac{c_{concrete(0)}}{c_{concrete(t)}}\right)^{-0.099} \qquad \text{Eq(9)}$$

Eq(9) shows, both steel and concrete costs show a positive correlation to the development of investment costs of natural gas plants c_{NG}, which are corrected for technological learning effects. However, this approach shows a good approximation of the future trend of investment costs of biomass energy plants as well, but needs to be further improved by more consistent data. Generally, the impact of concrete costs is much smaller as the steel cost impact as indicated by formula Eq(9) (i.e. $LCP_{steel} >> LCP_{concrete}$).

4.3.4 Results new methodology

4.3.4.1 The correlation between energy and raw material prices

Firstly, results with respect to the endogenously derived commodity costs are discussed, which only reflect the net impact of energy prices on the commodity prices. Both historic and future projections of steel-, silicon and concrete costs are presented.

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[40] Research on scale effects in biomass plants is currently ongoing but no detailed results are applicable up to now (status: end of 2010). However, it can be expected that new findings shall be applicable in the near future and would then consequently be incorporated in an envisaged update of this assessment.

Historic observations show a strong correlation between the coal price and the steel price[41] development. In contrast, only a weak correlation between the coke and steel price development can be identified, mainly due to strongly increased coke price in the last years caused by coke production shortages. Applying formula Eq(1) and conducting sensitivity test of the identified approach with two different sets of sources in different time periods resulted in a high match to the reported steel prices, see Figure 4-12. Obviously, in certain years a significant misinterpretation might occur, especially in times where coal and steel price have shown opposite changes caused by external effects such as increasing demand or strategic pricing. Figure 4-12 depicts a significant mismatch in the years 2001, when the calculated steel costs increased whereas the real steel prices decreased although coal price increased (and vice versa in 2002 and 2003). This stands in contrast to most other years where the price developments had the same sign.

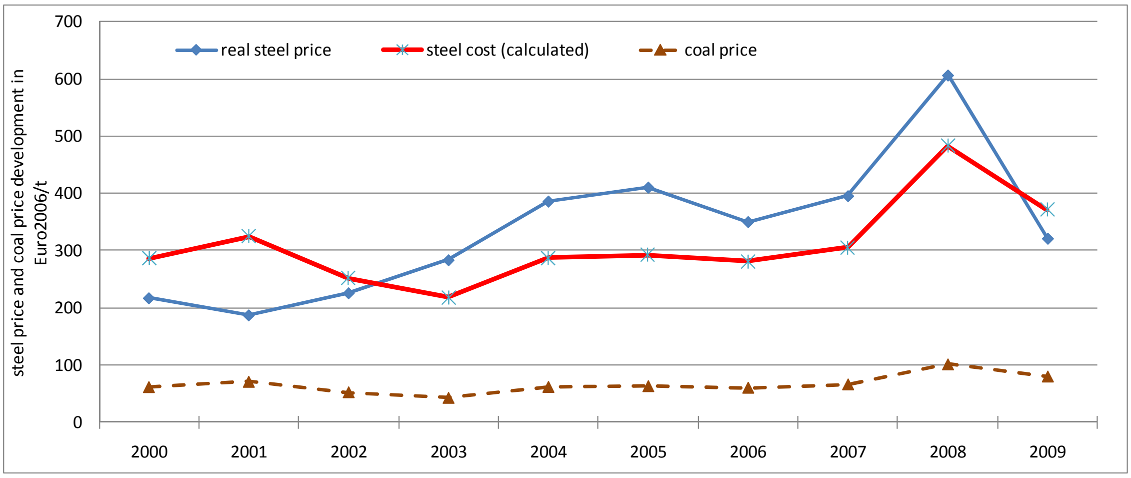

Figure 4-12 Historic observation of the steel price and the coal price as well as endogenously calculated steel costs in the period 2000 to 2009 in EUR2006/t

Nevertheless, Figure 4-12 confirms the theory, that only considering the impact of energy prices on commodity prices represents a good approximation for the trend of commodity prices. Therefore, this approach models the minimum impact that commodity price are holding on investment costs of RES technologies.

Next, silicon prices respectively silicon costs are discussed with respect to their dependence on the energy price impact. In this study, the electricity consumption and its price are identified as the key driver of silicon costs. Figure 4-13 indicates the historical development of

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[41] With respect to steel making processes, currently two methods are dominating the market, the Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) whereas the BOF process still holds the higher share. On the one hand, the BOF approach is much more carbon intensive and depends strongly on coal and coke inputs and respectively prices. On the other hand, the EAF system, showing promising future market penetrations, uses high share of steel scrap and thus reduces the demand for coal and coke. Moreover, less energy intensive steel making processes, as direct steel making processes, are already developed and might enter the market soon.

silicon prices, with an almost constant decrease until the year 2003 and a strong increase in the subsequent period[42] until 2008. Moreover, with an increasing demand of silicon for the photovoltaic industry a new technology of silicon production was invented – the solar grade silicon, which has a slightly higher degree of impurities than electronic grade silicon. Due to this difference, the energy consumption in the silicon production process could be reduced significantly.

