Morocco's Coal to Clean Journey: Optimised Pathways for Decarbonisation and Energy Security

Natasha Harland (natasharland@gmail.com)
Imperial College London
Malte Jansen
Imperial College London, University of Sussex
Rudolf Yeganyan
Imperial College London, Loughborough University
Naomi Tan
Imperial College London, Loughborough University
Carla Cannone
Imperial College London, Loughborough University
Mark Howells
Imperial College London, Loughborough University

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Abstract

Morocco depends on imported fossil fuels for 90% of its primary energy supply. This makes the country vulnerable to unstable fuel prices and supply cut-offs, and the reliance on fossil fuels releases CO_2 emissions which contribute to climate change. Renewable energy expansion, facilitated by Morocco's high potential for solar and wind capacity, could allow the country to improve its energy security and decarbonise its energy system, in line with its response to the Paris Agreement.

This study uses OSeMOSYS (the Open Source Energy Modelling System) to produce six cost-minimised decarbonisation scenarios for Morocco that consider energy independence. The results show that Morocco can achieve most of its decarbonisation targets through bulk wind and solar energy, with a coal phase-out being possible by 2031 at the latest. Natural gas is replaced by biomass and nuclear energy, with some evidence that fuel imports may stay relevant for the foreseeable future.

We conclude with policy recommendations. The study can provide insights for policymakers and stakeholders in Morocco's energy sector to achieve optimal pathways for decarbonisation.

Introduction

Morocco's energy supply is reliant on imported fossil fuels for 90% of its primary energy supply, making Morocco highly susceptible to international price shocks and supply volatility (IEA, 2019a; Vidican-Auktor, 2017). This vulnerability was particularly highlighted when Algeria halted its natural gas exports to Morocco in 2021 due to geopolitical tension over the governance of Western Sahara (Slimani & Orihuela, 2022).

In addition to import dependence, Morocco's energy system is also highly carbon intensive. Coal generates 68% of electricity in Morocco, emitting approximately 880 g CO_2/kWh_{el}. and annual energy-related CO_2-equivalent emissions are approximately 67 Mt (1.8 t_{CO2}/a per capita) (Climate Watch, 2019; IEA, 2022). Furthermore, Morocco is particularly vulnerable to the effects of climate change, with drought, extreme temperatures and flooding already affecting the country (Schilling *et al.*, 2012; World Bank, 2022b; Driouech *et al.*, 2021). This provides an important incentive for the country to switch to a low-carbon renewable energy system.

Morocco is rich in renewable energy resources, particularly wind and solar power (Bouabid, Sleptchenko & Mouline, 2019). 'Decarbonising' the energy system by retiring fossil-fuel power plants and expanding renewable energy power production could allow Morocco to decrease its imported fuels while reducing its greenhouse emissions. Morocco recognises this opportunity and it has implemented decarbonisation targets in its Nationally Determined Contribution (NDC) to the Paris Agreement (see Background section) (Royaume du Maroc, 2021).

Although many studies have focused on the impact of decarbonising Morocco's energy system, none have explored the pathways to improving energy security. Here, energy security is defined as stable and affordable energy, whilst considering decarbonisation targets. This study identifies the least-cost pathway for Morocco's energy system under energy security constraints and meeting its NDC decarbonisation targets. In addition, we explore the difference between energy independence (producing all energy domestically) and diversified dependence (diversifying fuel imports) with regard to Morocco's energy security.

The least-cost optimisation energy modelling tool OSeMOSYS (the Open-Source Energy Modelling System) is used (Howells *et al.*, 2011). It allows the creation of long-term least-cost pathways and the input of constraints on emissions, fuels, power production and infrastructure expansion. The study's scope is restricted to Morocco's energy system from 2015–2065, including the cooking and high heat sectors, excluding transportation. The full list of constraints and detailed description of the methodology for this paper is documented in the accompanying Zenodo repository: 'CCG: Morocco Coal to Clean Scenarios' (https://doi.org/10.5281/zenodo.7772178) (Harland, 2023).

We find that Morocco's decarbonisation targets (decreasing carbon emissions to 75 Mtons and reaching renewable electricity generation targets) are achievable at minimal additional cost to a least-cost projected pathway, whereas a fossil-fuel-dominant energy system would raise total costs by US 2019 $159 billion above a least-cost system by 2065. Pursuing energy security in addition to decarbonisation by transitioning to an independent energy system will have the second lowest total costs, predominantly by reducing primary fuel imports and rapidly expanding wind and solar production to reduce variable fuel costs. A '*Gas Diversification*' pathway, in which Morocco retains natural gas as a baseline energy source and pays US 2019 $5/GJ more to diversify its natural gas imports also results in low total costs while allowing Morocco to meet its decarbonisation targets.

Background

Morocco's Energy System

Morocco's final energy consumption in 2019 (the latest year for which detailed data are available) was approximately 194 TWh (700 petajoules) (IEA, 2019b). Morocco imports 90% of its primary energy supply to meet this demand (IEA, 2019a). Morocco imports coal predominantly from Russia and the USA, and oil from Algeria and the USA (Preston, 2021; OEC, 2020). Prior to 2021, Morocco imported approximately 70% of its natural gas from Algeria, but a diplomatic dispute halted the export of gas from Algeria to Morocco in late 2021 (Slimani & Orihuela, 2022). Spain has now reversed the flow of gas through the Maghreb–Europe pipeline, exporting regasified liquid natural gas (LNG) of non-Algerian and non-European origin to Morocco (as stated by the Minister for

Energy Transition) to Morocco (Redondo, 2022). Morocco is in discussion with Nigeria to build a Nigeria–Morocco Gas Pipeline Project (NMGP) to import natural gas, although construction has not yet begun (Offshore Technology, 2022).

Additionally, Morocco is the leading country in Africa for electricity access,with 99.9% of its population of 37 million people connected to electricity (from 56% in 1995) (IEA, 2019a; World Bank, 2019; 2020.). Morocco has historically imported the majority of its electricity from Spain and Algeria, but since 2019 it has been a net exporter of electricity to both countries (Bentaibi & Pape, 2021). Morocco and Spain are planning an additional interconnector by 2026. Together with the UK, the country is planning an interconnection of 3.6 GW to export renewable electricity from Morocco to the UK by 2027 (Pappis *et al.*, 2019; Power Technology, 2022). Electricity provided 33 TWh of energy for industrial, residential, and commercial use in Morocco in 2019 and the breakdown by source is shown in Figure 1 (IEA, 2019c). Renewable energy sources generated 18% of electricity in total (IEA, 2019c).

Table 1: Morocco's renewable energy targets as a percentage of total energy generation (Royaume du Maroc, 2021)

Renewable Energy Technology	2030 target	2040 target	2050 target
Solar	20%	20%	20%
Wind	20%	20%	20%
Hydropower	12%	12%	12%
Nuclear	No target	No target	No target
Biomass	No target	No target	No target
Total	52%	70%	80%

Morocco has some of the most ambitious climate targets in Africa. Its conditional Nationally Determined Contribution (NDC) to the Paris Agreement was updated in 2021, and it is dependent on receiving international financial aid of US 2021 $21.5 bn (Royaume du Maroc, 2021). The energy-specific decarbonisation targets included in this study are as follows: a pledge to build no new coal plants (since 2021), meet renewable power generation targets (Table 1) and meet a CO_2 emissions reduction target of 45.5% below a business-as-usual baseline scenario (Royaume du Maroc, 2021; Jones, 2021).

Modelling of Morocco's Energy System: Literature Review

Schinko *et al*. (2019) modelled the financial feasibility of renewable energy pathways for Morocco using the open-access renpassG!S model and insights from a stakeholder workshop. Their results show that a 100% renewable energy system can be feasible and cost-competitive with a fossil-fuel system, because the high capital costs would be balanced by low variable costs (Schinko *et al.*, 2019). A review of modelling studies in the Middle East and North Africa (MENA) region confirmed this finding, stating that higher renewable energy generation would lower costs and allow increased electricity exports to Europe (Brand & Blok, 2015).

