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A MULTI-PERIOD POWER INFRASTRUCTURE AND CHARGING STATION NETWORK PLANNING MODEL

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ABSTRACT

The United Arab Emirates (UAE) has embarked on an economic diversification strategy. One key priority is infrastructure development and environmental sustainability. The government is considering the integration of renewable and nuclear generation in the power sector as well as introducing electric vehicles into the transport sector to reduce fossil fuel consumption and air pollution. This research aims to determine the optimal arrangement between: electricity plants, charging stations, and power transmission and distribution interconnections. This to meet the electricity demand and production forecasts of a geographical region under operational and environmental constraints. The resulting electricity supply chain framework is modelled as a multi-period mixed integer linear programming (MILP) model. A case study of Abu Dhabi City from 2020-2030 was examined. The study results show that gas power still dominates by 2030, but at a lesser extent; whereas nearly 656 charging points are needed to cover 15,970 electric vehicles by 2030.

Keywords: power planning, electric vehicles, renewable resources, charging station, environment, multi-period

1. INTRODUCTION

The Abu Dhabi Emirate is projected to double its population by 2030, which anticipates an important increase in the residential and commercial power sector demand as well as number of passenger vehicles. This will result in further pollution, and traffic congestion problems for Abu Dhabi City. This will potentially interfere with the government plans to reduce air emissions by 40% in 2030 [1]. The optimal integration of renewable and nuclear power in the electricity grid as well as electric vehicles (EVs) in the transport sector unfold as an opportunity to overcome these challenges. Presently, there are only six locations with fully installed charging stations within the city, which accentuates the need for infrastructure deployment [2].

In the literature, previous studies on EVs adoption have largely emphasized on the downstream side of the EVs power supply chain. Therefore, the previous works have mainly focused on the EVs' operation side, such as the most suitable charging stations layout in public zones, or evaluate the extent to which a local electricity grid had the capacity to power an EVs fleet [3-4]. Also, other works have focused on the vehicle's movement and driving patterns as means to determine the optimal placement of EVs charging stations [5]. In view of that, it has become necessary to develop a comprehensive integrated electricity supply chain (ESC) framework in a multi-period fashion that considers both upstream and downstream components. This includes examining Abu Dhabi City's current power generation capacity and infrastructure (upstream); and determining the optimal

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manner in which it can be utilized and upgraded to satisfy the needs of an increasing population and higher penetration of EVs on roads within a given timeframe. Equally, this work proposes the optimal charging stations network required for EVs fleet per urban area (downstream) in Abu Dhabi City for the time period 2020-2030.

2. MODEL FORMULATION

The present work proposes an integrated multi-period optimization model for planning the power generation infrastructure as well as charging station network needed to simultaneously meet the electricity requirements in a given geographical region and growing penetration of EVs. The model considers upstream and downstream components. In the case of the upstream components, it includes power generation fuels (e.g., natural gas, uranium) and technologies (e.g., natural gas combined cycle, renewable, and nuclear power plants). The set of power plants *p* contains the following elements *p* = {*g*,*s*,*w*,*n*} where *g* denotes natural gas, *s* photovoltaic solar, *w* wind, and *n* nuclear. The downstream components comprise local electricity grid capacity and the optimal placement of EVs charging stations across the city. The problem's conceptual formulation and total cost of the proposed ESC for electric vehicles and remainder economic sectors for a given region are as follows:

$$\min_{\mu} CF = \sum_{p,l,t} CAPEX_{p,l,t} + \sum_{p,l,t} REX_{p,l,t} + \sum_{p,l,t} FEX_{p,l,t} + \sum_{p,l,t} OMEX_{p,l,t} + \sum_{l,z,t} TDEX_{l,z,t} + \sum_{i,z,t} HDWEX_{i,z,t} + \sum_{i,z,t} GRIDEX_{i,z,t} + \sum_{i,z,t} INSTEX_{i,z,t} + \sum_{i,z,t} RUNEX_{i,z,t} \quad (1)$$

