energies

Article

Utilizing Rooftop Renewable Energy Potential for Electric Vehicle Charging Infrastructure Using Multi-Energy Hub Approach

Syed Taha Taqvi [1,2], Ali Almansoori [3,*], Azadeh Maroufmashat [1] and Ali Elkamel [1,3,*]

[1] Chemical Engineering Department, University of Waterloo, Waterloo, ON N2L 3G1, Canada
[2] ABen Hub Incorporated, Kitchener, ON N2E 0E1, Canada
[3] Department of Chemical Engineering, Khalifa University of Science, Technology and Research (KUSTAR), Abu Dhabi P.O. Box 2533, United Arab Emirates
* Correspondence: ali.almansoori@ku.ac.ae (A.A.); aelkamel@uwaterloo.ca (A.E.)

Abstract: Electric vehicles (EV) have the potential to significantly reduce carbon emissions. Yet, the current electric vehicle charging infrastructure utilizes electricity generated from non-renewable sources. In this study, the rooftop area of structures is analyzed to assess electricity that can be generated through solar- and wind-based technologies. Consequently, planning an electric vehicle charging infrastructure that is powered through 'clean' energy sources is presented. We developed an optimal modeling framework for the consideration of Renewable Energy Technologies (RET) along with EV infrastructure. After examining the level of technology, a MATLAB image segmentation technique was used to assess the available rooftop area. In this study, two competitive objectives including the economic cost of the system and CO_2 emissions are considered. Three scenarios are examined to assess the potential of RET to meet the EV demand along with the Abu Dhabi city one while considering the life-cycle emission of RET and EV systems. When meeting only EV demand through Renewable Energy Technologies (RET), about 187 ktonnes CO_2 was reduced annually. On the other hand, the best economic option was still to utilize grid-connected electricity, yielding about 2.24 Mt CO_2 annually. In the scenario of meeting both 10% EV demand and all Abu Dhabi city electricity demand using RE, wind-based technology is only able to meet around 3%. Analysis carried out by studying EV penetration demonstrated the preference of using level 2 AC home chargers compared to other ones. When the EV penetration exceeds 25%, preference was observed for level 2 (AC public 3ϕ) chargers.

Keywords: renewable energy; rooftop; energy hub; multi-period optimization; energy planning; electric vehicle; charging infrastructure

Citation: Taqvi, S.T.; Almansoori, A.; Maroufmashat, A.; Elkamel, A. Utilizing Rooftop Renewable Energy Potential for Electric Vehicle Charging Infrastructure Using Multi-Energy Hub Approach. *Energies* **2022**, *15*, 9572. https://doi.org/10.3390/en15249572

Academic Editor: Luis Hernández-Callejo

Received: 1 September 2022
Accepted: 3 November 2022
Published: 16 December 2022

1. Introduction

One of the major challenges the electric vehicle industry faces, as opposed to combustion engine vehicles, is the lack of infrastructure across many countries [1]. Historically speaking, the first car was driven by Karl Benz in 1886 [2]. It was not until 1913 when the first filling station was built for automobiles [3]. On the other hand, even though the first electric vehicle was invented in the 1800s, the first mass produced hybrid vehicles were introduced in 1997 [4]. By December 2013, an electric vehicle charging infrastructure was completed by Estonia with nationwide coverage [5].

In contrast, Abu Dhabi, the capital of the United Arab Emirates, is one of the largest producers of energy globally. However, more than 99% of its electricity is generated from fossil-based fuels [6]. The government aims to increase its dependence on renewables up to 7% by 2020 as a step to mitigate carbon emissions [7]. The country has also promoted the use of electric vehicles (EV) by offering financial incentives in order to mitigate emissions from the transport sector [8,9]. Coupled with rise in fuel prices, there exists potential for a significant shift to electric vehicles.

As EVs are a promising solution for emission and pollution reduction in urban areas, many governments propose different types of tax credits or incentives for purchasing EVs. Although this will ease the penetration of EVs into the urban area in the city, there are many challenges. Regardless of the challenges of coupling of EVs with grid, the underlying challenge for the integrating of renewable power generations with EVs remains. There is already significant research into the design and applications of electric vehicle integration and vehicle to grid operation to help intermittency challenges of renewable energy [10–12]. However, the focus of our work is to optimally design and integrate renewable technologies with EV charging at the city scale with emphasis on the investigation of carbon emission reduction.

Bhatti et al. [13] conducted a comprehensive review of EV charging using solar photovoltaic (PV) technology. This work only considers solar PV with the simulation approach, while our work considers different rooftop renewable energy technologies including wind and different types of solar considering an optimal planning approach. Another study investigated the optimal design of renewable energy for EV charging in high-density areas. They considered Hong Kong as their case study [14]. Osório et. al. [15] reviewed many research studies, discussing solar PV, EV changing, as well as the challenges of integration of a PV system for EV charging. Minh et al. investigated the techno-economic aspect of coupling PVs with EV changing infrastructure with an emphasis on solar irradiation in Vietnam [16].

Within the past decade, several renewable energy projects have been initiated or completed outside the Abu Dhabi (AD) city, such as Shams CSP, Masdar PV and Bani Yas Wind farm, to aid in meeting the AD 2020 target. Abu Dhabi has been exploring rooftop RET deployment schemes since 2008 [17]. Yet, these have been limited to policy-making stages, and the idea of utilizing rooftop area of major structures within the metropolitan region toward renewable energy generation has not been studied. Thus, this study aims to utilize the rooftop area of major structures within the Abu Dhabi city for electricity generation using renewable energy technologies. This produced energy is used in planning of electric vehicle charging infrastructure as well toward meeting the Abu Dhabi electricity demand. Economic and environmental considerations are made in addition to technical limitations. Different scenarios have been analyzed to investigate the impact of various parameters on the total cost and overall carbon emission reduction.

2. Electric Vehicles (EVs)

There are mainly four types of electric vehicles: Battery Electric Vehicle (BEV), Plug-in Hybrid Electric Vehicle (PHEV), Hybrid Electric Vehicle (HEV) and Fuel-cell electric vehicle [1,18]. BEVs, also referred to as EVs, are completely powered by the battery and can be charged using an external source of electricity [18]. PHEVs and HEVs, in contrast, are equipped with both driving systems: internal combustion as well as electric drivetrain. PHEVs rely highly on the battery and can be recharged using on-grid electricity whereas HEV batteries are charged entirely by consuming gasoline. Fuel-cell electric vehicles (FCEV) generate power to operate its electric motor, using stored hydrogen and oxygen from the air. Since HEVs and FCEVs do not benefit from an EV charging infrastructure; these vehicles are not considered in this study.

2.1. Specifications

Several automobile manufacturers have invested in the EV industry and have produced vehicles that are already commercially available. Apart from the cost of the vehicle, another important factor in determining what EV to purchase is its driving range. Table 1 shows the ranges and prices of some electric vehicles that are commercially available. It is observed that even the cheapest EVs listed have a range of more than 100 km.

Table 1. Specifications of some electric vehicles (EV) available on the market [19–21].

Model	Manufacturer	Range (km)	Price (USD)	Li-ion Battery Size (kWh)	Type
Cayenne S E	Porsche	23	87,700	10.8	PHEV
i8	BMW	24	150,000	7.1	PHEV
A3 Sportback	Audi	25	39,500	8.8	PHEV
GLE550e	Mercedes Benz	29	66,300	8.7	PHEV
Fusion Energi	Ford	34	31,995	7.6	PHEV
Optima PHEV	Kia	47	35,000	9.8	PHEV
Pacifica PHEV	Chrysler	52	43,090	16	PHEV
Volt	Chevrolet	85	33,220	14	PHEV
i-MiEV	Mitsubishi	100	23,485	16	BEV
Electric Drive	Smart	110	25,750	16.5	BEV
Focus Electric	Ford	122	29,995	23	BEV
Spark EV	Chevrolet	132	25,995	19	BEV
e-Golf	Volkswagen	134	29,815	36	BEV
500e	Fiat	140	32,780	24	BEV
B250e	Mercedes Benz	140	42,375	36	BEV
Soul EV	Kia	150	32,800	30	BEV
Leaf	Nissan	170	29,860	80	BEV
i3	BMW	181	42,275	33	BEV
Bolt	Chevrolet	383	37,496	60	BEV
IONIQ 5	Hyundai	345–448	−47,650	58–77.4	BEV
EV6	Kia	410	44,000–570,000	58–77.4	BEV
Model S	Tesla	435	69,500	85	BEV
Clarity Fuel Cell	Honda	589	60,000	-	FCEV
Nexo	Hyundai	595	55,000	-	FCEV

2.2. Chargers

There are generally three levels of chargers commercially available for electric vehicles (BEV and PHEV) [22]. Each charger is subjected to different technical limitations that affect the time it takes to charge EVs. For example, a level 1 (110 V) charger may take up to 10 h to fully charge a 20 kWh EV battery, whereas level 2 home chargers may fully charge a similar battery in about 5 h. On the other hand, level 3 AC chargers may charge about 80% of a 20 kWh battery in less than half an hour [23,24]. Table 2 shows the specifications of the electric chargers commercially available. One significant element of information is the number of 20 kWh charging cycles each charger can provide in a day. Super-fast DC public chargers have up to 288 cycles, while level 2 AC public chargers have a maximum of 4 cycles. In contrast to charging, options exist where batteries may be swapped with fully charged ones to save time (i.e., 3 min) [20]. However, this alternative requires stocking batteries which may differ from one EV to the other [23]. Moreover, not all EVs are equipped with easily replaceable energy storage systems.

