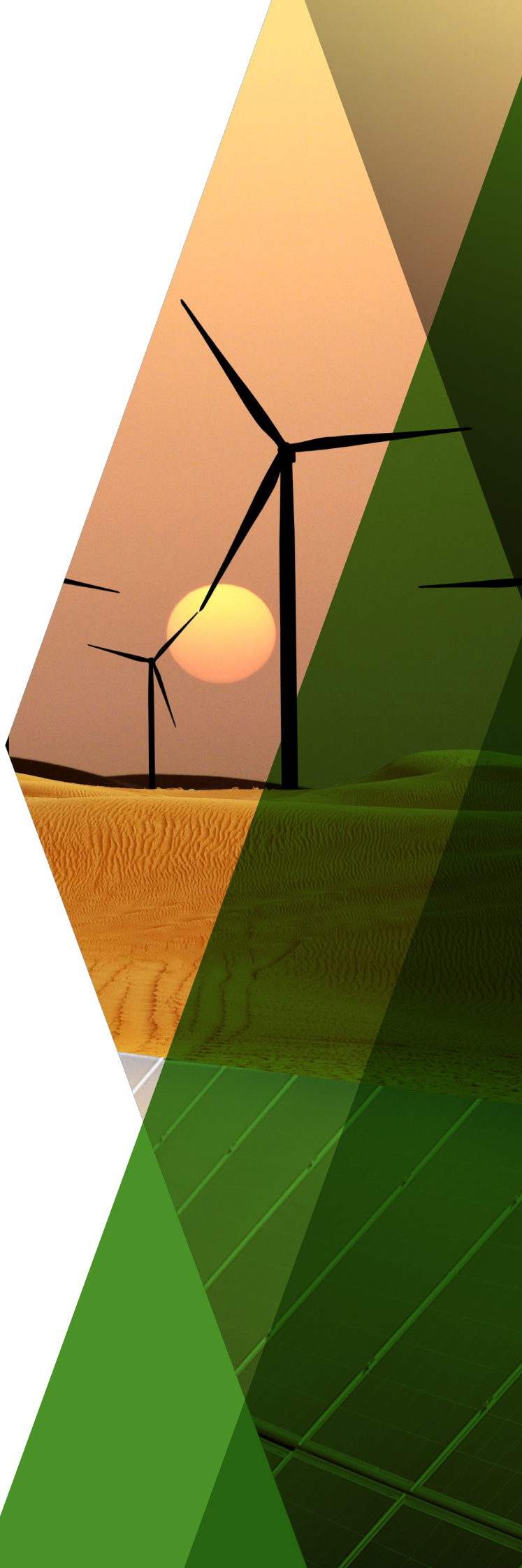
KAPSARC
مركز الملك عبدالله للدراسات والبحوث البترولية
King Abdullah Petroleum Studies and Research Center

Discussion Paper

Are There Adequate Materials and Land Resources for the Saudi Power Sector to Achieve Net Zero by 2060?



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KAPSARC is an advisory think tank within global energy economics and sustainability providing advisory services to entities and authorities in the Saudi energy sector to advance Saudi Arabia's energy sector and inform global policies through evidence-based advice and applied research.

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Abstract

Saudi Arabia has committed to net-zero (NZ) greenhouse gas emissions by 2060. This requires substantial emission reductions across key sectors, including the power generation sector. We assess the technological options, critical mineral requirements, renewable energy resource requirements, and costs associated with transforming the Saudi power sector to NZ by 2060. We incorporate global critical mineral constraints scaled down to Saudi Arabia, country land use, and renewable energy resource limitations. The capacity expansion model, which simultaneously co-optimizes for generation and transmission expansion using an hourly temporal resolution, includes 18 generation technologies and variations, including battery storage and hydrogen. We find that achieving NZ emissions in the Saudi power sector by 2060 is feasible but, as expected, costlier than business-as-usual. Shortages of some critical materials (out of a total of 38 materials considered) may be faced during the transition, but these can be mitigated through planning, technology substitution, stockpiling, financial contracts, and other measures. Renewable resources and land availability are, by and large, not constraining, although land limits are generally approached in the northeastern region.

Introduction

Many countries have committed to net-zero emissions of greenhouse gases in response to climate change and the Paris Agreement's goal to limit the average global temperature rise to 1.5 degrees Celsius above pre-industrial levels (Paris Agreement 2015). In addition, governments and policymakers are concerned with ensuring energy security and economic development – the other two components of the energy trilemma (Shakya et al. 2023). Worldwide, many net-zero (NZ) energy plans aim for a NZ power sector. This is due to the fact that the power sector has access to more advanced and lower-cost technologies than other energy sectors – because it is a major emitter, and because it is a key enabler of the decarbonization of other sectors (Rahman et al. 2021). Hence, many studies have focused solely on the decarbonization of the power sector.

Single-country net-zero (NZ) studies have covered countries like China, India, and the United States, given their large share of global emissions. The Kingdom of Saudi Arabia, on the other hand, has not received the same attention (Fälth et al. 2021). A member of the Group of Twenty (G20), Saudi Arabia has the 19th-largest gross domestic product globally, which is projected to grow robustly in the short to medium term. In addition to being the world's leading oil exporter (Statista 2024; OEC 2022), Saudi Arabia is also among the top-10 overall carbon dioxide (CO_2) emitters, with nearly 608 million metric tons of annual emissions (Statista 2024). In 2021, Saudi Arabia's energy-related CO_2 emissions totaled 497 million metric tons, making it the 11th highest worldwide emitter according to the International Energy Agency (IEA) (IEA 2021a). Saudi Arabia also boasts a significant electricity generation capacity, with around 90 gigawatts (GW) of available generation (SERA 2022b). The country also proactively shapes security, diplomacy, energy, economic, and other policies in the Middle East and North Africa (MENA) region and beyond. As a ratifier of the Paris Agreement, Saudi Arabia has committed to achieving NZ greenhouse gas emissions by 2060 (Al-Sinan, Bubshait, and Alamri 2023; SMEGI 2022).

Considering the above, we investigate the feasibility of the power sector in Saudi Arabia achieving NZ by 2060 with the aid of four models. We use a state-of-the-practice generation and transmission capacity expansion model (GTCEM), running at an hourly temporal resolution, which evaluates 18 electricity supply and energy storage technologies (Table 1). The materials model considers global supplies for 38 materials used in clean electricity technologies, while the land use model integrates a graphical information system (GIS) land resource model with six layers. Our demand projections, on the other hand, are based on an intra-regional economic model of electricity demand that incorporates forecast gross domestic product, population, and other parameters. This is the first time that such a modeling framework has been undertaken for Saudi Arabia.

Table 1. Candidate technologies considered for the capacity expansion modeling: electricity generation, electricity storage, hydrogen-related, and transmission.

Electricity generation technologies	**Abbreviations**
Simple-cycle gas turbine	GAS-SC
Combined-cycle gas turbine	GAS-CC
Simple-cycle gas turbine with carbon capture and storage (CCS)	GAS-SC+CCS
Combined-cycle gas turbine with CCS	GAS-CC+CSS
Nuclear (including small modular reactors, or SMRs)	NUC
Solar photovoltaics (PV)	PV
Concentrating solar power (CSP) with 10-hour thermal storage	CSP
On-shore wind	WNDL
Off-shore wind	WNDS
Bioenergy with CCS	BECCS
Waste-to-electricity with CCS	WECCS
Geothermal	GEO
Electricity storage technologies	**Abbreviations**
Battery with 2-hour storage	BATT-2h
Battery with 4-hour storage	BATT-4h
Battery with 10-hour storage	BATT-10h
Pumped hydroelectric energy with 4-hour storage	PHES-4h
Pumped hydroelectric energy with 10-hour storage	PHES-10h
Power-to-hydrogen-to-power technologies (P2H2P)	**Abbreviations**
Electrolyzer (power-to-hydrogen) and Fuel Cell (hydrogen-to-power)	ELZR and FCL
Transmission technologies	**Abbreviations**
High-voltage overhead line	HVOL

Distinguishing between NZ energy-related emissions (NZ energy) studies and NZ power-related emissions (NZ Power) studies (Bistline and Young 2022) is important. Generally, the former precedes the latter to provide and lay out the framework for more detailed subsequent sector-specific studies (Williams et al. 2021). For example, Barrett et al. (2022) assessed energy demand reduction options for meeting zero-emission targets in the United Kingdom (UK), considering several sectors, including materials and products, transportation, household, and power, using the UK TIMES Model, and, as expected, the resolution of such a model would be "coarse" – a widely accepted practice given the large scope of these country-wide energy-system models.

DeAngelo et al. (2021) reviewed 177 NZ energy studies and found that substantial amounts of renewable energy deployment in the power sector would be needed (including from biomass) to achieve NZ energy. High levels of electrification are also a common finding in these analyses. At a more granular level, Handayani et al. (2023) summarize 23 papers focused exclusively on NZ power. The review suggests that common to the findings of NZ energy studies, substantial amounts of renewable energy are needed, including the deployment of renewable hydrogen, some nuclear energy development, increased electrification, and energy storage to balance supply and demand. The energy mix, the timing of technology deployment, and the scale of the transition all depend on the specific country, its available resources, and its timetable for achieving NZ. As mentioned earlier, many NZ energy and/or NZ power studies have been published for several countries, with a focus on China (Fan et al. 2023),

India (Gulagi et al. 2022), and the United States (Bistline and Young 2022), given that they are the top emitters globally. However, there are only a limited number of NZ energy studies (or similar) for Saudi Arabia.

A dated study for Saudi Arabia employed integrated resource planning to evaluate the cost-effectiveness of renewable energy (Alnatheer 2005). It found that an expansion plan that includes the non-market benefits of solar and wind has a lower social cost than a business-as-usual plan. More recently, one study conducted an economy-wide assessment of the country's ability to achieve NZ (Al-Sinan, Bubshait, and Alamri 2023) emissions by 2060. It indicated that Saudi Arabia is making progress, with its steel and cement industries being the more challenging sectors. Another recent study focused on the Saudi electric power sector (Rahman et al. 2021); it quantitatively and qualitatively reviewed various mitigation technologies but did not provide a detailed expansion plan.

Our work builds on other recent studies. Durand-Lasserve (2023) reviews NZ energy macroeconomic studies of fossil fuel exporting countries and contributes to the literature by constructing a dynamic forward-looking model of Saudi Arabia. The major finding with respect to electricity is that the least-cost NZ pathways involve increasing the electrification of the power sector and deploying renewable energy, natural gas with carbon capture and storage (CCS), and nuclear technology (Durand-Lasserve 2023). Kamboj et al. (2023), on the other hand, use an integrated assessment model (IAM) to analyze the long-term implications of the Saudi power sector achieving NZ by 2060. They find that decarbonizing the electricity sector is critical to accomplishing the country's goal, alongside massive investments in renewable resources and the grid, and they also find that novel technologies, such as carbon dioxide removal (CDR), will be needed. With a different modeling framework, Matar, Mansouri, and Umeozor (2024) employ an energy sector model for Saudi Arabia with a more detailed electricity module than Durand-Lasserve (2023) and Kamboj et al. (2023), finding that the Saudi energy sector can contribute to approximately half of the targeted greenhouse gas reductions by the year 2030, and also finding that a non-prescriptive policy that does not mandate technologies is substantially less expensive than a prescriptive one.

This paper enhances prior work by providing significant additional electricity sector specifics, mineral considerations, and land resource constraints extended to 2060. It also provides considerable details that can better inform policymakers and planners compared with other studies. First, we capture the unique characteristics of power systems to complement broader macroeconomic and IAM models, including additional features, such as hourly demand profiles, detailed energy storage performance, a richer array of power generation technology candidates, power system reliability, transmission, operational constraints, and other intra-regional characteristics not considered by (macro-) economy models. Second, our capacity expansion model includes Saudi-specific technical, planning, and policy constraints that affect the deployment of renewable energy, nuclear power, and energy storage, including topography and weather conditions, for example. Third, we analyze the implications of critical mineral constraints on Saudi Arabia's power sector, as recommended by Wang et al. (2022), which are typically ignored in expansion planning models (Levin et al. 2023).

Our paper makes several contributions to this area of study. This is the first study to conduct a long-term, power system-specific, detailed generation and transmission expansion study of Saudi Arabia's transition to NZ power. These detailed simulations pertaining to the power sector are viewed in the context of their land-use and mineral implications until 2060 for the first time. Each of these elements is important, and we integrate them into a single modeling framework to inform technology monitoring, selection, and deployment.

The evolution of the Saudi power sector on its NZ pathway to 2060 was explored through a dedicated modeling suite that embeds four main models: a demand model, a generation and transmission capacity expansion model (GTCEM), a land-use GIS model, and a minerals model. Several scenarios have been considered. Our scenarios vary by annual demand until 2060, with one reference scenario, denoted ***RefDem***, and one high electrification scenario, denoted ***HiDem***. The hourly electricity load pattern also differs in both demand scenarios to account for the additional demand caused by electrification, i.e., higher industrial electrification and higher electric vehicle (EV) penetration, as detailed in the "Supplementary Information". For both demand scenarios, we run the GTCEM with an annual limit on carbon emissions for the power sector, which decreases linearly from around 250 megatons of carbon dioxide ($MtCO_2$) in 2024 to 0 $MtCO_2$ in 2060. These zero emission scenarios, denoted ***ZEP-RefDem*** and ***ZEP-HiDem***, correspond to reaching a zero-emissions power sector in 2060, i.e., only zero-emission technologies would be used to generate

electricity in 2060, while other technologies (such as gas power plants) could still support capacity adequacy. For ***HiDem***, we also explore alternative scenarios where some gross emissions are allowed in 2060 but would then be removed via CDR technologies. Finally, additional scenarios have been tested to measure the results' sensitivity to the availability of generation technologies and the potential for transmission grid expansion. For comparison purposes, a business-as-usual scenario (***BaU-HiDem***) is also simulated, which removes the cap on CO_2 emissions. All these scenarios are summarized in Table 2.