where $CAPEX_{p,l,t}$ denotes the capital expenditures related to the p^{th} power plant located in the *l* production node at time period *t*, $REX_{p,l,t}$ the retrofit expenditures, $FEX_{p,l,t}$ the fuel expenditures, $OMEX_{p,l,t}$ the operating and maintenance expenditures, $TDEX_{l,z,t}$ are the power transmission and distribution expenditures from the *l* production node to z^{th} supply node, $HDWEX_{i,z,t}$ represents the i^{th} charging station's hardware expenditures, $GRIDEX_{i,z,t}$ the station's grid connection expenditures, $INSTEX_{i,z,t}$ the station's installation expenditures, $RUNEX_{i,z,t}$ the station's running expenditures; whereas μ denotes the decision variables' set (e.g., type and number of power plants, new power plants location, type and number of charging stations, charging stations' location, retrofitted power units, and power transmission and distribution routes per time period). The optimization approach aims to minimize both the electricity generation and charging stations network costs, under renewable generation targets and increasing EVs penetration rates per period.

2.1 Integrated electricity supply chain expenditures

The power production plant's capital expenditures are given as:

$$CAPEX_{p,l,t} = IN_{p,l,t}\, \mathrm{IC_p}\, \mathrm{CAPF_{p,t}}\, \mathrm{AF_p}\,, \quad \forall p,l,t \quad (2)$$

where $IN_{p,l}$ is an integer variable denoting the number of power plant's *p* in the l^{th} production node at time period *t*, $\mathrm{IC_p}$ the plant's installed capacity, $\mathrm{CAPF_{p,t}}$ the plant's capital expenditure factor per period, and $\mathrm{AF_p}$ the plant's yearly capital amortization factor. The retrofit expenditures are given as:

$$REX_{p,l,t} = IN_{p,l,t}\, \mathrm{IC_p REF_{p,t}}\, \mathrm{RAF_p}\,, p = g\,;\ \forall l,t \quad (3)$$

where $\mathrm{REF_{p,t}}$ is the plant's retrofit expenditure factor, and $\mathrm{RAF_p}$ the plant's yearly retrofit amortization factor. The fuel expenditures are as follows:

$$FEX_{p,l,t} = IN_{p,l,t} \mathrm{FHV_p FR_{p,t} FP_{p,t} OT}\,, p = g,n\,;\ \forall l,t \quad (4)$$

where $\mathrm{FHV_p}$ is the p^{th} plant's fuel heating value, $\mathrm{FR_{p,t}}$ the p^{th} plant's fuel consumption rate, $\mathrm{FP_{p,t}}$ the p^{th} plant's fuel price, and OT the plant's yearly operating time. The plant's operating and maintenance expenditure are given as:

$$OMEX_{p,l,t} = IN_{p,l,t}\, \mathrm{IC_p}\, \mathrm{CAPF_{p,t}}\, \mathrm{OMF_{p,t}}\,, \quad \forall p,l,t \quad (5)$$

where $\mathrm{OMF_{p,t}}$ is the plant's operating and maintenance expenditure factor. The electricity transmission and distribution expenditures are given as follows:

$$TDEX_{l,z,t} = Q_{l,z,t}\, (\mathrm{OT})\, TDF_t\, \mathrm{TDD_{l,z}}\,, \quad \forall l,z,t \quad (6)$$

where $Q_{l,z,t}$ denotes the electricity transferred from plants at the *l* node to the z^{th} supply node in time period *t*, TDF_t is the electricity transmission and distribution expenditure factor, and $\mathrm{TDD_{l,z}}$ is the electricity transmission and distribution distance. On the other hand, the charging station's hardware expenditures can be estimated as follows:

$$HDWEX_{i,z,t} = INS_{i,z,t}\, \mathrm{HF_{i,t}}\, \mathrm{SAF_i}\,, \quad \forall i,z,t \quad (7)$$