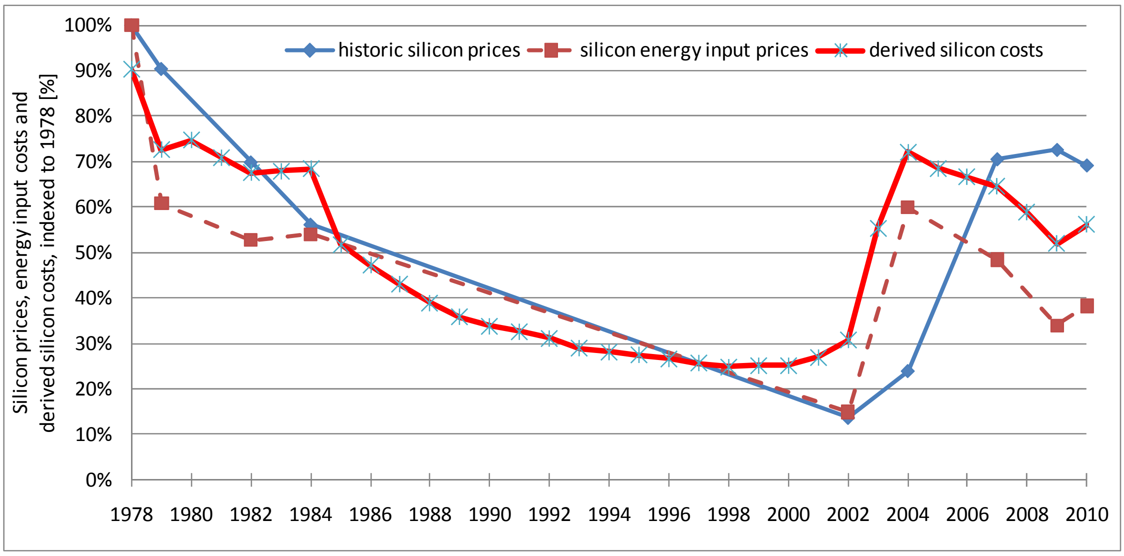

Figure 4-13 Historic observation of the silicon price and the energy input price for silicon production as well as endogenously calculated silicon costs in the period 1978 to 2010, indexed to the year 1978

Some of the derived silicon costs shown in Figure 4-13 are higher than observed silicon prices for some time periods, because used silicon energy input prices are derived from a mixture of electronic grade and silicon grade silicon types. Consequently, the energy input into silicon production is overestimated, especially in the years 2002 to 2005, see Pizzini et al. (2010).

Finally, a focus is put on concrete. In contrast to the previously discussed commodities, concrete prices increased only moderately in the same time period of increasing and volatile energy prices (1998-2010). However, key drivers for concrete costs, specifically cement costs, are heat costs, whereby coke or biomass is commonly used as fuel. The mathematical expression of concrete costs is given in formula Eq(3), while a graphical representation of historic actual prices and calculated cost is given in Figure 4-14. Obviously, concrete costs follow the trend of observed market prices within the assessed time period with some slight differences. In general, concrete costs are very sensitive to the energy portfolio used for heat supply. Depending on the fact whether the energy portfolio is more coke or biomass driven, the im-

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[42] Until 2004 silicon for the photovoltaic industry was only supplied by waste products of the electronic industry. However, with an increasing demand for silicon, new production plants had been established. Since this process took some time, silicon prices increased strongly throughout this period.

pact of these two parameters might vary. Therefore, Figure 4-14 represents an average of historic observations and does not reflect concrete costs within a certain region.

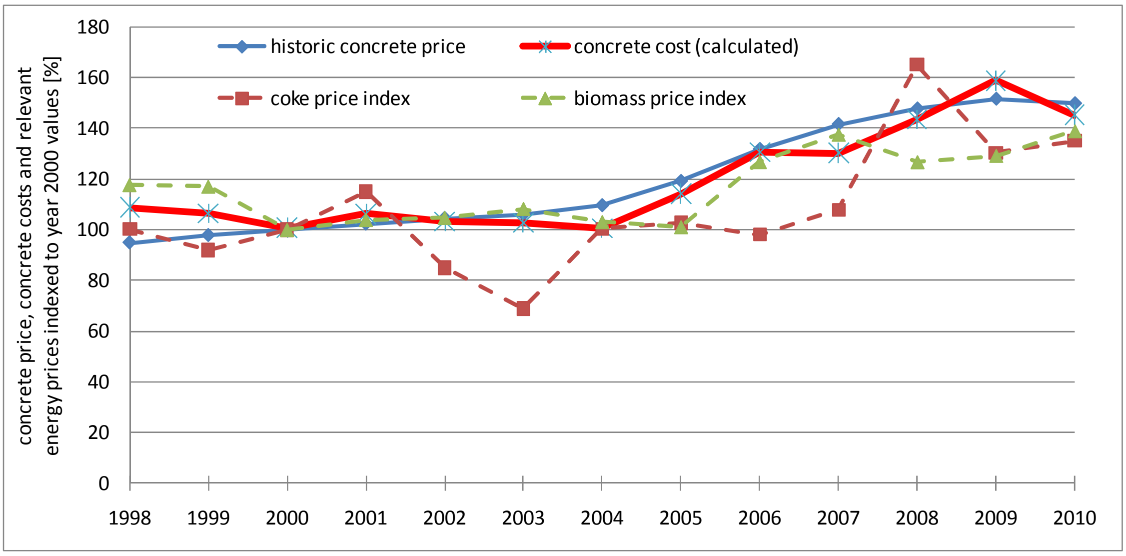

Figure 4-14 Historic observation of the concrete price, the coke price and the biomass price as well as endogenously calculated concrete costs in the period 1998 to 2010 indexed to the year 2000

Based on the historic analysis presented above, future projections of the commodity costs until 2030 are derived. Assumptions related to the development of energy prices refer to the PRIMES baseline scenario (see NTUA, 2009). Furthermore, electricity wholesale prices are calculated endogenously within *Green-X* in line with these energy price and demand trends. These projections are depicted in Figure 4-15 below.

