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Research Article

Life Cycle and Environmental Impact Assessment of Sustainable Energy Systems in Building Construction: Comparative Analysis of Fossil Fuels and Solar Energy in Mashhad

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Abstract

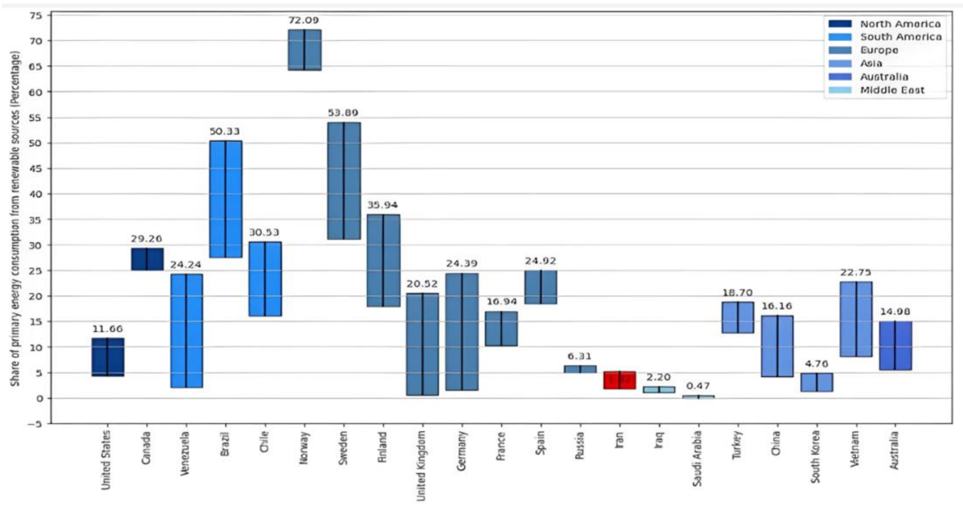
Rapid urbanization and the growing demand for sustainable development have emphasized the need to transition from fossil fuels to renewable energy sources in the construction sector. This study presents a comprehensive Life Cycle Assessment (LCA) and Environmental Impact Assessment (EIA) to compare the carbon footprints of fossil fuel-based and solar energy systems in residential buildings in Mashhad, Iran. Results from Revit simulations and MATLAB modeling based on Leopold matrix highlight the significant advantages of solar energy, with life cycle CO_2 emissions peaking at only 2.5 kg in the most emission-intensive months, compared to 120 kg for fossil fuels during electricity generation in July. Furthermore, the annual cumulative emissions of fossil fuels reached nearly 1800 kg CO_2, whereas solar energy remained under 100 kg CO_2. These findings show the critical role of solar energy in achieving sustainability. The research offers actionable insights for reducing greenhouse gas emissions and advancing green engineering practices by addressing the seasonal and lifecycle phases of energy systems.

Keywords: Life Cycle Assessment; Environmental Impact Assessment; Sustainability; Building; Leopold Matrix; Carbon Footprint; Renewable Energy.

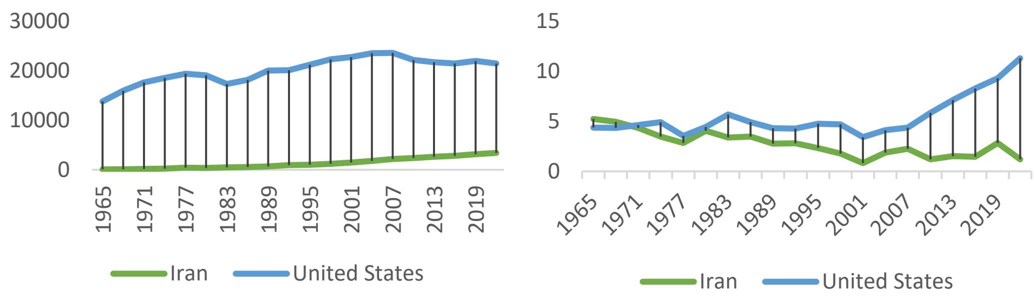
INTRODUCTION

Megacities' population is growing at a faster rate due to urbanization, which raises the demand for structures [1, 2]. A new environmental catastrophe is being created as a result of the increase in construction activities, which raises carbon emissions related to the planning and building processes [3, 4]. The construction sector releases greenhouse gases before to, during, and following project completion, making it a significant source of carbon emissions [5]. Interestingly, inhabitants' energy use when the facility is in operation is the main cause of these emissions [6]. However, by controlling energy consumption and making use of renewable energy sources, these issues can be resolved. For lowering urban pollution and minimizing environmental effects, ideas like Life Cycle Assessment (LCA) [7], Environmental Impact Assessment (EIA) [8], and carbon footprint [9] analysis are essential.

In order to optimize building design and encourage more sustainable practices in the construction sector, life cycle assessment, or LCA, has become an essential tool [10]. Sustainability in this industry is influenced by a number of aspects, such as the availability of resources, economic considerations, environmental circumstances, and the selection of equipment and materials [11]. Energy consumption is one of the most important of these, and it varies greatly by location. These differences are highlighted in Figure 1-a, which shows the percentage of primary energy consumption from renewable sources in different nations. For example, because of their ongoing reliance on fossil fuels, Middle Eastern nations like Iran are not very interested in implementing renewable energy. In contrast, Scandinavian nations, particularly Norway and Sweden, lead with the highest percentages of renewable energy usage, reflecting their strong commitment to sustainable energy. South American countries such as Brazil and Chile also demonstrate significant investment in green technologies. Asia demonstrates a diverse progression in renewable adoption, with Vietnam achieving significant advancements, while South Korea shows comparatively slower development. Similarly, Australia and North America display moderate renewable energy utilization, with Canada surpassing the United States. This data reveals global differences in renewable energy adoption and the transition towards sustainable energy systems. Unlike many other regions, Iran has seen a decline in renewable energy usage [12].



(a)



(b) (c)

Figure 1. (a) Renewable Energy Consumption Change (1965-2023) by Country and Region: Shades of blue show regional growth in renewables, with Iran in red as the only country showing a decrease in renewable adoption. (b) Fossil fuel consumption in Iran and the United States, measured in terawatt-hours (TWh) (1965–2022, in three-year intervals). (c) Comparison of the share of primary energy consumption from renewable sources between Iran and the United States (%) (1965–2022), in three-year intervals [12]

Figure 1b and 1c show that in 1965, renewable resources constituted approximately 5.23% of Iran's total energy mix. However, after fluctuating over the years, this figure significantly dropped to just 1.20% by 2022. Conversely, the United States increased its renewable energy share from 4.37% in 1965 to 11.29% in 2022, marking a growth of nearly 9% over 57 years. This comparison highlights a troubling trend: while both renewable energy and fossil fuel consumption have risen in the United States, Iran has witnessed a decrease in renewable energy use and an increasing dependence on fossil fuels. This shift poses serious concerns for policymakers in Iran, as it exacerbates carbon emissions and air pollution, demanding urgent attention and action [13]. Figure 2 presents the conceptual model of the carbon release cycle within the construction industry's energy provision framework.

