

Discussion Paper

How Can Bilateral Contracts Support Electricity Trade?

A Regional Electricity Model Perspective for the GCC Plus Egypt, Jordan, and Iraq

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Abstract

Cross-border electricity trading in the Middle East and North Africa (MENA) can provide cost and environmental benefits. However, for historical reasons, electricity trading has not reached a mature stage in this region. Based on a bespoke economic dispatch model for the 2030 horizon, this paper investigates the cost and emission implications of electricity trade in Gulf Cooperation Council (GCC) countries plus Egypt, Jordan, and Iraq. The model adopts an hourly resolution demand profile and considers current and future network interconnections. We focus specifically on the trade between Saudi Arabia and Egypt, given that they have the largest power sectors in the region. The results indicate that implementing hourly market coupling can decrease a region's annual generation cost by 1.6% while avoiding 34% of renewable curtailment and reducing carbon dioxide (CO₂) emissions by 8 million metric tons.

The development of fully fledged regional markets in a region requires political commitment, time and financing. As an alternative solution, we explore how bilateral long-term arrangements can support electricity trade. The results show that if Saudi Arabia and Egypt are willing to trade electricity through long-term arrangements, then contracts should follow a daily pattern to maximize the economic value of the electricity trade, limit the curtailment of renewable energy and reduce CO₂ emissions.

Keywords: Power system; electricity market integration; cross-border trade; Gulf Cooperation Council; Middle East and North Africa.

Highlights

- Network-constrained economic dispatch is performed for 2030 for the interconnected Gulf Cooperation Council (GCC) countries plus Egypt, Jordan and Iraq.
- Electricity trading can decrease the aggregated annual variable generation cost of electricity in the nine countries by US\$ 1.1 billion (-1.6%) in 2030. Twenty percent of this economic gain is attributed to the interconnection between Saudi Arabia and Egypt.

- Electricity trading also brings about additional benefits in terms of reducing the curtailment of renewable energy (by 34%) and carbon dioxide (CO₂) emissions to a lesser extent.
- Within the nine considered countries, Saudi Arabia is the largest electricity exporter, with an annual export volume of 28 terawatt-hours (TWh).
- The results show that the interconnection lines through which Saudi Arabia exports electricity to Jordan, Iraq and the GCC are highly utilized in that single direction. However, Saudi Arabia and Egypt are complementary, with Saudi Arabia exporting to Egypt during the day when solar photovoltaic (PV) generation is high and importing from Egypt during summer nights.
- If long-term contractual arrangements are developed between Saudi Arabia and Egypt, then a contract with a fixed volume throughout the day would significantly decrease the economic value of the electricity trade between the two countries to less than 20% of its maximal economic value. This situation would mean that the economic value would decrease from US\$ 210 million with hourly trading to US\$ 26 million in the worst case. Alternatively, a long-term contract with a volume that follows a daily pattern appears to be more suitable and allows for the capture of more than 50% of the maximum economic value of the Saudi-Egyptian interconnector.
- Regarding externalities, contracts with a daily pattern also limit the curtailment of renewable energy and reduce CO₂ emissions.

I. Introduction

Although 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 to transitioning to renewable energy sources of electricity (Poudineh, Sen, and Fattouh 2018; Alharbi and Csala 2020; Bhatt 2021; Alnaser, Albuflasa, and Alnaser 2022). There is also growing interest in developing electricity trading in this region, which can be observed both in the academic literature and in previous and ongoing interconnection projects on the ground. One of the MENA's most significant efforts to interconnect electricity systems is the GCC Interconnection Authority (GCCIA) link, which 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 to Egypt, Jordan, and Iraq.

The benefits of cross-border electricity trading have been largely identified in the literature. Such trading can increase cost savings by reducing unserved energy, decreasing variable generation costs, lowering the costs of ancillary services, and avoiding/deferring investment in generation (Turvey 2006). When renewables account for a significant share of the generation mix, developing internal networks or interconnectors between countries has the benefit of reducing the curtailment of renewable energy (Golden and Paulos 2015; Newbery, Strbac, and Viehoff 2016; Newbery 2021). Similarly, interconnectors can also play a role in reducing greenhouse gas emissions (Denny et al. 2010; Pean, Pirouti, and Qadrdan 2016). Despite the technical and political challenges, some papers consider interconnections at the global level (Chatzivasileiadis, Ernst, and Andersson 2013; Brinkerink, Gallachóir, and Deane 2019; Lopez Prol et al. 2023).

Efforts to expand regional electricity trading in the MENA region are widespread (Leal-Arcas, Akondo, and Alemany Rios 2017; Timilsina and Curiel 2023). Similar to other regions, in the MENA, electricity trade could substantially reduce the cost of achieving a 100% renewable electricity system (Aghahosseini, Bogdanov, and Breyer 2020). To enable regional electricity trade

in the MENA region, where administratively set fuel prices prevail in the power sector, wholesale electricity pricing mechanisms that handle international trade with domestic fuel pricing are needed (Wogan, Murphy, and Pierru 2019; Al-Awadhi et al. 2022; Muñoz et al. 2023; Petitet, Felder, and Elshurafa 2024). Specifically, removing fossil fuel subsidies for electricity generation and expanding cross-border trade across the MENA would bring about economic savings and reduce carbon dioxide (CO₂) emissions (Timilsina and Curiel 2020, 2023).

Despite the many studies identifying the benefits of regional electricity trade, none have presented detailed results on the types of electricity transactions in which GCC or MENA countries would engage. This paper fills this gap by developing a bespoke network constraint economic dispatch model for GCC countries plus Egypt, Jordan, and Iraq. This model is used to analyze the implications of these transactions for trade volume, variable generation costs, the curtailment of renewable energy, and emissions. Given that Saudi Arabia and Egypt possess the two largest power generation sectors in the region that is being considered, we dedicate particular attention to their trading arrangements. In the context of the growing interest in electricity trading in

the GCC particularly and also in the MENA region more broadly, this paper aims to answer the following two main questions: (1.) What is the benefit, if any, of an hourly electricity market between interconnected GCC countries plus Egypt, Jordan, and Iraq within the 2030 horizon? (2.) Given their size, what long-term bilateral electricity trade arrangements might evolve between Saudi Arabia and Egypt to create a win–win scenario for both countries? The results inform the possible evolution of a MENA electricity market that garners the most benefits from electricity trading within the policy context and specificities of the region.

The remainder of this paper is organized as follows. Section 2 conducts a literature review of previous studies that have focuses 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 and discusses the results obtained from the model, specifically comparing several long-term contractual arrangements between Saudi Arabia and Egypt that differ in terms of contracted electricity volume. Finally, Section 5 concludes the paper and suggests next steps.

2. Literature Review

In 2001, the GCCIA progressively developed a direct current 440-kilovolt (kV) grid comprising 1,049 kilometers of double-circuit overhead lines and submarine cables. The power traded through the GCCIA has increased continuously since 2016 (with 2019 being an exception), reaching 1,098 gigawatt-hours (GWh) in 2021, for an estimated electricity value of US\$ 136 million (Gulf Cooperation Council Interconnection Authority 2021). 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, rather than financial trade, between the two trading countries on average over the agreed-upon period. A previous study suggested that if day-ahead hourly trading were implemented and used optimally in 2022, then the GCCIA interconnectors could have supported up to 16 terawatt-hours (TWh) of day-ahead trade, corresponding to potential savings of US\$ 200 million annually for GCC countries (Gulf Cooperation Council Interconnection Authority 2021).

There is a limited but growing body of literature analyzing electricity trading in the GCC and the broader MENA region. Such literature 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 in CO₂ emissions in the power sector. Table 1 summarizes the key characteristics of the previous modeling-based analysis and shows how our work complements the 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, a concept that has been thus far absent from the literature. Furthermore, we also complete the literature review 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 generation and transmission capacity expansion planning models applied to GCC or MENA countries to investigate how various technologies and trading rules can impact installed capacities and, consequently, energy mix and emissions. The CESI (2014) conducted a feasibility study of the electrical interconnection and energy trade among Arab countries, finding that an increase in the level of investment in nuclear energy, renewables, and interconnections can reduce the cost of electricity. Aghahosseini, Bogdanov, and Breyer (2020) examined a 100% MENA renewable electricity system in 2030 and found that it has a lower cost than business as usual. The above authors also considered the same scenario with and without electricity trading for the 2030 horizon and showed that electricity trading allows for 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

¹ See Table 3 in Aghahosseini, Bogdanov, and Breyer (2020). Importantly, this reduction in opex of 13% is for two different installed generation capacity scenarios.

Table 1. Review and comparison of relevant literature.

Variables	Timilsina and Curiel (2023)	Aghahosseini, Bogdanov, and Breyer (2020)	Ek Fälvh et al. (2021)	De Monts de Savasse (2018)	This Paper
Modeling approach	CEP	CEP	CEP	Network-constrained economic dispatch	Network-constrained economic dispatch
Horizon	2018–2035	2014–2030	2040 (green field)	2016 & 2030	2030
Geography	MENA	MENA	MENA	GCC	GCC, Egypt, Jordan, and Iraq
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

Notes: CEP = capacity expansion planning (generation only or generation and transmission).

Source: Authors.

Detailed World Bank studies based on a capacity and transmission expansion model for the period 2018–2035 (Timilsina and Curiel 2020; World Bank 2021; Timilsina and Curiel 2023) have analyzed the interactions among fossil fuel subsidies, reduction policies for CO₂ emissions and regional electricity trading. These studies concluded that all three factors acting in concert would benefit the region. More specifically, studies have shown 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. Moreover, Ek Fälvh et al. (2021) used 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 and found that such a system would be less costly than it would in Europe and that optimal transmission expansion decreases system costs by 5–25%. Taliotis et al. (2023) focuses on electricity exchanges between the Middle

East and Eastern Mediterranean countries at the 2050 horizon, using an open-source capacity expansion model to show that in the current context with limited renewables, there is no need for more electricity trading. However, the above authors also found that in a scenario with climate neutrality goals, it is cost-effective to develop further interconnection infrastructure and, consequently, increase the level of electricity trading in the region.

