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An integrated electric vehicle network planning with economic and ecological assessment: Application to the incipient Middle Eastern market in transition towards sustainability

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This Supplementary Material provides additional information on the present study.

1. Problem definition

This section displays features of the optimization model for designing and planning the electricity production infrastructure and EVs charging network necessary to meet the energy demands in a specific geographical space and expanding electric vehicles adoption.

1.1 Model structure

The proposed framework includes renewable and fossil options for power generation (see Table A.1 for details). Carbon capture and storage systems are available for natural gas and coal technologies due to the economies of scale. The power transmission interconnections, from power generation (power plants) to distribution (EVs' charging stations) nodes, are estimated according to associated charges and incurred power losses. Moreover, EVs' charging options are offered in terms of power dispatch speed and costs. Tables A.1 and A.2 display the list of electricity production technologies and key charging stations modeling data considered in the framework.

Table A.1. Electricity production technologies considered in the optimization model.

Electricity plant	Techno-economic data sources
Natural gas	
NGCC electricity plat	(Black & Veatch Holding Company, 2012; Rubin et al., 2007, 2005)
NGCC electricity plant including CO_2 capture	(Rubin et al., 2007, 2005)
Oxyfuel (gas)	(Davison, 2007)
Oxyfuel (gas) including CO_2 capture	(Davison, 2007)
Steam Turbine	(Energy and Environmental Analysis and ICF International Company, 2008)
Turbine (gas)	(U.S. Energy Information Administration, 2013)
Coal	
Gasification (coal)	(Ordorica-Garcia et al., 2006)
Gasification (coal) including CO_2 capture	(Ordorica-Garcia et al., 2006)
Oxyfuel (coal)	(Davison, 2007)
Oxyfuel (coal) including CO_2 capture	(Davison, 2007)
Renewable	
Wind Turbines	(Fraunhofer Institute for Wind Energy and Energy System Technology, 2014; International Renewable Energy Agency, 2015)
Solar (Photovoltaic)	(International Renewable Energy Agency, 2015)
Biomass	(International Renewable Energy Agency, 2015, 2012)
Nuclear	
Power Reactor	(Nuclear Energy Institute, 2013; World Nuclear Association, 2019)

Table A.2. Key charging stations modeling data (German National Platform for Electric Mobility, 2015; NRW Invest Germany, 2011; Wynne, 2009)

Data	Unit	Charging point		
Nominal		**50 kW**	**22 kW**	**3.7 kW**
Mean charging time	h	0.1	1.2	7.8
Operating time	h/d	12	18	18
Charging outlets	Quantity	2	2	2
Expenditures*				
Hardware and planning	$	18300	3900	1300
Installation	$	3900	2200	550
Grid connection	$	3900	2200	1100
Operating	$/y	1670	830	550
Charging network assumptions				
Battery electric vehicles battery capacity	kWh		24	
Plug-in hybrid electric vehicles battery capacity	kWh		16	
Battery electric vehicles battery driving range	km		160	
Plug-in hybrid electric vehicles battery driving range	km		64	
Battery depletion before charge	%		75	
Capital charge factor	y		10	
Yearly interest	%		3	
Yearly operating days	d/y		365	

*Expenditures are considered to decline 3% yearly.

1.2 Electric vehicles power demand estimation

The EVs power requirements by demand node and time period can be estimated based on 1) projected population growth in geographical location under analysis and adjacent areas, 2) ratio between number of vehicles and residents, 3) assumed BEVs and PHEVs penetration rates per time period, 4) driver's annual driving distance, 5) EVs fuel economy, 6) EVs driving range, and 7) EVs fueling frequency.

1.3 Criteria for selection and location of charging stations

Two main criteria were used in the mathematical optimization model for the selection and location of charging stations: 1) the current petrol station distribution network was used as a proxy for residents' driving patterns, and 2) the population density was used to estimate the number of vehicles according to the geographical location's designated usage (e.g., residential, commercial, industrial, mix, etc.). Additionally, the model was formulated in a way that it can meet up designated power increases (peaking demand) compared with the baseline demand for both EVs fleet and the rest of economic sectors according to the annual seasonal changes. Moreover, the EVs peaking demand also account for projected population growth in adjacent locations. Another important model feature is that the combined power supply from charging stations in neighboring distribution nodes must be able to meet the overall electricity demand from adjacent consumption nodes. Accordingly, charging stations are not only thought to service its inherent domestic demand, but also they must be capable of servicing EVs from adjacent consumption nodes.

