

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

28 list of electricity production technologies and key charging stations modeling data considered
 29 in the framework.

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

Electricity plant	Techno-economic data sources
Natural gas	
NGCC electricity plant	(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)

31

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

Data	Unit	Charging point		
		Nominal	50 kW	22 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	

34 *Expenditures are considered to decline 3% yearly.

35 *1.2 Electric vehicles power demand estimation*

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

41 *1.3 Criteria for selection and location of charging stations*

42 Two main criteria were used in the mathematical optimization model for the selection and
 43 location of charging stations: 1) the current petrol station distribution network was used as a
 44 proxy for residents' driving patterns, and 2) the population density was used to estimate the
 45 number of vehicles according to the geographical location's designated usage (e.g., residential,
 46 commercial, industrial, mix, etc.). Additionally, the model was formulated in a way that it can
 47 meet up designated power increases (peaking demand) compared with the baseline demand for

48 both EVs fleet and the rest of economic sectors according to the annual seasonal changes.
 49 Moreover, the EVs peaking demand also account for projected population growth in adjacent
 50 locations. Another important model feature is that the combined power supply from charging
 51 stations in neighboring distribution nodes must be able to meet the overall electricity demand
 52 from adjacent consumption nodes. Accordingly, charging stations are not only thought to
 53 service its inherent domestic demand, but also they must be capable of servicing EVs from
 54 adjacent consumption nodes.

55

56 **2. Additional Equations**

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

58

$$59 \quad LCOE_t = \frac{\sum_{p,l} CAP_{p,l,t} + \sum_{p,l} RE_{p,l,t} + \sum_{p,l} FUEL_{p,l,t} + \sum_{p,l} OM_{p,l,t}}{\sum_{p,l} EP_{p,l,t} (1-PLF_t)^{OT}} , \quad \forall t \quad (A.1)$$

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

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

$$64 \quad CF_{p,t} = DE_{p,t} AH_t N_p A_p , \quad p = s; \quad \forall l, t \quad (A.2.a)$$

65 where $DE_{p,t}$ is the solar photovoltaic panel's derate efficiency (%), AH_t is the fraction of
 66 available sunlight hours (%), N_p is the total array number, and A_p is the panel's area (m²).

67 The wind turbine's capacity factor is given as:

$$68 \quad CF_{p,t} = FLH_t N_p , \quad p = w; \quad \forall l, t \quad (A.2.b)$$

69 where FLH_t is the wind turbine's full load hours (%).

70 **3. Details on Case Study: Abu Dhabi City's proposed EVs power supply** 71 **chain network for timeframe 2020-2030**

72 The Abu Dhabi Emirate's number of residents is anticipated to increase two-folds by the year
73 2030 (Kader, 2016). Likewise, as more people are estimated to migrate to the cities, it
74 anticipates a significant increase in the number of vehicles, greenhouse gasses, and traffic
75 bottleneck in the capital city. Which may hinder government greenhouse gas reduction targets
76 towards 2030. The optimal integration of EVs unfolds as a unique occasion to resolve part of
77 these challenges. At present, there are about 18 and 32 charging stations within Abu Dhabi City
78 and the entire Emirate, respectively (Recargo Inc., 2019; Tesla Motors, 2019). For instance,
79 competent consultancy companies anticipate that current lack of infrastructure deployment is
80 a pivotal weakness to EVs acceptance (Kedem, 2017). The optimal distribution and sufficient
81 availability of charging points across the city are essential to EVs adoption considering that
82 Abu Dhabi drivers travel on average over 25 km per day, aggravated by the vehicles cooling
83 requirements during the summer (Abu Dhabi Department of Transport, 2012).

84 This section lays out the key assumptions of the application of the developed optimization
85 model to an Abu Dhabi City case study for the timeframe 2020-2030. Census data revealing
86 Abu Dhabi's population density was crucial to determine important variables such as: expected
87 number of BEVs and PHEVs (Herries, 2017). The PHEVs and BEVs penetration rates per time
88 period are assumed as follows: 0.05% and 0.1% for 2020, 0.25% and 0.5% for 2022, 0.5% and
89 1% for 2024, 1% and 2% for 2026, 2% and 4% for 2028, 2.5% and 5% for 2030. For instance,
90 other developing countries such as Mexico, India, and Chile the current market share for
91 electric vehicles is 0.1% (Teter et al., 2019). The UAE figures have been selected based on two
92 main factors: 1) EVs penetration have gained momentum in the last few years and is expected
93 to keep growing in the next decade, 2) countries/regions working on EVs integration for over
94 two decades (such as Germany and California) have achieved scarcely 1% penetration rate

