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Paving the way: Analysing energy transition pathways and green hydrogen exports in developing countries – The case of Algeria

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ABSTRACT

The measures needed to limit global warming pose a particular challenge to current fossil fuel exporters, who must not only decarbonise their local energy systems, but also compensate for the expected decline in fossil fuel revenues. One possibility is seen in the export of green hydrogen. Using Algeria as a case study, this paper analyses how different levels of ambition in hydrogen exports, energy efficiency and fuel switching affect the cost-optimal expansion of the power sector for a given overall emissions reduction path. Despite falling costs for photovoltaics and wind turbines, the results indicate that in countries with very low natural gas prices, such as Algeria, a fully renewable electricity system by 2050 is unlikely without appropriate policy measures. The expansion of renewable energy should therefore start early, given the high annual growth rates required, which will be reinforced by additional green hydrogen exports. In parallel, energy efficiency is a key factor as it directly mitigates CO2 emissions from fossil fuels and reduces domestic electricity demand, which could instead be used for hydrogen production. Integrating electrolysers into the power system could potentially help to reduce specific costs through load shifting. Overall, it seems advisable to analyse hydrogen exports together with local decarbonisation in order to better understand their interactions and to reduce emissions as efficiently as possible. These results and the methodology could be transferred to other countries that want to become green hydrogen exporters in the future and are therefore a useful addition for researchers and policy makers.

1. Introduction

The Paris Agreement on climate change calls for a drastic shift away from fossil fuels in order to achieve its goals [1,2]. Aside from improving energy efficiency and using renewable electricity, clean fuels like green hydrogen are also seen as a piece of the puzzle for deep decarbonisation for certain applications such as hard-to-decarbonise industrial sectors and air transport [3,4]. Some of the total demand for green hydrogen is expected to be met by international trade, given the expected high demand in countries such as Germany or Japan and the greater renewable energy (RE) potential in other regions [5–7]. From a global perspective, it is therefore important to consider the impact of green hydrogen production on the local energy transition in exporting countries and to ensure that it does not discourage domestic emission reductions by using RE sources to produce hydrogen for export instead of serving local electricity needs. Rather, the development of export capacities and the domestic transformation process should ideally take place in synergy, as the production of hydrogen through electrolysis could even encourage the integration of RE into the electricity system.

This is particularly relevant for fossil fuel exporters such as Algeria, which are currently heavily dependent on fossil fuels for both domestic energy supply and exports and may see green hydrogen as an option to partially compensate for the expected decline in fossil exports. Different publications show that the export of green fuels could be an opportunity for fossil fuel exporters in the Middle East and North Africa (MENA) region to diversify their economies and leverage their existing energy infrastructure and trade relationships [5,8–11]. In this context, it is important to note that Algeria not only has a large potential for fossil fuel energy production but also for renewables [12–17]. Despite ambitious targets, the uptake of RE is slow in Algeria compared to other African countries [13,17]. Identified barriers for the energy transition include a lack of stringent policies and incentives [13–15,18], high burden on foreign investments [13,15], fossil fuel subsidies [15,18] and low levels of expertise in the country [13,15,16]. Between 2000 and 2021, Algeria's total primary energy supply more than doubled to 747 TWh, with natural

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Abbreviations

CAGR – Compound Annual Growth Rate
CAPEX – Capital Expenditures
CCGT – Combined Cycle Gas Turbine
CCS – Carbon Capture and Storage
CO2 – Carbon Dioxide
FED – Final Energy Demand
GDP – Gross Domestic Product
H2 – Hydrogen
INDCs – Intended Nationally Determined Contributions
LEAP – Low Emissions Analysis Platform
MENA – Middle East and North Africa
NEMO – Next Energy Modeling system for Optimization
OPEX – Operational Expenditures
PV – Photovoltaics
RE – Renewable Energies
SCGT – Simple Cycle Gas Turbine
USD – US-Dollar

gas and oil accounting for more than 99 % of supply in 2021. Electricity generation more than tripled to 85 TWh, with natural gas-fired power plants covering 99 % [19]. Nevertheless, Algeria has a strong political interest in exporting green hydrogen in the future due to the very good RE potential, the proximity to potential offtakers in Europe and the existing pipeline infrastructure [20,21]. Analyses of the production costs of hydrogen from different renewable sources have been carried out by Douak and Settou [22] for wind, Rahmouni et al. [23] for wind and solar photovoltaics (PV), Mraoui and Menia [24] for solar PV and Boudries [25] for concentrating solar power. Such studies are important for selecting suitable locations and minimising the production costs associated with the various technologies. However, they do not take into account the integration of hydrogen production plants into the local energy system. Lux et al. [26] include an estimation of the local electricity demand of eleven MENA countries, including Algeria, when calculating supply curves for different gaseous electricity-based fuels for Europe in 2030 and 2050, but do not address the demand for other fuels or the local carbon dioxide (CO2) emissions. Saiaha and Stambouli [27] conduct a scenario-based long-term optimal energy planning for Algeria and consider both the electricity sector and the sectoral final energy demand. However, neither hydrogen exports nor emission limits are considered. Both, Brand [28] and Boie et al. [29] explore cost-optimised paths for an interconnected electricity system with five North African countries, including Algeria, but do not address hydrogen production in their studies.

To our knowledge, there is no work that combines the modelling of ambitious local energy transition scenarios for Algeria with green hydrogen exports. The objective of this work is therefore to investigate how different levels of ambition in terms of 1) hydrogen exports, 2) energy efficiency rates and 3) fuel switch affect the final energy demand and the expansion of the power sector until 2050. We assume that the emission budget is given, based on Algeria's position as a party to the Paris Climate Agreement. The development of the energy system, thus in combination with the ambition to export hydrogen determines a "corridor" for the electricity system in Algeria to develop. Depending on the scenario, the remaining CO2 budget acts as a restriction for the development of the power sector. In some cases, this could lead to very high expansion rates for RE and storage technologies – and, related to this, high investment costs. The paper is structured as follows: Section 2 describes the data and methods used and explains the scope, the scenario definition as well as the approach for the power sector expansion planning. Section 3 presents the results for the evolution of final energy demand and the power sector in Algeria until 2050 under the different scenarios. Finally, section 4 discusses the key findings and derives overall conclusions, which are also transferable to other fossil fuel exporters which may follow similar pathways. Also countries, which may become hydrogen exporters without being fossil fuel producers (e.g. Morocco), may face partly similar questions on the synergies between decarbonisation efforts and hydrogen production for exports.

