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Cross-border electricity trading in the GCC countries, Egypt, Jordan and Iraq: Hourly market coupling or bilateral agreements?

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ABSTRACT

Cross-border electricity trading in the Middle East and North Africa region can provide cost and environmental benefits. Several projects of interconnectors are on-going or under consideration in the region, and policymakers must develop the appropriate contractual scheme to trade electricity. Based on an economic dispatch model at the 2030 horizon, this paper investigates implications of the electricity trade in the Gulf Cooperation Council countries plus Egypt, Jordan, and Iraq. The model adopts an hourly resolution, accounting for time zone differences between countries, and considers current and future network interconnections. The results indicate that implementing an hourly market coupling, formulized as a regional cost-based power pool, can decrease the region's annual generation cost by 1.6 % on average, while avoiding 35 % of renewable curtailment and reducing carbon dioxide (CO_2) emissions by 8 million metric tons in 2030.

Developing full-fledged regional markets in the region would require political commitment, time and financing. As an alternative compromise solution, we explore how bilateral long-term arrangements could support electricity trade. Specifically, we simulate and analyze physical contracts on the interconnector between Egypt and Saudi Arabia (the two largest power systems of the region), integrated to the rest of the region through volume coupling. The results show that the contracted volume profile of such contracts can significantly influence the benefits reached at the regional level. Among the volume profiles considered, the daily profile contract, which follows a daily pattern with an hourly timestep, provides the most benefits to the region.

1. Introduction

While the Gulf Cooperation Council (GCC) countries and the broader Middle East and North Africa (MENA) region have historically relied on national fossil-fuel resources to generate electricity, the overall region is on a pathway toward transitioning to renewable energy sources of electricity [1–4]. There is also growing interest in developing electricity trading in this region, as evidenced by both the academic literature and ongoing or completed interconnection projects on the ground. One of MENA's most significant efforts to interconnect electricity systems is the Gulf Cooperation Council Interconnection Authority (GCCIA) link that connects Saudi Arabia, Kuwait, Bahrain, Qatar, and the United Arab Emirates (UAE) through high voltage direct current (HVDC) links. Other projects are also underway to interconnect Saudi Arabia with Egypt, Jordan, and Iraq. Recently, after many years of discussions, the Arab League signed an agreement in December 2024 to launch the Arab Common Electricity Market [5].

The benefits of cross-border electricity trading are well documented in the literature. It can bring cost-savings by reducing unserved energy, decreasing variable generation costs, lowering the costs of ancillary services, and avoiding or deferring investment in generation assets [6]. When renewables account for a significant share of the generation mix, developing internal networks or interconnectors between countries also helps reduce the curtailment of renewable energy [7–9]. Developing more interconnectors can constitute a cost-effective option to reach very high penetration of renewables [10,11]. Similarly, interconnectors can also play a role in reducing greenhouse gas emissions [12,13]. Despite the technical and political challenges, some papers have explored interconnections on a global scale [14–16].

Efforts to expand regional electricity trading in the MENA region are widespread [17,18]. Similar to other regions, MENA electricity trade could substantially reduce the cost of achieving a 100 % renewable electricity system [19]. To enable regional electricity trade in the MENA region, where administratively set fuel prices prevail in the power

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Table 1
Review and comparison of relevant literature.

	Timilsina and Curiel [18]	Aghahosseini, Bogdanov, and Breyer [19]	Fälth et al. [28]	De Monts de Savasse [29]	This paper
Modelling approach	CEP	CEP	CEP	Network-constrained economic dispatch	Network-constrained unit-commitment
Horizon	2018–2035	2014–2030	2040 (green field)	2016 & 2030	2030
Geography	MENA	MENA	MENA	GCC	GCC, Egypt, Jordan, and Iraq
Network constraints	Interconnectors between countries	Interconnectors between countries	Interconnectors between countries	Interconnectors, and simplified transmission network for KSA and UAE	Interconnectors between countries
Operational reserves	Yes	No	No	No	Yes
Electricity trading	Hourly market coupling	Hourly market coupling	Hourly market coupling	Hourly market coupling	Hourly market coupling
Bilateral contracts	No	No	No	No	Yes

Note: CEP= Capacity Expansion Planning (generation only or generation and transmission). GCC = Gulf Cooperation Council. MENA = Middle East and North Africa.

sector, wholesale electricity pricing mechanisms that handle international trade with domestic fuel pricing are needed [20–23]. Specifically, removing fossil fuel subsidies for electricity generation and expanding cross-border trade across MENA countries would bring economic savings and reduce carbon dioxide emissions ([24], [25]).

Despite many studies identifying the benefits of regional electricity trade, none provide results on the specific types of electricity transactions that GCC or MENA countries would engage in. This paper fills this gap by exploring and comparing the benefits of electricity trading in the case of an hourly market coupling versus long-term bilateral agreements based on a network constraint economic dispatch model for GCC countries, plus Egypt, Jordan, and Iraq. Specifically, we compare a cost-based power pool at the regional level to a physical long-term bilateral agreement implemented as volume coupling with the rest of the region. First, the model is used to analyze the implications of a regional hourly market coupling formalized as a cost-based pool among national single buyers. We present implications on trade volume, variable generation costs, renewable energy curtailment, and emissions. Second, we simulate and analyze an alternative trading scheme based on a physical contract between two countries, which is then incorporated into the regional coupling through volume coupling. This is similar to what has been historically done between the Central West Europe (CWE) region and the Nordic market [26]. This choice is motivated by our understanding that establishing regional-level market coupling may take time; therefore, alternative schemes are expected to emerge in the interim. We consider several types of volume profiles for these long-term physical agreements, and test them for electricity trading between Saudi Arabia and Egypt. Our choice to focus on these two countries is motivated by the fact that they possess the two largest power generation sectors in the region.

In the context of the growing interest in electricity trading in the GCC, and the MENA region more broadly, this paper answers two main questions: (1) What are the benefits of an hourly electricity market between the interconnected GCC countries, plus Egypt, Jordan, and Iraq within the 2030 horizon?; and (2) Given their size, what long-term bilateral electricity trade arrangements might emerge between Saudi Arabia and Egypt, and what are the implications for the region? Regarding this second question, the paper assesses the regional benefits these arrangements can bring compared to region-level hourly coupling, but the practical implementation of such physical contracts is left for future investigation. Our results, indeed, inform the possible evolution of a MENA electricity market that garners the most benefits from electricity trading while considering the policy context and specificities of the region.

The remainder of the paper is organized as follows. Section 2 reviews prior studies on regional electricity trading in GCC countries or the wider MENA region. Section 3 presents the methodology and associated model developed to analyze regional electricity trading between Saudi Arabia and its neighbors. Section 4 presents the results obtained from the model with and without hourly electricity trading among the countries, and also for predefined contracts. Specifically, it compares several long-term contractual arrangements between Saudi Arabia and Egypt that differ by the contracted electricity volume. Section 5 discusses these results and situates them within the regional context. Finally, section 6 concludes and suggests next steps.

2. Literature review

Established in 2001, the GCCIA has progressively developed a direct current 440 kV (kV) grid comprising 1049 km of double-circuit overhead lines and submarine cables. The energy traded through the GCCIA has increased continuously since 2016 (2019 was an exception), reaching 1098 GW-hours (GWh) in 2021, for an estimated electricity value of US$ 136 million [27]. However, this interconnection capability is still vastly underutilized, and most of the electricity trade is done 'in-kind'; i.e., there is a net-zero electricity flow between the two trading countries on average over the agreed period, rather than a financial trade. A previous study suggests that if day-ahead hourly trading were implemented and used optimally in 2022, the GCCIA interconnectors could have supported up to 16 TW-hours (TWh) of day-ahead trade, corresponding to potential savings of US$ 200 million annually for the GCC countries [27].

There is a limited but growing body of literature analyzing electricity trading in the GCC and the broader MENA region. It focuses on the feasibility of electricity trading, the impact of fossil fuel subsidies on the amount of trade, the expansion of renewable electricity generation, and the reduction of carbon dioxide emissions in the power sector. Table 1 summarizes the key characteristics of previous modeling-based analyses and shows how our work complements the existing literature. Specifically, the table shows that the novelty of our analysis lies in developing a bespoke economic dispatch model for the region that includes technical details such as operational reserves. Equally important is our modeling of contractual arrangements for cross-border electricity trading. This latter aspect has been absent from the literature thus far. Furthermore, we complete the cited literature by providing a deep analysis of the hourly flows on the interconnectors between Saudi Arabia and its neighbors.

A subset of the literature uses generation only, or generation and transmission, capacity expansion planning models applied to GCC countries or the broader MENA region to investigate how various technologies and trading rules could impact installed capacities and, consequently, the energy mix and emissions. Including an endogenous representation of cross-border electricity flows is particularly important in such models as pointed out in Mertens et al. [30]. Focusing on a similar geographic perimeter than the one in this article, CESI [31] conducts a feasibility study of the electrical interconnection and energy trade (electricity and natural gas) among Arab countries. It finds that an increase in investment in nuclear, renewables, and interconnections could reduce the cost of electricity. Aghahosseini, Bogdanov, and Breyer [19] examine a 100 % MENA renewable electricity system in 2030 and find that it has a lower cost than business as usual. They also compare the same scenario with and without electricity trading for the 2030 horizon and show that electricity trading allows a reduction in total capital expenditure (capex) of 6 % (due to a reduction in installed generation capacities) and a reduction in total operating expenses (opex) of 13 %.[1]

Detailed World Bank studies, based on a capacity and transmission expansion model for the period 2018–2035 [24,32,18], have analyzed the interactions between fossil fuel subsidies, carbon dioxide reduction policies and regional electricity trading. They conclude that all three factors acting in concert would benefit the region. More specifically, the studies find that, based on international fuel prices, electricity trade could lower total electricity costs, including investment costs, by 6.7 %, corresponding to US$ 90 billion in savings over the period 2018-35. Fälth et al. [28] use a green-field linear capacity expansion model to investigate the role of transmission expansion and nuclear power in expanding the MENA region's use of renewable resources. They find that such a system would deliver a lower levelized cost of electricity compared to Europe and that optimal transmission expansion reduces system costs by 5 %–25 %. Taliotis et al. [33] focus on electricity exchanges between the Middle East and Eastern Mediterranean countries by 2050. They use an open-source capacity expansion model to show that, in the current context of limited renewables, there is no need for more electricity trading. However, they also find that in a scenario with climate neutrality goals, it is cost-effective to develop further interconnection infrastructure and, consequently, increase electricity trading in the region.

Another research route opted to keep the installed generation capacities unchanged and focus on the effect of electricity trading on economic dispatch. To the best of our knowledge, De Monts de Savasse [29] is one of the few studies conducted along these lines for the GCC region. The study investigates how to improve the use of the GCC Interconnector to reduce operational costs. It conducts a network-constrained multiperiod economic dispatch with a detailed network representation of GCC countries and GCCIA interconnectors. It finds that the operational costs of GCC electricity trade could be reduced by about 2 % when international fuel prices are considered for dispatch.

The GCC and/or broader MENA regions have also been discussed using more qualitative or energy-wide approaches. El-Katiri [34] highlights the political and legal frameworks, alongside information and transparency, necessary for the GCC to move toward more electricity trading. Other qualitative discussions stress the importance of removing fuel subsidies and developing electricity trading in the GCC or MENA region to support their respective energy transitions [35,36].

The literature discussed above, however, does not investigate the trading benefits of the specific types of cross-border transactions that countries may consider and their implications for the evolution of the region's electricity market structure. In addition, although electricity trading is discussed, these papers generally provide annual cost comparisons without detailing hourly trends or the drivers of trade.