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

97 The optimization approach targets the minimization of the electricity production and charging
98 network expenses constrained by nuclear and renewable power targets. Abu Dhabi City was
99 divided in two zones: Zone 1 and Zone 2, and 36 consumption nodes (sectors) for convenience.
100 The former enables calculating the city’s population density distribution more precisely. Hence,
101 more accurate model inputs estimations result in more precise solutions (see Section 4 for
102 further details). The population density map was found in (Herries, 2017). Conversely, the
103 power demand forecast for the timeframe 2020-2030 in the Abu Dhabi Emirate is given as:
104 120,000 GWh/y in 2020, 135,000 GWh/y in 2022, 146,000 GWh/y in 2024, 158,000 GWh/y in
105 2026, 172,000 GWh/y in 2028, and 190,000 GWh/y in 2030. Each charging station consists of
106 two points or outlets.

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

117

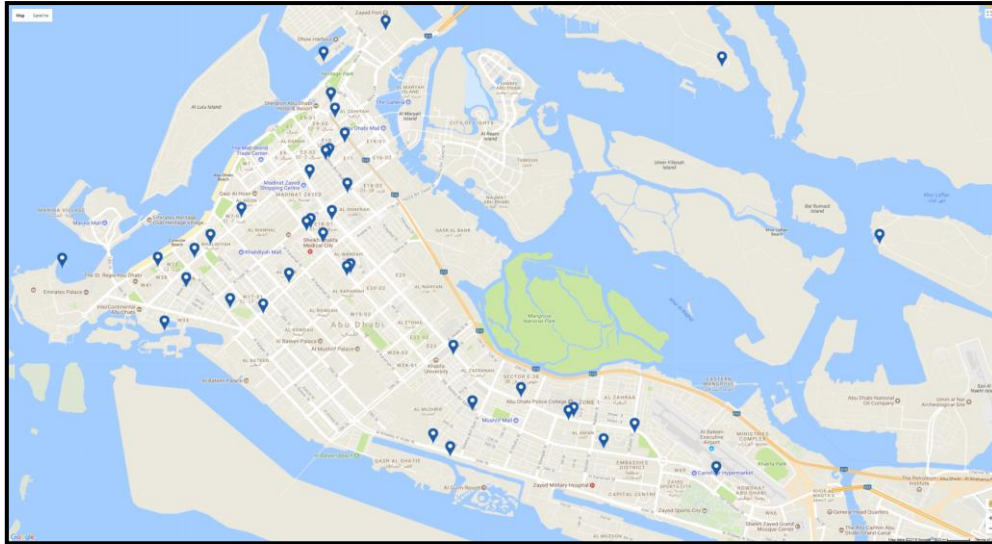
118 **Table A.3.** Key input data and assumptions for Case Study (Betancourt-Torcat and Almansoori,
 119 2015).

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

120

121 **4. Supply Chain Data Collection**

122 The data used to build the EVs power supply chain was collected from different available
 123 sources, particularly Abu Dhabi Government and industry reports. Additionally, it is important
 124 to mention that for the charging station distribution, this work used the current petrol stations
 125 strategic position as reference point. For instance, petrol stations are optimally placed
 126 accounting for driving behaviors as crucial components. Consequently, assuming the gasoline
 127 station network as proxy for driving behavior; while considering available spots at their
 128 neighboring areas as prospective charging point’s placements permits using enormous
 129 mobilization information otherwise difficult to access. The petrol station distribution data was
 130 available in location finder website (Abu Dhabi National Oil Company (ADNOC) Distribution,
 131 2019) (see Figure A.1 for details).