Table 2. Summary of scenarios.

Scenario name	Emissions from the power sector	Investment candidates	Electricity demand
Zero-emissions power sector (ZEP)			
ZEP-RefDem	Zero gross emission in 2060	All investment candidates (generators, storage assets, electrolyzers, grid expansion)	Reference
ZEP-HiDem			High electrification of the industrial and transportation sectors
Net-zero emissions power sector (NZEP)			
NZEP-HiDem-XM, X from 10 to 100	Net zero in 2060 with X $MtCO_2$ gross emissions removed by CDR	All investment candidates (generators, storage assets, electrolyzers, grid expansion)	High electrification of the industrial and transportation sectors
Other scenarios presented in "Supplementary Information"			
ZEP-HiDem-NoCSP	Zero gross emission in 2060	All investment candidates (generators, storage assets, electrolyzers, grid expansion) **except CSP**	High electrification of the industrial and transportation sectors
ZEP-HiDem-LimGrid	Zero gross emission in 2060	All investment candidates (generators, storage assets, electrolyzers, grid expansion) **with limited grid expansion**	High electrification of the industrial and transportation sectors

The major finding for policymakers is that achieving NZ emissions in the Saudi power sector by 2060 is possible. However, as expected, the transition would be costlier than business-as-usual. Moreover, expanding the set of available technologies in later years, even if not presently cost-effective, may lead to additional cost reductions. This is because policymakers would not have to commit to deploying technologies now but could wait to see how their costs and performance unfold (Felder et al. 2023). During the transition period, there is the potential for shortages of some critical materials, but this can be addressed by, among other available options, substituting different technologies, such as switching from one type of solar photovoltaics (PV) to another.

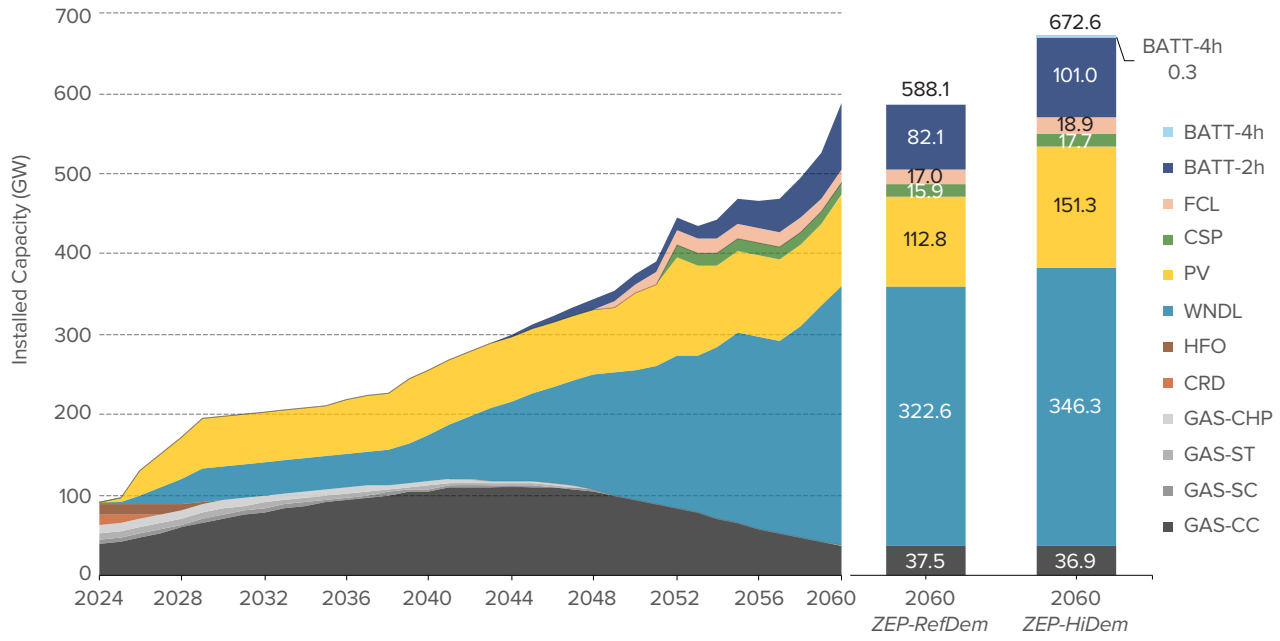
Results and Discussion

Generation Capacity Expansion to Reach Zero-Emitting Power Sector by 2060

The first set of scenarios explores Saudi Arabia's path to achieving NZ emissions in the power sector (***ZEP***) by 2060, i.e., zero gross emissions and no CDR. They use two electricity demand trajectories that differ by their levels of electrification: the reference demand (***ZEP-RefDem***) and the high electrification demand (***ZEP-HiDem***), as explained earlier. Our demand modeling gives the peak load and generation for 2060 under the reference demand scenario as 137 GW and 797 terawatt-hours (TWh), respectively, and 161 GW and 924 TWh, respectively, for the high-demand scenario. For context, the current peak and energy consumption in the Kingdom are 70 GW and 327 TWh, respectively, as of 2023 (SERA 2023).

Figure 1 shows the installed capacities for both scenarios in 2060 and the detailed capacity expansion between 2024 and 2060 in the ***ZEP-RefDem*** scenario. In 2030, the energy mix reaches a point where renewables represent ~50% of the total installed generation capacities (aligning with the Saudi Vision 2030 (Vision 2030 2024)), which results in 122-125 $MtCO_2$ emitted by the Saudi power sector (nearly half of 2024 levels). During the 2030-2040 decade, the transition relies heavily on the deployment of PV and wind, accompanied by new gas generation units to serve as baseload. Battery storage appears in the mid-2040s and continues to develop until 2060 to reach 82 GW in ***ZEP-RefDem*** and 101 GW in ***ZEP-HiDem***. Additionally, two new technologies, concentrated solar power (CSP) and power-to-hydrogen-to-power (P2H2P, i.e., electrolyzers and fuel cells), appear in the early 2050s. Interestingly, fuel cells are not dispatched then. Rather, the model deploys fuel cells for capacity adequacy purposes to satisfy the firm capacity requirement. Fuel cells begin to generate electricity from hydrogen in 2060, replacing gas combined-cycle (GAS-CC) generation to achieve the zero-emissions goal.

Figure 1. Installed generation capacities in GW.



Source: Authors.

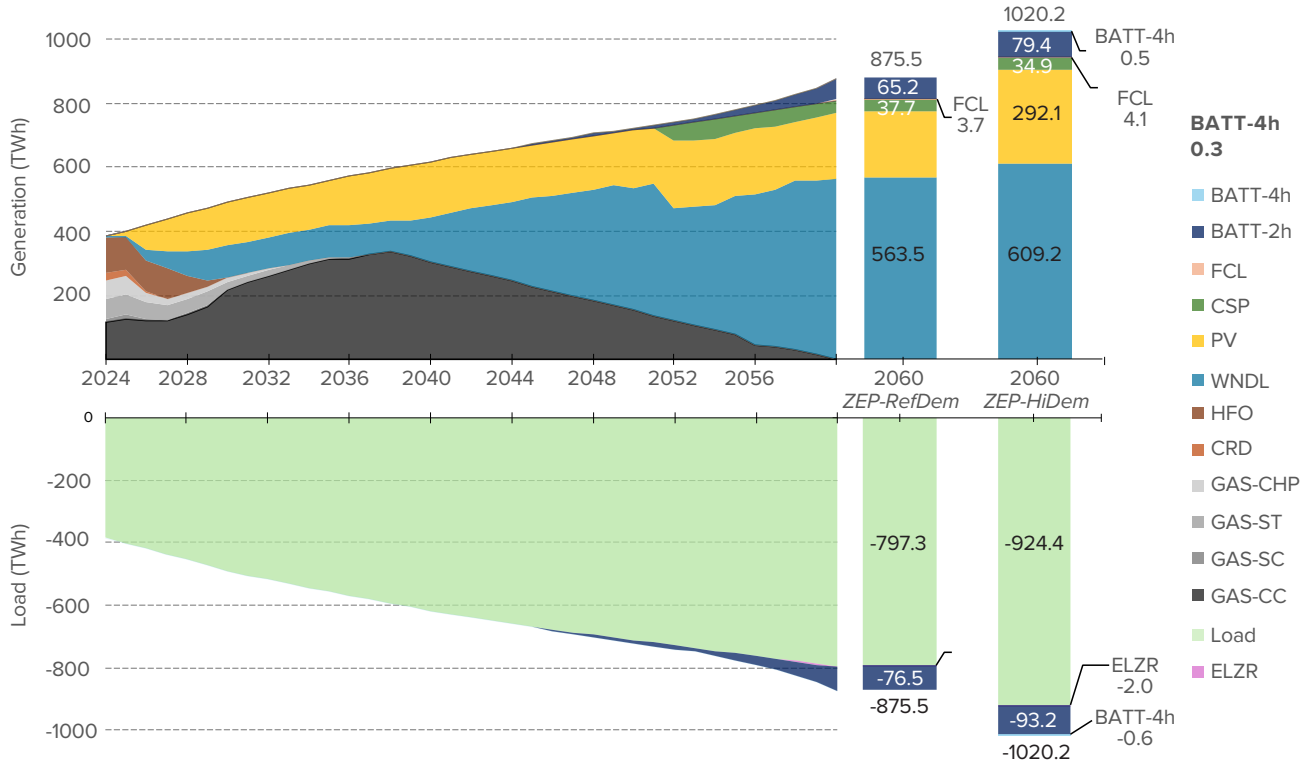
Note: The stacked area plot on the left shows the ZEP-RefDem evolution of the installed generation capacities from 2024 until 2060. The two bars on the right-hand side correspond to the installed capacities in 2060 in ZEP-RefDem (left bar) and ZEP-HiDem (right bar).

Figure 1 reveals that the primary difference between the ***RefDem*** and ***HiDem*** scenarios lies in the increased capacities of each technology in 2060 in the HiDem scenario, except for gas (combined cycle). Onshore wind constitutes the largest share of the energy mix, with ~55% in the ***ZEP-RefDem*** scenario and ~52% in the ***ZEP-HiDem*** scenario, and no offshore wind capacity was built by the model in any scenario due to its capital cost. The dominance of wind energy over PV, despite PV possessing a lower average cost, is due to wind's higher capacity factors and contribution to firm capacity throughout the day and night. CSP and fuel cells maintain almost the same percentage across the two scenarios, with CSP at ~2.7% and fuel cells at ~2.8%. The variability from the substantial share of non-dispatchable renewables in the energy mix in both scenarios is addressed with considerable two-hour storage (13.9% in the ***ZEP-RefDem*** scenario and 15% in the ***ZEP-HiDem*** scenario). Notably, in the ZEP-HiDem scenario, four-hour storage begins to appear (at 0.3 GW), suggesting an emerging role for longer-duration energy storage solutions in this scenario.

Even when assuming small modular reactor (SMR) development and allowing nuclear to be built in the in-land regions away from water bodies needed for cooling, the model deems nuclear costly, leading to no nuclear plants being built. Furthermore, among the technologies considered, candidates for capacity expansion were waste-to-electricity with CCS (WECCS), bioenergy with CCS (BECCS), and geothermal, as shown in Table 1. However, these were not part of the optimal generation mix obtained in 2060.

We see that wind meets well over half of the demand in both demand scenarios, as shown in Figure 2. As can be seen, an additional ~10% of energy is needed to fulfill the requirements for battery charging and hydrogen production. Excluding CSP leads the model to compensate by building nuclear power, four-hour storage, WECCS, and GAS-CCS (see Figure 3 and SI).

Figure 2. Evolution of the annual electricity generation and load in terawatt-hours (TWh) until 2060 in the *ZEP-RefDem* and *ZEP-HiDem* scenarios.



Source: Authors.

Note: The trajectory on the left-hand side in the top half of the figure shows the annual electricity generated by each technology from 2024 to 2060 and the annual electricity load in ZEP-RefDem. The two bars on the right-hand side correspond to the electricity generation and load in 2060 in ZEP-RefDem (left bar) and ZEP-HiDem (right bar). Generation values are represented positively, i.e., in the top half of the figure. In the bottom half of the figure, we show the electricity load (light green), and the load caused by batteries (blue) and electrolyzers (pink). The electrolyzer load, however, is too small to be visible.