Table 2. EV chargers specifications [24].

Type of Chargers	Level 3			Level 2		
	'Super-Fast DC' Public	DC Public	AC Public	AC Public 3ϕ	AC Public	AC Home
Lifetime (years)	10	10–15	10–15	10–15	10–15	10–15
Load limit (V)	2000	500	400	230	230	230
Power limit (kW)	250	62.5	50	7.3	3.6	3.6
Duration of 20 kWh charge cycle (min)	5	19	24	164	333	333
Maximum number of 20 kWh charging EV/day	288	75	60	8	4	1
Cost incl. installation (US$/kW)	585	1780	2100	1600	1624	325

2.3. Greenhouse Gas (GHG) Emissions

Electric vehicles, in general, faced several economic and technical challenges such as high cost and limited mileage. Due to these factors, they failed to compete with internal combustion engine vehicles and were not able to penetrate the market [4]. However, these factors have now become relatively competitive to those of ICE vehicles. Moreover, the rise in environmental concerns, due to high CO_2 emissions, has driven governments to battle these issues by promoting 'cleaner' alternatives.

Electric cars can emit GHG emissions ranging from 0 to 155 g/km, depending on the fuel type in use [25]. As mentioned earlier, BEVs run entirely on batteries; hence, they do not emit any significant level of direct GHG emissions. However, a comprehensive life-cycle analysis may dictate significant emissions associated with these energy storage systems at the manufacturing stage. Measures may be taken during that process to mitigate or reduce harmful pollutants. A scenario within this study considers life-cycle emissions and depicts results based on these emissions. PHEVs and HEVs, on the contrary, are equipped with internal combustion engines that could emit about 50 to 130 g/km of direct CO_2 emissions, assuming various ratios of electricity and petrol consumption [25].

2.4. Rooftop Assessment

Renewable energy technology has become technically viable such that it can be employed for designing a sustainable energy framework. However, when it comes to rooftop RET, several factors such as shading and orientation affect potential energy output. There are several approaches to account for these limitations. A study was conducted that identified strategies to aid the effective implementation of rooftop solar PV in the United Arab Emirates [17]. Studying mentioned strategies and factors in detail is beyond the scope of this paper, since this work focuses on the feasibility of EV infrastructure based on renewable energy.

3. Methodology

3.1. Superstructure

Figure 1 shows the superstructure that outlines the renewable energy sources considered in this study as well as the energy hubs and electric vehicle chargers.

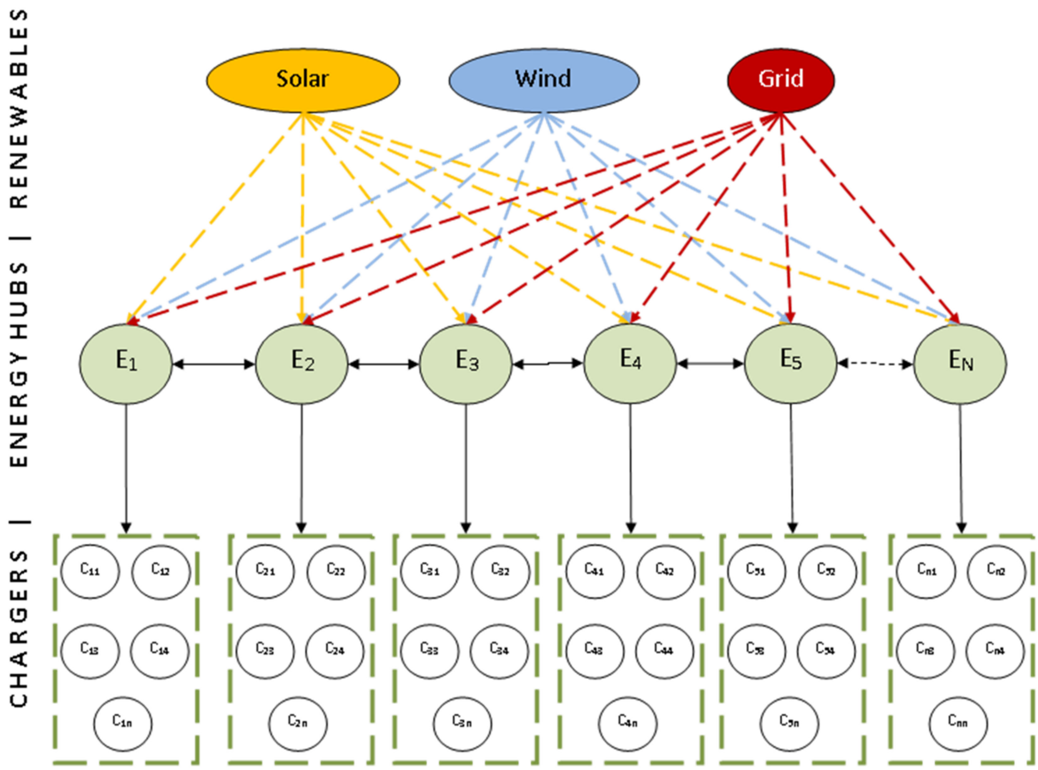


Figure 1. Superstructure of electric vehicle (EV) charging and energy infrastructure.

Electric vehicle (EV) charging stations, powered by energy hubs, will be located in different areas in the city. These locations may include residential sites, work locations, schools, hospitals and other notable places where vehicles may be parked for a significant amount of time. Even though superchargers exist for electric vehicles that could charge the battery for 30 min resulting in the range of 270 km, most vehicles can drive about an additional 18 km per hour when charging with standard chargers (Level 2) [26]. Therefore, Level-2 charging stations would be considered primarily for these locations.

The infrastructure would consist of several charging points across the city in areas where vehicles will be parked for a significant amount of time. These charging points would be powered by energy hubs that will facilitate the integration of renewables. In the superstructure, presented in Figure 1, E represents an energy hub at a particular site (i.e., rooftop) whilst Cij, within the green rectangle, represents each charger connected to this energy hub. In addition to charging electric vehicles, energy generated by these hubs may be used to partially meet the energy demand of Abu Dhabi city. For electricity generation from solar energy, both solar PV and Micro-CSP technologies have been considered in this study. In addition, small wind turbines are used to generate electricity from wind energy.

3.2. Rooftop Area Estimation

As mentioned earlier, there are several factors that affect rooftop energy potential including solar irradiance, direction of tilt of solar roof and rooftop area. In order to calculate the rooftop areas, different tools can be utilized for processing images of aerial maps, such as watershed segmentation, template matching, level set theory, and other LiDAR-based tools. However, as stated, the aim of the research to determine the feasibility of rooftop RET is in line with the designing of EV charging infrastructure. Thus, MATLAB Image Segmenter 7.0 and Image Region Analyzer v1.39 tools were simply used to detect and analyze the rooftop area from map images. A detailed study of other relevant factors is beyond the scope of this research. The satellite images of the studied area were captured using Google maps. In this section, the application of these tools is demonstrated.

Abu Dhabi is the largest emirate that accounts for about 87% (67,640 km^2) of the United Arab Emirates by land. However, the Abu Dhabi city comprises 972 km^2 with a population of about 1.5 million as of 2013 [27]. Moreover, the city is designed in blocks of localities. A satellite image of each block of structures is captured, as seen in Figure 2, as long as adequate details of each building can be observed. The image is then segmented where a threshold is applied to it. Based on the detail of the image, an appropriate level of threshold is applied, resulting in an image where the rooftop is made distinct from other noises (i.e., non-rooftop area), as evident from the last image in Figure 3.

Figure 2. Map image showing the aerial view of structures within the sample region considered in Abu Dhabi city.

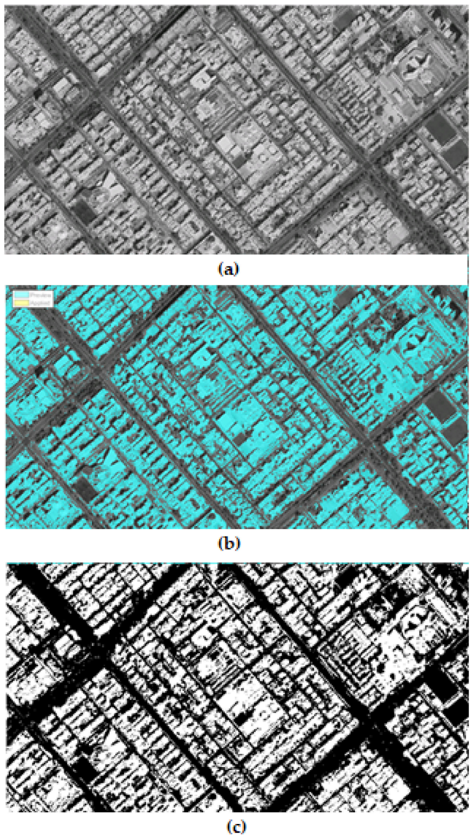
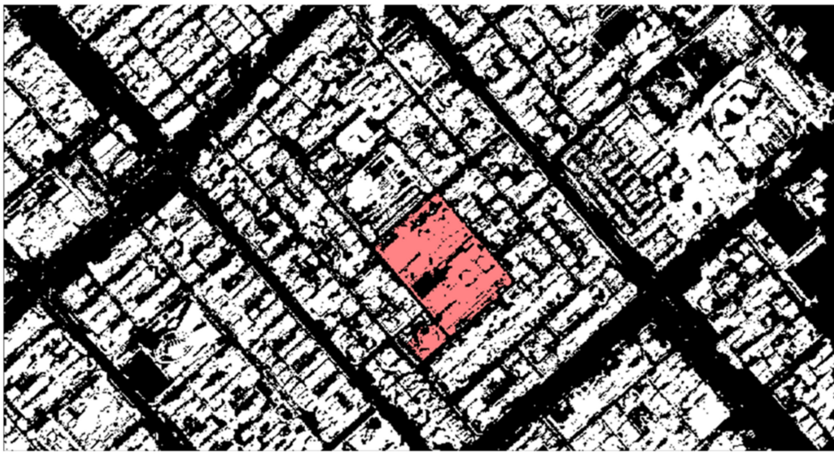


Figure 3. (**a**) Pre-processing, (**b**) threshold adaptation, and (**c**) post-processing images depicting the rooftop area of buildings in the sample region.