Another stream of research opted to keep the installed generation capacities unchanged and focused on the effect of electricity trading on economic dispatch. To our knowledge, the study of De Monts de Savasse (2018) is one of the few studies performed along these lines for the GCC region, investigating how to improve the use of the GCC interconnector to reduce operational costs. The abovementioned study conducted network-constrained multiperiod economic dispatch with a detailed network representation of GCC countries and GCCIA

interconnectors, showing that the operational costs of GCC electricity trade can be reduced by approximately 2% when international fuel prices are considered for dispatch.

The GCC and/or broader MENA regions have also been discussed using more qualitative or energywide approaches. El-Katiri (2011) highlighted the political and legal frameworks, alongside information and transparency, necessary for the GCC to move toward more electricity trading. Other qualitative discussions stressed the importance of removing fuel subsidies and developing electricity trading in GCC or MENA countries to support their respective energy transitions (Poudineh, Sen, and Fattouh 2021; Shaar and Leal-Arcas 2023).

The above-discussed literature, however, did not investigate the trading benefits of the specific types of

cross-border transactions that countries may consider or their implications for the evolution of the region's electricity market structure. In addition, although their focus included electricity trading, these works generally provided annual cost comparisons without providing details on hourly trends or drivers of trade.

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

3. Methodology

Our approach consists of creating a dataset (electricity demand, power generation units, and transmission capacities between countries) for 2030 based on publicly available information and then running a network-constrained hourly economic dispatch in PLEXOS. The details of the model and how it was created are provided in this section and further detailed in the Appendix.

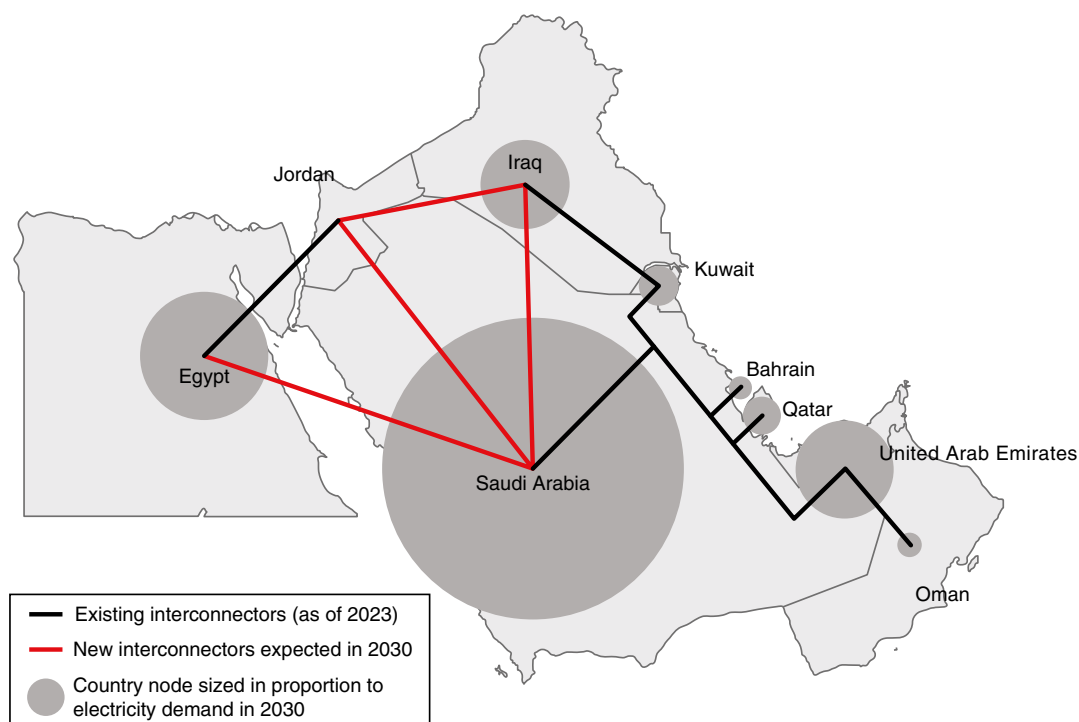
3.1. Model Overview

3.1.1 Geographical Scope and Interconnection Network

The geographical scope covered by our model includes the following nine countries, as presented in Figure 1 (in alphabetical order): Bahrain, Egypt, Iraq, Jordan,

Kuwait, Oman, Qatar, Saudi Arabia and the UAE. Each country is represented by a single node. The interconnection capacity between a pair of countries

Figure 1. Geographical perimeter of the model and interconnectors between countries.



Source: Authors.

is defined based on the capacity of the announced interconnection line. Thus, we implicitly assume that other (internal) network constraints do not limit cross-border flows. In addition, network line losses are incorporated into demand based on historical data, as further described in the Appendix.

3.1.2 Electricity Demand

To forecast the annual electricity demand in 2030, we extrapolate the historical electricity demand for 2020 (Enerdata 2023a) 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, taken from Mikayilov and Darandary (2023), to calculate Saudi GDP growth during this period.

Hourly electricity demand is derived from the forecasted annual demand by applying the country-specific hourly factors from Brinkerink and Deane (2020). Refer to the Appendix for more details.

3.1.3 Generation Capacities

To obtain 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 obtained based on the project pipeline reported in Enerdata (2023b) and adjusted nationally to adhere to the 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. The reason for this is that six years is too short for long-term capacity expansion planning to occur. In this relatively short time frame, most utilities would already be locked into 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 technologies, wherever applicable. The installed generation capacities and their technical and economic characteristics are presented in the Appendix.

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 the approaches taken in World Bank (2021) and Timilsina and Curiel (2023) to remove this barrier. This approach is

also in line with using fuel opportunity costs to dispatch electricity in fuel-rich regions (Petitet, Felder, and Elshurafa 2024).

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 the Appendix, operational reserves are defined at the country level and are provided only by the generators located in the country (there is no reserve sharing between countries). These reserves correspond to symmetrical spin-up and spin-down reserves, sized according to the largest generation unit in the country considered.

3.2 Simulated Scenarios

The first topic investigated in this paper is the benefits of hourly electricity trading in the region. For this purpose, 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. Third, we run a scenario that focuses on hourly electricity trading among GCC states only (i.e., we ignore Egypt, Jordan and Iraq). The analysis and comparison of these scenarios allow us to estimate the maximal benefits of electricity trading performed through hourly wholesale electricity market coupling. However, given that such a mechanism requires strict 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 those of other regions, and investigate the associated benefits of the below scenarios. The first scenario features hourly electricity trading but with no flows between Egypt and Saudi Arabia and is used to estimate the maximal value of the electricity trade between the two countries. The four subscenarios feature different contractual schemes for the electricity trade between Egypt and Saudi Arabia. Specifically, the four long-term bilateral arrangements that we test combine two different patterns (a fixed and daily pattern) and different degrees of time granularity (weekly, monthly, or quarterly). In total, we run eight scenarios, which are summarized in Table 2.

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 performed with optimal hourly electricity trading between countries.
Hourly trade among GCC states only (HT_GCC)	The GCC system with six countries is performed with optimal hourly electricity trading between countries. Egypt, Jordan and Iraq are not considered.
Hourly trade with no flows between Egypt and Saudi Arabia (HT_noEG-SA)	This is 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 contract (4 scenarios)	This is based on the HT scenario, but flows between Saudi Arabia and Egypt are fixed as inputs. Four different contractual profiles are tested. See the details in Section 4.2. Case 1: A fixed profile defined for each month. Case 2: A fixed profile defined for each week. Case 3: A daily profile defined for each quarter. Case 4: A daily profile defined for each month.

Source: Authors.

4. Results and Discussion

4.1. Benefits of Hourly Electricity Trading

This section provides the general outputs for the scenario without electricity trading first (i.e., the **NT** scenario) to provide the reader with the benchmark against which other scenarios can be compared. Then, we discuss the results that stem from trading for the specific geographies/countries identified, as explained in 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 can also reduce the level of investment in generation on a regional basis, and thus, additional benefits can be achieved in the long term.

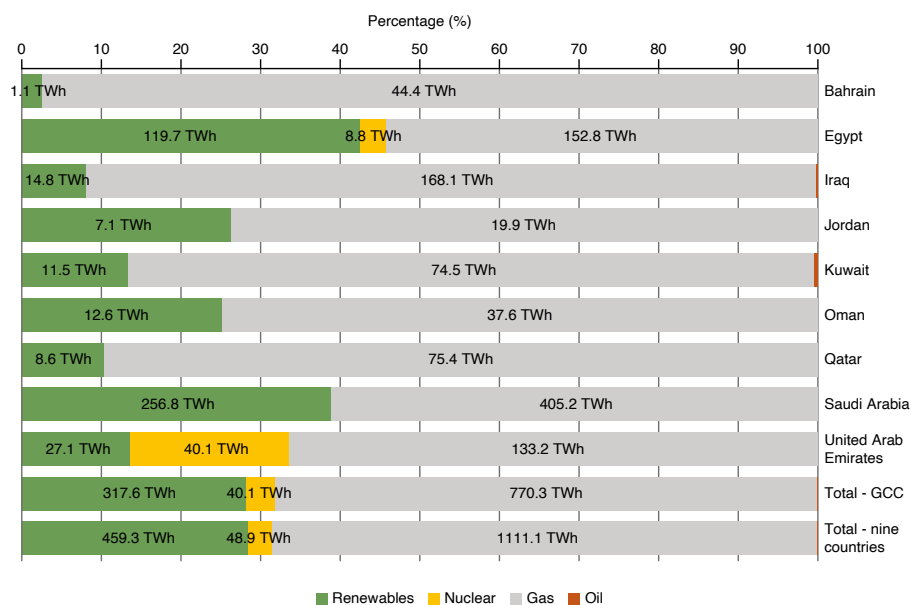
4.1.1 Overview of the NT Scenario

Overall, we find that gas will be dominant (69%) in the electricity energy mix in 2030, as shown in Figure 2. This mix, obtained for the **NT** scenario, will result in 506.8 million metric tons of CO₂ (MtCO₂) in 2030. Furthermore, renewable energy (PV, wind, and hydropower) meets 28% of the energy requirement, corresponding to 459 TWh. Saudi Arabia and Egypt are the largest renewable energy producers, with 257 and 120 TWh generated, respectively. Here, importantly, the total curtailed energy from renewables is at a low level, at only 13.5 GWh, corresponding to 3.1% of the available electricity generation of PV and wind among the countries

considered. Most of this curtailment occurs in Saudi Arabia, given the large amount of renewable installed capacity in the country.