2. Material and methods

Energy system modelling combined with scenario analysis is a widely used method for energy planning. It allows decision-makers to assess the costs and benefits of different energy pathways, identify potential risks and uncertainties, and make informed decisions based on a comprehensive understanding of the energy system. The *Low Emissions Analysis Platform* (LEAP) [30] is a tool specifically designed for emerging and developing economies, which often face challenges in establishing a sustainable and affordable energy system. It was developed by the Stockholm Environment Institute and is used worldwide to support energy planning and policy analysis [31]. LEAP provides the capability to perform cost optimal capacity expansion for the power sector using the *Next Energy Modeling system for Optimization* (NEMO) [32]. It allows defining different boundary conditions and scenarios, such as renewable energy targets, emission penalties and constraints, or different economic assumptions on capital expenditure (CAPEX), operational expenditure (OPEX), and discount rates. Examples of the use of LEAP in combination with NEMO at a national level to develop and analyse cost-optimal power sector expansion pathways include case studies for Colombia [33], Kenya [34], Indonesia [35,36], and other Southeast Asian countries [37]. Elberry et al. [38] use LEAP and NEMO to evaluate the integration of seasonal hydrogen storage into the Finnish electricity system. In the North African context Ouedraogo [39] applied LEAP to model transition pathways in line with the Intended Nationally Determined Contributions (INDCs) under the Paris Agreement.

2.1. Overall scope

Both the IPCC WGIII report [2] and the assessment of 177 net-zero scenarios by DeAngelo et al. [40] show that fossil fuel use, offset by sinks such as bioenergy and carbon capture and storage (CCS), is still likely to play a non-negligible role in 2050. In addition, there are also regional differences, so that even with global net zero emissions, some regions will probably remain net positive emitters. This is particularly relevant with regard to a potential effort sharing between industrialised countries and emerging and developing economies. In the case of Algeria, we therefore assume a decarbonisation pathway with strong reductions but certain remaining CO2 emissions in 2050. This reflects discussions with local stakeholders and the fact that there is no concrete net-zero target to date.

The scope of the analyses presented in this paper covers the energy and CO2 balances of final energy demand (FED) and electricity generation up to 2050. All scenarios are subject to the same emissions constraint, which reverses the historical trend and linearly reduces the corresponding annual CO2 budget from 141 Mt in 2021 to 135 Mt in 2030 and 50 Mt in 2050 (see Fig. 1). While the overall pathway is the same for all scenarios, the distribution of emissions from the final energy and the power sector depends on the scenario. In each scenario, FED and hydrogen exports are specified exogenously by varying different parameters (see section 2.2), while the power sector expansion is modelled endogenously in a subsequent step using cost optimisation (see section 2.3).

2.2. Final energy demand scenarios

To analyse the impact of different factors on electricity demand and CO2 emissions, the annual FED per fuel is decomposed into gross domestic product (GDP), energy intensity and fuel share. In addition,

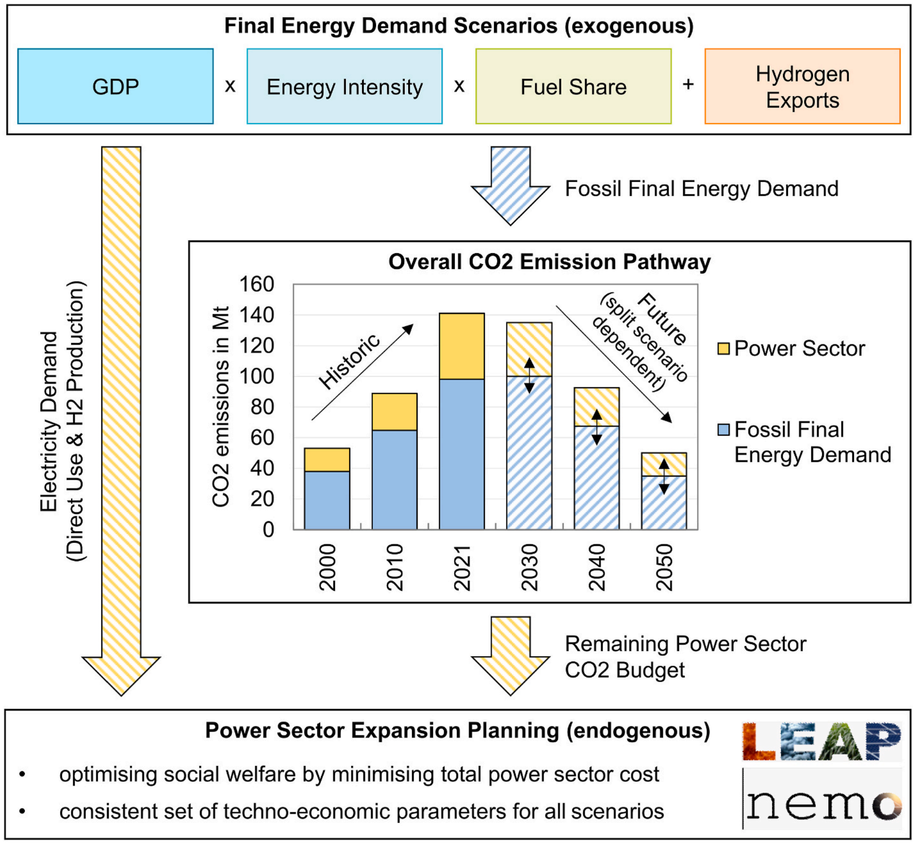

Fig. 1. Schematic overview of the scope of the modelling and the interaction between final energy demand, electricity generation and total CO2 emissions.

potential hydrogen exports are added, as they can be considered as "external FED", directly affecting the electricity demand in the exporting country. Based on the FED decomposition and the assumed hydrogen export volumes, four future scenarios are developed using historical data from 2000 to 2021 as input. Starting from the lead scenario "Ambitious Decarbonisation", in each of the three alternative scenarios one factor is reduced to a lower level of ambition, while the others remain unchanged (see Fig. 2). Each factor is described in more detail below.

The **GDP** projection as the main driver of energy demand is derived from the Shared Socio-economic Pathways (SSP) [41], a consistent set of socio-economic indicators for all countries worldwide under different climate scenarios used for the 6th IPPC Assessment Report [42] and updated by Koch and Leimbach in 2023 [43]. There are five SSPs in total, representing different global trends and covering a broad range of plausible future scenarios. For this analysis, the "Middle of the Road" pathway (SSP2) is considered, which reflects a vision with moderate socio-economic challenges for both mitigation and adaptation, where historical trends broadly continue, while taking into account the INDCs [44]. In such a future, Algeria's historical GDP growth is expected to continue, increasing from about 490 billion 2017$PPP in 2021 to almost 930 billion 2017$PPP in 2050 (see Fig. 3a).

Between 2000 and 2021, **final energy intensity** in Algeria increased from 2.39 to 3.65 MJ/2017$PPP. This trend is assumed to reverse in the future due to energy efficiency measures and a gradual decoupling of economic growth from energy demand, as observed in other countries, as economic development progresses [45]. Typical energy efficiency measures on the final energy demand side could include upgrading existing appliances to higher efficiency standards, insulating and renovating buildings, or installing heat recovery systems to reuse waste heat from industrial processes. In the "Ambitious" trajectory, this effect is assumed to be more pronounced and to start earlier, resulting in a 54 % reduction in energy intensity by 2050 compared to 2021. In the "Lower Energy Efficiency" scenario, the effect is less prominent and leading to an overall decrease in energy intensity of 35 % by 2050 (see Fig. 3b).