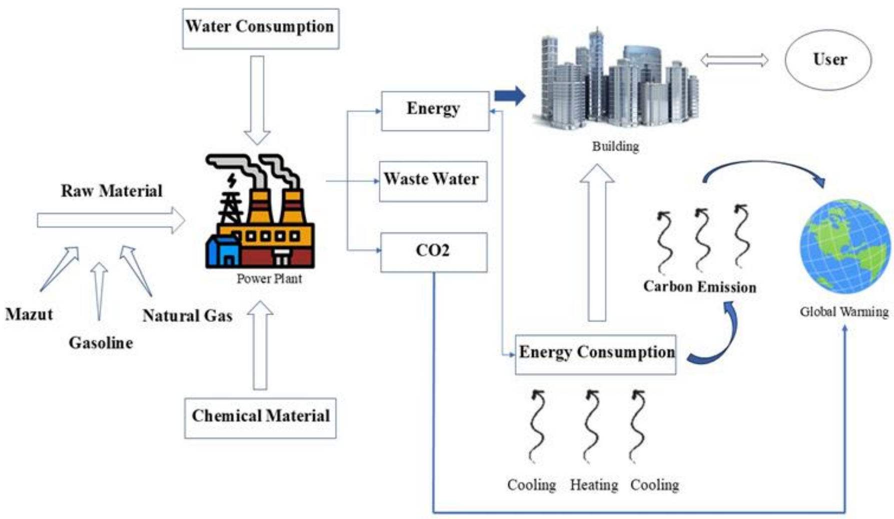


Figure 2. Conceptual model of the carbon release cycle

The construction industry is a significant contributor to carbon emissions, primarily through the release of carbon dioxide into the atmosphere. Specifically, residential buildings emit 30.0 kg of CO_2 per square foot.

In the field of carbon life cycle assessment (LCA) and energy consumption in buildings, numerous research studies are summarized in Table 1. As shown in Table 1, various studies have developed LCA frameworks to accurately determine carbon emissions and other environmental impacts. The table also indicates that energy consumption evaluations are commonly conducted using a variety of tools, while the use of Revit simulations is relatively rare.

Table 1. Summary of the literature review

Researchers	Methodology	Goal(s)	Achievement(s)
Wu et al., 2021 [14]	- Life cycle assessment (LCA), IPCC and AWARE method - Utilized a synthetic index called the footprint-friendly negative index (FFNI) to evaluate battery packs. - Analyzed global warming potential (GWP), water consumption, and ecological impact.	- Assess the environmental footprint of electric vehicle battery packs during production and use phases. - Compare environmental friendliness of different battery types and electricity grids.	- Found that LFP batteries have a lower FFNI compared to NMC batteries. - Identified the battery management system (BMS) as a significant contributor to environmental impact. - Highlighted the influence of electricity grids on environmental footprints.
Alyssa R. et al, 2021 [15]	LCA methodology; Monte Carlo and Sensitivity Analysis Methodology	Quantify the life cycle climate change impact of electricity generated from waste-to-energy, treating electricity as the primary product and disaggregating the life cycle greenhouse gas (GHG) emissions avoided from its additional functions.	System expansion significantly reduced the life cycle climate change impact (LCCCI) of electricity generated from waste-to-energy (WTE), with the baseline LCCCI of the coproduct scenario being 89% lower than that of the electricity scenario.
Raugei et al., 2021[16]	Life-cycle impact and energy assessment method.	- Compare environmental impacts of conventional rooftop and integrated concentrating photovoltaic (PV) in an ecological living module. - Examines the impact of the building sector on energy and environmental benefits of photovoltaic systems	-Potential of integrated concentrating photovoltaic (PV) to reduce reliance on nonrenewable resources compared to traditional grid supplies. - Advanced integrated concentrating solar façade (ICSF) system has minimal environmental impacts from its solar cells, its structural components are less eco-

		compared to traditional municipal utility supplies.	friendly than conventional solar PV - Performance of PV systems vary by location, highlighting the need for context-specific assessments, suggesting potential for district-scale power generation and reduced urban heat effects in suitable climates.
Chodnekar et al., 2021[17]	- Analysis of green building rating systems - Questionnaire survey of construction industry professionals - Analytical Hierarchical Process (AHP) used for pair-wise comparison of criteria to determine their relative importance	Evaluate factors associated with different green building rating systems.	- High capital costs, lack of resources, and lack of skilled personnel hinder the adoption of green construction principles. -Government incentives and regulations are needed to promote energy-efficient techniques. -Increasing market awareness and training for green skills among professionals is crucial.
Abbasi & Noorzai (2020) [18]	- BIM model developed to extract geometric data and material quantities - Extracted information entered into LCA tool (Revit)	-Combine multi-objective optimization algorithm with BIM and LCA - Determine trade-offs between embodied and operational energy with a focus on renewable energy use	- Achieved about a 65% reduction in the building's life cycle energy compared to typical construction practices in Iran. - Identified optimal trade-offs between increasing embodied energy and reducing operational energy, highlighting the benefits of using renewable energy systems like solar panels. - Proposed method effectively utilizes a genetic algorithm to optimize the building design for energy efficiency. - Validated on a case study, demonstrating its versatility in balancing embodied and operational energy.
Opher et al.,2021[19]	- One Click LCA software to assess embodied carbon from cradle to grave. -Data is collected from construction logs, delivery receipts, and site observations.	-Achieve net zero carbon emissions by assessing embodied and operational carbon emissions. -Provide insights for future heritage building	- Embodied Carbon is calculated as 1250 tons of CO_2 equivalent, with 69% attributed to materials, 20% to material replacement, and 11% to construction energy and waste. Significant contributors include

	- TRACI impact assessment method providing characterization factors for Life Cycle Impact Assessment (LCIA), industrial ecology, and sustainability metrics	refurbishments to achieve carbon neutrality.	renewable energy systems (31%) and the raised concrete floor (26%). -Estimated operational energy savings from renewable energy systems and an improved building envelope are expected to offset the embodied carbon of the retrofit within 8 years..
Miguel et al,2021[20]	- Life Cycle Assessment (LCA) to evaluate the environmental impacts of the Bipolar Electrodialysis-based Flow Battery (BEDFB). - Utilized ReCiPe 2016 methodology with SimaPro v9.4 software and Ecoinvent v3.5 database. - Life Cycle Inventory (LCI) compiled data on materials and energy used- Cumulative Energy Demand (CED) and Energy Return on Investment (EROI) were calculated to assess energy efficiency. - Sensitivity Analysis e xamined the impact of varying parameters such as energy/power ratios and chemical compositions on environmental outcomes.	-Environmental Impact Assessment to assess the potential environmental impacts of the BEDFB technology. -Guide eco-design and development. - Support Renewable Integration to e valuate how BEDFB can support wind and solar installations in the Mexican grid. - Socio-Ecological Impact to analyze socio-ecological impacts of deploying BEDFBs in the National Transmission Network (NTN)	- BEDFB showed lower terrestrial ecotoxicity and global warming impact compared to vanadium flow batteries. (Reduced Environmental Impact) - Demonstrated potential to mitigate energy losses from renewable energy sources in Mexico -BEDFB could integrate 304 modules to address current renewable energy losses during peak demand periods. (Scalability and Feasibility) - Minimal use of fossil fuels and chemicals in manufacturing, promoting sustainability in energy storage.