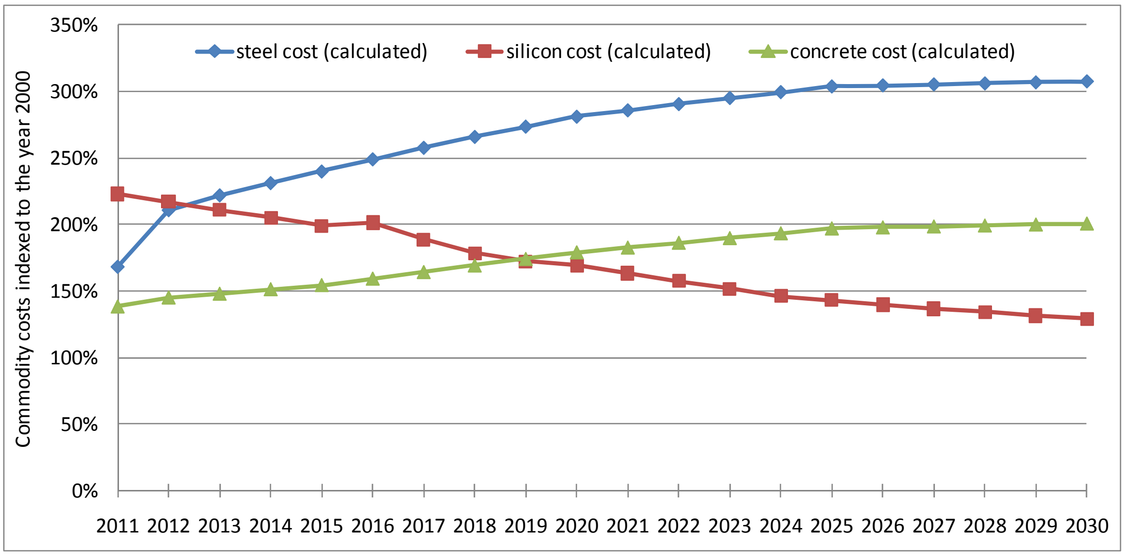

Figure 4-15 Future projections of the steel-, silicon and concrete costs according to energy prices forecasts of the PRIMES reference scenario, NTUA 2010 expressed in index of 2000 values

With respect to the steel price projections in Figure 4-15, a stronger increase is expected within the near future years, which declines in later years. On the one hand, it is expected that with increasing energy prices, especially coal prices, more efficient production processes will be developed and therefore the impact of energy prices on steel costs will decline. On the other hand, the impact of coal prices on steel costs will decrease due to material substitutions and switching towards more novel, energy-efficient production processes (i.e. from BOF to EAF).

In contrast, concrete costs will continuously increase until 2030 and only level off close to 2030 due to some efficiency improvements. Again, the development of concrete costs, driven by the energy input price for cement production, is very sensitive to the location of the production site. Hence, cement production supplied by coke heat might affect concrete costs stronger than cement production where the necessary heat input stems from biomass energy.

Finally, silicon costs are expected to decrease again leading to values before the silicon demand increase occurred, as Figure 4-15 depicts. On the one hand the shift from electronic grade to silicon grade silicon is now ongoing, and this trend will be continued resulting in less electricity consumption of silicon producers. On the other hand, also the production of silicon-grade silicon still offers a high potential for energy efficiency improvements. Apparently, the trend of less energy consumption is partly compensated by increasing electricity prices, based on the assumed energy prices.

4.3.4.2 Impact assessment – resulting investment costs for RES technologies

Applying the multifactor learning approach to assess the historic and future development of investment costs for RES technologies considers both the technological learning effect and the impact of the main raw material costs. First, according to the approach discussed above, future projections for **wind onshore** until the year 2030 are derived and presented in Figure 4-16. Obviously, the impact of steel price explains the historic observation of investment costs for wind onshore comparatively well since technological learning effects are compensated and investment costs even increase in between.

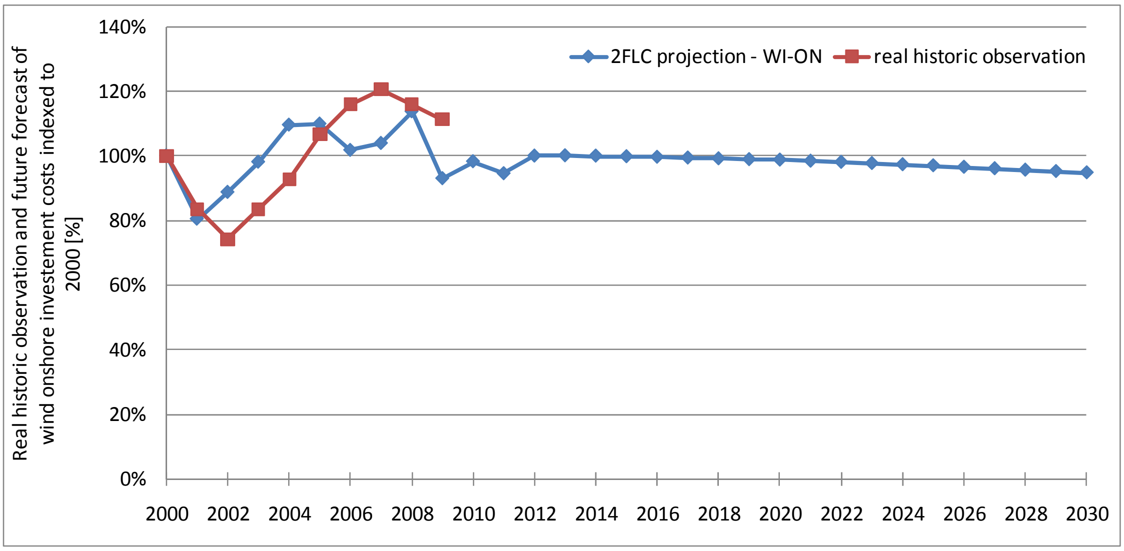

Figure 4-16 Wind onshore investment costs based on the multi factor learning approach and historic evidence indexed to the year 2000 (in constant EUR) for the time period 2000 to 2030

It is important to note that in Figure 4-16, historic wind onshore investments are compared to future predictions based on steel cost impacts. Therefore, calculations cannot entirely meet the historic observations, but they show the same trend. With respect to future predictions, a rather constant development is calculated caused by the exogenous scenarios[43] of continuously increasing energy prices, where volatility as observed in recent years is not applicable. In relation to wind onshore investment cost of the year 2000, costs declined in the beginning of the decade but increased shortly afterwards due to increasing steel costs/prices which peaked between 2006 and 2008. Since 2008, a decrease of investment costs due to reduced raw energy prices, caused by the economic crisis etc. is notable. Within the period 2010 to 2030, a rather constant development of wind onshore investment costs is predicted, whereby the impact of constantly increasing steel costs almost compensates the effect of technological learning. Generally, a constant learning rate of seven percent for each doubling of cumulative capacity is considered over the total time period and based on a strengthened national policy support with respect to the RES deployment, see Resch et al. (2011). Due to the impact of steel costs, an overall cost reduction in 2030 compared to 2000 is achieved of about 5.23 percent, which would equal a learning rate of the standard one factor learning curve of LR=1.2 percent.

