



Solar Energy Based Model for Decarbonization: A Case Study in Istanbul

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Cite this study: Kartal, B., & Alkan, R.M. (Year). Solar energy based model for decarbonization: a case study in Istanbul. International Journal of Engineering and Geosciences, 11(1), 64-77.

<https://doi.org/10.26833/ijeg.1648588>

Keywords

Rooftop Solar
Renewable Energy
Solar Radiation
Solar Mapping
Carbon Footprint

Research Article

Received:

Revised:

Accepted:

Published:



Abstract

This study investigated the suitability of rooftops in Istanbul for solar panels using a GIS (Geographic Information Systems) based approach. The characteristics of the roofs of approximately 1.3 million buildings in Istanbul, such as slope, area and orientation, solar radiation, were calculated with ArcGIS by Esri software, and the electrical energy they would generate and the carbon footprint (CFP) they would prevent if solar panels were placed on the roof of each building were calculated. Various scenarios were created for the years 2030, 2040, and 2050, and the change in the amount of carbon footprint over the years was analyzed. Istanbul's solar energy potential is 258.59 TWh, and the electricity generation if monocrystalline silicon solar panels are used on rooftops is 29.72 TWh. Since the effect of roof obstructions on the efficiency of solar panels is not considered, PV power generation may be overestimated. Istanbul's total rooftop electricity production has the potential to meet 70% of the total electricity consumption for the year 2023. In addition, a solar building information system has been established to help citizens and policymakers in the future and to raise awareness, including various data such as the solar potential of buildings, the amount of electricity generation, and how much carbon emissions will be prevented, and will be available online soon. This study can contribute to Istanbul reaching its carbon neutrality goals and producing effective results on a global scale.

1. Introduction

Industrialization over the past 200 years has resulted in urban growth, with more people living in urban areas than in rural ones. By 2030, it is anticipated that 5 billion people will live in towns and cities [1]. Cities may account for 40 to 70% of human-induced (or anthropogenic) greenhouse gas (GHG) emissions [2]. Urban life is significantly impacted by the worldwide phenomenon known as climate change [3] and creates many environmental, economic and social impacts worldwide, and the role of local governments or other public organisations in the management of these impacts is very important [4]. Local governments, usually responsible for urban policies, are key actors in the fight against climate change [5]. Due to the fact that the adverse effects of climate change are becoming more noticeable at the local level, they must incorporate climate adaptation procedures into their planning procedures [6]. Municipalities, as the smallest organization with decision-making authority on energy planning, have an

important role to play in reducing energy dependence on fossil fuels. Most government incentives and investments are directed toward addressing our growing energy needs in light of population growth, industrial expansion, and technological advancements [7]. Renewable energy is a key component in lowering emissions from the electrical supply. It is projected that greater use of wind and solar energy will increase the share of renewable energy in global electricity generation to over 90% in 2050 and 60% in 2030 [8]. Solar energy is the best renewable energy source for a household, even though other renewable energy sources are found to offer comparable benefits [9]. The potential for rooftop solar in metropolitan areas is the cornerstone of renewable energy strategies and action plans for sustainable energy at the local or national levels [10].

In 2019, buildings accounted 21% of global GHG emissions [11]. As a renewable energy source, solar buildings have been an important milestone in reducing carbon emissions [12]. Building energy use has become a major worldwide concern, and various design strategies

have been developed to increase energy efficiency across several countries [13]. Solar energy generated from individual buildings could have a major impact on country policies to reduce carbon emissions [14]. According to Turkey's National Energy Plan, 25.5% of final energy consumption was in residential buildings in 2020, and this is expected to decline to 20.7% in 2035 [15]. Therefore, reducing greenhouse gas emissions and the environmental impact requires lowering building energy consumption [16]. The electrical energy obtained from buildings with solar panels will also contribute to the achievement of development goals 7, 11 and 13 of the sustainability goals determined by the United Nations [17]. As the demand for clean energy increases worldwide, zero-energy and zero-emission buildings that do not pollute the environment are becoming increasingly important [18]. Energy is necessary for all crucial facets of life, including trade, industry, housing, and transportation. But the world's leading energy supplies, like water and fossil fuels, are constantly running out. Managing natural resources and planning for the future is the biggest challenge facing society [19]. Groundwork for sustainable development can be established by identifying fundamental and universal solutions applicable in urban areas [20]. Municipalities and other public organisations can develop and implement various strategies to combat climate change.

Many different applications for Geographic Information Systems (GIS) deal with location data. A lot of applied professions have begun to use GIS as a key common concept [21]. GIS is used in solar cadastral surveys to assess the solar photovoltaic potential of building facades and roofs [22]. Solar cadastres are a valuable tool to promote rooftop PV installations among city and municipal residents. Furthermore, to support the development of district energy supply programmes, it is important to calculate local PV potentials [23]. Several investigations have been carried out by various researchers worldwide that apply various algorithms and models to estimate roof-top PV potential using GIS tools and techniques. Melius et al. determined that fixed value, manual selection, and GIS-based methods were used to determine the suitability of rooftop solar panels and also found that most solar roof analyses were estimated using GIS-based methods [24].

Stack and Narine [25], conducted a study in Auburn University, which has a campus area of 1875 acres, as the study area. They used Light Detection and Ranging (LiDAR) data to create a digital surface model (DSM), and then used GIS to calculate the DSM's slope, aspect, and total solar radiation. They determined that 323 of the 443 buildings on the campus are suitable for solar panels and that these selected roofs can generate 27,068,055 kWh of energy per year. Adjiski et al. [26], used 1m resolution LiDAR data to determine the latent features of roofs such as their areas, aspects, slopes and shadings etc. The annual maximum solar capacity on the selected roofs was determined and the evaluation of roof areas was investigated with publicly available big data. Koster et al. [9], conducted a study by using open source data, determines the solar potential of buildings with the help of GIS, and in addition to decarbonizing the building

sector, it also leads to mapping the solar energy potential for countries that have difficulty accessing data. They also made a comparison that includes socio-economic factors in determining the solar potential. Domínguez et al. [27] aimed to develop solar maps in rural areas using GIS in Cuba. The aim of these maps is to encourage the use of sustainable and renewable energy.

