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Transition to zero-net emissions for Qatar: A policy based on hydrogen and direct air capture development

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Abstract : We assess different scenarios for a transition to zero-net emissions in Qatar. The key technologies involved in the transition include electric mobility, hydrogen, carbon capture and storage and direct air capture. Our numerical simulations show that Qatar should i) start immediately to foster hybrid and electric cars for mobility, ii) develop electricity generation from solar sources, iii) develop carbon-free hydrogen production, iv) introduce carbon capture and storage in all industrial sectors and, v) develop actively direct air capture with carbon capture and storage to produce emission permits to be sold on an international carbon market. We estimate that new exports of carbon-free hydrogen and emission permit sales could compensate the revenue losses of gas exports expected in a global zero-net emissions context.

Keywords : Net-zero emissions, Qatar energy system, carbon dioxide removal, hydrogen, international carbon market, policy analysis

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1 Introduction

The aim of this paper is to develop a bottom-up analysis of a transition to a zero-net emission regime in Qatar, a Gulf region country and Gulf Cooperation Council member state. The potential role of electric mobility, hydrogen, Carbon Capture and Storage and Direct Air Capture will be highlighted.

At 21^{st} Conference Of the Parties in Paris, more than 160 nations, have agreed to reduce greenhouse gas emissions in order to reach a goal of limiting the temperature change at the end of 21st century at 1.5^{o}C. At this occasion several Gulf Cooperation Council member states, including Saudi Arabia and Qatar, made a commitment to reduce their per-capita emission levels, which are among the highest in the world. These commitments have been renewed in the successive Conference Of the Parties until the 26^{th} one held in Glasgow in 2021. To deal with these challenges, the Gulf countries count on a substitution from fossil fuel sources to variable renewable ones (as well as, to some extent, to nuclear power generation in United Arab Emirates, Kingdom of Saudi Arabia and Iran). Indeed, harnessing wind and solar energy sources seems promising in the region, with some caveats due to intermittency of wind blowing, or dust and sand storms reducing the efficiency of solar panels. These oil and gas rich countries can also develop "clean fossil fuel" usage based on carbon capture and storage and direct air capture. In 2018 the Intergovernmental Panel on Climate Change found that global net anthropogenic CO_2 emissions would need to reach a zero-net emission regime around 2050 in a pathway consistent with limited global temperature increases to 1.5°C. The European Union is considering zero-net emission as an objective for 2050 and other Organisation for Economic Co-operation and Development (OECD) countries seem likely to do the same.

In this context, several actions have been taken by Qatar to strengthen its climate policy. Qatar has created in 2011 a national plan for energy efficiency, optimisation and resource utilization (QPEERU), to serve as a driver for the greenhouse gas mitigation initiatives under the United Nations Framework Convention on Climate Change. Qatar was still proactive in discussing plans for fight against climate change at the 26^{th} Conference Of the Parties in 2021. [1] Recent actions to address climate change in Qatar are described by Taofiki Auwa who discusses a possible Emissions Trading Scheme in Qatar (Auwa, 2022) and in Hamad Al Maraikhi thesis on "Adoption of smart and sustainable strategies in the State of Qatar" (Maraikhi, 2021). Qatar Energy [2] announced commitments to set up facilities to store 7 million tons per year and supply carbon-neutral fuel to Singapore effectively from 2023, as well as building facilities capable of capturing and storing more than 7 million tons of carbon dioxide per year in Qatar by 2030. Also note the signing of agreements in March 2022 for the construction of the large 800 MW Al Kharsaah solar photovoltaic plant. [3] Tarsheed, the National Programme for Conservation and Energy Efficiency by the General Electricity and Water Corporation (Kahramaa) is designed to bring down carbon emissions and conserve water and electricity. To control carbon emissions and to fight climate change, Kahramaa initiated steps to diversify energy sources and to bring down the use of fossil fuels. To attain this, an electric vehicle policy was launched and schemes were introduced to encourage electric vehicles in the country in line with the policy. Qatar Solar Energy provides innovative products, like solar energy powered micro-grids that will accelerate the adoption of renewable energy in Qatar and around the world. [4] This sample of actions indicates Qatar's seriousness in designing an effective energy transition strategy. Therefore, modelling a transition to a zero net emissions regime in Qatar is fully justified.

In several model-based scenarios for long-term global strategies consistent with the Paris Agreement, direct air capture emerges as a promising technology for achieving a zero-net emission regime

1. See https://www.gco.gov.qa/en/top-news/qatar-cop26/ about COP26.
2. In 2021, Qatar Petroleum changed its name to Qatar Energy to better signal a new strategy that focuses on energy efficiency and environmentally-friendly technology such as capturing and storing carbon dioxide, its chief executive said on Monday. "It's more of a reflection of what we're actually doing that wasn't reflected by the name that we had," said Saad al-Kaabi, who is also the Qatari minister of state for energy.
3. Announced in Gulf Times, March 3, 2022 issue. Kahramaa president Essa bin Hilal al-Kuwari said the Corporation decided to go forward with a utility-scale solar power plant as it will help Qatar bring down carbon emissions.
4. Gulf Times March 8, 2022.