Rye *et al*. (2016) used a least-cost flow-based model to determine the best strategy for Morocco to meet its decarbonisation targets in 2030. They found that significant investments in grid infrastructure would be needed to transmit the increased electricity generation, but it would be lower cost than increasing fossil fuel capacity. However, they conclude that the export potential to Europe is low because of the projected increase in demand in Morocco. Bouabid, Sleptchenko & Mouline (2019) also used a least cost model to determine the optimal generation mix in 2030 for Morocco, finding that wind will experience the largest growth in capacity in Morocco because of its high potential.

Although these modelling studies provide helpful findings on renewable energy deployment in the short term (mostly to 2030), they do not offer insight into the effects of Morocco's decarbonisation targets on energy security. As such, there is an important gap in the research for modelling the relationship between energy security and decarbonisation in Morocco, particularly past 2030.

Methodology

The scenarios were created using the Morocco Starter Data Kit Least Cost version 2 (LCv2) file (Cannone *et al.*, 2022a). Energy demand, residual capacity and technology activity and capacity limits were updated for this study, and different constraints were applied to create the six scenarios. The original data for the LCv2 file is described in Cannone *et al.* (2021; 2022a) and all updated input data and sources, the constraints applied for each scenario, and the instructions for running the scenarios on OSeMOSYS Cloud are described in the 'CCG: Morocco Coal to Clean Scenarios' Zenodo repository that accompanies this paper (Harland, 2023). The Methodology section in this paper is an abridged version of the full methodology in the Zenodo repository.

OSeMOSYS

The Open-Source Energy Modelling System (OSeMOSYS) tool was used to model the scenarios in this study and the Simple And Nearly Done (clicSAND) interface was used for easier accessibility within OSeMOSYS (Howells *et al.*, 2011; Cannone *et al.*, 2022b). OSeMOSYS is a bottom-up, cost-optimisation model used for modelling future energy supply systems, and it ensures that all energy demands and constraints are met in its solution to the scenarios (Howells *et al.*, 2011). Instructions for running the scenarios on OSeMOSYS Cloud are documented in the Zenodo repository (Harland, 2023).

Energy supply follows a linear pathway in OSeMOSYS. Energy sources (e.g., imported natural gas) are converted into fuels (e.g., natural gas) which are then converted by technologies (e.g., natural gas powerplant) to meet a certain demand (e.g., industrial high heat). This is depicted in the Reference Energy System diagram (Figure 3).

OSeMOSYS has been used in two previous studies to model Morocco's energy transition with regard to decarbonisation. Slimani *et al*. (2021a) allowed OSeMOSYS to choose the share of each renewable energy technology within the overarching NDC decarbonisation target of 52% of demand provided by renewable energy by 2030. Their results showed that wind is preferable to solar for reducing costs, and natural gas is likely to be the main fossil fuel technology providing stable energy supply into the future. Slimani *et al*. (2021b) also used OSeMOSYS to model three scenarios of renewable deployment in Morocco: a least cost scenario, a current energy strategy scenario (using current NDC decarbonisation targets) and an accelerated renewables scenario (with higher targets), observing that solar and wind will be the predominant renewable technologies in both decarbonisation scenarios.

The main limitation of OSeMOSYS is that it does not model the flexibility of its generated energy pathways or the impact on natural resources like land and water. However, the scenarios in this study can be input into modelling tools like FlexTool (which models the flexibility of different energy sources for the electricity grid) and CLEWS (Climate, Land use, Energy and Water Systems model, which models the impact of energy production on different natural resource systems) to assess these effects (Beltramo *et al*., 2021).

Modelling Input

The scenarios in this study were created using the Morocco Starter Data Kit (Cannone *et al*., 2021). The Morocco Least Cost Version 2 (LCv2) model was used as the foundation for all the scenarios (Cannone *et al*., 2022a).

Time is represented in the model as 'time slices' that split the year into 8 segments: winter day and night (December to February), spring day and night (March to May), summer day and night (June to August) and autumn day and night (September to November). The day slices represent 06:00 to 18:00 and the night slices represent 18:00 to 06:00 (Figure 2). Technology capacity factors and the split of energy demand across the year is portioned into the appropriate time slices. The available data for technology capacity factors that was used to create the Starter Data Kit file was only available to the level of granularity of four seasons (day and night), thus the time slices in the scenarios were reduced from 96 to 8 to match the detail of this data.

The energy demand for 2015–2021 was taken from the Starter Data Kit (Cannone *et al*., 2021). The projected annual growth rate of energy demand from 2022 onwards was changed to 1.5% in 2022–2050 and 1% in 2050–2070 (to reflect a reasonable balance between the current growth rate of real gross domestic product (1.1% in 2022, projected to increase to 3.6% in 2023) and population (0.5 – 1.5%, projected to decrease to 0 – 0.7% by 2050)) (World Bank, 2022a; United Nations, 2022). The percentage of each demand (residential cooking, industrial high heat, commercial electricity, etc.) within the total demand for each year were kept the same.

Transport demand was removed to allow for a more realistic investigation into energy security. It contributes approximately 35% of total final energy consumption in Morocco, which is supplied predominantly by oil imports (IEA, 2019c). The *Independence 2050* scenario requires all imported fuels to be phased out to 0 by 2050, thus requiring bio-fuelled or electric cars to completely replace diesel and gasoline cars by 2050. This was assumed to be an unreasonable assumption; thus transport was removed as a demand from all scenarios to allow for direct comparison to the *Independence 2050* scenario.

The maximum imported electricity amount was set to the 2021 level for the full time period in all scenarios except the *Independence 2050 scenario*, to remove the choice of importing more electricity to meet demand (imported electricity was constrained to 0 by 2050 in the *Independence 2050 scenario*). The exported electricity amount was also set to the 2021 level for the full time period in all scenarios except the *Independence 2050 scenario*, to represent the continuation of Morocco's geopolitical export relationships (exported electricity was reduced to 0 after 2021 to represent a fully independent energy system that only provides for local energy demands). Future planned electricity export pipelines (to Spain and the UK) were not input into the model because they will likely be dependent on private renewable energy projects being built specifically for these export purposes, and this study solely focuses on the provision of local demand and existing exported electricity demand (Africa Energy Portal, 2019; Power Technology, 2022).

Figure 3 shows the current flow of energy in Morocco as a Reference Energy System (RES), using the data from the Morocco Starter Data Kit (Cannone *et al.,* 2021). Imported energy commodities and local energy resources are listed along the left, feeding into the relevant power generators to meet demand on the right. The RES is a simplified depiction of how OSeMOSYS uses energy commodities to meet demand.

Scenarios

Six scenarios were created using the 'Morocco LCv2 SAND' file from the Morocco Starter Data Kit, from 2015 to 2065, to investigate Morocco's goals of meeting its decarbonisation targets and achieving energy security (Cannone *et al.,* 2022a; Table 2). The first three scenarios are Base scenarios, created to compare the difference between pursuing a least-cost energy system with no significant constraints (*Least Cost scenario*) with a fossil fuel-dominated energy system (*Fossil Future scenario*) and an energy system that meets Morocco's decarbonisation targets (*Decarbonisation* scenario). The other three scenarios are Security scenarios, created to compare the different ways that Morocco could achieve energy security while meeting its decarbonisation targets. These security scenarios investigate varying degrees of energy independence for Morocco; the *Gas Diversification* scenario models the diversification of Morocco's imported natural gas reliance between two differently priced commodities, the *No Gas scenario* models the effect of removing natural gas entirely from the energy system and the *Independence 2050* scenario models the removal of all imported fuels from the energy system by 2050. The full list of constraints applied are described in the Zenodo repository (Harland, 2023).