Post-threshold adaptation, the image is transformed such that the identified areas within it can be analyzed quantitatively. An area, based on the scale of the transformed image and its pixels, is calculated, as shown in Figure 4. The actual area of the rooftop is, then, obtained, using the scale at which the image was captured.



Rooftop	Area (m^2)
1	49,559
2	26,292
3	22,122
4	21,380
5	17,418
6	16.464
7	14.466
8	13,280
9	12,821
10	12,290
11	11,193
12	10,827
13	10,725
14	10,686
15	10,549
16	9688
17	8747
18	8564
19	8423
20	7774
21	7137
22	6926
23	6567
24	6292
25	6110
26	6093
27	5863
28	5201
29	4940
30	4871
31	4804

Figure 4. Rooftop area calculation for the sample region within Abu Dhabi city in m^2.

3.3. Model Formulation

3.3.1. Objective Function

The main purpose of investing in RET is to mitigate carbon emissions. Hence, the main objective function, g, is to develop based on the amount of CO_2 emissions produced from energy consumption (g^{Energy}) and utilization of electric/ICE vehicles (g^{Veh}), as seen from Equation (1). g^{Energy}, as seen in Equation (2), is calculated by multiplying the amount of electricity production from each energy source with the associated CO_2 emissions per unit of electricity. g^{Veh}, expressed using Equation (3), considers the number of different types of vehicles, the emissions generated from them per km and the average mileage these vehicles have over the considered timeframe. For example, if the annual emissions reduction is studied, the average mileage over a year may be considered.

$$g^T = g^{Energy} + g^{Veh} \tag{1}$$

$$g^{Energy} = \sum_t \sum_s \sum_j P_{s,j,t} CO_{2_{s,j}} \tag{2}$$

$$g^{Veh} = n^{ICE} g^{ICE} km^{ICE} + n^{EV} g^{EV} km^{EV} + n^{PHEV} g^{PHEV} km^{PHEV} \tag{3}$$

On the other hand, another objective function, the total economic cost (z), employing respective renewable energy and electric vehicle charging technologies, is evaluated using Equation (4). These two objective functions are formulated in order to study different scenarios as well as develop a Pareto front to identify outcome at various stages. In order to develop this frontier, the modified epsilon constraint method is employed. The total economic cost comprises of energy generation cost (CE^T) as well as cost of electric vehicle charging infrastructure (CI^T).

$$z = CE^T + CI^T \tag{4}$$

The cost of energy includes the capital and operating cost as well as fuel costs if required by the energy generation plant. Since electricity is the only output energy vector considered in this study, the cost of energy is calculated using the levelized cost of electricity (LCOE) values of different energy generation technologies. This levelized cost of electricity incorporates the capital, operation, and maintenance costs of utilizing a particular energy generation technology, when considering the tax rate, discount rate and other imperative factors. The cost of EV charging infrastructure comprises capital costs and operating and maintenance costs of charging infrastructure, as seen in Equation (6). The capital cost incurred at energy hub "s" at time "t" is represented using Equation (7). In this study, the total cost of chargers (CCH_s^T) installed at energy hub s is amortized considering a constant discount rate (D) and a similar lifetime for all chargers (N_{CH}). Moreover, Equation (8) represents the calculation of total cost of charges, where CCH_s^T is equal to the total number of each type of charger (nCH_s) installed at energy hub s multiplied by the cost (CCH) of corresponding chargers, respectively. The cost of each charger includes the cost of equipment, parts for installation and labor costs. In this work, we consider three types of level 2 chargers and three models of level-3 ones, as mentioned in Table 2. Here, "21" refers to level-2 charging AC public 3ϕ, while "22", and "23" refer to AC public and AC home, respectively."31" refers to Level-3 DC superfast charging DC public, while "32" and "33" refer to DC public, and AC public, respectively.

$$CE^T = \sum_s \sum_t \sum_j \left(LCOE_j \times P_{s,j,t} \right) \tag{5}$$

$$CI^T = \sum_s \sum_t \left(CCI_{s,t}^{cap} + CCI_{s,t}^{O\&M} \right) \tag{6}$$

$$CCI_{s,t}^{cap} = \frac{CCH_s^T}{\frac{(1+D)^{N_{CH}}-1}{D(1+D)^{N_{CH}}}} \tag{7}$$

$$CCH_s^T = \left(nCH_s^{21}CCH^{21} + nCH_s^{22}CCH^{22} + nCH_s^{23}CCH^{23} + nCH_s^{31}CCH^{31} + nCH_s^{32}CCH^{32} + nCH_s^{33}CCH^{33} \right) \tag{8}$$

3.3.2. Energy Hub

The energy hub, in this study, is modeled without a storage technology, using the following equation. Multiple input energy vectors and a single output energy (i.e., electricity) were considered.

$$L_{s,t} = \sum_j C_j P_{s,j,t} \tag{9}$$

The load ($L_{s,t}$) by each energy hub s at time t is met using electric power $P_{s,j,t}$, converted from energy vector j, and storage technology, q. In order to allow the networking of energy hubs, this load is defined by the demand of the energy ($Dem_{s,t}$) and the energy transfered ($T_{s,b,t}$) from/to other energy hubs, provided a connection exists between them with the transmission factor of ($\alpha_{s,b}$), as seen in Equation (10).

$$L_{s,i,t} = Dem_{s,t} + \sum_{b \in S-s} T_{s,b,t}\alpha_{s,b} \tag{10}$$

$Dem_{s,t}$ mainly constitutes the electric chargers connected to this energy hub. Since this information is readily available, this demand can be simulated based on the number of electric vehicles that have penetrated the transport industry, as a percentage of total cars. In one the observed scenarios, this is extended to the region's electricity demand.

3.3.3. Renewable Energy Technology

The yield of electric power from each RET is subjected to technical limitations. Electricity generated from solar photovoltaic (PV) technology is defined by Equations (11) and (12), whereas electricity produced from concentrated solar power (CSP) technologies is defined by Equations (13) and (14). Energy derived from wind turbines is expressed using Equations (15) and (16). Several other formulations exist in the literature that consider additional parameters for added accuracy. In this paper, the area required for each type of RE technology, denoted by $Land$, is defined by Equations (17)–(19). GHI and DNI, in Equations (11) and (13), are the global horizontal irradiance and direct normal irradiance, respectively. PR is the performance ratio while CF is the capacity factor of deployed technology. N represents the number of units, $Power$ represents the power output of each unit, and h represent operational hours of this unit. In Equation (14), ρ_{air} is the density of air, A_{swept} is the area swept by the blades of the wind turbine and ws is the wind speed. Other parameters, such as $Area_{PV-module}$, $Aperture_{SCA}$, $length_{SCA}$, represent the area of each PV module, aperture and length of each solar collector assembly, as the terms suggest, respectively.

$$P_{s,PV,t} \leq Land_{s,PV} \times GHI_t \times PR_{PV} \tag{11}$$

$$\sum_t P_{s,PV,t} = N_{s,PV-module} \times CF_{PV} \times Power_{PV-module} \times PR_{PV} \times h_{PV} \tag{12}$$

$$P_{s,CSP,t} \leq Land_{s,CSP} \times DNI_t \times PR_{CSP} \tag{13}$$

$$\sum_t P_{s,CSP,t} = N_{s,CSP-SCA} \times CF_{CSP} \times Power_{CSP-SCA} \times PR_{CSP} \times h_{CSP} \tag{14}$$

$$P_{s,WT,t} \leq Land_{s,WT} 0.5 \rho_{air} A_{swept} ws_{s,t}^3 h \tag{15}$$

$$\sum_t P_{s,CSP,t} = N_{s,WT} \times CF_{WT} \times Power_{WT} \times h_{WT} \tag{16}$$

$$Land_{s,PV} = 1.5 \times Area_{PV-module} \times N_{s,PV-module} \tag{17}$$

$$Land_{s,CSP} = 4 \times Aperture_{SCA} \times length_{SCA} \times N_{s,CSP-SCA} \tag{18}$$

$$Land_{s,WT} = 5 \times rotor_{WT}{}^2 \tag{19}$$

The factors 1.5 and 4 in Equations (17) and (18) account for the structure of these technologies when they are mounted. In Equation (19), *rotor* refers to the rotor diameter of the blades of the wind turbine. Each wind turbine needs to be placed approximately 5 rotor diameters apart in order to avoid the wake effect. The sum of the required spaces for each RET is constrained by the maximum roof area available at energy hub sites.