Martín et al. [28], by applying LiDAR data and GIS-based models to determine the solar potential in urban areas, they have carried out studies for solar radiation analysis, creation of solar potential maps and investigation of photovoltaic potential of the study area. Muhammed et al. [29], investigated a study in Egypt, it was aimed to determine the solar energy potential by modelling solar radiation with GIS, Solar Analyst tool and to determine the potential of PV panels mounted on roofs for the whole study area. Dodig and Djapic [30], used a DSM was created from LiDAR data, solar radiation was calculated with ArcGIS Solar Analyst, suitable roofs were found where solar panels could be placed, and how much electricity could be produced per year from the panels on suitable roofs was investigated. Macancela et al. created a three-dimensional model of the rooftops in Santa Isabel's (Azuay, Ecuador) downtown using LiDAR technology. The area, slope, orientation, and amount of solar radiation on the rooftop were calculated to estimate its theoretical, technical, and financial photovoltaic potential. They found that 68.8% of the roof's surface can be used for PV panels, meaning that 62.39 GWh of photovoltaic potential is theoretically possible [31]. Using building footprints, digital elevation models, GIS, and high-resolution satellite imagery, Mondal et al. assessed Chennai's potential for solar rooftop installations by identifying the best rooftop locations for solar panel installations while taking aspect, slope, and solar radiation into account. The findings indicate that the total suitable roof area of Chennai is approximately 140,674,391.4 m², with the potential to produce 35,936 GWh of electricity per year [32].

In this study, a city-scale dynamic model is proposed to reduce the CFP in Istanbul, one of the world's largest metropolises. Based on the CFP mitigation scenarios published by Istanbul Metropolitan Municipality (IMM), the modeling study investigates the impact of electricity generation on CFP by reducing the city's dependence on the electricity grid if solar panels are installed on building roofs. The solar potential of the roofs of approximately 1.3 million buildings in Istanbul was calculated with ArcGIS software by Esri and the electrical energy generation from solar potential was calculated. With various scenarios created according to the electricity energy targets to be obtained from renewable energy sources specified in the national energy plan, the short, medium and long term impact of electricity energy to be generated only from buildings on the city's CFP was modelled. In addition, in order to help citizens and policy makers in the future and to raise awareness, a solar building information system, including various data such as the solar potential of buildings, the amount of electricity to be generated and how much carbon emissions will be prevented, has been established and will be serve online soon.

2. Method

By committing to becoming carbon neutral by 2053, Turkey signed the Paris Agreement. The activities that increase carbon emissions the most are caused by oil and its derivatives. From a global and local perspective, buildings are known to significantly increase CFP, as previously mentioned in the literature. Therefore, the fact that a significant portion of energy is consumed in buildings and fossil fuels will one day be depleted plays an important role in using buildings effectively.

Türkiye, a developing nation where the study region is located, contributed 1.2% of the world's greenhouse gas emissions, which increased to 1.3% in 2023 [33,34]. According to the Business as Usual (BAU) scenario, which uses 2012 as the base year, Turkey has committed to reducing its greenhouse gas (GHG) emissions by 41% by 2030 (695 MtCO_{2e} in 2030) as part of the Paris Agreement, which went into effect in 2021 [35]. As shown in Figure 1, 42% of the electricity generated in Türkiye is from renewable energy sources [36], which is above the global average of 39% [37].

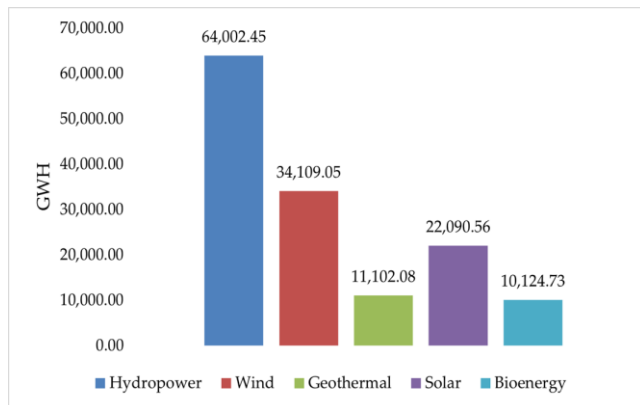


Figure 1. Distribution of electricity generation by renewable energy sources

2.1. Study Area

Istanbul province, Türkiye was selected as the study area. The province of Istanbul accounts for 18.34% of Turkey's population, with a population of 15 million 655

thousand 924 people as of 2023 [38], and Istanbul's total electricity consumption is equal to 16.67% of Turkey's total electricity consumption [39]. Strategically located at the intersection of Europe and Asia, Istanbul's diverse urban landscape offers vast rooftop areas suitable for solar photovoltaic installations. The city is bisected by the Bosphorous Strait, with the Sea of Marmara to the south and the Black Sea to the north, creating distinct climatic and solar exposure conditions. The study area is shown in Figure 2.

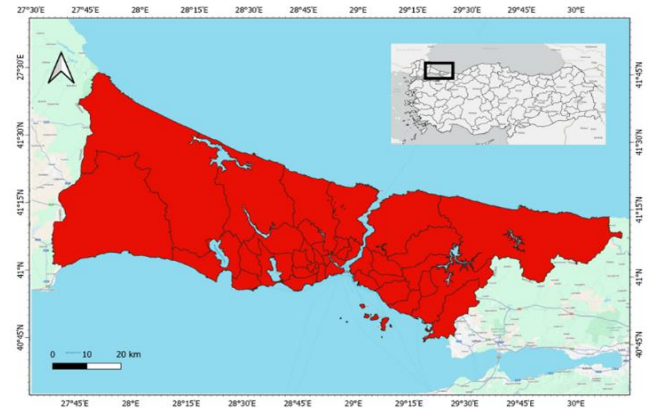


Figure 2. Study area, Istanbul

In order to reduce CFP, a model was designed and inputs and outputs were determined. In this designed model, the activities that cause CFP and the activities that reduce them are shown in Figure 3 [40]. Within the scope of this study, it is investigated how much of the electricity consumption will be met with the electricity generation to be obtained if solar panels are installed on the roofs of all buildings in study area, which is one of the mentioned mitigation activities. In addition, according to the scenarios created, it is also determined how much it will reduce the carbon footprint in the short, medium and long term. This model is a dynamic system suitable for adding new inputs.