Table 2: Descriptions of the six cost-minimised scenarios created using OSeMOSYS to investigate decarbonisation and energy security in Morocco. Further information about the scenario constraints is available in the Zenodo repository (https://doi.org/10.5281/zenodo.7772178). Note that all costs are in US 2019 $.

Base scenarios	*Least Cost*	The *Least Cost scenario* has no additional constraints applied.
	Fossil Future	The *Fossil Future scenario* has a maximum energy infrastructure capacity investment constraint of 0 for all renewable energy infrastructure from 2022 onwards, except biomass. Although biomass is not a fossil fuel, it is permitted in this scenario because it releases high quantities of carbon emissions, thus it could be considered to fit into a 'Fossil Future'.
	Decarbonisation	The *Decarbonisation scenario* has a maximum capacity investment constraint of 0 on coal power plants from 2021 onwards (representing Morocco's pledge for 'no new coal' at COP26 in Glasgow, 2021) (Jones, 2021). A limit on CO_2 emissions of 75 Mt per year is added from 2030 onwards to represent Morocco's target to reduce its CO_2 emissions by 45.5% compared to an unrestricted emission trajectory (Royaume du Maroc, 2021). Morocco's renewable energy targets are added as minimum electricity generation constraints; see Table 1 in Background for details).
Security scenarios	*Gas Diversification*	All decarbonisation targets above are included. The upper restriction on imported natural gas in the model is reduced to 30% of its original consumption in the *Least Cost scenario*, from 2022 onwards. This simulates the loss of imported natural gas from Algeria in late 2021, which provided approximately 70% of the natural gas needed in Morocco (Ratcliffe & Oriheula, 2022). A secondary imported natural gas commodity is added, with a price that is US$5/GJ higher than the projected prices for the original imported natural gas commodity. This represents a more expensive LNG import that Morocco may have to rely upon to compensate for the loss in natural gas from Algeria. There is no upper restriction on the consumption of this secondary natural gas commodity. This scenario represents a 'diversified dependence' interpretation of energy security.
	No Gas	All decarbonisation targets are included. The upper activity limit on natural gas power plants and fuel is constrained to 0 from 2022 onwards, to model the effect of removing natural gas from Morocco's energy system completely.
	Independence 2050	All decarbonisation targets are included. The upper activity restriction on imported electricity decreases from its 2021 activity level by one-third each decade after 2030, reaching 0 in 2050. Exported electricity is also constrained to 0 from 2021 onwards. The upper restriction on primary fuel imports (oil products, biomass, coal, natural gas and uranium) is set to 0 from 2050 onwards. Energy-efficient technologies are allowed to operate in this scenario to reduce demand (to allow the scenario to run feasibly). This scenario examines the impact of relying on local energy generation completely, representing an 'energy independence' interpretation of energy security.

Results

Electricity generation

Figure 4 presents the annual electricity generation in each scenario and Figure 5 presents the annual capacity additions. In all scenarios except *Fossil Future* and *Independence 2050*, annual electricity generation rises to approximately 300 – 400 TWh by 2065. Electricity generation is lower in *Fossil Future* at approximately 160 TWh in 2065, suggesting that some sectors (like industrial heating or cooking) would be powered directly by fossil fuels instead of fossil fuel-generated electricity (because it is more expensive to build electrification infrastructure if it is not necessary). Generation is much higher in the *Independence 2050 scenario*, likely for the opposite reason; all sectors would need to be electrified if primary fuels cannot be used.

Our results demonstrate that almost all of Morocco's decarbonisation targets can be met. However, the hydropower target, representing 12% of electricity demand by 2040, was impossible to meet, due to low hydropower potential of 2.5 GW in Morocco. The maximum percentage of demand that hydropower could meet in Morocco was determined to be 4% (Figure 4).

In all scenarios except *Fossil Future*, coal power is phased out by 2031. Although coal generation continues until 2031 in these scenarios, the model still deems this compatible with Morocco's emission reduction target.

Similarly, wind and solar occupy extremely large shares of power generation in all scenarios except *Fossil Future*, with the largest share in the *Least Cost* scenario (because there were no flexibility limitations applied to renewable technologies in this scenario). Notably, onshore wind is prioritised over offshore wind, likely because onshore wind has cheaper capital costs and fixed costs compared to offshore wind (see Cannone *et al.,* 2021;2022a for details on technology costs). Additionally, all scenarios prefer solar photovoltaic generation (solar PV) to concentrated solar power (CSP) because solar PV generation has cheaper capital and fixed costs compared to CSP (see Cannone *et al.,* 2021;2022a for details on technology costs).

In the *Gas Diversification* scenario there is very little natural gas electricity production compared to the *Least Cost*, *Fossil Future* and *Decarbonisation* scenarios, although it is still present. This indicates that even a US$5 higher natural gas price makes biomass and nuclear cheaper for baseline power generation in the long run. Notably, CSP generates a similar share of electricity to nuclear in *Independence 2050*. This is likely because nuclear may not have time to build up to the capacity needed to fully compensate for the loss of imported fuels by 2050, due to the slower build-out rates of 0.1 GW/a assumed for nuclear than for CSP at 0.2 GW/a.

Imported primary fuel demands

Figure 6 presents the annual primary imported fuel demands in each scenario. The highest imported fuel demand is in the *Fossil Future scenario* (at 290 TWh in 2065; 179 TWh higher than the *Decarbonisation scenario* which has the next highest imported fuel demand). The lowest imported fuel demand is in the *Independence 2050 scenario* (at a maximum of 107 TWh in 2022), reflecting the extreme difference in renewable energy generation between *Fossil Future* and *Independence 2050*. *Fossil Future* imports more coal than natural gas, as the cost of imported coal is projected to be lower than natural gas into the future.

Biomass or uranium were not chosen to be imported in any scenario, as unlimited domestic production was assumed. For nuclear, Morocco is assumed to build appropriate uranium enrichment infrastructure to utilise local uranium deposits (World Nuclear Association, 2021).

Decarbonisation and *Least Cost* have remarkably similar imported primary fuel demands: both rise to approximately 100 TWh by 2065 from a minimum around 2040. The rise in imported fuels towards the end of the time period likely reflects the combination of increasing energy demand and the difficulty in fully electrifying some sectors (like industrial heating). *Decarbonisation* and *Least Cost* depend predominantly on natural gas after coal is phased out.

Although natural gas imports are not phased out completely in the *Gas Diversification* scenario, they decrease significantly after the more expensive gas import is introduced in 2022. Additionally, imports are diversified between oil and natural gas from 2030 to 2051. In the *No Gas scenario*, however, natural gas is completely replaced by imported oil, which is less efficient in power generation and heating processes than natural gas (Cannone *et al.*, 2022a). As such, the higher oil imports make the imported fuel demand in 2065 in *No Gas* significantly higher than in *Gas Diversification*, at 56 TWh compared to 41 TWh.

CO_2 emissions

The CO_2 emissions per year in the modelled scenarios are shown in Figure 7. The highest annual emissions in the *Fossil Future scenario* rise to 170 Mt, compared to the *Least Cost, Decarbonisation* and Security scenarios' emissions which stabilise at 75 Mt. This is due to the high emissions intensity of the *Fossil Future* fuels. The drop in emissions in the *Fossil Future* scenario around 2025 is due to the decrease in coal generation at that time. The *Least* Cost, *Decarbonisation* and Security scenarios have similar emissions trajectories and thus were combined. These all decrease to 75 Mt by 2030 because of the emissions constraint (Table 1). Although *Least Cost* did not have the emissions constraint applied, its emissions followed a similar trend to the *Decarbonisation* and Security scenarios, likely because the *Least Cost* scenario has a similarly high and rapid deployment of renewable energy to these scenarios.