This paper complements the existing literature by building a power sector model for the GCC, Egypt, Jordan and Iraq, with a network-constrained economic dispatch formulation at an hourly resolution for the year 2030. We use this model to assess hourly trends and drivers of cross-border electricity exchanges. Further, the model is used to simulate and analyze, for the first time, different bilateral contractual arrangements between Saudi Arabia and Egypt, one of the unique aspects of this paper that distinguishes it from previous studies.

[1] See Table 3 in Aghahosseini, Bogdanov, and Breyer [19]. It is important to note that this reduction in opex of 13 % is for two different installed generation capacity scenarios.

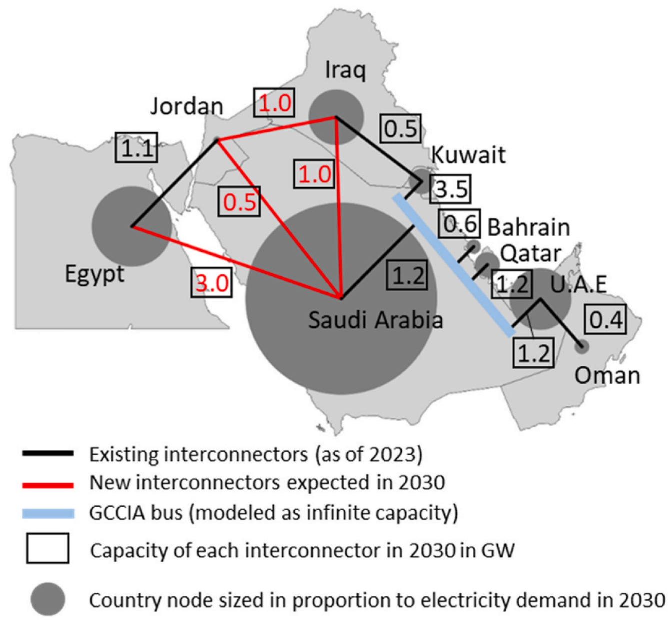

Fig. 1. Geographical perimeter of the model and interconnectors between countries with their respective capacities.

3. Methodology

Specifically designed and customized for the region, our model is a network-constrained hourly economic dispatch that includes a Scenario Analysis method to account for hourly variations in electricity generation from wind and solar. The model is implemented and run using the commercially available software package PLEXOS. We also developed a dataset for the region (including electricity demand, power generation units, and transmission capacities between countries) for the year 2030, based on publicly available information. The details of the model are summarized in this section and further detailed in Appendix A.

3.1. Overview of the model

3.1.1. Geographical scope and interconnection network

The geographical scope covered by our model includes nine countries, as illustrated in Fig. 1: Bahrain, Egypt, Iraq, Jordan, Kuwait, Oman, Qatar, Saudi Arabia and the UAE (listed in alphabetical order). This specific region was selected as it represents a relevant and practical perimeter for power trading by 2030. Notably, this scope aligns with the extended GCCIA, which includes countries already interconnected with one of its members, as well as those anticipated to establish interconnections in the near future. At the boundaries of this geographical scope, certain countries are either interconnected (e.g., Egypt–Libya and Iraq–Iran) or have potential interconnection opportunities beyond our focus area (e.g., Egypt–Greece). However, based on available data [37], these interconnections are currently limited, not actively utilized, or their operational status by 2030 remains highly uncertain.

Each of the nine countries is represented by a single node. The interconnection capacity between a pair of countries is defined based on the capacity of the planned interconnection line. Thus, we implicitly assume that other (internal) network constraints do not limit cross-border flows. In addition, network line losses are included by incorporating them into the demand based on the historical data, as further described in Appendix A.

3.1.2. Electricity demand

To forecast the annual electricity demand in 2030, we extrapolate the historical electricity demand for 2020 [38] to 2030 based on an annual growth rate corresponding to the historical gross domestic product (GDP) growth observed for the countries in the study, except for Saudi Arabia, from 2010 to 2019. We use a Saudi-specific econometric model to forecast the annual Saudi electricity demand during this period, taken from Mikayilov and Darandary [39]. In 2030, we project an annual electricity demand of 1408 TWh for the nine countries, among which 561 TWh (40 %) is attributed to Saudi Arabia. Egypt follows, with an annual electricity demand of 236 TWh in 2030.

Hourly electricity demand is derived from the forecasted annual demand by applying the country-specific hourly factors from Brinkerink and Deane [40]. These hourly factors do not correspond to historical data for the region, due to limited publicly available data, but were obtained through country-specific synthetic profiles accounting for locational economic, technical and climatic characteristics [41]. Refer to Appendix A for more details on our demand assumptions. We obtain a peak demand of 97.5 GW for Saudi Arabia and 42.1 GW for Egypt, both reached during summer months.

3.1.3. Generation capacities

To get a realistic picture of the installed capacities for 2030, we use a project-based 2030 forecast instead of conducting capacity expansion planning. Thus, the installed generation capacities in 2030 are derived from the project pipeline reported in Enerdata [42] and adjusted nationally to meet a capacity margin requirement of 10 %. Note that we do not rely on a generation expansion plan; instead, we look at existing capacities and announced projects with planned operational dates before or in 2030. This is because six years is too short for a long-term capacity expansion plan to occur. In this relatively short time frame, most utilities would already be locked in their capacity builds and retirements. The mix includes all relevant technologies for the region, namely gas and oil units, wind turbines, solar photovoltaic (PV) and hydropower, wherever applicable. Installed generation capacities and their technical and economic characteristics are presented in Appendix A. Overall, for the region, the installed capacity reaches 527.1 GW, out of which PV and wind power represent 190.5 GW. The three largest power systems of the region are respectively Saudi Arabia with 241.5 GW, Egypt with 87.6 GW and UAE with 61.1 GW.

As explained in Section 2, oil and natural gas used for electricity generation by GCC countries are currently priced below international prices, which can present significant challenges for regional electricity trading. In this study, we consider international fuel prices similar to Deluque Curiel [32] and Timilsina and Curiel [18] to remove this barrier. This is also in line with using fuel opportunity costs to dispatch electricity in fuel-rich regions [23].

Our dataset includes 20 weather profiles from the period 2003–2022, which are used to simulate electricity generation from wind and solar in the nine countries, as further detailed in Appendix A. The 20 weather profiles are simulated with a Scenario Analysis method, while ensuring the correlation between hourly generation from wind and solar, as well as between countries.

3.1.4. Operational reserves

The model includes operational reserves, i.e., a constraint on the available generation capacity to meet unscheduled changes in consumption or generation. As further detailed in Appendix A, operational reserves are defined at the country level and provided only by the generators located in the country (no reserve sharing between countries). These correspond to symmetrical spin-up and spin-down reserves with an activation duration of 10 min, sized according to the largest generation unit in the considered country and the volumes reported in Gulf Cooperation Council Interconnection Authority [43]. To represent the dynamics of each generation technology, the model considers assumptions for the maximum ramp rate, as described in Appendix A.

Table 2
Description of the scenarios.

Scenario name (abbreviation)	Description
No trade (NT)	Each of the nine countries is considered in isolation, and no electricity trade is allowed between countries.
Hourly trade (HT)	The complete system with nine countries is simulated with optimal hourly electricity trading between countries.
Hourly trade with no flows between Egypt and Saudi Arabia (HT_noEG-SA)	Identical to the HT scenario, but the flow between Egypt and Saudi Arabia is fixed at zero. This scenario is used to estimate the value of the trade between Egypt and Saudi Arabia.
KSA-EG long-term physical contract (4 scenarios)	Based on the HT scenario but flows between Saudi Arabia and Egypt are fixed as inputs. Four different contractual profiles are tested. See details in Section 4.2. **SA-EG_fixed_month**: a fixed profile defined for each month. **SA-EG_fixed_week**: a fixed profile defined for each week. **SA-EG_daily_quarter**: a daily profile defined for each quarter. **SA-EG_daily_month**: a daily profile defined for each month.

3.2. Simulated scenarios

The first area investigated in this paper is the benefits of hourly electricity trading in the region. To do so, we define and run several scenarios for 2030. First, we run a benchmark scenario where no electricity trade is allowed. This scenario serves as a basis against which all other subsequent scenarios are compared. Second, a scenario is run where electricity trading is performed on an hourly basis between all nine countries. This second scenario corresponds to a regional cost-based power pool, which can be implemented through the cooperation of the national single buyers. The analysis and comparison of these scenarios allow us to estimate the maximal benefits of electricity trading performed through an hourly wholesale electricity market coupling – i.e., the trading of energy based on its production costs while considering the constraints of available cross-border capacity. Our results highlight that the highest volume of electricity trade occurs between Saudi Arabia and Egypt given the size of their power systems and the capacity of the interconnector (3 GW).

However, given that establishing a coupling of national electricity markets in the region would require strong political and time commitments, we also investigate the benefits of alternative contractual arrangements. To do so, we focus on the interconnection between Egypt and Saudi Arabia, given the significant size of their electricity systems relative to others in the region, and investigate the associated benefits of physical contracts[2] between the two countries' single buyers. More specifically, we adopt a two-step approach. First, we fixed the volume of the physical contract between Egypt and Saudi Arabia based on the results obtained from the full coupling of the region (i.e., based on the **HT** scenario). Then, we run the regional model, corresponding to the coupling of national markets, while taking these imposed flows on the Saudi-Egyptian interconnector as a constraint. This process mimics a volume coupling similar to the one that was used between Central West Europe (CWE) and the Nordic power market, known as Interim Tight Volume Coupling [26]. Volume coupling has also been considered more recently between Great Britain and Central Europe as a post-Brexit solution to support offshore wind [44]. This approach allows us to estimate the effect of having a pair of countries use bilateral agreements while the rest of the exchanges are based on hourly coupling at the

[2] The physical contract leads to a physical flow on the considered interconnector. This flow follows the contracted volume profile.

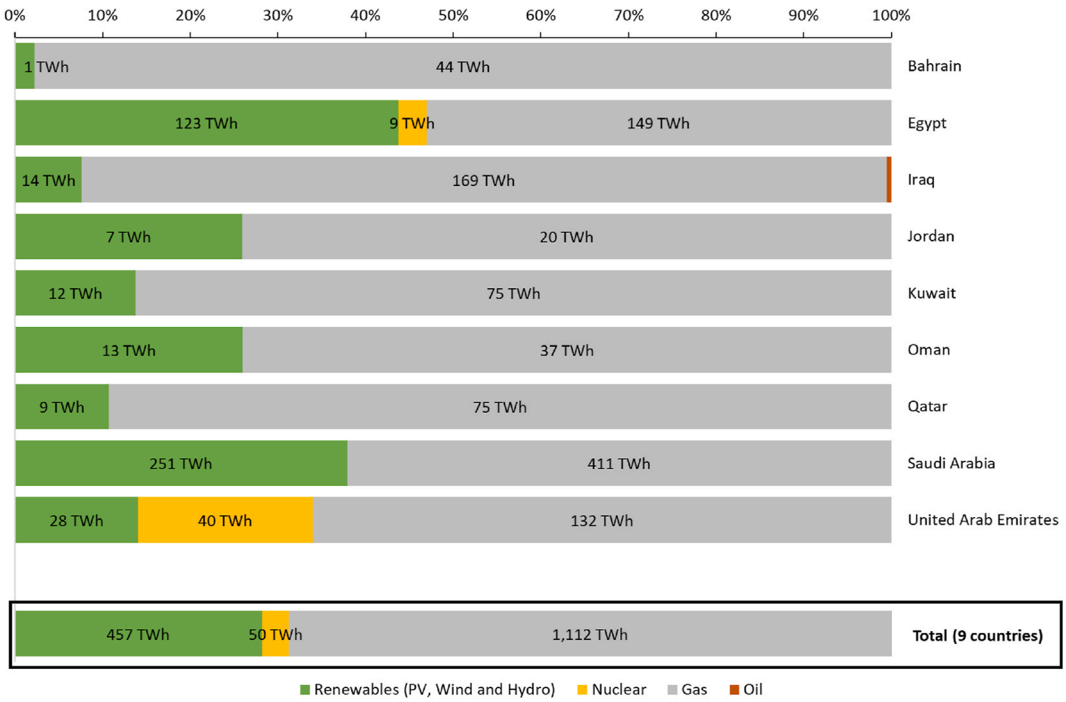

Fig. 2. Electricity power generation mix in 2030 in the NT scenario, average values for the 20 weather profiles.
Note: Oil accounts for less than 1 % of electricity power generation for the nine countries considered in this study.

regional level; it does not directly address the situation in which all electricity trading in the region relies solely on bilateral agreements. In our simulations with bilateral agreements between Egypt and Saudi Arabia, for instance, the two countries can still readjust their trade through the Jordanian border.[3]

We explore four types of volume profiles for the physical contract between Egypt and Saudi Arabia. Specifically, the four long-term bilateral arrangements that we test combine two different patterns (a fixed and a daily pattern) and different time granularity (weekly, monthly, or quarterly). For these runs with long-term bilateral arrangements, flows between Saudi Arabia and Egypt are not optimized by the model, but are fixed as input to the model, similarly to the approach used in Kanyako et al. [45]. Flows between other pairs of countries are simulated as in the **HT** scenario, i.e., hourly volumes and directions are optimized by the model. Additionally, we also run a scenario that features hourly electricity trading but with no flows between Egypt and Saudi Arabia. It is used to estimate the maximum value of the electricity trade between both countries.