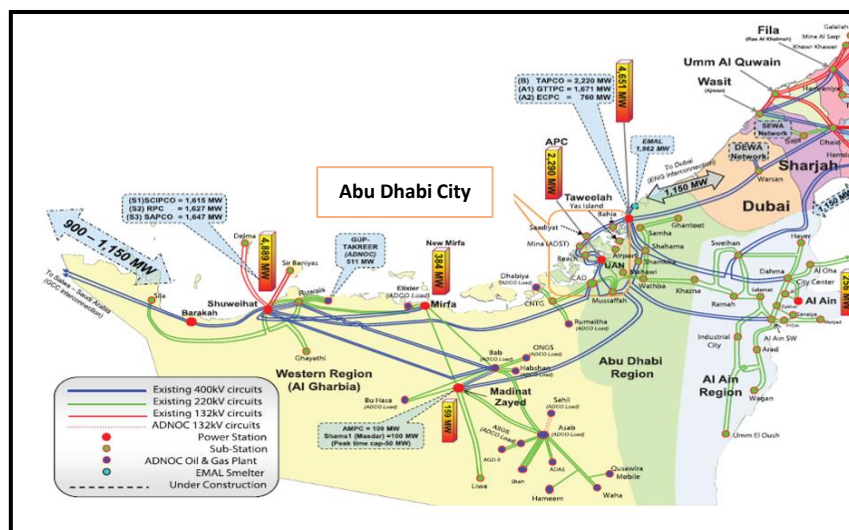


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133 **Figure A.1.** ADNOC's petrol station distribution in Abu Dhabi City (Abu Dhabi National Oil
 134 Company (ADNOC) Distribution, 2019).

135

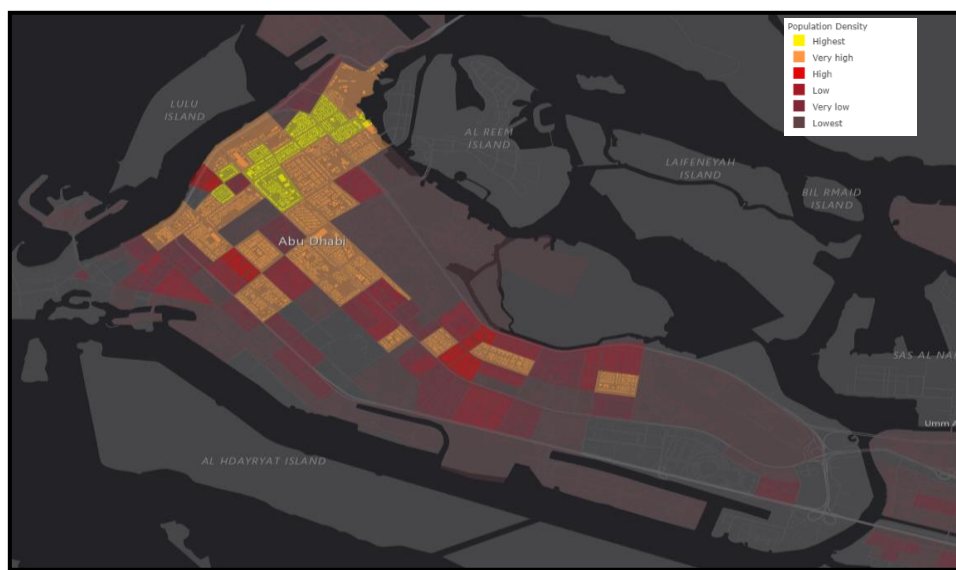
136 Power stations location were also crucial in this study. Figure A.2 shows the main power
 137 generation sites and capacities along with the power transmission network (Abu Dhabi Water
 138 and Electricity Company (ADWEC), 2016). This map was used to assign distances between
 139 power stations and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



141

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

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



151
152 **Figure A.3.** Abu Dhabi City population density (Herries, 2017).
153

154 Yellow represents the highest population concentration exceeding 30,000 persons per square
155 kilometer (persons/km²), orange stands for very high-density areas accounting for more than
156 7,000 persons/km², red-rose is for high density areas exceeding 5,200 persons/km², red crimson
157 for low density exceeding 3,330 persons/km², and red-brick for very low-density areas
158 exceeding 1,500 persons/km². Abu Dhabi City was divided in two Zones: Zone 1 and Zone 2
159 (see Table A.4 and Figure A.4 (Google LLC, 2017) for details). Moreover, each Zone was
160 divided into small sections indicating the neighborhoods/communities across the city,
161 accounting for 36 sectors. The population in each sector can be estimated as the product of the