Costs

Figure 8 compares the total discounted costs for the six scenarios in US 2019 $, using a discount rate of 10%. Capital costs include the cost of planning and design, technology parts and materials, construction and commissioning, fixed costs include worker salaries, operations and maintenance and taxes and variable costs largely represent the cost of fuel (Climate Compatible Growth, 2022b). The Fossil Future scenario has the highest costs, at US$549.31 bn. This is due to the high variable fuel costs in *Fossil Future*. *Decarbonisation* has approximately US$90 bn lower costs than *Fossil Future*, and US$53 bn (14%) higher costs than *Least Cost*. *No Gas* has significantly higher costs of US$554.47 (42% higher than *Least Cost*) reflecting the higher capital costs and reliance on imported oil in this scenario. *Independence 2050* has the lowest total costs at US$462.17 despite high capital costs, reflecting the large cost benefit over time of transitioning from fuel imports to domestic renewable generation. This cost is 16% higher than *Decarbonisation*.

Discussion and Policy Recommendations

Our results support the findings of previous Morocco modelling studies. We affirm the conclusion that decarbonising Morocco's energy system is feasible and cheaper than a fossil-fuel-powered energy system (Schinko *et al.*, 2019; Brand & Blok, 2015; Rye *et al.*, 2016). Our results also support the insight from Bouabid, Sleptchenko and Mouline (2019) that solar and wind will be the predominant renewable energy technologies for decarbonisation in Morocco, and Slimani *et al.*'s (2021b) conclusion that natural gas may continue to be an important fuel for providing stable baseload supply during the transition. Additional insights from our results are described below, with policy recommendations for Morocco.

Wind and solar energy expansion

Importantly, although the phase-out of coal does increase the reliance on natural gas, it also promotes a rapid expansion of wind and solar PV generation. This increases the diversification of energy sources in the transition period, contrary to the concerns of Berdysheva and Ikonnikova (2021) that the energy transition will decrease the diversity of energy sources.

However, the expansion of wind and solar PV will need policy support to occur quickly.

Policy recommendations for expanding wind and solar power generation

Solar PV and wind power construction will need to increase quickly to meet Morocco's decarbonisation targets. Since hydropower can only provide 4% of electricity demand, wind and solar will have to compensate for this.

Recommendation 1: Detailed expansion plans for wind and solar PV, including five-year capacity checkpoints and cost estimations, need to be developed and implemented within the next two years for the period of 2025–2065, to ensure that these technologies meet their required capacities. These strategies should be legally binding and modelled after the Hawai'i Clean Energy Initiative which has introduced mandates for its renewable energy targets (Hawai'i State Energy Office, 2023). The strategies should also be used in negotiations with multilateral development banks to facilitate their greater involvement in the financing of renewable energy in Morocco, which will reduce the perceived risk to private renewable energy investors.

Recommendation 2: The legislative framework for feed-in tariffs proposed by Morocco should be amended and introduced within the next two years (Bentaibi & Papi, 2021). Particularly, low-voltage grid connections in Morocco should be expanded, and feed-in tariffs should subsequently be opened to low-voltage power production in addition to high and medium voltage. Additionally, tax exemptions and low-interest loans should be considered to reduce the high capital cost of small solar power systems for customers (Siliprandi et al., 2022). This initiative will likely be developed by the Moroccan Ministry for the Energy Transition and Sustainable Development (MEM) and overseen by the Moroccan Energy Authority (ANRE).

Flexibility problems

In addition to their rapid expansion rates, the penetration of solar and wind technologies in the *Decarbonisation* and Security scenarios is extremely high, reaching between 74% to 83% of power generation. The West African Power Pool study by the International Renewable Energy Agency (IRENA) states that intermittent renewable energy (e.g., wind and solar power) should provide a maximum of 30% of demand to prevent inflexibility in the electricity grid (IRENA, 2013). This indicates that the penetration of intermittent renewable energy technologies will create problems with flexibility for Morocco's power system (see the Limitations and Further Research chapter for recommended future research on flexibility). Currently, Morocco lacks a strategy for preventing future flexibility problems.

Policy recommendations for improving the flexibility of the electricity grid

High penetration of intermittent renewable energy may create flexibility problems for the grid, including blackouts and curtailment. Morocco does not have a strategy or regulatory framework for energy storage or demand response measures.

Recommendation 1: A strategy for expanding large-scale power storage capacity should be developed in 2023, using detailed pathways of the future energy system to assess storage needs. A regulatory framework for storage providers should be included in the strategy, including the proposed fiscal compensation for storage provision. This will reduce uncertainty for private investors, making clear the payment scheme for storage provision into the future. This initiative will likely be developed by the Moroccan Ministry for the Energy Transition and Sustainable Development (MEM) and overseen by the Moroccan Energy Authority (ANRE).

Recommendation 2: A time-based pricing system for power consumption during peak versus off-peak hours should be tested for electricity consumers, beginning as soon as possible. The scheme could mimic the German Ordinance on Interruptible Loads (AbLaV) which allowed electricity customers to reduce their demand during peak times in exchange for financial credit (Cardosoo & Ren, 2016; Maksimenko, 2022). This initiative will likely require coordination between the Moroccan Energy Authority (ANRE) and the Moroccan National Office of Electricity and Drinking Water (ONEE).

Energy security

The results suggest that Gas Diversification ensures the most stable and affordable energy supply compared to the other scenarios. Firstly, domestic electricity generation can be assumed to be more stable than relying on imported fuels in this study. This is because the unstable aspects of local electricity generation (like the variable capacity factors of renewable energy) are already input into the model. Additional issues, like unforeseen intermittency, can be planned for with the flexibility recommendations (Section 5.2.1). Conversely, the cost and stability of imported fuels are dependent on geopolitical relationships, which cannot be input into the model nor planned for as easily. The Base scenarios and the *No Gas* scenario have high imported fuel demands and the *Independence 2050* scenario has an unrealistic cost, thus the Gas Diversification scenario is the best scenario to increase Morocco's energy security.

The large-scale expansion of renewable energy generation in the *Gas Diversification* scenario supports the conclusion that renewable energy will help Morocco to achieve a higher level of energy security. This finding supports that of the preceding literature (Scholten & Bosman, 2016; Jewell *et al.*, 2016; Valentine, 2011; Vakulchuk, Overland & Scholten, 2020). However, the *Gas Diversification* scenario shows that natural gas should not be phased out completely since it is still relied upon for baseline power generation and industrial high heat in this scenario. Instead of phasing out gas, Morocco should focus on reducing the amount of imported natural gas.

Policy recommendations for improving the energy security of natural gas

Morocco may need to rely on natural gas beyond 2040.

Recommendation 1: Domestic regasification and storage infrastructure construction will help Morocco to avoid overreliance on Spain's regasification infrastructure. This should be expanded beyond the approved storage and regasification plant in Mohammedia, which can only regasify 0.83 TWh of natural gas annually by 2040, and the 6,000 m3 storage plant in Tendrara (Pekic, 2022; LNG Prime, 2022). A recommended target is 5 TWh of regasification capacity by 2065, which would meet Morocco's regasification needs in the *Decarbonisation* scenario, significantly reducing the dependence on the Spain–Morocco gas pipeline.

Recommendation 2: Morocco should increase domestic natural gas exploration and implement a clear regulatory system for gas production. Significant natural gas reserves have been identified in the Tendrara and Gharb regions, and exploration should expand in these areas in particular (IEA, 2019a). Establishing transparent financing regulations would increase Morocco's production capacity more quickly.