Next, **wind offshore** is discussed. In contrast to wind onshore, not only steel costs influence the investment costs but also concrete costs, caused by the extra investments for foundation and the offshore infrastructure. Therefore, investment cost projections of wind offshore build

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[43] Since these scenarios are conducted on a yearly basis until 2030, no intermediate volatilities caused by exogenous events (i.e. economic crisis, production shortages, etc.) can be considered

on above presented results of wind onshore with an additional term modeling the extra investments of wind offshore according to formula Eq(6).

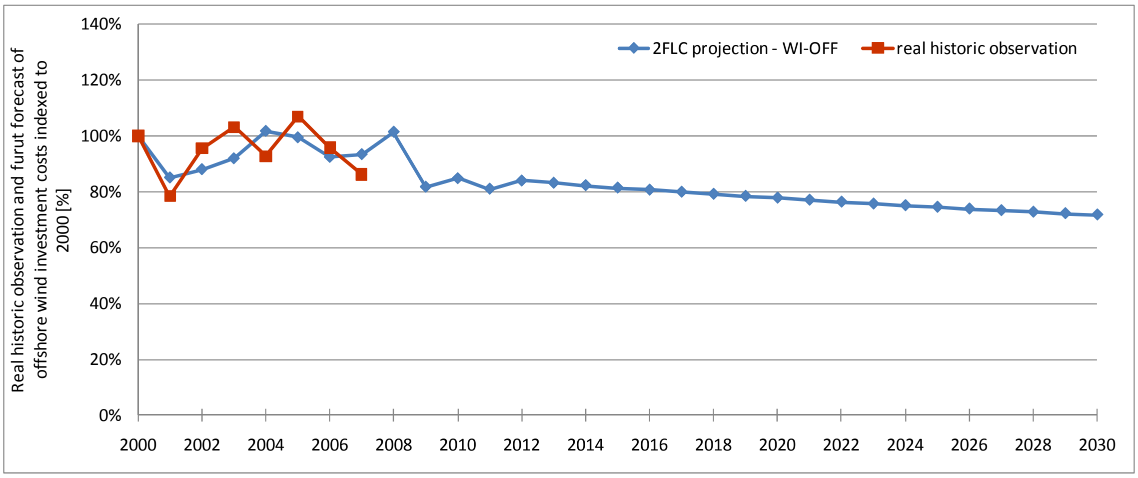

Figure 4-17 Wind offshore investment costs based on the multi factor learning approach and historic evidence indexed to the year 2000 (in constant EUR) for the time period 2000 to 2030

Figure 4-17 above presents the future expectations of investment costs for wind offshore, taking into account technological learning as well as the impact of steel and concrete costs. Additionally, the historic evidence for the period 2000 to 2007 is depicted. Comparing Figure 4-16 to Figure 4-17 indicates that wind offshore costs are less sensitive to steel costs, since their additional investment costs are influenced more strongly by concrete costs, which have been more constant throughout the last decade. In general, the derived projections of wind offshore investment costs follow the historic observation to a high degree. Again, it needs to be pointed out, that the projections refer to the impact of commodity costs, not to the impact of commodity prices. as already indicated above, future expectations show less volatility than projections for the past decade due to the conditioned energy price trend for future years which neglect volatility. Nevertheless, since wind offshore potentials are so far less exploited than wind onshore potentials, the technological learning effect is only partly compensated by the impact of raw material costs. Hence, assuming a learning rate of nine percent for the extra investment of wind offshore technologies, an overall cost reduction of 28.3% between 2000 and 2030 may be achieved[44].

In contrast to the wind energy technologies, investment costs for **photovoltaic** are mostly driven downwards by commodity costs, specifically silicon costs. Thus, considering silicon costs in addition to technological learning even reduces future investment costs of photovoltaic modules. The overall projection of future PV investment costs according to formulas Eq(4) and Eq(7) is illustrated in Figure 4-18.

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[44] With respect to the definition of a one factor learning approach, this would result in an overall learning rate of 1.2%, as for wind onshore. However, since wind offshore is less exploited so far, technological learning effects are stronger influencing the overall result, as depicted in this report.

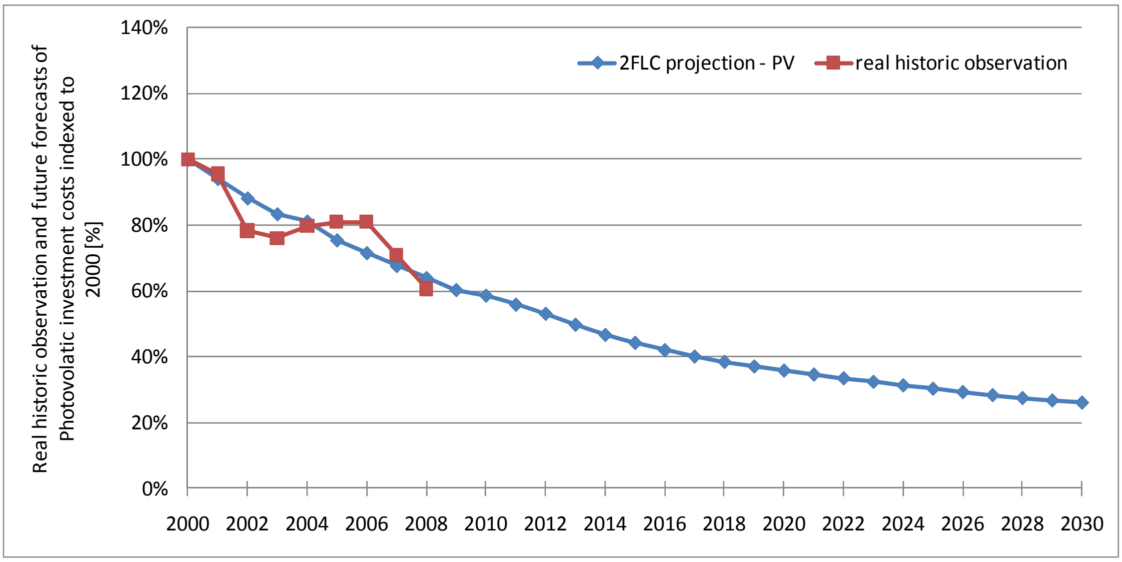

Figure 4-18 Photovoltaic investment costs based on the multi factor learning approach and historic evidence indexed to the year 2000 (in constant EUR) for the time period 2000 to 2030

Figure 4-18 compares real historic observations to projections of future PV investment costs based on technological learning and silicon costs[45]. As silicon costs and prices showed volatile trends in the last decade, this volatility is also, to a minor extent[46], notable in the projection of photovoltaic investment costs. Nevertheless, this impact of silicon costs is only weak compared to the influence of technological learning for this technology. Since it is a rather new technology, learning effects are expected to remain strong, caused by a high learning rate of 16% and the fast growing market with fast doublings of installations, according to the strengthened national policy scenario of the futures-e project, see Resch et al. (2011). As Figure 4-15 indicates, silicon costs are expected to decrease, investment costs for PV modules will decline to about only 26 percent of the level for the year 2000. This corresponds to a technological learning rate with the ordinary one factor learning curve approach of about 16.3%.