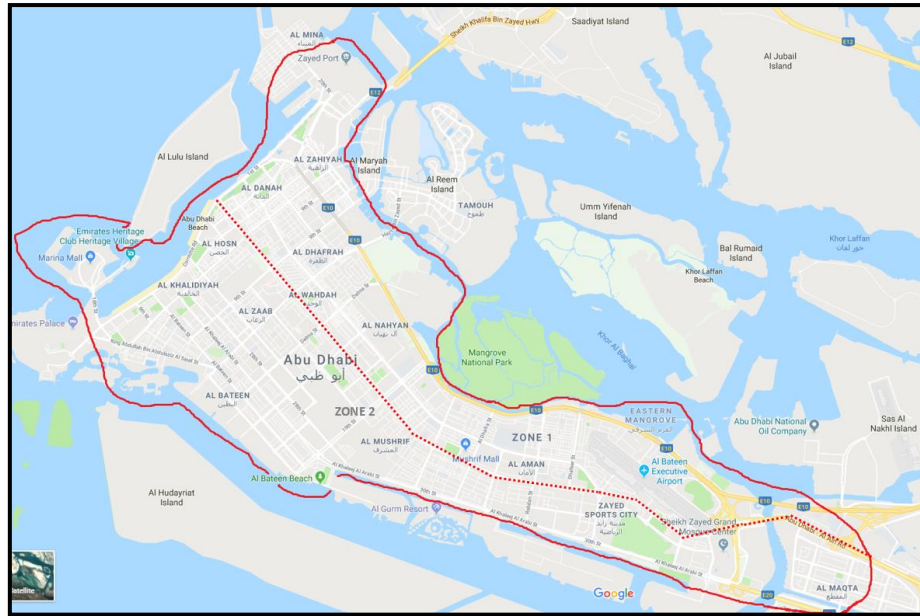
162 sector's population density (persons/km²) and its corresponding surface area (km²). The
 163 population density is readily available as previously described, whereas each sector's surface
 164 area needs to be estimated. Accordingly, the city of Abu Dhabi was gridded into squares of
 165 equal area. Then, the number of squares making up a particular sector were summed up to
 166 obtain the total sector's surface area. As a result, the total population could be estimated for
 167 each one of the city sectors.

168 **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	Z34	Al Maqta
	Executive	Z35	Um Al Emarat Park
	Airport	Z36	Al Ain University Block

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171
172 **Figure A.4.** Abu Dhabi City – Zone 1 (right) & Zone 2 (left) (Google LLC, 2017).

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

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

181 182 **5. Further Discussions**

183 The UAE reliance on natural gas for power generation has exacerbated since 2008 when the
184 country became a net importer of gas, especially from Qatar (U.S. Energy Information
185 Administration, 2017). Natural gas is use in enhanced oil recovery (EOR) operations, and more
186 recently, it has been extended to non-traditional industries (e.g., aluminum and steel) as part of

187 the country's economic diversification strategy. Abu Dhabi's global install and generation
188 capacity will rise from 20.8 GW to 34.1 GW and 129.40 TWh/y to 204.78 TWh/y, respectively
189 between 2020 and 2030 (see Table A.5 for details).

190 Electricity generation by renewable sources is presently negligible. There are just a few solar-
191 photovoltaic systems and wind turbines in the Emirate. Figure A.5 shows the electricity
192 generation shares from 2020 to 2030. The share of renewable energy sources continuously
193 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%
194 in 2030. Although renewable sources' install capacity consistently grows every year, nuclear
195 power outgrows renewables and by 2030 represents over 20% of the net electricity generation.
196 Most renewable power proceeds from solar with a tiny fraction of wind power. Wind power's
197 negligible portion is generated in farms located on the country's West coast where conditions
198 are appropriate to harness wind.

199 On the other hand, natural gas-based generation remains the cornerstone of Abu Dhabi's
200 electricity system. Nonetheless, gas-based generation declines from recent 99% to 78% by
201 2030, marking the emergence of alternative energy sources, particularly nuclear. Net gas
202 generation increases over time, but at a slower rate. This generation capacity is strategic given
203 its flexibility compared with nuclear to maintain baseload and reach varying peaking capacity,
204 particularly during the summer months. It is worth noticing that even though Abu Dhabi
205 promotes alternative energy sources as a key element of future domestic sustainability and
206 economic diversification, the current strategy mainly focuses on nuclear energy. In contrast,
207 Dubai (neighboring Emirate) has focused more on renewable energy sources, particularly solar
208 photovoltaic given the abundance of sunlight year-round.