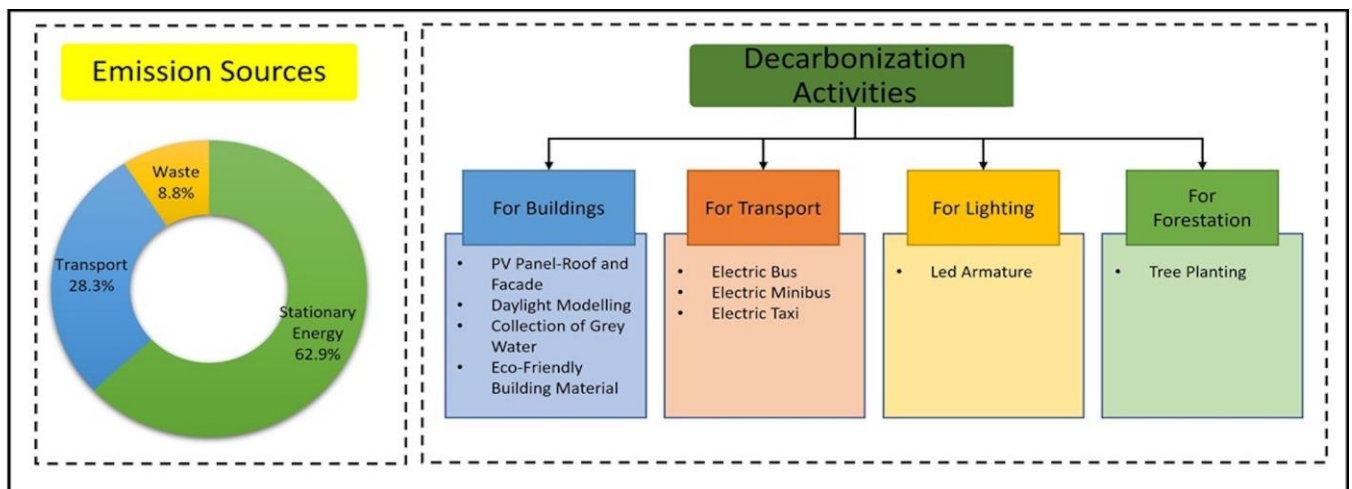


Figure 3. Emission sources and decarbonization activities for study area

In the Istanbul Sustainable Energy and Climate Action Plan (SECAP) prepared by IMM, the total CFP is

approximately 50.9 MtCO_{2e} and 3.3 tCO_{2e} per capita according to the greenhouse gas inventory calculated

based on 2019 for Istanbul. 49.20% of the emissions in the stationary energy sector come from residences and commercial buildings, and 99% of the emissions in the transport sector come from road transport [40].

2.2. Methodology

The methodology that is used in this study is graphically shown in 4 steps in Figure 4.

The main steps in this diagram are:

- Step 1: Creating solar radiation map.
- Step 2: Identifying suitable roofs.
- Step 3: Calculation of electrical energy from solar radiation values and creating a web-based solar potential map.
- Step 4: Creating various scenarios to reduce CFP.

These steps are explained in the following chapters.

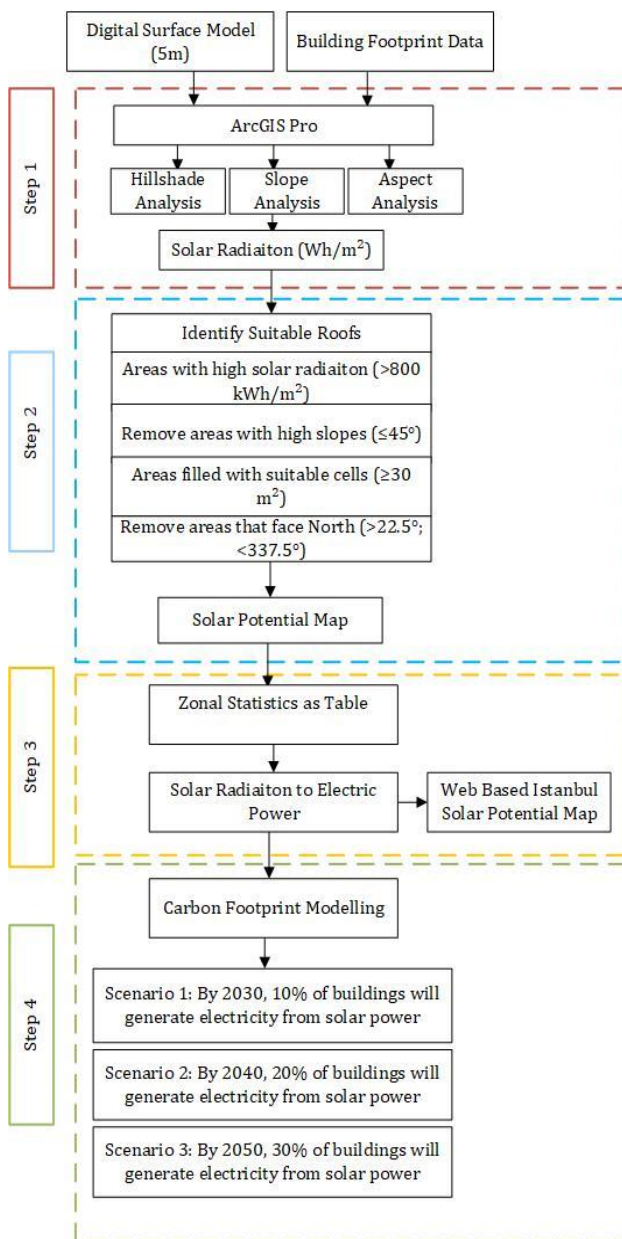


Figure 4. Workflow of this study

Step 1:

Although there is much commercial software for determining solar potential, ArcGIS software by Esri was

used in this study. A geometric solar radiation model was created as part of the Solar Analyst Tool to compute direct and diffuse solar radiation from digital elevation models (DEMs) [41]. Global radiation is the total of direct and diffuse radiation of all sun and sky map sectors (Global_{tot}) [42]. Solar radiation analysis tools assess the sun's impact on a specific region at different times by considering various factors. These include the terrain's steepness (slope), altitude and latitude, atmospheric effects, and compass direction (aspect). They also consider changes in the sun's angle throughout the day and season, as well as the shadows created by the surrounding terrain [43].

The Field Solar Radiation tool requires the user to select input parameters to make the application [44]. These parameters were chosen to provide the best compromise between an acceptable computational time and the accuracy of the results. The parameters selected in the input settings are given in Table 1.

Table 1. Input settings for the solar analysis

Input settings for the solar analysis	
Sky size/Resolution	200
Time configuration	Whole year (2023)
Hour interval	1 hour
Z factor	1
Slope and aspect input type	From the input surface raster
Calculation directions	16
Sky zenith divisions	8
Sky azimuth divisions	8
Diffuse model type	Uniform overcast sky

The Solar Radiation tool requires raster or vector data inputs as it is a GIS-based application. In particular, a DEM is required as an input by the Area Solar Radiation tool in order to model solar radiation over geographic areas. To generate high-resolution temperature maps, high spatial resolution and high-quality DEMs need to be used [45]. In this study, the Digital Elevation Model (DEM5-L0) produced by the General Directorate of Mapping of the Ministry of National Defense by automatic matched from 30 cm resolution stereo aerial photographs with 5 m grid spacing was used (Figure 5a). To evaluate the effect of spatial resolution on the outputs generated, irradiance calculations were also performed utilizing a DEM of 5 m. Although various methods have been proposed to automatically obtain the roofs of buildings [46-48] the footprints of all buildings within the scope of this study were taken from Istanbul Metropolitan Municipality (IMM) in the form of polygons in shape format (Figure 5b). The solar radiation values of the roofs of all buildings in Istanbul were obtained with the parameters in Table 1 by the Area Solar Radiation Tool module of the ArcGIS.