(Meadowcroft, 2013). Using MERGE-ETL (Kypreos, 2007) or WITCH (Bosetti et al., 2006) integrated assessment models in Marcucci et al. (2017) and Chen and Tavoni (2013), direct air capture technologies have been shown to play an important role in achieving deep decarbonisation goals and in reducing regional and global mitigation costs. Using the computable general equilibrium model GEMINI-E3 (Bernard and Vielle, 2008) with a dynamic game formulation of the strategic competition among different groups of countries in reaching the Paris Agreement objectives, it has been shown in Babonneau et al. (2021a) that direct air capture technologies alleviate the stranded asset risk of unburnable oil and offer Gulf Cooperation Council countries an opportunity for exploiting their gas reserves and the carbon storage capacity offered by depleted oil and gas reservoirs. Middle East countries have a competitive advantage in developing natural gas based direct air capture technologies [5] and accessing to large carbon storage capacities. It was also shown in Babonneau et al. (2021a) that the Gulf Cooperation Council countries could exploit this comparative advantage to sell emission rights on an international emissions trading system, if such a market is implemented. Thus the negative emissions could be exploited as a new resource with high economic value (Meadowcroft, 2013). In these scenarios, direct air capture technologies contribute to capture and store worldwide 20 or 40 $GtCO_2$ per year (a considerable amount) at the end of the century after reaching a net-zero emissions regime by 2075 or 2050, for a 2° C or 1.5° C warming limit, respectively.

The ETEM-Qatar model presented in this paper shows how carbon capture and storage and direct air capture, associated with usage of renewable energy sources and low-carbon hydrogen, will enable Qatar to make a significant contribution to reducing greenhouse gas emissions. In the power sector, carbon capture and storage can generate large reductions in emissions for electricity generation. In the other industrial sectors, the potential for carbon capture and storage is also significant, particularly if the technology is applied to carbon-intensive fuel production such as gas-to-liquids and liquid natural gas (LNG) processes. The potential for combining carbon capture and storage with enhanced oil and gas recovery is also an important argument in favour of this technology in Qatar and the Gulf Cooperation Council region (Meltzer et al., 2014). Direct air capture technologies contribute to offset hard-to-abate emissions and supply negative emissions sold as quotas on emissions trading markets. These technological developments are represented in the ETEM-Qatar bottom-up model, which is an extension of an energy modelling tool already developed for Qatar. [6] We drew on a recently developed bottom-up model, called QESMAT [7] described in Bohra and Shah (2020) to update and further develop ETEM-Qatar. QESMAT explored in particular the potential development of hydrogen in the Qatar energy system. In our analysis we focus on carbon capture and storage and direct air capture in addition to hydrogen as promising options for reaching a zero-net emission regime.

The rest of the paper is organised as follows : In Section 2 we recall the structure of the bottom-up energy model that belongs to the MARKAL-TIMES family of models [8] and we describe its calibration to the Qatar energy system ; in Section 3, we present three scenarios that are produced by ETEM-Qatar under different assumptions about the future of climate policy in the Gulf region and more globally in the world ; in Section 4 we conclude.

2 A bottom-up modelling approach

In this section we present the technology rich bottom-up modelling tool ETEM-Qatar and its application to create scenarios of a transition to zero-net emission (ZNE) for Qatar.

5. See (Keith et al., 2018) for a complete feasibility and techno-economic assessment of a direct air capture technology that uses natural gas for providing needed power and heat.

6. A previous ETEM model for Qatar was presented at the ARC-2018 Conference (Schenckery et al., 2018) as part of the project *Modelling Transition to Energy Sustainability in Smart Cities*, supported by Qatar National Research Fund from November 2013 to November 2016.

7. PhD thesis by Moiz Abid Bohra submitted in March 2020 at Imperial College-London, with title *Optimising Qatar's Energy Transition Through Model-Based Analysis* (Bohra, 2020).

8. See IEA-ETSAP web site for a description of TIMES methodology https://iea-etsap.org/.

2.1 ETEM in a nutshell

ETEM is a multi-sector, multi-energy, technology rich model specifically designed to analyse energy transition at regional and national level. A simplified representation of its reference energy system (RES) is shown in Figure 1. Like QESMAT, ETEM is a linear programming model related to the family of MARKAL/TIMES models (Berger et al., 1992; Fragnière and Haurie, 1996; Loulou and Labriet, 2008) developed under the aegis of the IEA/ETSAP. [9] A full description of the ETEM model is provided in Babonneau et al. (2017). A presentation of the possibility to represent demand and distribution constraints and options in ETEM in a smart energy system is given in Babonneau et al. (2016). The representation in ETEM of power flow constraints and nodal marginal prices is described in Babonneau and Haurie (2019).