2. Additional Equations

The Levelized Cost of Electricity per time period ($LCOE_t$) can be calculated as follows:

$$LCOE_t = \frac{\sum_{p,l} CAP_{p,l,t} + \sum_{p,l} RE_{p,l,t} + \sum_{p,l} FUEL_{p,l,t} + \sum_{p,l} OM_{p,l,t}}{\sum_{p,l} EP_{p,l,t}\,(1-\mathrm{PLF_t})\ \mathrm{OT}}\ ,\ \forall t \quad \text{(A.1)}$$

where the numerator indicates the present value of the total cost of building and operating the power plant infrastructure over an assumed lifetime ($/y), and the denominator represents the annual net electricity generation (kWh/y).

The solar photovoltaic plant's capacity factor can be specified as:

$$\mathrm{CF_{p,t}} = \mathrm{DE_{p,t}}\ \mathrm{AH_t}\ \mathrm{N_p}\ \mathrm{A_p}\ ,\ \ p = s;\ \ \forall l, t \quad \text{(A.2.a)}$$

where $\mathrm{DE_{p,t}}$ is the solar photovoltaic panel's derate efficiency (%), $\mathrm{AH_t}$ is the fraction of available sunlight hours (%), $\mathrm{N_p}$ is the total array number, and $\mathrm{A_p}$ is the panel's area (m^2).

The wind turbine's capacity factor is given as:

$$\mathrm{CF_{p,t}} = \mathrm{FLH_t}\ \mathrm{N_p}\ ,\ \ p = w;\ \ \forall l, t \quad \text{(A.2.b)}$$

where $\mathrm{FLH_t}$ is the wind turbine's full load hours (%).

3. Details on Case Study: Abu Dhabi City's proposed EVs power supply chain network for timeframe 2020-2030

The Abu Dhabi Emirate's number of residents is anticipated to increase two-folds by the year 2030 (Kader, 2016). Likewise, as more people are estimated to migrate to the cities, it anticipates a significant increase in the number of vehicles, greenhouse gasses, and traffic bottleneck in the capital city. Which may hinder government greenhouse gas reduction targets towards 2030. The optimal integration of EVs unfolds as a unique occasion to resolve part of these challenges. At present, there are about 18 and 32 charging stations within Abu Dhabi City and the entire Emirate, respectively (Recargo Inc., 2019; Tesla Motors, 2019). For instance, competent consultancy companies anticipate that current lack of infrastructure deployment is a pivotal weakness to EVs acceptance (Kedem, 2017). The optimal distribution and sufficient availability of charging points across the city are essential to EVs adoption considering that Abu Dhabi drivers travel on average over 25 km per day, aggravated by the vehicles cooling requirements during the summer (Abu Dhabi Department of Transport, 2012).

This section lays out the key assumptions of the application of the developed optimization model to an Abu Dhabi City case study for the timeframe 2020-2030. Census data revealing Abu Dhabi's population density was crucial to determine important variables such as: expected number of BEVs and PHEVs (Herries, 2017). The PHEVs and BEVs penetration rates per time period are assumed as follows: 0.05% and 0.1% for 2020, 0.25% and 0.5% for 2022, 0.5% and 1% for 2024, 1% and 2% for 2026, 2% and 4% for 2028, 2.5% and 5%for 2030. For instance, other developing countries such as Mexico, India, and Chile the current market share for electric vehicles is 0.1% (Teter et al., 2019). The UAE figures have been selected based on two main factors: 1) EVs penetration have gained momentum in the last few years and is expected to keep growing in the next decade, 2) countries/regions working on EVs integration for over two decades (such as Germany and California) have achieved scarcely 1% penetration rate

(Department of Motor Vehicles Forecasting Unit, 2017; Germany's Federal Motor Vehicle Office (Kraftfahrt-Bundesamt), 2016).

The optimization approach targets the minimization of the electricity production and charging network expenses constrained by nuclear and renewable power targets. Abu Dhabi City was divided in two zones: Zone 1 and Zone 2, and 36 consumption nodes (sectors) for convenience. The former enables calculating the city's population density distribution more precisely. Hence, more accurate model inputs estimations result in more precise solutions (see Section 4 for further details). The population density map was found in (Herries, 2017). Conversely, the power demand forecast for the timeframe 2020-2030 in the Abu Dhabi Emirate is given as: 120,000 GWh/y in 2020, 135,000 GWh/y in 2022, 146,000 GWh/y in 2024, 158,000 GWh/y in 2026, 172,000 GWh/y in 2028, and 190,000 GWh/y in 2030. Each charging station consists of two points or outlets.