$$\sum_s Land_{s,PV} + Land_{s,CSP} + Land_{s,WT} \leq Area_s^{max} \tag{20}$$

3.3.4. EV Charging

As part of the EV charging infrastructure, parking spaces need to be designated for electric vehicles where chargers are installed. Thus, each charger occupies a parking space. The parking ratio, ratio of parking spaces to building area, is used to constraint the available EV parking spaces. Equations (21) and (22) are used to define the minimum and maximum parking spaces available at each energy hub site. These conditions are necessary for the promotion of EVs whilst accommodating ICE vehicles in the transition period. Level 31 chargers are the 'Super-fast DC' public chargers that are mainly perceived as chargers at dedicated EV charging stations. Therefore, the number of level 31 chargers at these stations is subjected to the constraint presented in Equation (23). At these stations, EVs would stopover and recharge in a similar manner as ICE vehicles would refuel at gas stations. nch, in the equations below, represents the number of each type of charger required at each energy hub. For example, nch_s^{21} is the number of level 21 chargers that are installed at energy hub s. $Park^{min}$ and $Park^{max}$ are the minimum and maximum allowable parking ratio of the entire parking lot that is dedicated for electric vehicle charging. $Areamax$ is the total number of parking spaces at a particular energy hub.

$$nch_s^{21} + nch_s^{22} + nch_s^{23} + nch_s^{32} + nch_s^{33} \geq Park^{min} \times Spots(s) \tag{21}$$

$$nch_s^{21} + nch_s^{22} + nch_s^{23} + nch_s^{32} + nch_s^{33} \leq Park^{max} \times Spots(s) \tag{22}$$

$$nch_{min}^{31} \leq nch_s^{31} \leq nch_{max}^{31} \tag{23}$$

In this study, rooftops of structures involving hospitals, high-rise buildings, schools and malls have been considered where vehicles are parked for a considerable amount of time. Not all chargers may be appropriate for each type of site. Thus, the types of chargers not suitable for a particular site need to be eliminated, as shown below.

$$nch_s^{23} + nch_s^{31} + nch_s^{32} + nch_s^{33} = 0 \ \ \forall s \in school \tag{24}$$

$$nch_s^{23} + nch_s^{31} = 0 \ \ \forall s \in mall$$

$$nch_s^{23} + nch_s^{31} + nch_s^{32} = 0 \ \forall s \in hospital$$

$$nch_s^{31} + nch_s^{32} = 0 \ \ \forall s \in building$$

$$nch_s^{21} + nch_s^{22} + nch_s^{23} + nch_s^{32} + nch_s^{33} = 0 \ \ \ \forall s \in station$$

The number of electric vehicles that can be charged by each type of charger needs to be constrained by values that are dictated by feasibility and the technical limitations of the type of charger. For example, as seen from Table 2, the maximum number of 20 kWh EVs that can be charged by a level-21 charger (AC public 3ϕ) is 8 in 24 h. They may not be feasible to use at sites where parking time is restricted to a couple of hours. On the other hand, if charging stations with level-31 chargers are studied, a minimum number of vehicles needs to be considered that will be serviced by these stations. Thus, the following constraints are imposed (Equation (25)).

$$Nev_{s,min}^{21} \ \leq \ Nev_{s,t}^{21} \leq \ Nev_{s,max}^{21} \tag{25}$$

$$Nev_{s,min}^{22} \ \leq \ Nev_{s,t}^{22} \leq \ Nev_{s,max}^{22}$$

$$Nev_{s,min}^{23} \ \leq \ Nev_{s,t}^{23} \leq \ Nev_{s,max}^{23}$$

$$Nev_{s,min}^{31} \ \leq \ Nev_{s,t}^{31} \leq \ Nev_{s,max}^{31}$$

$$Nev_{s,min}^{32} \ \leq \ Nev_{s,t}^{32} \leq \ Nev_{s,max}^{32}$$

$$Nev_{s,min}^{33} \ \leq \ Nev_{s,t}^{33} \leq \ Nev_{s,max}^{33}$$

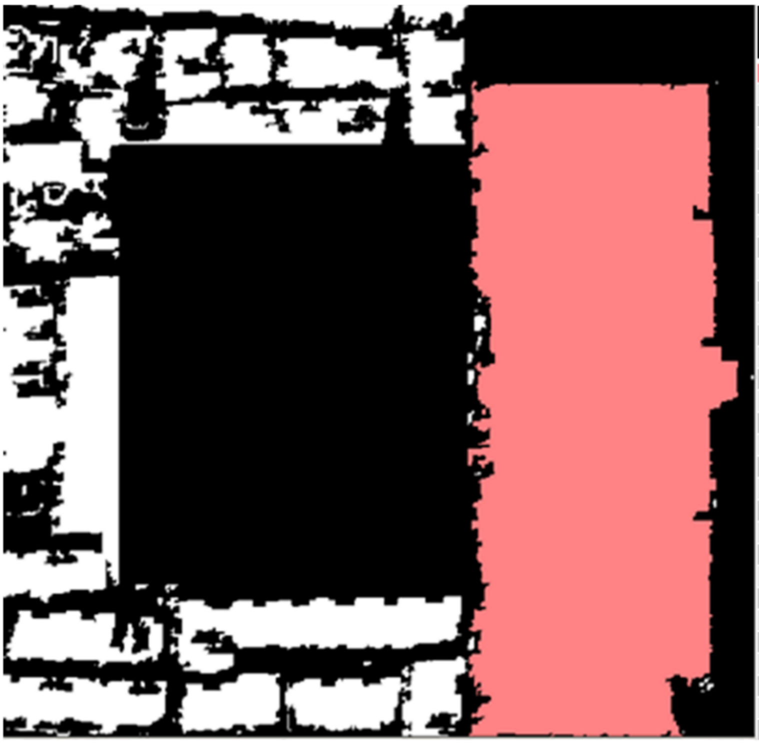
4. Results and Discussion

In this section, the results from the rooftop area estimation analysis are presented. Additionally, various scenarios, involving EV demand, Abu Dhabi electricity demand and life-cycle emissions of RET and EVs, are presented. Impact of different EV penetration within the transport sector on annual costs and carbon emissions is analyzed and discussed.

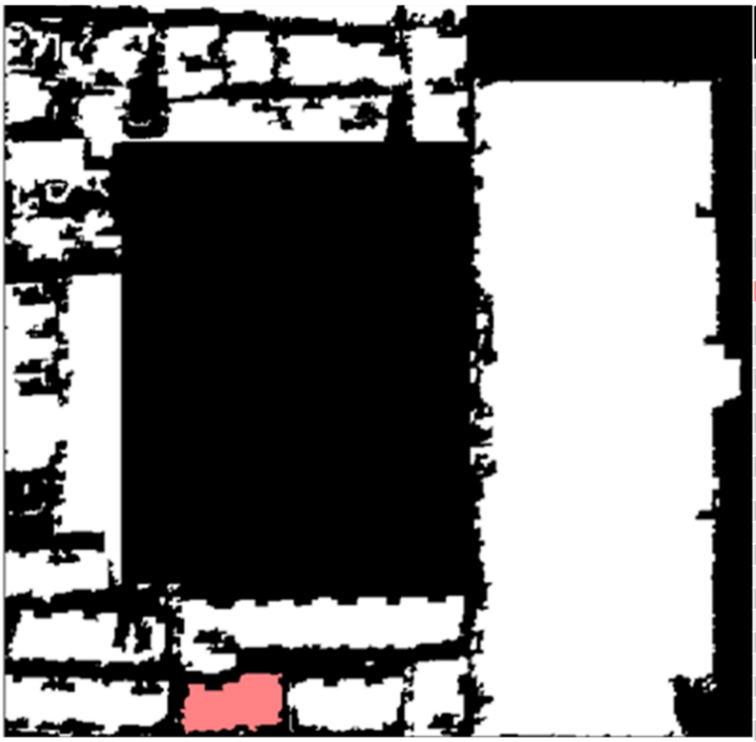
4.1. Rooftop Area

In this study, the rooftop area of major structures within Abu Dhabi city was determined using the tools discussed in the earlier sections. The area yielded from this method was compared to the actual rooftop area of the structures. Figure 5 shows the structures used with their respective unscaled areas, which were used for comparison.

After scaling the areas, the average percentage difference between the actual and calculated areas, based on MATLAB tools, was found to be 18.55%. This area accounts for the entire rooftop, including rooftop area covered with installations such as HVAC equipment. In a study conducted by Koo et al. [28], the average rooftop area available for RET installation was found to be 61.2% of the building area. Thus, this value is considered in this study, as well, when considering RET technologies.



Rooftop	Area (m²)
1	42,919
2	7686
3	5634
4	3794
5	3769
6	2884
7	2433
8	2082
9	1875
10	1638
11	1293
12	889
13	842
14	625
15	39
16	31
17	29
18	28
19	22
20	22
21	17
22	17
23	16
24	16
25	15
26	15
27	14
28	13
29	12
30	12
31	11



Rooftop	Area (m²)
1	42,919
2	7686
3	5634
4	3794
5	3769
6	2884
7	2433
8	2082
9	1875
10	1638
11	1293
12	889
13	842
14	625
15	39
16	31
17	29
18	28
19	22
20	22
21	17
22	17
23	16
24	16
25	15
26	15
27	14
28	13
29	12
30	12
31	11

Figure 5. Example of unscaled areas of two structures used to calculate the percentage difference between the actual and detected rooftop area.

4.2. Scenario 1: Considering Renewable Energy Technologies with EV Demand Only

In this scenario, rooftop renewable energy technologies are exclusively utilized to meet EV charging demand. The annual cost and CO_2 emissions realized for 10% EV penetration, for different energy generation configurations, have been recorded in Figure 6. The Pareto front, in this case, is denoted by the green dotted line which is generated using the epsilon constraint method, considering the objective function pertaining to total carbon emissions

(g^T) and total economic cost (z). The electricity produced by each of the technologies as well as the RET equipment installed is noted in Table 3.