Finally, **biomass** energy plants are addressed. Several different plant types exist, and moreover, a broad range of different scales is installed. Depending on the type and the scale of the plant, historic investments varied strongly. Moreover, due to little data availability, all different biomass plants are considered in this assessment within one generic category, representing an analysis of the overall biomass energy sector[47]. Thus, Figure 4-19 depicts the results for the biomass sector.

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[45] This aspect is especially crucial in the case of silicon costs versus silicon prices for the period between 2003 and 2008, when silicon price increased strongly due to market driven mechanisms.

[46] Especially in the year 2004 a slight increase of PV module costs is notable

[47] Please see therefore the subsequently suggested improvements for further research within this topical area.

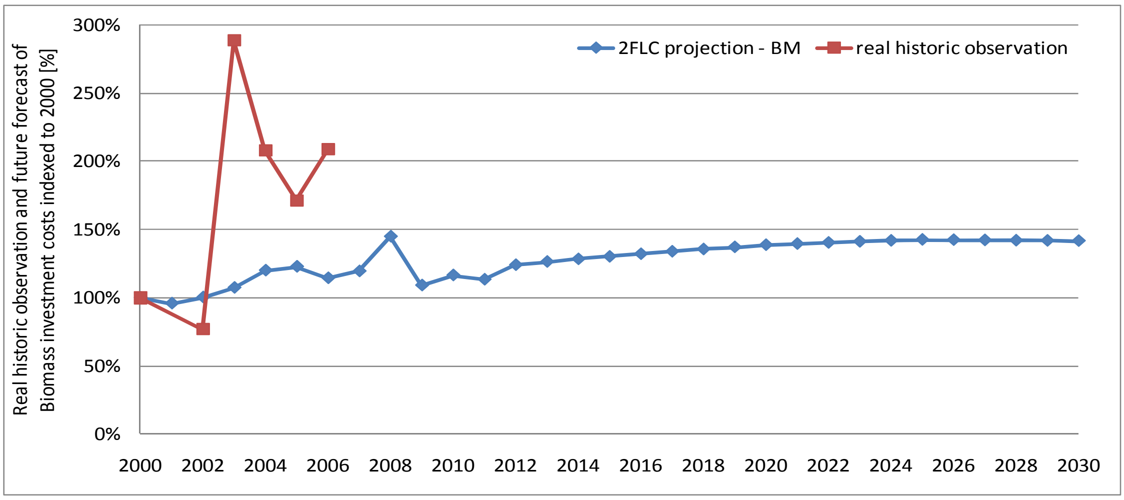

Figure 4-19 Biomass plant investment costs based on the multi factor learning approach and historic evidence indexed to the year 2000 (in constant EUR) for the time period 2000 to 2030

Due to the inclusion of different types and scales of biomass plants into one generic technology cluster, the historic observation of investment costs in Figure 4-19 shows a high volatility. Additionally, the calculated future projections do not meet the historic observation at any time. But obviously, both the historic observation and the calculated future projection show similar trends over time. Generally, most of biomass technologies, especially these represented in this study, are already very advanced technologies and consequently show only minor technological learning effects. Therefore, the technological learning is hereby totally compensated by the commodity cost impact. In this study a learning rate of 3.5% is assumed, but due to the already high exploited potential its impact is rather limited. Hence, the impact of commodity costs, i.e. steel- and concrete costs, dominates the future projection of biomass investment costs resulting in a 41% increase in the year 2030 compared to 2000.

Concluding, the effect of the new approach according to formula Eq(4), the multi-factor learning curve, compared to the traditional technological learning methodology is depicted in Figure 4-20. In Figure 4-20, the hundred percent label signals no difference between the traditional one factor learning curve to the new multi factor learning curve approach. Higher labels indicate that due to considering commodity costs in addition, technological learning effects are (partly) compensated, whereas labels below hundred percent indicate that commodity costs in addition to default learning cause a stronger decrease of investment costs for the assessed RES technologies than in the case of pure consideration of technological learning.

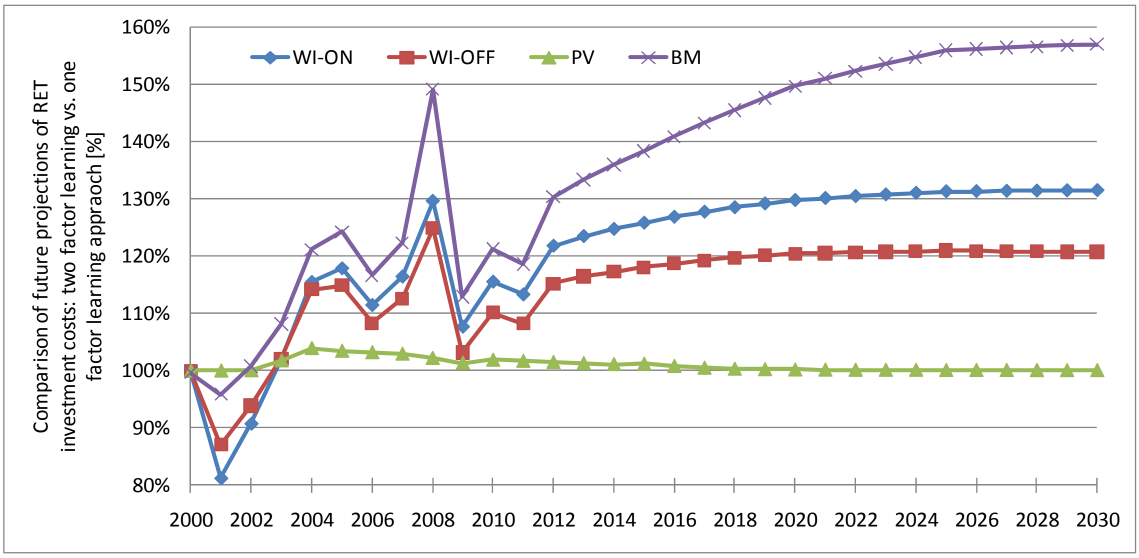

Figure 4-20 Comparison of the new multi factor learning curve approach to the traditional standard one factor learning curve approach. Illustrating the projections of investment costs of wind on- and offshore, photovoltaic and biomass energy technologies up to 2030.