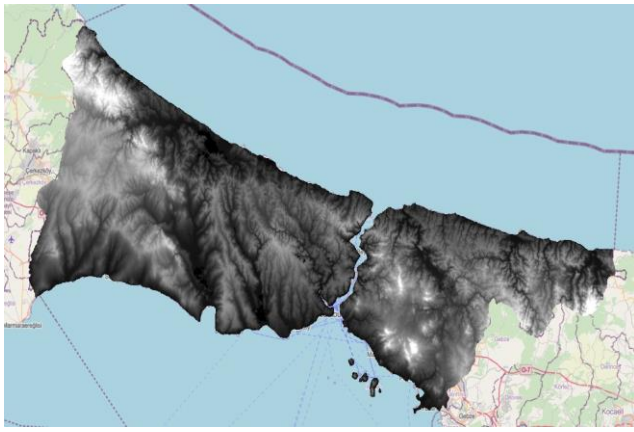


Figure 5 (a). Digital Surface Model

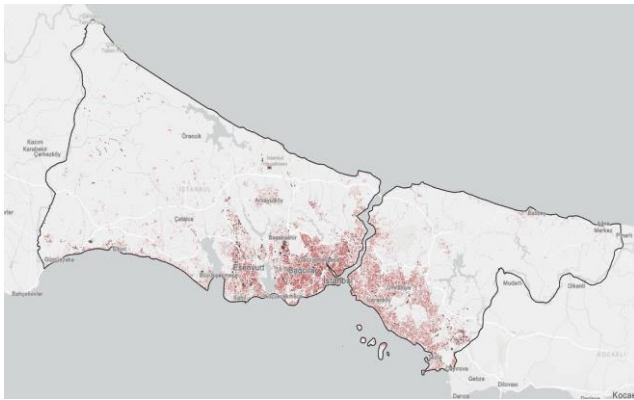


Figure 5 (b). Buildings footprints

Step 2

After determining the solar radiation levels of the roof of each building, it was seen that there are some criteria

for determining solar roofs. In order to determine suitable roofs for solar panels, some desired features need to be specified. As indicated in Figure 4, suitable orientation, suitable slope and high radiation roofs have been determined [49]. Solar panels are usually mounted in the same plane as the surfaces of pitched roofs, the slope of the roofs is determined to estimate the PV accurately [31]. Roofs with a slope less than 45° are used as the slope parameter in this study [50]. Each cell's values in the output raster indicate the compass direction that the surface faces at that point, when the downslope direction is identified using aspect analysis [51]. In the northern hemisphere, north-facing surfaces ($0-22.5^\circ$ and $337.5^\circ-360^\circ$) are less suitable for solar panels as they receive less solar energy [49]. Therefore, north-facing roofs are not taken into account. If a building's suitable roof surface is less than 30 m^2 [52], it is generally not suitable for solar panel installation, but some studies in the literature indicate that 10 m^2 is also sufficient [53]. Since the obstacles on the roofs are ignored, a minimum of 30 m^2 is assumed as a suitable area. It is assumed that the solar panels are placed on the roofs according to their slope and that the panels' angle is constant throughout the day. The solar radiation map was obtained by creating a hill shade raster from DSM and masking it with the footprints of the buildings using ArcGIS software by Esri. Then, slope raster and aspect raster were created to analyze suitable roofs for PV installation. Figure 6 displays maps that were created by Esri using the ArcGIS program.

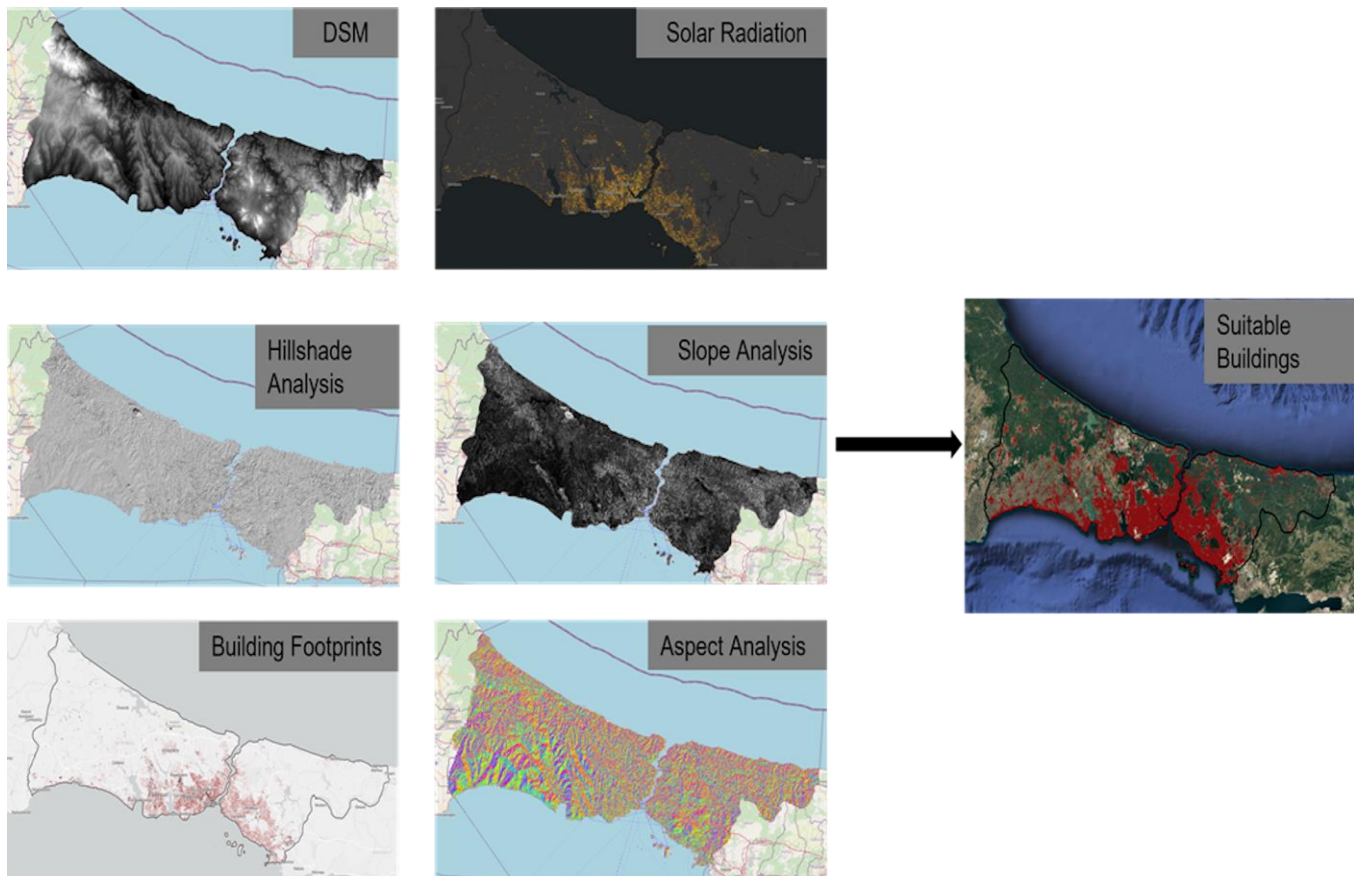


Figure 6. Workflow of identifying suitable roofs

Step 3:

Using the solar potential values obtained after determining the suitable roofs and multiplying the available solar radiation values with efficiency (η) and performance ratio (PR) values, the electricity generation was determined for each building in this step. The solar potential to be obtained from solar radiation is calculated according to the formula in Equation 1 [54].

$$\text{Solar Potential (SR)} = A * I \quad (1)$$

where A = Total solar panel area (m^2)
 I = Annual average solar radiation (kWh/m^2)

The electricity generation is calculated according to the formula in Equation 2.

$$\text{Electricity Generation (E)} = \text{SR} * \eta * \text{PR} \quad (2)$$

Where η = Solar panel efficiency (%)
 PR = Performance ratio (%)
 E = Energy (kWh)

Gazbour et al. determined the average efficiency of monocrystalline silicon solar panels to be 14.37%. They observed that the PR range of these panels varied between 0.75 and 0.80 [55]. In this study, the average efficiency for the monocrystalline silicon solar panel selected as the solar panel type is 14.37%, and the PR is assumed to be 80%.

In this step, aimed to transfer the solar potential map produced in the Step 3 to a web-based environment so that citizens and policy makers have a preliminary knowledge about the solar potential of buildings. The web-based map was developed with ArcGIS Web AppBuilder. WebGIS makes geospatial data available to everyone. It produces a quick and sophisticated environment without regard to time, location, or the constraints of powerful computers and processing power [56]. In addition, information such as the area of each building, average solar potential value, solar potential, electricity generation, and information such as how much CFP will be prevented and for example, how many trees will be saved if its electrical energy potential is utilised have been added to the database to raise awareness.

Step 4:

This step examines the environmental benefits of implementing the power generation system discussed in the previous section, using the scenarios that were created. The CFP in Istanbul was calculated as 50.89 MtCO_2e for 2019. Private, public and commercial road transport (28.1%), housing (27.8%), commercial and institutional buildings (21.4%) and industry (12.9%) sectors are responsible for the majority of the city's emissions. The population of Istanbul is predicted to grow by 22% in 2030 to reach 17.9 million, 35% in 2040 to reach 19.7 million, and 46% in 2050 to reach 21.3 million, compared to 2015 [40]. Within the scope of this study, scenarios were developed for the years 2030, 2040 and 2050 to reduce the CFP from buildings.

As the city's population and economy continue to grow, greenhouse gas emissions are predicted to surpass 76 MtCO_2e in 2030, get close to 95.22 MtCO_2e in 2040,

and reach 115 MtCO_2e in 2050 [57]. Table 2 shows the CFP values of Istanbul in the upcoming years.

Table 2. Istanbul CFP by year

Year	Population (Million)	CFP (MtCO_2e)	CFP per Capita ($\text{tCO}_2\text{e}/\text{person}$)
2019	15.5	50.9	3.30
2030	17.9	76.80	4.29
2040	19.7	95.22	4.83
2050	21.3	115.25	5.41

In this model, the activities to be carried out in order to reduce the CFP of Istanbul, which is selected as the study region, have been calculated one by one by creating various scenarios for the years 2030, 2040 and 2050 according to the mitigation strategies specified in IMM's SECAP report and their effects on CFP have been investigated. With this study, short, medium and long-term policies were developed to reduce the CFP of Istanbul and to guide policy makers in the future. According to the Turkish National Energy Plan, the target set for the Share of Resources in Electricity Generation for solar energy increases by approximately 5% annually every 5 years [15]. With this assumption, it is expected that 10% of the buildings will use solar energy in 2030, 20% in 2040 and 30% in 2050. The policies produced were taken from the SECAP report published by IMM and the scenarios are given in Table 3.

Table 3. Istanbul CFP mitigation strategy

Scenario	Year	Mitigation Strategy
Scenario 1	2030	By 2030, 10% of buildings will generate electricity from solar power
Scenario 2	2040	By 2040, 20% of buildings will generate electricity from solar power
Scenario 3	2050	By 2050, 30% of buildings will generate electricity from solar power

To calculate the CFP, the common theoretical method is to multiply the activity data by the activity emission coefficient. The basic equation is as shown in Equation 3 [58]:

$$\text{Emissions} = \text{AD} * \text{EF} \quad (3)$$

where EF is the emission factor and AD is the activity data. Activity data shows how much human activity results in emissions or removals over a given time period [59].

Although electricity consumption point emission factors vary depending on the connection point, The Turkish National Electricity Grid Emission Factor includes factors for calculating GHG emission reductions to be achieved through renewable energy-sourced electricity generation. For every MWh of electricity generation by solar or wind power, 0.6261 tons of CO_2 emissions will be avoided, according to the emission factor. For this purpose, this coefficient is used to calculate the tons of CO_2 emissions to be avoided [60].

3. Results

The electricity generation from the roof of buildings in the province of Istanbul has been investigated and studied with larger scale data. The study's findings, when applied to building solar roof suitability criteria, indicate that about 1.2 million building roofs are appropriate for the installation of solar panels. This corresponds to approximately 90% of the total number of buildings. The average annual solar radiation for 2023 was determined to be 1,170 kWh/m² and the total solar potential to be obtained from the roofs of the buildings was found to be 258.59 TWh.

Dust and dirt, reflection, irradiation, spectral losses, array mismatch, thermal losses, DC cable losses, inverter losses, and AC cable losses are some of the factors that impact the efficiency of solar panels [61]. The production capacity of solar panels decreases over time due to degradation [62]. In this study, the degradation of the panels over the years is neglected when calculating the electricity generation. Electricity generation was found to be 11.35 TWh on the Anatolian side and 18.37 TWh on the European side. The total electricity generation to be produced by all buildings was calculated as 29.72 TWh. This shows that the actual electricity generation of each building is on average 25 MWh.

The solar potential information from the entire city of Istanbul has been assembled over 219.83 million square kilometers of roof space covered by the nearly 1.2 million buildings whose solar PV potential was simulated as seen in Table 4.