A detail inventory of the Emirate's present power capacity was carried out to determine the number of power plants, technology, installed capacity, and location. This data helped defining the existing capacities while estimating suitable locations for new plants deployment. The average interconnection distance from power generation to consumption nodes was estimated using maps of the countries transmission lines and google maps. Likewise, Abu Dhabi drivers'data was collected from the Abu Dhabi Travel Pattern Survey 2009 (Abu Dhabi Department of Transport, 2012). All costs in this study are given in US$ (2017). The present study neither considers CCS methods nor coal power plants because presently they are not among the options contemplated in Abu Dhabi's strategic vision nor plans. Table A.3 lists key input data and assumptions for the Case Study considered in the present analysis.

Table A.3. Key input data and assumptions for Case Study (Betancourt-Torcat and Almansoori, 2015).

Data	Unit	2020	2022	2024	2026	2028	2030
Emirate's power demand	TWh/y	120	135	146	158	172	190
Full nuclear power operating capacity	GW	0	1260	2520	3780	5040	5040
New installed renewable capacity	MW	250	500	750	1000	1250	1500
Natural gas cost	US$/GJ	3.50	4.00	4.50	5.00	5.25	5.50
Transmission & Distribution cost	US$/MW	79	74.5	70.2	66.2	62.4	58.8
BEVs penetration	Numb	213	1065	2129	4258	8516	1064
PHEVs penetration	Numb	106	532	1065	2129	4258	5323

4. Supply Chain Data Collection

The data used to build the EVs power supply chain was collected from different available sources, particularly Abu Dhabi Government and industry reports. Additionally, it is important to mention that for the charging station distribution, this work used the current petrol stations strategic position as reference point. For instance, petrol stations are optimally placed accounting for driving behaviors as crucial components. Consequently, assuming the gasoline station network as proxy for driving behavior; while considering available spots at their neighboring areas as prospective charging point's placements permits using enormous mobilization information otherwise difficult to access. The petrol station distribution data was available in location finder website (Abu Dhabi National Oil Company (ADNOC) Distribution, 2019) (see Figure A.1 for details).

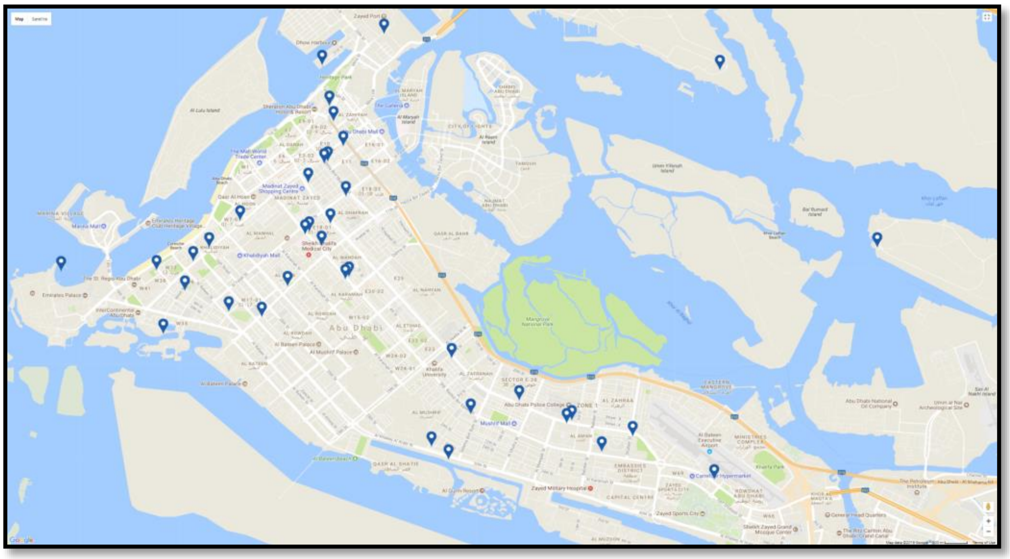

Figure A.1. ADNOC's petrol station distribution in Abu Dhabi City (Abu Dhabi National Oil Company (ADNOC) Distribution, 2019).

Power stations location were also crucial in this study. Figure A.2 shows the main power generation sites and capacities along with the power transmission network (Abu Dhabi Water and Electricity Company (ADWEC), 2016). This map was used to assign distances between power stations and Abu Dhabi city as well as assigning existing power plants generation capacities.