The total variable generation cost of electricity in 2030 in the **NT** scenario is presented in Table 3 by country and for the two aggregates (GCC and GCC plus Egypt, Jordan and Iraq). This value corresponds to the cost of fuel used to generate electricity plus the variable operation and maintenance costs of the generation units. For the nine countries, the variable generation cost will reach US\$ 67.4 billion in 2030.

Figure 2. Electricity power generation mix in 2030 in the **NT** scenario.



Note: Renewable energy (in green) includes electricity generated from PV, wind and hydropower sources. Oil accounts for less than 1% of the electrical power generation for the nine countries considered in this study.

Source: Authors.

Table 3. Variable generation cost of electricity in 2030 in the NT scenario.

Country	Total Variable Generation Cost (Million US\$)	Average Variable Generation Cost (US\$/MWh)
Bahrain	2,677	58.9
Egypt	8,806	31.3
Iraq	11,671	63.6
Jordan	1,207	44.7
Kuwait	4,637	53.7
Oman	2,267	45.2
Qatar	4,627	55.1
Saudi Arabia	23,052	34.8
UAE	8,494	42.4
Total – GCC	45,754	40.6
Total – nine countries	67,438	41.6

Notes: This table corresponds to the variable generation cost only. Investment costs and network costs are excluded.

Source: Authors.

4.1.2 Volume of Electricity Traded Across the Region

Table 4 presents the import and export volumes for each country in the **HT** and **HT_GCC** scenarios. The GCC-only simulation (**HT_GCC**) shows the potential for hourly

trading of 14.0 TWh among GCC countries in 2030. In the HT scenario, the annual electricity volume exchanged among the nine countries increases to 55.5 TWh. In both scenarios, Saudi Arabia is the largest exporter of electricity, with 10 TWh exported to GCC countries and 18 TWh exported to Egypt, Jordan, and Iraq.

Table 4. Annual exports and imports of electricity in 2030 in the HT and HT_GCC scenarios.

Scenario	Hourly Trading Within the Nine Countries (HT)		Hourly Trading Within GCC Countries (HT_GCC)	
	Exports (TWh)	Imports (TWh)	Exports (TWh)	Imports (TWh)
GCC				
Bahrain	1.6	0.2	1.5	0.2
Kuwait	3.4	9.7	0.2	8.7
Oman	1.2	0.1	1.2	0.1
Qatar	0.2	2.2	0.2	2.0
Saudi Arabia	28.2	3.3	10.0	0.3
UAE	1.1	2.7	1.0	2.7
Non-GCC				
Egypt	10.2	6.4	0.0	0.0
Iraq	0.7	19.8	0.0	0.0
Jordan	8.7	11.1	0.0	0.0

Source: Authors.

Table 5 presents the flow between pairs of interconnected countries in absolute TWh in 2030 and the directional load of the line. To aid readers, Figure 3 graphically illustrates the directional load presented in Table 5. The results show that some lines are heavily used in one direction, whereas other lines 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 remaining GCCIA

(96%), the line from Saudi Arabia to Iraq (97%) and the line from Jordan to Iraq (92%). Long-term contractual arrangements can 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, compared to hourly market coupling, can decrease the value of electricity trading.

Table 5. Annual electricity flows in the HT scenario (in TWh with the annual directional loading of the interconnector in parentheses (%)).

From → To ↓	Bahrain	Egypt	Iraq	Jordan	Kuwait	Oman	Qatar	SA	UAE	GCCIA*
Bahrain										0.2 (4%)
Egypt				0.4 (4%)				6.0 (23%)		
Iraq				8.1 (92%)	3.2 (73%)			8.5 (97%)		
Jordan		7.5 (77%)	0.0 (0%)					3.6 (83%)		
Kuwait			0.7 (17%)							9.0 (29%)
Oman									0.1 (3%)	
Qatar										2.2 (221%)
SA		2.8 (11%)	0.0 (0%)	0.3 (6%)						0.3 (3%)
UAE						1.2 (35%)				1.5 (14%)
GCCIA*	1.6 (31%)				0.2 (1%)		0.2 (2%)	10.1 (96%)	1.0 (10%)	

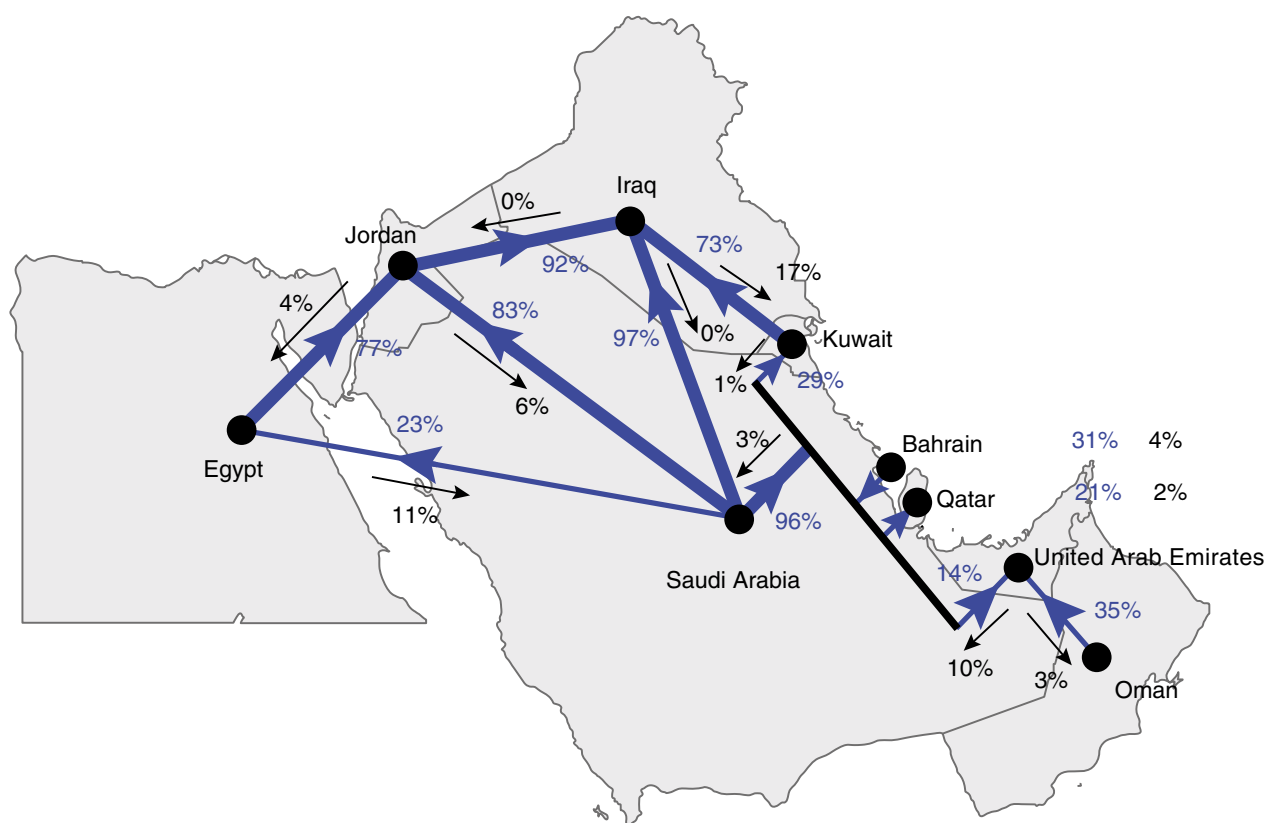
Abbreviations: SA: Saudi Arabia.

Notes:

* Given the typology of the GCCIA interconnector/bus, we provide flows for the GCCIA rather than detailing them by pairs of countries.

Source: Authors.

Figure 3. Annual loading of the interconnection lines (in %) in the **HT** scenario.