In total, we run seven scenarios, which are summarized in Table 2. Another scenario which simulates an hourly electricity trading among the GCC countries only rather than the nine countries has also been simulated and is presented in Appendix B.

Table 3
Annual and average variable generation cost of electricity in 2030 in the NT scenario, on average for the 20 weather profiles.

	Annual variable generation cost (million US$)	Average variable generation cost (US$/MWh)
Bahrain	2,676	58.9
Egypt	8,562	30.4
Iraq	11,792	64.3
Jordan	1,217	45.1
Kuwait	4,611	53.4
Oman	2,256	45.0
Qatar	4,605	54.8
Saudi Arabia	23,381	35.3
United Arab Emirates	8,376	41.8
Total – GCC	45,904	40.7
Total – nine countries	67,475	41.7

4. Results

4.1. Benefits of hourly market coupling

This section gives the general outputs for the scenario without electricity trading first (i.e., the **NT** scenario). This provides the benchmark against which other scenarios can be contrasted. Then, we discuss the results that stem from trading for the specific geographies/countries identified, as explained in the scenarios sub-section 3.2. Here, it is important to recall that we consider the same installed generation capacities in all the simulations. Therefore, only the short-term benefits of reductions in variable generation costs are identified. In practice, once electricity trading is well established, it would also reduce investment in generation on a regional basis, and thus would generate additional benefits in the long term.

4.1.1. Overview of the NT scenario

In aggregate, we find that gas is dominant (69 %) in the electricity energy mix in 2030, as shown in Fig. 2. This mix, obtained for the **NT** scenario, results in 506.8 million metric tons of carbon dioxide ($MtCO_2$) in 2030. Further, renewable energy (PV, wind, and hydro) meets 28 % of the electricity requirement, corresponding to 457 TWh. Saudi Arabia and Egypt are the largest renewable energy producers, with 251 TWh and 123 TWh generated, respectively. Here it is important to note that the total curtailed energy from renewables is small at only 14.5 GWh, corresponding to 3 % of the available electricity generation of PV and wind among the countries considered. Most of this curtailment occurs in

[3] This effect is relatively limited due to two factors: (1) the wheeling charge applied to the interconnectors, as explained in Appendix, and (2) the limited capacity of the interconnector between Jordan and Saudi Arabia (500 MW, compared to 3 GW for the interconnector between Egypt and Saudi Arabia).

Table 4
Annual exports and imports of electricity in 2030 in the HT scenario, on average for the 20 weather profiles.

	Exports (TWh)	Imports (TWh)	Net position (TWH)
Bahrain	1.5	0.2	1.4
Egypt	11.1	5.4	5.7
Iraq	0.5	20.2	−19.7
Jordan	8.8	11.4	−2.6
Kuwait	3.7	9.9	−6.3
Oman	1.2	0.1	1.1
Qatar	0.2	2.0	−1.8
Saudi Arabia	27.1	3.9	23.1
United Arab Emirates	1.4	2.4	−1.0

Note: The last column presents the net position of imports/exports, defined as the volume of exports minus the volume of imports during the year.

Saudi Arabia, given the large amount of renewable capacity installed in the country.

The total variable generation cost of electricity in 2030 in the **NT** scenario is presented in Table 3 by country. It corresponds to the cost of fuel used to generate electricity plus the variable operation and maintenance cost of the generation units, while investment and network costs are excluded. For the nine countries, the variable generation cost reaches US$ 67.5 billion in 2030 on average over the 20 weather profiles.

4.1.2. Volume of electricity traded across the region

Table 4 presents the import and export volumes for each country in the HT scenario. The annual electricity volume exchanged among the nine countries reaches 55.5 TWh in 2030. Saudi Arabia is the largest exporter of electricity, with 27.1 TWh exported annually to other countries on average. The net position is defined as the volume of exports minus the volume of imports over the year. The results highlight that Saudi Arabia is the largest net exporter with a net position of 23.1 TWh, whereas Iraq is the largest net importer with a net position of −19.7 TWh.

Table 5 presents the flow between pairs of interconnected countries in absolute TWh in 2030 and the corresponding directional load of the line is graphically illustrated in Fig. 3. The results show that some lines are heavily used in one direction, whereas others are used in both directions. More specifically, three lines are loaded at more than 90 % in a single direction: the line from Saudi Arabia to the rest of the GCCIA (94 %), the line from Saudi Arabia to Iraq (97 %) and the line from Jordan to Iraq (94 %). Long-term contractual arrangements could easily be put in place for such lines that are heavily used in a single direction. However, for lines that are used in both directions, it is important to investigate to what extent long-term contractual arrangements would decrease the value of electricity trading compared to hourly market coupling.

Fig. 4 details the loading of each interconnector with Saudi Arabia. More specifically, this figure displays the scattered plot of the directional loading on the interconnectors for each quarter of the year 2030, with the hours of the day shown on the x-axis. It displays the results obtained for all the 20 weather profiles (in blue) and the average loading for each hour is indicated by the dark markers. The figure confirms the previously mentioned observation that the lines between Saudi Arabia and the GCCIA, and between Saudi Arabia and Iraq, and to a lesser extent between Saudi Arabia and Jordan, are heavily used in one direction to import electricity from Saudi Arabia. It also shows that Saudi Arabia imports electricity from Egypt, Jordan and the GCCIA mainly at night during the third quarter (July, August, and September). Throughout the year, Saudi Arabia exports electricity to Egypt during the day and imports it from Egypt at night. This last observation is further explained in Section 4.2, which focuses on Saudi Arabia and Egypt.

4.1.3. Variable generation cost of electricity

Table 6 presents the total variable generation cost in 2030 for different scenarios. The variable generation cost presented here only accounts for fuel costs and variable operation and maintenance costs. Other externalities, such as the cost of carbon or the cost of curtailed energy, are not included here but are discussed in dedicated subsections.

When electricity is traded among all nine countries (**HT** scenario), the saving in variable generation costs for the year 2030 reaches US$ 1,099 million on average, which corresponds to a reduction of 1.6 %. In practice, the identified decrease in the variable generation costs should be compared to the investment cost of the interconnectors, and the regulatory and implementation costs of establishing an hourly market coupling in the region.

Given the additional scenario presented in Appendix B that simulates hourly electricity trading among the GCC countries only, our results suggest that expanding electricity trading beyond the GCC states to Egypt, Jordan and Iraq is particularly relevant. More specifically, as detailed in Section 4.2, the interconnection between Saudi Arabia and

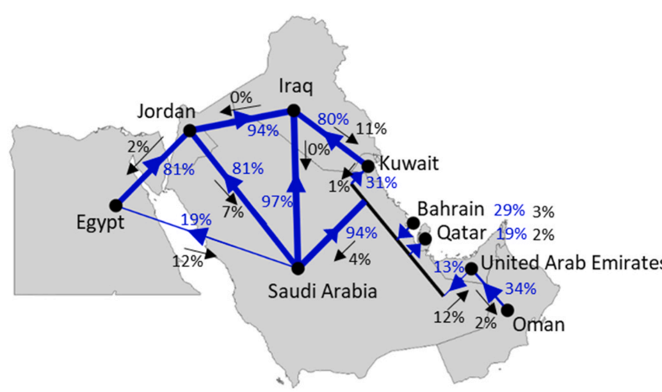

Fig. 3. Annual directional loading of the interconnection lines (in %) in the HT scenario, average loading for the 20 weather profiles.

Table 5
Annual electricity flows on interconnectors in the HT scenario, average value for the 20 weather profiles.

From → To ↓	Bahrain	Egypt	Iraq	Jordan	Kuwait	Oman	Qatar	SA	UAE	GCCIA[a]
Bahrain										0.2
Egypt				0.2				5.1		
Iraq				8.2	3.5			8.5		
Jordan		7.8	0.0					3.5		
Kuwait			0.5							9.4
Oman									0.1	
Qatar										2.0
SA		3.3	0.0	0.3						0.4
UAE						1.2				1.2
GCCIA[a]	1.5				0.2		0.2	9.9	1.4	

[a] Given the topology of the GCCIA interconnector/bus, we provide flows for the GCCIA rather than detailing them by pairs of countries. SA= Saudi Arabia. Refer to Appendix A for more details on the topology of the GCCIA interconnector.