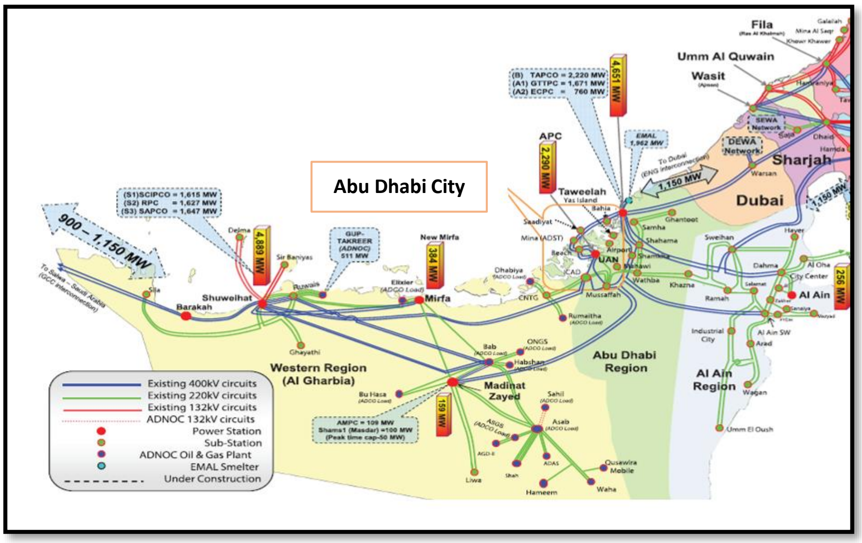

Figure A.2. United Arab Emirate's power system network (Abu Dhabi Water and Electricity Company (ADWEC), 2016).

Hereafter, Google maps was key to find the distance between each petrol service station vicinity in Abu Dhabi city and each power plant available in the Abu Dhabi Emirate. This data (the distance) was one of the foundations to build the optimization model, so that the program could find the optimal power plants layout as well as power transmission and distribution network while computing the optimal number, type, and charging stations location. Abu Dhabi City population density was also fundamental to the optimization model. This information was available at (Herries, 2017) as shown in Figure A.3.

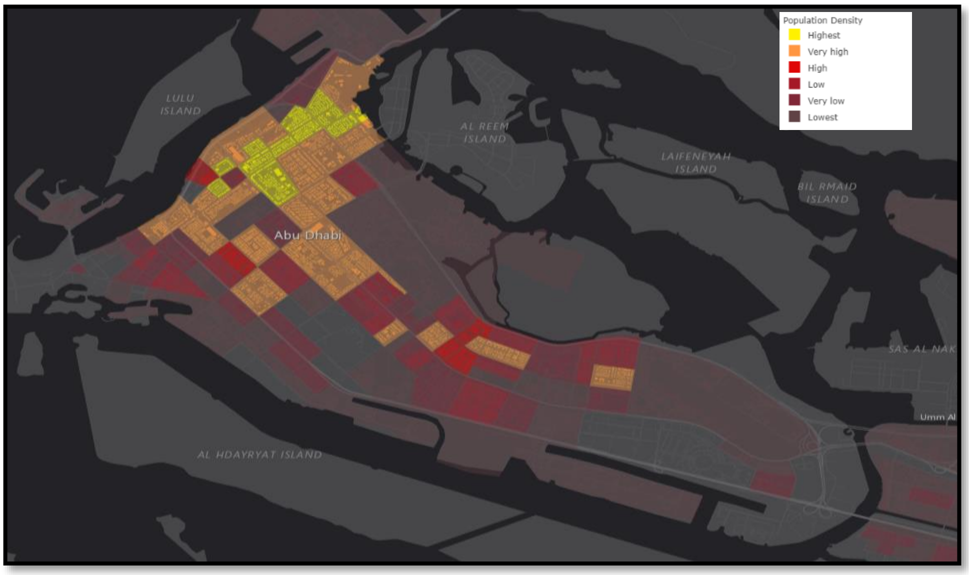

Figure A.3. Abu Dhabi City population density (Herries, 2017).

Yellow represents the highest population concentration exceeding 30,000 persons per square kilometer (persons/km^2), orange stands for very high-density areas accounting for more than 7,000 persons/km^2, red-rose is for high density areas exceeding 5,200 persons/km^2, red crimson for low density exceeding 3,330 persons/km^2, and red-brick for very low-density areas exceeding 1,500 persons/km^2. Abu Dhabi City was divided in two Zones: Zone 1 and Zone 2 (see Table A.4 and Figure A.4 (Google LLC, 2017) for details). Moreover, each Zone was divided into small sections indicating the neighborhoods/communities across the city, accounting for 36 sectors. The population in each sector can be estimated as the product of the sector's population density (persons/km^2) and its corresponding surface area (km^2). The population density is readily available as previously described, whereas each sector's surface area needs to be estimated. Accordingly, the city of Abu Dhabi was gridded into squares of equal area. Then, the number of squares making up a particular sector were summed up to obtain the total sector's surface area. As a result, the total population could be estimated for each one of the city sectors.