Allowing Some Gross Emissions

We test another set of scenarios where the power sector is allowed to emit some CO_2 in 2060, but CDR technologies are used to balance out these emissions and reach net zero, and these scenarios are denoted ***NZEP***. Different ***NZEP*** scenarios allow gross emission values to vary from 10 to 100 $MtCO_2$ in increments of 10 $MtCO_2$. However, only selected results are shown in Figure 3 for the year 2060 (see "Supplementary Information" for more details). For example, ***NZEP-HiDem-40M*** refers to the high-demand scenario where 40 $MtCO_2$ is allowed to be emitted. As can be seen in Figure 3, as the level of allowed emissions increases, the total installed capacity of renewables decreases, and the total installed capacity of gas increases. Once again, we observe the dominance of wind and PV capacities in the ***NZEP*** scenarios, underscoring their critical role in the transition to a no- or low-carbon future (a net-zero or near-net-zero future). We also notice the trend in installations between gas, wind, and PV. Explicitly, when the allowed emissions in 2060 increase, the generation capacity mix evolves toward more gas and less wind but more PV. This is driven by similarities in the use of gas and wind, i.e., these technologies are mainly used to generate electricity during nighttime. Note that gas with CCS is limited to an installed capacity of less than 1 GW in scenarios with gross emissions lower than 20 $MtCO_2$. Furthermore, the role of gas generation units differs across the scenarios, as illustrated in Figure 3. When no emissions are allowed, the role of gas is limited to providing capacity adequacy.

Figure 3. Installed generation capacities (GW) and electricity generation (TWh) in 2060 for each scenario.



Source: Authors.

Note: The upper figure (a) displays the installed generation capacities in 2060. The bottom figure (b) displays the electricity generated from each technology in 2060, with loads from electrolyzers and batteries in negative values.

Additionally, battery storage plays a significant role, with most scenarios showing 80-100 GW of installed capacity. This capacity is driven by the need to store the high amounts of surplus electricity generated by solar and wind energy at different times, ensuring a balanced energy supply. Hydrogen also plays a key role in the results, as illustrated in Figure 3, with electrolyzers built at least five years before hydrogen is used. This allows the model to generate hydrogen each year, building up stored hydrogen until 2060. Then, fuel cells generate electricity exclusively in the year 2060 to meet the zero-emissions target. To minimize end-model effects, we extended the simulation several years beyond 2060, and we confirmed that the model continues to utilize hydrogen in subsequent years. We note that the role of P2H2P decreases when gross emissions are allowed in 2060. In scenarios allowing more than 20 $MtCO_2$, such as the ***NZEP-HiDem-40M*** scenario, no electricity is produced from hydrogen, but fuel cells are still part of the mix to satisfy the firm capacity requirement. This change is due to enough gas being available within the gross emissions limit to cover the needed supply, making hydrogen production unnecessary in these scenarios where emissions are allowed.

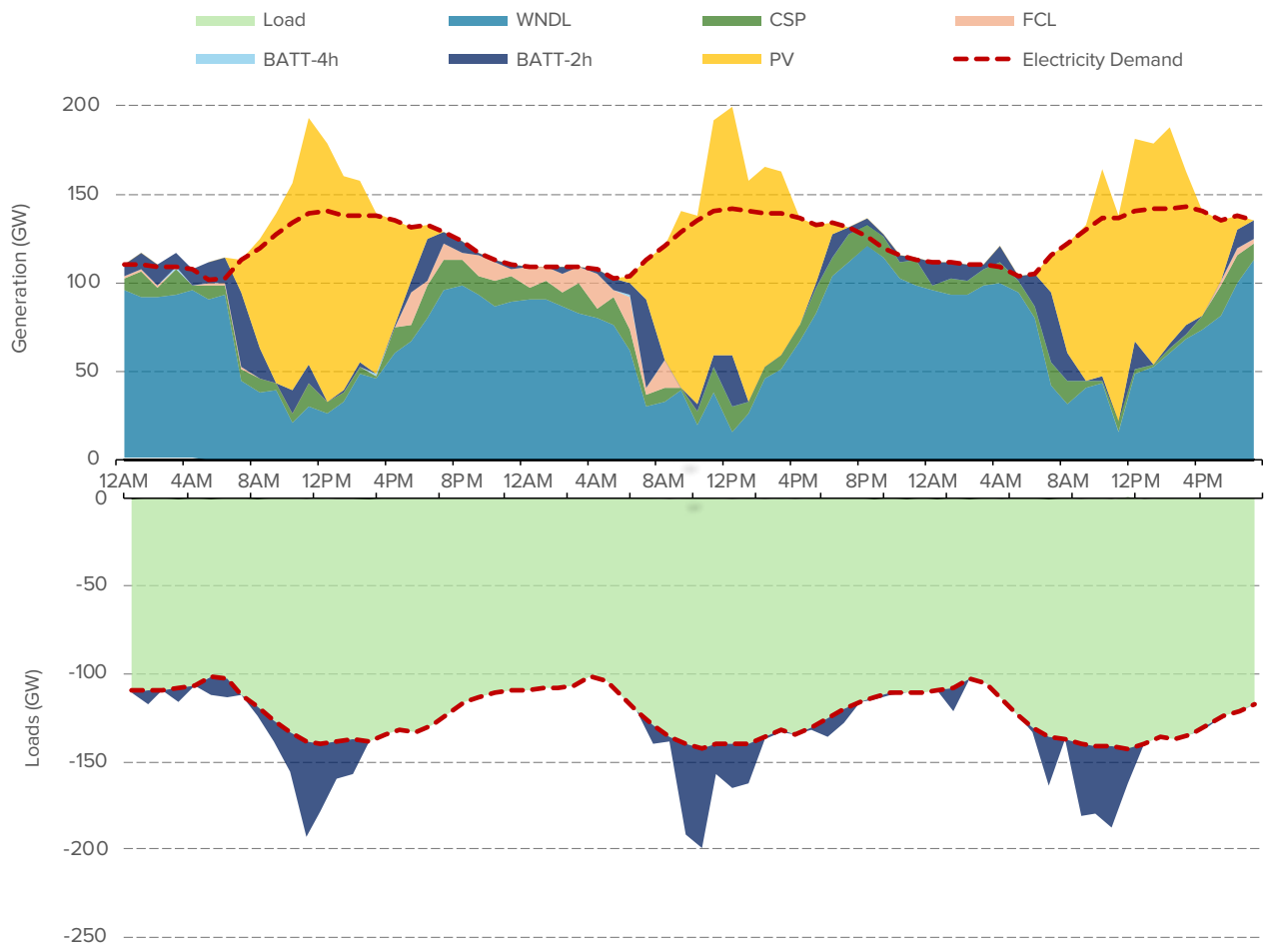
Hourly Dispatch

In the hourly dispatch performed for the full year of 2060, fuel cells are primarily used during the summer when demand is high. Furthermore, in the ***NZEP-HiDem-40M*** scenario, we also find that fuel cells generate no electricity but are part of the mix for firm capacity reserve purposes. This underscores the important role of gas when gross emissions are permitted, further highlighting the cost-effectiveness of gas with respect to P2H2P in such scenarios. At first sight, observing that gas generation is more cost-effective than hydrogen generation may be counter-intuitive because hydrogen is produced at no (or low) cost, i.e., only with excess renewable energy generation. In other words, the variable fuel cost for hydrogen is negligible. However, we note that the capital cost of hydrogen is not only the cost of fuel cells – it must effectively include both the fuel cells and the electrolyzers. Further, and as included in our modeling, the costs of P2H2P include hydrogen storage. Moreover, it is important to note that the green hydrogen route takes a toll on efficiency where considerable losses occur at the electrolyzer and then again at the fuel cell. Collectively, these factors favor deploying and dispatching gas generation – especially if some emissions are allowed, as can be seen in Figure 3, and further details of these factors are provided in subsequent sections. Given these challenges associated with hydrogen, battery deployment and dispatch become more favorable. The roundtrip efficiency of battery storage is around 90% (see "Supplementary Information", Table 17) – much higher than the efficiency of the P2H2P, which is roughly 40% (see "Supplementary Information", section 2.3.1). In practice, (stored) hydrogen could be used in other sectors, such as industrial processes or transportation. The decision of whether to store hydrogen for a long period or to use it for other purposes will depend on future hydrogen storage developments and market demand. In addition, the installed capacity of CSP progressively decreases when more gross emissions are allowed in 2060. There is no CSP in the Saudi electricity mix in 2060 for 100 $MtCO_2$ and above.

Figure 4 shows the hourly electricity generation dispatch for each technology and loads for three days in August 2060 for the ***HiDem*** scenario. CSP is being used for almost 24 hours per day, fuel cells during nighttime, wind throughout the day, and, of course, PV in the daytime. Note that this dispatch includes both the actual electricity demand and the demand required to charge batteries and produce hydrogen. As expected, we do see that solar PV is generally the technology used to charge batteries. Wind energy can be viewed as playing the role of meeting baseload, as is also shown in Figure 4.

Overall, from the discussion above, we see the clear role that each technology would play in a purely zero-carbon scenario versus a scenario where some emissions are allowed, i.e., the energy versus the capacity role. Further, we find that hydrogen would bestow maximum value in scenarios with no or limited emissions. When some emissions are allowed, however, we see that gas can better facilitate a reliable and relatively clean power sector.

Figure 4. *ZEP-HiDem* hourly electricity generation and load for three consecutive days in August 2060.



Source: Authors.

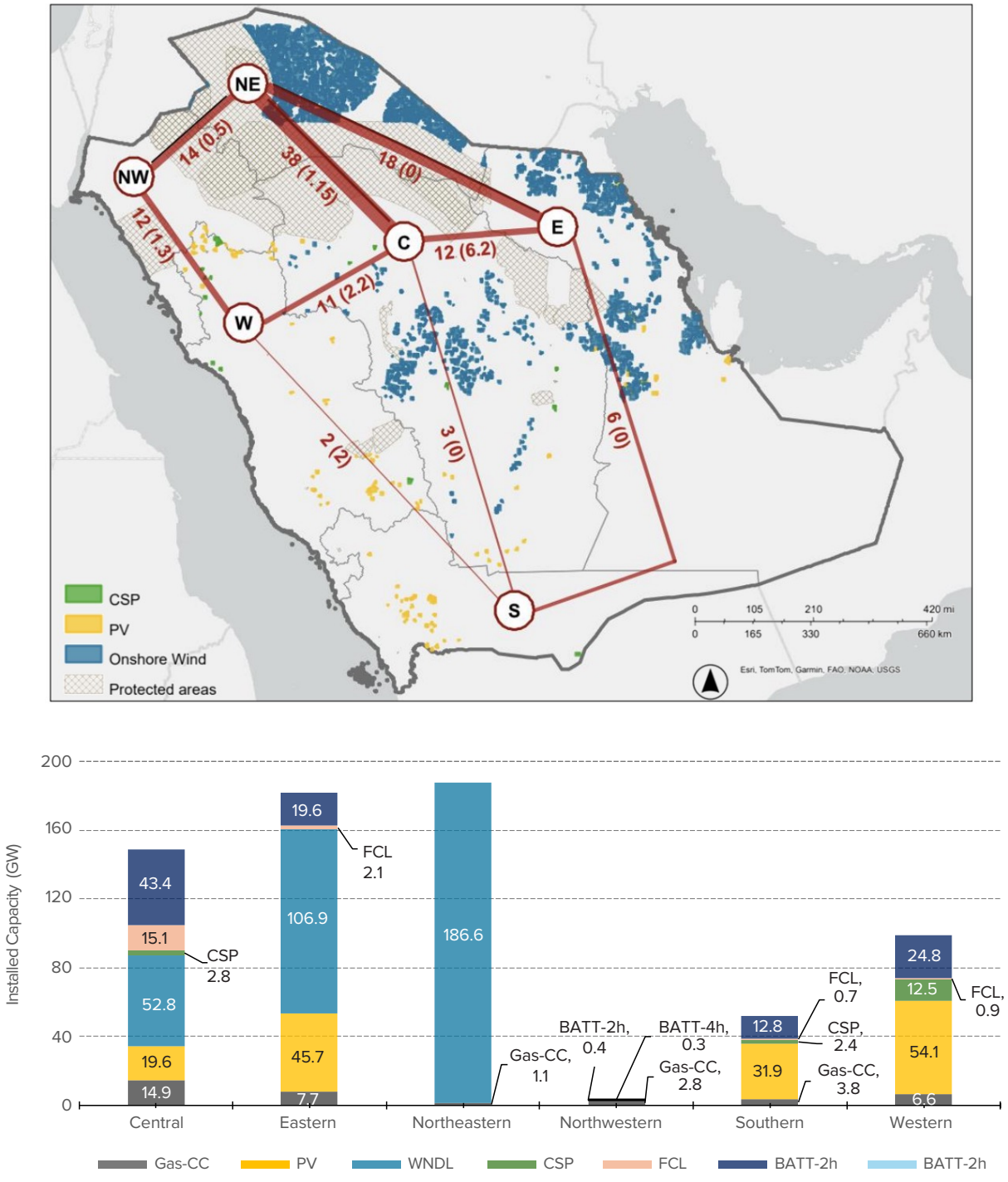
Note: The red demand line represents the electricity demand load only. In the bottom half of the figure, i.e., at negative values, the figure distinguishes between electricity demand (in light green) and demand from storage (in dark blue). Note that in these three specific days chosen in August, there is no electricity load from four-hour storage and electrolyzers.

Effects on Land Use

Here, we estimate the land footprint necessary to deploy the renewable energy capacities that we arrived at above. Six regions were modeled, as shown in Figure 5. As illustrated in Figure 5 for ***ZEP-HiDem***, PV solar is present in four regions, with the highest installed capacity in western and southern regions, where it represents ~55% and 62% of their total capacity shares, respectively. CSP is installed in three regions, with the western region having the largest share at ~13% of its regional installed capacity.