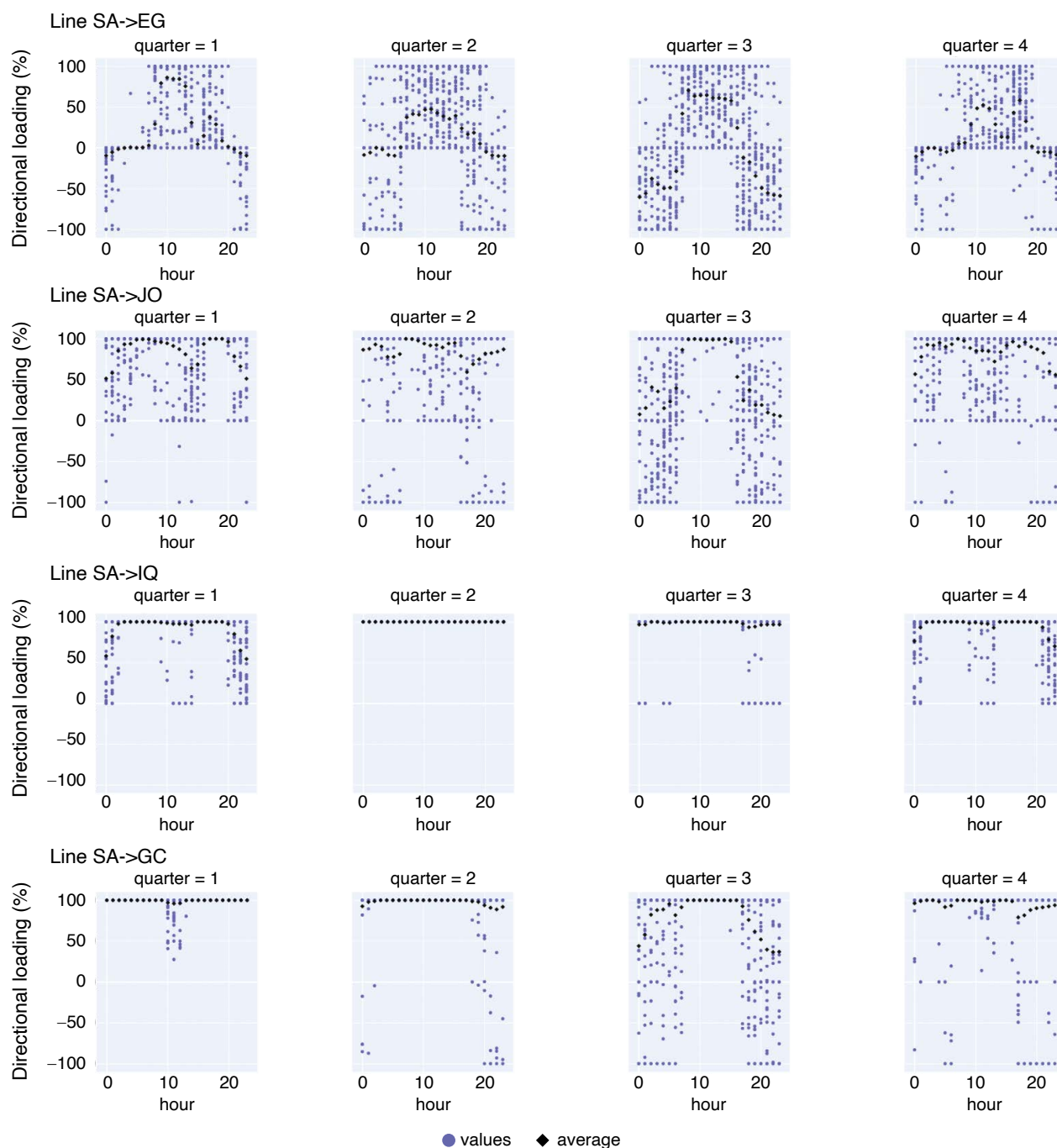


Source: Authors.

Figure 4 details the loading of each interconnector with Saudi Arabia. More specifically, this figure displays a scatterplot of the directional loading on the interconnectors for each quarter of 2030, with the hours of the day shown on the x-axis. The dark markers indicate the average loading for each hour. The figure confirms the previously mentioned observation that the lines between Saudi Arabia and the GCCIA, 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. Moreover, Saudi Arabia imports electricity from Egypt, Jordan and the GCCIA mainly at night during the third quarter (July, August, and September). Moreover, 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.

Figure 4. Directional loading on the lines 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. GC=Gulf countries and corresponds to the GCCIA interconnector, EG=Egypt, and IQ=Iraq.

Source: Authors.

4.1.3 Variable Generation Cost of Electricity

Table 6 presents the total variable generation cost in 2030 for the different scenarios. The variable generation cost presented here accounts only 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 savings in variable generation costs for 2030 reach US\$ 1,072 million, which corresponds to a reduction of 1.6%. The **HT_GCC** scenario, compared to the **NT** scenario without electricity trade, brings about a saving of US\$ 275 million in variable generation

costs for 2030, which is in line with the results in Gulf Cooperation Council Interconnection Authority (2021). In practice, the identified decrease in the variable generation costs should be compared to the regulatory and implementation costs of establishing hourly market coupling in the region.

Our results suggest that expanding electricity trading beyond GCC countries to Egypt, Jordan and Iraq is particularly relevant. More specifically, as detailed in Section 4.2, the interconnection between Saudi Arabia and Egypt will bring about a gain in variable generation costs of US\$ 210 million in 2030, which corresponds to 20% of the total trading benefits in the region.

Table 6. Total variable generation cost in 2030 at the GCC perimeter for the NT, HT and HT_GCC scenarios.

Scenario	Total Variable Generation Cost for the Nine Countries (Million US\$)
No trade (NT)	67,438
Hourly trade within the nine countries (HT)	66,366
<i>Delta w.r.t. NT</i>	-1,072 (-1.6%)
GCC trade (HT_GCC)	67,163
<i>Delta w.r.t. NT</i>	-275 (-0.4%)

Notes: w.r.t.: with respect to.

Source: Authors.

4.1.4 Renewable Energy Curtailment

Table 7 presents the curtailment of PV and wind power in the **NT** and **HT** scenarios. Here, we define curtailment as the reduction in the electricity generated from PV and wind sources that is injected into the grid compared to what it can otherwise produce given the available resources (Golden and Paulos 2015). The curtailment

obtained in our simulations occurs when generation from wind and solar energy is greater than the load and when interconnectors are unable to further accommodate this surplus of energy. However, this estimated curtailment does not include the curtailment that can occur in practice due to internal network constraints within a given country.

Initially, 3.1% of the available electricity generated by PV and wind sources is curtailed in the **NT** scenario. The results presented in Table 7 confirm that electricity trading reduces the curtailment of PV and wind power, which has already been identified in the literature (Golden and Paulos 2015; Newbery, Strbac, and Viehoff 2016; Newbery 2021). When electricity trade is allowed in the GCC (**HT_GCC** scenario), the level

of energy curtailment is reduced by 1.2 GWh, and curtailment is further avoided when trade is performed among all nine countries (**HT** scenario). The curtailment reduction decreases from 13.5 TWh in the **NT** scenario to 8.9 TWh (2.0% of the PV and wind power generation) when electricity is traded among the nine countries (**HT** scenario), corresponding to a reduction of 34%.

Table 7. Curtailment of PV and wind power in 2030 in the NT and HT scenarios.

	PV and Wind Generation (TWh)	No Trading (NT)		Hourly Trading (HT)	
		Curtailed Energy, GWh (%)	Hours of Curtailment (h)	Curtailed Energy, GWh (%)	Hours of Curtailment (h)
Bahrain	1.1	–	–	–	–
Egypt	93.4	94 (0.1%)	79	5 (0.0%)	4
Iraq	10.9	–	–	–	–
Jordan	7.4	268 (3.4%)	677	1 (0.0%)	6
Kuwait	11.5	6 (0.1%)	30	0.3 (0.0%)	2
Oman	13.4	861 (6.4%)	748	627 (4.7%)	629
Qatar	8.6	1 (0.0%)	5	0.3 (0.0%)	3
Saudi Arabia	268.9	12,048 (4.5%)	774	8,202 (3.1%)	591
UAE	27.3	227 (0.8%)	164	92 (0.3%)	86
Total – GCC	330.7	13,142 (4.0%)	979	8,921 (2.7%)	794
Total – nine countries	442.4	13,504 (3.1%)	1,241	8,927 (2.0%)	794

Source: Authors.

4.1.5 CO₂ Emissions

In terms of emissions, the scenario with electricity trading among the nine countries (**HT** scenario) shows a reduction in emissions of 8.0 million MtCO₂ in 2030 compared to the **NT** scenario, which corresponds to a reduction of 1.6%, as presented in Table 8. This reduction in emissions 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 can be performed on a regional basis and thus influence the installed capacities, which can 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 and that they are linked with a 3 gigawatt (GW) line (the largest of all lines within this study), it is important to focus specifically on the trade between these two countries. While an hourly trade market

Table 8. CO₂ emissions (in million MtCO₂) from electricity generation in 2030 in the NT and HT scenarios without electricity trading and with hourly electricity trading.

Country	No Trading (NT)	Hourly Trading (HT)
Bahrain	19.3	20.0
Egypt	67.4	68.6
Iraq	90.9	78.5
Jordan	8.7	7.6
Kuwait	33.4	30.3
Oman	16.4	16.8
Qatar	33.5	32.3
Saudi Arabia	177.6	186.6
UAE	59.6	58.2
Total – GCC	339.7	344.1
Total – nine countries	506.8	498.8

Notes: These emissions correspond to direct emissions when the fuel is burned. Emissions related to construction, maintenance, or dismantlement are excluded.

Source: Authors.

theoretically brings about considerable value, establishing such a market may be difficult and require time. As a compromise 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.

First, we provide more details on the use of the Saudi-Egyptian interconnector in the **HT** scenario and estimate its economic value. 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

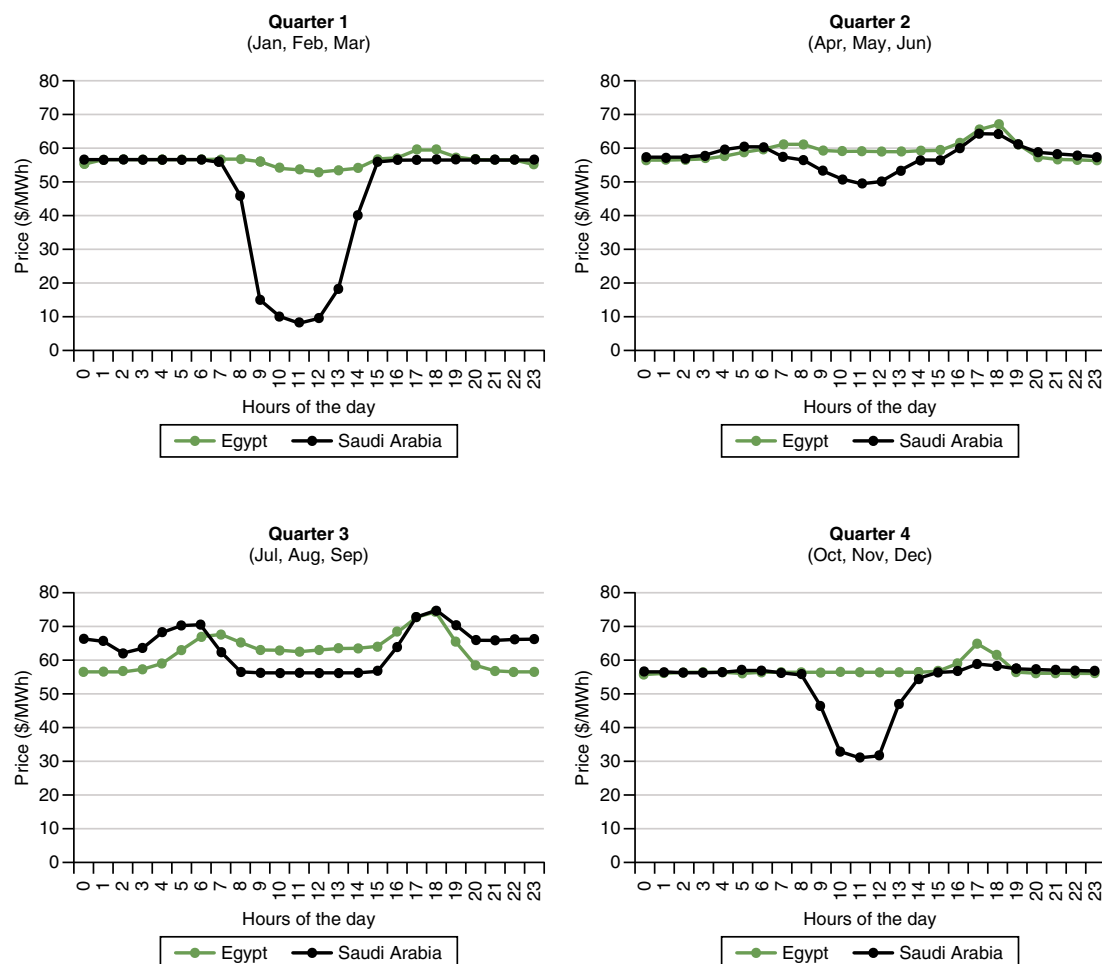
As illustrated in Figure 4, throughout the year, Saudi Arabia exports to Egypt during the day and imports from Egypt at night. Imports from Egypt to Saudi Arabia occur mainly during the third quarter of the year (corresponding to July, August, and September). To understand the root

causes of this trend, Figure 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 greater demand and needs to use gas steam turbines (STs), with a variable cost of US\$77.5/MWh at night, whereas the Egyptian main marginal unit remains the gas combined cycle (CC) at night, with a variable cost of US\$56.5/MWh.