Obviously, the investment cost projections of the assessed RES technologies in Figure 4-20 indicate that the multi factor learning curve approach results in higher investment costs of RES technologies in times of high commodity costs. Therefore, around 2004, higher silicon costs increased PV investment costs, and high steel costs around 2008 strongly impacted the wind energy technologies as well as biomass investment costs. Moreover, the volatile character of investment costs, as observed throughout the last decade, can be described by the new approach. Generally, the more novel a technology is and, consequently, the higher the potential for technological progress, the smaller are the impacts of commodity costs in comparison to the traditional technological learning effects. This issue is especially significant for the photovoltaic and wind offshore technologies, see Figure 4-20. Therein it is apparent that these technologies show less difference between the two approaches than the other technologies. With respect to future expectations of investment costs for RES technologies, the impact of commodity costs strongly depends on the scenarios of energy prices.

4.3.5 Key findings

In order to sum up this section, some conclusions and recommendations are drawn here. In principle the multi factor learning curve approach allows to model investment costs for RES technologies more precisely and therefore also allows a better matching with historic observations. Moreover, concentrating on the impact of commodity costs rather than of commodity prices prevents to overestimate the influence of commodities. In contrast, neglecting market mechanisms with respect to commodity prices represents a simplified modeling approach and does not reflect real developments under all circumstances. Generally, identifying commodity costs is very sensitive to the input data and therefore the data collection is a crucial task of this work. In this respect, it must be noted that results presented here, refer to an ongoing process of research and will be constantly further improved. On the one hand, statistical tests need to be intensified in order to prove the robustness of the identified regression models and, on the other hand, especially concrete prices and costs as well as biomass energy investment costs need to be updated. The latter need to be divided into more different clusters, either sorted by scale or by type. Summing up, results have shown the importance of considering next to technological learning also commodity costs, but the preparation of input data is of key importance.

5 Summary and conclusions

This report aims to provide the background information to form the long term vision beyond 2020 for the renewable energy sector. Sub-objectives are:

- Refinement and extension of the long term potentials for renewable energy sources in the Green-X database;
- Update and further elaboration of diffusion characteristics of new renewable energy technologies;
- Update and proper model-incorporation of long-term cost development trajectories of renewable energy technologies including trade-offs between high energy and raw material prices and RES cost as observed in the past.

This chapter summarizes the main findings and for each of the three areas mentioned above and draws some conclusions on how the new data may be implemented into Green-X.

5.1 Long term potentials for renewable energy

Starting with the renewed assessment of the long-term potentials of **wind onshore and PV**, the comprehensive analysis of the technical and realizable potentials in the EU is a major step forward compared to the previously available data and studies. The GIS-based approach to assess the realizable potential of both technologies allowed for the creation of internally consistent and highly detailed generation and capacity potentials (which are then combined in generation bands). Combined with assumptions on (updated current) production costs, this has led to the creation of new cost-resource curves for the EU-27 for both onshore wind and PV. This method also required some simplifications (e.g. the limitation to a single wind turbine type or specific assumptions on the available area of roof surfaces and PV power plants on free fields), which causes some uncertainties (e.g. underestimation of the costs due to the exclusion of grid connection costs). However, we think that the resulting cost-resource curves reflect the current situation quite accurately, and could (and should) therefore be used to replace the current curves in Green-X. Of course, future cost developments should be modeled endogenously, as discussed below in section 5.3.

For the evaluation of the long-term **biomass potential** in the EU-27 (both from residues and from dedicated energy crops), we evaluated a large number of recent studies, and compared them with the current assumptions in Green-X. The analysis revealed that with regard to **energy crops**, Green-X is relatively optimistic for the current potential, but assumes increasingly conservative/low potentials for 2020 and especially 2030. For the period of 2030-2039, it assumes a potential of about 3.5 EJ, while the range of study varies from about 2.5 to 13 EJ. Bioenergy crop potentials for 2050 may vary between 15-20 EJ (but this is only based on a single study). A country-based comparison with the Refuel-study results shows that the higher estimated potentials in 2030 in REFUEL (5.8 EJ) compared to Green-X (3.5 EJ) are mainly due to differences in Central and Eastern European Countries. Also regarding the assumed production costs of energy crops, there are differences between Green-X and Refuel. While both in Green-X and REFUEL, lignocellulosic energy crops (grassy crops and SRC) are the cheapest whereas oil crops (rapeseed and sunflower) are the most expensive, the cost for biomass in REFUEL is significantly lower compared to Green-X, partly due to the relatively high potential in CEEC countries with lower production cost due to land and labor prices in these regions. Also regarding future developments, in REFUEL, the cost of, especially lignocellulosic crops, is assumed to decrease in time due to accumulated experience (learning) whereas in Green-X, the cost increase over time in relation with increasing trends in fossil fuel prices. The comparison of the **forestry resource assessment studies** show very different results for primary and secondary forestry products and residues compared to Green-X. For primary forestry products and residues, Green-X includes the most optimistic potentials whereas for secondary forestry residues, Green-X includes the most conservative potentials within the spectrum of studies assessed. The differences are mainly the result of wood categories included and a result of different potential types (technical, economical, sustainable) approaches (demand or supply driven) and future scenario assumptions including demands from non-energy uses. The total potential of primary and secondary products and residues as found in all studies from forestry ranges from 1.2 EJ to 4.3 EJ for the current situation (2000-2009). For comparison, the total potential in Green-X (primary and secondary forestry products and residues) increases from 3.5 EJ in 2005 to 4.2 EJ in 2030, which is the highest figure of all studies investigated. Potential explanation for the high potentials of primary forestry products and residues in Green-X could the wide range found in the total potential of decentralized heat generation from biomass due to the uncertainty and lack of data. For example, Held, Ragwitz et al. estimated 2.32 EJ final heat to be produced in decentralized and 0.32 EJ final heat in centralized systems in 2008, whereas the EUwood estimates 1.48 EJ primary biomass to used by households for the EU-27. Another important factor is the allocation of biomass to material users such as wood panel industries and pulp and paper mills.