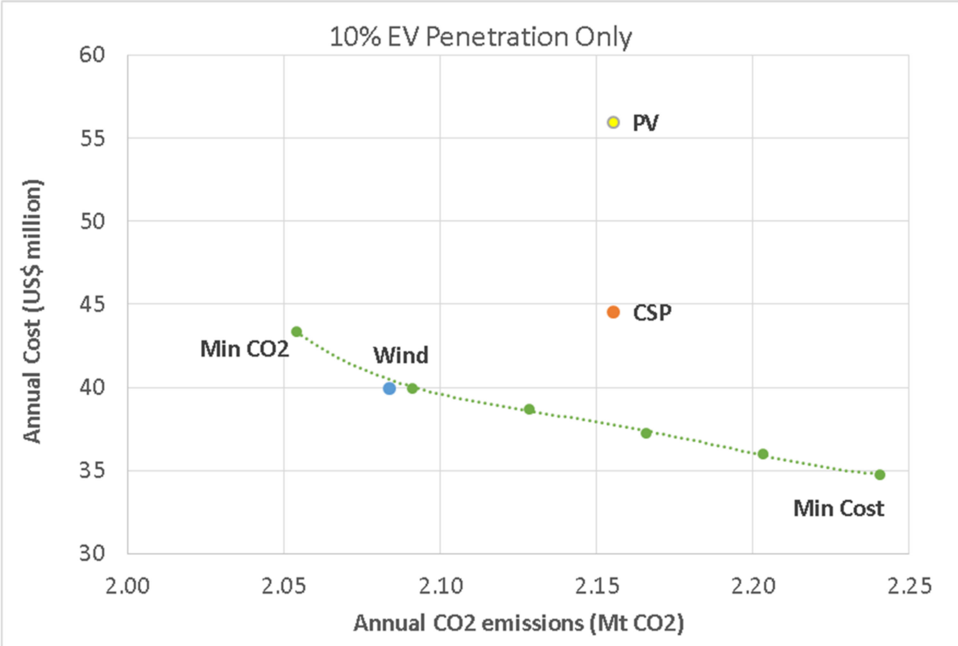


Figure 6. Tradeoff between annual cost and carbon emissions for each case study (different energy generation configurations) for considering 10% EV charging demand.

Table 3. SCA: solar collector assembly, WT: wind turbines, CSP: concentrate solar power.

Case	**Power Generated-GWh**				**Number of Each Technology**		
	PV	**CSP**	**Wind**	**Grid**	**PV Module**	**SCA**	**WT**
Min Cost	0.00	0.00	0.00	277.81	0	0	0
Min CO_2	0.00	44.31	233.41	0.09	0	79,489	131,578
PV only	126.88	0.00	0.00	150.93	2,781,672	0	0
CSP only	0.00	126.88	0.00	150.93	0	227,607	0
Wind only	0.00	0.00	233.41	44.40	0	0	131,578

Case studies are as follows:

Case 1: best economic option (min Cost);
Case 2: best environmental option (min CO_2);
Case 3: to consider only PV and grid for power generation (PV only);
Case 4: to consider only Concentrate Solar Power (CSP) for power generation and grid (CSP only);
Case 5: to consider only wind and grid for power generation (Wind only).

The share of electricity generation for each energy generation technology and the number of RET equipment installed for each case study are introduced in Figure 6.

As evident from Figure 6, the least amount of emissions annually are observed for the 'Min CO_2' case where almost all electricity demand is met via renewable energy technologies, mainly through wind energy (84%). In this case, 131,578 small wind turbines and 79,849 micro-CSP solar collector assemblies are installed. In contrast, the least annual cost for energy generation and EV charging infrastructure yields when all electricity is purchased from the local electrical grid. The difference in annual costs, as evident from Figure 6, for the two scenarios (i.e., min cost and min CO_2) is $8.59 million. In addition, the reduction in emissions observed, by employing RET, is about 187 ktonnes CO_2, annually. This cost roughly translates to $46 per ton of CO_2 mitigated. In comparison to the average carbon capture and storage (CCS) cost from point source, as reported by Rubin et al. [29], the cost appears to be $8 cheaper per ton CO_2. The reported cost for utilizing RET also includes mitigating emissions that would, otherwise, be emitted to ambient air. Capturing these emissions, from ambient air, would be more difficult and result in higher costs.

If opting for a single RET, investing in wind energy would be more economically and environmentally beneficial, as indicated by the results in Figure 6. Generating electricity from wind is cheaper than generation through solar energy. Furthermore, solar PV and CSP, without energy storage systems, are only able to meet about 46% of the given EV demand. The installation of storage system will allow these technologies to meet further demand; however, this will result in higher costs.

4.3. Scenario 2: Considering Renewable Energy Technologies with EV + Abu Dhabi City Demand

In this scenario, rooftop RET installations were utilized in order to meet electric vehicle energy demand as well as Abu Dhabi city electricity consumption. The hourly electricity demand for each month is shown in Figure 7. At least 80% of the total energy demand of buildings is attributed toward cooling systems [30]. The average afternoon temperature in Abu Dhabi ranges from 24 to 42 °C throughout the year. Thus, cooling systems are utilized all year around. As observed in Figure 7, the highest hourly electricity consumption in a day occurs at about 4 PM, whereas the highest monthly electricity consumption takes place in July, reflecting the increased usage of cooling systems in warm weather.

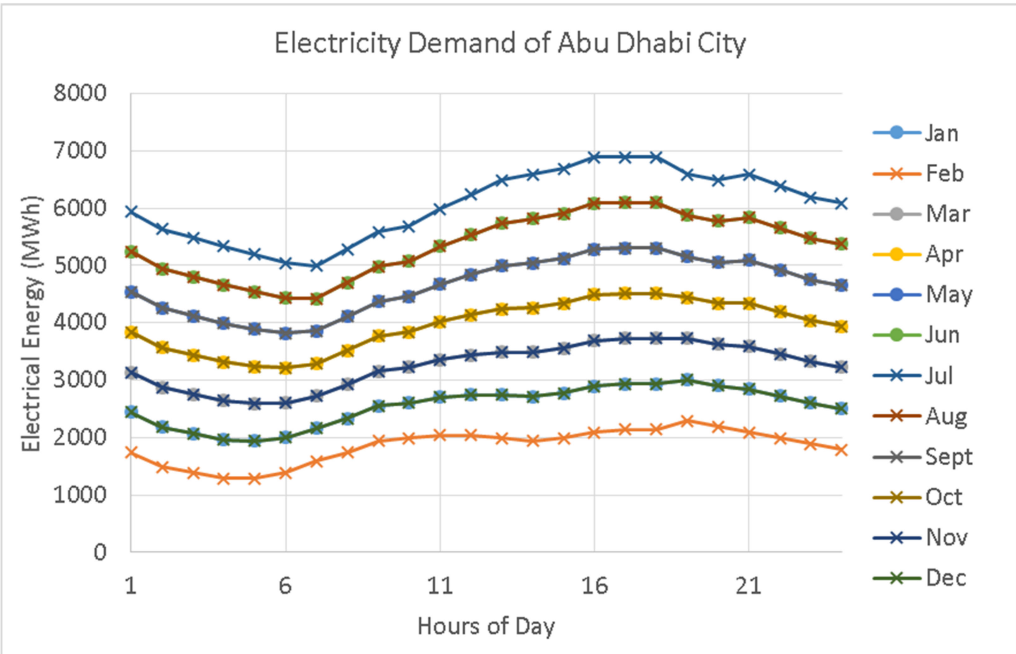


Figure 7. Hourly electricity demand of Abu Dhabi city for each month [31].

Case studies are as follows: Case 1: best economic option (min Cost), Case 2: best environmental option (min CO_2), Case 3: to consider only PV and grid for power generation (PV only), Case 4: to consider only Concentrate Solar Power (CSP) for power generation and grid (CSP only), Case 5: to consider only wind and grid for power generation (Wind only).

Figure 8 shows the cost incurred and the carbon emissions generated for the entire year when using different energy configuration. With the minimum carbon emissions scenario, about 730 ktonnes of CO_2 are mitigated, at an additional cost of $24 million, as compared to the minimum cost scenario where all electricity is purchased from the electrical grid, as evident from Table 4. Unlike the previous case (i.e., EV demand only), most of the electricity consumed is purchased from the electrical power grid. About 3.12% of the electricity is generated via small wind turbines. A small contribution of about 23.3 MWh of electricity is made via 511 solar PV modules installed. In this study, the considered micro-CSP technology was found to be effective for sites with at least 2700 m^2 available area. Moreover, dedicated charging stations with level-31 chargers were only allowed solar PV technology. This restriction was placed, as these stations are mainly surrounded with high-rise structures where small wind turbines may not prove to be efficient. Therefore, despite solar micro-CSP being a more economic option, the model suggests the installation of PV modules. For the cases of PV only and CSP only, the latter was observed to produce 16 GWh more electricity than the former.