We also see a significant amount of wind energy installed in the northeastern region given its excellent wind resources. However, this region is also characterized by low electricity demand due to its small population and moderate economic activity. Hence, the regional electricity generation from wind far exceeds the regional electricity demand (Figure 6). Consequently, electricity generated from wind power in the northeastern region is mostly exported via the considerable expansion of regional transmission capacities, as shown in Figure 5.

Figure 5. *ZEP-HiDem* regional installed generation capacity and transmission capacities in 2060.



Source: Authors.

Note: The top map in (a) displays the localization of onshore wind (blue), PV (yellow), and CSP (green) for each region, and the transmission capacity connecting a pair of regions in GW. E = eastern region, C = central region, NE = northeastern region, NW = northwestern region, S = southern region, and W = western region. The red numbers adjacent to the lines connecting the regions show the total capacity of the transmission in 2060, while the red numbers in parentheses represent the current transmission line capacity in 2024. In the bottom bar plot in (b), we show the installed capacity within each region by technology in 2060.

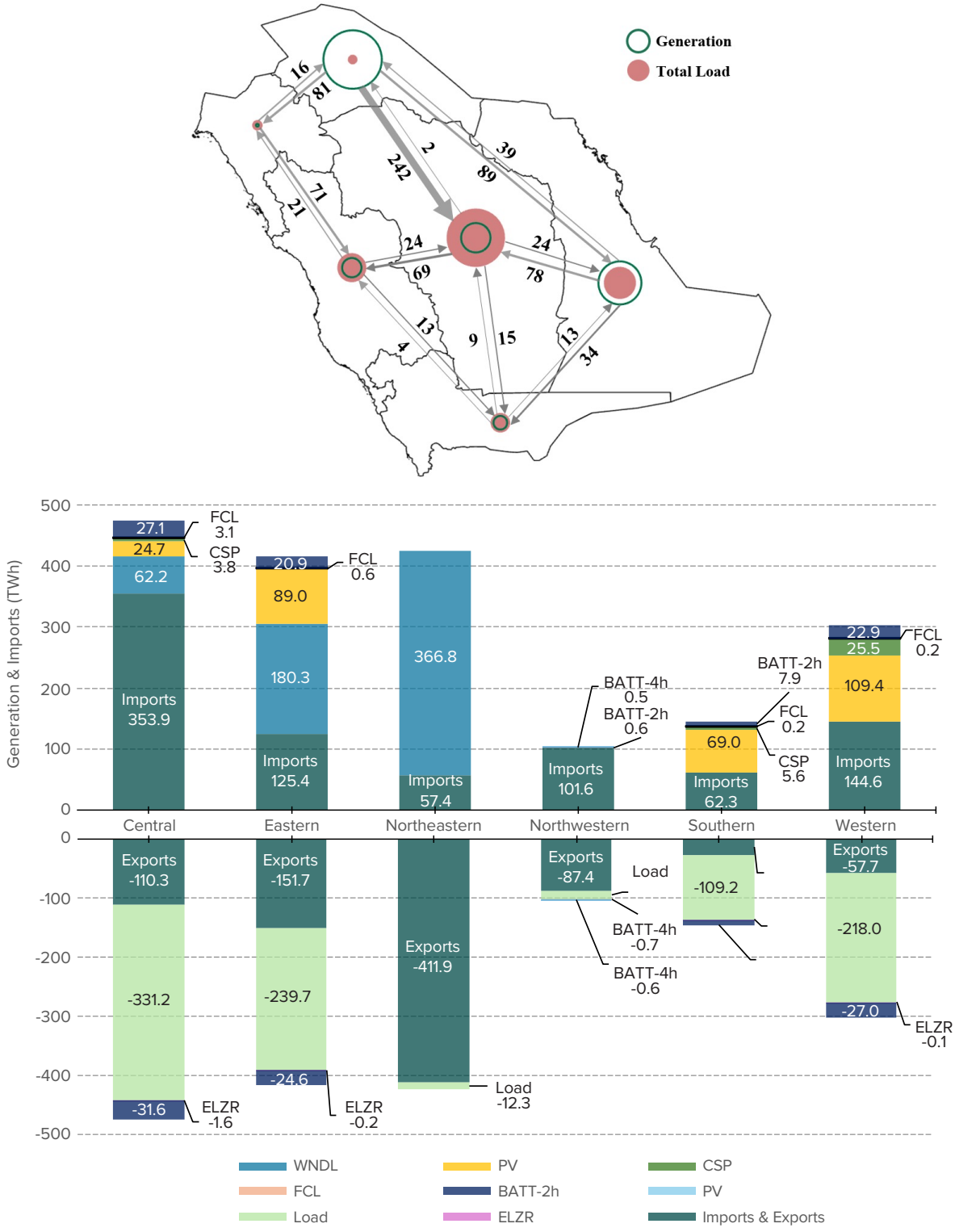
The map in Figure 5 displays the land required to install PV, CSP, and wind across the six regions in the ***ZEP-HiDem*** scenario – the most land-demanding scenario – which we will focus on herein. We restrict the discussion to renewable energy technologies because they require significantly more footprint per unit of installed power compared with conventional generation. Assuming that renewables can be installed within 50 kilometers (km) from existing transmission lines (Al Garni and Awasthi 2017), the 2060 energy mix arrived at earlier can be achieved in all regions without challenges, except for the northeastern region. Overall, our land analysis suggests that the power sector can occupy up to 3.6% of Saudi Arabia's total land area of 2.15 million square kilometers in 2060 in the extreme case (i.e., ***ZEP-HiDem***). Furthermore, wind energy dominates the land area requirements. This is due to its high overall installed capacities and wind's low land use factor (megawatts per square kilometer, or MW/km^2). As a result, wind energy accounts for approximately 94.4% of the total area required for all technologies, covering around 73,059 km^2. Notably, ~54% of this land is concentrated in the northeastern region. If we consider the restriction of needing to install wind within 50 km of existing power lines, the land available for the power sector in the northeastern region (i.e., 18,900 km^2) can accommodate only half of the wind capacities required in the ***ZEP-HiDem*** scenario. However, if we relax this constraint to 100 km, it is possible to accommodate the entire capacity while simultaneously keeping all protected land and sanctuaries untouched.

We also tested a scenario where we incorporate these land constraints in the capacity expansion model. This scenario is named ***ZEP-HiDem-LimGrid*** (refer to "Supplementary Information" for more details). Here, the model resorted to building more capacities in other regions, more line interconnections in the remaining regions, and additional long-term battery storage. Thus, we conclude that land challenges associated with the development of wind power could arise in the northeastern region, but that these are manageable through network expansion, building generation capacity in other regions, and/or relaxing the distance that wind turbines can be built from existing infrastructure.

PV and CSP generation require significantly less land compared to wind energy. Specifically, PV plants cover 4.55% (3,519 km^2) and CSP plants cover 0.9% (700 km^2) of the total area needed for all technologies. Consequently, when compared to the available and suitable areas for these renewable technologies, PV and CSP do not pose any limitations.

From this analysis, including the several runs and iterations we conducted, land resources do not pose any hard constraints for renewable deployment in the Kingdom. Only the northeastern region would require extra attention during the transition. If any land or transmission constraints were to be faced in that region, which would be unlikely, they could be addressed by building additional generation capacity and transmission capacity in other regions.

Figure 6. *ZEP-HiDem* regional electricity generation, inter-regional imports and exports, and regional annual load in 2060.



Source: Authors.

Note: The top map in (a) displays the electricity generated in each region (green circle), the regional electricity demand (pink circle), and the annual inter-regional electricity flows in each direction (gray arrows, with the annual flow in TWh). The bottom graph in (b) shows the generation, load, imports, and exports for each region. The highest inter-regional electricity flow is observed from the northeastern region to the central region (242 TWh in 2060).

Implications for Critical Minerals

Now we move to mineral needs, and we estimate the mineral amounts needed to enable the generation capacities to be deployed within the ***ZEP-HiDem*** scenario and identify where and when material considerations may be critical. Alternative electricity generation and storage technologies require different quantities of materials, e.g., wind turbines require much greater volumes of steel than solar PV panels (European Commission: Joint Research Centre et al. 2020). A critical channel through which critical minerals will impact upon the deployment of generation technologies is through prices. Imbalances between demand and supply will manifest themselves in prices, and this will in turn impact the deployment of technologies, which will then impact demand of minerals. Capturing this endogeneity is extremely challenging due to data constraints. Therefore, we focus on estimating volumetric requirements of the specific capacity expansion in ***ZEP-HiDem*** by utilizing the annual generation and storage capacity installations and retirements from the scenario along with the EV deployment assumptions, and by combining them with a materials intensity matrix (see the "Methods" section for more details).

In addition, a further set of assumptions is required as the material intensity of wind turbines and solar PV panels depends not just on the scale of their deployment but also on assumptions about the specific types of technologies deployed (Calderon et al. 2024). For example, wind turbines may be direct drive or geared, with the latter requiring much smaller volumes of rare-earth elements. We define these types as "sub-technologies," and we note that the material intensity of these sub-technologies can differ significantly – impacting total material requirements. As the capacity expansion projected installations are at a relatively high level, we need to define sub-technology shares (e.g., the share of direct-drive vs. geared turbines for onshore wind). As a starting point, we select shares of these sub-technologies based on predicted market trends (as outlined in "Supplementary Information").

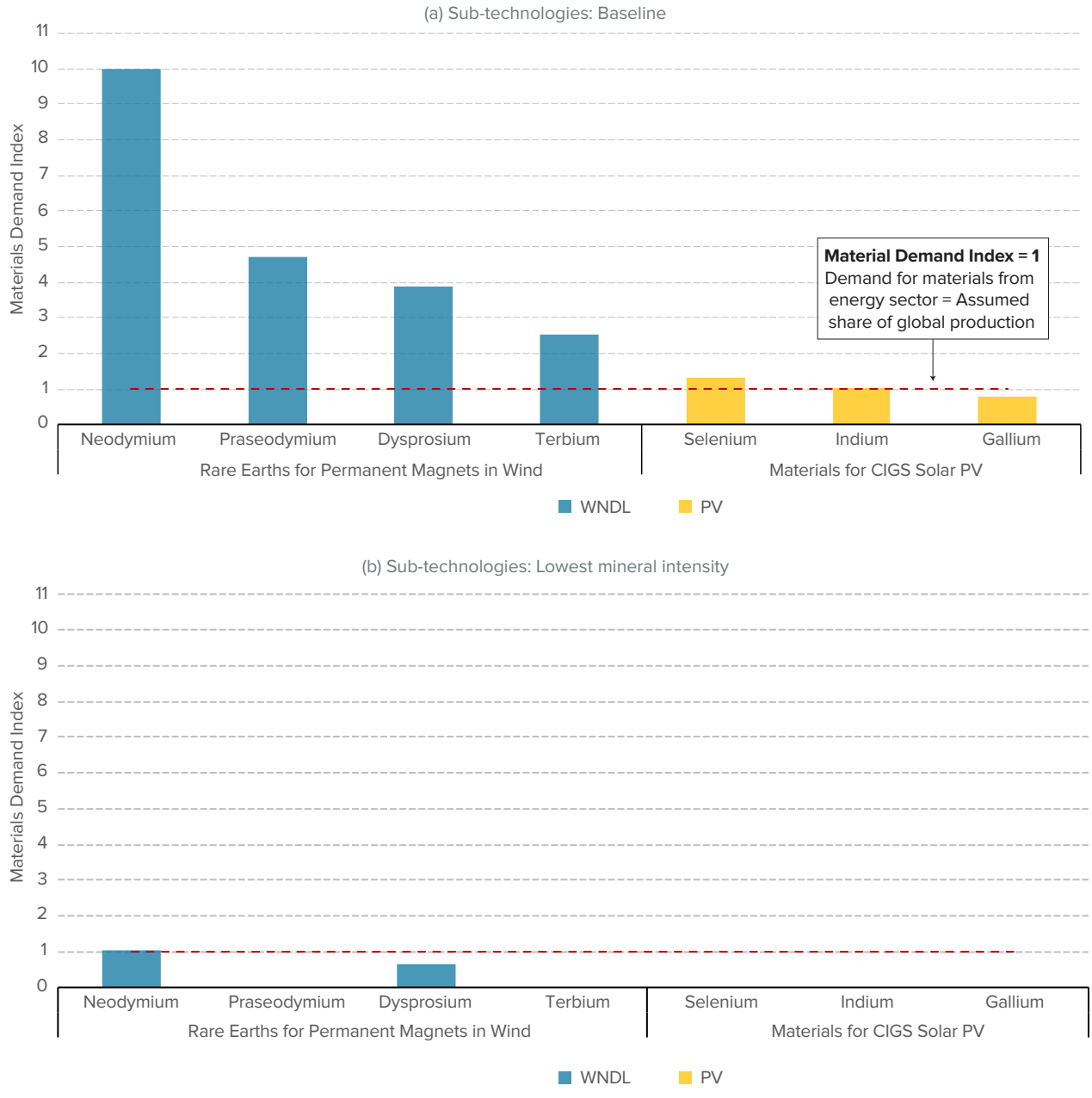
To place tonnage estimates of mineral requirements into context, a further step is required to understand the supply that may be available, which is difficult. Given the challenges in estimating future global supply scenarios for such a variety of materials (38 of them in our case) and other challenges in identifying the amount of this global supply that may be available to individual countries, a "Material Demand Index" (MDI) is utilized. This index is described in "Methods" and "Supplementary Information." It compares the material requirements of the energy sector with an assumed share for the Kingdom of the current global production of each material based on the relative size of the Saudi economy. Conceptually, this measure can be viewed as equivalent to the country's ability to pay for the material. A value of 1 for the MDI means material demand is equal to Saudi Arabia's share of global production; a value larger than 1 means that the demand for the material is higher than what is "allocated" for Saudi Arabia. Ideally, all materials will possess an MDI of less than 1, i.e., indicating the demand for the material is lower than what is allocated for the Kingdom. The lower the MDI, the better – as this allows us to account for the uncertainties in the demand for and supply of a given material.