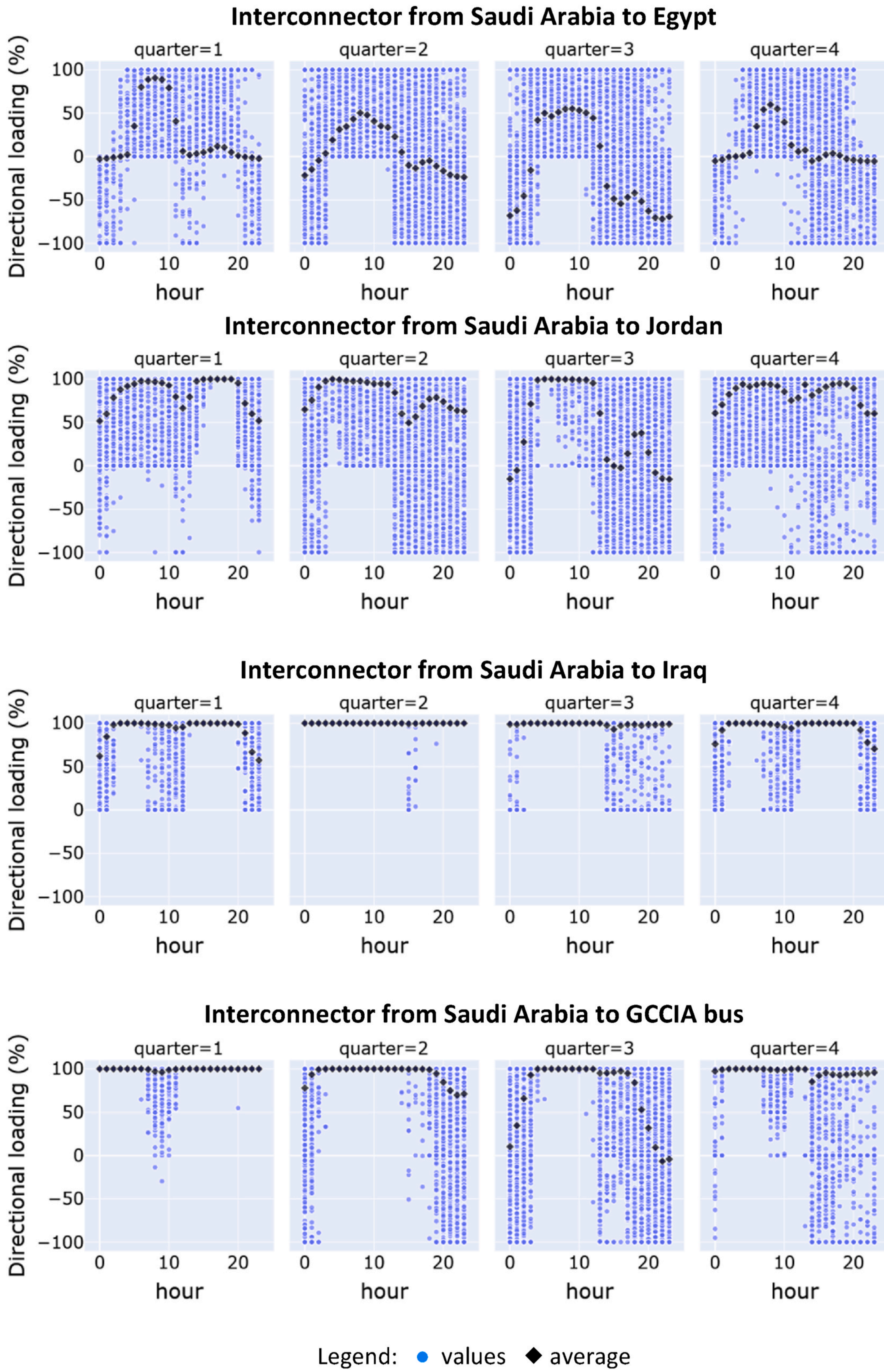

Fig. 4. Directional loading for each hour, on the interconnectors between Saudi Arabia and interconnected countries.
Note: The first quarter corresponds to January, February, and March. The second quarter corresponds to April, May, and June. The third quarter corresponds to July, August, and September. The fourth quarter corresponds to October, November and December. The figure displays the directional loading for the 20 weather profiles (in blue) and the average for each hour (in black).

Table 6
Total variable generation cost in 2030 in the NT and HT scenarios, mean value and standard deviation for the 20 weather profiles.

Scenario	Total variable generation cost for the nine countries (million US$)	
	Mean	Standard deviation
No trade (NT)	67,475	588
Hourly trade within the nine countries (HT)	66,376	540
delta w.r.t. NT	*−1,099 (-1.6 %)*	

Note: w.r.t = with respect to.

Table 7
Generation potential and curtailment of PV and wind on average in 2030 in the NT and HT scenarios.

	PV and wind generation potential* (TWh)	No Trading (NT) Curtailed renewable energy		Hourly Trading (HT) Curtailed renewable energy	
		GWh	%	GWh	%
Bahrain	1.1	0	0.0	0	0.0
Egypt	96.5	119	0.1	5	0.0
Iraq	9.7	0	0.0	0	0.0
Jordan	7.1	186	0.0	0	0.0
Kuwait	11.6	2	0.0	0	0.0
Oman	13.7	929	6.8	640	4.7
Qatar	8.8	0.1	0.0	0.1	0.0
Saudi Arabia	264.5	13,044	4.9	8,700	3.1
United Arab Emirates	28.1	194	0.7	66	0.2
Total – nine countries	**441.2**	**14,475**	**3.3**	**9,411**	**2.1**

Note: * Values presented in this column correspond to the average yearly potential for electricity generation from PV and wind power given the considered installed capacities, i.e. the generation before curtailment on average for the 20 weather profiles.

Egypt brings a gain in variable generation costs of US$ 220 million in 2030, which corresponds to 20 % of the total trading benefits in the region.

4.1.4. Curtailment of renewable energy

Table 7 presents the curtailment of PV and wind in the NT and HT scenarios. Here, we define the curtailment as the reduction in the electricity generated from PV and wind that is injected into the grid compared to what it could otherwise produce given the available resources [7]. The curtailment obtained in our simulations occurs when generation from wind and solar is higher than the load and interconnectors are unable to further accommodate this surplus of energy. But this estimated curtailment does not include the curtailment that could happen in practice due to internal network constraints within a given country.

Initially, 14.5 TWh of the available electricity generated by PV and wind is curtailed on average in the **NT** scenario, corresponding to 3.3 % of the renewable energy potential. These results confirm that electricity trading reduces the curtailment of PV and wind, which has already been identified in the literature [7–9,46]. On average over the 20 weather profiles, the curtailment reduction decreases from 14.5 TWh in the **NT** scenario to 9.4 TWh (2.1 % of the PV and wind generation) when electricity is traded among the nine countries (**HT** scenario), corresponding to a reduction of 35 %.

Table 8
CO_2 emissions from the power sector and carbon intensity of electricity in 2030 in the NT and HT scenarios.

	CO2 emissions (million tons of CO_2)		CO2 intensity (g CO_2/kWh)	
	No trading (NT)	Hourly Trading (HT)	No trading (NT)	Hourly Trading (HT)
Bahrain	19.3	19.9	425	426
Egypt	65.5	67.6	233	236
Iraq	91.7	78.8	500	482
Jordan	8.8	7.6	326	310
Kuwait	33.3	30.3	386	378
Oman	16.3	16.7	325	325
Qatar	33.3	32.3	396	392
Saudi Arabia	180.1	187.6	272	274
United Arab Emirates	58.7	57.6	293	289
Total – nine countries	**507.0**	**498.8**	**313**	**308**

Note: These emissions correspond to direct emissions when the fuel is burnt. Emissions related to construction, maintenance, or dismantlement are excluded. The table provides average values for the 20 weather profiles.

4.1.5. CO_2 emissions

Regarding emissions, the scenario with electricity trading among the nine countries (**HT** scenario) shows a reduction in emissions of 8.2 million tons of CO_2 ($MtCO_2$) in 2030 compared to the **NT** scenario, which corresponds to a reduction of 1.6 %, as presented in Table 8. Classically, despite the reduction achieved at the regional level, for some countries emissions can increase in the **HT** scenario compared to the **NT** scenario. This is due to more electricity being produced in this country to be exported to other countries. Specifically, emissions in Saudi Arabia increase by 7.5 $MtCO_2$ in the **HT** scenario compared to the **NT** scenario to accommodate the additional electricity generation for exports (net exports of 23.1 TWh), but this increase allows to reduce emissions in other countries where electricity is exported such as Iraq and Jordan.

At the regional level, the reduction in emissions of 8.2 $MtCO_2$ can be monetized. If we assume a carbon price in the range of 50–100 US $/tCO_2$ in 2030, the observed change in emissions corresponds to a saving of US$ 410–820 million, to be added to the savings in the total variation generation cost of electricity (US$1,099 million).

The reduction in emissions that we present here is achieved by a change in the generation units' dispatch while keeping the same installed capacities. However, in practice, once electricity trading is well established in the region, capacity expansion planning could be performed on a regional basis and thus influence the installed capacities, which could also contribute to a reduction in emissions.

4.2. Contractual schemes between Saudi Arabia and Egypt

Given that Saudi Arabia and Egypt possess the largest generation fleet linked with a 3 GW line (the largest of all within this study), it is important to focus specifically on the trade between these two countries. While an hourly trade market brings about considerable value theoretically, establishing one may be difficult and will require time. As a midway/compromise solution between having no trade and having a full hourly market, contractual arrangements can be put in place with associated economic benefits, as discussed in this section.

To begin with, we provide more details on the use of the Saudi-Egyptian interconnector in the **HT** scenario, and we estimate the economic value brought by this interconnector in the **HT** scenario. Then, we explore and analyze four different types of long-term bilateral contractual arrangements between Saudi Arabia and Egypt.

4.2.1. Electricity flows on the Saudi-Egyptian interconnector in the HT scenario

As illustrated in Fig. 4, and throughout the year, Saudi Arabia exports

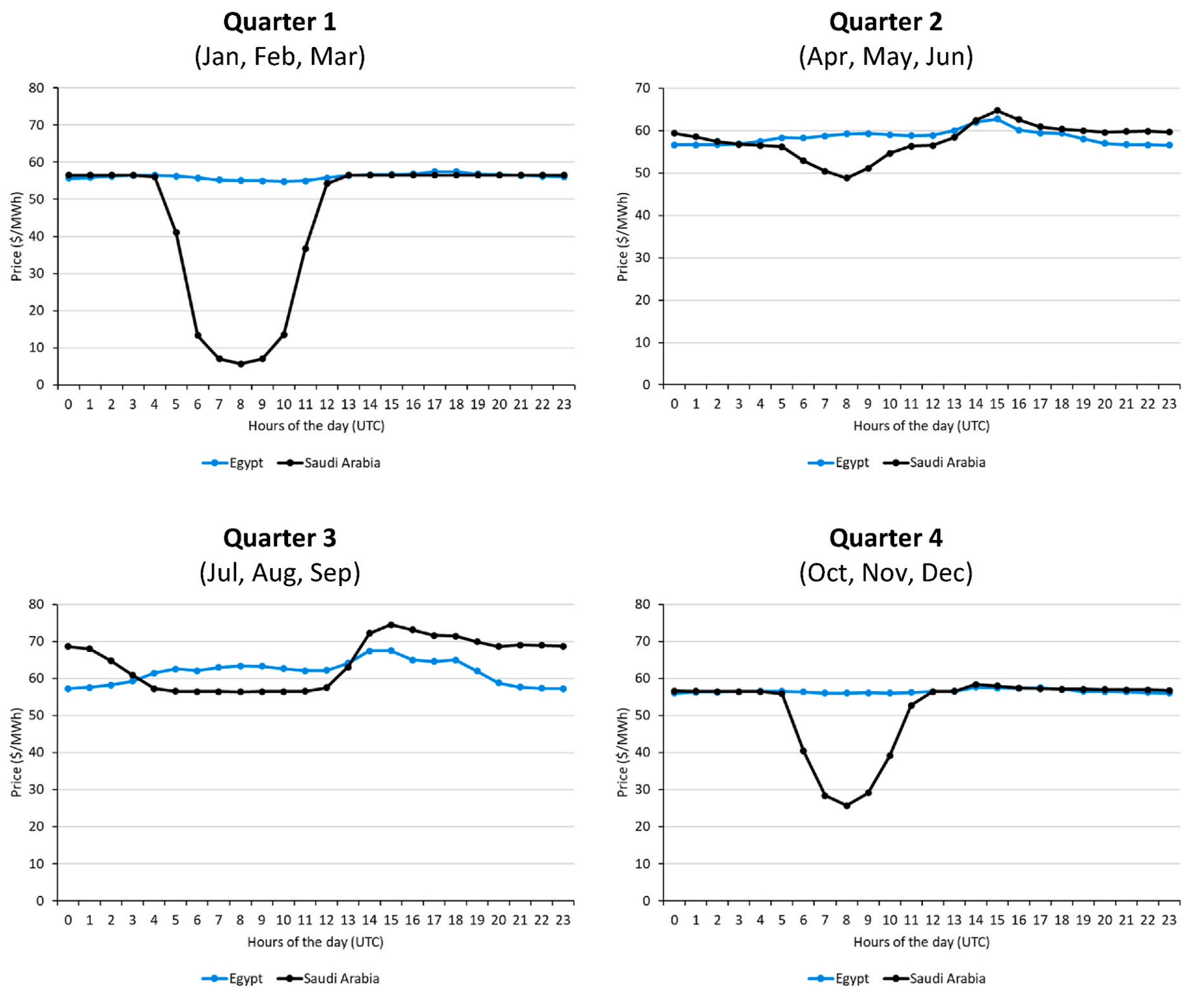

Fig. 5. Average hourly electricity prices by quarter in Egypt and Saudi Arabia in the HT scenario.

to Egypt during the day and imports from Egypt at night. Imports from Egypt to Saudi Arabia happen mainly during the third quarter of the year (corresponding to July, August, and September). To understand the root causes of this trend, Fig. 5 displays the average hourly electricity prices in Egypt and Saudi Arabia. During the day, the Saudi price decreases due to its PV generation, thus allowing Egypt to import electricity from Saudi Arabia. During the night, both Egyptian and Saudi prices align with the marginal costs of gas-fired generation units. During the third quarter (July, August, and September), Saudi Arabia faces higher demand and needs to use gas steam turbines, with a variable cost of 77.5 US$/MWh at night, whereas the Egyptian main marginal unit remains gas-combined cycle (CC) at night, with a variable cost of 56.5 US$/MWh (see Fig. 5).