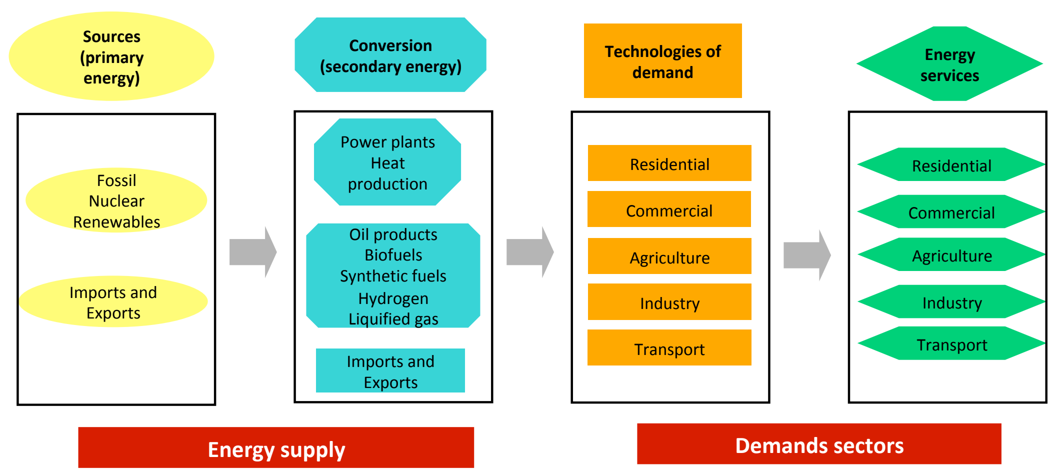


Figure 1 – Reference energy system for ETEM

In its standard version, the model is driven by exogenously defined useful energy demands (i.e. demand for energy services) and imported energy prices. All technologies are defined as resource transformers and are characterised by technical coefficients describing their inputs and outputs, efficiency, capacity limits, date of availability (for new technologies), and lifetime, among other features. The economic parameters define the costs of energy use and the costs of energy supply, including the investment, operation and maintenance costs for each technology. The planning horizon is usually long enough to allow the energy system to have a complete technology mix turnover. Typically ETEM proposes an optimal development path for an efficient regional/national energy system with a planning horizon of 20 to 80 years generally divided into periods $t \in T$ of 5 to 10 years (10 years in the simulations presented in this paper). In each period, a few typical days are considered. Each of these days is subdivided into hours or groups of hours to finally obtain a set of time slices $s \in S$ that will be used to represent load curves, demand distribution and resource availability in different seasons and at different times of the day. This temporal structure is particularly important to correctly represent the dynamics of demand and how its flexibility can be exploited. ETEM calculates an investment plan and a supply/demand balance at each time slice for a set of typical days. In order to adapt to possible variations in demand (in particular, peak demand) and to compensate for the intermittency of variable renewables (e.g. wind and solar), reserve requirements are then modelled in ETEM.

9. See the IEA/ETSAP site at https://iea-etsap.org/.

2.2 ETEM-Qatar : a model for energy transition in Qatar

To simulate and assess a possible transition to a ZNE regime for the Qatar energy system, we developed the model ETEM-Qatar. The model has an horizon 2100 and it covers all energy sectors including electricity, water desalination, gas and oil, industry, transport, commercial and residential sectors.

The transition is represented on a time horizon of height 10-year periods from 2020 to 2100. To capture the different patterns of demands and of VRE [10] production, we consider time slices structured as follows : 2 typical days, a winter day (W) and a summer day (S) ; each typical day is then decomposed in 4 groups of hours, i.e., 23h-6h (N), 6h-13 (P1), 13h-18h (M) and 18h-23h (P2).

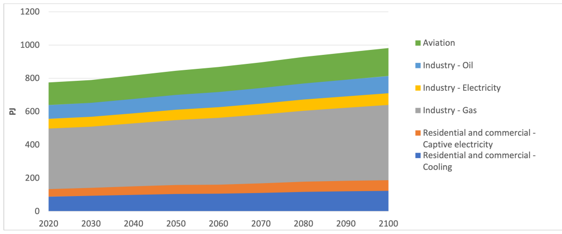
Useful demands reported in Table 1 are calibrated on the 2019 reference year, the latest available statistics on the IEA website. All energy data are given in Petajoule (PJ). Demand in transport is expressed in thousand kilometers per day (kkmd) and thousand kilometer-passengers per day (kkmpd) and water demand is given in Million of cubic meters (Mm^3). IEA statistics have been disaggregated into transport, residential/commercial and industry demands according to estimates available in Bohra (2020) and Bohra and Shah (2020). The industry sector has been decomposed into 6 categories (i.e., oil and gas, petrochemical, construction, metal, LNG and other) each with a captive demand of electricity, oil and/or gas.

Table 1 – Useful demands in 2019

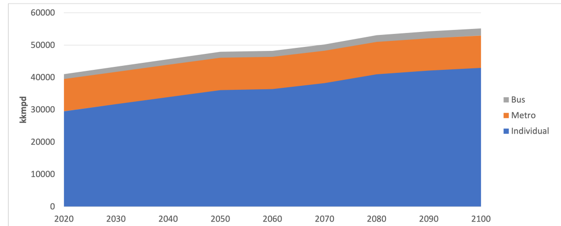
Label	Name	Demand in 2019	
	Transport Sector		
TA	Public Transports : Bus	1’500	Kkmpd
TE	Automobile	29’492	Kkmpd
TH	Truck	9’600	Kkmd
TM	Metro	10’017	Kkmd
TT	Taxi	34	Kkmpd
Tav	Aviation	136	PJ
	Residential and Commercial Sector		
RFC	Residential cooling (small household)	12.5	PJ
RFE	Captive electricity (small household)	7.9	PJ
RVC	Residential cooling (large household)	31.2	PJ
RVE	Captive electricity (large household)	19.7	PJ
CC	Cooling (Commercial)	20.1	PJ
CE	Captive electricity (Commercial)	9.5	PJ
OC	Other demands for cooling	24.4	PJ
OE	Other demands for captive electricity	8.2	PJ
	Industry		
IE1	Electricity demand for oil and gas industry	10.1	PJ
IE2	Electricity demand for Petrochemical industry	3.5	PJ
IE3	Electricity demand for Construction industry	22.3	PJ
IE4	Electricity demand for Metal industry	7.5	PJ
IE5	Electricity demand for LNG industry	10.0	PJ
IE6	Electricity demand for Other industry	5.1	PJ
IG2	Gas demand for Petrochemical industry	127.1	PJ
IG3	Gas demand for Construction industry	47.2	PJ
IG4	Gas demand for Metal industry	157.0	PJ
IG6	Gas demand for Other industry	33.1	PJ
IO6	Oil demand for industry	40.8	PJ
WAT	Water demand	605.7	Mm^3

Figure 2 displays the evolution of useful demands on the time span 2020-2100, relying on World Bank’s population and economic indicators [11] and on values used in Bohra and Shah (2020).