Based on these observations, it could be worthwhile to assess whether the long-term potential for bioenergy crops in Green-X may be changed to a more optimistic scenario, whereas the availability of forestry residues can be classified as optimistic. Finally also the production costs of lignocellulose crops as currently contained in Green-X seem on the high side. The impacts of technological learning and yield increases on the one hand and increasing fossil prices on the other on lignocellulose production costs may also be a relevant topic for further research.

5.2 Elaboration of diffusion characteristics

In accordance with general diffusion theory, penetration of a market by any new commodity typically follows an “S-curve” pattern. The Green-X model works with a concept related to technology diffusion that can be summarised as follows: With regard to the technical estimate of the logistic curve, a method has been employed by a simple transformation of the logistic curve from a temporal evolution of the market penetration of a technology to a linear relation between annual penetration and growth rates. This procedure for estimating the precise form of the logistic curve appears more robust against uncertainties in the historic data. Furthermore, this method allows the determination of the independent parameters of the logistic function by means of simple linear regression instead of nonlinear fits involving the problem of local minima. In section 3.2 of this report we briefly illustrate the effect of the derived approach using scenarios on the future RES deployment with and without mitigation of non-economic barriers. We show that mitigation of non-economic barriers can have a significant impact on RES(-E) diffusion rates, which in turn may also strongly increase consumer expenditures. This indicates the need to align support conditions to the expected / observed market development, as otherwise specifically novel RES technologies would achieve significant over-support in case of future mass deployment. For further details on the policy scenario assessment we also refer to the forthcoming corresponding RE-Shaping scenario report.

5.3 Long-term cost development trajectories of renewable energy technologies

Based on the review of recent studies investigating experience curve, we conclude that the learning rates as employed by Green-X (see Annex II) are within the ranges found in (recent) literature. However, it has also become clear that technological experience curves are sensitive to changes in variables (e.g. time frame, region size), and that especially input prices (i.e. material) prices can have a substantial effect on experience curves, which has previously not been taken into account. Therefore, a novel approach was developed, in which the fossil energy and electricity prices (as given exogenously by PRIMES) are used to model the price development of concrete, steel and silicon, which in turn is used to evaluate the development of the production costs of solar PV, wind onshore, wind offshore and biomass technologies. The analysis shows dramatic changes for wind energy and biomass technologies when the raw material price changes are taken into account (next to the technological learning effect): especially for biomass, investment cost might actually show an increase by over 50% in 2030 compared to 2000 levels, whereas wind onshore and wind offshore may increase by 20% to 30%. Only PV shows stable investment costs – which however still differ substantially from the ‘technological learning only scenario’, where otherwise significant further price reductions were expected.

However, it is very important to point out that these results are still preliminary. Statistical tests need to be intensified in order to prove the robustness of the identified regression models, concrete prices and costs need to be updated, and biomass energy investment costs need to be divided into more different clusters, either sorted by scale or by type. Furthermore, the current analysis covers the most important, but not all renewable energy technologies in Green-X, so an implementation of the new methodology for only these technologies would lead to distorted results. Even more important is the fact, that the investment cost of fossil fuel technologies will also (strongly) increase with increasing cement and steel cost – but these are currently taken exogenously from PRIMES. Overall, we conclude that while the novel approach has revealed potential large impacts on the cost development of renewable energy technologies, the approach still needs to be further refined before it can definitely be implemented in Green-X.

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Annex I

Table A-1 Assumed suitability factors per land use category

Level 1	Level 2	Level 3	Suitability
1. Artificial surfaces	1.1. Urban fabric	1.1.1. Continuous urban fabric	0
		1.1.2. Discontinuous urban fabric	0
	1.2. Industrial, commercial and transport units	1.2.1. Industrial or commercial units	0
		1.2.2. Road and rail networks and associated land	0
		1.2.3. Port areas	0
		1.2.4. Airports	0
	1.3. Mine, dump and construction sites	1.3.1. Mineral extraction sites	0
		1.3.2. Dump sites	0
		1.3.3. Construction sites	0
	1.4. Artificial non-agricultural vegetated areas	1.4.1. Green urban areas	0
		1.4.2. Sport and leisure facilities	0
2. Agricultural areas	2.1.Arable land	2.1.1. Non-irrigated arable land	0.35
		2.1.2. Permanently irrigated land	0.35
		2.1.3. Rice fields	0.35
	2.2. Permanent crops	2.2.1. Vineyards	0.1
		2.2.2. Fruit trees and berry plantations	0.1
		2.2.3. Olive groves	0.1
	2.3. Pastures	2.3.1. Pastures	0.35
	2.4. Heterogeneous agricultural areas	2.4.1. Annual crops associated with permanent crops	0.1
		2.4.2. Complex cultivation	0.1
		2.4.3. Land principally occupied by agriculture, with significant areas of natural vegetation	0.1
		2.4.4. Agro-forestry areas	0.1
3. Forests and semi-natural areas	3.1. Forests	3.1.1. Broad-leaved forest	0.1
		3.1.2. Coniferous forest	0.1
		3.1.3. Mixed forest	0.1
	3.2. Shrub and/or herbaceous vegetation association	3.2.1. Natural grassland	0.5
		3.2.2. Moors and heathland	0.5
		3.2.3. Sclerophyllous vegetation	0.5
		3.2.4. Transitional woodland shrub	0.5
	3.3. Open spaces with little or no vegetation	3.3.1. Beaches, dunes, and sand plains	0.1
		3.3.2. Bare rock	0
		3.3.3. Sparsely vegetated areas	0.8
		3.3.4. Burnt areas	0
		3.3.5. Glaciers and perpetual snow	0