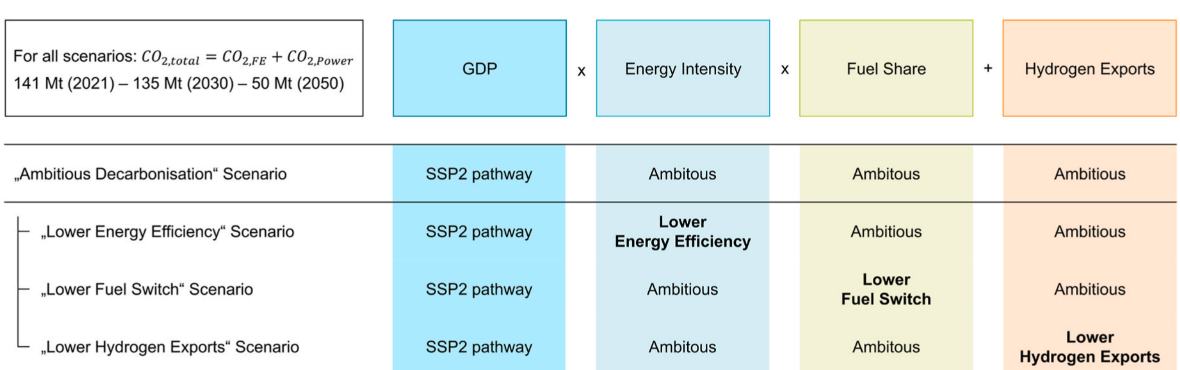

Fig. 2. Graphical representation of the scenario design and the different investigated influencing factors.

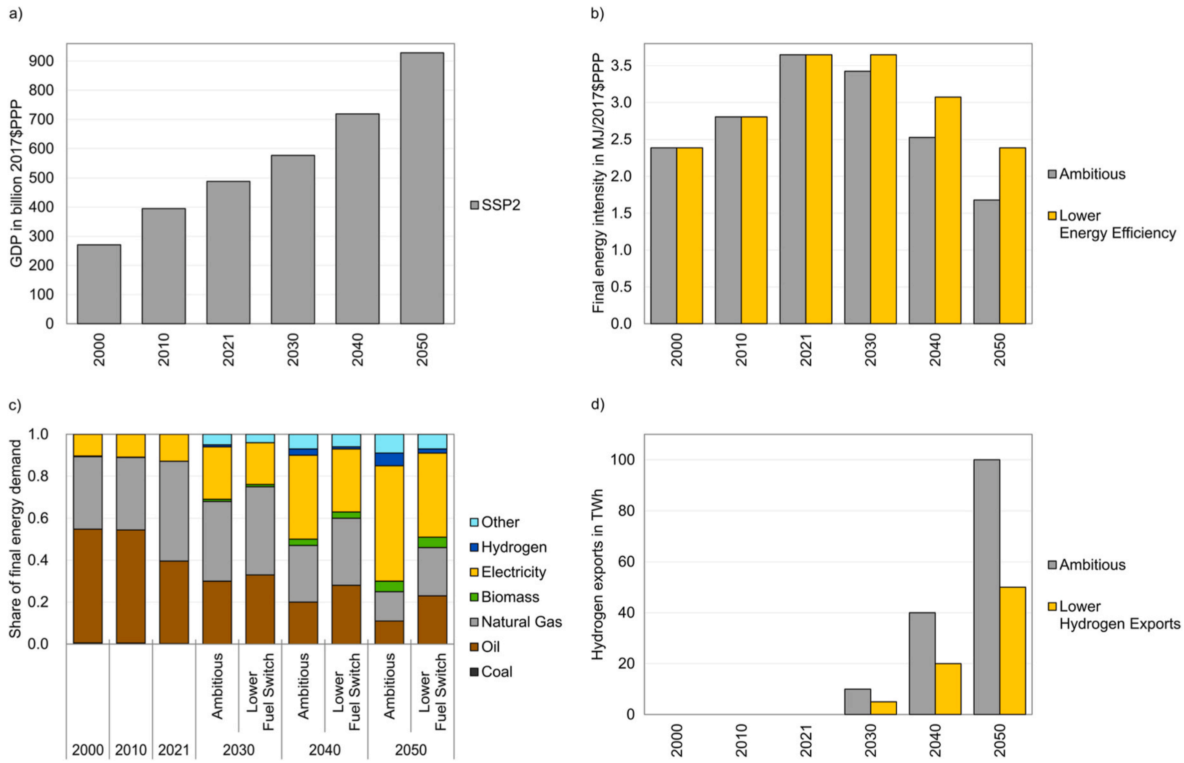

Fig. 3. Development of Algeria's a) GDP, b) final energy intensity, c) fuel shares and d) hydrogen exports between 2000 and 2050 with historical data and future trajectories based on data from Refs. [19,41,47–49] and own assumptions.

The assumed **fuel shares** for the future scenarios are based on the World Energy Outlook 2022 of the International Energy Agency [46] with country-specific adjustments derived from historical data. Historically, oil has been the dominant fuel, followed by natural gas and electricity. As a result of assumed technological changes, such as battery electric vehicles in the transport sector, the share of electricity is expected to rise sharply to 55 % by 2050 on the "Ambitious" path, while the share of oil and natural gas decreases to 11 % and 14 %, respectively. The rest of the FED is met by biomass (5 %), hydrogen (6 %) and other renewable fuels (9 %), such as ambient and solar heat. The "Lower Fuel Switch" scenario assumes a slower transition to renewable fuels in end-use applications, resulting in a higher remaining share of oil (23 %) and natural gas (23 %) in 2050 and thus higher final energy-related CO2 emissions. Domestic use of hydrogen, for example in industrial applications or heavy-duty transport, plays a minor role compared to electricity in both trajectories. In particular in the "Lower Fuel Switch" scenario, which assumes a smaller technology shift from natural gas and oil to hydrogen compared to the "Ambitious" pathway, the role of hydrogen remains small at 2 % of FED in 2050 (see Fig. 3c).

The last varied parameter is the national **hydrogen export target**. For the "Ambitious" case, the amount of exported hydrogen increases gradually from 0 TWh in 2025 to 10 TWh in 2030, 40 TWh in 2040 and 100 TWh in 2050 (see Fig. 3d). This is in line with Algeria's hydrogen strategy that aims to export 30–40 TWh in 2040 which would cover 10 % of the European demand for clean hydrogen [47]. The value for 2050 is estimated based on the total European hydrogen demand projections from Refs. [48,49] in combination with an Algerian market share of about 10 %. The "Lower Hydrogen Exports" scenario assumes that future export volumes are only 50 % of the "Ambitious" values, which in turn reduces electricity demand and thus the additional renewable energy capacity required. The local demand for hydrogen described above is not affected by the different hydrogen export trajectories.