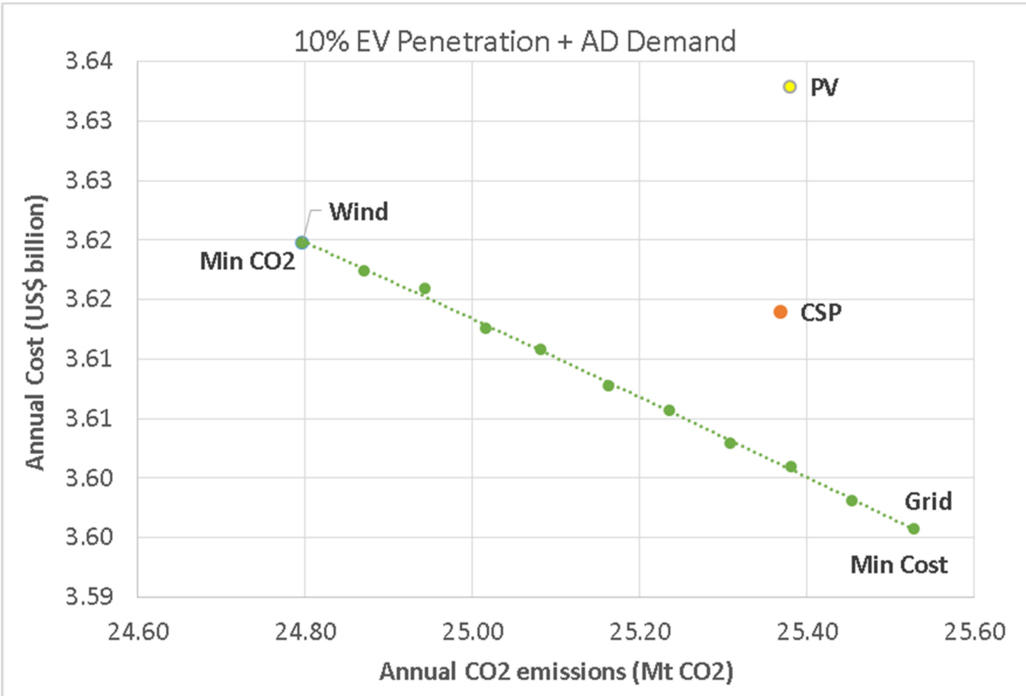


Figure 8. Trade-off between annual cost and CO_2 emissions in different case studies for meeting both 10% EV and Abu Dhabi city electricity demand.

Table 4. The share of electricity generation for each energy generation technology and the number of RET equipment installed for each case study introduced in Figure 8.

Case	Power Generated—TWh				Number of Each Technology		
	PV	CSP	Wind	Grid	PV Module	SCA	WT
Min Cost	0.00	0.00	0.00	34.90	0	0	0
Min CO_2	~0	0.00	1.09	33.81	511	0	611,984
PV	0.22	0.00	0.00	34.68	4,824,427	0	0
CSP	0.00	0.24	0.00	34.66	0	424,890	0
Wind	0.00	0.00	1.09	33.81	0	0	611,984

SCA: solar collector assembly, WT: wind turbines, CSP: concentrated solar power.

Another observation is made when comparing the two cases, meeting EV demand only and meeting EV + Abu Dhabi city demand. It is observed that in this case, more energy is generated via renewable energy technologies even though the same rooftop area is available. This is because excess energy is not allowed by the model since no energy storage systems are considered. Therefore, in the previous case, electricity generated via wind turbines is restricted by the demand of electric vehicles. Even if more wind speed was observed during a particular hour, an amount of electricity that suffices the hourly EV demand is only generated. In this case, on the contrary, energy generated by wind turbines is used to meet Abu Dhabi (AD) demand as well. This demand is considerably much higher than the required EV demand. Consequently, the electricity generated is mainly dictated by the available wind speed rather than electricity demand. The same situation occurs for solar energy technologies. Electric power generated during sunlight hours contributes toward meeting the overall demand. Therefore, a much higher contribution of solar energy generated electricity is observed. In addition, the optimality region, lying between min CO_2 and min cost, appears to be a straight line, since the demand is very high as compared to RET-produced electricity.

4.4. Scenario 3: Considering Life-Cycle Emissions of EVs

In this scenario, we study renewable energy technologies with EV demand while considering their life-cycle emissions. The United Arab Emirates takes pride in having the largest industrial battery plant in the Gulf. Moreover, it has already invested significantly in renewable energy and plans to increase the share of renewable energy. In addition, the UAE plans to explore several manufacturing industries in the future [32]. It is possible that the UAE may consider manufacturing of RET equipment and electric vehicles parts, locally, as it currently does for some ICE vehicles. Hence, life-cycle emissions of RET and EVs are accounted for in this scenario. The results obtained are depicted in Figure 9.

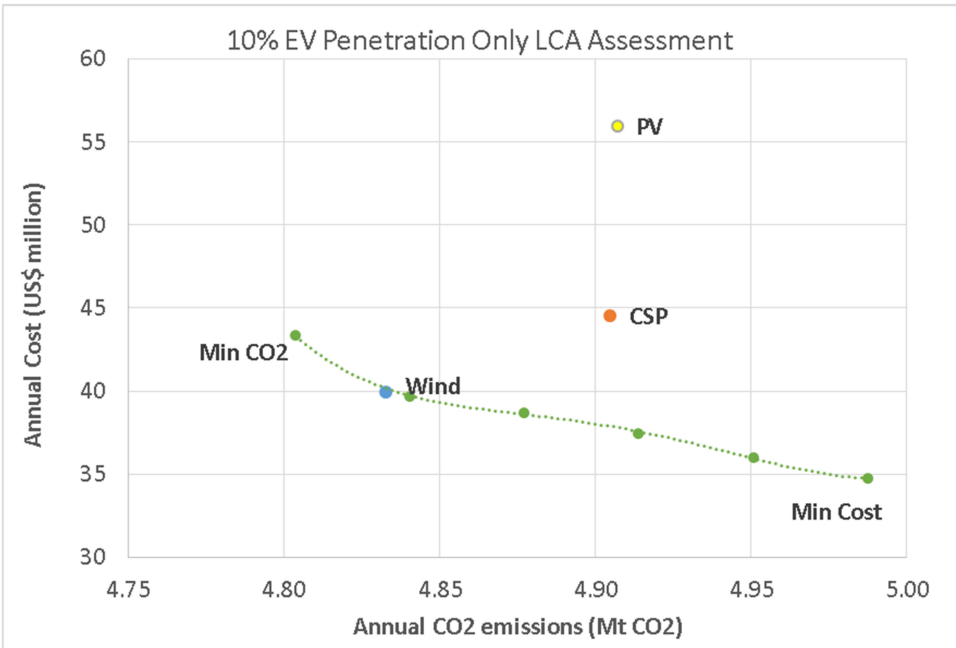


Figure 9. Trade-off between annual cost and CO_2 emissions in different case studies for meeting 10% EV whilst considering life-cycle emissions using different energy configurations.

The general outlook appears to be very similar to the scenario where EV demand is only studied. However, comparing the minimum carbon emissions scenario with that of minimum cost, about 183 ktonnes of CO_2 is mitigated annually at a cost of $8.59 million. In this particular case study, life-cycle emissions of both ICEs and EVs were considered. Since the percentage of EV penetration is considered, the resulting emissions will be offset. Nevertheless, to investigate the true impact, a detailed study on this aspect alone needs to be conducted.

4.5. Sensitivity Analysis—Market Share of EVs

In the previous scenarios, the impact of 10% EV penetration was assumed, and annual costs and emissions were studied. In this case, a different market share of EV penetration is studied when meeting EV demand only and coupled EV-Abu Dhabi demand. Figures 10 and 11 show the results obtained for each of these cases, respectively.

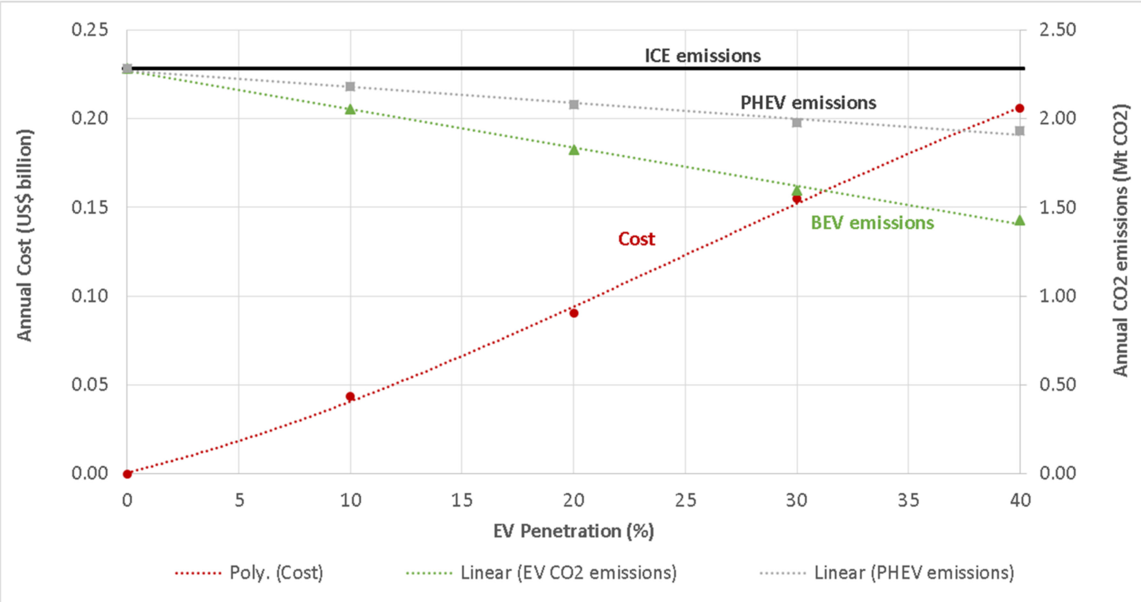


Figure 10. Trade-off between annual cost and carbon emissions for different EV penetration ratios when meeting EV electricity demand.