Limitations and Further Research

An important limitation of this study is that transport is not included to allow a comparison of all scenarios with *Independence 2050* (in which transport had to be removed to allow the model to run). This limits the applicability of the results, and further research should aim to include the transport sector in its demands. Future research efforts should also focus on assessing the energy system flexibility, as well as the land and water requirements of these modelled scenarios, using software like FlexTool and CLEWS (Beltramo *et al.*, 2021).

In terms of energy security, an important limitation of this study is that the *Gas Diversification* scenario solely focused on natural gas. Future modelling that analyses the best electricity interconnections for Morocco would be valuable for improving Morocco's energy security in the future.

Conclusion

In this study we have performed modelling analysis to explore the best pathway for Morocco to achieve energy security and decarbonisation. The difference in energy stability and affordability between two interpretations of energy security ('energy independence' and 'diversified dependence') was also explored. We updated the Morocco Starter Data Kit 'LCv2' file and created three Base scenarios (*Least Cost*, *Fossil Future*, *Decarbonisation*) and three Security scenarios (*Gas Import Diversification*, *No Gas*, *Independence 2050*) to explore these different energy security futures for Morocco.

We compared and analysed the scenario results, showing that achieving Morocco's decarbonisation targets is cheaper than following a *Fossil Future* pathway by US$90 bn, and similar in cost to a *Least Cost* pathway. Although achieving energy security in addition to the decarbonisation targets will raise costs above a *Decarbonisation*-only pathway, an energy independence pathway will minimise the cost increase while decreasing reliance on imported fossil fuels. As such, the *Independence 2050* scenario – incorporating a mix of independent renewable energy power generation and gradual phase-out of imported fossil fuels – was identified as the best pathway for achieving energy security while meeting the decarbonisation targets. Since the *Decarbonisation* and *Gas Diversification* scenarios show a continued reliance on natural gas, we also recommend that Morocco invests in domestic regasification infrastructure and natural gas exploration to avoid overreliance on the Spain–Morocco gas pipeline during the transition to renewable energy.

Overall, the study shows encouraging results for Morocco being able to achieve its decarbonisation targets, whilst increasing energy independence in several possible least-cost scenarios. The study affirms the importance of Morocco's renewable energy potential, particularly wind and solar. We recommend that the Moroccan government create detailed solar PV and wind capacity expansion strategies to de-risk renewable energy investment, improve their regulation for grid's flexibility, increase electricity storage capacity and demand-response measures to achieve their ambitious decarbonisation targets.

Declarations

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CRediT Statement

Malte Jansen: Supervision, Writing – Review & Editing. Mark Howells: Supervision. Rudolf Yeganyan: Software, Validation. Naomi Tan: Software, Validation. Carla Cannone: Methodology.

Declaration of competing interest

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

U4RIA Compliance

This work follows the U4RIA guidelines (Howells *et al.*, 2021) which provide a set of high-level goals relating to conducting energy system analyses in countries. This paper was carried out involving stakeholders in the development of models, assumptions, scenarios and results (Ubuntu / Community). The authors ensure that all data, source code and results can be easily found, accessed, downloaded and viewed (retrievability), licensed for reuse (reusability) and that the modelling process can be repeated in an automatic way (repeatability). The authors provide complete metadata for reconstructing the modelling process (reconstructability), ensuring the transfer of data, assumptions and results to other projects, analyses and models (interoperability) and facilitating peer-review through transparency (auditability)."

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Figures

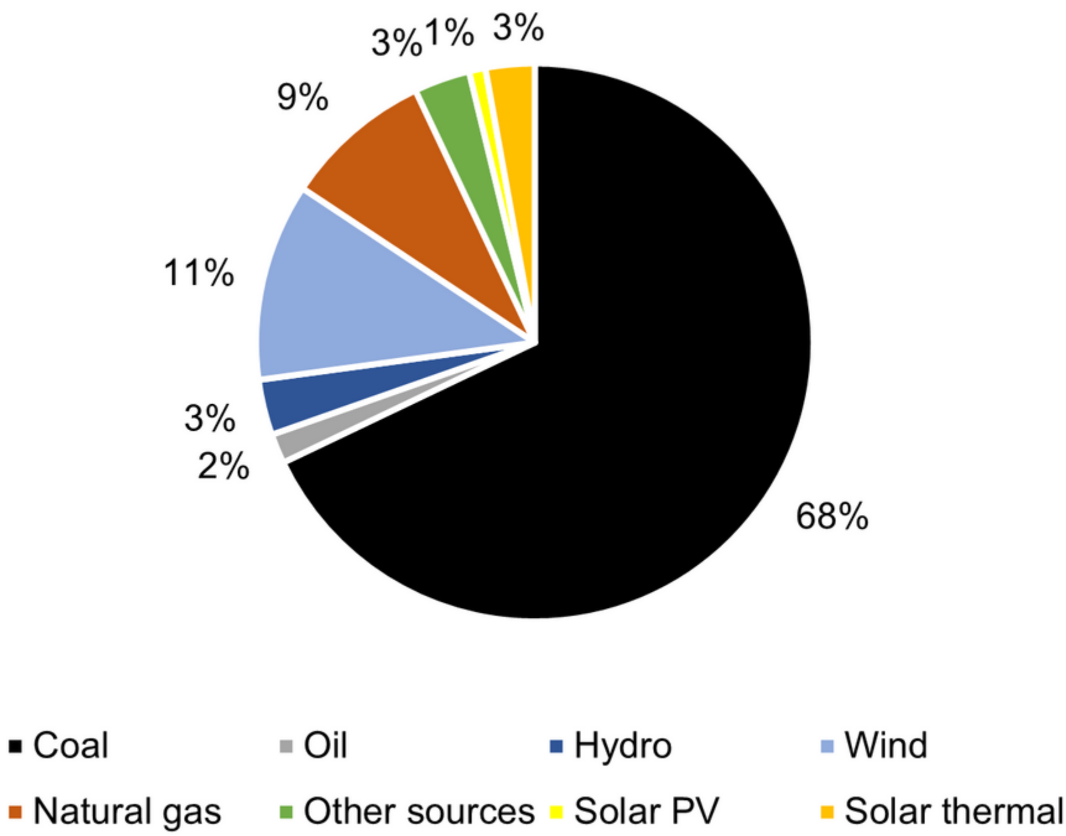

Figure 1

Electricity generation by source in Morocco in 2019. Other sources include generation from chemical heat. Adapted from IEA (2019c).