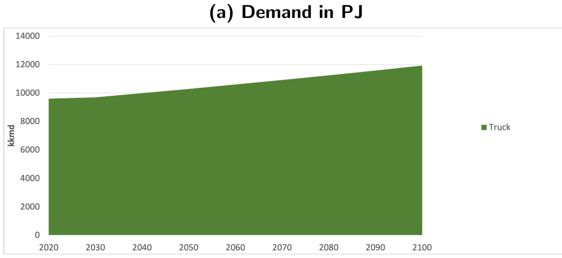
10. Variable renewable energy.
11. http ://data.worldbank.org/.



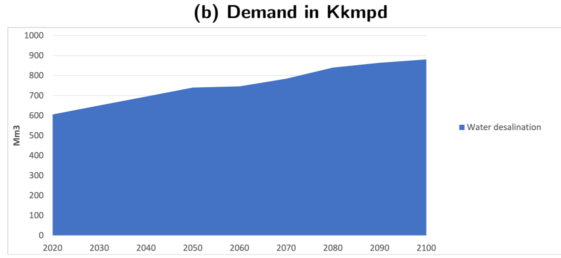
(a) Demand in PJ



(b) Demand in Kkmpd



(c) Demand in Kkmd



(d) Demand in Mm^3

Figure 2 – Evolution of demands on 2020-2100

Qatar energy system has some specificities that were taken in consideration in our model calibration. Qatar is the second largest natural gas exporter and the world leader in term of LNG exports. Two companies are responsible for extracting gas (mainly the North Field, shared with Iran) : RasGas and QatarGas. Most of the extracted natural gas is liquefied and exported by LNG tanker ships. Natural gas is also exported through a pipeline connecting Qatar with the UAE and Oman (Dolphin Pipeline). According to the IEA, Qatar has produced 6'939 PJ of natural gas in 2019, of which 5'161 PJ were exported, including 738 PJ exported through the Dolphin Pipeline.

For domestic usage, natural gas is mainly used by power plants, desalination, liquefaction facilities and other industries. According to IEA, the final consumption of Qatar in 2019 for transport sector (motor gasoline and diesel) was about 160 PJ. We decomposed this consumption into gasoline for private transport (56 PJ), diesel for private transport (42 PJ) and other transport categories (62 PJ).

Electricity is almost entirely produced locally by gas power plants. There is no electricity import or export. In 2019, electricity consumption reached 47.1 TWh (169 PJ). Water desalination plants exploit heat generated by power plants. Their total production in 2017 was around 602.3 Mm3 of water. Figure 3 shows 2019 emissions, in percentage by sector for a total of around 100Mt CO_2. For more details on the current energy system of Qatar we refer to the extensive analysis presented in Bohra (2020) and Bohra and Shah (2020).

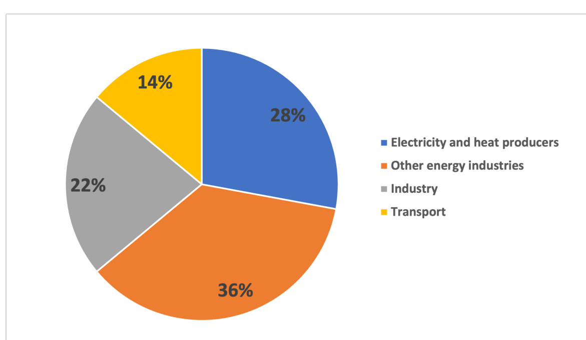


Figure 3 – Emissions by sectors in 2019

2.3 Technologies for hard-to-abate emissions

Table 2 gives the list of technologies that are considered in ETEM-Qatar, including power/desalination plants and LNG trains, with investment costs and residual capacities. Hard-to-abate emissions sources include aviation, shipping, iron and steel production, chemicals manufacture, high-temperature industrial heat, long-distance and long-haul road transport and, especially in dense urban environments or off-grid, heat for buildings. For reducing emissions in industry, we rely mainly on the Carbon Capture and Storage (CCS) option whose cost in ETEM-Qatar is decomposed into capture and transport/sequestration costs. We use a unique levelized cost of 30\$/t-CO_2 for capture and of 30\$/t-CO_2 for transport and sequestration. The capture efficiency rate varies by industry from 85% for new gas-fired power plants, 80% for the LNG and Hydrogen industries to 65% for others. Remaining emissions from industry sector (and others) can be removed at a higher cost with Direct Air Capture (DAC) technology. Cost assumptions for DAC are consistent with the levelized cost of 300\$/t-CO_2 used in Babonneau et al. (2021a).

Hydrogen could also be a leading option for reducing these hard-to-abate emissions. It has to be low-carbon hydrogen produced from renewable electricity electrolysis route (HE in Table 2) or from steam gas reforming (HSMR in Table 2) with CCS. Low-carbon hydrogen price could be around 6000\$/ton in the second half of the century. Middle East has a potential big market for exporting Ammonia to Japan.