Table A.4. Abu Dhabi City Consumption Nodes/Sectors.

Consumption Node (z) / City sector	Zone 1	Consumption Node (z)	Zone 2
Z1	Al Meena	Z18	Al Markaziyah
Z2	Al Marina	Z19	Al Manhal
Z3	Al Zahiyah	Z20	Al Tibiya
Z4	Al Danah	Z21	Al Zaab
Z5	Madinat Zayed	Z22	Al Khalidiya
Z6	Sector E18-03	Z23	Al Khubeirah
Z7	Al Dhafrah	Z24	Al Bateen
Z8	Sector E18-01	Z25	Al Rowdah
Z9	Al Wahda	Z26	Al Karamah
Z10	Al Nahyan	Z27	Al Musalla
Z11	Al Etihad	Z28	Al Mushrif
Z12	Al Zafaranah	Z29	Embassies District
Z13	Sector E-38	Z30	Capital Centre
Z14	Al Rayhan	Z31	Zayed Sports City
Z15	Al Aman	Z32	Sheik Zayed Grand Mosque
Z16	Al Zahraa	Z33	Khor Al Maqta's
Z17	Al Bateen Executive Airport	Z34	Al Maqta
		Z35	Um Al Emarat Park
		Z36	Al Ain University Block

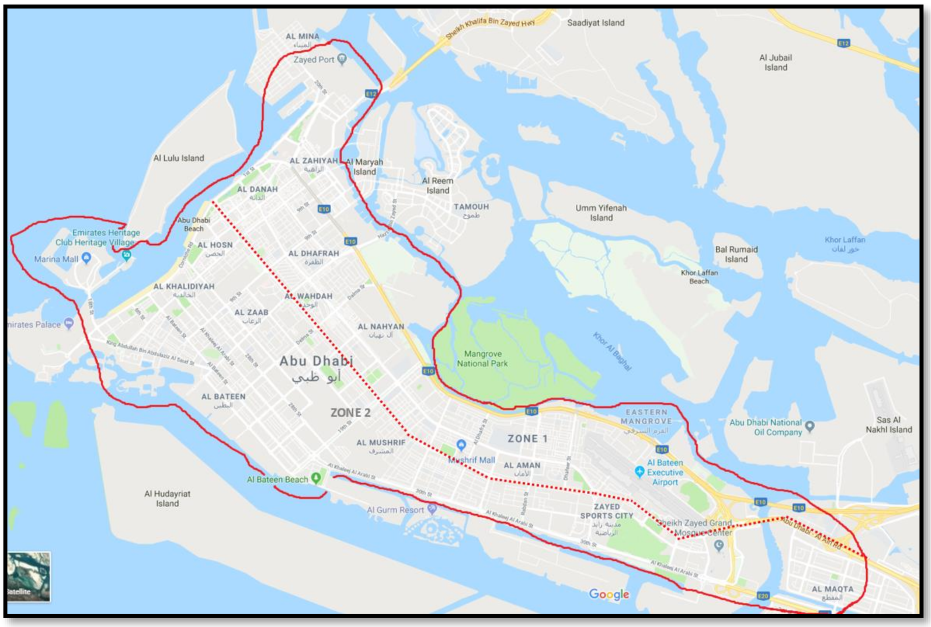

Figure A.4. Abu Dhabi City – Zone 1 (right) & Zone 2 (left) (Google LLC, 2017).

According to Abu Dhabi Travel Pattern's survey (DoTAD, 2012), for every 2 Abu Dhabi residents there is approximately 1 private light vehicle in the city. Therefore, the number of vehicles per sector was calculated by dividing each sector's population by 2.

The above information was input into the GAMS mathematical model in order to decide the most suitable arrangement of power plants, production nodes, EVs charging options, and electricity transmission and distribution (from production to consumption nodes) interconnection options. The aim is meeting the power demand and generation forecasts under operational and environmental constraints.

5. Further Discussions

The UAE reliance on natural gas for power generation has exacerbated since 2008 when the country became a net importer of gas, especially from Qatar (U.S. Energy Information Administration, 2017). Natural gas is use in enhanced oil recovery (EOR) operations, and more recently, it has been extended to non-traditional industries (e.g., aluminum and steel) as part of the country's economic diversification strategy. Abu Dhabi's global install and generation capacity will rise from 20.8 GW to 34.1 GW and 129.40 TWh/y to 204.78 TWh/y, respectively between 2020 and 2030 (see Table A.5 for details).