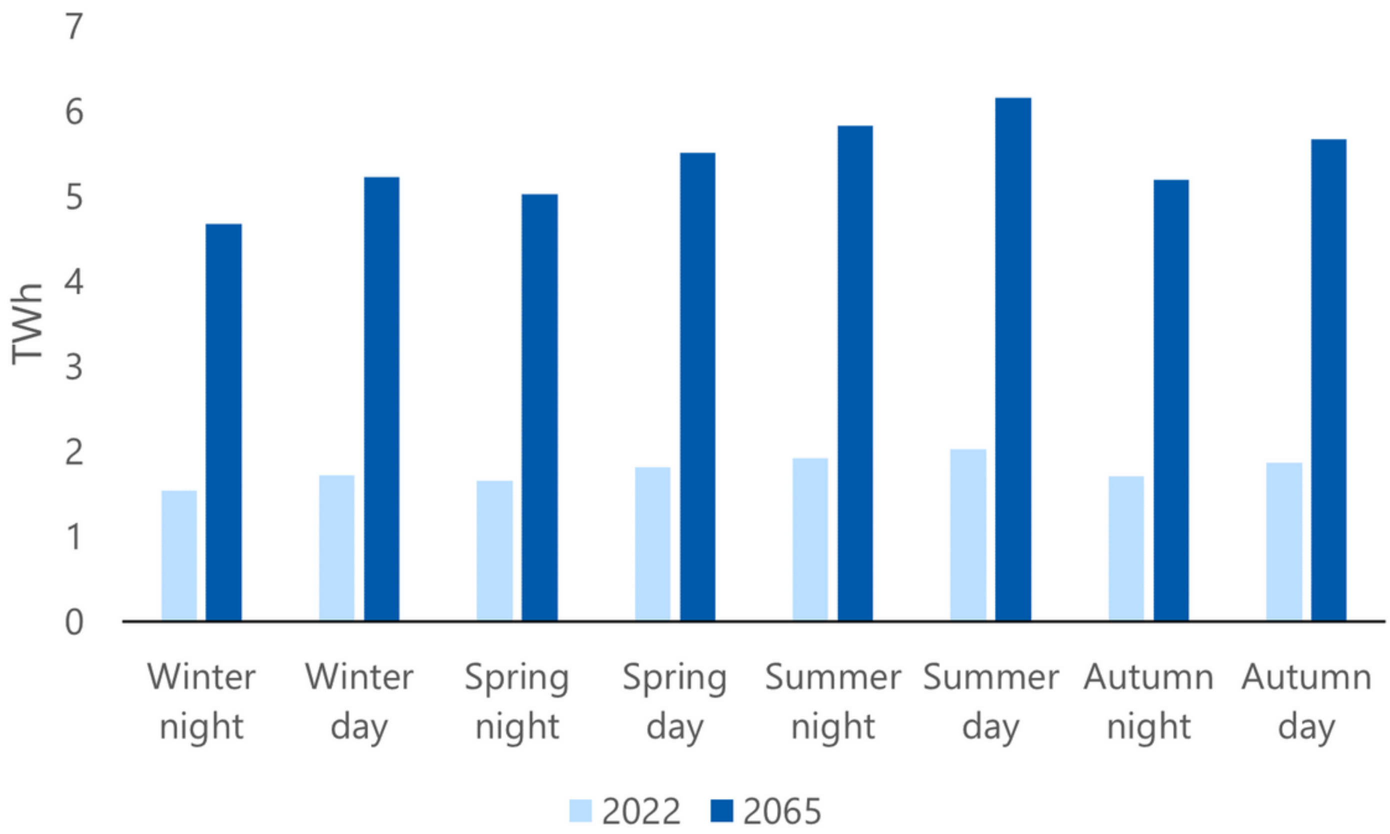

Figure 2

Specified demand profiles for residential electricity demand by time slices: a comparison between 2022 and 2065. Data adapted from The Electricity Model Base for Africa (TEMBA) taken from Cannone et al. (2021) and projected to 2065.

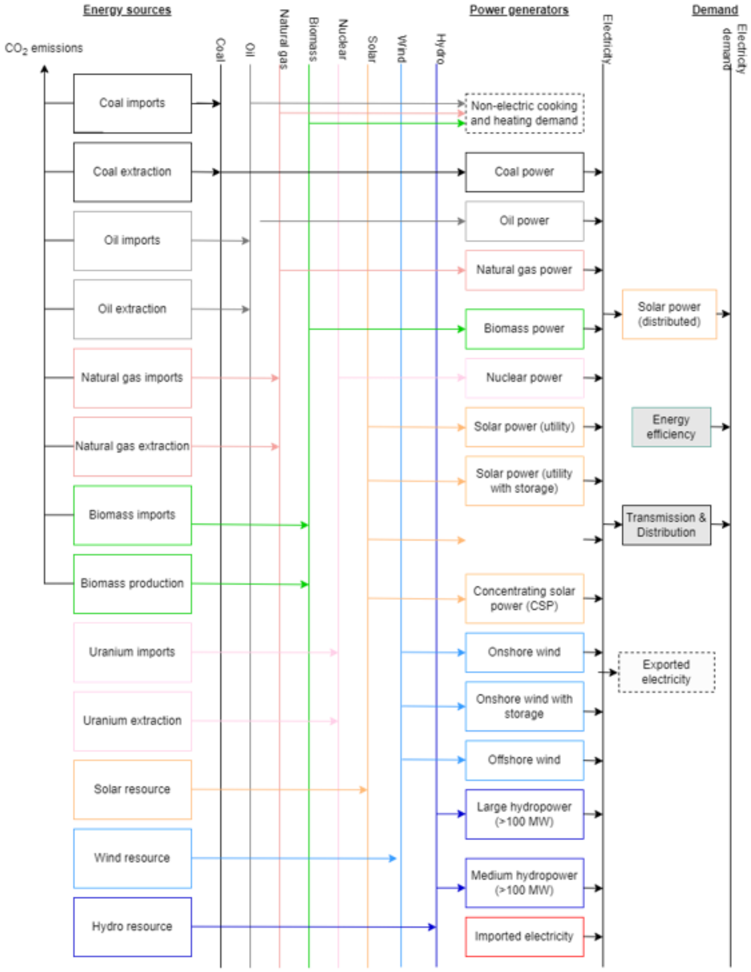

Figure 3

A simplified Reference Energy System (RES) diagram for Morocco's electricity system, created from Climate Compatible Growth (2022a) for this study.

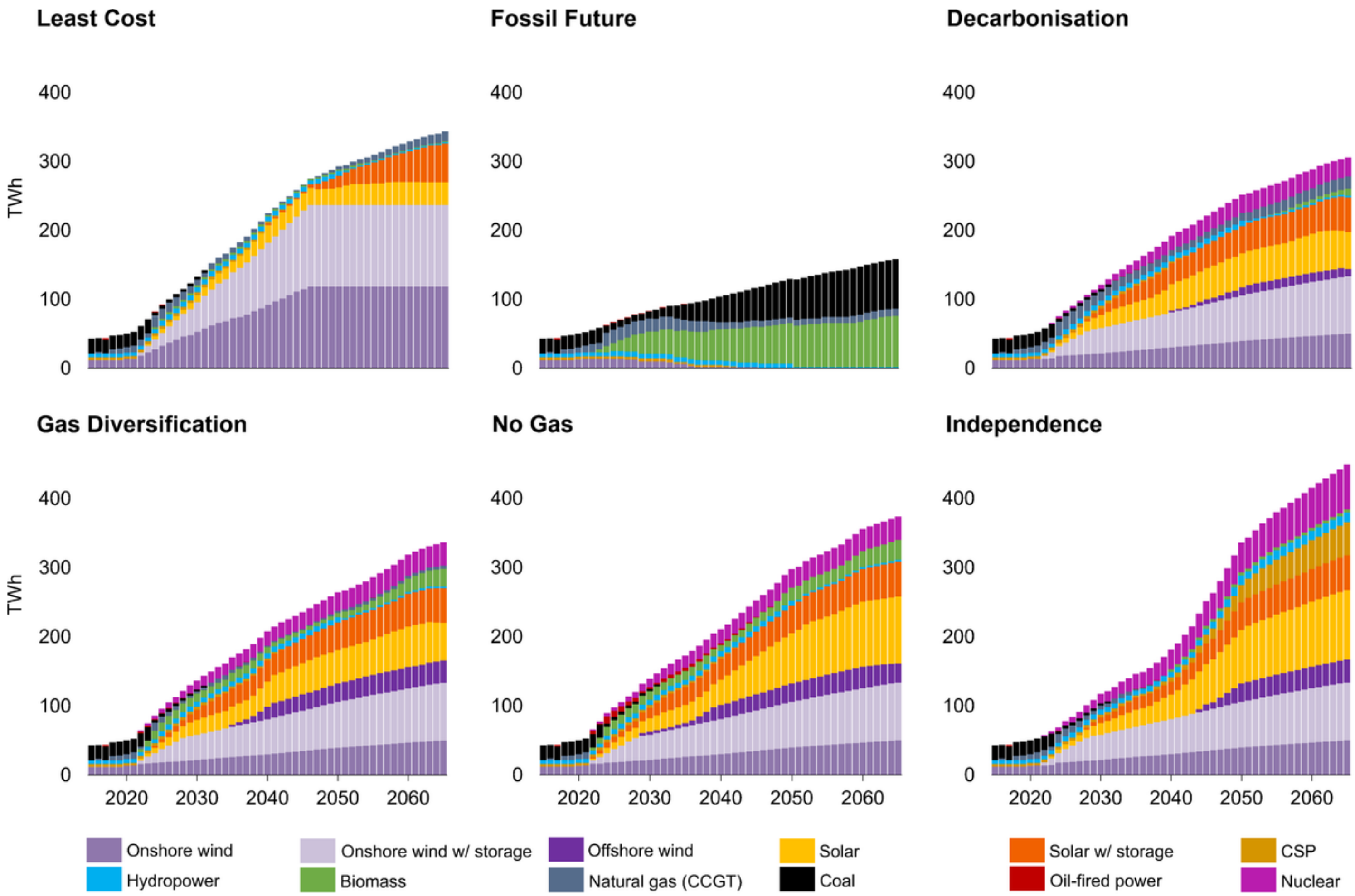

Figure 4

Projected annual electricity generation in Morocco in TWh by energy source, from 2015 to 2065.