Table 4. Solar potential data of Istanbul

	Number of Buildings	Roof Space (km ²)	Solar Potential (TWh)	Electricity Generation (TWh)
Anatolian Side	448,685	83.59	98.76	11.35
European Side	727,635	136.24	159.83	18.37
Total	1,176,320	219.83	258.59	29.72

The Turkish Energy Market's report claims that, the annual electricity consumption of Istanbul province for 2023 is 42.51 TWh. It has been determined that the electricity generated from building roofs could meet approximately 70% of Istanbul's total electricity consumption in 2023. Similar to this study, in the research conducted for Istanbul, Yildirim et al. [63], a three-dimensional city model was used to determine solar radiation and the total electrical energy produced by PV panels. A mobile vehicle metering system measured these variables over 410 days at eight different points across the city. Determined that if solar panels were added to the roofs of approximately 1.3 million buildings in Istanbul, they would meet approximately 67% of Istanbul's electricity consumption, with the electrical energy to be obtained for 2019.

Following the calculation of each building's solar radiation values and the amount of electricity it will generate, the Istanbul Province Solar Map, a web-based application, was developed with ArcGIS Web AppBuilder by Esri and made available to everyone, as shown in Figure 7.

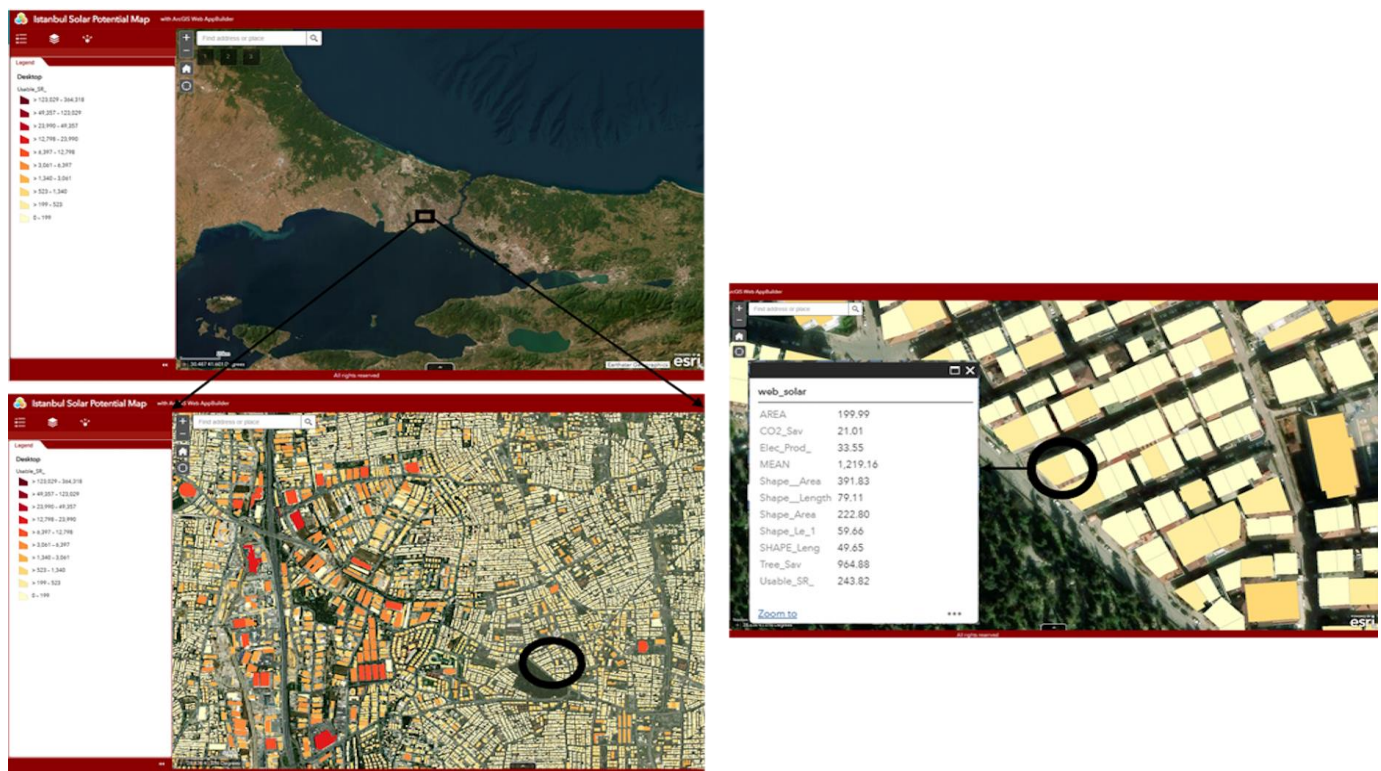


Figure 7. Web based Istanbul Solar Potential Map

This online map provides citizens, policymakers and local government in Istanbul with an invaluable first estimate of PV panels installed on buildings, including information such as the area of each building, average solar

potential value, annual average solar potential, solar energy and electricity generation and how many tons of carbon emissions 1 MWh of electricity generated from solar panels will prevent for each selected building and

how many trees will be saved. Thanks to this user-friendly interface, investors and property owners will be able to see the energy efficiency potential of their real estate, contributing to the formation of an energy-efficiency market [64].

From an environmental perspective, to reduce CFP city-wide, as seen in Figure 8, while the CFP per capita estimated for Istanbul in 2030 is 4.29 tCO₂e/person, this value decreases to 4.19 with installing solar panels on

only 10% of the buildings and obtaining electricity. While the CFP per capita estimated for 2040 is 4.83 tCO₂e/person, this value decreases to 4.64 with solar panels installed on 20% of the buildings. In 2050, it was found that the per capita CFP decreased from 5.41 to 5.15. Even if the targeted mitigation strategy is implemented only for buildings, there is a decrease in the CFP per capita.