Using these assumptions and criteria, we identify seven materials in two categories out of the 38 materials considered that pose potential risks to the sought future in the ***ZEP-HiDem*** scenario (defined by having an MDI of greater than, or very close to, 1). The first category of materials, shown on the left in Figure 7a, comprises the rare-earth elements: neodymium, praseodymium, dysprosium, and terbium, which are needed predominantly for the deployment of wind turbines (especially direct drive, which utilizes large permanent magnets). Under our assumptions about sub-technology, the MDI for these materials is considerably higher than 1. The MDI for neodymium is 10 – implying the demand is almost 10 times the assumed level of Saudi's share. The second category, shown on the right in Figure 7a, comprises materials utilized in solar PV capacity deployment, which we assume will be met by thin-film solar PV panels (given global market shares). These materials are selenium, indium, and gallium, which have MDI values close to 1.

In addition, there could be indirect challenges to the materials required for battery storage (lithium has an MDI of 2.5 and cobalt's MDI is 1.4) depending on the scale and nature of EV deployment. While not the primary focus of this research, the adoption of EVs is closely connected to the transition to a net-zero energy system. This is especially true as shortages of battery materials could hinder the deployment of stationary battery storage, even if the demand for such storage is relatively low. These findings highlight that there could be some material limitations to the transition to a zero-carbon power system, with the greatest challenge to the deployment of EVs, which mirrors the findings of Hund et al. (2023) and the IEA (2021b).

The results are, however, highly sensitive to our assumptions about future sub-technology market shares. To highlight this, we develop an alternative scenario that corresponds to the least mineral-intensive (LMI) sub-technologies for solar PV and wind, with the results shown in Figure 7b. Our assumptions are outlined in "Supplementary Information," but, essentially, the sub-technology with the lowest mineral intensity of those metals deemed to be at the highest risk provides all the required capacity. By shifting to this scenario, the MDI of most minerals directly related to power generation and storage falls well below a value of 1. Neodymium, as shown in the left panel of Figure 7b, has an MDI of just above 1. This implies that its demand is approximately equivalent to Saudi Arabia's share of global production.

Figure 7. Materials Demand Index (MDI) for selected materials under the *ZEP-HiDem* scenario.



Source: Authors.

Note: The figure displays the MDI for selected materials for both (a) the baseline sub-technology assumptions, and (b) the lowest mineral intensity (LMI) sub-technology mix. The analysis focuses on the power sector and therefore does not account for the materials used in electric vehicles. The materials shown in (a) had the highest MDI values of all the 38 materials modeled. MDI=1 means that demand for the material from the energy sector is equal to the assumed share of global production.

Even though demand for materials could be met over the entire study horizon on average, there may be specific periods or years when deployment challenges will arise if the situation is not adequately managed. For example, even with the move to the LMI sub-technologies, the MDI for neodymium peaks in the 2050s – potentially creating challenges in sourcing the material unless its global supply increases. There are also features of the Saudi power sector that reduce the materials challenge further than may be the case in other countries. These include the relatively low transmission requirement and the absence of material-intensive technologies such as offshore wind.

Thus far, the mineral demand analysis has only included requirements for energy technologies. However, for some materials, there may also be significant growth in demand from the wider economy, which may cause challenges in securing supplies – even for materials that are below our assumed supply threshold. To capture this, an in-depth analysis was carried out for material, i.e., copper, which has an MDI well below 1 but that is likely to face rising demand from a variety of other sectors. The analysis captures wider demand (from additional installed generation, storage technologies, and EVs, and also from other uses across the economy) and future supply projections (a high global copper supply scenario and a conservative low supply scenario) (Bonakdarpour 2022). Through using the concept of accumulated reserves (the summation of projected annual surpluses or deficits), this analysis highlights where potential copper challenges may occur for Saudi Arabia.

As in the discussion above, copper's use differs across sub-technologies. Given this, Figure 8 shows copper demand from energy technologies across two sub-technology scenarios for (a) solar PV, (b) wind, and (c) other technologies. Figure 8a highlights that shifting solar crystalline silicon (c-si) PV (baseline) to thin film (the least materially intensive use of copper) reduces the demand for copper by approximately 40% in 2025-2030. Figure 8b shows the same effect from shifting from direct-drive wind turbines (baseline) to geared (lowest material intensity). In Figure 8d, the combination of these two demand scenarios (with units on the left-hand axis) and the two supply scenarios (to give four pathways of accumulated reserves shown on the right-hand axis) is shown. This analysis shows that there could be deficits in the copper available to the energy sector in Saudi Arabia in the late 2020s and early 2030s (across all scenarios, as shown by the negative accumulated reserves in that period), and again in the 2050s in the low global supply scenario, assuming baseline sub-technologies (shown in Figure 8d by the solid red line).

The copper shortages projected for the early 2030s result from a combination of relatively small expansions in the global supply coupled with ambitious renewable targets, as per Saudi Vision 2030 (Vision 2030 2024). These shortages could lead to higher prices for copper and, therefore, higher renewable costs during this period. However, given the potential "spare" copper for the energy sector in the decades after the shortages, these challenges could potentially be managed through demand-side measures, such as planning capacity deployment (accounting for possible projected material shortages), and supply-side measures, such as managing accessibility to copper through contractual arrangements.

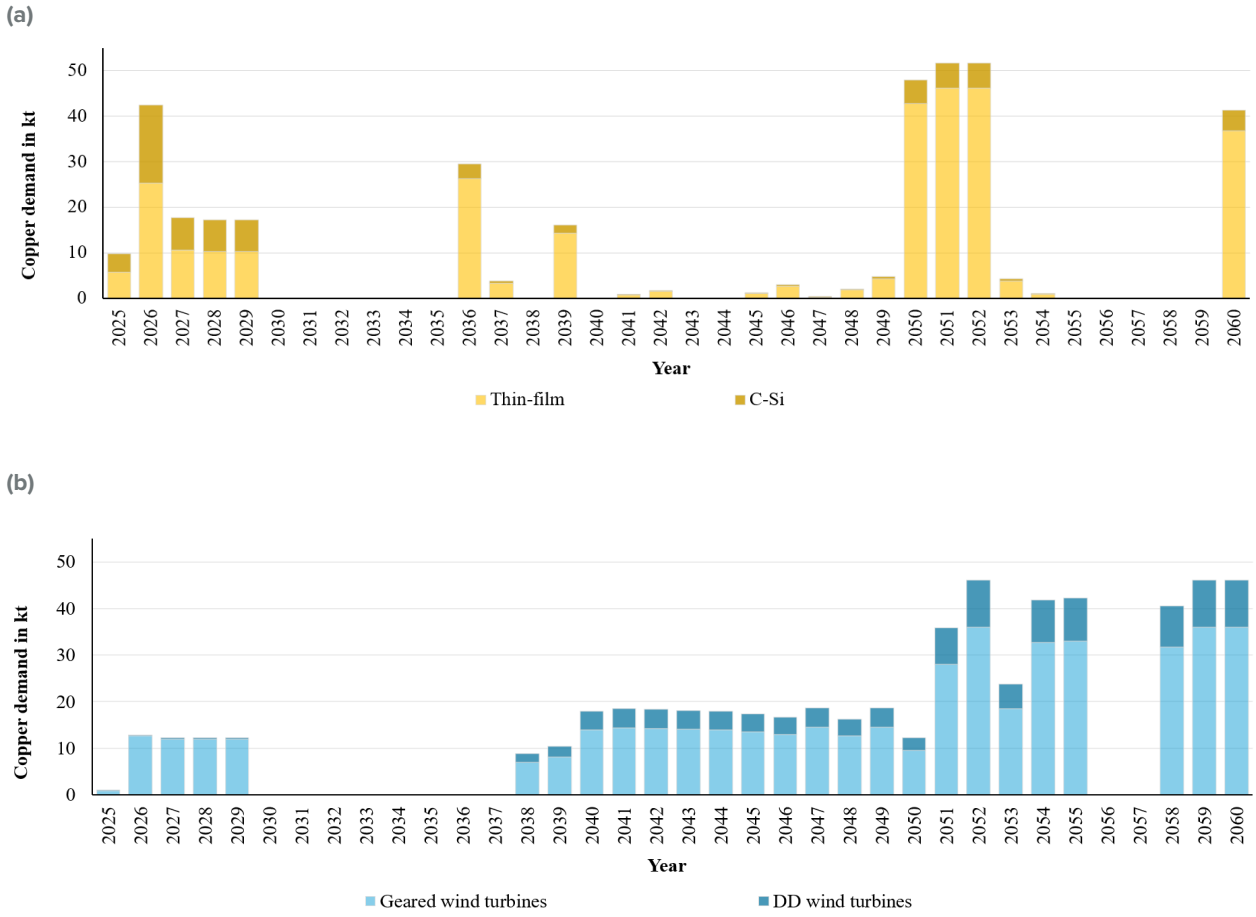
Under a low global supply scenario in the 2050s, however, supply-side management is likely to be more challenging (although increasing domestic supply may help, reducing the reliance on imported copper from a tight global market). In other words, greater demand-side measures may be needed to mitigate these challenges. As shown in Figures 8a and 8b, shifting to less copper-intensive sub-technologies is one option for mitigation (e.g., assuming all the onshore wind turbines built between 2051-2055 are geared rather than direct-drive reduces copper requirements from wind in that period by 22%, or 41 kilotons [kt]). There are further options beyond wind, e.g., shifting solar PV to thin film throughout reduces the overall copper deficit by 38%, while central receiver systems for CSP use just 44% of the copper of parabolic troughs (Watari et al. 2019). Shifting just half of solar PV to thin film and wind turbines to geared throughout the scenario is sufficient to eliminate the copper deficit in the 2050s (purple dotted line in Figure 8d). However, switching to technologies that use less copper, such as thin film, will result in an increased demand for other materials, such as gallium, indium, and selenium (or cadmium and telluride, depending on the technology). Hence, markets should find a suitable balance between these technologies, depending on the shortages, and there is a role here for national planning.

Beyond shifting technologies, there may be further mitigation options for resolving shortages. Copper used in technologies currently employed may also decrease: copper use per MW in thin film technologies is projected to reduce by 29% by 2050 (Gervais et al. 2022), for example, and shortages may encourage even more efficiency improvements. These changes may be induced endogenously through higher prices driven by copper

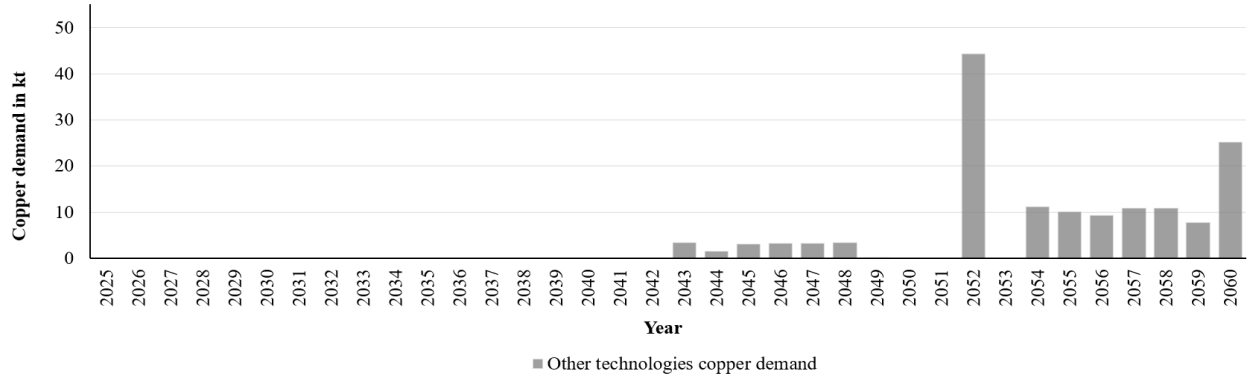
shortages. There may also be a role for regulatory action. Beyond the energy sector, there are substitution options that could mitigate shortages over a longer timeframe up to 2060. For example, aluminum (which is globally and domestically abundant) can be substituted for copper in many applications, including in buildings, but this may require changes in regulations and building codes (IAI 2023).

Depending on the nature of the materials used for transmission, further challenges could arise, though. We have assumed here that transmission would be more aluminum-intensive, given that 90% of Saudi Arabia's transmission lines are high-voltage overhead (SERA 2022b) lines, reflecting current global trends (Bloomberg News 2024). However, should a more copper-intensive system arise, this could increase copper's supply/demand challenges, especially in the 2050s, when a large amount of transmission installation is projected.