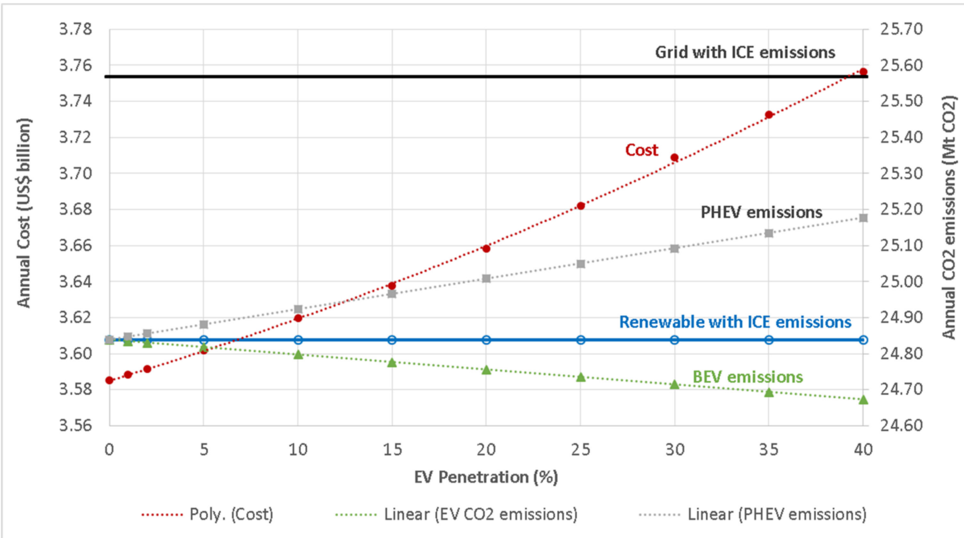


Figure 11. Trade-off between annual cost and carbon emissions for different EV penetration ratios when meeting both EV and Abu Dhabi electricity demand.

As observed in Figure 10, as the EV penetration increases, the annual carbon emissions mitigated increases for both, BEVs and PHEVs. Moreover, the annual cost appears to increase as a result of more RET and EV charging infrastructure installed. On the other hand, in the case of EV plus Abu Dhabi demand, the emissions generated by BEV decreases as more battery electric vehicles penetrate the transport sector. However, the annual emissions when considering PHEVs increases with increasing EV penetration. This is because, in the second case, EV charging demand is mainly met through electricity purchased from the grid. PHEVs do reduce ambient air emissions, but they increase the point sources emissions. However, due to increasing EV charging demand, the amount of electricity consumed from the grid, eventually produced through fossil fuels, increases. This leads to an increase in point source emissions from power plants. For the PHEVs option, the construction of further renewable energy projects may be planned to increase the RE share to the grid, or CCS technology may be utilized to mitigate these point source emissions.

As evident from Figure 12, as the EV penetration ratio increases, the required number of chargers increases as well. However, the number of chargers does not exceed a maximum of 108,810 for this case study. Since all chargers occupy a parking space, each charger represents an available EV parking space. These parking spaces are restricted by a minimum and maximum, as indicated in Equations (20) and (21). Therefore, a different type of charger is selected rather than adding a parking space. Initially, at a low EV penetration ratio, the results suggests the operation of dedicated charging stations where level-31 chargers ('Super-fast DC' public) are installed. Once the maximum is reached for these dedicated stations (i.e., 10 chargers per station), level-23 (AC home) chargers are installed. Once 20% of the transport sector comprises EVs, level-32 (DC public) and level-22 (AC public) are utilized. However, at 25%, the maximum parking spaces allocated for EVs is reached. Thus, level-23 (AC home) chargers are compromised with level-21 (AC public 3ϕ) chargers. This trend continues until no more EV penetration can occur with the same designated parking ratio, as stated in Equation (21). At that stage, since EVs would have penetrated most of the transport industry, the parking ratio can be increased in order to facilitate more chargers.

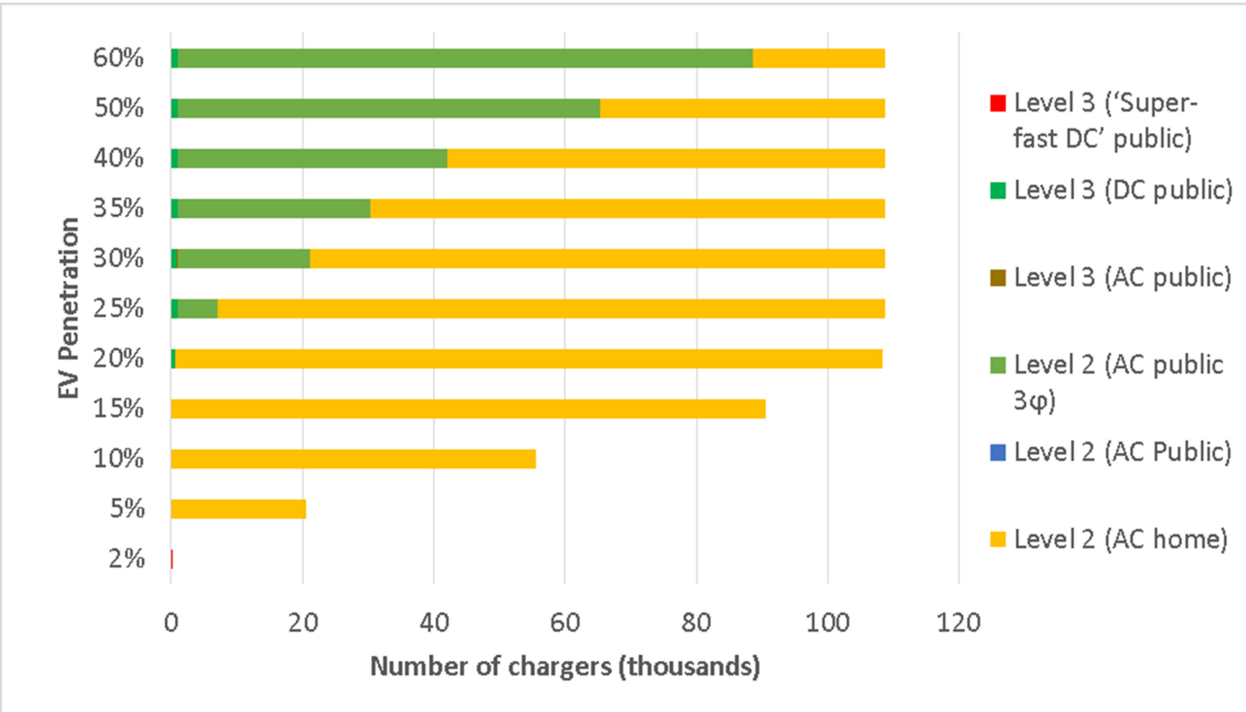


Figure 12. Number of each type of EV chargers installed for each ratio of EV penetration.

5. Conclusions

In this research work, a comprehensive study was carried out to determine the rooftop renewable energy potential for the optimal designing of an EV charging infrastructure. Using MATLAB segmentation and region analyzing tools, the average percentage difference between the actual and calculated rooftop areas was found to be 18.55%. We developed a mathematical modeling framework to optimally design Renewable Energy Technologies (RET) in the presence of electric vehicle demand using a multi-energy hub approach; two competitive objectives including the economic cost of the system and CO_2 emissions are considered. Three scenarios are examined to assess the potential of RET to meet the EV demand along with the Abu Dhabi city one, while considering the life-cycle emission of RET and EV systems.

In scenario 1 (with EV demand only), the deployment of wind turbines and CSP technology for electricity generation resulted in least emissions. Yet, minimum economic cost was realized when electricity was purchased completely from the grid. In scenario 2 (with both EV and Abu Dhabi city demand), the grid majorly contributed in meeting electricity demand, whilst wind technology was considered to meet a part of this demand. In scenario 3 (with life-cycle emissions of RET and EV systems), wind technology was found to produce the least life-cycle emissions whilst realizing the least economic cost compared to other renewable energy technologies.

Sensitivity analysis on the market share of EVs was carried out to show that battery-based electric vehicles can reduce environmental impact with an increased EV market share. The number and type of chargers to be utilized under each scenario was also determined with increasing EV penetration.

Future work will be on the consideration of other storage systems in each energy hub along with the stochastic modeling of EV demands. Moreover, the characteristics of the bidirectional energy source of BEV can be reflected in future research.