where $INS_{i,z,t}$ is an integer variable denoting the number of charging station's *i* in the z^{th} supply node at period *t*, $\mathrm{HF_{i,t}}$ the station's hardware expenditure factor, and $\mathrm{SAF_i}$ the station's yearly capital amortization factor. Moreover, the station's grid connection expenditures are given as:

$$GRIDEX_{i,z,t} = INS_{i,z,t}\, \mathrm{GCF_{i,t}}\, \mathrm{SAF_i}\,, \quad \forall i,z,t \quad (8)$$

where $\mathrm{GCF_{i,t}}$ is the station's grid connection expenditure factor in period *t*. The station's installation expenditures are estimated as follows:

$$INSTEX_{i,z,t} = INS_{i,z.t}\, \mathrm{INSTF_{i,t}}\, \mathrm{SAF_i}\,, \quad \forall i,z,t \quad (9)$$

where $\mathrm{INSTF_{i,t}}$ is the station's installation expenditure factor. The station's running expenditures are given as:

$$RUN_{i,z,t} = INS_{i,z,t}\ \mathrm{RUNF_{i,t}}\,, \qquad \forall i, z, t \tag{10}$$

where $\mathrm{RUNF_{i,t}}$ denotes the station's running expenditure factor per time period.

2.2 Operational and environmental constraints

The mathematical model's general energy balance is given as follows:

$$\sum_{p,l} EP_{p,l,t}\,(1 - \mathrm{PLF}) - \sum_{l,z} Q_{l,z} > \frac{ED_t}{(1 - \mathrm{TDL})\ \mathrm{OT}} \tag{11}$$

where $EP_{p,l,t}$ is the p^{th} power plant's gross electricity production rate from the *l* node at time period *t*, PLF the electricity production losses factor, ED_t the forecast electricity demand for the geographical region under study, and TDL the average electricity transmission and distribution losses for the electricity system. Likewise, the electricity supply/demand balance at each supply node is given as:

$$\sum_{\substack{i \\ z = adjacent\ to\ y}} \frac{VES_{i,z,t}}{COT_i} \geq VED_{y,t}\,, \qquad \forall y, t \tag{12}$$

where $VES_{i,z,t}$ is the total electricity dispatched from the i^{th} charging stations located at the z^{th} supply node at period *t*, COT_i the operating time associated to the i^{th} charging station, and $VED_{y,t}$ the total expected EVs' electricity demand at the y^{th} consumption node at time period *t*. This constraint differs from more conventional approaches considering one supply node-to-one demand node; instead the proposed approach allows combining the electricity dispatch capacity from two or more adjacent supply nodes *z* to simultaneously meet the demand of various nearby demand nodes *y*. As one could expect in a dynamic environment as transportation. On the other hand, the power infrastructure renewable resources targets are given as:

$$\sum_{p \in \{s,w\}} RE_{p,t} \geq \mathrm{RET}_t \tag{13}$$

where $RE_{p,t}$ denotes the power from the p^{th} power plants (solar and wind), and $\mathrm{RET_t}$ the renewable power target set per time period.

The proposed multi-period optimization model was developed in the General Algebraic Modeling System (GAMS) as a mixed integer linear programming (MILP) formulation. The model consists of 287,726 equations, 18,808 continuous variables, and 3,734 discrete variables. The problem was solved using CPLEX. The CPLEX solver uses a branch and cut algorithm that solves a series of LP subproblems. The algorithm is summarized as follows: 1) Detects infeasibilities and redundancies, improve bounds and rounding. 2) Solves the linear programming relaxation problem. 3) Add cuts to shrink the feasible region. 4) Apply heuristics to rapidly generate suitable solutions. 5) Select integer variables to generate new subproblems. 6) Choose a subproblem and solve. 7) Repeat steps 1–6 until termination criteria is met (tolerance).