Based on the reviewed research, it is evident that the integration of Revit modeling, LCA, and EIA has not been adequately explored in previous studies. This research aims to fill that gap within the scientific community. The current process leads to significant environmental pollution, resulting in various negative environmental and health impacts. Reducing these pollutants can help mitigate environmental destruction at an accelerated rate. Today, many engineers and builders are focused on constructing low-energy buildings with a higher share of embodied energy throughout the building's life cycle. LCA is used to assess the environmental impact of a building from cradle to grave [21, 22].

The methodology for this study starts with the use of Revit 2019 software to model a residential structure in Mashhad, Iran. A comprehensive digital model of the building, including its architectural design, materials, and spatial geometry, may be produced using this Building Information Modeling (BIM) [23] technology. This modeling phase's main goal is to determine the entire amount of energy needed for lighting, heating, and cooling based on the building's design specifications and the Mashhad-specific climatic factors. This procedure is made easier by Revit's energy analysis features, which enable the evaluation of energy demand based on a number of variables, including orientation, insulation levels, and internal systems like HVAC (heating, ventilation, and air conditioning).

The next step after building modeling is to construct the structure as a system that incorporates simulations of solar energy. Through the integration of renewable energy sources, specifically solar electricity, the study seeks to improve the sustainability of the building. Taking into account factors like direction, efficiency, and local sunshine availability, the solar energy simulations assess the possibility of producing renewable energy using solar panels. This stage is crucial because it establishes the proportion of the building's energy requirements that can be satisfied by renewable energy sources, hence lowering reliance on nonrenewable energy. The study compares the building's energy use to the amount of solar energy produced in order to evaluate the solar system's energy supply. This assessment makes it possible to clearly see how well the solar system meets the building's energy needs. The building's entire energy profile is revealed by recording any decrease in solar energy use as dependency on conventional energy sources.

The framework for this study starts with utilizing Revit 2019 to model a residential structure in Mashhad, Iran. The building's energy consumption is calculated after the sum of the energy used for lighting, heating, and cooling. Furthermore, solar energy simulations are incorporated into the building's design as a renewable resource. The energy supply is then assessed using a solar system, and the LCA and EIA are computed using the output from both MATLAB 2019b (for the Leopold matrix) and Revit (for building modeling and energy simulation). For the LCA, carbon footprint calculations assess the environmental impact of energy supply in residential buildings or organizational buildings, utilizing a gate-to-gate evaluation approach [24–27].

The present research aims to:

- Apply Life Cycle Assessment (LCA) for precise calculation of carbon emissions.
- Present the Leopold Matrix for Environmental Impact Assessment (EIA) of carbon emissions related to energy production.
- Utilize green energy solutions to meet urban energy demands.
- Estimate the impact of solar energy use in buildings.

In the following, the materials and methods, including the Leopold Matrix, are presented in Section 2. Subsequently, Section 3 outlines the key outcomes and results, and Section 4 presents the main conclusions.

MATERIALS AND METHODS

This section outlines the research road map, case study, and Revit simulation steps undertaken in this study.

Research Road Map

The research road map is illustrated in Figure 3. The initial phase consists of a comprehensive literature review and bibliometric analysis, which serve to establish the theoretical foundation and contextual background for the study. Finding current research gaps and laying the groundwork for the analysis that follows depend on this phase.

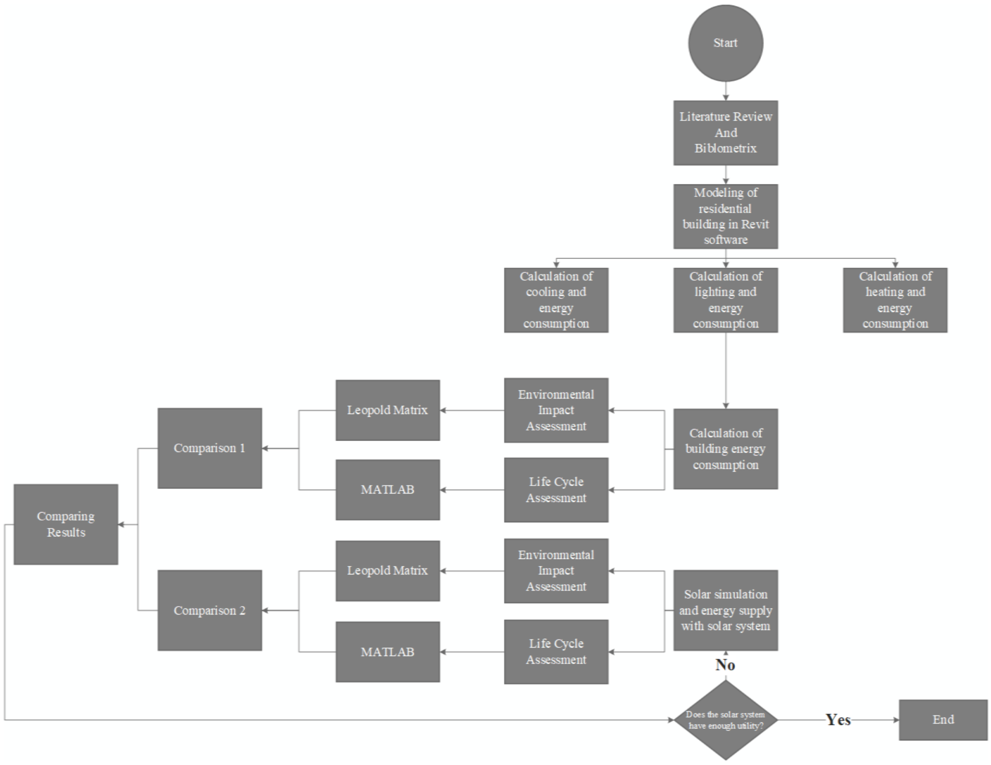


Figure 3. Study schematic map.

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After the model is finished, calculations for lighting, heating, and cooling are made in Revit, incorporating different building systems and allowing for a thorough assessment. Revit software is used to model the building under inquiry after the literature review. In this modeling procedure, the energy performance of the structure and architectural layouts are detailed.

Two analytical paths are then explored:

1. The Leopold Matrix is applied for Environmental Impact Assessment (EIA), while MATLAB 2019b is utilized for Life Cycle Assessment (LCA) to quantify the building's energy consumption. A thorough assessment of the environmental effects linked to the building's energy consumption is made possible by this dual method.

2. In order to assess the viability and efficiency of incorporating a solar system into the building's energy portfolio, solar simulation and energy supply calculations are also carried out in a way akin to the earlier method.