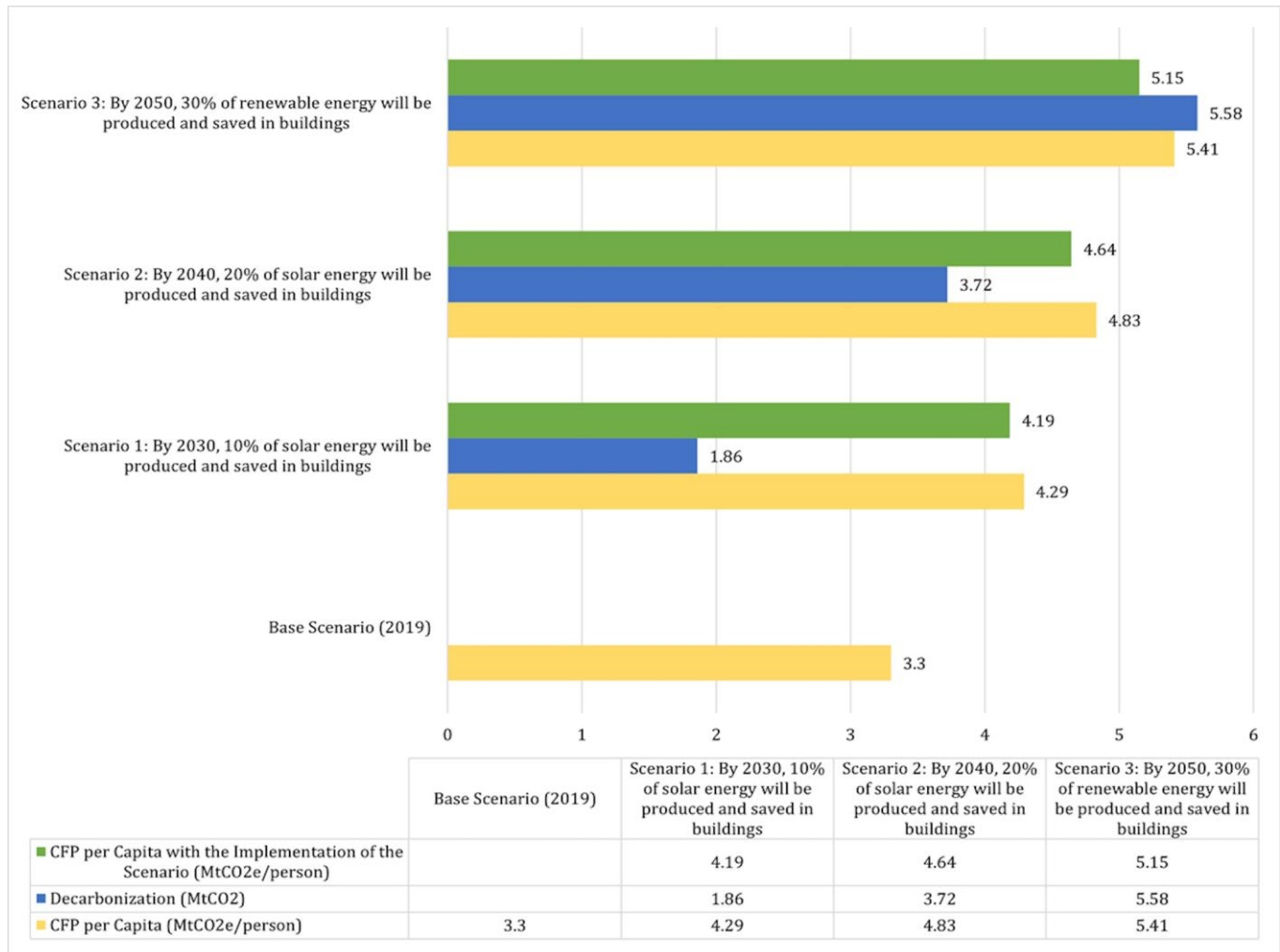


Figure 8. Modelling results of CFP in Istanbul.

Another critical issue in PV installation is the investment cost [65]. The installation of solar power plants is one of the factors influencing the installed capacity situation globally from an economic standpoint; however, the cost per unit of energy produced is steadily declining [66]. Achieving cost-effectiveness and shortening the time it takes for investors to receive their money back is essential for expanding the use of solar energy. Solar PV power generating prices ranged from €42 to €168/MWh, with 75% of results falling below €101/MWh [67]. Assuming an average annual generation of 25 MWh for a building, the cost of rooftop PV installations is approximately €2,525 using a value of €101/MWh. Therefore, the investment cost of installing solar panels on 10% of buildings to reach the 2030 decarbonisation target is expected to be at least €315 million.

One of the most common methods in economic evaluation is the payback period method. This method gives investors a clear return expectation by calculating

how long it will take for a project to recoup its initial investment [68]. The payback period is determined by taking into account the electricity tariff, and can be expressed using the Equation 4 [69]:

$$\text{Payback Period} = \frac{\text{CAPEX}}{E \cdot T - \text{OPEX}} \dots \dots \dots (4)$$

where CAPEX = Installation cost of solar power plants
 E= Electricity generation
 T= Electricity tariff (€0.13/kWh [70])
 OPEX = Operational and maintenance costs (1.1% of capital cost [71])

4. Discussion

This study investigates how tracking and modelling city-wide emissions can change carbon emissions. The findings obtained within the framework of the results obtained from the study are discussed below.

4.1 Summary of Findings

When the literature studies are analysed, it is seen that the usability of solar energy, its effect on CFP per capita has not been investigated and a web-based solar energy map has not been developed. In this research, which was carried out with large-scale data, it was aimed to develop a CFP monitoring and tracking model proposal at the city level and to fill some gaps in the literature.

This study contributes to the help the decision maker or mayor how to do something when deciding on something, planning a city or revising existing buildings. The inputs of this system, which consists of inputs and outputs, are the factors that cause the CFP, and the outputs are the monitoring of the change in the CFP according to the modelling results. Therefore, answers are sought to questions such as whether the selected activity should be changed, reduced or, if there is no chance of reduction, whether it is necessary to switch to a new technology. The purpose of this system is to add new inputs to the system to reveal each of the activities to be selected according to the CFP mitigation strategies.

4.2 Contributions to the Field

By 2050, electricity consumption will increase to 43% in transport and 68% in buildings, and 86% of this electricity need is expected to be provided from renewable sources [72] and due to the lack of land uses for PV electricity generation, using building rooftops is an extremely attractive choice [73]. The total number of buildings in Istanbul is nearly 1.3 million and buildings have a share of 27.8% in the total CFP. If no mitigation strategies are taken to reduce carbon emissions in Istanbul, the CFP is expected to increase in 2050 with the increasing population [40]. To reduce the carbon footprint (CFP) from buildings is crucial to tackling climate change, which is why net zero emission buildings (NZEB) are of great importance [74]. Considering the seismicity of Istanbul, it is expected that an average of 300,000 houses will be transformed by 2026 as a result of urban transformation practices. New buildings to be built within the scope of urban transformation should be designed as NZEB buildings.

A plan for transitioning the nation's building stock to zero-emission structures by 2050 and for phase-out of fossil fuels for heating and cooling by 2040 at the latest should be part of National Building Renovation Plans if they are completely included into National Energy and Climate Plans [75]. In the building sector, building-integrated solar panels also need to be taken into account in long-term policy formulation [76]. As new city blocks are being constructed, new systems should be designed to be used efficiently solar energy [77]. According to Turkey's National Energy Plan, 25.5% of final energy consumption was in residential buildings in 2020, and this is expected to decline to 20.7% in 2035 [15].

Macancela et al. stated that the panels producing 23 GWh of electrical energy per year will prevent 6,805 tonnes of CO₂ emissions during their 25-year economic life, taking into account the deterioration of the panels [31]. In 2010, Sun et al. pointed out that generating electricity from solar panels could reduce about 3.8 million tonnes of CO₂ per year in built-up areas in Fujian [78].

