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Optimising the role of solar PV in Qatar's power sector

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Abstract

Qatari policymakers must balance domestic energy needs with the economic imperative to maximise hydrocarbon exports. We have modelled the optimal evolution of Qatar's electricity system over the next few decades, with the goal of quantifying the potential for solar energy (and other low-carbon technologies) in the grid. Our results show that there is scope for up to 60,000 GWh per year of electricity production from solar PV by the 2040s, complemented by investments in grid-scale intra-day battery storage and cross-border transmission capacity. Adding renewables to the grid not only reduces the carbon footprint of Qatari consumers, but also frees up more hydrocarbons for export, particularly low-carbon hydrogen derived from steam reforming of natural gas (with CCS), for which Japan may be a prime consumer.

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Keywords: Energy systems; Renewables; Optimisation

1. Introduction

Qatar entered a new era in its development with its first shipment of liquefied natural gas (LNG) to Japan in 1997 [1]. This set the stage for a boom in Qatar's LNG export capability, and natural gas surpassed crude oil as the key source of hydrocarbon revenues for the country. Today, Qatar has the capacity to not only produce 77 million tons of LNG for export, but also meet its industrial feedstock, electricity, desalinated water and transport fuel needs from domestic gas production. Currently, the national electricity demand is met solely through gas-fired power plants, and the low cost of fuel, along with new investments in large, still underused, plants, makes the case for introducing renewables to the grid weaker. At the same time, however, steep reductions in the capital cost of solar photovoltaic systems are expected to continue [2].

Moreover, as Qatar looks to increase its natural gas exports in the future, given the increasing global demand for this cleaner-burning fuel, investments in solar energy to meet domestic demands can free up more natural gas for export.

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Qatari policymakers must balance domestic energy needs with the economic imperative to maximise hydrocarbon exports. We have developed the Qatar Energy System Modelling and Analysis Tool, or QESMAT [3], to enable policymakers to determine the most effective investments in energy infrastructure, and plan the best export strategy, over a long-term horizon. Our model covers major energy carriers (oil, gas, electricity), refined products (gasoline, diesel), petrochemicals (urea, methanol), metal processing (steel, aluminium), and multiple sectors of consumption (residential, agricultural, industrial, transportation). While other researchers have used the tools of energy system modelling to study the infrastructure of other Gulf states [4–6], our model is the first to look at the overall energy system in Qatar.

In the present work, we have investigated the evolution of the national electricity infrastructure in Qatar over the long term (from 2020 to 2050) using QESMAT, to determine the key drivers of electricity consumption in the country, and to study the feasibility of deploying low-carbon technologies such as grid-scale solar PV, grid-scale battery storage, district cooling systems and electric vehicles.

2. Method

Almost all of the data used in QESMAT is publicly accessible and compiled from a number of sources: newspaper articles, journal publications, government and company reports, and global databases such as the online statistics from the International Energy Agency [7]. This data was used to build a reference energy system for Qatar, which shows the current state of the energy infrastructure in Qatar. This includes the dominant oil and gas industries, along with their associated refining and petrochemicals operations, electricity generation infrastructure (gas-fired power plants) and various sectors of domestic demand (residential, industrial, agricultural, transportation, etc.).

Domestic demands for electricity and air conditioning were calculated based on historical data and population projections for the next few decades. We assumed a fixed per capita demand for two types of households, large and small (as defined by the Qatar Statistics Authority in its household census [8]), and multiplied this demand by the future population (projected by us), and small factors based on the efficiency of future electric appliances and the increase in air conditioning demand due to temperature increases induced by climate change. Our demand forecasts are shown in Table 1.

Table 1. Domestic electricity and cooling demand forecasts.

Year	Electricity (GWh)	Cooling (BTU)
2020	24,282	7.83E+13
2025	26,551	7.95E+13
2030	30,164	8.44E+13
2035	35,069	9.19E+13
2040	40,666	9.98E+13
2045	47,043	1.08E+14
2050	54,301	1.16E+14

The optimisation model is based on the Resource-Technology Network framework developed in our research group [9]. It is a linear programming model that selects the least-cost technology options to produce, transform or consume resources (or meet fixed demands). The model consists of 5-year time steps from 2020 to 2050, with six time slices within each year to capture seasonal and diurnal trends, and the model balances supply and demand of resources at each of these time steps/slices. The objective function is the discounted sum of revenues and costs over the entire modelling horizon, and includes domestic and export revenues, and capital, operating and fixed expenses. The model used in the current analysis is deterministic and assumes perfect foresight, although we have also developed a scenario-dependent optimisation framework. The key equations in QESMAT are described in the following sub-sections.