In order to determine whether installing a solar system has a major positive impact on sustainability and energy efficiency, the outcomes of the two analytical routes are finally compared. In order to improve energy performance in comparable architectural contexts and guide future design decisions, this comparative analysis is essential.

Case Study

Iran's second-largest city, Mashhad, is situated in the country's northeast. With 3,001,184 residents, it is the provincial capital of Razavi Khorasan. As seen in Figure 4, the city is located at 36.20º North latitude and 59.35º East longitude.

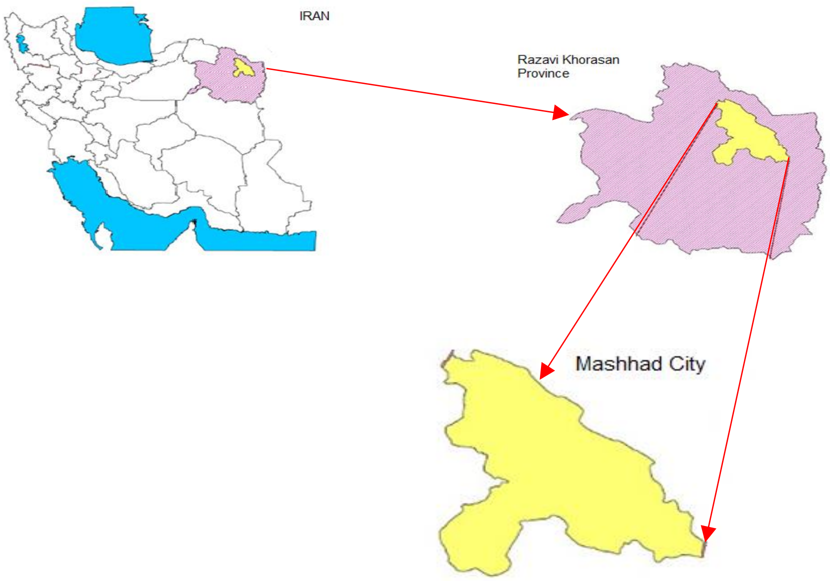


Figure 4. Mashhad is located in Iran's Razavi Khorasan Province.

Revit Modelling

During this phase, Revit software was used to model the chosen building, combining all architectural layouts and executive details to produce an accurate picture. Accurately placing structural components, interior finishes, and building systems—all necessary for carrying out a thorough analysis—was part of the modeling process.

After finishing, Autodesk Insight will get the Revit output for energy analysis. In order to assess the building's energy performance and find areas where energy efficiency can be improved, this stage is essential. A thorough evaluation of the building's energy use is made possible by the use of Insight, with the goal of lowering operating expenses and minimizing environmental effect.

The following are the modeled building's specifications:

- Type of Building: Concrete
- Number of Floors: Four, including a ground floor
- Dimensions: 17.13 m x 9.79 m

This modeling approach not only facilitates energy analysis but also provides insights into the overall performance of the building within the context of energy efficiency. Figure 5 presents the floor plan for the discussed building, highlighting the various parts and functions within the plan.

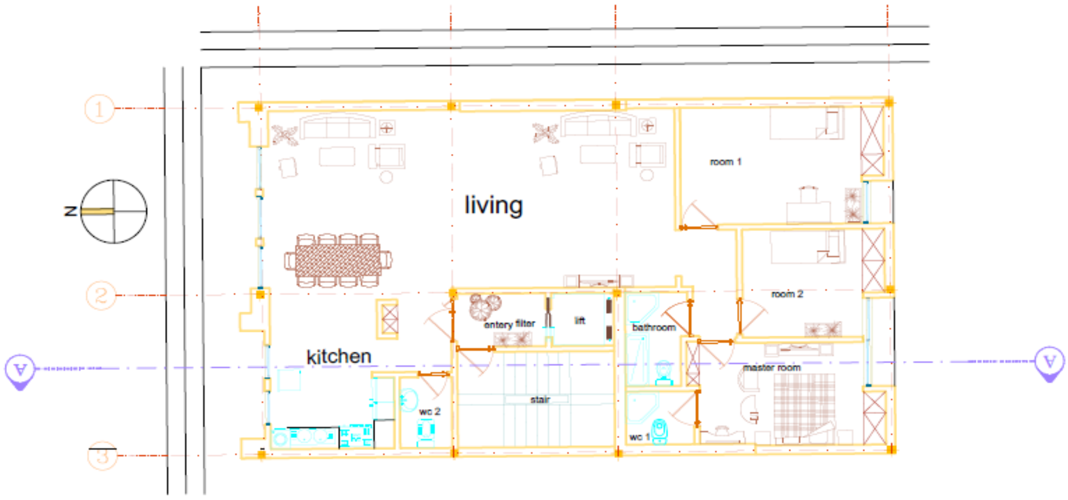


Figure 5. architectural plan of the first floor

This graphic is essential for comprehending how the building's many areas affect its total energy usage. Examining the layout makes it simpler to pinpoint important locations with high energy requirements, like HVAC systems, lighting, and equipment, all of which are crucial for determining the building's environmental effect.

Environmental Impact Assessments (EIAs), especially those that examine a building's carbon footprint, necessitate intricate computations that consider a number of factors. Estimating the greenhouse gas emissions linked to the building's energy use is the main focus of the assessment. Although particular approaches may vary based on the tools and scope employed, the basic procedure adheres to the essential elements listed below:

1. Energy Consumption Calculation

Finding out how much energy the building uses overall is the first step. This covers the energy required for heating, cooling, power, and other operating needs. To give a thorough picture of the building's energy profile, each energy source is measured.

To standardize the comparison of various energy kinds, the total consumption is transformed into a common energy unit, such as megajoules (MJ) or gigajoules (GJ), after it has been determined.

2. Emission Factor

The emission factor for each energy source must be ascertained after the energy consumption has been calculated. The quantity of carbon dioxide (CO_2) or equivalent greenhouse gases (CO2e) released per unit of energy produced is represented by an emission factor, which is a coefficient. For example, renewable energy sources like solar or wind have lower emission factors than fossil fuels like coal or natural gas.

The standard unit of measurement for emission factors is kilograms of CO_2 equivalent per unit of energy (kg CO2e/GJ). It is possible to estimate the overall emissions related to the building's energy use by knowing the emission factor for each energy source.

3. Carbon Footprint Calculation

The total energy usage is then multiplied by the associated emission factor for each energy source to determine the building's carbon footprint. This stage calculates the building's carbon footprint, which measures the environmental impact of its energy use.

A comprehensive picture of the building's contribution to greenhouse gas emissions is provided by the final stage, which entails adding up all of the emissions from various sources to determine the building's overall carbon footprint.

The carbon footprint (CF) can be mathematically expressed as equation (1):

$$CF = \Sigma_i (Energy_i \times EmissionFactor_i) \quad (1)$$

Where i represents each energy source.

Making decisions about how to lower emissions, increase energy efficiency, and even include renewable energy sources into the building's design requires an understanding of the carbon footprint. The success of these interventions can be assessed by comparing the carbon footprint before and after putting methods like solar energy or more efficient HVAC systems into place.