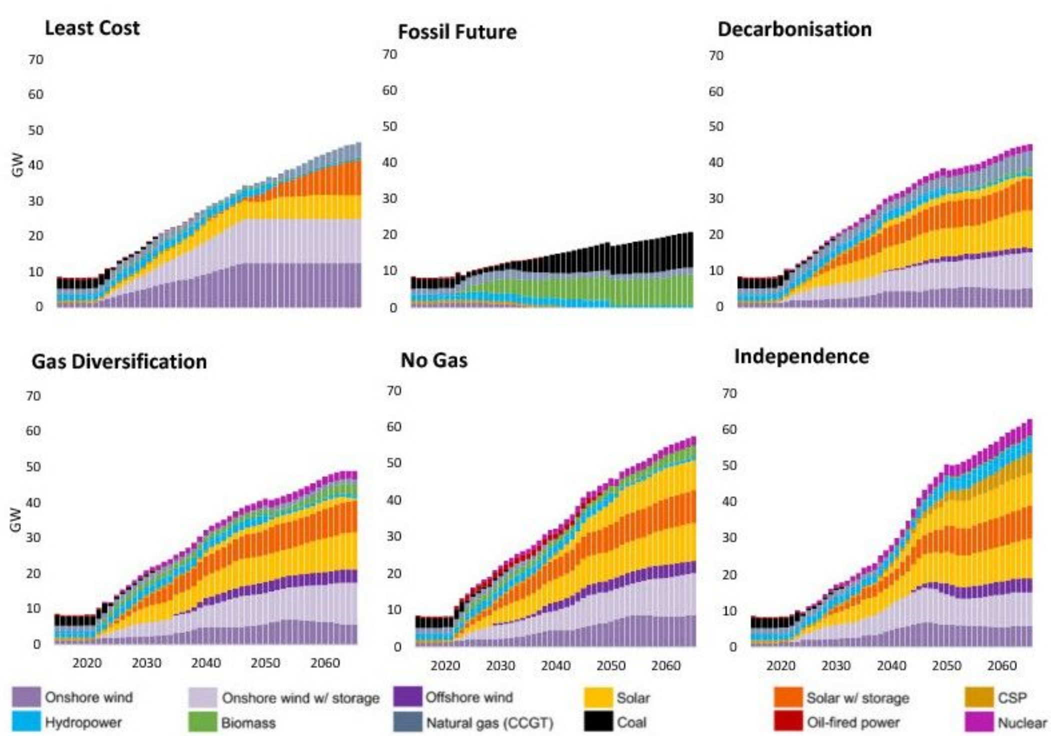

Figure 5

Projected annual capacity additions in Morocco in GW by energy source, from 2015 to 2065.

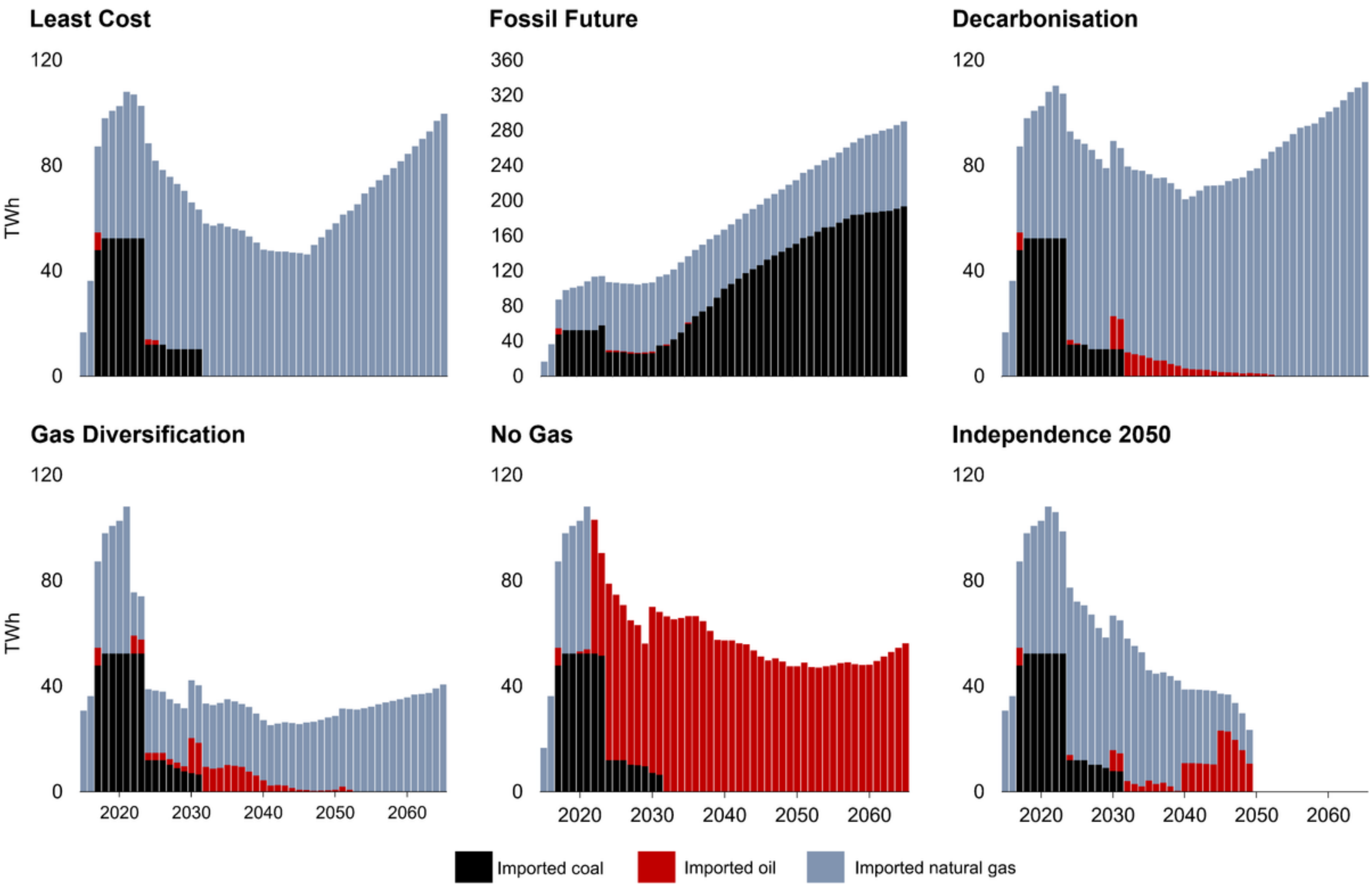

Figure 6

Projected annual imported primary fuel consumption of modelled scenarios in Morocco. Note: imported oil includes light fuel oil, heavy fuel oil and crude oil.