4.2.2. Maximum economic value of the Saudi-Egyptian interconnector from the HT scenario

To estimate the economic value of the Saudi-Egyptian interconnector, we use a simulation identical to the **HT** scenario but with no trade allowed between Saudi Arabia and Egypt (noted **HT_noEG-SA)**. This scenario allows us to quantify the maximum economic value of the interconnection, which is obtained for hourly market coupling between the two countries. This approach to assess the value of a new transmission line is sometimes referred to as *TOOT* in the literature [47]. However, other assessment methods also exist [48,49].

When no electricity flow is allowed between Saudi Arabia and Egypt, the total variable generation cost for the nine countries increases from US$ 66,376 million (**HT** scenario) to US$ 66,596 million (**HT_noEG-SA** scenario). This indicates that electricity trading between Saudi Arabia and Egypt can bring a maximal value of US$ 220 million in 2030. Recall that this value corresponds to the variable generation costs only, but additional benefits can be achieved in the longer term when investment decisions are considered.

Table 9
Description of the considered contractual schemes.

	Type of daily profile	Granularity
SA-EG_fixed_month	fixed	monthly
SA-EG_fixed_week	fixed	weekly
SA-EG_daily_quarter	hourly profile, identical for each day	quarterly
SA-EG_daily_month	hourly profile, identical for each day	monthly

4.2.3. Analysis of long-term contractual arrangements

We investigate alternative bilateral contractual arrangements between Saudi Arabia and Egypt and estimate the economic benefits of both types compared to the maximal benefits of US$ 220 million in 2030, achieved with hourly market coupling. We define four types of long-term contracts for electricity exchange between Saudi Arabia and Egypt as follows (see summary in Table 9).

- **SA-EG_fixed_month:** A fixed profile defined with monthly granularity: for each month, the flow between Saudi Arabia and Egypt is defined to correspond to the equivalent net flow of the hourly simulation. See Fig. 6a.

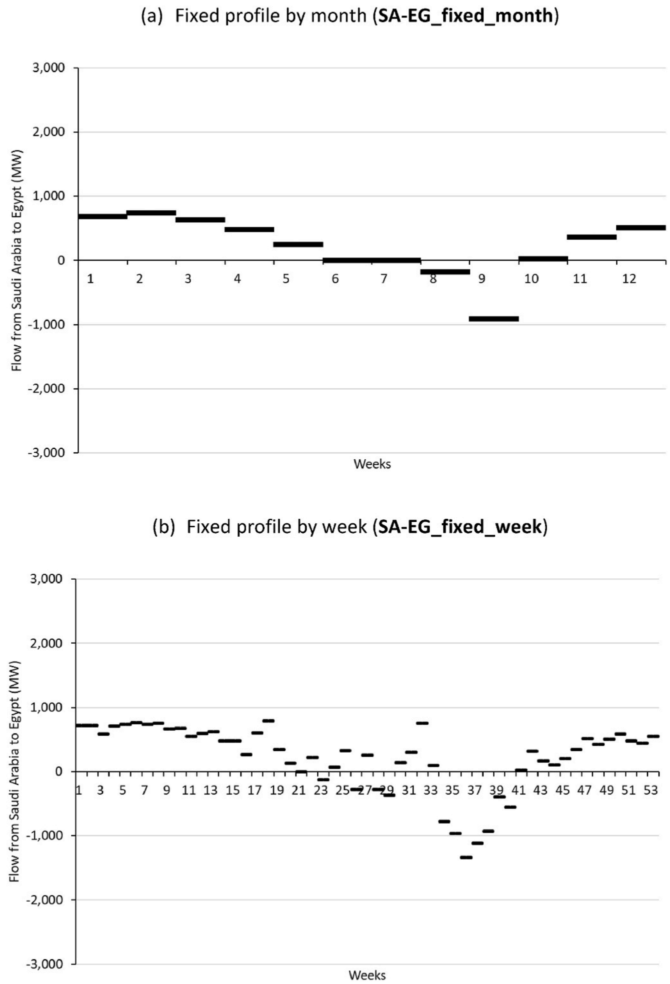

Fig. 6. Profiles of the two fixed-profile contractual schemes between Saudi Arabia and Egypt (SA-EG_fixed_month and SA-EG_fixed_week scenarios). (a) Daily profile by quarter (**SA-EG_daily_quarter**).

- **SA-EG_fixed_week:** A fixed profile defined with weekly granularity: for each week, the flow between Saudi Arabia and Egypt is defined to correspond to the equivalent net flow of the hourly simulation. See Fig. 6b.
- **SA-EG_daily_quarter**: A daily profile defined for each quarter: for each quarter, we define a typical daily profile at an hourly timescale, which corresponds to the average profile observed during the same quarter in the hourly simulation. See Fig. 7a.
- **SA-EG_daily_month**: A daily profile defined for each month: for each month, we define a typical daily profile at an hourly timescale, which corresponds to the average profile observed during the same month in the hourly simulation. See Fig. 7b.

All types of contracts keep the net electricity exchange between Saudi Arabia and Egypt unchanged. However, the annual export and import volumes between the two countries differ for each type of contract scheme, as presented in Table 10. As expected, the daily profile with monthly granularity (**SA-EG_daily_month** scenario) allows export and import volumes to be more representative of the hourly trade.

To assess the benefits that could be achieved by the different contractual schemes between Saudi Arabia and Egypt, Table 11 presents the total variable generation cost for the entire perimeter of our model, which comprises nine countries. It shows that defining a fixed profile by month (**SA-EG_fixed_month** scenario) or week (**SA-EG_fixed_week** scenario) brings a benefit of only US$ 26–33 million, which corresponds to 12 %–16 % of the maximum value of the interconnector. Alternatively, defining a daily profile for each quarter (**SA-EG_daily_quarter** scenario) or each month (**SA-EG_daily_month** scenario) increases the economic benefits to US$ 112–122 million, representing 54 %–58 % of the maximum value of the interconnector. This justifies the interest in developing well-designed bilateral contractual arrangements as a compromise solution between having no trade and having full hourly market coupling. These estimates consider the uncertainty in the generation from PV and wind (20 weather profiles are analyzed), but, in practice, other sources of uncertainty may arise such as the hourly load. Developing forecasting methods with high accuracy (renewables' generation, hourly load) is thus crucial to optimize the value brought by long-term contracts in practice.

To complement the cost analysis, Table 12 provides the curtailment of renewable energy and CO_2 emissions for the four contractual arrangements considered. It shows that both curtailment and emissions are negatively impacted when long-term arrangements are used compared to hourly market coupling. Specifically, the fixed contracts (**SA-EG_fixed_month** and **SA-EG_fixed_week** scenarios) show worse results, with an increase of 17 % and 0.3 % in the curtailment of renewable energy and emissions, respectively, compared to the **HT** scenario. The contracts with a daily pattern (**SA-EG_daily_quarter** and **SA-EG_daily_month** scenarios) perform better, with an increase in renewable energy curtailment of only 6 %–7 % compared to the **HT** scenario, and additional emissions of 0.7 million $MtCO_2$.

To complement our analysis of the long-term bilateral arrangements, Fig. 8 shows the directional loading on the interconnector versus the price difference between Egypt and Saudi Arabia, similar to the analysis provided in Guo and Newbery [50]. It graphically illustrates the 'non-economic' flows when long term contracts are in place. Specifically, these 'non-economic' flows go from the country with the higher electricity price to the one with the lower electricity price at the specified hour, corresponding to the points in the two light red quadrants. Based on Fig. 8, we obtain that non-economic flows are observed 12 % of the time on average in the **SA-EG_fixed_month** scenario, whereas it decreases to only 3 % of the time in the **SA-EG_daily_month** scenario. This confirms the importance of well-designed volume profiles for the contractual arrangements.

Fig. 8 also shows that, overall, the interconnector is better utilized in the SA-EG_daily_month scenario, i.e. the corresponding points (upper-left figure) indicate a higher loading of the interconnector, reaching up to almost 100 %. By contrast, the points in dark and gray are concentrated in the center of the y-axis, indicating a low utilization of the interconnector in the **SA-EG_fixed_month** and **SA-EG_fixed_week** scenarios.

5. Discussion

5.1. Market coupling with hourly products

Market coupling with hourly products is often envisaged as an objective in the GCC countries and beyond, as evidenced in discussions around the Arab Common Electricity Market [5]. Given the current organization of power systems and planned network developments, we have focused our analysis on the GCC countries, plus Egypt, Jordan, and Iraq, which appear to be a relevant and practical subregion for electricity trade by 2030. In this region, power sectors have evolved from a vertically integrated structure to a single-buyer market design. In this context, electricity market coupling can translate into a cost-based regional power pool where single-buyers optimize electricity costs at the regional level.

Our results demonstrate that interconnecting all nine studied countries (GCC countries, plus Egypt, Jordan, and Iraq) yields significant economic advantages. Specifically, hourly electricity trading is estimated to save US$ 1,099 million by 2030 on average, corresponding to a variable cost reduction of 1.6 %. As presented in Appendix, limiting trading to the GCC region alone still results in a notable annual variable