4. Wetlands	4.1. inland wetlands	4.1.1. Inland marshes	0.1
		4.1.2. Peat bogs	0.1
	4.2. Coastal wetlands	4.2.1. Salt marshes	0.1
		4.2.2. Salines	0.1
		4.2.3. Intertidal flats	0.1
5. Water bodies			0

Source: Land use categories taken from CORINE land cover 2000

Annex II

Learning rates Green-X

Table A-2 Assumed suitability factors per land use category

RES technology category	Short-term approach*	Assumptions on technological learning	
		Learning parameter	Geographical scope
RES-Electricity			
Geothermal electricity	Cost increase up to 2009: +9% (compared to 2006)	LR (learning rate): 5% (2009-2010), 8% from 2011 on	Global learning system
Hydropower	Cost increase up to 2009: +9% (compared to 2006)	LR: 0% (2009-2010), 5% from 2011 on	Global learning system
Solar thermal electricity (CSP)	No cost increase foreseen	LR: 18% until 2010, 12% from 2011 on	Global learning system
Photovoltaics	No cost increase foreseen	LR: 20% until 2010, 17.5% from 2011 to 2020, 15% from 2021 on	Global learning system
Tidal stream energy	Expert judgement of cost development until 2015	LR: 12.5% - learning assumptions refer to assumed market entrance (after 2015)	Global learning system
Wave power	Expert judgement of cost development until 2015	LR: 12.5% - learning assumptions refer to assumed market entrance (after 2015)	Global learning system
Wind energy	Cost increase up to 2009: +17% (compared to 2006)	LR: 0% (2010), 9% from 2011 to 2020, 6% from 2021 on	Global learning system
Gaseous biomass - power plant (pure power)	Cost increase up to 2009: +9% (compared to 2006)	LR: 7.5% (2009-2010), 10% from 2011 on	Global learning system
Gaseous biomass - CHP	Cost increase up to 2009: +9% (compared to 2006)	LR: 7.5% (2009-2010), 10% from 2011 on	Global learning system
Biomass - small-scale power plant	Cost increase up to 2009: +9% (compared to 2006)	LR: 7.5% (2009-2010), 10% from 2011 on	Global learning system
Biomass - small-scale CHP plant	Cost increase up to 2009: +9% (compared to 2006)	LR: 7.5% (2009-2010), 10% from 2011 on	Global learning system
Biomass - large-scale power plant (pure power)	Cost increase up to 2009: +9% (compared to 2006)	LR: 2.5% (2009-2010), 5% from 2011 on	Global learning system
Biomass - large-scale CHP plant	Cost increase up to 2009: +9% (compared to 2006)	LR: 2.5% (2009-2010), 5% from 2011 on	Global learning system
Biomass - cofiring (pure power)	Cost increase up to 2009: +9% (compared to 2006)	Expert judgement of future cost development (Cost decrease: -1.25% per year)	
Biomass - cofiring CHP	Cost increase up to 2009: +9% (compared to 2006)	Expert judgement of future cost development (Cost decrease: -1.25% per year)	
Biowaste - small-scale plant	Cost increase up to 2009: +9% (compared to 2006)	LR: 2.5% (2009-2010), 5% from 2011 on	Global learning system
Biowaste - large-scale plant	Cost increase up to 2009: +9% (compared to 2006)	LR: 2.5% (2009-2010), 5% from 2011 on	Global learning system

Note: *In the period 2006 to 2008 for most RES technologies (similar to conventional energy technologies) a cost increase was becoming apparent - in line with high energy and raw material prices. This is reflected in the scenario calculations by exogenously changing default learning assumptions (more precisely, the hereby applied approach is defined in line with an expected future energy price development according to the 'PRIMES high energy price' case)

Table A-3 Assumed suitability factors per land use category

RES technology category	Short-term approach*	Assumptions on technological learning	
		Learning parameter	Geographical scope
RES-Heat			
Geothermal heat (district heat)	Cost increase up to 2009: +9% (compared to 2006)	LR: 5% (2009-2010), 8% from 2011 on	European learning system
Biomass heat (districit heat)	Cost increase up to 2009: +9% (compared to 2006)	LR: 0% (2009-2010), 5% from 2011 on	European learning system
Biomass heat - log wood (de-central - basic stoves)	Cost increase up to 2009: +9% (compared to 2006)	LR: 2.5% (2009-2010), 5% from 2011 on	European learning system
Biomass heat - wood chips (de-central)	Cost increase up to 2009: +9% (compared to 2006)	LR: 2.5% (2009-2010), 7.5% from 2011 on	European learning system
Biomass heat - pellets (decentral)	Cost increase up to 2009: +9% (compared to 2006)	LR: 2.5% (2009-2010), 10% from 2011 on	European learning system
Solar thermal heat and hot water supply	Cost increase up to 2009: +9% (compared to 2006)	LR (learning rate): 5% (2009-2010), 8% from 2011 on	European learning system
Heat pumos	Cost increase up to 2009: +9% (compared to 2006)	LR (learning rate): 5% (2009-2010), 8% from 2011 on	European learning system
Biofuels			
Bioethanol	Cost increase up to 2009: +9% (compared to 2006)	LR: 2.5% (2009-2010), 5% from 2011 on	European learning system
Biodiesel	Cost increase up to 2009: +9% (compared to 2006)	LR: 2.5% (2009-2010), 5% from 2011 on	European learning system
Lignocellulotic bioethanol	Expert judgement of cost development until 2015	LR: 10% - learning assumptions refer to assumed market entrance (after 2015)	European learning system
Biomass-to-Liquid	Expert judgement of cost development until 2015	LR: 10% - learning assumptions refer to assumed market entrance (after 2015)	European learning system

Note: *In the period 2006 to 2008 for most RES technologies (similar to conventional energy technologies) a cost increase was becoming apparent - in line with high energy and raw material prices. This is reflected in the scenario calculations by exogenously changing default learning assumptions (more precisely, the hereby applied approach is defined in line with an expected future energy price development according to the 'PRIMES high energy price' case)