4.3 Implications for Policy and Practice

Municipalities play a critical role in combating climate change. Local-level policies can significantly contribute to the achievement of global climate goals. Creating a web-based information system for building stock can greatly enhance the management process. This system will include a web-based map that policymakers, planners, investors, and the general public can use as a decision-making tool for local renewable energy initiatives [79]. The potential of the buildings should be determined by establishing a GIS-based Solar Building System, which includes the following items:

1. Creating a Geographic Information Building System and giving each building a unique number like its own identification number,
2. Obtaining real electricity / water / heating data from relevant institutions (creating a database for buildings and adding the energy consumption of buildings to this system),
3. Calculating the CFP of each building after obtaining the relevant consumption,
4. Investigating the energy potential of roofs,
5. Demonstrating a comparative example of using solar panels in buildings for renewable energy,
6. Long-term benefit/cost analysis of systems such as solar panels to be added to buildings to produce their own energy.

A detailed building information system covering all the above items should be designed and all buildings should be monitored and analysed. Therefore, a neighbourhood-based and district-based carbon information system is suggested here to show decision makers what they need to do within an information system. The database created can be integrated into the relevant municipalities' systems, and the buildings can be monitored on a local basis. By adding the buildings' consumption data to the system, the amount of carbon emitted to the environment can be determined, and if solar panels are installed in the buildings, the system can be updated to monitor whether the CFP is reduced. When new information arrives, a tree is planted in the district, a building starts using solar panels, or a building is demolished and rebuilt, the dynamic model will be completely updated and the CFP will be tracked. With more people living in cities worldwide, developing sustainable living environments has been a top concern [80]. To meet the carbon neutrality target while constructing new housing and lowering the carbon footprint of existing housing, concrete measures should now be taken to address the climate crisis and reduce the CFP, mainly in the short term by 2030 and in the long term by 2050. When all legal bases, regulations and action plans are examined, it has been determined that the problem of establishing a building information

system and monitoring and analysing them should be solved.

Due to the net zero commitment given in the Paris Agreement, when developing a city or designing a new building, modelling should be done according to daylight to get the maximum efficiency from solar energy; CFP should be taken into account when transforming an existing structure, the system should be considered as a whole, and the future scenario should be taken into account. For example, when urban transformation is to be carried out, questions such as how many buildings existed before, how many households lived there, etc., should be calculated, and how they will affect the CFP in the future should be planned accordingly. The current urban arrangement activities in terms of sustainability principles realisation is an inevitable necessity [81].

Although electricity generated from solar panels is seen as an opportunity to access renewable energy and reduce CFP, it is theoretically a difficult process to implement. Within the framework of the laws and regulations in force in Turkey; according to the Law on Condominiums, roofs must be common areas and the approval of all owners must be obtained, the roofs of the buildings must be statically suitable, the legal process for unlicensed electricity production is long, the system to be installed must not disrupt the aesthetics of the building, the economic cost, as well as the inadequacy of credit incentive mechanisms and the lack of sufficient public awareness, obstacles can be countered.

4.4 Limitations

This study also had some limitations. In the 2030, 2040, and 2050 projections, the electricity generation from solar panel panels is assumed to be constant. But it should be known that, the production capacity of solar panels decreases over time due to degradation [62]. The roofs of existing buildings often require various installation features, such as air conditioning vents, chimneys, overhangs, and antennas. These elements may have an impact on rooftop solar panels' ideal positioning and effectiveness [82]. It is assumed that there are no obstructions on the roofs, and the potential impact of roof obstructions such as air conditioning equipment and chimneys on the available roof area is not discussed, so PV power generation may have been overestimated. In future studies, the physical properties of roofs can be analyzed with more detailed data using LiDAR technology [83]. Furthermore, in addition to the general developments in atmospheric science and climate modelling, more targeted research, such as simulation studies, measurement campaigns, and enhanced renewable energy models, can be carried out in the future to investigate the effects of solar radiation modification on renewable energy [84].

Since ArcGIS is a commercial software, it cannot be used without purchasing a license. Access to data is the primary constraint for GIS research [85]. To generate high-resolution temperature maps, high spatial resolution and high-quality DEMs need to be used [42]. One of the most critical problems in creating a solar map is the excessive calculation time, which can last day [86].

4.5 Suggestions for Future Research

In future studies, the effects of fluctuations in solar energy due to weather and seasonal changes should also be considered to predict solar energy and it is recommended to conduct sensitivity analysis. Another suggestion is to investigate the impact of transportation, which causes the highest carbon emissions after buildings, on the CFP in Istanbul by creating various scenarios according to the mitigation activities specified in the SECAP report. And also, solar parking lots can also be considered as an alternative to reduce carbon emissions. By using these areas in cities for energy generation, carbon emissions can be reduced by using the electricity generated here while charging electric vehicles [87].

5. Conclusion

With this study, a dynamic CFP model was developed for the first time on a city scale in Istanbul, one of the world's most populous metropolises. A significant part of the CFP in Istanbul comes from buildings and transportation. Energy efficiency, renewable energy sources, and sustainable urbanisation are critical to reduce carbon emissions. This dynamic model is very suitable for improvement and adding new inputs. Energy efficiency and sustainability of buildings stand out as fundamental strategies to reduce CFP. The measures to be taken by decision-makers in this process are very important in terms of developing effective policies. In addition, it is anticipated that creating a dynamic model and transferring it to mobile platforms will be beneficial in increasing social awareness.

Various policies have been developed in the short, medium, and long term to reduce the CFP, and attention has been drawn to the change and reduction in the CFP if these policies are implemented. Therefore, to achieve the zero-emission city target, various policies need to be developed and implemented. It should not be forgotten that reduction efforts made at the local level will have a major impact globally.

This study can contribute to Istanbul reaching its carbon neutrality targets and producing effective results on a global scale. Creating a solar building information system can monitor buildings responsible for 21% of the worldwide CFP. CFP can be modelled and monitored for existing or newly constructed buildings using this model. Although this model proposal was made for Istanbul, it can be applied to all of Türkiye or other cities in the world in future studies.

Acknowledgement

This research is a part of Doctoral Dissertation of first author carried out at Istanbul Technical University, Graduate School. The authors would like to thank the Republic of Turkey's Ministry of National Defense General Directorate of Mapping for providing the DSM data used in the study. The corresponding author is deeply grateful to her supervisor, Prof. Dr. Reha Metin Alkan for his guidance.

Author contributions

Büşra Kartal (Ph.D. Candidate): Conceptualization, methodology, resources and data acquisition, software and analysis, writing-original draft **Reha Metin Alkan:** Investigation, data curation, supervision, verification of results, writing-review and editing.

Conflicts of interest

The authors declare no conflicts of interest.

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