4.2.2 Maximum Economic Value of the Saudi-Egyptian Interconnector in the HT Scenario

To estimate the economic value of the Saudi-Egyptian interconnector, we use a simulation identical to that in the **HT** scenario but with no trade allowed between Saudi Arabia and Egypt (denoted as **HT_noEG-SA**). This scenario allows us to quantify the maximum economic

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



Source: Authors.

value of the interconnection, which is obtained for hourly market coupling between the two countries. When no electricity flow is allowed between Saudi Arabia and Egypt, the total variable generation cost for the nine countries increases from US\$ 66,366 million (**HT** scenario) to US\$ 66,576 million (**HT_noEG-SA** scenario). This finding indicates that electricity trading between Saudi Arabia and Egypt could reach a maximum value of US\$ 210 million by 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. In the case of hourly electricity trading (**HT** scenario), the congestion rent² of the line between Saudi Arabia and Egypt will increase to US\$ 171.41 million in 2030, for an annual flow of 8.8 TWh (both directions included).

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

² The congestion rent is defined as the difference between Egyptian and Saudi prices multiplied by the flow on the interconnector and summed up for all hours of the year. Losses are not considered in the congestion rent.

to the maximal benefits of US\$ 210 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 the 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.
- **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.
- **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 month in the hourly simulation.

- **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.

For all types of contracts, the net electricity exchange between Saudi Arabia and Egypt remains unchanged. However, the annual export and import volumes differ between the two countries 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 for export and import volumes to be more representative of hourly trade.

Table 9. Description of the considered contractual schemes.

Scheme	Type of Daily Profile	Granularity
SA-EG_fixed_month	Fixed	Monthly
SA-EG_fixed_week	Fixed	Weekly
SA-EG_daily_quarter	Hourly	Quarterly
SA-EG_daily_month	Hourly	Monthly

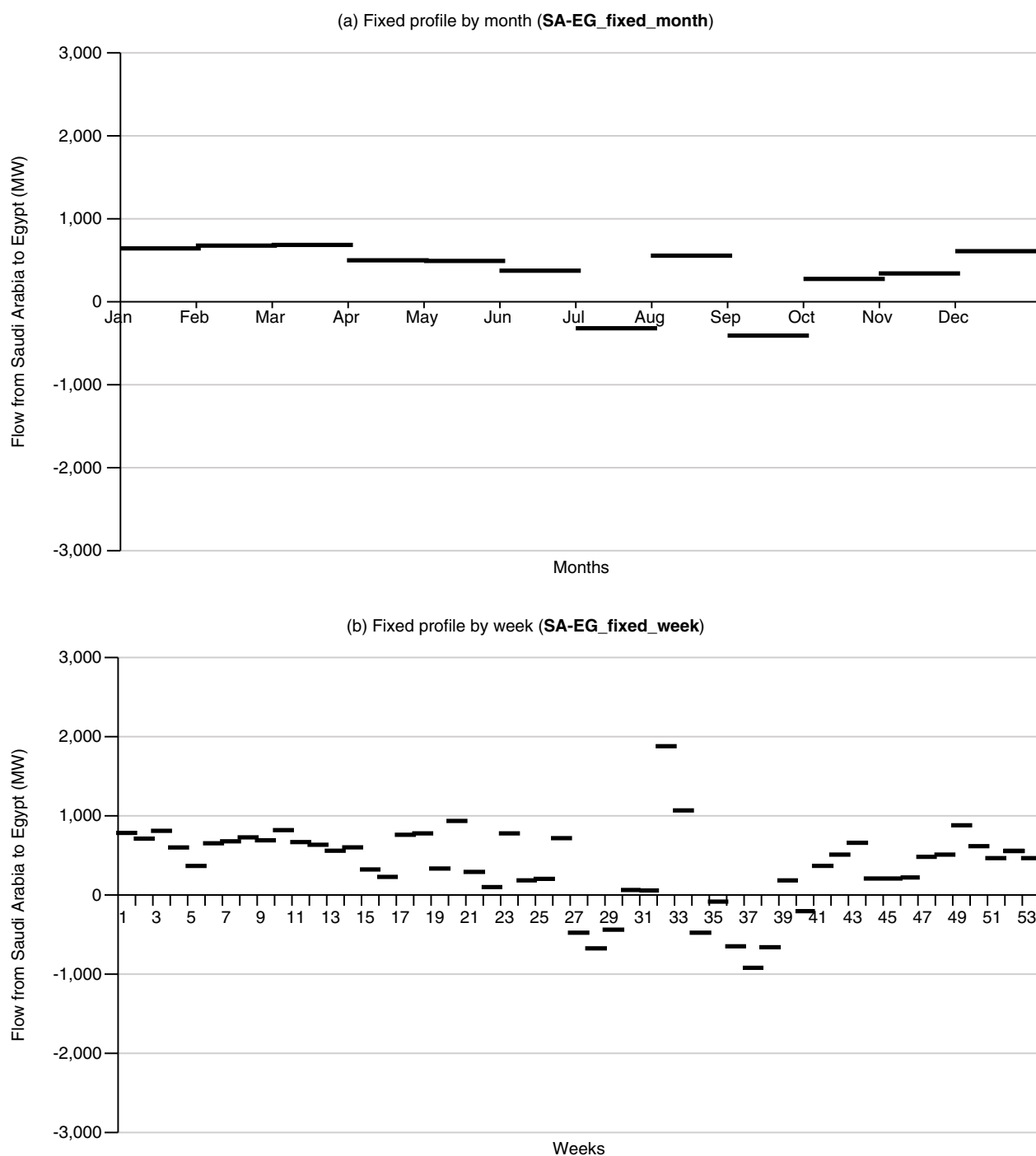
Source: Authors.

Table 10. Electricity flows between Saudi Arabia and Egypt for different contractual arrangements.

Scheme	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	3.8	0.5	3.2
SA-EG_fixed_week	4.0	0.8	3.2
SA-EG_daily_quarter	5.3	2.1	3.2
SA-EG_daily_month	5.4	2.2	3.2
HT	6.0	2.8	3.2

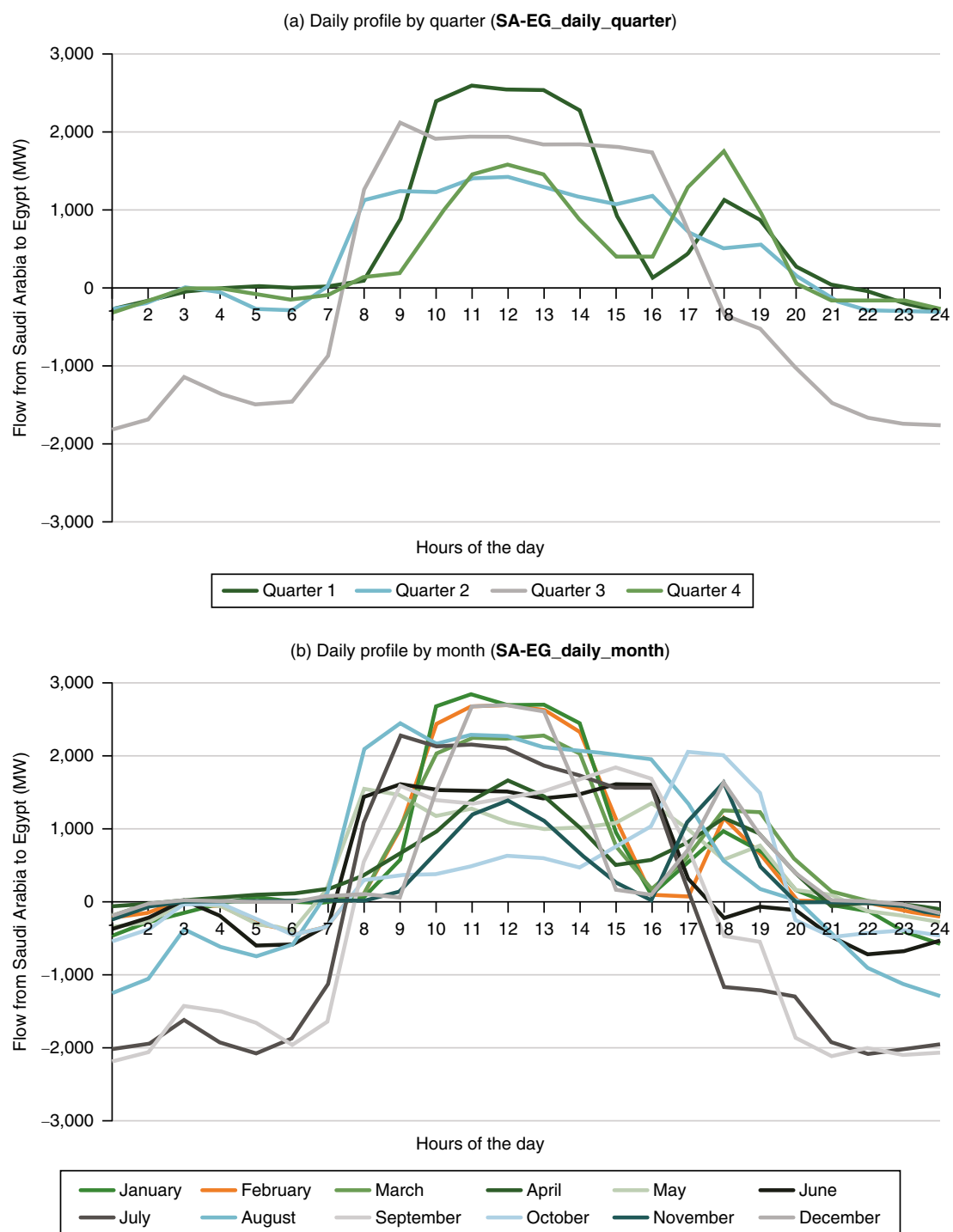
Source: Authors.