The impact of external environmental conditions, such temperature and radiation, on the building's energy consumption and carbon footprint must be taken into account in addition to assessing the efficacy of energy interventions. Higher air temperatures are directly associated with higher radiation levels, as shown in Figure 6a. This has a substantial impact on energy usage, especially when it comes to cooling. January and February exhibit somewhat lower energy usage than other months, albeit the difference is not statistically significant, according to an analysis of the year-over-year trends of energy consumption, as shown in Figure 6b. On the other hand, July and August have the highest monthly energy use, which comes to about 300 kWh. The increasing reliance on cooling equipment, such air conditioning, during the hotter summer months is the cause of this uptick. These findings highlight how crucial it is to incorporate climate factors into evaluations of a building's energy efficiency. We can find possibilities to optimize energy systems by acknowledging the relationship between environmental conditions and energy use. In addition to increasing efficiency, these modifications help to lessen the building's total environmental effect.

Figure 6. (a) Correlation between temperature and radiation, (b) Monthly energy consumption, (c) Monthly energy consumption and PV Energy

The next observations, which continue the examination of energy dynamics, provide a monthly comparison of photovoltaic (PV) energy output and consumption, highlighting seasonal fluctuations and their consequences for energy management. Figure 6c shows a comparison between the monthly energy production from photovoltaic (PV) systems and the annual energy usage. The following are the main takeaways from this chart:

Winter Low output Months: Due to shorter daylight hours and less intense sunshine, solar energy output is much lower in January, February, November, and December. Even while energy use is comparatively low during these months, it is still greater than the energy generated by the sun.

High generation Months (Summer): The generation of solar energy peaks between May and September. Because of longer daylight hours and stronger sunshine during this time, the chart shows that energy generation significantly outpaces consumption levels.

Distinction Between Production and Consumption: Energy production continuously exceeds consumption in the majority of months, especially during the spring and summer months of April through September. This extra energy can be saved for later use or supplied back into the system.

Performance Ratio: The solar system's efficiency is demonstrated by its high conversion rate of incoming solar energy into electrical energy, which stands at 88.06%.

Annual Totals: Over the course of a year, the PV system produces 9,817 kWh. With a particular yearly yield of 1,636.23 kWh/kWp (kilowatt-hours per kilowatt peak), the system generates 1,636.23 kWh per year for every 1 kWp of installed capacity. This metric, which takes seasonal and environmental aspects into consideration, shows how effective the system is in actual use. The overall output demonstrates the extent to which the PV system can reduce the building's dependency on outside energy sources by offsetting its energy demand.

In conclusion, the solar system performs exceptionally well in the summer, producing more energy than it uses. In order to meet consumption needs, other energy sources must be used during the winter months when energy production decreases. The system runs very efficiently, as seen by its remarkable 88.06% performance ratio.

Leopold Matrix

This methodology describes how the effects of fossil fuel and solar energy sources on carbon emissions are evaluated. MATLAB 2019b was used for the analysis, which included expert assessments, monthly energy consumption data, and mathematical models to measure and contrast the effects of the two energy sources.

First, the study extracted monthly energy demand data for a fictitious region (in kWh, or kilowatt-hours). January (230 kWh), February (250 kWh), March (270 kWh), April (290 kWh), May (310 kWh), June (330 kWh), July (320 kWh), August (300 kWh), September (280 kWh), October (260 kWh), November (240 kWh), and December (220 kWh) were the respective months with the highest energy demands.

Both fossil fuels and solar energy were assumed to contribute equally to the overall energy demand for the sake of this analysis, with each source meeting 50% of the monthly energy requirements. Equations (2) and (3) were used to determine the contribution from each energy source:

$$solar\ Energy\ (i) = 0.5 \times energy\ Demand\ (i) \quad (2)$$

$$fossil\ Fuel\ (i) = 0.5 \times energy\ Demand\ (i) \quad (3)$$

In which I stand for every month from January through December. The environmental effects of the two energy sources on carbon emissions might be easily compared thanks to this assumption.

To evaluate the environmental effects of fossil fuels and solar energy on carbon emissions, expert opinions were gathered. Each month, seven experts assigned grades based on their assessments of each energy source's environmental impact. A matrix representing the expert scores for solar energy was created, with each row representing the monthly scores of a particular expert. For the effect scores of fossil fuels, a comparable matrix was created.

The expert scores for solar energy were as follows:

[15,20,25,30,35,40,45,40,35,30,25,20],

[10,15,20,25,30,35,40,35,30,25,20,15],

[20,25,30,35,40,45,50,45,40,35,30,25],

[15,20,25,30,35,40,45,40,35,30,25,20],

[10,20,30,40,50,60,70,60,50,40,30,20],

[20,30,40,50,60,70,80,70,60,50,40,30],

[10,15,20,25,30,35,40,35,30,25,20,15]

The following were the expert scores for the effects of fossil fuels:

[60,65,70,75,80,85,90,85,80,75,70,65],

[65,70,75,80,85,90,95,90,85,80,75,70],

[70,75,80,85,90,95,100,95,90,85,80,75],

[60,65,70,75,80,85,90,85,80,75,70,65],

[70,80,90,100,90,80,70,80,90,100,90,80],

[80,90,100,90,80,70,60,70,80,90,100,90],

[65,70,75,80,85,90,95,90,85,80,75,70]

All seven experts' expert scores were summed to determine the average effect of each energy source on carbon emissions. For month j, the average solar impact was determined to be:

$$solar\ Impact\ (j) = \frac{1}{N}\sum_{i=1}^{N} solar\ Impact\ Experts\ (i,j) \tag{4}$$

Where N represents the number of experts. The average fossil fuel impact was calculated similarly:

$$fossil\ Impact(j) = \frac{1}{N}\sum_{i=1}^{N} fossil\ Impact\ Experts(i,j) \tag{5}$$

These averages offer a monthly summary of the perceived environmental effects of fossil fuel and solar energy sources. In order to examine the effects of fossil fuels and solar energy on carbon emissions, the Leopold Matrix was created. The following formula was used to create the matrix, which shows the average monthly impacts of each energy source:

$$leopold\ Matrix = \begin{bmatrix} solar\ Impact \\ fossil\ Impact \end{bmatrix} \tag{6}$$

This matrix offers a clear comparison of the relative impact of each energy source on monthly carbon emissions, highlighting key differences in their environmental footprints.

MATLAB Analysis

The monthly energy consumption, E_m, is defined as a vector representing the energy used (in kilowatt-hours, kWh) for each month of the year:

$$E_m = [250, 240, 230, 220, 210, 200, 210, 220, 230, 240, 250, 240\,]$$

This vector indicates that January's energy consumption is 250 kWh, February's is 240 kWh, and so forth.

Emission Factors for Energy Sources: Emission factors represent the co_2 emissions produced (in kilograms) per kilowatt-hour of energy consumed during each lifecycle phase.