Table 2 – Technologies investment costs and residual capacities

Label	Name	Investment cost		Residual capacity	
		Transport Sector			
TE1	Car Diesel	0.46	$M/Kkmpd	0	Kkmpd
TE2	Car ICE	0.43	$M/Kkmpd	35’000	Kkmpd
TEH1	Car hydrogen	0.55	$M/Kkmpd	0	Kkmpd
TEM	Car methanol	0.44	$M/Kkmpd	0	Kkmpd
TEN	Car comp. nat. gas	0.50	$M/Kkmpd	0	Kkmpd
TES	Car elec. S/M	0.93	$M/Kkmpd	0	Kkmpd
THY	Full Hybrid car	0.50	$M/Kkmpd	0	Kkmpd
TH3	Truck diesel	0.18	$M/Kkmd	10’560	Kkmd
THM	Truck methanol	0.19	$M/Kkmd	0	Kkmd
T1Q	Car Fuel Cell H2	2.00	$M/Kkmpd	0	Kkmpd
T1R	Car Fuel Cell Meth.l	1.37	$M/Kkmpd	0	Kkmpd
T1S	Car Fuel Cell Ga.	1.37	$M/Kkmpd	0	Kkmpd
T1T	Car Fuel Cell Nat.Gas	1.37	$M/Kkmpd	0	Kkmpd
TM1	Metro		-	10’118	Kkmd
T38	Truck Fuel Cell H2	0.27	$/Kkmd	0	Kkmd
TAK	Aircraft		-	149	PJ
TA1	Bus Diesel	1.74	$M/Kkmpd	1’950	Kkmpd
TA3	Bus Gas	2.14	$M/Kkmpd	0	Kkmpd
TAH	Bus Liquid H2	2.68	$M/Kkmpd	0	Kkmpd
TAM1	Bus Methanol 90%	1.76	$M/Kkmpd	0	Kkmpd
TAM2	Bus Methanol 100%	1.76	$M/Kkmpd	0	Kkmpd
T4F	Bus Fuel Cell H2	5.23	$M/Kkmpd	0	Kkmpd
		Residential and commercial sectors			
RFC1	Air-conditioning (small households)	363	$M/GW	0.3	GW
RFE1	El. Appliances (small households)	300	$M/GW	0.1	GW
RVC1	Air-conditioning (large households)	363	$M/GW	1.2	GW
RVE1	El. Appliances (large households)	300	$M/GW	0.3	GW
CC1	Other air-conditioning	475	$M/GW	1.8	GW
CE1	Other captive electricity	300	$M/GW	0.5	GW
LB2	District cooling	500	$M/GW	0.01	GW
		Electricity sector			
RAFA	Ras Abu Fontas A	-	-	0.68	GW
RAFB	Ras Abu Fontas B	-	-	0.61	GW
RAFB1	Ras Abu Fontas B1	-	-	0.42	GW
RAFB2	Ras Abu Fontas B2	-	-	0.57	GW

Table 2 – continued from previous page

Label	Name	Investment cost		Residual capacity	
RLA	Ras lafan A	-	-	0.76	GW
RLB	Ras lafan B	-	-	1.03	GW
RLC	Ras lafan C	-	-	2.73	GW
MES	Mesaieed Powerstation	-	-	2.00	GW
R1N	New power plant with CCS	2000	$M/GW	0	GW
E07	Solar Panel	1500	$M/GW	0.05	GW
CSP	Concentrated solar panel	7400	$M/GW	0	GW
	LNG/Gas sector				
RAS1	Qatar Gas 1	-	-	362	PJ
RAS2	Qatar Gas 2	-	-	774	PJ
RAS3	Qatar Gas 3	-	-	856	PJ
RAF1	Ras Lafan 1	-	-	549	PJ
RAF2	Ras Lafan 2	-	-	856	PJ
RAF3	Ras Lafan 3	-	-	428	PJ
RAF4	Ras Lafan 4	-	-	428	PJ
RAFN	Ras Lafan New	1500	$M/PJ	0	PJ
DOL	Dolphine pipeline		-	738	PJ
	Water desalination sector				
WRAFA	Ras Abu Fontas A	-	-	91	Mm^3
WRAFB	Ras Abu Fantas B	-	-	55	Mm^3
WRAFB1	Ras Abu Fantas B -B1	-	-	48	Mm^3
WRAFB2	Ras Abu Fantas B -B2	-	-	75	Mm^3
WRLA	Ras Lafan A	-	-	66	Mm^3
WRLB	Ras Lafan B	-	-	100	Mm^3
WRLC	Ras Lafan C	-	-	105	Mm^3
	Others				
HSMR	Steam methane reforming (hydrogen)	805	$M/GW	0	GW
HE	Electrolyser (hydrogen)	1750	$M/GW	0	GW
REF1	Oil Refinery	339	$M/PJ	294	PJ
REF2	Condensate Refinery	338	$M/PJ	296	PJ
DAC	Direct Air Capture	3500	$M/GW	0	GW

3 Pathways to ZNE in Qatar

3.1 Scenario definition

We define three scenarios that differ according to the Qatar objective and the international context :

— The Reference scenario, where no climate constraints are imposed on the Qatar economy. In this scenario, the exports of fossil fuels remain at a business as usual level for the extended future as indicated in the World Energy Outlook 2020 report (Birol, 2020) in the Stated Policies Scenario (STEPS).

— The Zero Net Emissions scenario (ZNE), where an emissions profile reaching ZNE by 2070 is imposed in Qatar. In this scenario, the exports of fossil fuels over the horizon 2100 are derived from the IEA scenario of convergence to a worldwide ZNE regime (IEA, 2021).

— The Zero Net Emissions scenario with the active participation of Qatar in an International Carbon Market (ZNE_{ICM}). In this scenario we assume that there exists an international carbon market, with a cap & trade system imposed on each country. Qatar can decide to buy or sell emission rights. The anticipated carbon price that we use is consistent with macroeconomic simulations reported in Babonneau et al. (2021a) and Babonneau et al. (2021b).

We now detail the scenario assumptions for fossil fuel exports and the future of carbon prices on an international market. In Table 3, we report our assumptions on fossil fuel export for Qatar. Estimates for the reference scenario are consistent with the IEA STEPS scenario (Birol, 2020) which foresees almost a doubling of gas production in Middle East countries by 2040. We assume that exports remain constant after 2050 and that gas exports through the Dolfin pipeline do not vary over the time horizon. Regarding ZNE scenarios, we assume as in IEA (2021) a strong reduction of fossil fuel production and export. Exports of oil almost disappear while gas remains at a significant level given the low extraction and production costs that give Qatar a competitive advantage. Again we consider constant values after 2050. These estimates are also consistent with the assumptions made in QESMAT (Bohra and Shah, 2020), where one observes a long-term decline in the export of crude oil, oil products, and natural gas, due to both supply and demand concerns.