Figure 6. Profiles of the two fixed-profile contractual schemes between Saudi Arabia and Egypt (**SA-EG_fixed_month** and **SA-EG_fixed_week** scenarios).



Source: Authors.

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



Source: Authors.

To assess the benefits that can 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. Defining a fixed profile by month (**SA-EG_fixed_month** scenario) or week (**SA-EG_fixed_week** scenario) brings about a benefit of only US\$ 26-33 million, which corresponds to 12-16% of the maximum value of the interconnector, respectively. 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, respectively. This finding justifies the interest in developing well-designed bilateral contractual arrangements as a compromise between having no trade and having full hourly market coupling. These estimates are optimistic because, in practice, uncertainty about the contractual profile, which must be defined significantly ahead of delivery, can reduce the value brought about by long-term contracts.

Table 11. Total variable generation costs and their associated benefits for the four different contractual arrangements between Saudi Arabia and Egypt.

Scenario	Total Variable Generation Cost (Million US\$)	Gain Associated With the SA-EG Interconnector (million US\$)	% of the Maximum Value
HT_noEG-SA	66,576		
SA-EG_fixed_month	66,550	26	12%
SA-EG_fixed_week	66,543	33	16%
SA-EG_daily_quarter	66,463	112	54%
SA-EG_daily_month	66,454	122	58%
HT	66,366	210	100%

:Source: Authors.

To complement the cost analysis, Table 12 provides the curtailment of renewable energy and CO₂ emissions for the four contractual arrangements considered. The table 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 increases 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 MtCO₂.

Table 12. Curtailment of PV, wind and CO₂ emissions for the four different contractual arrangements between Saudi Arabia and Egypt.

Scenario	Total Variable Generation Cost (Million US\$)	Curtailment of PV and Wind Power (GWh)	CO ₂ Emissions (Million MtCO ₂) (%)
SA-EG_fixed_month delta w.r.t. HT	66,550 +0.3%	10,465 +17.2%	500.2 +0.3%
SA-EG_fixed_week delta w.r.t. HT	66,543 +0.3%	10,443 +17.0%	500.2 +0.3%
SA-EG_daily_quarter delta w.r.t. HT	66,463 +0.1%	9,584 +7.4%	499.5 +0.1%
SA-EG_daily_month delta w.r.t. HT	66,454 +0.1%	9,496 +6.4%	499.5 +0.1%
HT	66,366	8,927	498.8

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

Source: Authors.

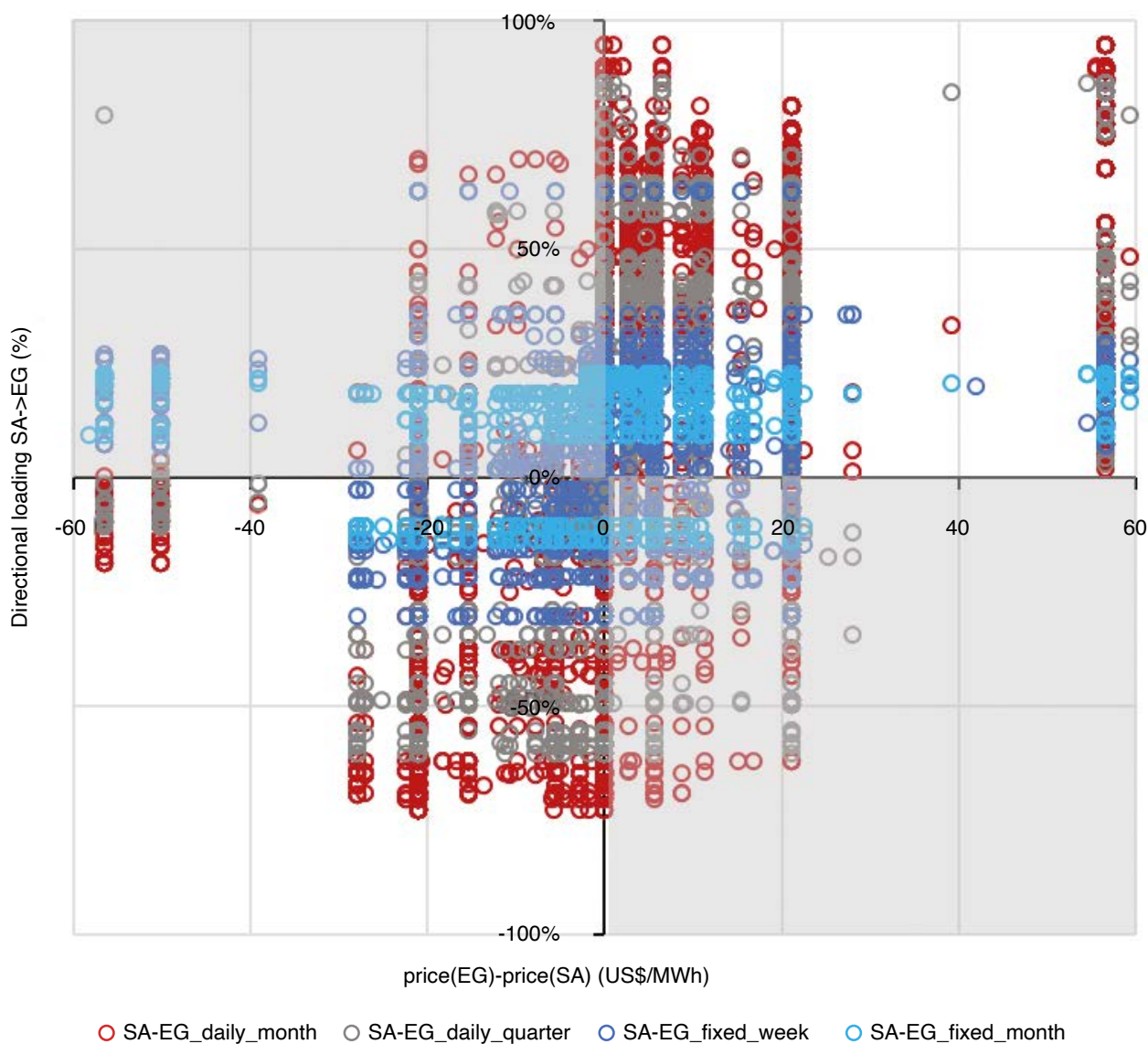
To complement our analysis of these long-term bilateral arrangements, Figure 8 shows the directional loading on the interconnector versus the price difference between Egypt and Saudi Arabia, similar to the analysis provided in Guo and Newbery (2021). The figure graphically illustrates the “nonoptimized” flows when long-term contracts are in place. Overall, the interconnector is better utilized in the **SA-EG_daily_month** scenario; i.e., the red circles reflect a higher loading of the interconnector of up to almost 100%. In contrast, the light blue circles are concentrated in the center of the y-axis, indicating low-level utilization of the interconnector in the **SA-EG_fixed_month** scenario. In Figure 8, the two quadrants in gray correspond to noneconomic contractual long-term directional flows, i.e., the flows from the country with the highest electricity price to that with

the lowest electricity price at the specified hour. The number of points corresponding to noneconomic flows reaches 993 (11% of the time) in the **SA-EG_fixed_month** scenario (light blue circles) and decreases to 352 (4% of the time) in the **SA-EG_daily_month** scenario (red circles). This finding confirms the importance of well-designed contractual arrangements.

The prices of long-term contracts between Saudi Arabia and Egypt can be negotiated to fall between the Saudi and Egyptian electricity prices. In other words, the pricing is set according to how to split the congestion rent of the interconnector between the two countries. Congestion rent is defined as the difference between Egyptian and Saudi prices multiplied by the flow on the interconnector and summed for all hours of the year.³

³ The congestion rent presented here does not account for network losses on the interconnector.

Figure 8. Directional loading and price differences of the Saudi-Egyptian interconnector in the four scenarios with contractual arrangements.



Source: Authors.

Classically, congestion rent can be split according to the division of investment costs of the interconnector between the two countries. Table 13 presents the congestion rent generated by the interconnector between Saudi Arabia and Egypt in 2030 for the different contractual schemes and for the **HT** scenario. The table confirms the previous observation for total generation costs; i.e., compared to the hourly trade scenario, congestion rent can decrease

to 14% in the fixed-by-month contract scenario (**SA-EG_fixed_month** scenario). Among the scenarios with long-term contracts, the highest congestion rent is achieved when the contract follows a typical daily profile defined for each month (**SA-EG_daily_month** scenario), corresponding to US\$ 112.97 million, which is 66% of the congestion rent obtained in the **HT** scenario.

Table 13. Congestion rent for the interconnector between Saudi Arabia and Egypt in 2030.

Scenario	Congestion Rent (million \$)	% w.r.t. Maximal Congestion Rent Achieved in HT
SA-EG_fixed_month	23.98	14%
SA-EG_fixed_week	31.53	18%
SA-EG_daily_quarter	101.80	59%
SA-EG_daily_month	112.97	66%
HT	171.41	100%

Notes: w.r.t. = with respect to. The congestion rent presented here does not account for network losses.

Source: Authors.

5. Conclusions and Policy Implications

This paper presents a network-constrained economic dispatch model encompassing nine countries (GCC interconnected countries plus Egypt, Jordan and Iraq), with corresponding assumptions calibrated to 2030. Overall, we find that the interconnection between all nine countries brings about important benefits.