Solar Energy Emission Factors:

Site Assessment: $e\_{solar,site}$=0.001 kg co_2/kWh

System Design: $e_{solar,design}$=0.002 kg co_2/kWh

Permits: $e_{solar,\ permits}$=0.001 kg co_2/kWh

Procurement: $e_{solar,\ procurement}$=0.003 kg co_2/kWh

Installation: $e_{solar,\ installation}$=0.01 kg co_2/kWh

Commissioning: $e_{solar,\ commissioning}$=0.001 kg co_2/kWh

Grid Connection: $e_{solar,\ grid}$=0.002 kg co_2/kWh

Maintenance: $e_{solar,\ maintenance}$=0.001 kg co_2/kWh

Decommissioning: $e_{solar,\ decommissioning}$=0.005 kg co_2/kWh

Fossil Fuels Emission Factors:

Exploration: $e_{fossil,exploration}$=0.005 kg co_2/kWh

Extraction: $e_{fossil,\ production}$=0.02 kg co_2/kWh

Production: $e_{fossil,\ production}$=0.015 kg co_2/kWh

Transportation: $e_{fossil,\ transportation}$=0.02 kg co_2/kWh

Refining: $e_{fossil,\ refining}$=0.025 kg co_2/kWh

Electricity Generation: $e_{fossil\ ,electricity}$=0.5 kg co_2/kWh

Distribution: $e_{fossil,\ distribution}$=0.01 kg co_2/kWh

Environmental Management: $e_{fossil,\ management}$=0.002 kg co_2/kWh

Decommissioning: $e_{solar,\ decommissioning}$=0.005 kg co_2/kWh

Total Lifecycle Emissions Calculation: The total lifecycle emissions are calculated by summing the emission factors for each phase and then multiplying by the monthly energy consumption.

Fossil Fuels Total Emission Factor: The total emission factor for fossil fuels, $e_{fossil,total}$, represents the combined emissions from all lifecycle phases of fossil fuel energy production, see equation (7):

$$e_{fossil,\text{total}}=e_{fossil,\text{exploration}}+e_{fossil,\text{extraction}}+e_{fossil,\text{production}}+e_{fossil,\text{transportation}}+e_{fossil,\text{refining}}+e_{fossil,electricity}+e_{fossil,distribution}+e_{fossil,management}+e_{fossil,decommissioning} \quad (7)$$

Substituting the values:

$$e_{fossil,\text{total}}=0.005+0.02+0.015+0.02+0.025+0.5+0.01+0.002+0.005=0.0602$$

Therefore, the total monthly emissions for fossil fuels, for each month m, are calculated as:

$$Emissions_{fossil,total,m}=E_m \times e_{fossil,\text{total}} \quad (8)$$

For example, in January ($E_1 = 250kWh$):

$$Emissions_{fossil,total,January} = 250 \times 0.602 = 150.5kg\ CO2$$

Solar Energy Total Emission Factor: Similarly, the total emission factor for solar energy, $e_{solar,total}$, is calculated as shown in equation (9).

$$e_{solar,total} = e_{solar,site} + e_{solar,design} + e_{solar,permits} + e_{solar,procurement} + e_{solar,installation} + e_{solar,commissioning} + e_{solar,grid} + e_{solar,maintenance} + e_{solar,decommissioning} \quad (9)$$

Substituting the values:

$$e_{solar,\text{total}}=0.001+0.002+0.001+0.003+0.01+0.001+0.002+0.001+0.005=0.026$$

Therefore, the total monthly emissions for solar energy, for each month m, are calculated as equation (10):

$$Emissions_{solar,total,m} = E_m \times e_{solar,total} \quad (10)$$

For example, in January ($E_1 = 250kWh$):

$$Emissions_{solar,total,m} = 250 \times 0.026 = 6.5\ kg\ CO2$$

RESULTS AND DISCUSSIONS

This section presents a detailed analysis of the carbon emissions associated with solar energy and fossil fuels over a one-year period. Figure 7 illustrates a radar chart comparing the carbon emissions impact of solar energy versus fossil fuels over a twelve-month period. This visualization is based on average expert assessments of the environmental impacts associated with each energy source. The following discussion interprets these findings, as reflected in the chart, and considers their broader implications.

In Figure 7, the blue line on the radar chart represents the carbon emissions impact of solar energy. Solar energy consistently shows a low impact on carbon emissions throughout the year, with impact scores averaging from 15 in January to 40 in June. The lowest impact score, around 15, is seen in January and December, likely due to reduced sunlight availability affecting solar energy production. The peak impact in July, at approximately 40, reflects increased sunlight and higher solar output. This trend reinforces solar energy's environmentally friendly nature, maintaining a minimal carbon footprint across seasons.

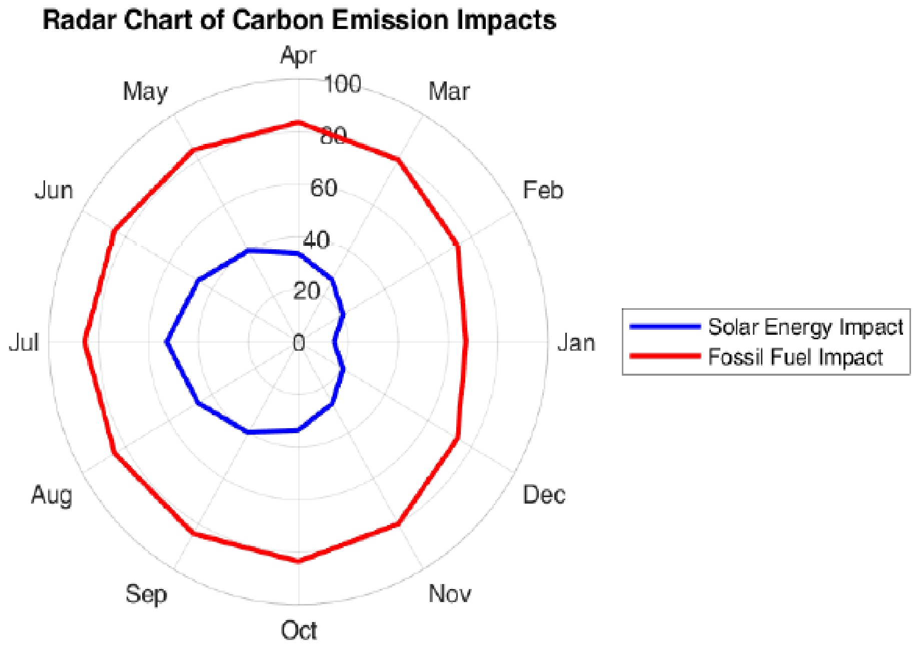


Figure 7. Radar chart of carbon emissions impact

Conversely, the red line illustrates the impact of fossil fuels on carbon emissions, which is considerably higher. Fossil fuel impact scores begin at 60 in January, peak near 100 in July, and decrease to around 65 by December. Higher scores during the summer can be attributed to increased energy demands, particularly for cooling. The peak impact score of approximately 100 in July underscores a high reliance on fossil fuels during peak energy demand periods, highlighting their substantial contribution to carbon emissions.