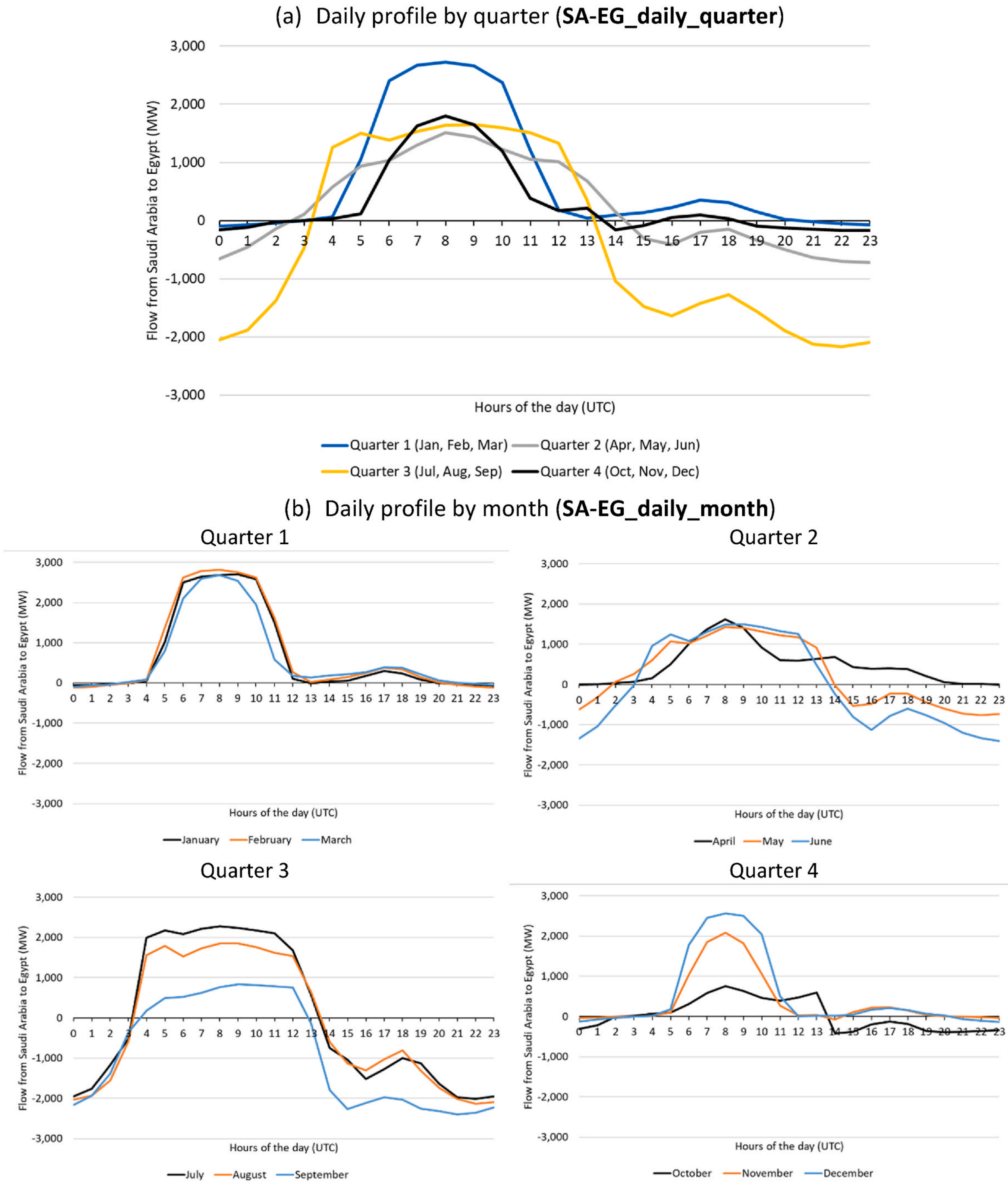

Fig. 7. Profiles of the two daily-profile contractual schemes between Saudi Arabia and Egypt (SA-EG_daily_quarter and SA-EG_daily_month scenarios).

Table 10
Electricity flows between Saudi Arabia and Egypt for the different contractual arrangements compared to the ones in the HT scenario.

	Annual export from Saudi Arabia to Egypt (TWh)	Annual export from Egypt to Saudi Arabia (TWh)	Net exchange from Saudi Arabia to Egypt (TWh)
SA-EG_fixed_month	2.7	0.8	1.9
SA-EG_fixed_week	3.1	1.2	1.9
SA-EG_daily_quarter	4.5	2.7	1.9
SA-EG_daily_month	4.6	2.8	1.9
HT	4.8	3.0	1.9

cost reduction of US$ 256 million on average. In addition, the planned 3 GW interconnector between Saudi Arabia and Egypt plays a pivotal role in facilitating regional trade, contributing an estimated value of US$ 220 million in 2030.

Furthermore, regional electricity trading provides other benefits regarding renewable energy integration and CO_2 emissions. Our results

Table 11
Total variable generation costs in 2030 for the different scenarios.

Scenario	Total variable generation cost (million US$)	Gain associated with the SA-EG interconnector (million US$)	% of the maximum value achieved in HT
HT_noEG-SA	66,596	–	–
SA-EG_fixed_month	66,566	30	14 %
SA-EG_fixed_week	66,562	33	15 %
SA-EG_daily_quarter	66,472	123	56 %
SA-EG_daily_month	66,461	134	61 %
HT	66,376	220	100 %

Table 12
Curtailment of PV, wind and CO_2 emissions for the four different contractual arrangements between Saudi Arabia and Egypt.

Scenario	Total variable generation cost (million US$)	Curtailment of PV and wind (GWh)	CO_2 emissions (million $MtCO_2$)
SA-EG_fixed_month	66,566	11,178	500.3
delta w.r.t. HT	*+0.3 %*	*+18.8 %*	*+0.3 %*
SA-EG_fixed_week	66,562	11,174	500.3
delta w.r.t. HT	*+0.3 %*	*+18.7 %*	*+0.3 %*
SA-EG_daily_quarter	66,472	10,130	499.6
delta w.r.t. HT	*+0.1 %*	*+7.6 %*	*+0.1 %*
SA-EG_daily_month	66,461	10,026	499.5
delta w.r.t. HT	*+0.1 %*	*+6.5 %*	*+0.1 %*
HT	66,376	9,411	498.8

Note: w.r.t. = with respect to (see Fig. 7).

show a 35 % reduction in renewable energy curtailment in 2030 when hourly electricity trading is implemented. The environmental benefits of regional electricity trade are also noteworthy, with an estimated reduction of 8 $MtCO_2$ in 2030. This reduction translates into an annual monetized value of US$ 410–820 million, assuming a carbon price range of US$ 50–100 per ton of CO_2.

These benefits identified in our results are short-term effects. However, in the long-term, coordinated generation and network investments at the regional level would be necessary to unlock further long-term gains. Specifically, when electricity trading becomes well established, it can decrease the need for new generation investments as the electricity and reserve services can be exchanged between countries.

5.2. Bilateral agreements: an alternative that makes sense in the region

Developing and implementing a mature market coupling requires time and strong political commitment. The example of the GCCIA suggests that the physical network is not sufficient to fully optimize regional electricity trading, as this interconnector remains highly underutilized. Therefore, given the context of the region under consideration, we have assessed the benefits of an alternative trading structure. Specifically, we have simulated and analyzed bilateral agreements in the form of physical contracts between the two largest power systems in the region, namely Saudi Arabia and Egypt. This pair of countries is particularly interesting because our results indicate daily flow patterns between them. During the daytime, Saudi Arabia exports electricity to Egypt due to high photovoltaic (PV) generation, while imports from Egypt increase during summer nights. In contrast, interconnectors such as the Saudi-Jordanian or Saudi-Iraqi ones exhibit predominantly unidirectional flows, which may justify simpler bilateral contractual structures.

Our simulations consider several types of physical contracts between Egypt and Saudi Arabia, with volumes based on the results obtained from the market coupling with hourly products, as would be done in practice by a scheduling optimization model. Physical contracts are tested for each weather profile in 2030. Specifically, the volume of the contract is set as a constraint to the model (i.e., a constraint on the flow between Egypt and Saudi Arabia), while flows on other interconnectors are endogenously optimized, similar to the concept of volume coupling.

Our analysis of the bilateral agreements maintains the same approach used throughout the paper, i.e., it identifies the benefits at the regional level rather than at the individual country level.[4] It shows that the volume pattern fixed in the physical contract significantly influences the performance of the bilateral agreement. In the case of Egypt and Saudi Arabia, the findings demonstrate that rigid contracts with fixed volumes throughout the day significantly reduce the economic value of electricity trading to less than 20 % of its maximum potential. Instead, contracts with daily volume variations capture over 50 % of the maximum economic benefit, making them a preferable alternative. These flexible contracts can be further optimized with monthly or quarterly adjustments without substantial economic loss.

6. Conclusion

Our quantitative findings can be leveraged to provide key recommendations to policymakers in the GCC and broader MENA regions. As of today, most power sectors in this region are organized with a single buyer model and establishing market coupling would still require substantial time and effort. In this context, we recommend considering bilateral agreements in the form of physical contracts as an effective approach to electricity trade. More importantly, these agreements should be customized to reflect country-specific electricity trading patterns, as demonstrated in the Saudi-Egyptian case.

Our work also highlights several promising directions for further research. First, our model accounts for variability in renewable energy generation, but it does not consider other sources of uncertainty. Future research should evaluate the impact of forecast errors that could arise in practice and how digital technologies could help mitigate these errors, especially in the context of integrating a higher share of renewables. Second, further studies should investigate whether, and to what extent, the internal networks of the nine countries and network losses (on internal networks as well as interconnectors) might limit the use of interconnectors at their maximum capacities, and analyze how this translates into a potential reduction in electricity trade, as well as explore solutions to relieve these limitations. Third, expanding the analysis to include bilateral contracts across all regional interconnectors, as well as potential trade with neighboring countries beyond the study area, would provide a more comprehensive assessment of cross-border electricity trading dynamics. Finally, the model framework can be expanded to quantify the benefits of deeper regional cooperation, including coordinated capacity and transmission expansion, coordinated maintenance planning, or a shared regional operating reserve.

CRediT authorship contribution statement

Marie Petitet: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Conceptualization. **Benjamin Ricaud:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Frank A. Felder:** Writing – review & editing, Conceptualization, Methodology. **Amro M.**

[4] Given the approach adopted in the paper, the analysis of gains and losses at the national level is beyond our scope. Future research should address national impacts, as well as price determination, and risk management.

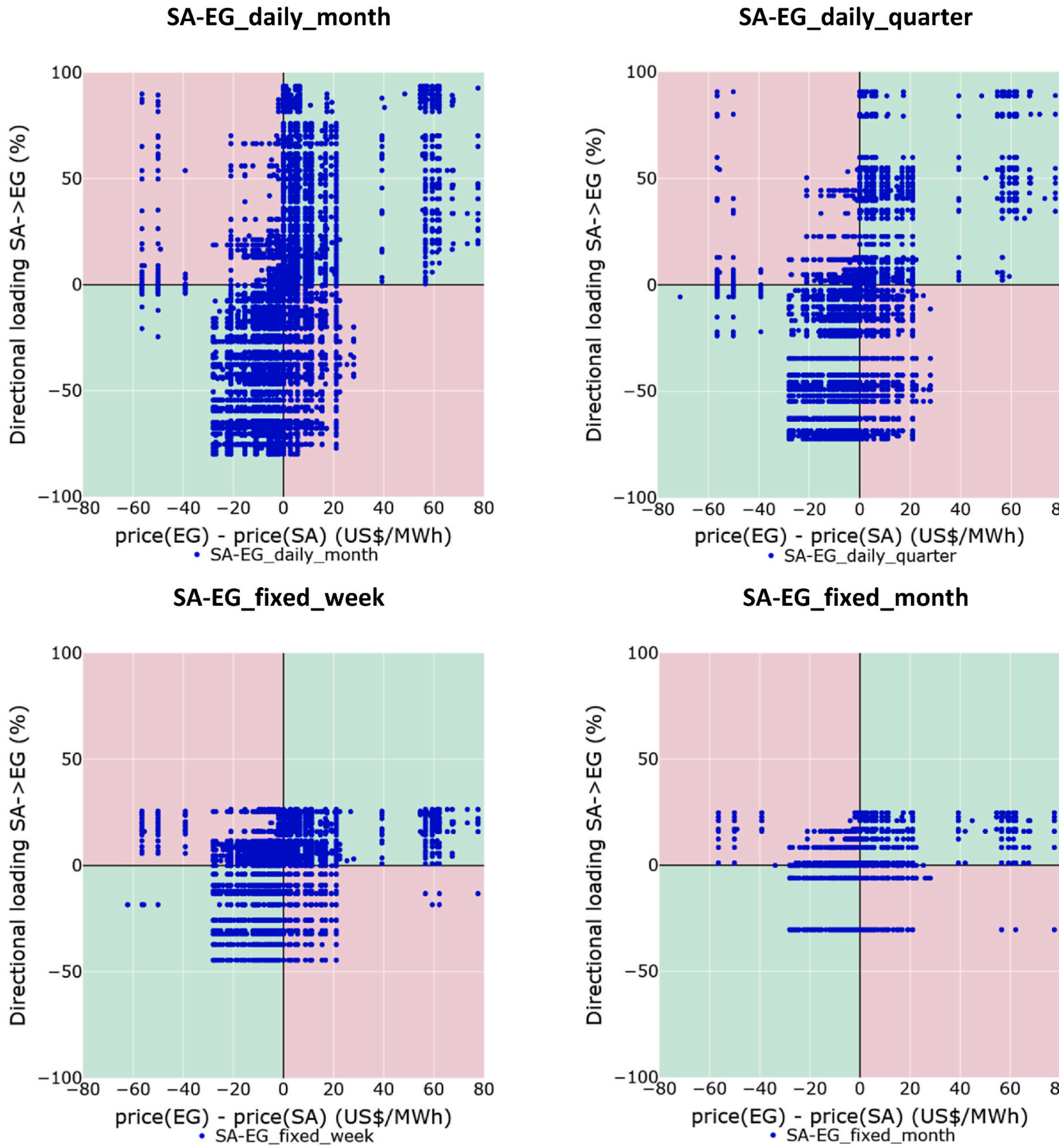

Fig. 8. Directional loading and price differences for the Saudi-Egyptian interconnector in the four scenarios with contractual arrangements, for the 20 weather profiles.