The model is used to quantify the benefits of hourly electricity trading in the region. At the 2030 horizon, hourly electricity trading can save a variable generation cost of US\$ 1,072 million for the studied region, which comprises GCC countries plus Egypt, Jordan and Iraq, corresponding to a decrease in variable generation costs of 1.6%. Alternatively, if hourly electricity trading is performed among only GCC countries (i.e., excluding Egypt, Jordan and Iraq), then this can save US\$ 275 million in variable generation costs. The planned interconnector of 3 GW between Saudi Arabia and Egypt is a key element of regional trading, as it has a value of US\$ 210 million. In addition, the simulations also show the benefit of regional electricity trading in integrating renewables into power systems. Specifically, our results show that hourly electricity trading reduces the degree of curtailment by 34% (4,577 GWh) in the region in 2030.

Our results indicate that a small reduction in CO₂ emissions is achieved after the interconnection commences. However, this effect exists only in the short term, given the same installed capacities with and without electricity trading. In the long term, further benefits can be achieved when investment decisions are coordinated at the regional level.

The results show considerable variation in the transmission flows between countries in both directions. Hence, contractual agreements should be tailored to these observations. In particular, we note that

specific attention should be paid to the Saudi-Egyptian interconnector, given the size of the power sector in both countries, the size of the interconnector, and the significant flow that occurs daily between the two countries. Indeed, we observe that Saudi Arabia exports to Egypt during the daytime when PV generation is at a high level and imports from Egypt during summer nights. In contrast, other interconnectors, such as the Saudi-Jordanian or Saudi-Iraqi interconnectors, are used mainly in a single direction and thus require less complex volume patterns in bilateral long-term contracts.

Furthermore, the model is used to analyze bilateral long-term arrangements between Saudi Arabia and Egypt. This objective, which constitutes an original contribution to the literature, is relevant to GCC countries and the broader MENA region, given that developing hourly market coupling is not yet on the agenda. Therefore, it is important to inform policymakers of the best way in which to trade electricity within the long-term arrangements that can be envisaged in practice. We simulate and compare four contractual schemes between Saudi Arabia and Egypt that differ in terms of the profiles of the contracted volumes. The results show that contracts with fixed volumes throughout the day significantly decrease the economic value of electricity trading between the two countries to less than 20% of the maximal economic value obtained when hourly market coupling is considered. Alternatively, a long-term contract with a volume that follows a daily pattern appears to be more suitable and allows for the capture of more than 50% of the maximum

economic value of the Saudi-Egyptian interconnector; in this case, the daily pattern can be negotiated at a monthly or quarterly scale, with no significant difference in the economic value achieved.

Our work offers several avenues for further research. First, our model is used in the context of a perfect forecast, but it would be informative to quantify the effect

of those forecast errors that could arise in practice and how digital devices could help in reducing these errors, especially in the context of a high share of renewables. Second, the model framework could be expanded to quantify the benefits of further regional cooperation, such as coordinated capacity and transmission expansion, coordinated maintenance planning, or regional operating reserve sharing.

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7. Appendix: Model

7.1. Demand Assumptions

The annual electricity demand, presented in Table A1, is obtained for each country, except Saudi Arabia, based on the following methodology:

1. The annual demand data for 2020 are collected from Enerdata (2023a).
2. The average GDP growth is computed over the period 2010-2019 (to exclude the effects of coronavirus disease 2019 (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 (2023).

The electricity demand is then adjusted in the model to account for network losses, as further detailed in Section 7.4.

Table A1. Annual electricity demand and peak demand by country in 2030 (excluding network losses).

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
UAE	182.2	33.6

Source: Authors.

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 A2 provides the hour at which the peak load occurs in each country. More details on the daily peak load are given in Figure A1.

Our dataset accounts for differences in time zones and is provided for the Coordinated Universal Time (UTC) time zone. To convert the UTC time zone to local time zones,

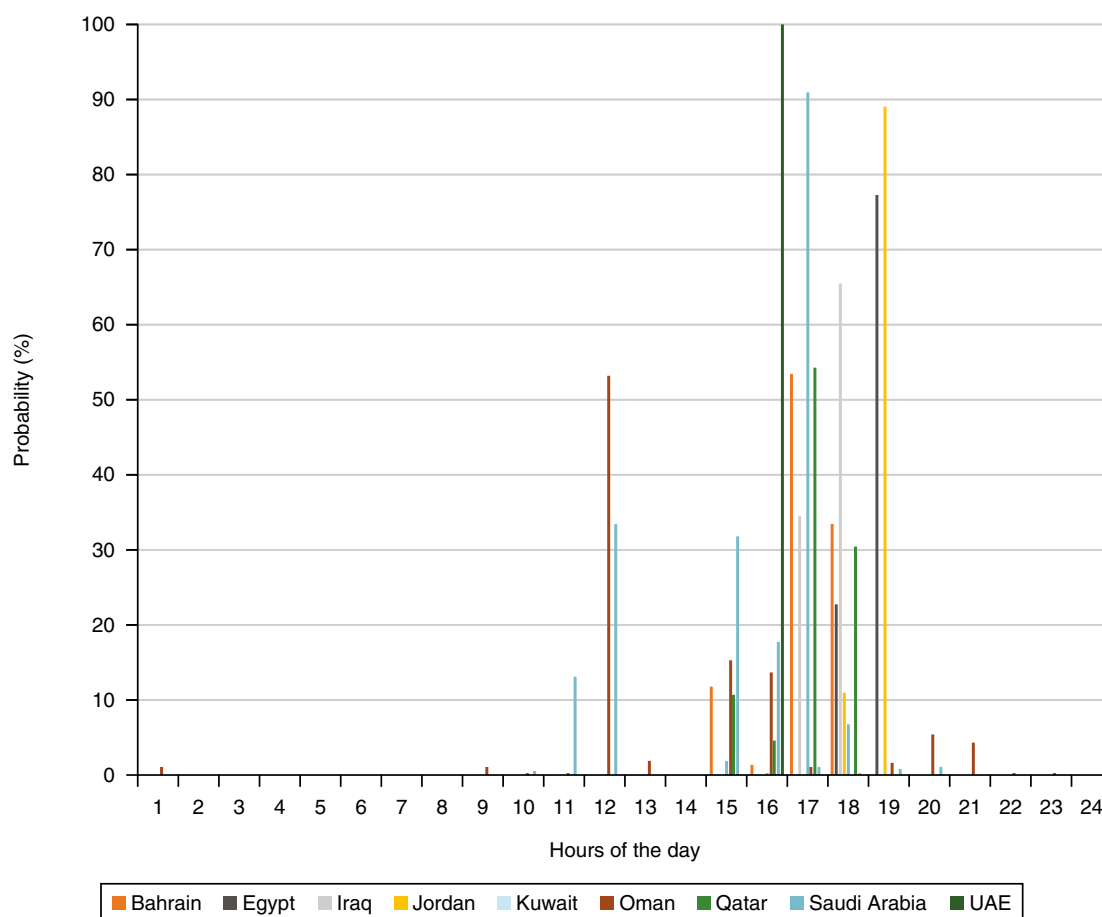
please note that our perimeter covers countries at UTC+2 (Egypt), UTC+3 (Bahrain, Iraq, Jordan, Kuwait, Qatar and Saudi Arabia), and UTC+4 (Oman and the UAE). For all nine countries, the weekend days are Friday and Saturday in our dataset (with 2015 as the reference year). However, since 2022, the UAE has moved its weekend days to Friday afternoon, Saturday and Sunday. The potential changes in the hourly electricity consumption of the UAE since the change in weekend days are not integrated into our study.

Table A2. Hour at which the daily peak load occurs most frequently and the corresponding frequency for each country.

Country	Hour at Which the Daily Peak Demand Occurs More Frequently	Frequency (%)
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%
UAE	15	100.0%

Source: Authors.

Figure A1. Probability density of the daily load peak for the nine countries.



Source: Authors, based on the hourly load profiles from the PLEXOS-World 2015 Harvard Dataset (Brinkerink and Deane 2020; Brinkerink, Gallachóir, and Deane 2021).

7.2. Generation Assumptions

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

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 (2023b). The reason for this is

that 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 into their capacity builds and retirements. We adjust the obtained capacities to meet a capacity margin of 10% of the peak demand assumed for 2030. Table A3 provides the installed capacities assumed for each country in 2030.

For Saudi Arabia, we assume that oil generation units will be fully retired by 2030 and that 90 GW of PV power and 30 GW of wind power will be installed in 2030 to align with Saudi Vision 2030 (Vision 2030 2023).

Table A4 provides the characteristics of the thermal generation units. The fuel and CO₂ emission assumptions

are provided in Tables A5 and A6, respectively. For nuclear energy, which is part of the electricity mix in Egypt and the UAE, we assume a variable cost of US\$ 6.4/MWh.

Additional assumptions regarding ramp rates and reserve provision are detailed in Section 7.5.

Table A3. Installed capacities assumed in 2030 in GW.

Country	Gas-CC	Gas-GT	Gas-ST	Nuclear	Oil-GT	Oil-ST	Hydro	PV	Wind
Bahrain	9.6	1.4	0.7		0.2			0.6	
Egypt	28.9	6.8	14.6	1.2	2.3	1.3	5.2	4.1	23.2
Iraq	11.2	16.1	4.0		4.7	3.3	1.8	5.6	
Jordan	3.9	1.0	1.3		0.1	0.7		2.1	1.2
Kuwait	12.2	1.2	2.0			4.0		5.8	0.4
Oman	8.8	2.0			0.2			6.0	0.7
Qatar	12.5	5.4						5.0	
Saudi Arabia	86.3	16.6	18.6					90.0	30.0
UAE	24.2	12.2	2.0	5.4	0.1			15.7	0.1

Source: Authors, accounting for projects reported in Enerdata (2023b).

Table A4. Characteristics of the 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\$/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

Notes: For nuclear power, we also include a minimum on time of 72 hours and a minimum off time of 24 hours.

Source: Authors, based on expertise from the EDF-Ingeum.

Table A5. 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
UAE	7.5	14.9

Source: World Bank (2021).

Table A6. Emission factors of the different fuels used for electricity generation.