Electricity generation by renewable sources is presently negligible. There are just a few solar-photovoltaic systems and wind turbines in the Emirate. Figure A.5 shows the electricity generation shares from 2020 to 2030. The share of renewable energy sources continuously grows from 0.5% in 2020, 0.8% in 2022, 1.1% in 2024, 1.4% in 2026, 1.6% in 2028, to 1.7% in 2030. Although renewable sources' install capacity consistently grows every year, nuclear power outgrows renewables and by 2030 represents over 20% of the net electricity generation. Most renewable power proceeds from solar with a tiny fraction of wind power. Wind power's negligible portion is generated in farms located on the country's West coast where conditions are appropriate to harness wind.

On the other hand, natural gas-based generation remains the cornerstone of Abu Dhabi's electricity system. Nonetheless, gas-based generation declines from recent 99% to 78% by 2030, marking the emergence of alternative energy sources, particularly nuclear. Net gas generation increases over time, but at a slower rate. This generation capacity is strategic given its flexibility compared with nuclear to maintain baseload and reach varying peaking capacity, particularly during the summer months. It is worth noticing that even though Abu Dhabi promotes alternative energy sources as a key element of future domestic sustainability and economic diversification, the current strategy mainly focuses on nuclear energy. In contrast, Dubai (neighboring Emirate) has focused more on renewable energy sources, particularly solar photovoltaic given the abundance of sunlight year-round.

Table A.5. Key Case Study results.

Variable	Unit	2020	2022	2024	2026	2028	2030
Total Power Installed Capacity	GW	20.8	23.7	25.9	28.2	30.9	34.1
Total Power Generation	TWh/y	129.40	145.51	157.51	170.73	186.04	204.78
Average unit power production cost	US$/kWh	0.038	0.041	0.043	0.045	0.046	0.047
Average charging network cost	US$/kWh	0.039	0.034	0.032	0.030	0.029	0.028
Levelized Cost of Electricity	US$/kWh	0.117	0.116	0.113	0.111	0.109	0.106
Average EVs dispense cost	US$/kWh	0.156	0.149	0.145	0.141	0.138	0.134
BEVs power dispense cost	US$/km	0.023	0.022	0.022	0.021	0.021	0.020
BEVs power dispense cost	US$/km	0.039	0.037	0.036	0.035	0.035	0.034
Power Systems Emissions	g CO_2 eq.	367	339	315	295	279	286
BEVs life cycle GHG emissions	g CO_2 eq.	123.31	114.82	107.08	100.02	93.65	91.35
PHEVs life cycle GHG emissions	g CO_2 eq.	198.48	185.59	173.95	163.45	154.08	151.51
Vehicles/Charging points	Ratio	8	17	19	21	24	24

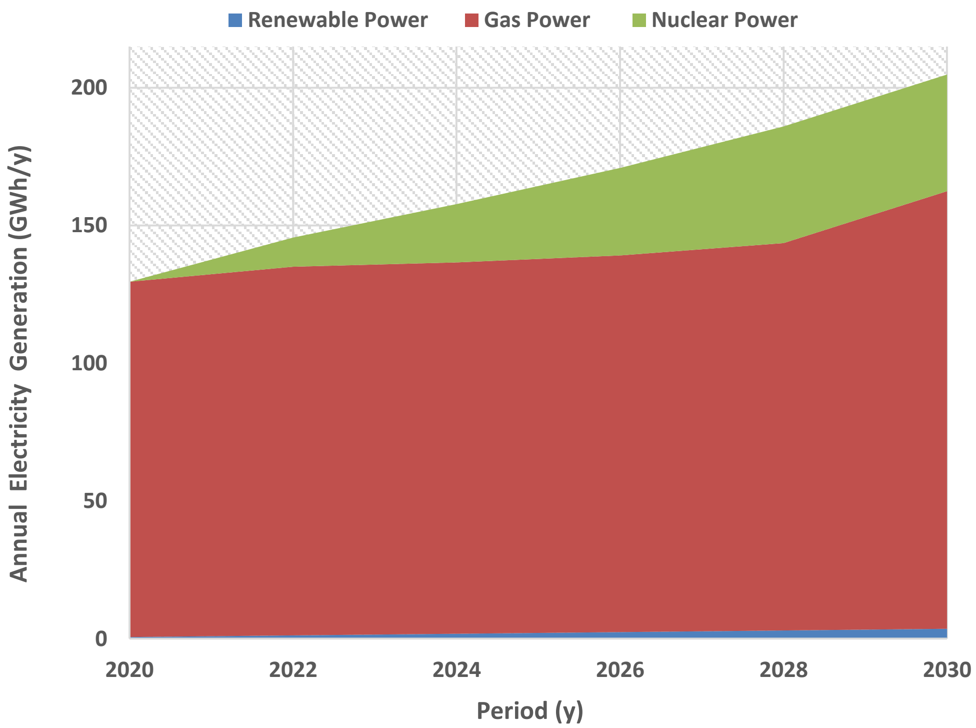

Figure A.5. Emirate of Abu Dhabi yearly electricity production share from 2020 to 2030.