3. RESULTS AND DISCUSSIONS

This section discusses the results of the integrated ESC infrastructure design proposed for Abu Dhabi City from the year 2020 to 2030. This case study assumes the following penetration rates for battery electric (BEVs) and plug-in hybrid electric vehicles (PHEVs) per time period, respectively: 0.1% and 0.05% for 2020, 0.5% and 0.25% for 2022, 1% and 0.5% for 2024, 2% and 1% for 2026, 4% and 2% for 2028, and 5% and 2.5% for 2030. In this work, Abu Dhabi City geographical area was split into 36 sectors for practical purposes. This allowed to better calculate the city's population density distribution; and thus, provide better inputs to the program so it could find the required number and type of charging stations in a particular location. The population density map was obtained from [6]. On the other hand, the Abu Dhabi Emirate forecast electricity demand from 2020 to 2030 is assumed as follows: 120 TWh/y in 2020, 135 TWh/y in 2022, 146 TWh/y in 2024, 158 TWh/y in 2026, 172 TWh/y in 2028, and 190 TWh/y in 2030. Moreover, it is assumed each charging station consists of two charging points.

3.1 Proposed power infrastructure for the Abu Dhabi Emirate from 2020 to 2030

The optimization results showed that in the Abu Dhabi Emirate, the electricity mix is still set to be dominated by gas-based electricity generation by 2030. However, there is a decline in gas-based generation from current levels 98% to 78% by 2030. Abu Dhabi's overall installed capacity and electricity generation will rise from current 15,220 MW to 34,077 MW and 80,527 GWh/y to 204,780 GWh/y, respectively by 2030. Power generation by renewable sources is currently negligible, but it is expected to represent 1.7% in 2030. Figure 1 shows the power generation shares from 2020 to 2030. The levelized cost of electricity (LCOE) is estimated to range from 0.119 to 0.129 US$/kWh (including transmission and distribution costs) between 2020 and 2030 (current real costs amount 0.093 US$/kWh). The cost increment can be attributed to inflation and fuel cost adjustments. The previous costs do not include possible governmental subsidies on the power sector, and are given in US$(2017).

Abu Dhabi's power system average emissions gradually decrease from 367 to 279 g CO_2 eq./kWh between 2020 and 2028; then slightly surge to 286 g CO_2 eq./kWh in 2030. These values are lower than most countries' electricity system nowadays usually over 400 g CO_2 eq./kWh [7]. In addition, BEVs emission footprints (from power generation to tailpipe) range between 55 and 42 g CO_2 eq./km from 2020 to 2028, slightly increasing to 43 g CO_2 eq./km in 2030. Likewise, PHEVs emissions on electric mode range between 92 and 70 g CO_2 eq./km from 2020 to 2028, slightly increasing to 72 g CO_2 eq./km. These trends can be explained by the gradual deployment of new nuclear power plants between 2022 and 2028. On the other hand, on average internal combustion vehicles consuming gasoline or diesel generate approximately 213 g CO_2 eq./km and 244 g CO_2 eq./km just at the tailpipe, respectively.