2.3. Power sector expansion planning

In a subsequent step, the expansion planning of the power sector is done with the objective of increasing social welfare by minimising the sum of the total power system costs over all years, while complying with all defined constraints. This primarily means that electricity demand must be met at all times without exceeding the defined annual CO2 budget. To this end, different generation and storage technologies can be installed, dispatched and decommissioned over the entire period. The open source solver HiGHS [50] is used to solve the underlying linear optimisation problem [51] in order to enable a high degree of reproducibility of the methodology without financial barriers.

To account for daily and seasonal variations in electricity demand and supply, the model has a temporal resolution of 288 time slices per year, corresponding to one reference day per month of 24 h each. The share of self-consumption and transmission and distribution losses in the electricity system is assumed to decrease linearly from 24.4 % in 2021 [19] to 12.0 % in 2050. Power plant capacities that already exist or are currently under construction are taken into account as exogenous input in the modelling, based on data from the Statistical Bulletins of the Arab Union of Electricity [52], the Global Energy Monitor [53] and IRENA [54]. It is assumed these capacities will be decommissioned at the end of their technical lifetime. The resulting evolution of exogenously specified power plant capacity, given to the model as available in each year, is shown in Fig. 4.

Natural gas turbines dominate the current power system and their installed capacity increased strongly over the last years. Based on the age structure and assuming that no new capacity is added beyond the plants currently under construction, the last existing fossil-fuel power plants in the system would phase-out between 2040 and 2045. However, the optimisation still allows for the endogenous installation of new fossil power plants if all constraints are met, resulting in a lower total system cost. All natural gas turbines installed until 2021 are referred to as "existing" and retain the efficiencies calculated from historical data. Capacities currently under construction and power plants that may be

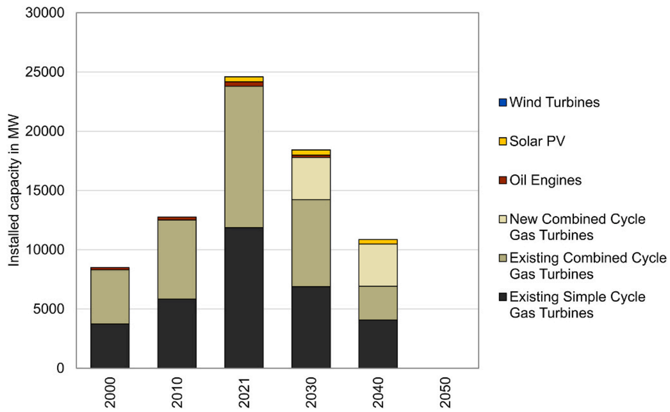

Fig. 4. Development of Algerian power plant capacity exogenously available to the model between 2000 and 2050, based on the age structure of power plants in operation and under construction, assuming decommissioning at the end of technical lifetime (own compilation based on [52–54]).

added endogenously by the model in the future (see results in section 3.2) are labelled as "new" and have updated techno-economic parameters based on [55], which translate into efficiency gains in electricity generation due to higher thermal efficiencies of new gas turbines. For renewable electricity supply, solar PV and wind turbines are considered using open-source time series from renewables.ninja [56–58]. In addition, the model also includes batteries and hydrogen as options for short-term and seasonal electricity storage. Following the approach of Elberry et al. [38], the seasonal hydrogen storage module is modelled by combining the techno-economic parameters of electrolysers for hydrogen production, salt caverns for physical hydrogen storage and hydrogen turbines for electricity generation. All hydrogen, both for domestic use and for export, is assumed to be produced by electrolysis. To account for future developments in the efficiency of electrolysis, the efficiency is increased from 60 % in 2020 to 75 % in 2050. Further techno-economic data can be found in Table A 1 in the appendix, which is attached as a separate supplementary file, and in the extensive supplementary data set, which is openly available on Zenodo [59].

3. Results

The results section is divided into two main parts. First, the estimates of FED development and then the expansion of the power sector are presented.

3.1. Final energy demand

Algeria's FED has increased sharply from 179 TWh in 2000 to 494 TWh in 2021 (see Fig. 5). For the assumed "Ambitious" energy intensity trajectory, this trend slows down and peaks around 2030 at 549 TWh and then declines to 429 TWh by 2050. For the "Lower Energy Efficiency" scenario, on the other hand, the FED continues to increase until 2040 (614 TWh) and reaches 609 TWh in 2050. The "Lower Fuel Switch" scenario leads to the same total FED as the "Ambitious Decarbonisation" and the "Lower Hydrogen Export" scenario. However, the fuel distribution is different here due to the assumed slower technological transition, which leads to a higher remaining demand for natural gas (100 TWh) and oil (100 TWh) in 2050, while the demand for electricity and hydrogen is lower. In contrast, the fuel split in the "Lower Energy Efficiency" scenario is the same as in the "Ambitious Decarbonisation" scenario, but with an overall higher FED, resulting in higher demand for both fossil and renewable fuels. The historically already very low FED share for coal (<1 %) is reduced to zero in all scenarios, resulting in no future demand for coal in Algeria.

The increased use of oil and gas in recent years has led to a rise in direct CO2 emissions from the final energy demand sectors in Algeria from 38 Mt in 2000 to 98 Mt in 2021. At the same time, the growing demand for electricity has been met mainly by building new fossil-fuel power plants (see Fig. 4), which has consequently also increased CO2 emissions from the power sector from 15 Mt to 43 Mt over the same period, resulting in overall emissions of 141 Mt CO2. For the future scenarios, a linear decrease of the total combined CO2 budget from 135 Mt in 2030 to 50 Mt in 2050 is assumed (see Fig. 1). Depending on the amount of fossil final energy sources used in the respective scenarios, the remaining budget for the power sector thus varies. The second important factor for the expansion planning of the power sector (see section 3.2) is the electricity demand of the respective scenarios. In addition to the direct electricity demand for end-use applications, this also includes the indirect demand for green hydrogen production using electrolysis, both for domestic use and export. Fig. 6 therefore depicts for the different senarios the future electricity demand split by application type on the left axis together with the remaining CO2 budget ot the power sector on the right axis.