Table 3 – Exports of fossil fuels for reference and ZNE scenarios in PJ/y

	2020	2030	2040	2050	2070	2100
	Reference scenario					
LNG	3767	5103	7026	9603	9603	9603
Gas Dolfin	756	756	756	756	756	756
Oil	3471	4290	5441	6900	6900	6900
	ZNE scenarios					
LNG	3767	3376	2673	1970	1970	1970
Gas Dolfin	756	678	537	395	395	395
Oil	3558	2239	1120	335	335	335

The price of emission permits on an international carbon trading market used in scenario ZNE_{ICM} is derived from the macroeconomic simulations reported in Babonneau et al. (2021b). The carbon price is expected to increase to 350$/t CO_2 in 2050, 1000$/t CO_2 in 2060 and then to stabilize at 1200$/t CO_2 in 2080.

3.2 Scenarios analysis

In this section, we present the results of our numerical simulations. Figure 4 shows emissions trajectories for the three scenarios described above. We observe that emissions of the reference scenario are maintained at an almost constant level over the entire time horizon despite a growth in useful demand. This is mainly due, as we will see later, to the development of the solar and hydrogen sectors. The ZNE scenario follows, as expected, the emission reduction trajectory that was imposed exogenously in the model. Finally, in the ZNE_{ICM} scenario, emissions follow the cap & trade objectives imposed on Qatar until 2070 (corresponding to the ZNE profile). Significant negative emissions activity develops from 2070 onwards, due to the high price of carbon on the international market and to a strong development of CCS and DAC activities.

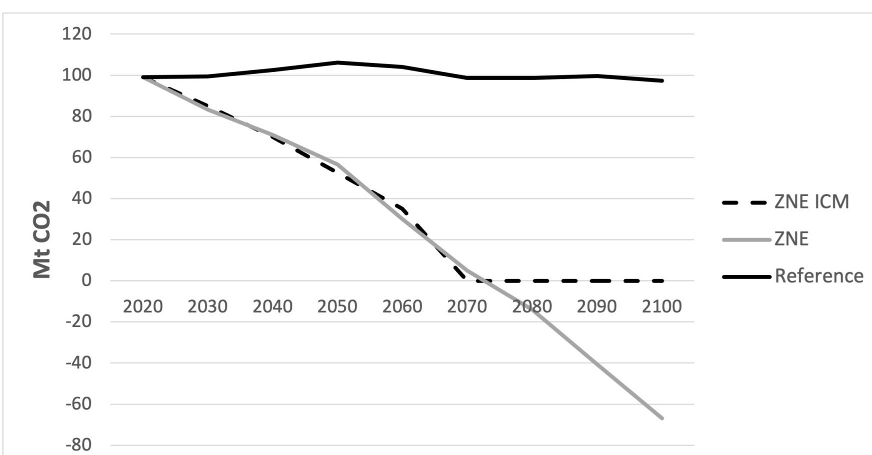
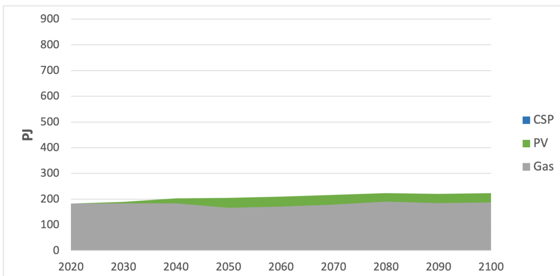
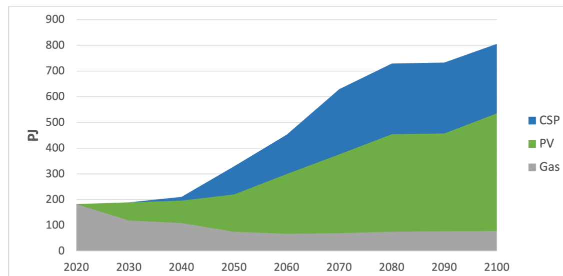


Figure 4 – Emissions profile (Mt CO_2)

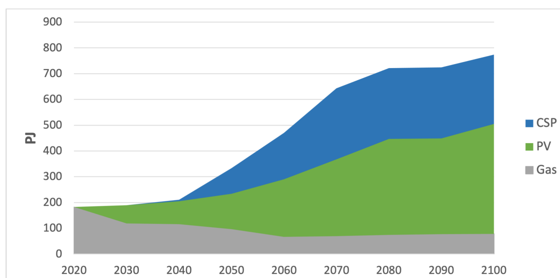
Electricity sector. Figure 5 shows the evolution of power generation for the three scenarios. In the Reference scenario, the limited increase in electricity production is provided by photovoltaic panels. The two ZNE scenarios lead to a significant increase in electricity production (a factor 4 compared to the reference scenario), which come from solar sources, mainly via photovoltaic and concentrated solar power plants. To reach the ZNE objective, production from gas is halved by 2060. The development of negative emission technologies, hydrogen and electric mobility are the main reasons for this electrification of the Qatar economy.



(a) Reference



(b) ZNE



(c) ZNE$_{ICM}$

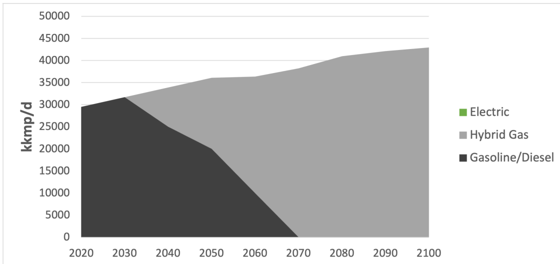
Figure 5 – Electricity production by source

Transport sector. For private transport, the petrol cars are abandoned after 2070 at the latest in all scenarios as shown in Figure 6. They are replaced in the Reference scenario by gas-powered hybrid cars, which is consistent with the government strategy defined in its Qatar National Vision 2030. In the ZNE scenarios, electric cars represents about 70% of the private transport activities after 2060 as they contribute to reduce CO_2 emissions.