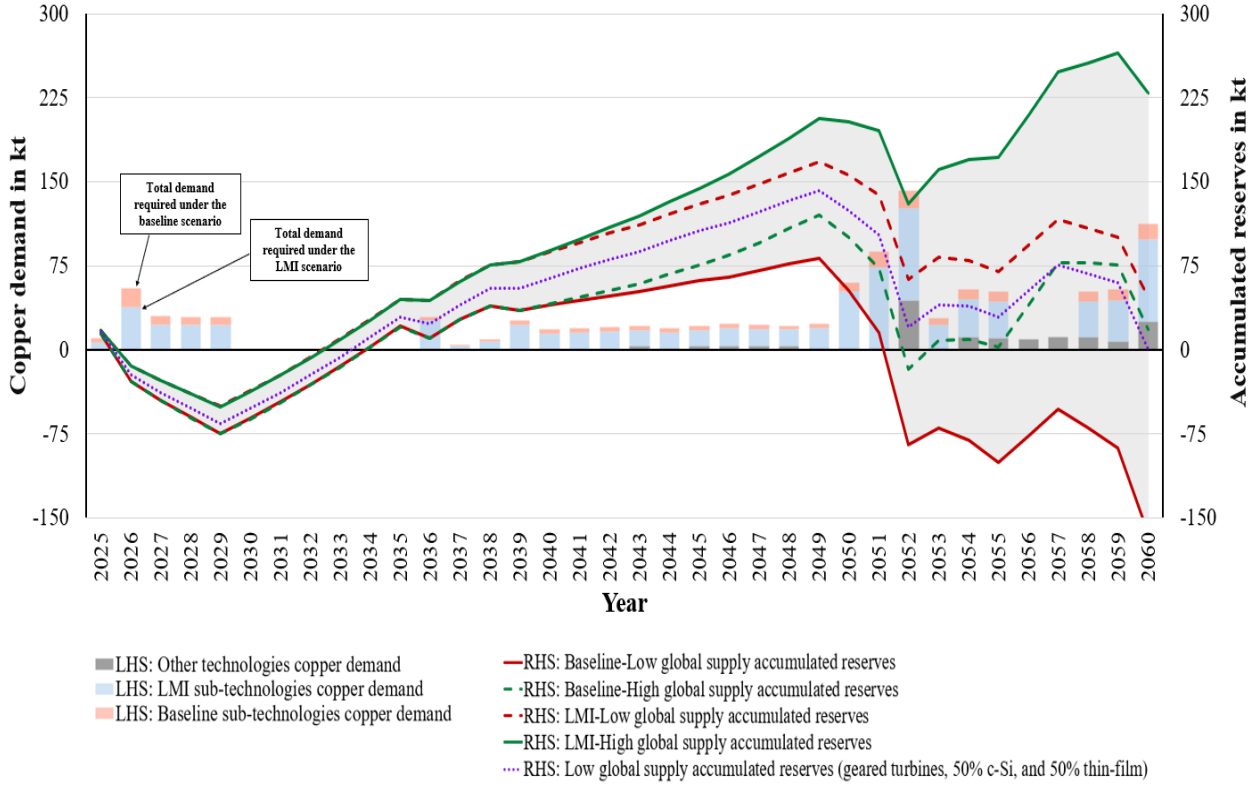
Figure 8. Projected copper to be used within the Saudi power sector alongside Saudi power-sector-specific accumulated copper reserves in the *ZEP-HiDem* scenario.



(c)



(d)



Source: Authors.

Note: Figures 8a and 8b display the annual copper demand from the Saudi power sector from 2025 to 2060 across different sub-technologies represented in bars. Figure 8c shows the annual demand from other technologies (including CSP, battery storage, fuel cells, and electrolyzers). Figure 8d shows the annual total required demand for copper under two scenarios: baseline sub-technologies (solar PV: C-Si, wind: direct-drive turbines) and lowest material intensity (solar PV: thin film, wind: geared turbines). The demand is represented by stacked bars, segmented by technology scenarios, with units on the left-hand axis. The total height of the bars corresponds to the overall demand required under the baseline scenario. Additionally, the combined height of the grey and blue bars represents the copper demand under the LMI scenario. On the right-hand axis, the accumulated reserves of copper specific to the Saudi power sector are represented with lines. The reserves, calculated from the annual surpluses or deficits associated with each technology, are shown for two global copper supply scenarios: a low global copper supply scenario (red lines) and a high global copper supply scenario (green lines). In contrast to the previous lines, which assume either the baseline or LMI sub-technologies for the entire period, the purple dotted line represents the reserves under a scenario incorporating a mix of c-Si, thin-film PV, and geared turbines. In this analysis, we assume that transmission expansion relies exclusively on aluminum and does not require copper. More details on the copper analysis and the two global copper supply scenarios are provided in the "Supplementary Information."

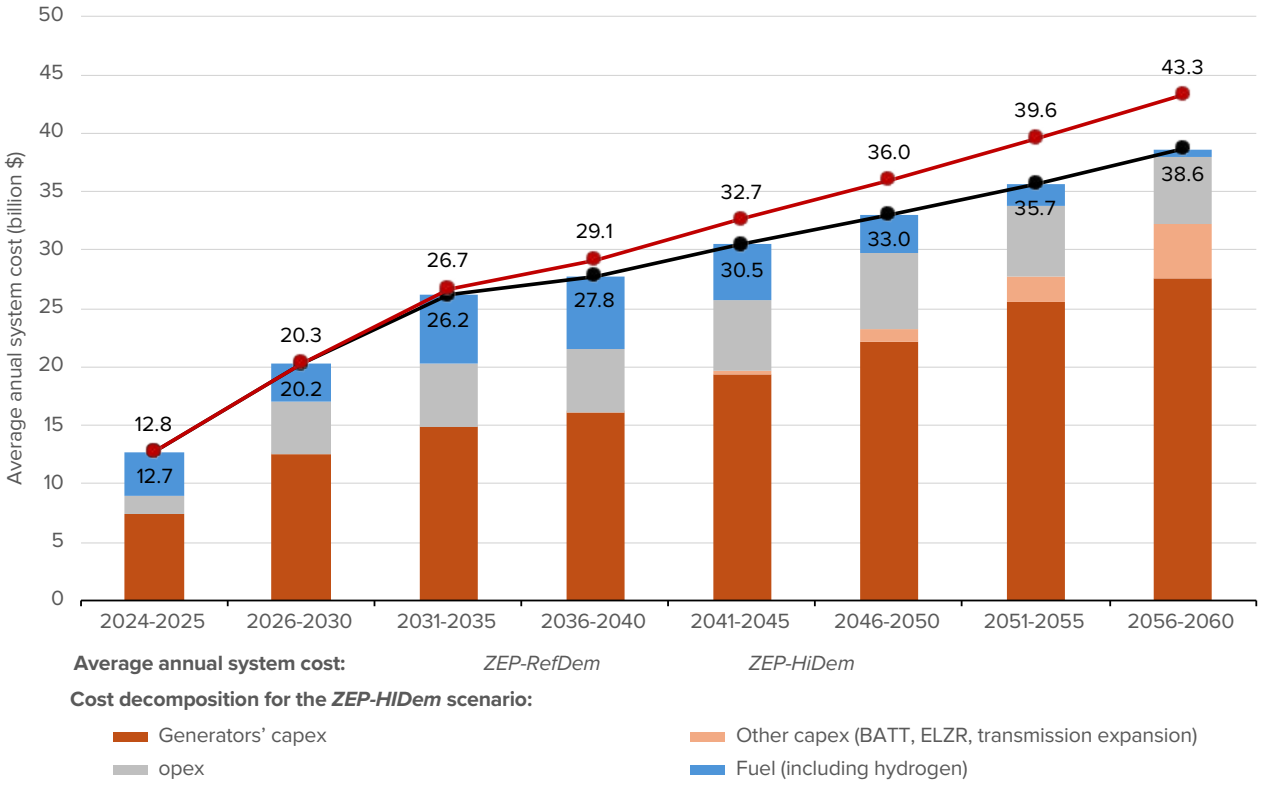
Our analysis has highlighted that there may be material challenges to the transition to NZ power in Saudi Arabia. However, there are mitigation options and substitution opportunities available to craft a pathway through these challenges. When analyzing a wide basket of materials, the most substantial challenges occur in rare earth elements, but options exist in technological substitution (e.g., solar PV for wind) and sub-technologies (e.g., geared turbines for direct drive) to mitigate these concerns. The availability of copper could pose a challenge to the realization of NZ power in the Kingdom. However, there are options available to mitigate these challenges, both in the aggregate up to 2060 and in specific time periods. Selecting technologies and sub-technologies that minimize copper demand, along with material substitution within technologies (e.g., substituting relatively abundant aluminum for copper in transmission), would help to remove demand-side shortages. Incentivizing recycling, expanding domestic supply, and securing supplies from the global market (through overseas investments in mining and processing operations, and through financial instruments such as futures) are supply-side options that could also help to mitigate the challenge.

Policymakers are advised to consider and assess how demand and supply-side opportunities are to be used to manage material constraints. Further, it is important to take a deeper view to assess whether market signals (e.g., higher rare earth prices in times of shortages) are sufficient to drive choices between technologies and sub-technologies (along with incentivizing supply-side opportunities). These aspects that have arisen from the analysis point to several options, including mandating technology (or sub-technology) targets, managing domestic stockpiles of materials, subsidizing/encouraging expansion in domestic materials production, and managing trade-offs between different critical minerals in technology and sub-technology choices.

Implications for System Costs and CDR Competitiveness

Compared with business-as-usual, and as expected, the transition to NZ, along with electricity demand growth, results in a significant rise in the annual cost of electricity generation for the two ***ZEP*** scenarios. The annual system cost includes annualized investments, operational expenditures, and fuel costs for the entire electricity sector represented. The annual system cost of the Saudi power sector in 2060 is 3.6 times that of 2024 in the ***NEP-RefDem*** scenario and 4 times in the ***NZEP-HiDem*** scenario, reaching $44.3 and $49.6 billion, respectively. For comparison, the annual system cost in 2060 is only $27.3 billion in the BaU-HiDem scenario (with no CO_2 cost included). Most of the cost increases observed in the ZEP scenarios (see Figure 9) are driven by the investments needed in generation, which represent 71% of the annual cost in 2060, while transmission grid expansion accounts for only 3%. Over the 2024-2060 period, the net present value of the Saudi power system reaches $453 billion in the ***ZEP-RefDem*** scenario and $477 billion in the ***ZEP-HiDem*** scenario, which corresponds to an increase of 5% and 10%, respectively, compared to the ***BaU-HiDem*** scenario ($433 billion).

Figure 9. Evolution of the average annual cost of the Saudi power system until 2060 in the ZEP-RefDem and *ZEP-HiDem* scenarios.



Source: Authors.

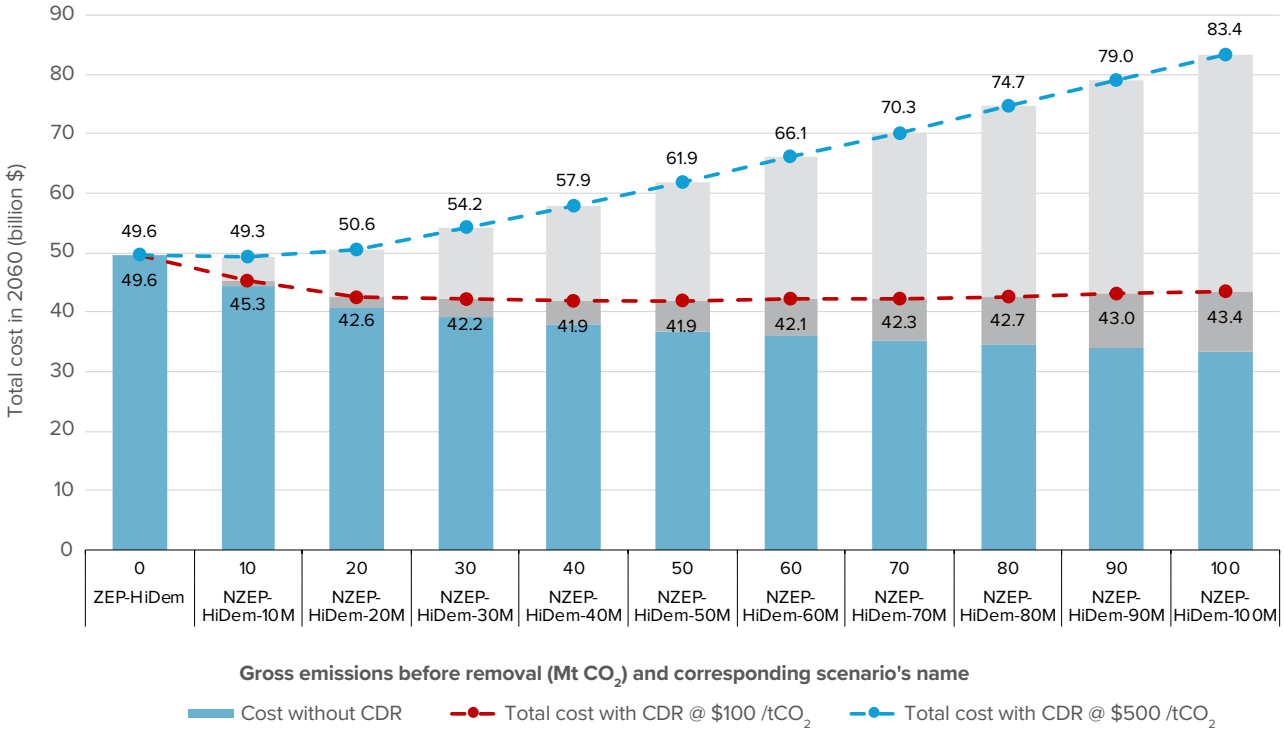
Note: The cost breakdown (capital expenditure, i.e., CAPEX of generation, CAPEX of other technologies including storage, electrolyzers, transmission, etc.; operating expenditure, i.e., OPEX; and fuel) is provided for the ZEP-RefDem scenario only. The average annual cost of the Saudi power system is given for each five-year period in the ZEP-RefDem (black line) and ZEP-HiDem (red line) scenarios.