Author Contributions: S.T.T.: formal analysis, investigation and datd curation; A.A.: software, resources and project administration; A.M.: validation and writing—review & editing; A.E.: writing—review & editing, superivision and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Details regarding database can be made accessible upon reasonable request to the authors.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Indices	Explanation	Unit
i	Type of output energy carrier	
j	Type of input energy carrier	
t	Time period	
s, b	Particular energy hub	
Sets		
I	Set of output energy carriers	
J	Set of input energy carriers	
S	Set of energy hubs	
T	Time period (30 years)	
Parameters		
A_{swept}	Area swept by a blade in wind turbine ($\pi rotor_{WT}^2$)	m^2
$Aperture_{SCA}$	Aperture of a solar collector assembling in CSP technology	m
$Area_{PV-Module}$	Area of a photovoltaic (PV) module	m^2
$Area^{max}$	Maximum area allocated for energy generation technologies installations at a particular energy hub	m^2

C	Coupling matrix	
CCH	Cost of a particular electric vehicle charger	\$
CF	Capacity factor of a particular energy generation technology	
CO_2	Carbon emissions associated with each energy generation technology	gCO_2/kWh
CRF	Capital Recovery Factor	
D	Discount rate	%
D_{PV}	Depreciated present value	
DNI	Direct Normal Irradiance exposed to CSP technology	W/m^2
g^{ICE}	Emissions associated with each internal combustion engine (ICE) vehicle for each km of distance traveled	gCO_2/km
g^{EV}	Emissions associated with each battery-powered electric vehicle (EV) for each km of distance traveled	gCO_2/km
g^{PHEV}	Emissions associated with each plug-in hybrid electric vehicles (PHEV) for each km of distance travelled	gCO_2/km
km^{ICE}	Average distance travelled by internal combustion engine (ICE) vehicles	km
km^{EV}	Average distance travelled by battery-powered electric vehicles (EV)	km
km^{PHEV}	Average distance travelled by plug-in hybrid electric vehicles (PHEV)	km
$LCOE$	Levelized cost of electricity for a particular energy generation technology	\$/kWh
Nev_{max}	Maximum number of electric vehicles that can be charged using a particular electric vehicle charger	
$Park^{min}$	Ratio of minimum parking spaces allocated for charging electric vehicles at a particular energy hub	
$Park^{max}$	Ratio of minimum parking spaces allocated for charging electric vehicles at a particular energy hub	
$Power$	Power rating of a particular energy generation technology	W
PR	Performance ratio of a particular energy generation technology	
$rotor_{WT}$	Rotor diameter of the blades of single wind turbine	
T	Tax rate	%
$Spots$	Total parking spaces available at a particular energy hub	
α	Matrix defining connection between energy hubs with their transmission factors	
ρ_{air}	Density of air	
Continuous Variables		
CCH^T	Total cost of electric vehicle chargers	\$
CCI^{cap}	Capital cost of electric vehicle charging infrastructure	\$ \$
$CCI^{O\&M}$	Operating and maintenance cost of electric vehicle charging infrastructure	\$
CE	Total annual cost associated with energy generation	\$
CI	Total annual cost associated with electric vehicle charging infrastructure	\$
Dem	Total energy demand by a particular energy hub	kWh
g^T	Total annual generated emissions —objective function	gCO_2

g^{Energy}	Annual CO_2 emissions produced from energy consumption through various technologies including renewable and non-renewable	gCO_2
g^{Veh}	Annual CO_2 emissions produced from utilization of electric/ Internal Combustion Engine (ICE) vehicles	gCO_2
P	Energy generated from each of the different energy generation technologies	kWh
Tr	Energy transferred between energy hubs	kWh
Z	Total annual cost- objective function	$
Integer Variables		
n^{EV}	Number of battery-powered electric vehicles (EV)	
n^{ICE}	Number of internal combustion engine (ICE) vehicles	
n^{PHEV}	Number of plug-in hybrid electric vehicles (PHEV)	
$N_{CSP-SCA}$	Number of solar collector assemblies (SCA) using solar concentrated power (CSP)	
$N_{PV-module}$	Number of photovoltaic (PV) modules	
N_{WT}	Number of wind turbines	
nch	Number of electric vehicle chargers	
Nev	Number of electric vehicles charged by a particular electric vehicle charger	

References

1. Egbue, O.; Long, S. Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. *Energy Policy* **2012**, *48*, 717–729. [CrossRef]
2. Dietsche, K.-H.; Kuhlgatz, D. History of the automobile. In *Fundamentals of Automotive and Engine Technology*; Springer Vieweg: Wiesbaden, Germany, 2014; pp. 1–7. [CrossRef]
3. Mills, J. Test Your Knowledge: Where and When Was the World's First Petrol Station Established. *The Sunday Times*, 24 July 2015.
4. Matulka, R. The History of the Electric Car. Available online: https://www.energy.gov/articles/history-electric-car (accessed on 2 November 2022).
5. Gerdes, J. Estonia Launches Nationwide Electric Vehicle Fast-Charging Network. *Forbes*, 26 February 2013.
6. U.S. Energy Information Administration. Annual Energy Outlook 2015. *Off. Integr. Int. Energy Anal.* **2015**, *1*, 20585.
7. Mezher, T.; Dawelbait, G.; Abbas, Z. Renewable energy policy options for Abu Dhabi: Drivers and barriers. *Energy Policy* **2012**, *42*, 315–328. [CrossRef]
8. Graves, L. Dubai Announces New Electric Vehicle Incentives. *The National*, 24 September 2017.
9. Baldwin, D. UAE Paves Way for Zero-Carbon Electric Cars. *Gulf News*, 18 December 2017.
10. Yu, H.; Niu, S.; Shang, Y.; Shao, Z.; Jia, Y.; Jian, L. Electric vehicles integration and vehicle-to-grid operation in active distribution grids: A comprehensive review on power architectures, grid connection standards and typical applications. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112812. [CrossRef]
11. Shang, Y.; Liu, M.; Shao, Z.; Jian, L. Internet of smart charging points with photovoltaic Integration: A high-efficiency scheme enabling optimal dispatching between electric vehicles and power grids. *Appl. Energy* **2020**, *278*, 115640. [CrossRef]
12. Zheng, Y.; Shao, Z.; Jian, L. The peak load shaving assessment of developing a user-oriented vehicle-to-grid scheme with multiple operation modes: The case study of Shenzhen, China. *Sustain. Cities Soc.* **2021**, *67*, 102744. [CrossRef]
13. Bhatti, A.R.; Salam, Z.; Aziz, M.J.B.A.; Yee, K.P. A critical review of electric vehicle charging using solar photovoltaic. *Int. J. Energy Res.* **2016**, *40*, 439–461. [CrossRef]
14. Huang, P.; Ma, Z.; Xiao, L.; Sun, Y. Geographic Information System-assisted optimal design of renewable powered electric vehicle charging stations in high-density cities. *Appl. Energy* **2019**, *255*, 113855. [CrossRef]
15. Osório, G.J.; Gough, M.; Lotfi, M.; Santos, S.F.; Espassandim, H.M.; Shafie-khah, M.; Catalão, J.P. Rooftop photovoltaic parking lots to support electric vehicles charging: A comprehensive survey. *Int. J. Electr. Power Energy Syst.* **2021**, *133*, 107274. [CrossRef]
16. Minh, P.V.; Le Quang, S.; Pham, M.H. Technical economic analysis of photovoltaic-powered electric vehicle charging stations under different solar irradiation conditions in Vietnam. *Sustainability* **2021**, *13*, 3528. [CrossRef]
17. Griffiths, S.; Mills, R. Potential of rooftop solar photovoltaics in the energy system evolution of the United Arab Emirates. *Energy Strategy Rev.* **2016**, *9*, 1–7. [CrossRef]
18. CAA, Types of Electric Vehicles. Canadian Automobile Association. 2016. Available online: http://electricvehicles.caa.ca/types-of-electric-vehicles/ (accessed on 1 August 2016).
19. Granovskii, M.; Dincer, I.; Rosen, M.A. Economic and environmental comparison of conventional, hybrid, electric and hydrogen fuel cell vehicles. *J. Power Sources* **2006**, *159*, 1186–1193. [CrossRef]
20. Liu, J. Electric vehicle charging infrastructure assignment and power grid impacts assessment in Beijing. *Energy Policy* **2012**, *51*, 544–557. [CrossRef]

21. Edelstein, S. Electric Car Price Guide: Every 2015–2016 Plug-In Car Specs. Green Car Reports. 2016. Available online: http://www.greencarreports.com/news/1080871_electric-car-price-guide-every-2015-2016-plug-in-car-with-specs-updated (accessed on 2 August 2016).
22. Morrow, K.; Karner, D.; Francfort, J.U.S. Department of Energy Vehicle Technologies Program—Advanced Vehicle Testing Activity Plug-in Hybrid Electric Vehicle Charging Infrastructure Review Novem Charging Infrastructure Review. *Power* **2008**, *58517*, 34. [CrossRef]
23. CAA, Charging Stations. Canadian Automobile Association. 2016. Available online: http://electricvehicles.caa.ca/types-of-electric-vehicles/charging-stations/ (accessed on 2 August 2016).
24. Schroeder, A.; Traber, T. The economics of fast charging infrastructure for electric vehicles. *Energy Policy* **2012**, *43*, 136–144. [CrossRef]
25. Van Vliet, O.; Brouwer, A.S.; Kuramochi, T.; van den Broek, M.; Faaij, A. Energy use, cost and CO_2 emissions of electric cars. *J. Power Sources* **2011**, *196*, 2298–2310. [CrossRef]
26. Shahan, Z. Electric Car Charging 101. EV Obsession. 2015. Available online: https://evobsession.com/electric-car-charging-101-types-of-charging-apps-more/ (accessed on 2 August 2016).
27. Ahmad, A. Abu Dhabi Population Swells. *The National*, 4 November 2014.
28. Koo, C.; Hong, T.; Park, H.S.; Yun, G. Framework for the analysis of the potential of the rooftop photovoltaic system to achieve the net-zero energy solar buildings. *Progress Photovolt. Res. Appl.* **2014**, *22*, 462–478. [CrossRef]
29. Rubin, E.S.; Davison, J.E.; Herzog, H.J. The cost of CO_2 capture and storage. *Int. J. Greenh. Gas Control* **2015**, *40*, 378–400. [CrossRef]
30. Kaul, N. The Bad Boys of Energy Consumption. *Gulf News*, 8 November 2017.
31. ADWEC (Abu Dhabi Water & Electricity Company). Statistical Report 1999–2016. Abu Dhabi: ADWEC. 2016. Available online: https://www.ewec.ae/sites/default/files/documents/2016%20Statistical%20Report.pdf (accessed on 2 November 2022).
32. Wright, I. UAE Aims to Become International Manufacturing Hub. Available online: https://www.engineering.com/story/uae-aims-to-become-international-manufacturing-hub (accessed on 2 November 2022).