In all scenarios, electricity demand is expected to continue to grow rapidly. While it was 19 TWh in 2000 and already 64 TWh in 2021, the projections for direct electricity consumption range between 110 TWh ("Lower Fuel Switch") and 146 TWh ("Lower Energy Efficiency") in 2030 and even between 173 TWh and 338 TWh in 2050. The additional electricity demand for hydrogen production, including electrolysis conversion losses, rises sharply after 2030, reaching values between 101

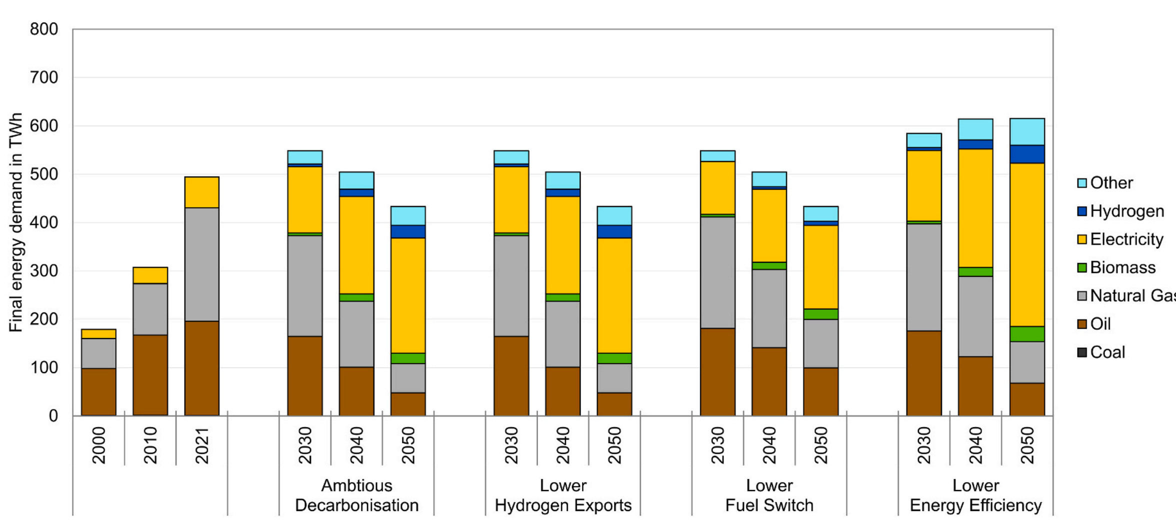

Fig. 5. Development of Algeria's final energy demand in TWh for the historical period between 2000 and 2021 and the four future scenarios until 2050.

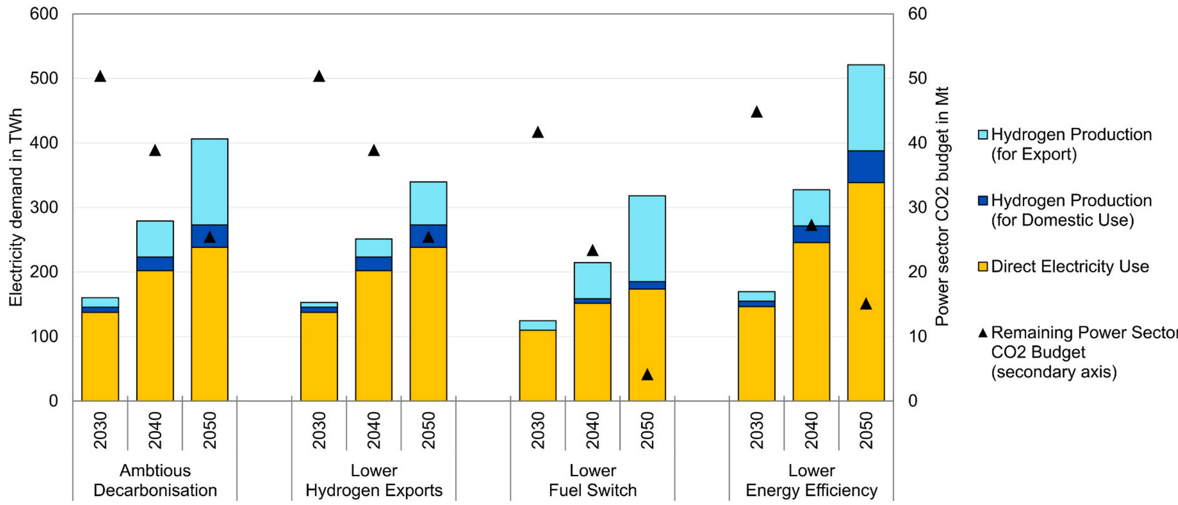

Fig. 6. Development of Algerian electricity demand in TWh, divided into direct electricity use and hydrogen production for domestic use and export (stacked bars, left axis), together with the remaining power sectorr CO2 budget in Mt (black triangle, right axis) for the four scenarios in the years 2030–2050.

TWh ("Lower Hydrogen Exports") and 183 TWh ("Lower Energy Efficiency") in 2050, with exports exceeding domestic consumption in all scenarios. The future electricity demand for hydrogen exports alone could be more than twice the total electricity demand in 2021 and account for 20–42 % of the total electricity demand in 2050. While the "Ambitious Decarbonisation" and the "Lower Hydrogen Export" scenarios show the fastest reductions in final energy-related CO2 emissions, the "Lower Fuel Switch" scenario leads to the highest levels of CO2 emissions from end-use sectors. Thus, the remaining CO2 budget for the power sector is lowest in this scenario, which in turn increases the pressure on a faster energy transition in the power sector.

3.2. Power sector

The results of power sector expansion planning for the "Ambitious Decarbonisation" scenario are shown in Fig. 7. Electricity generation is expected to increase more than fivefold between 2021 and 2050, reaching 476 TWh. The values for generation are generally higher than the demand shown in Fig. 6, as they also take into account self-consumption and losses. The total installed capacity increases from 23 GW in 2021 to 58 GW in 2030 and 276 GW in 2050. While the capacity of gas turbines remains relatively constant until 2040 and then decreases slightly, mainly solar PV in combination with battery storage is expanded to meet the growing electricity demand. Between 2030 and 2040, 67 GW of solar PV and 22 GW of battery storage are added, corresponding to a compound annual growth rates (CAGR) of 14.1 % and 28.0 %, respectively. In the following ten years, another 81 GW of solar PV and 29 GW of battery storage is installed, resulting in total installed capacities of 173 GW solar PV and 53 GW battery storage. In addition, there are 28 GW of wind turbines in the system in 2050, which are added relatively evenly over the entire period. To put this into perspective, Germany added 36 GW of solar PV and 28 GW of wind turbines between 2010 and 2020, with CAGRs of 11.5 % and 7.3 % respectively. China, the country with the strongest expansion, achieved CAGRs of 76.5 % and 24.9 %, installing 252 GW of solar PV and 243 GW of wind turbines over the same period [54].