2.1. Technology balance

$$N_{j,tm} = N_{j,tm-1} + INV_{j,tm} - RET_{j,tm} \forall j, tm$$

The total number of technology units **N** in the current time period is equal to the number of technology units from the previous time period (tm-1) plus any new investments **INV** minus any retired technology units **RET** for

each technology j and time period tm . The number of retired technology units depends on the lifetime of each technology and the number of time periods that have passed since the investment made in that technology.

2.2. Production balance

$$P_{j,t,tm} \leq N_{j,tm} * cf_{j,t} * \frac{\text{Capacity}_j}{6} \forall j, t, tm$$

The production level \mathbf{P} from a technology is less than or equal to the product of the number of units \mathbf{N} of that technology, the capacity factor cf , and the annual production capacity divided by six (the number of time slices in a year), for each technology j , in each time slice t , in each time period tm . Thus, a technology may not always produce a resource at its full capacity.

2.3. Demand balance

$$\text{DemFrac}_{r,t} * D_{r,tm} * (1 - \text{Subs}_{r,tm} * \text{Elas}_{r,tm}) = \sum_j \mu_{j,r} * P_{j,t,tm} - \text{EXP}_{r,t,tm} + S_{\text{take}_{r,t,tm}} - S_{\text{put}_{r,t,tm}} \forall r, t, tm$$

The left-hand side of this equation represents the fixed demand for a resource. It is the product of the annual demand D and DemFrac , a parameter which breaks down the annual demand into individual seasonal/diurnal time slices, adjusted with a factor accounting for how a domestic subsidy Subs changes the demand for a price-elastic (with elasticity Elas) resource. Electricity is sold to local consumers in Qatar at approximately a third of the production cost, thus having a subsidy of 66%.

The right side of this equation consists of a production term (production level \mathbf{P} multiplied by μ , a parameter describing how each technology transforms each resource), the export quantity \mathbf{EXP} of each resource, and the quantities brought from storage S_{take} or sent to storage S_{put} . The left and right sides of this equation must be equal for each resource r , in each time slice t , in each time period tm .

2.4. Storage balance

$$\sum_t S_{\text{take}_{r,t,tm}} = \text{Max Stor}_r \forall r, tm$$

$$\sum_t S_{\text{put}_{\text{elec}'_{t,tm}}} = \sum_t S_{\text{take}_{\text{elec}'_{t,tm}}} \forall tm, \quad t = \text{summer or winter time slices}$$

The first constraint specifies the maximum annual storage capacity MaxStor for a given resource, while the second constraint equates the amount of electricity sent and received from battery storage. Note that the storage balance applies separately to summer and winter time slices, thus only allowing for intra-day electricity storage rather than seasonal storage.

2.5. Key constraints

The major constraints in the QESMAT model are: annual production limits on oil and natural gas, with a self-imposed reduction in crude production to zero and natural gas production to 40,000 ktoe (a quarter of current production) by 2050. Electricity exports are constrained to 10,000 GWh/year in 2020 due to a lack of significant cross-border transmission capacity, but this capacity is assumed to increase to 40,000 GWh/year by 2050.

3. Results

QESMAT was run on a Windows computer with 16 GB RAM and an Intel Core i7 CPU using the optimisation suite AIMMS with a solution time of under five seconds. We ran a scenario where crude oil prices go from \$60/barrel

at present to \$52/barrel in 2050, while natural gas prices go from \$5/MMBTU today to \$6/MMBTU in 2050, and electricity prices go from \$80/MWh today to \$30/MWh in 2050. Other hydrocarbons and petrochemicals are pegged to the oil and gas prices. These prices represent a scenario of neither high nor low hydrocarbon prices in the long-term, as global demands only gradually shift away from hydrocarbons and supplies remain abundant. Solar PV costs drop from \$1/W in 2020 to \$0.6/W in 2050 as the technology shows further cost reductions [10], while gas-fired power plants (Integrated Water and Power Plants, or IWPPs) cost a fixed \$1.3/W until 2050 due to their technological maturity. A carbon price of \$50/ton was set, along with a CCS cost of \$50/ton, in order to encourage the export of low-carbon hydrogen, for which Japan has set a price of 25 yen/m³ or around \$3.7/kg, which we estimate to go up to \$4/kg in 2050. The initial (2015) technology set comprises of hydrocarbon upstream and downstream processes, gas-fired electricity, hydrocarbon-powered transport, a small public transit system, and a small district cooling capacity complementing individual air conditioning units).