The cost trajectory follows a similar trend in the ***NZEP*** scenarios. However, given that gross emissions are allowed in 2060, the annual system cost, excluding the carbon removal cost, is lower in these scenarios compared to the *ZEP* scenario. Figure 10 shows that relaxing the carbon emission constraint slightly (i.e., allowing emissions and not capturing or offsetting them) reduces the costs significantly (blue bars). This decrease flattens at 40 $MtCO_2$ in our case. Allowing a relatively small amount of carbon emissions to be released (i.e., not fully reaching NZ) in exchange for substantial cost savings could be a viable strategy for policymakers. However, to achieve NZ as pledged, we could use these cost savings to reduce emissions in other sectors. For example, we note from Figure 10 that the cost of reducing emissions in the ***NZEP-HiDem-10M*** scenario is $4.3 billion, or $430/ton lower than in the ***ZEP-HiDem*** scenario. However, there may be other solutions (even if not available or viable today) that would achieve negative emissions in other sectors at a lower cost.

With a CDR cost of $100/$tCO_2$, the ***NZEP-HiDem-50M*** scenario is the most cost-effective scenario of those tested, with a reduction in the total annual cost in 2060, including CDR, of 16% compared to the ***ZEP-HiDem*** scenario. However, with a CDR cost of $500/$tCO_2$, ***NZEP-HiDem-10M*** becomes the most cost-effective scenario, with a reduction in the total annual cost in 2060, including

CDR, of only 0.5% compared to the ***ZEP-HiDem*** scenario. Our findings are similar to those of Bistline and Young (2022), who conclude that natural gas-fired generation with carbon removal can lower the cost of decarbonizing the power sector.

Figure 10. Annual cost of the Saudi power system in 2060 assuming different annual allowed gross emissions.



Source: Authors.

Note: The figure displays the annual cost of the Saudi power system in 2060 while excluding the CDR cost (blue bars) and the total cost including CDR for an assumed CDR cost of $100/tCO$_2$ (dotted red line) and $500/tCO$_2$ (dotted blue line). The low and high assumptions considered for the CDR cost are derived from the range available in the literature, as further detailed in the "Supplementary Information."

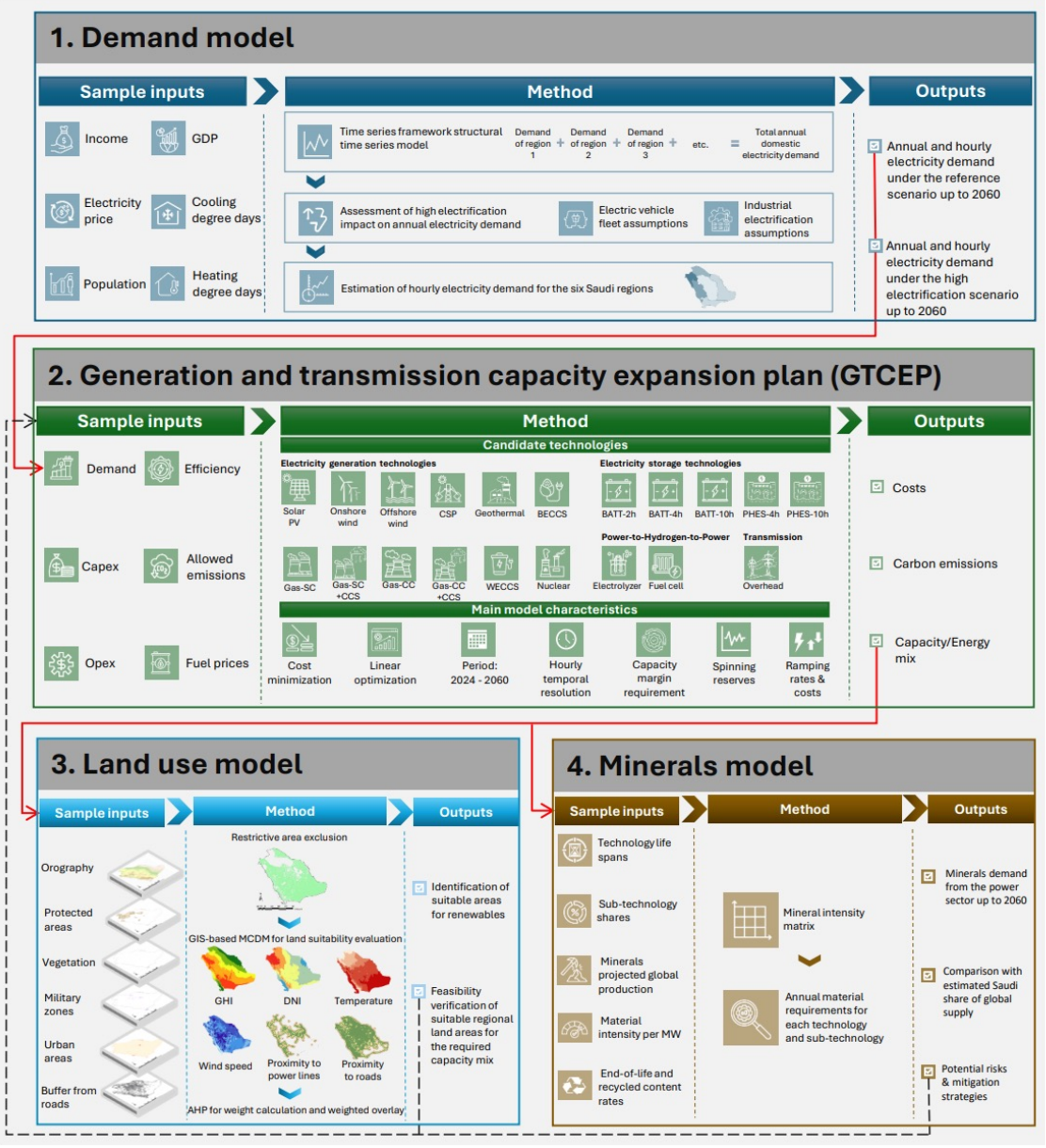
Challenges and Uncertainties

In this research, we have modeled how the Saudi power sector could evolve to become net zero by the year 2060 while simultaneously considering land and mineral requirements. Within the scope of our effort, we conclude that Saudi Arabia's decarbonization goals for its electricity sector are generally achievable. While changing cost and firm capacity assumptions of candidate generation technologies, for example, would change our energy mix, the main conclusion related to materials and land requirements would still, by and large, hold. As with any similar modeling effort, however, limitations and other tradeoffs exist between model realism and tractability (Levin et al. 2023), and these could be grounds for further analysis. For example, it is important to incorporate more weather years (Chandramowli and Felder 2014; Tidwell et al. 2020) and assess how they would impact the energy mix. Further, additional reliability analysis is warranted, given the substantial amounts of renewables deployed. This analysis would include deeper scrutiny related to resource adequacy, system stability, inertia (including grid-forming inverter integration), and other aspects of reliability (Cole et al. 2021). Another enhancement would be future load profile synthesis, given the uncertainty of load profile evolution. The latter is especially important as we expect an increase in transportation and industrial electrification. While our analysis considered two demand scenarios, the impact of different electricity uses, flexible loads, and distributed generation should be also considered (Barrett et al. 2022). More generally, looking into the possibility of achieving negative emissions is also important. Finally, we note that the premise of the analysis assumed no electricity trading with neighboring countries. This assumption, coupled with an expanded list of candidate technologies that may evolve in the future, serves as a foundation for further research.

Methods

Our framework comprises four integrated models with interlinkages, as presented in Figure 11: a demand model, a generation and transmission capacity expansion model (GTCEM), a land-use GIS model, and a minerals model. Next, we describe each model and how they are interlinked.

Figure 11. Overview of the approach and models.



Source: Authors.

Note: Gross domestic product (GDP); capital expenditures (CAPEX); operational expenditures (OPEX); concentrated solar power (CSP); bioenergy with carbon capture and storage (BECCS); battery with two-hour storage (BATT-2h); pumped hydroelectric energy with four-hour storage (PHES-4h); simple-cycle gas turbine (GAS-SC); combined-cycle gas turbine (GAS-CC); carbon capture and storage (CCS); waste-to-electricity with CCS (WECCS); multiple-criteria decision-making (MCDM); analytical hierarchy process (AHP); global horizontal irradiance (GHI); direct normal irradiance (DNI); megawatts (MW).

Demand Forecast Model

Annual Electricity Demand in the RefDem Scenario

The annual reference demand is obtained from a region-specific electricity demand model for Saudi Arabia. Electricity demand per capita is defined as a function of per capita real income, the electricity price in real terms, cooling degree days, and heating degree days (Mikayilov and Darandary 2024). The model utilizes the general-to-specific modeling approach (Hendry and Doornik 2014) and is implemented through Autometrics (a multipath search machine learning algorithm) (Doornik and Hendry 2013). This estimation (Mikayilov and Darandary 2024) identifies income and price as the primary drivers of electricity consumption in Saudi Arabia. The general functional specifications used in the empirical estimations are as follows:

$$dele_{t,r} = a_0 + \sum_{1}^{2} a_i\, dele_{t-i} + \sum_{0}^{2} a_i\, \beta_i inc_{t-i} + \sum_{0}^{2} \gamma_i p_{t-i} + \sum_{0}^{2} \delta_i\, CDD_{t-i} + \sum_{0}^{2} \emptyset_i\, HDD_{t-i} + \sum_{1}^{T} \vartheta_i\, IIS_t + \sum_{1}^{T} \tau_i\, SIS_t + \sum_{1}^{T} \varphi_i\, DIIS_t + \sum_{1}^{T} \omega_i\, TIS_t + \varepsilon_t$$

where *dele* is the demand for electricity in each region *r* at time *t* and is a function of real income per capita (*inc*), *p* is the real inflation-adjusted electricity price, *CDD* is cooling degree days, and *HDD* is the heating degree days. All variables are expressed in logarithmic form, and T is the number of observations. The Auto-metrics approach also enables the identification of potential exogenous interventions, *IIS*, *SIS*, *DIIS*, and *TIS*, which represent the impulse indicator saturation, step indicator saturation, differenced impulse indicator saturation, and trend indicator saturation dummies, respectively. Additionally, it examines parameters for potential variability over time using the multiplicative-indicator saturation approach (Ericsson 2012; Castle, Hendry, and Martinez 2017; Castle and Hendry 2019). The parameters $a_i, \beta_i, \gamma_i, \delta_i, \emptyset_i, \vartheta_i, \tau_i, \varphi_i,$ and ω_i are estimated within this framework, while ε_t represents the error term.

The methodology encompasses two steps. In the first step, all theoretically related variables are fixed with two lags, and intervention dummies are chosen based on the chosen significance level. In the second step, we fix the chosen dummies, and the final model is determined on various diagnostic tests. The multipath selection process is performed by the PcGive econometric modeling program (Doornik and Hendry 2018). Electricity prices are assumed to be constant in real terms, with inflation assumed to grow by 2% per year (Oxford Economics 2024). For GDP and population growth, we sourced Oxford Economics' growth rate projections for Saudi Arabia to 2050 and extrapolated the inherent growth rate until 2060.

Method to Derive the Annual Electricity Demand in the HiDem Scenario

To estimate the demand for electricity from electric vehicles in the ***HiDem*** scenario, we first project the number of vehicles in Saudi Arabia out to 2060, given our population assumptions and considering a fixed ratio of vehicles per person. Second, we derive the electricity demand based on the latest available Saudi data, which suggests that each electric vehicle would require an average of 94.7 TWh per year (Sheldon, Dua, and Alharbi 2023; Sheldon and Dua 2021), split between the regions based on population distribution.

In the ***HiDem*** scenario, we also assume that some industries will be progressively electrified between 2030 and 2060. Our literature review suggests that industrial electricity demand would increase by 10% at the 2050-5060 horizon due to electrification (Mai et al. 2018; Guminski et al. 2019; Li et al. 2023). Following this trend, we assume that the electrification of industries increases the industrial electricity demand linearly between 2030 and 2060, rising eventually by +10% in 2060. This is applied at the regional level, based on the share of total electricity demand that industrial demand represents (SERA 2022a).