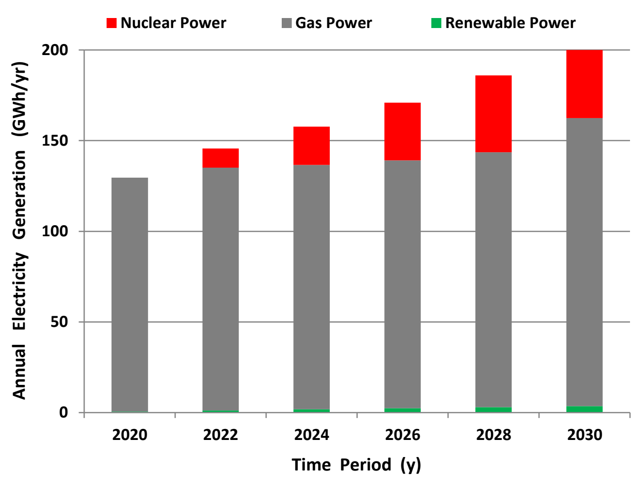

Fig 1 Abu Dhabi Emirate's annual electricity generation share from 2020 to 2030

3.2 Proposed EVs charging station network for Abu Dhabi City from 2020 to 2030

The proposed charging stations network has been designed for Abu Dhabi City; therefore, the network is delimited and concentrated in this specific geographical area (see Table 1 and Figures 2A and 2B for details). As a result, all the power transferred to the city's proposed charging stations network comes from the Sas Al Nakhl power station given its close proximity to the city. This arrangement allows diminishing the power transmission and distribution losses. The optimization results suggest there are two pivotal sectors in Abu Dhabi City containing the highest concentration of EVs' charging points: Al Danah and Madinat Zayed. Al Danah encloses the following charging point's zones (supply nodes): Al Jazeera (Z2), Al Yasat (Z3), and Al Madeenah (Z21); while Madinat Zayed contains a charging point's zone under the same name (see Table 1 and Figures 2A and 2B for details).

The present work uses the location of current ADNOC's petrol service stations inside the city [8] as reference for the charging point's placement. Accordingly, all charging points placed in a zone in proximity to a specific petrol station are named following ADNOC's station syntax [8]. These common syntax may help users to more easily locate potential charging stations in the future. The placement of charging stations in the vicinity of petrol stations is in line with Dubai's Emirate experience; whose charging stations network is the most developed in the Middle East region.

Petrol stations are optimally located using algorithms that take into account driving patterns as key elements. Thus, taking the petrol station locations as a proxy for driving patterns in Abu Dhabi city and assuming suitable available sites at their vicinities as potential placement for charging stations allows taking advantage of vast mobilization data that is not easily accessible otherwise.

Table 1: Abu Dhabi City charging station network deployment schedule

Charging stations' zones / Supply nodes	Total charging stations					
	T1	T2	T3	T4	T5	T6
Freeport (Z1)	1	-	-	-	-	-
Al Jazeera (Z2)	-	-	12	1	31	-
Al Yasat (Z3)	3	11	1	21	6	2
Madinat Zayed (Z4)	-	-	-	5	15	24
Al Naser (Z5)	1	1	2	3	6	3
Al Khalidiya I (Z6)	-	-	-	2	-	-
Al Khalidiya II (Z7)	-	-	1	-	-	-
Al Corniche (Z8)	-	1	1	2	3	2
Al Bateen (Z9)	-	-	-	-	1	-
Al Buteen Marina (Z10)	1	-	-	-	-	-
Souq Al Bateen (Z11)	-	-	-	2	-	-
Al Manasir (Z12)	1	1	1	-	5	4
Al Zaab (Z13)	1	2	1	1	2	1
Al Taawun (Z14)	1	-	-	-	-	-
Al Saada (Z15)	-	1	1	2	3	2
Al Dhafrah (Z16)	1	-	2	1	2	1
Al Manhal (Z17)	-	1	-	-	-	-
Al Falah (Z18)	1	-	-	-	-	-
Al Hosn (Z19)	-	1	-	-	-	-
Al Jawazath (Z20)	-	2	1	1	2	1
Al Madeenah (Z21)	1	2	3	6	11	6
Al Salam (Z22)	-	-	-	-	1	-
Al Maha (Z23)	-	1	1	3	3	4
Al Mina (Z24)	-	-	-	1	-	-
Al Zafarana (Z25)	1	1	1	2	3	2
Rabdan (Z26)	-	-	-	-	1	-