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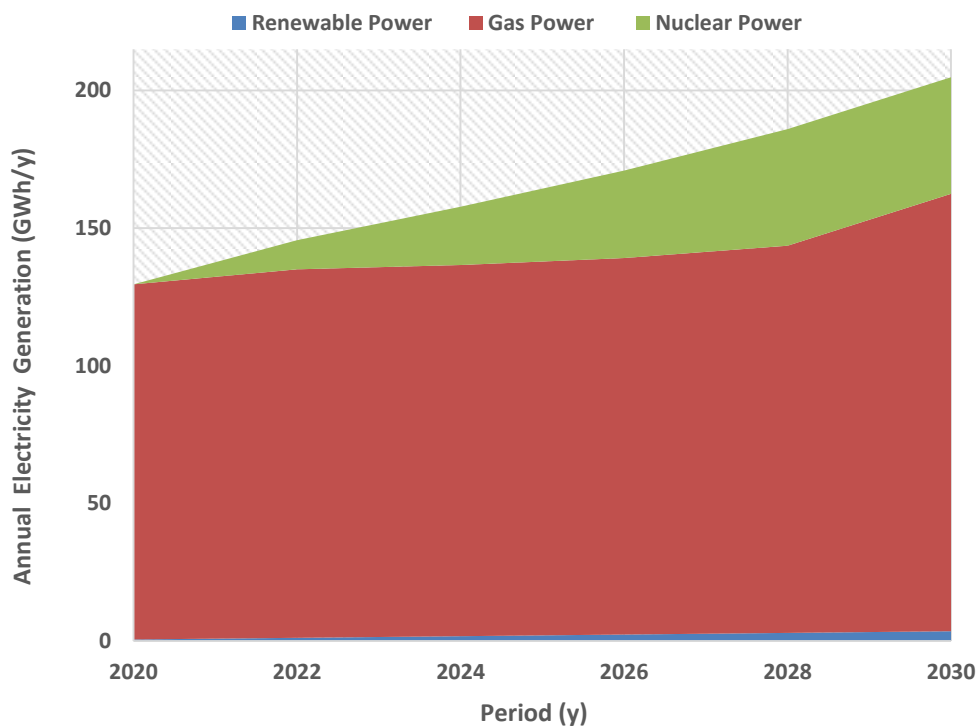
210 **Table A.5.** Key Case Study results.

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

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214

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

216 The proposed electricity generation infrastructure is designed to handle the Emirate’s peaking

217 periods. The peaking capacity is made up of gas-based plants given its predominance and high-

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

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

242 **Table A.6.** Abu Dhabi City’s electric vehicles daily average power demands per vehicle type
 243 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

244

245 **6. Model Nomenclature**

246 **1. Indices**

247 i = type of charging station

248 l = electricity production node

249 m = power plant operating mode

250 p = type of power plant

251 s = designated CO₂ storage site

252 t = time period

253 v = type of electric vehicle

254 z = electricity consumption node by vehicles

255 **2. Sets and Subsets**

256 b = biomass power plant

257 c = coal power plant

258 e = GHG emission type

259 g = natural gas power plant

260 h = hydropower plant

261 n = nuclear power plant

262 off = off operation position for power plants

263 on = on operation position for power plants

264 r = concentrated solar power plant

265 s = photovoltaic solar power plant

266 w = wind farm power plant

267 η = model's decision variables

268 **3. Continuous Variables**

269 $CAP_{p,l,t}$ = capital cost for the p^{th} power plant at the l node in time period t [\$/y]

270 $CC_{p,l,t}$ = CO₂ capture in power plant p of l node in time t [t/h]

271 $CC_{p,l,s,t}$ = CO₂ capture in power plant p of node l directed to storage site s in time t [t/h]

272 $CCS_{p,l,s,t}$ = carbon capture and storage cost for plant p sending CO₂ from the l to the s node in
273 time t [\$/y]

274 CF = objective cost function [\$/y]

275 $EP_{p,l,t}$ = gross power generation from the p^{th} plant at l node in time t [kW]

276 $FUEL_{p,l,t}$ = fuel cost for plant p at the l node in time period t [\$/y]

277 $GC_{i,z,t}$ = charging stations' grid connection cost [\$/y]

278 $GHG_{e,p,l,t}$ = GHG emission type e generated by the p^{th} power plant at the l node in time t [t CO₂
279 eq./y]