Fig. 1 shows the evolution of the electricity infrastructure from 2020 to 2050, according to the optimal solution of QESMAT. Solar PV plays an increasingly important role in the grid, especially when coupled with grid-scale intra-day battery storage starting in 2035. Excess electricity from solar PV is exported in winter. District cooling satisfies cooling demand, while other technologies such as electric cars and reverse osmosis for desalination also use small amounts of electricity. The country’s major export shifts from LNG to low-carbon hydrogen (from the steam reforming of methane, with CCS installed to capture the CO₂ byproduct). The objective function has an optimal value of \$976 Billion, which shows the scale of wealth generated by commodity exports even under a scenario of decreasing hydrocarbon production. This wealth may be invested in a sovereign wealth fund to maintain Qatar’s prosperity in a post-carbon world.

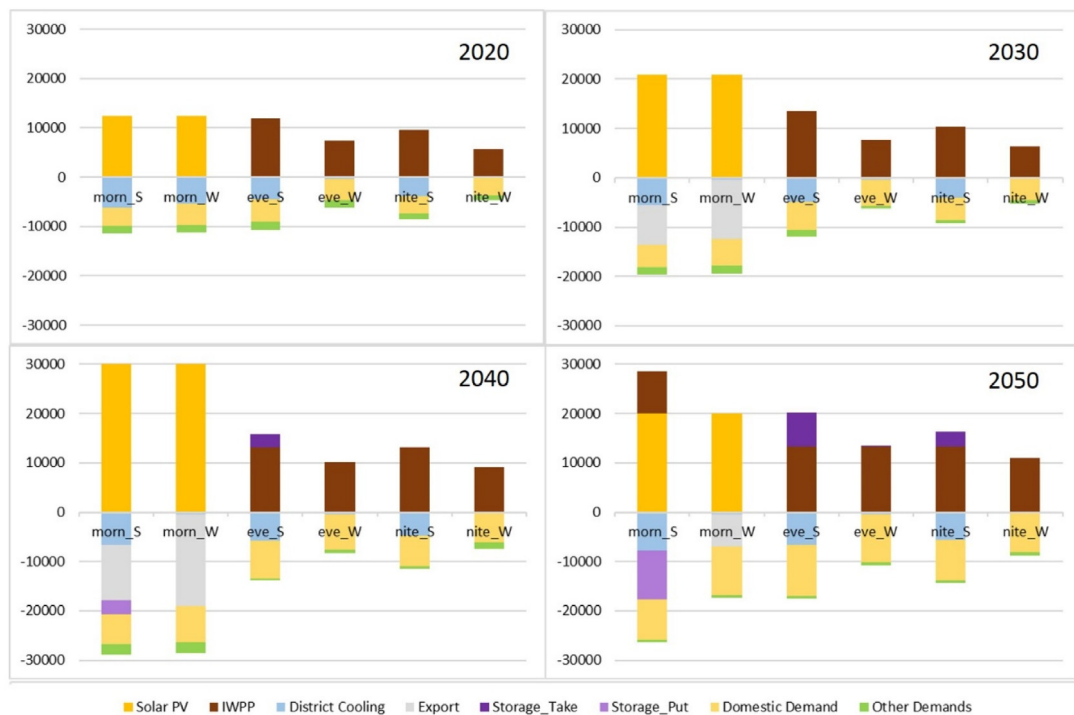


Fig. 1. Qatari electricity system forecast to 2050, shown by time slice (morn, eve and nite indicate periods of the day, while S and W indicate seasons). All values in GWh. Positive values indicate supplies, negative values indicate demands/exports.

4. Conclusions

The aim of our work was to study the evolution of Qatar’s electricity system over the next few decades, with the goal of quantifying the potential for solar energy (and other low-carbon technologies) in the grid. We have shown that there is scope for up to 60,000 GWh per year of electricity production from solar PV, complemented by investments in grid-scale intra-day battery storage and cross-border transmission capacity. Adding renewables to

the grid not only reduces the carbon footprint of Qatari consumers, but also frees up more hydrocarbons for export, particularly low-carbon hydrogen, for which Japan may be a prime consumer.

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