Seasonal hydrogen storage in caverns is only needed after 2040 and has a storage capacity of around 2 TWh in 2050, which corresponds to around 4 GW power assuming 500 storage full load hours. Electricity generation from fossil power plants peaks around 2030, though the split between simple and combined cycle gas turbines changes over time. In 2030 and 2040, mainly newly built combined cycle gas turbines (CCGT) are used, as they exhibit higher efficiencies and thus lower specific fuel consumption and emissions. Between 2040 and 2050, the share of new single cycle gas turbines (SCGT) increases due to their higher flexibility as well as lower CAPEX and fixed OPEX, making them more economical

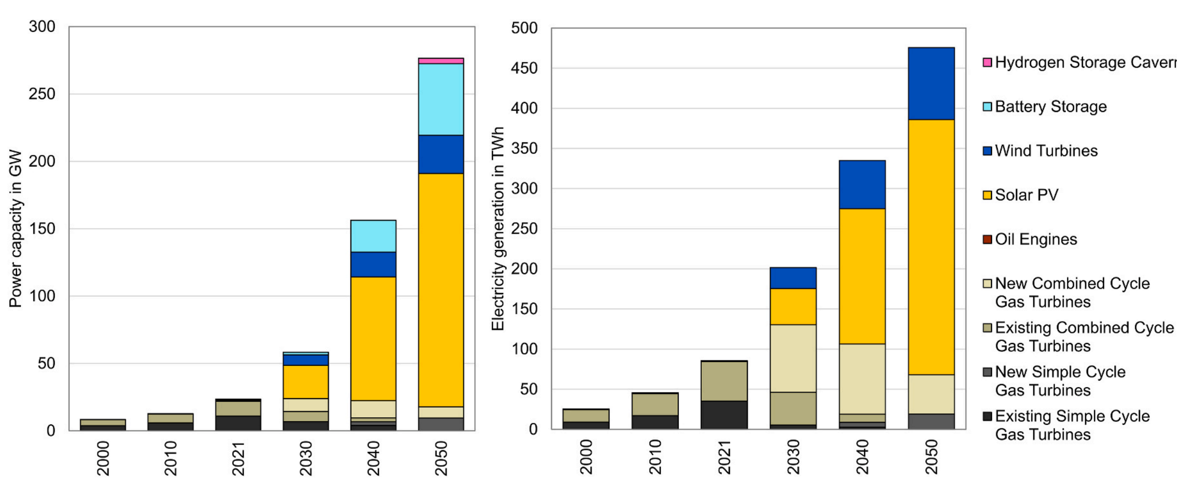

Fig. 7. Development of the Algerian power sector expansion between 2000 and 2050 for the "Ambitious Decarbonisation" scenario in terms of installed capacity in GW (left) and electricity generation in TWh (right) split by technologies.

than CCGT at lower operating hours. The total share of renewables in electricity generation increases from less than 1 % in 2021 to 35 % in 2030 and 86 % in 2050, largely dominated by solar PV especially in the long term.

The effects of the scenario variations on the power sector expansion are shown in Fig. 8 as difference to the "Ambitious Decarbonisation" scenario in terms of installed capacity and electricity generation. For the "Lower Hydrogen Exports" scenario, solar PV and battery capacity decreases by 53 GW and 9 GW, respectively, in 2050, while 5 GW of additional wind capacity is installed. This is also reflected in the electricity generation with 99 TWh less from PV and 15 TWh more from wind power plants, which can be explained by the reduced use of electrolysers, which mainly follow the availability of PV and thus influence the overall system load. In terms of fossil power capacity and generation, there are no substantial changes between the two scenarios. This is different in the "Lower Fuel Switch" scenario. Here, in particular, generation from fossil fuels is lower over the entire period compared to the "Ambitious Decarbonisation" Scenario. In 2050, 16 TWh (SCGT) and 42 TWh (CCGT) less electricity is generated using natural gas. As total electricity demand is lowest in this scenario, renewable electricity generation, mainly from solar, is also reduced. To compensate for the reduced use of flexible gas turbines due to the stricter CO2 constraint, the need for electricity storage increases. Therefore, additional seasonal hydrogen storage is installed, increasing the total capacity by35 % compared to the "Ambitious Decarbonisation" scenario in 2050. In addition, more wind turbines are also installed, albeit with higher curtailment rates, while PV and new gas turbines are installed less. The "Lower Energy Efficiency" scenario leads to the highest overall electricity demand and thus also to the strongest capacity addition. As the remaining CO2 budget for the power sector is lower compared to the "Ambitious Decarbonisation" scenario, generation from fossil fuels is reduced. Besides the stronger installation of PV and wind turbines, this is also compensated by additional electricity storage, both short-term (battery) and seasonal (hydrogen).

Compared to 2021, the specific costs of the power sector, given in constant 2021 USD per MWh, grow until 2050 for all scenarios (see Fig. 9). However, there is some initial decline in specific costs in all scenarios up to 2030, except the Lower Energy Efficiency scenario, due to the gradual integration of renewables replacing older and inefficient gas turbines. In the loner term, the "Ambitious Decarbonisation" scenario shows the smallest increase with +5 % and +9 % for the years 2040 and 2050, respectively, and a final value of 42 USD/MWh. The "Lower Hydrogen Export" scenario leads to only slightly higher costs, while the "Lower Fuel Switch" and "Lower Energy Efficiency" scenarios show substantially higher values, especially in the long run. While in 2040 the "Lower Energy Efficiency" scenario has the highest specific costs of 46 USD/MWh, in 2050 the "Lower Fuel Switch" scenario is with 58 USD/MWh even more than 14 % higher than the "Ambitious Decarbonisation" scenario. Both scenarios have higher shares of storage costs and lower shares of fossil power plant costs. This illustrates very well the challenge for countries with very low fossil fuel prices. Even if the LCOE of renewable technologies is cheaper than that of fossil technologies, their system integration causes additional costs for storage and curtailment due to their weather-dependent fluctuations in availability. This is especially true for electricity systems with a very high share of renewable generation, as it is the case for the "Lower Fuel Switch" scenario (97 %) and the "Lower Energy Efficiency" scenario (94 %) in 2050.

4. Discussion and conclusions

In this paper we analyse the impact of different factors, namely energy efficiency, fuel switching in end-use applications and the export of green hydrogen, on the local energy transition in developing economies, using Algeria as a case study. While the total CO2 budget is always the same, the distribution of emissions between end-use applications and the electricity sector varies depending on the scenario. Both the methodology and parts of the results could be transferred to other countries that may be following a similar path. This includes other fossil fuel exporters, but also countries that want to become hydrogen exporters without being fossil fuel producers today (e.g. Morocco). To facilitate the reproducibility of the methodology, freely available data sources and solvers have been used, and both model inputs and results are openly available as extensive supplementary material on Zenodo [59]. The developed approach contributes to broadening the scope of energy system modelling with LEAP by including hydrogen exports as an increasingly important policy aspect and linking it to other factors such as energy efficiency and fuel switching in end-use applications as well as cost-optimal power sector planning. Depending on the scenario, electricity demand and fossil final energy-related emissions differ, which affects the required installed capacities (see Table 1) and specific power sector costs (see Table 2). Five key findings derived from this are