The proposed electricity generation infrastructure is designed to handle the Emirate's peaking periods. The peaking capacity is made up of gas-based plants given its predominance and high-capacity factors. This should be sufficient to maintain reliable peakload electricity to cover for peaking hours. Traditionally the UAE has been a summer peaking country due to the season's high cooling requirements (Embassy of the UAE to the US, 2019). For instance, the temperature can reach over 50 degree Celsius during the summer. Additionally, there are upgrades required by the electricity grid to cope with potential EVs power load issues. EVs must be considered as one of the components of the electricity system as they connect to the grid to charge. The adoption of EVs into the transport system does not demand excessive power from the generation plant infrastructure. Nonetheless, there are risks of potential excessive power drawn from the power distribution system at a particular spatial-time point; especially if EVs adoption becomes high in densely populated sectors and users adopt similar driving and charging patterns. This would turn into temporary concentrated charging requirements, causing power variability to become a new operational challenge for the electricity system.

Accordingly, it is necessary to examine the feasibility of the distribution network to cope with the EVs adoption. One solution could be the adoption of regulation services in the electricity system. This would allow the automatic control of response power. This is technically feasible if the variability is within the system's saturation limits. However, these services are expensive and could turn into an extra cost to electricity consumers. The deployment of type III chargers would additionally require greater power capacity availability from power lines and transformers to avoid surpassing safety limits. Which translates into power lines and transformers upgrade. Another solution would be connecting each charging station to a higher distribution system voltage. The latter requires an exclusive charging station transformer. Both solutions are technically feasible; however, they require substantial capital investments that may affect the decision to adopt EVs. Table A.6 shows Abu Dhabi City's electric vehicles daily average power demands per vehicle type by time period.

Table A.6. Abu Dhabi City's electric vehicles daily average power demands per vehicle type by time period.

Vehicle Type	Abu Dhabi City's electric vehicles daily average electricity demands by period (kWh/d)					
	2020	**2022**	**2024**	**2026**	**2028**	**2030**
BEV	1456	7210	14428	28828	57630	72078
PHEV	116	591	1203	2406	4806	6006

6. Model Nomenclature

1. Indices

i = type of charging station

l = electricity production node

m = power plant operating mode

p = type of power plant

s = designated CO_2 storage site

t = time period

v= type of electric vehicle

z = electricity consumption node by vehicles

2. Sets and Subsets

b = biomass power plant

c = coal power plant

e= GHG emission type

g = natural gas power plant

h = hydropower plant

n = nuclear power plant

off = off operation position for power plants

on = on operation position for power plants

r = concentrated solar power plant

s = photovoltaic solar power plant

w = wind farm power plant

η = model's decision variables

3. Continuous Variables

$CAP_{p,l,t}$ = capital cost for the p^{th} power plant at the l node in time period t [$/y]

$CC_{p,l,t}$ = CO_2 capture in power plant p of l node in time t [t/h]

$CC_{p,l,s,t}$ = CO_2 capture in power plant p of node l directed to storage site s in time t [t/h]

$CCS_{p,l,s,t}$ = carbon capture and storage cost for plant p sending CO_2 from the l to the s node in time t [$/y]

CF = objective cost function [$/y]

$EP_{p,l,t}$ = gross power generation from the p^{th} plant at l node in time t [kW]

$FUEL_{p,l,t}$ = fuel cost for plant p at the l node in time period t [$/y]

$GC_{i,z,t}$ = charging stations' grid connection cost [$/y]

$GHG_{e,p,l,t}$ = GHG emission type e generated by the p^{th} power plant at the l node in time t [t CO_2 eq./y]

$HP_{i,z,t}$ = charging stations' hardware and planning cost [$/y]

$INST_{i,z,t}$ = charging stations' installation cost [$/y]

$OM_{p,l,t}$ = operating and maintenance cost for the p^{th} power plant at the l node in time period t [$/y]

$Q_{l,z,t}$ = gross power transfer from l production node to z consumption node in time t [kW]

$QNET_{l,z,t}$ = net electricity transfers from l production to z consumption node in time t [kW]

$RE_{p,l,t}$ = retrofit cost for power plant's p at l node in time period t [$/y]

$RUN_{i,z,t}$ = charging stations' running cost [$/y]

$SED_{p,l,s,t}$ = electricity demand for CO_2 transport from p^{th} plant at l node to carbon storage site s in time t [kW]