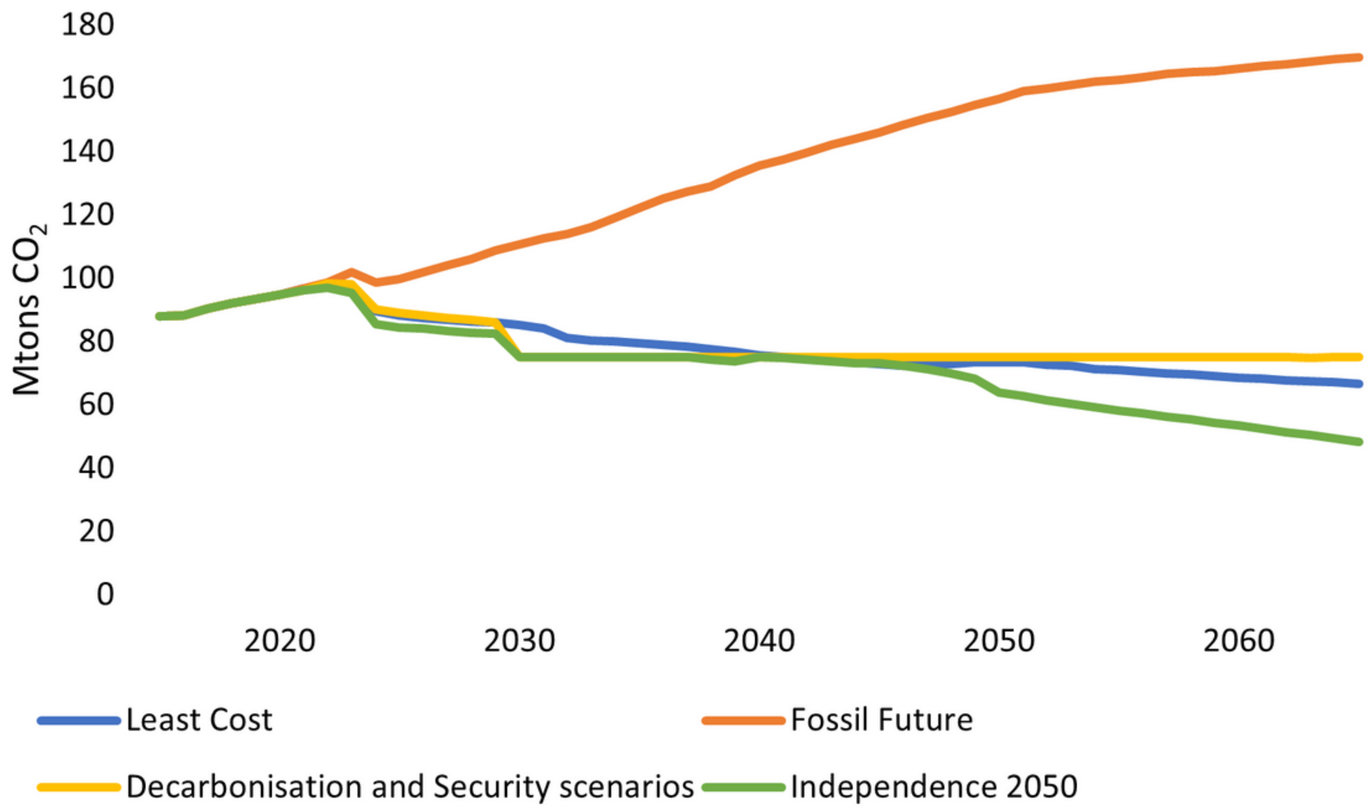

Figure 7

CO_2 emissions per year in Morocco for the modelled scenarios. The *Decarbonisation* and Security scenarios (*Gas Diversification*, *No Gas* and *Independence 2050*) had the same emissions trajectories after 2030 and approximately 5% fluctuation before 2030, thus were combined into one line.

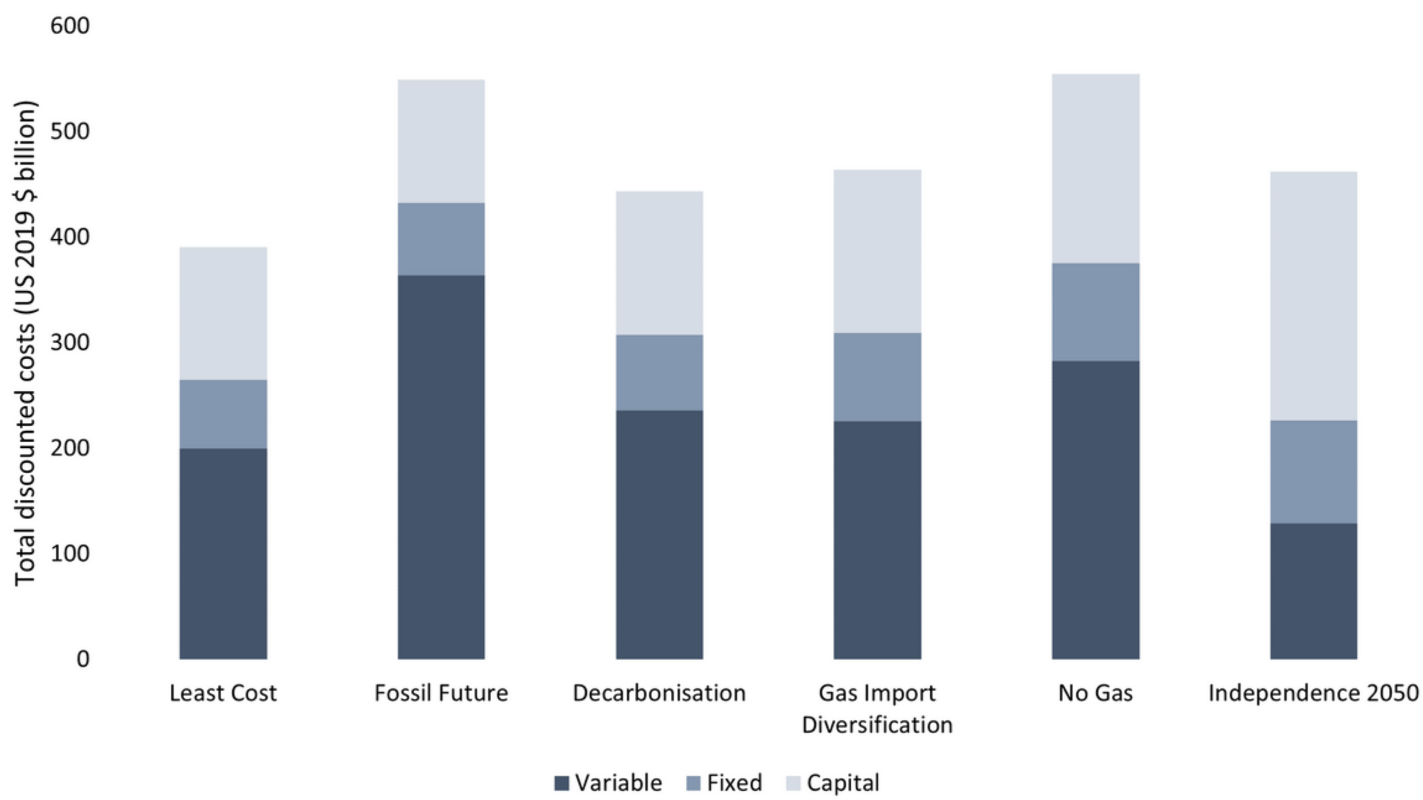

Figure 8

Total capital, fixed and variable discounted costs of modelled scenarios in US 2019 $ billion (using a discount rate of 10%), summed from 2015 to 2065.