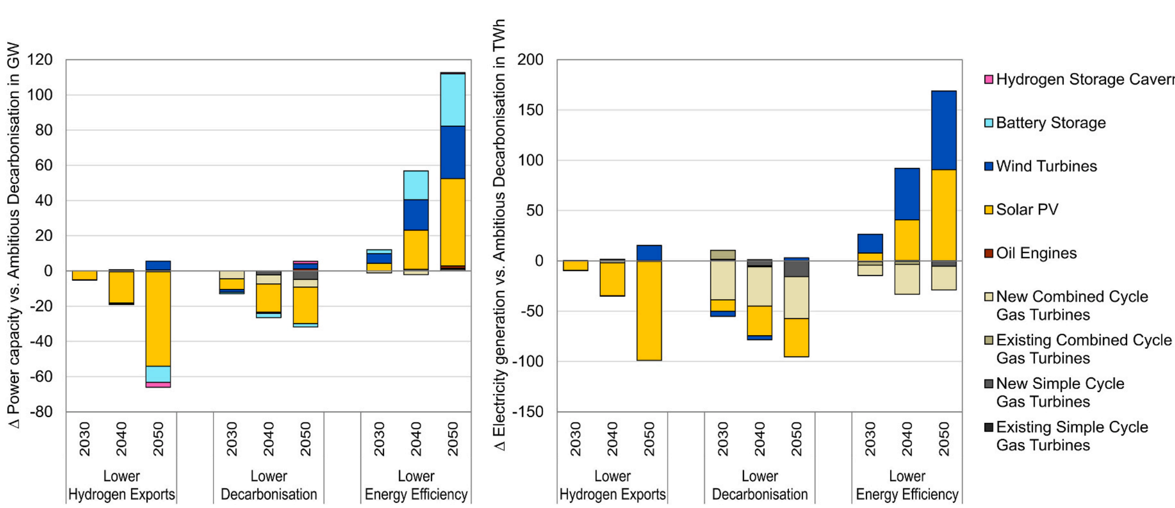

Fig. 8. Development of the Algerian power sector expansion between 2030 and 2050 for the three scenarios "Lower Hydrogen Exports", "Lower Fuel Switch" and "Lower Energy Efficiency" shown as difference to the "Reference" scenario in terms of installed capacity in GW (left) and electricity generation in TWh (right), split by technologies.

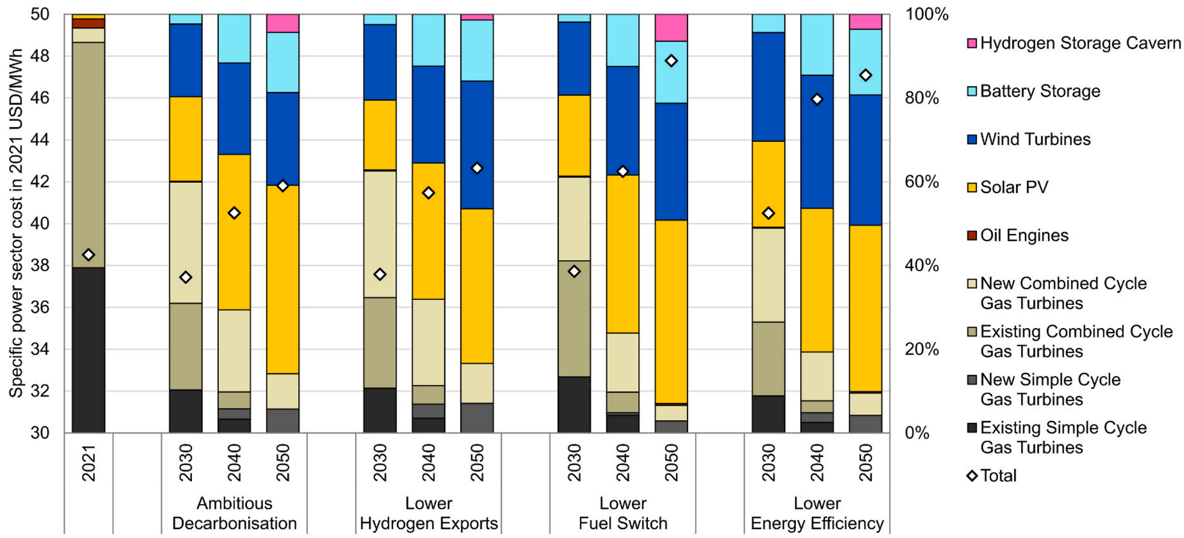

Fig. 9. Development of specific costs of the power sector in constant 2021 USD/MWh (diamond, left axis) for the historical year 2021 and the four future scenarios until 2050, including a breakdown of cost shares by technology in percent (stacked bars, right axis).

Table 1
Summary of the change in installed capacity of solar PV, wind turbines and gas turbines for the different scenarios between 2021 and 2050, given in GW and as compound annual growth rate.

Change in installed capacity (absolute in GW/CAGR in %) 2021–2050	Ambitious Decarbonisation	Lower Hydrogen Exports	Lower Fuel Switch	Lower Energy Efficiency
Solar PV	+173/+23.0 %	+119/+21.5 %	+152/+22.5 %	+222/+24.1 %
Wind turbines	+28/+31.5 %	+33/+32.3 %	+31/+32.0 %	+58/+34.8 %
Gas turbines (SCGT & CCGT)	−5/−0.8 %	−5/-0.8 %	−14/-3.3 %	−3/−0.6 %

Table 2
Summary of the change in the specific costs of the power sector for the different scenarios between 2021 and 2050, given in absolute (2021 USD/MWh) and relative (%) terms.

Change in specific power sector cost 2021–2050	Ambitious Decarbonisation	Lower Hydrogen Exports	Lower Fuel Switch	Lower Energy Efficiency
Absolute in 2021 USD/MWh	+3.3	+4.1	+9.3	+8.6
Relative in %	+8.6 %	+10.7 %	+24.1 %	+22.3 %

presented and discussed below.

The required strong capacity expansion for PV and wind is challenging, but feasible. Under the assumed overarching emissions pathway with significant CO2 reductions by 2050, the installed capacity of renewable power plants increases strongly in all scenarios. The expansion of solar PV is particularly high, replacing gas turbines as the dominant power generation technology in all scenarios between 2030 and 2040. Although the expansion of wind turbines is lower in absolute terms, the required annual growth rates are even higher than for solar PV, as only 10 MW of wind turbines were installed in Algeria in 2021. This poses substantial challenges, especially in the ramp-up phase, as there is little to no experience from existing projects to build on. In the “Ambitious Decarbonisation” scenario, the CAGR of solar PV and wind turbines between 2021 and 2050 is 23.0 % and 31.5 %, respectively. By comparison, Germany achieved a CAGR of 33.6 % and 10.8 % for the same technologies between 2000 and 2022, while the values for China were 61.4 % and 36.8 % respectively [54]. These figures clearly show that such an expansion of RE is ambitious, but certainly feasible. However, strong political support is needed to encourage early development.

“Energy efficiency first” benefits both the local energy transition and H2 exports. The challenges described above for the expansion of RE increase even more in the “Lower Energy Efficiency” scenario. On the one hand, the higher demand for electricity requires a faster expansion of electricity generation capacities. On the other hand, the higher final energy-related CO2 emissions limit the remaining budget for the electricity sector and therefore require a stronger and faster phase-out of fossil-fuelled power plants. Taken together, this results in an additional need for 29 % more solar PV plants and even 105 % more wind turbines by 2050. As their system integration implies a further expansion of storage capacities and in some cases a stronger curtailment of renewables, the specific costs of the power sector increase compared to the “Ambitious Decarbonisation” scenario. A reduction in FED through efficiency improvements could therefore not only support the local energy transition, but also unleash further potential for hydrogen exports, both in terms of economic resources and the actual expansion of renewable power plants. Feasible energy-saving measures should therefore be promoted and incentivised through specific policy measures and financial support. Efficiency improvements should also be targeted on the generation side. In particular, increasing the efficiency of water electrolysis can be an important lever.