Elshurafa: Supervision.

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

During the preparation of this work the authors used Chat GPT in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

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Appendix A. Model

The model used for this study was specifically developed for analyzing regional trading arrangements. It corresponds to a network-constrained hourly economic dispatch model and was implemented in the commercial software PLEXOS. Specifically, it uses a mixed-integer linear programming (MILP) approach to simulate the least-cost operation of power systems, optimizing generator outputs and power flows while adhering to technical and operational constraints. In our case, the objective function of the cost-minimization problem includes variable generation costs (fuel costs and variable operation and maintenance costs), transmission costs, reserve costs, and penalty costs incurred for unserved energy, if any.

The choice of an hourly timestep for the simulation and the selected electricity product is motivated by the historical specificities in the region, where electricity markets are still under discussion and emerging. Additionally, it aligns with the resolution of available data in the region. In the longer term, it would be valuable to assess whether transitioning to smaller electricity products (e.g., 15-min products, as in Europe, or 5-min products, as in the US) could provide additional benefits to the region.

Time zones

Our data set accounts for differences in time zones and is provided for the UTC time zone. To convert to local time zones, please note that our perimeter covers countries at UTC+2 (Egypt), UTC+3 (Bahrain, Iraq, Jordan, Kuwait, Qatar and Saudi Arabia), and UTC+4 (Oman and the United Arab Emirates).

Geographical scope

The model represents nine countries: Bahrain, Egypt, Iraq, Jordan, Kuwait, Oman, Qatar, Saudi Arabia and the UAE (listed in alphabetic order). This specific region was selected as it represents a relevant and practical perimeter for power trading by 2030, and interconnectors at the boundaries of our geographical scope of our geographical scope are either existing but used very sparingly (mostly for geopolitical reasons), or under consideration with expected operation after 2030. To ensure completeness, we used the global interconnectors database available in Brinkerink et al. [37] to identify at the boundaries.

- Egypt has an existing interconnector with Libya (240 MW) and a project to expand it, though no commissioning date has been announced. Egypt also has an interconnector with Sudan (300 MW currently operational and 1,000 MW under consideration, but without visibility on the commissioning timeline). Overall, data from International Energy Agency [51] indicates that Egyptian interconnectors to Libya and Sudan are rarely utilized, with an average export of only 200 MWh per hour, and an average import of 20 MWh per hour in 2022.
- Jordan has an existing interconnector with Syria (300 MW). However, the reported imports and exports for 2022 amount to less than 30 MWh on average [51]. The future use of this interconnector is also highly uncertain due to geopolitical tensions in the region.
- Iraq has an existing interconnector with Iran (1,500 MW), with Syria (300 MW) and Turkey (400 MW). For 2022 [52], shows no exports, and imports totaling 6,089 GWh, corresponding to an average of 700 MWh per hour. However, the instability of the country and geopolitical tensions in the region make it difficult to forecast how this could evolve in the future.
- Oman is only connected to the GCCIA but has no exiting or planned interconnector with Yemen.

This detailed analysis of the region suggests focusing on the nine countries cited above, while excluding electricity flows at the boundaries of our geographical scope due to the negligeable existing flows in some countries and high level of uncertainty for others.

Demand assumptions

The annual electricity demand, presented in Table A-1, is obtained for each country, except Saudi Arabia, based on the following methodology.

1. Annual demand for 2020 is collected from Enerdata [38].
2. The average GDP growth is computed over the period 2010–2019 (to exclude COVID-19).
3. The annual demand for the period 2021–2030 is computed by assuming an electricity demand growth rate corresponding to the average GDP growth from step 2.

For Saudi Arabia, the annual electricity demand in 2030 is estimated by a specific model developed by Mikayilov and Darandary [39].

Table A-1
Annual electricity demand and peak demand by countries in 2030 (network losses excluded).

Country	Annual demand (TWh)	Peak demand (GW)
Bahrain	44.1	8.6
Egypt	236.4	42.1
Iraq	163.7	30.4
Jordan	24.5	4.5
Kuwait	76.4	13.7
Oman	44.8	8.8
Qatar	75.0	13.2
Saudi Arabia	561.0	97.5
United Arab Emirates	182.2	33.6

The electricity demand is then adjusted in the model to account for network losses, as further detailed below.

The hourly demand is obtained by applying the hourly multipliers provided in the publicly available PLEXOS-World 2015 Harvard Dataset

(Brinkerink and Deane 2020; Brinkerink, Gallachóir, and Deane 2021). Table A-2 provides the hour at which the peak load occurs in each country.

For all the nine countries, the weekend days are Friday and Saturday in our dataset (with 2015 as the reference year). However, since 2022, the United Arab Emirates has moved its weekend day to Friday afternoon, Saturday and Sunday. Due to lack of available data, the potential changes in hourly electricity consumption of the United Arab Emirates since the change in weekend days have not been integrated into our study.

Table A-2
Hour at which the daily peak load occurs more frequently, and corresponding frequency, for each country.

Country	Hour at which the daily peak demand occurs more frequently	%
Bahrain	16	53.4 %
Egypt	18	77.3 %
Iraq	17	65.5 %
Jordan	18	89.0 %
Kuwait	16	91.0 %
Oman	11	53.2 %
Qatar	16	54.2 %
Saudi Arabia	11	33.4 %
United Arab Emirates	15	100.0 %

Generation assumptions

For the generation side, we consider three types of natural gas/oil generation units: combined cycle (CC), gas turbine (GT) and steam turbine (ST). We also consider nuclear units, hydropower, solar photovoltaic (PV) and wind turbines.

Storage is still in an early stage of development in the region given the current electricity generation technologies. Some projects have been announced[5] but their timeline remains highly uncertain, and most probably to be commissioned post 2030. Therefore, in our study, we assume that no storage will be available in 2030.

To define the installed capacities in 2030, we do not rely on a generation expansion plan; instead, we look at existing capacities and announced projects with planned operational dates before or in 2030 as reported in Enerdata [42]. This is because six years is too short for a long-term capacity expansion plan to occur. In this relatively short time frame, most utilities would already be locked in their capacity builds and retirements. We adjust the here-obtained capacities to meet a capacity margin of 10 % of the peak demand assumed for 2030. Table A-3 provides the installed capacities assumed for each country in 2030.

Table A-3
Installed capacities assumed in 2030, in GW.

	Gas-CC	Gas-GT	Gas-ST	Nuclear	Oil-GT	Oil-ST	Hydro	PV	Wind	Total
Bahrain	9.6	1.4	0.7		0.2			0.6		**12.5**
Egypt	28.9	6.8	14.6	1.2	2.3	1.3	5.2	4.1	23.2	**87.6**
Iraq	11.2	16.1	4.0		4.7	3.3	1.8	5.6		**46.7**
Jordan	3.9	1.0	1.3		0.1	0.7		2.1	1.2	**10.3**
Kuwait	12.2	1.2	2.0			4.0		5.8	0.4	**25.6**
Oman	8.8	2.0			0.2			6.0	0.7	**17.7**
Qatar	12.5	5.4						5.0		**22.9**
Saudi Arabia	86.3	16.6	18.6					90.0	30.0	**241.5**
UAE	24.2	12.2	2.0	5.4	0.1			15.7	0.1	**59.7**
Total	**197.6**	**62.7**	**43.2**	**6.6**	**7.6**	**9.3**	**7.0**	**134.9**	**55.6**	**524.5**

For Saudi Arabia, we assume that oil generation units will be fully retired by 2030, and that 90 GW of PV and 30 GW of wind will be installed in 2030 to align with Saudi Vision 2030 [53].

Table A-4 provides the characteristics of the thermal generation units. Fuel and CO_2 emission assumptions are provided in Table A-5 and Table A-6. For nuclear, which is part of the electricity mix in Egypt and the United Arab Emirates, we assume variable cost of 6.4 US$/MWh.

Table A-4
Characteristics of thermal generation units.

Technology	Gas-CC	Gas-GT	Gas-ST	Oil-CC	Oil-GT	Oil-ST	Nuclear
Pmax (MW)	260	75	664	115	80	660	1,200-1,345
Heat rate (Btu/kWh)	7,500	11,500	10,500	9,000	13,000	10,500	
VOM (US US$/MWh)	4	4	4	5	5	0	6.4
Min stable factor (% Pmax)	30 %	20 %	30 %	30 %	20 %	30 %	50 %
Forced outage rate (%)	7 %	3 %	5 %	7 %	3 %	5 %	10 %
Mean time to repair forced outage (h)	36	36	36	36	36	36	24
Maintenance (per year)	1	1	1	1	1	1	1
Mean time for maintenance (h)	400	400	400	400	400	400	400

Note: For nuclear, we also include a minimum ON time of 72 h and a minimum OFF time of 24 h.

[5] See, for example, https://www.saudigulfprojects.com/2025/01/saudi-arabia-awards-10500mwh-battery-energy-storage-system-contracts/.

Table A-5
Oil and gas prices assumed in 2030.

Country	Gas price (US$/MMBtu)	Oil price (US$/MMBtu)
Bahrain	7.5	14.9
Egypt	7.0	14.9
Iraq	7.0	14.9
Jordan	7.0	14.9
Kuwait	7.5	14.9
Oman	7.5	14.9
Qatar	7.5	14.9
Saudi Arabia	7.0	14.9
United Arab Emirates	7.5	14.9

Source: Deluque Curiel (2021)

Table A-6
Emission factors of the different fuels used for electricity generation.

Fuel	CO_2 emissions factor (lb/MMBtu)
Natural Gas	116
Oil	155
Nuclear	0

Assumptions for renewables (hydropower, PV and wind)

Hourly generation profiles from wind and PV are obtained from the Renewables Ninja website [54], which is derived from the method developed in Pfenninger and Staffell [55] and Staffell and Pfenninger [56]. We use 20 weather profiles corresponding to the period 2003–2022. For each country, data are retrieved for the location that we set to correspond to be close to the location with the biggest known wind or PV project.

Table A-7 and Table A-8 present the selected locations and the corresponding annual load factors for PV and wind power, respectively. Annual capacity factors of each weather profiles are also illustrated in Figure A-1 for solar and Figure A-2 for wind.

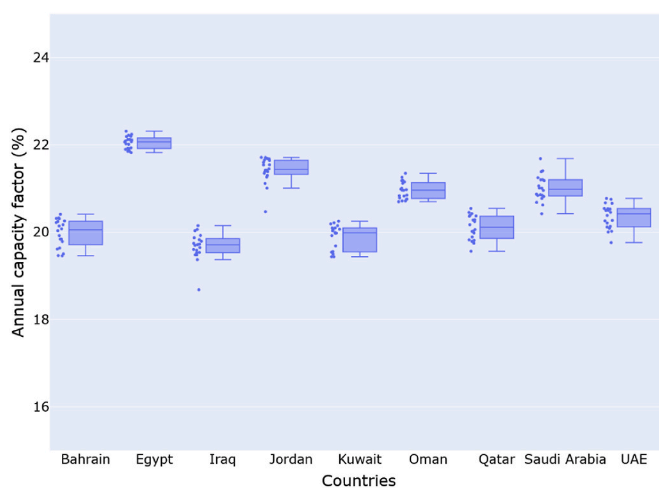

Fig. A-1. Box plot of annual capacity factor of solar for the 20 weather profiles.