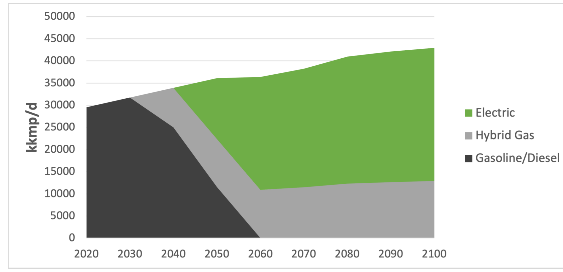
Regarding the other transport activities, the model shows the transformation of public and freight transport to hydrogen energy for the ZNE objectives. The reference scenario is still very much linked to diesel for these two sectors.

Cooling sector. These results do not show much difference between the three scenarios for the choice of technology in the residential and commercial cooling sectors. Almost all of the increase in cooling demand is met by district cooling systems, which are more efficient and competitive. The remaining demand is still met by distributed electric chillers.

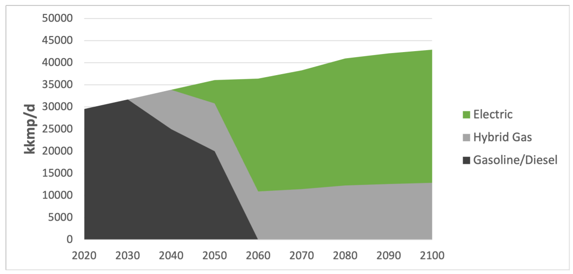
Hydrogen sector. Figure 7 shows that the industrial hydrogen production sector develops strongly in the ZNE scenarios, with the electrolysis option and especially the SMR-gas with CCS option. In these scenarios, most of the hydrogen production is exported in the form of ammonia, which partly compensates for the loss of revenue from LNG exports in a global ZNE context. We estimate that these ammonia exports could offset up to 45% of the revenue losses in 2100 compared to Reference case. The reference scenario foresees a limited production of hydrogen with SMR-gas technology, mainly for domestic consumption.



(a) BAU scenario

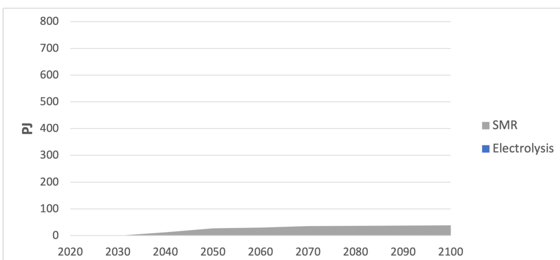


(b) ZNE

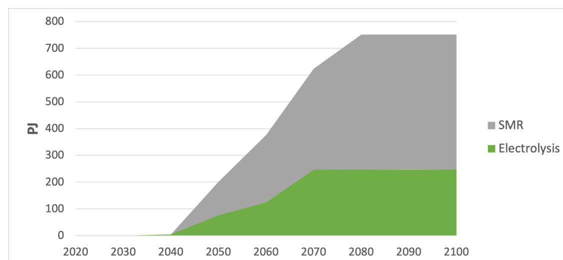


(c) ZNE$_{ICM}$

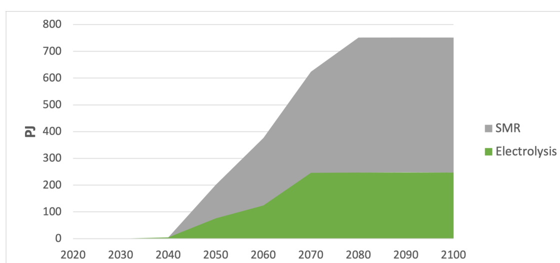
Figure 6 – Usage technology for private transport



(a) BAU scenario



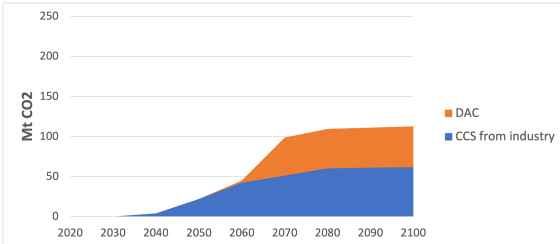
(b) ZNE



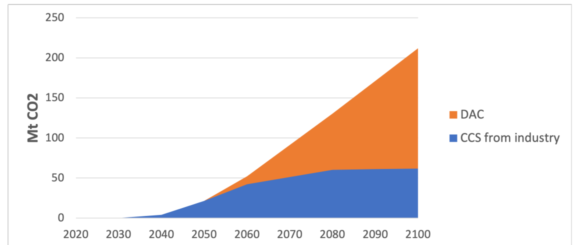
(c) ZNE$_{ICM}$

Figure 7 – Hydrogen production by source

DAC/CSS development. In Figure 8 we see that CO_2 storage in depleted oil and gas reservoirs develops strongly for both ZNE scenarios. In the reference scenario, there is no incentive to develop such an activity. We observe that the model first exploits the CCS option to its full potential. Then from 2050 onwards, the DAC activity develops and reaches a high level at the end of the century. In the ZNE scenario, DAC is mainly used to meet the ZNE target while producing hydrogen and still relying in some places on gas in the transport and electricity sectors. In the ZNE$_{ICM}$ scenario, we see the same behaviour with much higher levels of CO_2 captured after 2080. In 2100, about 150 Mt of CO_2 are captured and sequestered. This is equivalent to a consumption of 1000 PJ of gas.