Fully renewable power systems require a suitable political framework. In the long term, the “Lower Fuel Switch” scenario leads to the highest specific costs (see Table 2), illustrating that the slower electrification of end-use applications only supposedly relieves the pressure on the power sector. Although the reduced electricity demand leads to slightly lower PV addition rates, the remaining CO2 budget for the power sector, which is limited by the higher final energy-related emissions, requires the highest seasonal storage demand and the strongest renewable curtailment of all scenarios in 2050. It therefore makes sense to consider the decarbonisation of end-use applications and the power sector in parallel and to first pick the "low-hanging fruits" in all sectors in order to reduce overall emissions as efficiently as possible. The results also show that even in the long term, despite falling costs for renewable power plants and storage, an electricity system with a very high proportion of RE (>95%) is unlikely to materialise for purely economic reasons if cheap natural gas without CO2 pricing is available. It is important to analyse the reasons for this and to address any structural barriers. Direct subsidies for fossil fuels should be reduced, and possible opportunity costs arising from using domestic fossil resources at marginal cost instead of selling them on the international market should also be critically examined. The resulting financial savings and additional revenues from a potential carbon price could instead be used to support the energy transition.

Higher hydrogen exports might help to reduce the specific power system cost. Halving hydrogen exports from 100 to 50 TWh in the "Lower Hydrogen Exports" scenario has two main effects. First, the installed solar PV capacity in 2050 is reduced by 31 % (54 GW), which means that the required annual expansion rates are slightly lower. Second, the specific costs of the power sector increase by 2 % in 2050 compared to the "Ambitious Decarbonisation" scenario. The results therefore suggest that the integration of higher hydrogen exports into the power system and the resulting load shift towards hours with high PV generation could be favourable for the specific costs of the power sector. This should be analysed in more detail in further studies, with a stronger focus on the system integration of electrolysers and the interaction with other sector coupling technologies. If the findings are confirmed, the question remains as to whether the additionally required expansion rates can be realised and to what extent it can be ensured that the development of an export-oriented hydrogen economy actually promotes the decarbonisation of the power sector and does not hinder it.

Fossil capacity expansion must be stopped to avoid lock-ins and higher future costs. While renewable power plants and storage capacity are expanded strongly in all scenarios, the installed capacity of fossil-fuelled power plants initially remains largely constant and declines more or less rapidly in the long term. In the future, the historically observed strong expansion of fossil power plants should therefore be stopped and new gas turbines should only be used very carefully to modernise the existing power plant fleet. Particular attention should be paid to ensuring high flexibility and low operating costs at limited full load hours. Ideally, the possibility of retrofitting new gas-fired power plants to run on hydrogen is already considered at the planning stage. Otherwise, there is a risk of fossil lock-in effects and stranded assets, which would lead to higher costs for achieving emission reduction in the long term.

In this study, we have not included nuclear power plants in the power sector planning as they are subject to many uncertainties. Several examples from other countries in recent years show that the construction of nuclear power plants often took much longer and was more expensive than originally planned [60,61]. In Algeria itself, the use of nuclear power plants has been under discussion for some time, although the planned implementation dates have been repeatedly postponed indefinitely [62]. In the long term, next-generation fission power plants, particularly small modular reactors, and later perhaps fusion power plants, could be promising options for clean energy generation without the drawbacks of today's nuclear power plants. However, these are not yet technologically mature and therefore not an immediate option for Algeria's energy transition. From today's perspective, the preference for renewable power plants such as solar PV and wind turbines, which are faster and cheaper to build, appears to be the more viable and sensible way to decarbonise the power sector.

Another issue is the availability of sufficient freshwater for green hydrogen production. Tonelli et al. [63] analyse the water requirements for different global hydrogen demand scenarios at the country level and compare the results with the available freshwater resources. They show that the water requirements for electrolytic hydrogen production are generally small compared to current water withdrawals for agriculture, industry, and municipalities. For a global hydrogen demand of 400 million tons in 2050, the additional water demand would be less than three percent of today's level. However, they also show that there are countries, including Algeria and other MENA countries, that are already exceeding their sustainable domestic water resources without green hydrogen production. Especially for these countries with limited freshwater resources, the use of seawater desalination could be an alternative. In terms of additional electricity demand and cost, the impact would be modest, with values of 3–4 kWh/m3 and less than USD 1/m3 of desalinated water [64], which corresponds to less than 2% of the levelized cost of hydrogen [63]. However, this approach would require either the installation of electrolysers near the sea or the construction of freshwater pipelines to the production site. The environmental impact of brine disposal and potential water use conflicts between hydrogen production and other uses must also be considered. Therefore, it seems advisable to take an integrated view of future water supply planning for countries with high renewable potential but scarce water resources. A recent study by Riera et al. [64] shows that combining the planning of renewable power and desalination plants could be beneficial for the overall water-electricity nexus, as reverse osmosis plants could serve as flexible loads applicable for demand-side management.

Most of these findings apply not only to Algeria, but also to other countries that currently have a high proportion of fossil fuels in their energy system. However, there are of course specific characteristics that influence the results. In further case studies, this could be analysed in more detail with regard to the development of the population and GDP, the structure of the existing power plant fleet, the costs of fossil fuels and the RE potential in other potential hydrogen exporting countries. With regard to hydrogen production, all considerations in this paper focus exclusively on water electrolysis using renewable electricity. However, blue hydrogen produced by steam methane reforming with CCS is currently being increasingly discussed, especially as an option in the ramp-up phase [7,65]. For gas-exporting countries such as Algeria, this would naturally be an interesting option, especially given the fact that many fossil exporters are comparatively poorly positioned in the manufacturing of relevant technology components and would therefore be heavily dependent on technology imports for green hydrogen production [66]. However, the extent to which blue hydrogen is really only a bridging technology to green hydrogen, or whether the use of natural gas in combination with CCS will remain cheaper even in the long term, is questionable from an economic point of view [67]. This in turn raises further questions about sustainability [68,69] as well as the political and social acceptance of using CCS for fossil emissions, in particular in hydrogen importing countries with climate neutrality targets. Future research could address these aspects and investigate the extent to which blue hydrogen will compete with green hydrogen as an export commodity in Algeria and other natural gas producers in the future.

CRediT authorship contribution statement

Viktor Paul Müller: Conceptualization; Data curation; Formal analysis; Methodology; Software; Validation; Visualization; Writing - original draft; Writing - review & editing.

Wolfgang Eichhammer: Conceptualization; Methodology, Supervision; Writing - review & editing.

Detlef van Vuuren: Conceptualization; Methodology, Supervision; Writing - review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used DeepL in order to improve the language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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