280 $HP_{i,z,t}$ = charging stations' hardware and planning cost [\$/y]

281 $INST_{i,z,t}$ = charging stations' installation cost [\$/y]

282 $OM_{p,l,t}$ = operating and maintenance cost for the p^{th} power plant at the l node in time period t

283 [\$/y]

284 $Q_{l,z,t}$ = gross power transfer from l production node to z consumption node in time t [kW]

285 $QNET_{l,z,t}$ = net electricity transfers from l production to z consumption node in time t [kW]

286 $RE_{p,l,t}$ = retrofit cost for power plant's p at l node in time period t [\$/y]

287 $RUN_{i,z,t}$ = charging stations' running cost [\$/y]

288 $SED_{p,l,s,t}$ = electricity demand for CO₂ transport from p^{th} plant at l node to carbon storage site s

289 in time t [kW]

290 $TCOST_{l,z,t}$ = electricity transmission and distribution cost from plants at l generation node to

291 charging points at the z^{th} consumption node in time t [\$/y]

292 $VES_{i,z,t}$ = total electricity dispatched by charging stations type i at the z^{th} node in time t [kWh/d]

293 **4. Integer Variables**

294 $IN_{p,m,l,t}$ = number of plants type p on mode m at the l^{th} production node in time t

295 $INS_{i,z,t}$ = number of charging stations type i in the z^{th} node in time period t

296 **5. Parameters**

297 $ADD_{z,t}$ = daily average driving distance for vehicles located in the z^{th} node in time period t

298 [km]

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

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

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

302 $BC_{v,t}$ = typical battery capacity for the v^{th} vehicle in time period t [kWh]

303 $BR_{v,t}$ = battery driving range for the v^{th} vehicle in time period t [km]

304 $Capacity_{p,l,t}^{Max}$ = maximum installed power generation capacity for the p^{th} plant at the l node
305 in time t [kW]

306 $Capacity_{p,l,t}^{Min}$ = minimum installed power generation capacity for the p^{th} plant at the l node in
307 time t [kW]

308 $CAPF_p$ = capital cost factor for the p^{th} power plant [\$/kW]

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

310 CCP = compression power required to transport the captured CO₂ via pipeline [kWh/t/km]

311 $CCSF_t$ = captured CO₂ injection/storage cost factor for time t [\$/t]

312 $CCTF_t$ = captured CO₂ transport cost factor in time t [\$/t/km]

313 CED_{t_0} = base year electricity demand [kWh/y]

314 $CF_{p,t}$ = capacity factor for the p^{th} power plant in time t [%]

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

316 COT_i = hourly operation per day [h/d]

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

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

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

321 $FHV_{p,t}$ = fuel heating value for the p^{th} power plant in time t [MJ/kg or MJ/m³]

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

323 $FR_{p,t}$ = fuel consumption rate at the p^{th} power plant in time t [kg/h and m³/h]

324 f_t = forecast year [dimensionless]

325 f_{t_0} = base year [dimensionless]

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

327 $GEF_{e,p}$ = GHG emission factor for the e emission from the p^{th} plant [t CO₂ eq./kWh]

328 GET_t = electricity supply chain GHG emissions target for time t [t CO₂ eq./y]

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

330 $HR_{p,t}$ = heat rate per unit of power produced by the p^{th} plant [MJ/kWh]

331 IC_p = installed capacity of the p^{th} power plant [kW], [kW/m²]

332 $INSTF_i$ = charging station's i installation cost factor [\\$]

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

334 $NV_{v,z,t}$ = expected number of vehicles type v consuming power in the z^{th} node in time t

335 [dimensionless]

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

337 OT = annual operating time [h/y]

338 $PDF_{z,t}$ = EVs peak demand factor at z^{th} node in time t [%]

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

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

341 $RUNF_i$ = running cost factor per charging station i [\$/y]

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

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

344 $SD_{p,l,s}$ = pipeline length connecting the p^{th} plant at node l to CO₂ s storage site [km]

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

346 $TD_{l,z}$ = Electricity distribution and transmission distance from generation to consumption node

347 [km]

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

349 $VCF_{v,t}$ = vehicles' charging frequency factor per time period t [d]

350 $VED_{z,t}$ = EVs electricity demand at z^{th} node in time t [kWh/d]

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