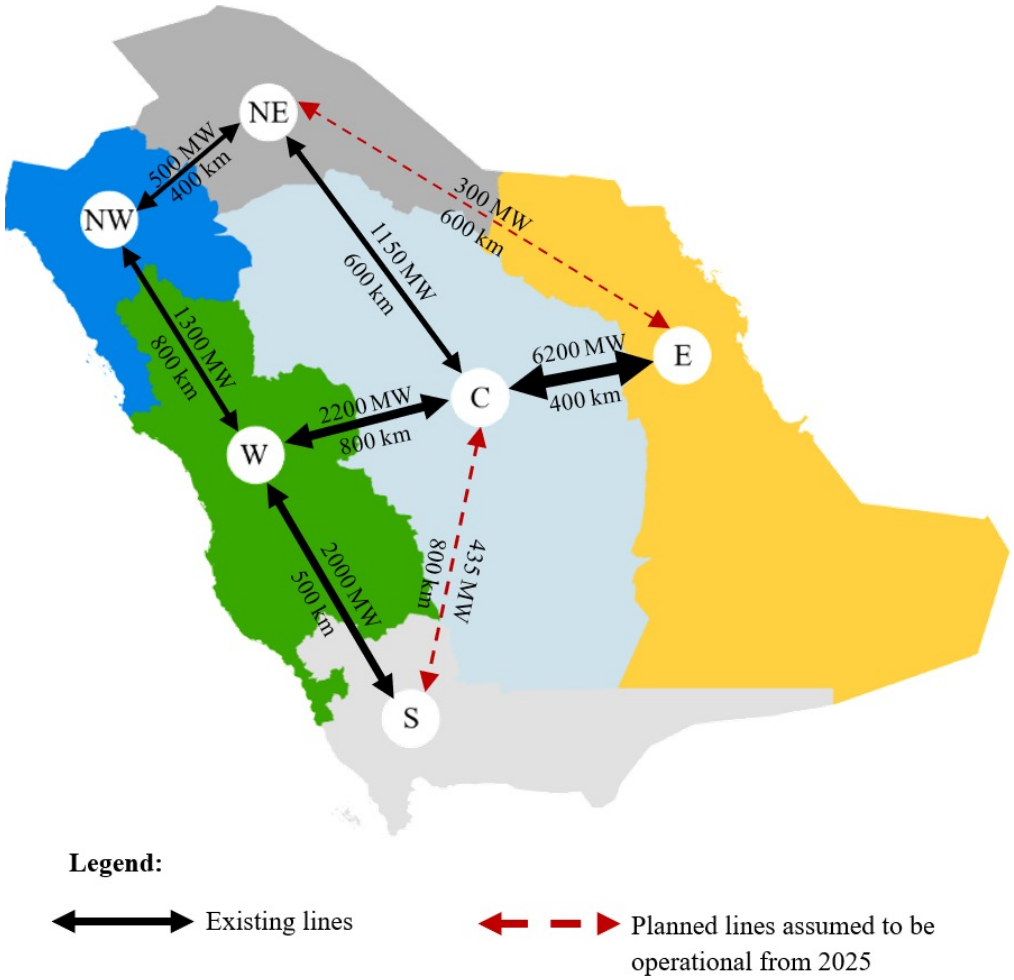
Method to Estimate the Hourly Demand Profiles for the Six Saudi Regions

For the ***RefDem*** scenario, the hourly electricity demand is derived from the annual demand by applying the 2018 historical profiles of each region, respectively. For the ***HiDem*** scenario, the historical hourly profile is modified to reflect the high electrification rate due to EVs and the electrification of industries. The annual electricity demand from EVs is converted to an hourly load by using the load patterns estimated in Almutairi et al. (2023), assuming 50% of the EVs charge at home and the remaining 50% at workplaces. For the additional electricity demand from the electrification of industries, we consider a constant hourly load, using an optimistic scenario with rapid technology advancement that allows industrial load profiles to be more predictable and stable (Mai et al. 2018; Jadun et al. 2017). This demand calculation is used as a fundamental input to the capacity expansion model, which is discussed in the next section Castle, Hendry, and Martinez 2017).

Generation and Transmission Capacity Expansion Plan (GTCEP)

The evolution of the Saudi electricity mix between 2024 and 2060 is obtained from a generation and transmission capacity expansion model (GTCEP) with an hourly temporal resolution, implemented via the commercially available software package PLEXOS. The GTCEP is a major development to the original KAPSARC Power model previously used (Elshurafa and Peerbocus 2020; Elshurafa et al. 2021; Soummane et al. 2023; Darandary, Mikayilov, and Soummane 2024). It has been significantly enhanced with the latest data on candidate technologies, technology performance, costs, interregional transmission line capacities, etc., and the simulation horizon was extended to 2060. All data used is shared in the “Supplementary Information” section, and the demand input/projections are taken from the demand model explained above. The GTCEP is formulated as a linear cost-minimization problem considering the constraints, technology capabilities, and financial assumptions associated with each technology. It includes 18 technologies, including generation and storage technologies, P2H2P, and transmission, as detailed in Table 1. It considers six interconnected Saudi regions with their respective transmission capacities, as presented in Figure 12.

Figure 12. The six Saudi power-system regions considered in the GTCEP.



Source: Authors.

Note: Each of the six Saudi regions is represented as a single node with its specific representative hourly load and renewable energy potential, and is discussed in the demand model section. The black arrows represent existing inter-regional transmission capacities, and the red dotted arrows are those planned to be operational from 2025. E = eastern region, C = central region, NE = northeastern region, NW = northwestern region, S = southern region, and W = western region.

Generation and transmission capacity expansion plan models can be challenging to implement in practice, depending on the country-specific context, the level of detail in the generation and network representation, and the study horizon. Given the large model size and the long horizon extending to 2060 (i.e., 37 years from 2024 to 2060, inclusive), the GTCEP used here was run in a linear optimization mode to reduce the problem size and the memory requirements. The long-term expansion plan was performed with 12 representative days each year for the simulated period 2024-2060. We also performed an hourly dispatch for all 8,784 hours in 2060, which is a leap year. The latter temporal detail is crucial as it goes beyond other high-level studies where only an annual energy balance between supply and demand is met. Annual energy balance analyses generally underestimate the capacities required to meet demand. When storage and renewable technologies are involved, the annual supply-demand balance is not enough for many reasons. These include the facts that the hours of renewable energy production will not always coincide with demand hours, that excess renewable production may be curtailed/dumped or stored depending on battery capacities and their state of charge, and that energy flows completely disregard transmission constraints.

Up until 2030, the model includes some planned renewable energy additions, as announced publicly. Further, note that we do not vary the prices of liquid fuels, as the Kingdom has decided that liquid fuels will be retired from its power sector by 2030. The cost and technical assumptions of all the technologies are detailed in "Supplementary Information." The model is run with a 5% discount rate for all the technologies (Elshurafa et al. 2021). Finally, the model also includes specific constraints to represent a required installed capacity reserve margin, an operating reserve, and an annual cap on CO_2 emissions (see "Supplementary Information" for more details).

Land Use Model

The results from the GTCEP above were used as one input, among others, to the land use model. The land availability model was mainly used subsequentially to the GTCEP. This is because it allows for a detailed land analysis and thus produces more relevant insights than including the land constraint directly into the GTCEP from the very beginning. However, some feedback was also considered (i.e., from the land use model back to the GTCEP model, as shown by the dashed black arrow in Figure 11). This resulted in some additional scenarios that were tested and that contributed to our overall analysis (refer to the "Supplementary Information" for more details).

The land-use model utilized a combination of GIS and multi-criteria decision-making (MCDM) techniques, recognizing that evaluating suitability is a complex issue influenced by multiple factors. The applied framework involves defining constraints for the exclusion map, which removes areas deemed unsuitable, and evaluation criteria. It then requires collecting relevant geospatial data and using various spatial analysis tools to derive surface, geometric, and distance parameters. The energy mix arrived at from the previous model is also taken as an input to this model to assess the land use requirements.

The analysis classified criteria into constraints and evaluation criteria. Constraints were used to exclude unsuitable areas, while evaluation criteria were employed to rank the suitability of each area for various renewable resources. Constraints were selected based on principles from the National Renewable Energy Laboratory and previous studies (Nebey, Taye, and Workineh 2020; Al Garni and Awasthi 2017; Li 2013; Albraheem and AlAwlaqi 2023; Ibarra et al. 2017). These constraints included topographical and land coverage factors. For example, certain slopes and aspects were excluded for each renewable technology, as well as protected areas, military zones, vegetation zones, water bodies, urban areas, and a 500-meter buffer from roads. Evaluation criteria encompassed orography, climatology, and location proximity. Climatology criteria included global horizontal irradiation for PV, wind speed for onshore wind, direct normal irradiation for CSP, and temperature for both PV and CSP. Orography criteria involved slope, which was common to all technologies but varied in degree, and aspect (orientation) for PV and CSP. The location proximity criteria considered distances from power lines and roads and is applicable to all renewable technologies. Further details can be found in "Supplementary Information".

Since the criteria had different ranges, values, and units, they were standardized by reclassifying them into nine classes ranging from 1 to 9. A pairwise comparison matrix was then constructed for each renewable energy type to determine the weights of each criterion. More details on these matrices can be found in "Supplementary Information." Following this, a weighted overlay was implemented to establish the final suitability rankings, scaled from 1 (least suitable) to 5 (most suitable), thus creating suitability maps for PV, onshore wind, and CSP. Finally, a composite suitability map for all renewable types

was developed to avoid spatial overlap by comparing the suitability rankings in each area and designating the highest-ranked renewable technology for that location. After determining the total regional land areas (km^2) for each renewable energy type from the final suitability map, land use factors (MW/km^2) were applied to calculate the land requirements for the capacity mix from the GTCEP model to ensure that the deployment of each renewable type was feasible at the required regional level.

Mineral Model

The minerals model covers the demand for 38 materials needed for the various power generation technologies. The model follows demand estimations by Hund et al. (2023), the IEA (2021b), and Watari et al. (2019). The material intensities matrix is extracted from the wider literature (see "Supplementary Information"). This matrix is then combined with installed capacity estimations and assumed (fixed) recycling rates to produce estimates of annual primary material demand requirements, which are then compared to current annual global production levels.

The matrix covers the technologies included in the power expansion model above (except for WECCS and BECCs), and also includes electric vehicles (lithium-ion batteries and motors). For a group of the technologies (solar PV, CSP, wind, batteries), the matrix contains intensities for a set of sub-technologies (e.g., geared, direct-drive wind), giving a greater granularity than the NZ power sector modeling. Sub-technology shares were assumed for this group (discussed further below). The matrix covers intensities up to 2060 and, where possible, covers intensity changes as projected in the literature.

These assumed material intensities are combined with the projected built and retired capacity and assumed recycling rates (end-of-life and recycled content rates). These are predominantly drawn from Graedel et al. (2011). It is assumed that materials from within the energy sector are recovered at end-of-life rates, with materials required from outside the energy sector following the recycled content averages. These recycling rates are assumed to be fixed over the time period. Primary material requirements for the transition of Saudi Arabia's power system to net zero through 2060 are computed from these assumptions. To contextualize these estimates, they are compared to current global annual production (2023 unless unavailable) and reserves (where available). Given the importance of sub-technology shares to minerals demand (e.g., geared vs. direct-drive wind turbines), two sub-technology scenarios were examined – a baseline and a lowest mineral sub-technology scenario. The details of these are outlined in "Supplementary Information".

A Materials Demand Index (MDI) was computed to understand material demand in the context of global supply. A share of current global annual production equivalent to the current Saudi share of global GDP was assumed, and this was then compared with average annual material demand. If the country's production share was equal to the demand from the Saudi energy sector, then the index has a value of 1, with higher values indicating higher demand than the country's production share, and lower values showing demand at levels lower than the assumed production share.

An in-depth analysis of copper was undertaken utilizing two copper supply scenarios, considering improved utilization and recycling rates versus historical trends, as guided by the S&P Global report (Bonakdarpour 2022) and the prioritization by Saudi Arabia of its non-electricity sectors, aligned with its blueprint for economic growth. One scenario assumes improvements in both mine utilization and recycling rates (high global supply), while the other scenario anticipates a tighter global copper supply due to the assumed historical trends in capacity utilization and recycling rates over the past decade (low global supply). Saudi Arabia's share of the global copper supply is maintained at its current level (Puri-Mirza 2022). We prioritize the allocation of copper supply for Saudi Arabia's non-electricity sectors, aligning it with the country's projected annual GDP growth rate. Two sub-technology scenarios were utilized on the demand side – a baseline scenario based on current market trends and a lowest mineral intensity scenario, which assumed that all technology deployment would follow the lowest copper-intensive sub-technology. We then estimated the copper demand from the electricity sector as described in "Supplementary Information" and compared it to the projected supply to produce annual surpluses and deficits, which were then summed into accumulated reserves. This assumes that historical surpluses can be stored and deficits offset, either through physical storage of the material or through suitable financial instruments, such as future delivery contracts.

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Authors' Note

Data and Code Availability

The data and models/codes that supported the findings of this article are available from the authors on reasonable request.

Contributions

KA and MP were responsible for data collection, model development and the simulation of the power module, results analysis, and writing, reviewing, and editing the original draft. AD was responsible for data collection, model development and the simulation of the demand module, results analysis, and writing, reviewing, and editing the original draft. SA was responsible for data collection, model development and the simulation of the geospatial module, results analysis, and writing, reviewing, and editing the original draft. TL was responsible for data collection, model development and the simulation of the mineral module, results analysis, and writing, reviewing, and editing the original draft. FF was responsible for overall results analysis, validation, writing, and editing the original draft. AE conceived the idea and was responsible for the methodology, model development, project administration, and reviewing and editing the original draft.

Competing Interests

The authors declare no competing interests.

Additional Information

Supplementary information is provided.

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[2] *https://transparency.entsoe.eu.*

About the Project

This study falls under the “Assessment of the Changing Economics of the Saudi Electricity Industry” project within KAPSARC’s Utilities and Renewables program. The study evaluates the feasibility of Saudi Arabia’s power sector reaching net-zero emissions by 2060 using four integrated models. These include a generation and transmission capacity expansion model (GTCEM) with hourly resolution, a materials model tracking 38 key resources, a GIS-based land use model, and an economic demand model. This comprehensive approach, applied for the first time for Saudi Arabia, provides insights into costs, resource needs, and strategies for a sustainable energy transition.



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