The radar chart clearly illustrates the significant differences in carbon emissions between the two energy sources. Solar energy maintains a low, stable emissions profile, contrasting sharply with the high and variable impact of fossil fuels. This disparity is especially evident in January, where fossil fuel emissions are more than double those of solar energy, underscoring solar energy's environmental benefits. These results have important policy ramifications. They stress how vital it is to take action to lessen reliance on fossil fuels and hasten the uptake of renewable energy sources like solar. Emissions reductions could be greatly impacted by specific policy goals, such as reaching carbon neutrality by 2050 or cutting the use of fossil fuels by 50% during the next ten years. In addition to improving energy security and resilience, switching to solar energy for building operations and community energy sources could reduce overall carbon footprints. Policymakers should support research to improve the efficiency of solar technology and energy storage systems, as well as take into account incentives to encourage the use of solar energy. To significantly cut carbon emissions, future research should concentrate on maximizing energy production and consumption during periods of high demand.

The radar graphic also offers a straightforward, numerical comparison of the environmental effects of fossil fuels and solar energy, highlighting the urgent need for a rapid and sustained transition to renewable energy in order to reach global climate targets. Increasing the use of solar energy has significant potential to lower carbon emissions, advance efforts to mitigate climate change, and support environmental sustainability. But as Garvin Heath et al. (2024) [28] point out, further legislative actions, technical developments, and greater funding for renewable energy will be necessary to achieve meaningful worldwide carbon reductions.

A thorough examination of the lifecycle greenhouse gas emissions linked to different energy sources is given by Pehl et al. (2017) [29], who point out important distinctions: solar power emits 6 grams of CO_2 equivalent per kWh, whereas nuclear and wind power each produce 4 grams. Fossil fuels, on the other hand, have significantly greater emissions: 109 gCO_2e/kWh for coal with carbon capture and storage (CCS), 78 gCO_2e/kWh for gas with CCS, and 97 gCO_2e/kWh for hydropower and bioenergy, respectively. Even after accounting for emissions from their production and building processes, the study shows that nuclear, wind, and solar power have much smaller carbon footprints than fossil fuels like coal and gas. This suggests that throughout the course of their whole existence, renewable energy sources are more environmentally beneficial. Because of the energy needed to manufacture and build them, critics frequently claim that renewable energy sources like solar and wind have a hidden carbon footprint. According to the analysis, the emissions reductions from eliminating fossil fuels over the course of these processes' operating lifespan surpass any "carbon debt" that may be related to them. Embodied energy, or the energy needed to construct power plants and supply them with fuel and other essential inputs, is also measured in the study. It concludes that the embodied energy of fossil fuels is substantially higher than that of solar, wind, and nuclear power. For instance, the energy required for construction and fuel supply causes a coal-fired power plant to counteract 11% of its energy output; nuclear power only offsets 5%, and wind and solar power even outperform it. These results support our conclusions that solar energy has a lower carbon footprint than fossil fuels.

These conclusions are further supported by a study by Gyamfi et al. (2021) [30] that looked at the environmental consequences of different energy sources, such as coal, nuclear, oil, gas, and renewables, on anthropogenic effects in E7 economies. The study was published in the Journal of Cleaner Production. Our chart's representation of solar energy's lower carbon emissions profile is supported by the study's conclusion that renewable sources, like solar energy, have substantially smaller environmental impacts than fossil fuels.

Increased use of renewable energy greatly lowers CO_2 emissions, according to a 2017 study by Dong et al. [31] that looked at the impact of natural gas and renewable energy consumption on CO_2 emissions throughout the BRICS countries. This result is consistent with our findings that solar energy has a negligible environmental impact, as shown in the radar chart. Similar to this, a 2020 study by Adedoyin et al. [32] examines the economic impact of economic growth, energy consumption, and regulatory measures on coal-related CO_2 emissions within the framework of the BRICS. According to the study, carbon damage fees and other regulatory measures have a surprisingly favorable impact on CO_2 emissions, highlighting the need for stronger environmental laws in countries that rely heavily on coal. This study emphasizes how crucial it is to shift the energy balance toward renewable sources in order to promote sustainable growth and solve the world's environmental problems.

The impact of fossil fuel and renewable energy consumption on sustainable economic development in emerging economies was studied by Faisal et al. (2021) [33]. According to their research, which was published in Environmental Science and Pollution Research, switching to renewable energy sources like solar can greatly lower CO2 emissions and advance sustainable development. This lends more credence to the relatively smaller impact of solar energy that our study found.

In a landmark study, Grossman and Krueger (1995) [34] looked at how economic expansion affects the environment and how different energy sources either exacerbate or lessen these effects. In line with our findings, their investigation of embodied energy—the energy used throughout the course of an energy source's lifecycle—confirms that renewable energy sources, including solar energy, offer a more sustainable option with fewer total CO2 emissions than fossil fuels.

The following heatmaps show the findings of a Life Cycle Assessment (LCA) that was carried out to measure the carbon dioxide emissions linked to the lifecycles of solar energy and fossil fuels, examined on a monthly basis over a 12-month period. Figure 8 (a), (b) shows that each row corresponds to a distinct lifecycle phase for each energy source, with color intensity reflecting the magnitude of emissions for each phase. The fossil fuel heatmap reveals significantly higher emissions, with phases like Electricity Generation and Refining exhibiting the greatest environmental impact. Emissions from these phases peak during the summer months, with Electricity Generation reaching approximately 120 kg CO_2 in July and Refining around 80 kg CO_2. This seasonal pattern likely corresponds to increased energy demand or production output during these months (Figure 8 (a)). In contrast, the solar energy heatmap shows the same seasonal trend but with much lower emissions across all phases. The Installation phase is the primary contributor, peaking at about 2.5 kg CO_2, particularly in January and November. This pattern emphasizes the reduced environmental impact of solar energy, as shown in the LCA results. Even in its most emission-intensive phases, solar energy remains significantly less impactful than the least intensive fossil fuel phases. These LCA findings highlight the substantial environmental benefits of shifting from fossil fuels to renewable energy sources like solar power, see Figure 8 (b).