$TCOST_{l,z,t}$ = electricity transmission and distribution cost from plants at l generation node to charging points at the z^{th} consumption node in time t [$/y]

$VES_{i,z,t}$ = total electricity dispatched by charging stations type i at the z^{th} node in time t [kWh/d]

4. Integer Variables

$IN_{p,m,l,t}$ = number of plants type p on mode m at the l^{th} production node in time t

$INS_{i,z,t}$ = number of charging stations type i in the z^{th} node in time period t

5. Parameters

$\mathrm{ADD}_{z,t}$ = daily average driving distance for vehicles located in the z^{th} node in time period t [km]

AF_p = annual capital amortization factor for the p^{th} power plant [% /y]

ARF_p = annual retrofitting amortization factor for the p^{th} power plant [% /y]

AVR = electricity demand growth/decay rate for the geographical area [%]

$\mathrm{BC}_{v,t}$ = typical battery capacity for the v^{th} vehicle in time period t [kWh]

$BR_{v,t}$ = battery driving range for the v^{th} vehicle in time period t [km]

$Capacity_{p,l,t}^{Max}$ = maximum installed power generation capacity for the p^{th} plant at the l node in time t [kW]

$Capacity_{p,l,t}^{Min}$ = minimum installed power generation capacity for the p^{th} plant at the l node in time t [kW]

$CAPF_p$ = capital cost factor for the p^{th} power plant [$/kW]

CCF_p = carbon capture rate factor for the p^{th} plant [t/kWh]

CCP = compression power required to transport the captured CO_2 via pipeline [kWh/t/km]

$CCSF_t$ = captured CO_2 injection/storage cost factor for time t [$/t]

$CCTF_t$ = captured CO_2 transport cost factor in time t [$/t/km]

CED_{to} = base year electricity demand [kWh/y]

$CF_{p,t}$ = capacity factor for the p^{th} power plant in time t [%]

CHC_i = charging capacity for the i^{th} charging station [kW]

COT_i = hourly operation per day [h/d]

DTL_t = grid's average transmission losses for time t [%]

ED_t = forecast global electricity demand in each geographical area per time period t (excluding EVs fleet expansion and CCS) [kWh/y]

FEP_t = forecast power generation in time period t [kW]

$FHV_{p,t}$ = fuel heating value for the p^{th} power plant in time t [MJ/kg or MJ/m^3]

FP_p = fuel price for the p^{th} power plant [$/MJ]

$FR_{p,t}$ = fuel consumption rate at the p^{th} power plant in time t [kg/h and m^3/h]

f_t = forecast year [dimensionless]

f_{to} = base year [dimensionless]

GCF_i = grid connection cost factor associated to the i^{th} station [$]

$GEF_{e,p}$ = GHG emission factor for the e emission from the p^{th} plant [t CO_2 eq./kWh]

GET_t = electricity supply chain GHG emissions target for time *t* [t CO_2 eq./y]

HPF_i = station *i* hardware and planning expenditure factor [$]

$HR_{p,t}$ = heat rate per unit of power produced by the p^{th} plant [MJ/kWh]

IC_p = installed capacity of the p^{th} power plant [kW], [kW/m^2]

$INSTF_i$ = charging station's *i* installation cost factor [$]

NCP_i = number of charging points/plugs per type of charging station *i* [dimensionless]

$NV_{v,z,t}$ = expected number of vehicles type *v* consuming power in the z^{th} node in time *t* [dimensionless]

OMF_p = operating and maintenance cost factor for the p^{th} power plant [% /y]

OT = annual operating time [h/y]

$PDF_{z,t}$ = EVs peak demand factor at z^{th} node in time *t* [%]

PLF_t = electricity generation loss factor for time period *t* [%]

REF_p = retrofit cost factor for the p^{th} power plant [$/kW]

$RUNF_i$ = running cost factor per charging station *i* [$/y]

SAF_i = capital amortization factor for the i^{th} charging station [% /y]

SCF_i = capacity factor for the i^{th} type of charging station [%]

$SD_{p,l,s}$ = pipeline length connecting the p^{th} plant at node *l* to CO_2 *s* storage site [km]

TCF_t = transmission and distribution cost factor per time period *t* [$/kWh/km]

$TD_{l,z}$ = Electricity distribution and transmission distance from generation to consumption node [km]

TLF_t = electricity distribution and transmission loss parameter in time *t* [% /km]

$VCF_{v,t}$ = vehicles' charging frequency factor per time period *t* [d]

$VED_{z,t}$ = EVs electricity demand at z^{th} node in time *t* [kWh/d]

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