Al Mushrif (Z27)	1	1	2	4	5	4
Al Khaleej Al Arabi (Z28)	-	-	1	-	-	-
Embassy Area (Z29)	1	1	1	1	3	1
Between Two Bridges (Z30)	1	1	1	2	1	2
Zayed Stadium (Z31)	1	1	1	2	5	2
Air Wing (Z32)	-	-	-	1	1	1
Police College (Z33)	-	-	-	1	-	-
Al Itihad (Z34)	-	-	-	1	-	-
Al Dana (Z35)	1	1	1	2	4	2
*T1: 2020, T2: 2022, T3: 2024, T4: 2026, T5: 2028, T6: 2030						

The aforementioned four charging zones or supply nodes concentrate almost 50% of the total charging points in the city by 2030. Moreover, they encompass the core of the city's downtown. For instance, it is worth noticing in Figures 2A and 2B that these charging stations are located in the city's more densely populated sectors. For example, Al Jazeera (Z2), Al Yasat (Z3), and Al Madeenah (Z21) charging stations' zones serve the Al Danah sector. Al Danah has seven times more inhabitants than the second most populated city sector (Al Zahiyah). Accordingly, Al Danah is a very busy sector with mix usage including: high rise residential buildings, commercial and business centers.

To meet the demands of such a comprehensive area, its charging network is mainly composed of type III DC fast chargers (50 kW, 10-20 minutes recharge time) and type II AC chargers (22 kW, 1-2 hours recharge time) given the limited availability of space. This type of station maximizes space use. Accordingly, they can dispatch power at higher rates and substantially reduce the EVs charging times compared with most traditional stations (type I AC chargers, 3.7 kW, 7-8 hours recharge time). This layout offers the flexibility to accommodate for peaking periods when the sector is very busy and users need a quick charge to continue their activities. On the other hand, the type II stations could serve residents in the area who may benefit from lower charging rates compared with type III stations.

Likewise, the Madinat Zayed sector concentrates the second largest number of charging stations. This city sector includes the remaining of Abu Dhabi City's downtown and houses the third largest population in the city. All charging points in this sector are type III. This given its highest population density and the commercial nature of the sector; which would be highly benefited from quick charging times.

Regarding the city's remaining charging points, the sectors designated usage (residential, commercial, business, industrial, etc.) and physical space available play an important role on determining the type and number of charging stations. Moreover, the model was developed in a way that the overall electricity demand from neighboring/adjacent sectors can be met by means of the combined available supply from various charging stations' zones. Thus, adjacent sectors complement each other, allowing a more comprehensive charging framework design compared with the traditional one demand/one supply arrangement. The complementary supply approach considered in this study is more elastic and realistic.