Fuel	CO ₂ Emissions Factor (lb/MMBtu)
Natural gas	116
Oil	155
Nuclear	0

Source: Authors, based on expertise from the EDF-Ingeum.

7.3. Assumptions for Renewables (Hydropower, PV and Wind)

Hourly wind and PV generation profiles are obtained from the Renewables.ninja website (Renewables.ninja

(2023), which is derived from the method developed in Pfenninger and Staffell (2016) and Staffell and Pfenninger (2016). For each country, the Renewables.ninja tool allows us to generate the hourly load factors estimated for weather year 2019 for a given location that we set to correspond to be close to the location with the largest known wind or PV project. Tables A7 and A8 present the selected locations and the corresponding annual load factors for PV and wind power, respectively. For PV power, Figure A2 shows the average daily generation profile.

Table A7. Annual load factor of solar PV power in different countries.

Country	Selected Location	Annual Load Factor (%)
Bahrain	Riffa	19.5%
Egypt	Aswan	21.8%
Iraq	Baghdad	22.1%
Jordan	Zarqa	21.4%
Kuwait	Al Jahra	19.5%
Oman	Muscat	20.6%
Qatar	Doha	19.6%
Saudi Arabia	Riyadh	20.8%
UAE	Dubai	19.8%

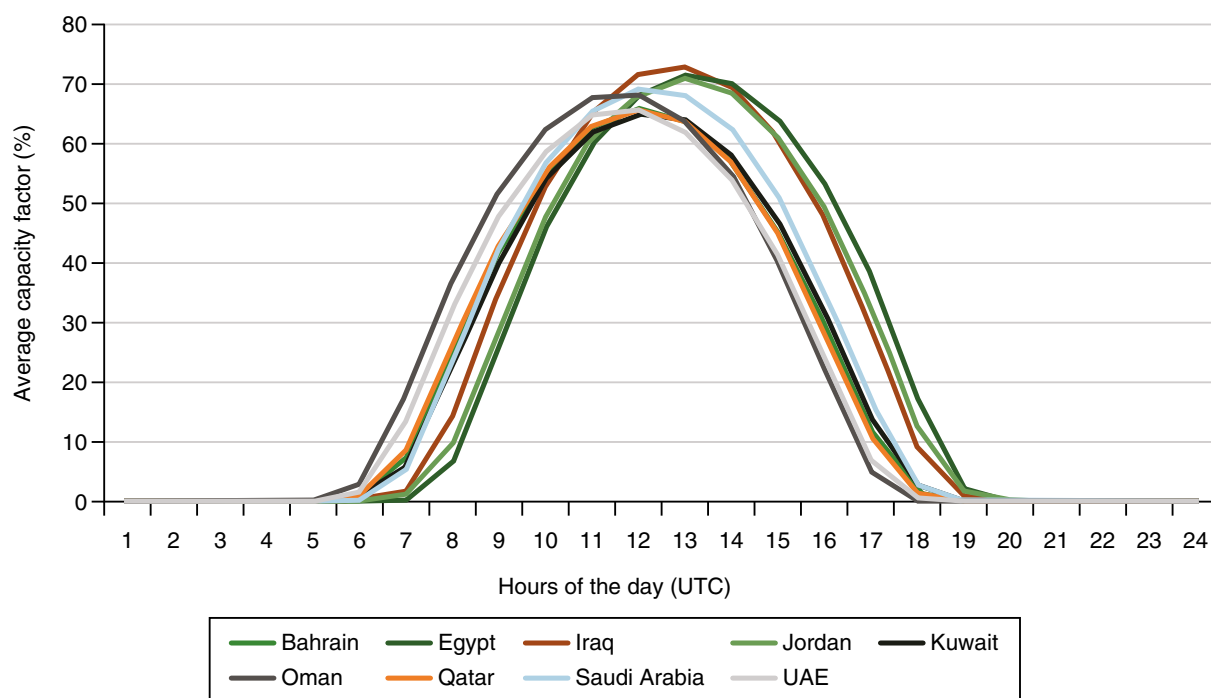
Source: Authors, based on load factors provided in Renewables.ninja (2023).

Table A8. Annual load factor of wind power in different countries.

Country	Selected Location	Annual Load Factor (%)
Bahrain	Durrat	35.2%
Egypt	Aswan	42.1%
Iraq	Baghdad	35.6%
Jordan	Ma'an	32.1%
Kuwait	Al Abdaliyah	43.5%
Oman	Tahamarit	42.2%
Qatar	Al Karaana	35.0%
Saudi Arabia	Riyadh	39.7%
UAE	Al Jahra	35.2%

Source: Authors, based on load factors provided in Renewables.ninja (2023).

Figure A-2. Average hourly profile of solar PV power by country.



Source: Authors, based on data from Renewables.ninja (2023).

Hydropower is assumed to be part of the electricity generation mix in Egypt and Iraq. As these countries rely mainly on reservoir hydropower, we model the total installed hydrocapacity 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 (2023) and International Renewable Energy Agency (2023), we limit the annual capacity factor of hydropower to 58% in Egypt and 25% in Iraq.

To mimic the hydrogeneration profile over the year, we also impose a maximum capacity factor for each month (see Figure A3) based on hydrogeneration profiles from Brinkerink and Deane (2020).

7.4. Network Assumptions

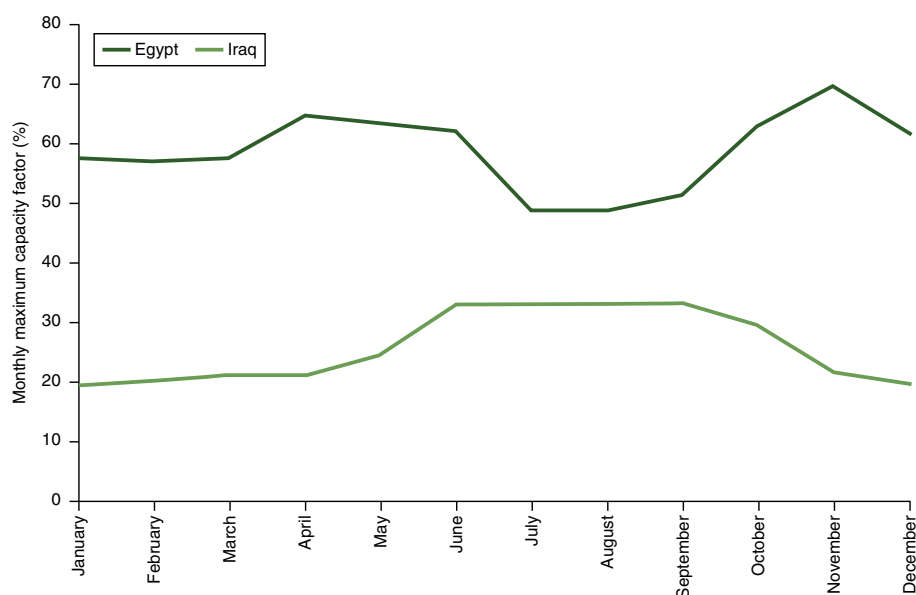
The model includes cross-border flow limits, which reference the existing and future interconnection projects

at the 2030 horizon based on the expertise and press announcements of the EDF-Ingeum. Table A9 provides the interconnection limits implemented in our model for 2030.

For each country, the internal network is not modeled (copper plate assumption). The model does include, however, the average network losses, which are defined to correspond to the average historical losses computed as the ratio between the generation and consumption reported in Enerdata (2023a) over the period 2017-2021 (see Table A10). These losses are accounted for in the demand.

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

Figure A3. Monthly maximum capacity factor assumed for hydropower in Egypt and Iraq.



Source: Authors, based on profiles reported in Brinkerink and Deane (2020).

Table A9. 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 – UAE	1.2
Iraq – Saudi Arabia	1.0
Iraq – Kuwait	0.5
Jordan – Iraq	1.0
Jordan – Saudi Arabia	0.5
Oman – UAE	0.4

Source: Authors.

Table A10. Network losses.

Country	Network Losses (%)
Bahrain	3.2%
Egypt	19.5%
Iraq*	12.0%
Jordan	9.7%
Kuwait	13.0%
Oman	12.3%
Qatar	12.3%
Saudi Arabia	18.0%
UAE	10.2%

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

Source: Authors, based on historical data from Enerdata (2023a) for the period 2017–2021.

7.5. Operational Reserves

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 assumed to be symmetrical and are modeled as follows:

- A spin-up reserve is provided within 10 minutes. For each country, the volume of the spin-up reserve corresponds to the installed capacity of the largest thermal generator.
- A spin-down reserve is provided within 10 minutes. 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 country considered.

Table A11 provides the spinning reserve volume by country, based on the data provided by the Gulf Cooperation Council Interconnection Authority (2019), adjusted to consider the new nuclear power plants in Egypt and the UAE.

Only thermal generators are allowed to provide reserves, according to their respective ramp rates, as shown in Table A12. However, we exclude nuclear power from providing the spinning reserve because the notice time of 10 minutes is too short, as suggested in Petit et al. (2019).

Table A11. 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
UAE	1,345

Source: Authors, based on Gulf Cooperation Council Interconnection Authority (2019) and adjusted for nuclear power plants in Egypt and the UAE.

Table A12. 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

Abbreviations: min: minute.

Source: Authors based on Joshi et al. (2020) and Sustainable Nuclear Energy Technology Platform (2020).

Notes

About the Authors



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Marie is an engineer, energy economist, and research fellow in the Utilities & Renewables program at the King Abdullah Petroleum Studies and Research Center (KAPSARC). Her current research focuses include power system modeling and market designs for energy transitions. Prior to joining the KAPSARC, Marie worked on long- and short-term electricity market design, transmission grids at the European scale and smart-charging opportunities for electric vehicles. Marie holds a Ph.D. in Economics from Dauphine University, PSL (France); an M.Sc. in Environmental and Energy Economics from École des Ponts ParisTech (France); and an M.Sc. in Engineering from the ENSTA Institut Polytechnique de Paris (France).



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About the Project

This discussion paper is part of the project “Regional Market Integration” under KAPSARC’s Utilities & Renewables program. This project has been initiated to explore the potential opportunities that could be harnessed by developing a common electricity market in GCC and MENA countries. The initiative examines a range of issues related to electricity market integration, including how pools have been developed in other regions and their potential application in the MENA region.



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