Table A-7
Annual capacity factor of solar photovoltaics in the different countries.

Country	Selected location	Annual capacity factor		
		Mean	Minimum	Maximum
Bahrain	Riffa	20.0 %	19.5 %	20.4 %
Egypt	Aswan	22.0 %	21.8 %	22.3 %
Iraq	Baghdad	19.7 %	18.7 %	20.2 %
Jordan	Zarqa	21.4 %	20.5 %	21.7 %
Kuwait	Al Jahra	19.9 %	19.4 %	20.2 %
Oman	Muscat	21.0 %	20.7 %	21.4 %
Qatar	Doha	20.1 %	19.6 %	20.5 %

(continued on next page)

Table A-7 (*continued*)

Country	Selected location	Annual capacity factor		
		Mean	Minimum	Maximum
Saudi Arabia	Riyadh	21.0 %	20.4 %	21.7 %
United Arab Emirates	Dubai	20.4 %	19.8 %	20.8 %

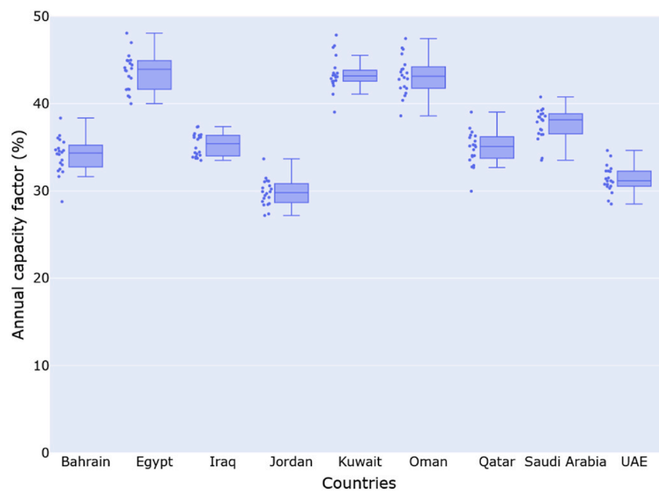

Fig. A-2. Box plot of annual capacity factor of wind for the 20 weather profiles.

Table A-8
Annual capacity factor of wind power in the different countries.

Country	Selected location	Annual capacity factor		
		Mean	Minimum	Maximum
Bahrain	Durrat	34.1 %	28.8 %	38.4 %
Egypt	Aswan	43.6 %	40.0 %	48.1 %
Iraq	Baghdad	35.3 %	33.5 %	37.4 %
Jordan	Ma’an	29.8 %	27.2 %	33.7 %
Kuwait	Al Abdaliyah	43.4 %	39.0 %	47.9 %
Oman	Tahamarit	43.2 %	38.6 %	47.5 %
Qatar	Al Karaana	34.9 %	30.0 %	39.0 %
Saudi Arabia	Riyadh	37.6 %	33.5 %	40.8 %
United Arab Emirates	Al Jahra	31.4 %	28.5 %	34.7 %

Hydropower is assumed to be part of the electricity generation mix in Egypt and Iraq. As these countries mainly rely on reservoir hydropower, we model the total installed hydro capacity in these two countries as reservoirs. We assume an annual capacity factor based on historical data. Based on historical data from the International Energy Agency [57] and International Renewable Energy Agency [58], we limit the annual capacity factor of hydropower to 58 % in Egypt and 25 % in Iraq. To mimic the hydro generation profile over the year, we also impose a maximum capacity factor for each month (see Fig. A-3) based on hydrogeneration profiles from Brinkerink and Deane (2020).

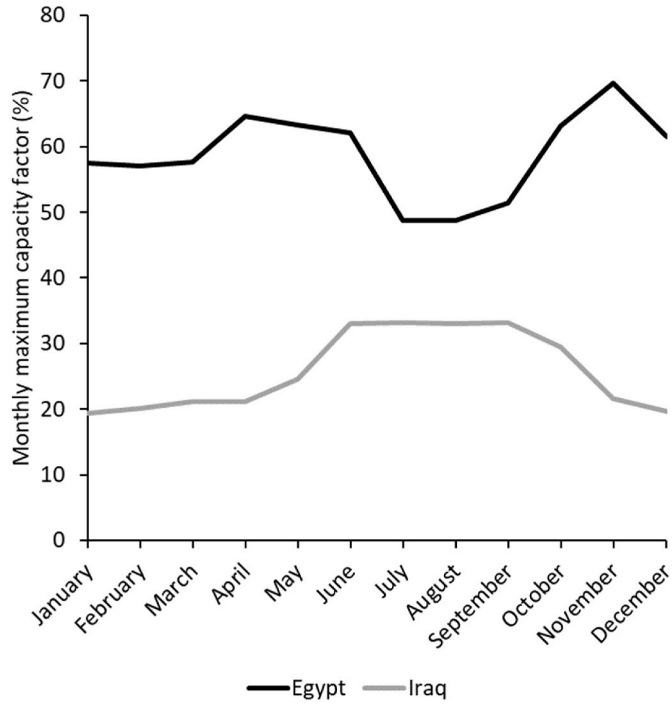

Fig. A-3. Monthly maximum capacity factor assumed for hydropower in Egypt and Iraq.

Network assumptions

The model includes cross-border flow limits, which reference the existing and future interconnection projects at the 2030 horizon based on EDF-Ingeum expertise and press announcements. Table A-9 provides the interconnection limits implemented in our model for 2030 and Figure A-4 details the topology of the GCCIA interconnector.

Table A-9
Assumptions for the maximum electrical flows between interconnected countries in 2030.

Line	Maximum flow (GW)
Bahrain – GCCIA	0.6
Egypt – Jordan	1.1
Egypt – Saudi Arabia	3.0
GCCIA – Kuwait	3.5
GCCIA – Qatar	1.2
GCCIA – Saudi Arabia	1.2
GCCIA – United Arab Emirates	1.2
Iraq – Saudi Arabia	1.0
Iraq – Kuwait	0.5
Jordan – Iraq	1.0
Jordan – Saudi Arabia	0.5
Oman – United Arab Emirates	0.4

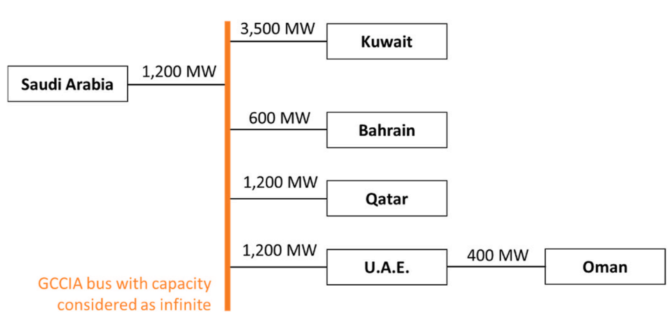

Fig. A-4. Simplified topology of the GCCIA interconnected system in 2030.
Source: based on GCCIA data.

For each country, the internal network is not modeled (copper plate assumption). In practice, network losses occur on the internal network of each country, and on the interconnectors depending on the volume of cross-border trade. In other words, in practice, the volume of electricity trade has a direct impact on network losses. However, for simplicity, the model does not account for this relationship. Instead, the model includes fixed network losses that are expressed as a percentage of the electricity demand for each country. Specifically, it includes the average network losses set to correspond to historical levels. In absence of more detailed data, historical network losses were estimated based on the ratio between the generation and consumption reported in Enerdata [38] over the period 2017–2021 (see Table A-10). Potentially, these losses include both technical and non-technical losses. These losses are accounted for in the demand entered to the model.

Table A-10
Network losses.

Country	Network losses (%)
Bahrain	3.2 %
Egypt	19.5 %
Iraq[a]	12.0 %
Jordan	9.7 %
Kuwait	13.0 %
Oman	12.3 %
Qatar	12.3 %
Saudi Arabia	18.0 %
United Arab Emirates	10.2 %

[a] Due to missing data, the value for Iraq is set to the average of the eight other countries.

To get economical flows between countries, we impose a wheeling charge of 1 US$/MWh in both directions when the interconnectors are used. As a result, the model allows flows between two countries when the price difference is greater than 1 US$/MWh.

Operational reserve

The model includes operational reserves defined at the country level, provided only by the generators located in the country (no reserve sharing between countries). Spin-up and spin-down reserves are supposed to be symmetrical and are modeled as follows.

- A spin-up reserve to be provided within 10 min. For each country, the spin-up reserve's volume corresponds to the installed capacity of the largest thermal generator.
- A spin-down reserve to be provided within 10 min. The spin-down reserve is defined symmetrically to the spin-up reserve, i.e., its volume corresponds to the installed capacity of the largest thermal generator in the considered country.

Table A-11 provides the spinning reserve volume by country, based on the data provided by the Gulf Cooperation Council Interconnection Authority [43], adjusted to consider the new nuclear power plants in Egypt and the UAE.

Table A-11
Spinning reserve requirement assumptions per country.

Country	Spinning reserve requirement (MW)
Bahrain	330
Egypt	1,200
Iraq	500
Jordan	500
Kuwait	616
Oman	412
Qatar	495
Saudi Arabia	730
United Arab Emirates	1,345

Only thermal generators are allowed to provide reserves, according to their respective ramp rates given in Table A-12. Ramp rate assumptions were adapted from Joshi et al. [59] and Sustainable Nuclear Energy Technology Platform [60]. We exclude nuclear from providing the spinning reserve because the notice time of 10 min is too short, as suggested in Petitet et al. [61].

Table A-12
Ramp rate assumptions for gas and oil power plants.

Technology	Gas-CC	Gas-GT	Gas-ST	Oil-CC	Oil-GT	Oil-ST
Pmax (MW)	260	75	664	115	80	660
Max ramp rate (MW/min)	±10.4	±6.0	±53.1	±4.6	±6.4	±52.8

Note: min = minute.

Appendix B. Results

Scenario with hourly trading among GCC countries only (noted HT_GCC)

In this scenario, noted **HT_GCC**, the GCC system with six countries is run with optimal hourly electricity trading among countries. Egypt, Jordan and Iraq are not run as isolated countries with no cross-border electricity trading.

Table B-1 below presents the exports and imports in the **HT_GCC** scenario. It shows a potential for hourly trading of 13.9 TWh among GCC countries in 2030.

Table B-1
Annual exports and imports of electricity in 2030 in the HT_GCC scenario, on average for the 20 weather profiles.

		Exports (TWh)	Imports (TWh)	Net position (TWh)
GCC	Bahrain	1.4	0.2	1.2
	Kuwait	0.2	8.8	−8.6
	Oman	1.2	0.1	1.1
	Qatar	0.2	2.0	−1.8
	Saudi Arabia	9.8	0.5	9.3
	United Arab Emirates	1.2	2.4	−1.2

Note: The last column presents the net position of imports/exports, defined as the volume of exports minus the volume of imports during the year.

When electricity trade is allowed in the GCC (**HT_GCC** scenario), 13.1 TWh of renewable energy is curtailed on average in the region (nine countries) during the year 2030. This corresponds to a reduction in energy curtailed of 1.4 TWh compared to the **NT** scenario. Notably, this reduction is significantly lower than the avoided energy curtailment of 5.1 TWh achieved in the **HT** scenario.

In the **HT_GCC** scenario, the total variable generation cost for the nine countries appears to be US$ 67,219 million on average in 2030, compared to US$ 67,475 million in the **NT** scenario and US$ 66,376 million in the **HT** scenario. Therefore, the **HT_GCC** scenario brings a saving of US$ 256 million in the variable generation costs for the year 2030 compared to the **NT** scenario without electricity trade, which is in line with the results in Gulf Cooperation Council Interconnection Authority [27].

Data availability

Data will be made available on request.

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