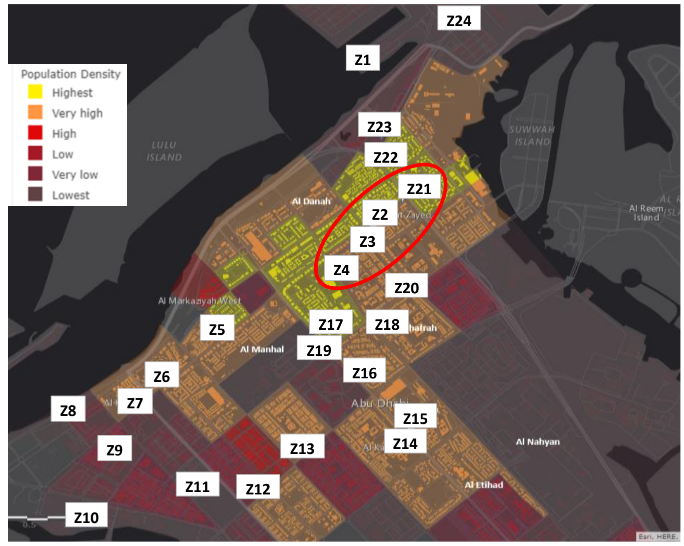

Fig 2A Abu Dhabi City downtown map with charging network

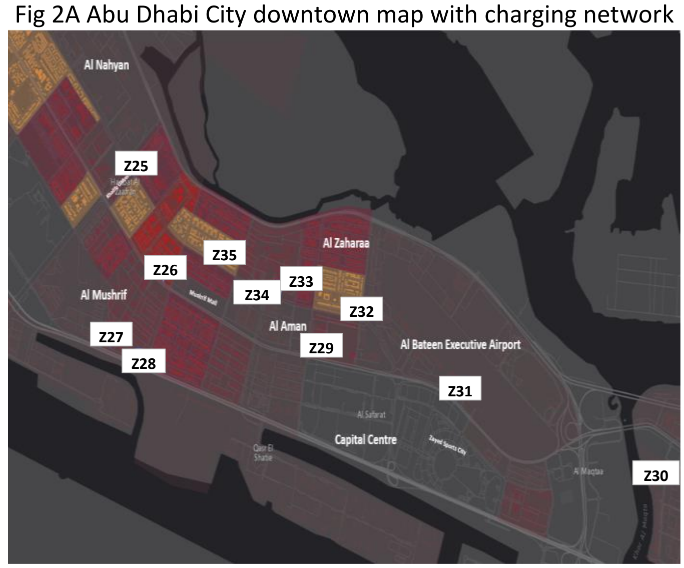

Fig 2B Abu Dhabi City outskirts map with charging network

It was found that approximately 656 charging points are required to meet the power demands expected from introducing and additional number of 15,970 EVs (10,646 BEVs and 5,324 PHEVs) into Abu Dhabi City roads by 2030. The ratio of EVs to charging points ranges from 8 to 24 from 2020 to 2030, respectively. It reaches a maximum of 24 by 2030. Although current trends target to keep this ratio ranging 10-15 [9] the fact that 45% and 38% of the charging points consist of type II and type III chargers, respectively; allows maintaining the overall average charging time low despite the moderately high ratio. This particular approach was considered in view that different studies [10] have indicated that EVs charging times is an important focus of concern for potential EV users in Abu Dhabi.

The average marginal cost of the proposed charging stations network alone was found to slightly decrease from US$ 0.039/kWh in 2020 to US$ 0.033/kWh in 2030 for each unit of power (kWh) dispatched to EVs. Likewise, the marginal electricity dispatch cost to EVs is estimated to slightly increase from US$ 0.158/kWh in 2020 up to US$ 0.162/kWh in 2030 due to higher electricity costs. This latter cost includes both charging network and electricity charges. According to reported information, current UAE's EVs charging costs amount approximately US$ 0.08/kWh [11]. This latter value corresponds roughly to the current subsidized residential electricity cost paid by Abu Dhabi customers [12]. This means that current EVs charging costs are heavily subsidized by the government as a mean to promote EVs adoption. Nonetheless, assuming the estimated marginal EVs electricity dispatch cost, approximately US$ 0.024/km and US$ 0.04/km driven would be spent by standards BEVs and PHEVs, respectively. For instance, a standard internal combustion vehicle (11 km/L gasoline) consumes US$ 0.055 worth of fuel per km driven under current UAE gasoline prices (US$ 0.6/L 95 octane gasoline). This shows that also savings could be attained when using EVs in terms of fuel spent per kilometer driven, even without governmental subsidies.

4. CONCLUSIONS

In this work a comprehensive integrated electricity supply chain for electric vehicles was developed in the GAMS software. The model was used to plan the power generation infrastructure of the Abu Dhabi Emirate simultaneously with the charging stations network required in Abu Dhabi City for different EVs penetration rates from the year 2020 to 2030. The case study results show that two city sectors upholds the majority of charging points: Al Danah and Madinat Zayed. This due to the sectors' high business/commercial/housing activities. This work proposes charging points placement across the city based on population density, parking space availability, and sector activity. The costs suggests that the UAE government is currently heavily subsidizing EVs' charging as means to promote electromobility. Moreover, even if the government decides to reduce the subsides, EVs charging would still be more cost efficient for consumers compared to internal combustion vehicles.

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