(a) ZNE



(b) ZNE_{ICM}

Figure 8 – CO_2 storage

Once the cap-and-trade targets are met, Qatar sells emission permits on the international carbon market, as shown in Figure 9. Assuming that in 2100 the permit price is \$1,200/t CO_2, the levelised cost of \$300/t-CO_2 for DAC and the ammonia export price of \$60/GJ, we estimate that these permit sales could offset 50% of the LNG revenue losses in 2100 compared to the reference case. These results show the importance of developing hydrogen production in conjunction with the DAC/CSS business in the context of a global ZNE regime with an international carbon market. Qatar could have the opportunity to reduce most of its expected revenue losses by being proactive in international climate negotiations and by investing in hydrogen and DRC technologies.

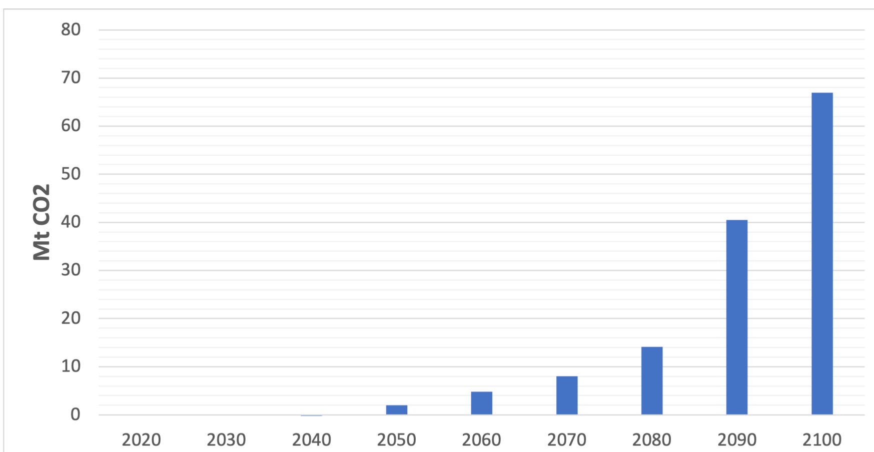


Figure 9 – Permit sales in the ZNE_{ICM} global scenario

These numerical simulations show that the implementation of an international carbon market per se does not have a significant impact on the national energy strategy once a ZNE target is defined. In both ZNE scenarios, we observe a strong electrification of Qatar's energy system with a deployment of hydrogen and CCS/DAC technologies. However, the international carbon market offers Qatar a new source of revenue with the sale of permits linked to increased DAC activity.

4 Conclusions and policy implications

In summary, to reach a zero-net emission regime by 2070 Qatar energy system could transform as follows :

1. Start immediately to foster the use of hybrid and electric cars ;
2. Develop electricity generation from solar sources ;
3. Develop district cooling ;

4. Develop hydrogen production through Stream Methane Reforming with carbon capture and storage or electrolysis, starting in 2040 ;
5. Introduce carbon capture and storage in all industrial sectors, starting in 2040 ;
6. Develop actively direct air capture with carbon capture and storage, starting in 2040.

All these new technologies are close to maturity, and demonstration units are already available. In the reference scenario, the cumulative CO_2 emissions from Qatar's energy system by 2020-2100 are about 8 Gt. In the zero-net emission scenarios, cumulative emissions over this time horizon amount to only 2.6 Gt and emissions are at a zero level from 2070 onwards. Therefore, convergence to zero-net emission in Qatar would be a significant contribution to the fight against global warming.

The marginal cost of electricity, which should be a major component of a tariff based on marginal cost pricing has been computed from the dual solution in the linear program. The average marginal cost over the different time slices of the year varies in the zero-net emission scenario from \$80/MWh in 2020, \$47/MWh in 2050 to \$40/MWh in 2100. Interestingly, this shows that tapping into Qatar's abundant source of solar energy will quickly tend to drive down the electricity bill in Qatar. Currently, Qatari customers do not see the real implicit price of electricity. The liberalisation of the electricity market, as part of a transition to zero-net emission, should not lead to unacceptable electricity prices.

Further analysing the simulation results, we observe that at the end of the century, gas export revenues in the Reference scenario would be about \$76.8 billion. [12] In the zero-net emission scenario, due to the assumed collapse of gas demand in the world market, this revenue would be reduced by 80%, or around \$15.8 billion. However, the sale of carbon-free hydrogen could partially offset this loss by generating \$42 billion of income. In addition, the potential sale of emission rights at a net price of \$900/t would be extremely profitable. In the zero-net emission scenario with implementation of an international carbon market (ZNE_{ICM}), \$61.2 billion in revenue is generated by the sale of 68 million tons of carbon emission rights. What is true for Qatar could also be possible for other Gulf Cooperation Council countries, albeit to a varying degree as their dependence on oil rather than gas exports could make a difference.

In conclusion, this modelling exercise tends to show that the regional energy system of a Gulf Cooperation Council country, like Qatar, can make a transition to zero-net emission by exploiting variable renewable energies, developing carbon-free hydrogen production and using a direct air capture technology, based on natural gas with a carbon capture and storage technology exploiting depleted oil and gas fields. In addition, the sale of carbon-free hydrogen and emission allowances from the direct air capture and carbon capture and storage business could offset the loss of revenue due to the decline in global oil and gas demand. This suggests that Gulf Cooperation Council countries, and Qatar in particular, could become proactive in the upcoming climate negotiations and promote the development of an international emissions trading scheme that will allow for the sale of emissions rights based on the direct capture of CO_2.

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