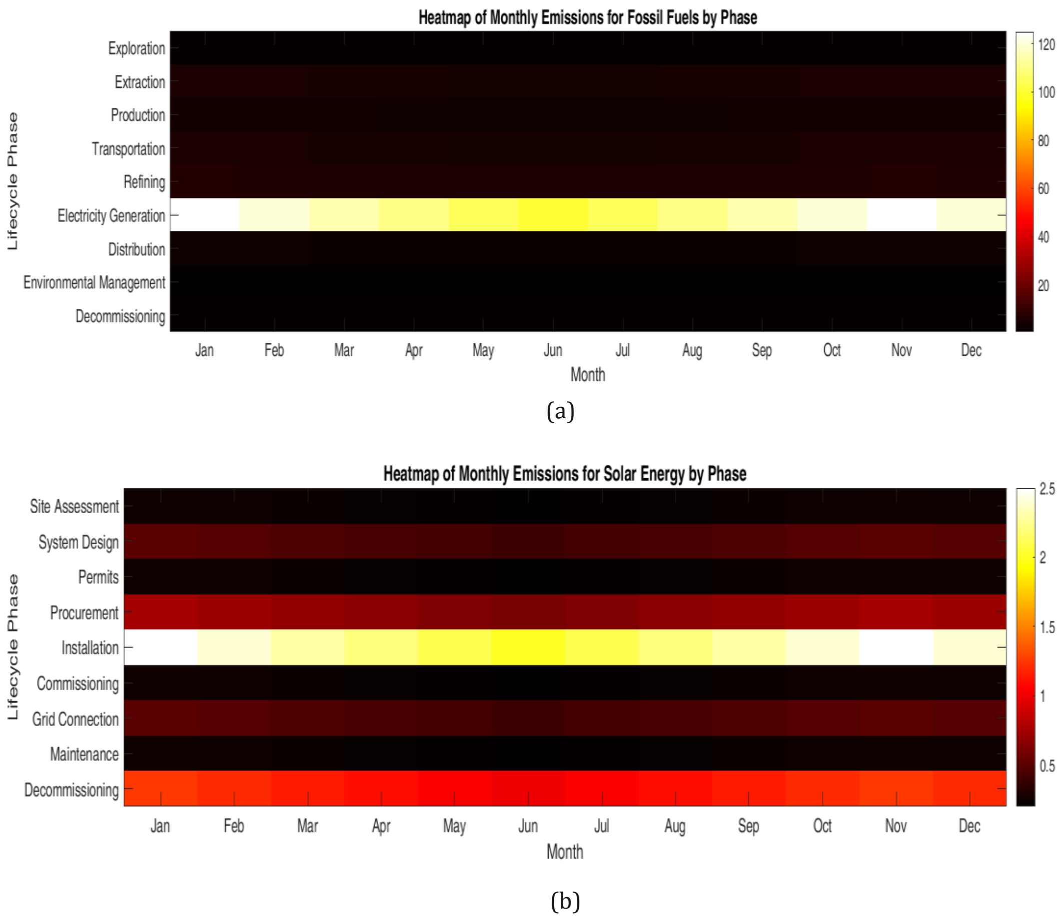
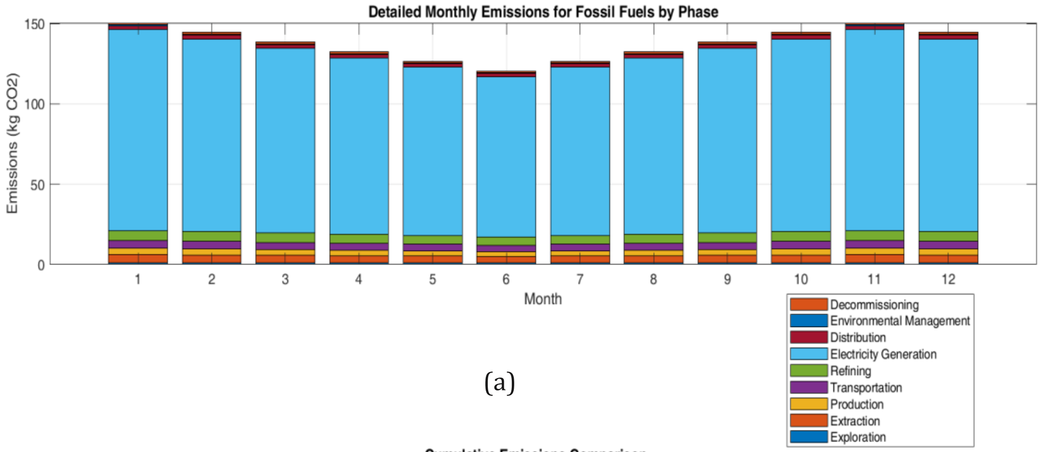


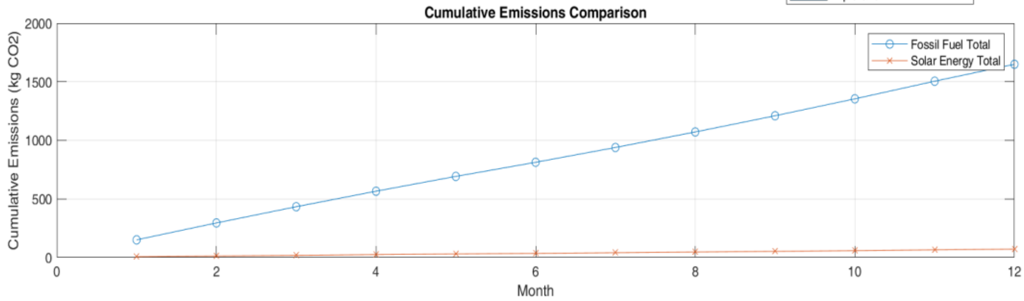
Figure 8. (a) Heatmap of Monthly Emission for Fossil Fuels, (b) Heatmap of Monthly Emissions for Solar Energy

The stacked bar chart at Figure 9 (a) provides a detailed monthly breakdown of CO_2 emissions from fossil fuels, illustrating the cumulative impact across various production phases. Electricity Generation stands out as the most substantial contributor, represented by a prominent blue section in each bar, overshadowing other phases like refining, transportation, and extraction. Emissions remain consistently high across all months, reflecting a steady demand and consumption of fossil fuels throughout the year, with average monthly emissions around 140 kg CO_2.

The line graph at Figure 9 (b) illustrates the cumulative CO_2 emissions from fossil fuels and solar energy throughout the year, highlighting a stark contrast between the two sources. Fossil fuels exhibit a steady increase, reaching nearly 1800 kg CO_2 by year-end, whereas solar energy’s cumulative emissions remain significantly lower, totaling just over 100 kg CO_2. This visual representation underscores the substantial difference in environmental impact between the energy sources, emphasizing solar energy's much cleaner profile compared to traditional fossil fuels.



(a)



(b)

Figure 9. (a) Detailed Monthly Emissions for Fossil Fuels by Phase, (b) Cumulative Emissions Comparison

The result of this study offers a comprehensive comparison of GHG emissions across various energy sources, underscoring that renewable sources like solar have significantly lower life cycle emissions than fossil fuels. The National Renewable Energy Laboratory (NREL) has found that emissions from coal energy generation can range from 1 kilogram CO_2e/kWh on average to 1.8 kg CO_2e/kWh [35]. On the other hand, photovoltaic (PV) solar energy system emissions generally average about 0.05 kg CO_2e/kWh, which is consistent with our heatmap data, which indicates that solar emissions peak at just 2.5 kg CO_2 during the months with the highest emission levels.

The carbon footprint for producing 1 kWh of energy from solar PV systems ranges from 25.2 to 43.6 g CO_2 equivalent, which is significantly less than emissions from fossil fuels, according to Task 12 of the International Energy Agency’s Photovoltaic Power Systems (IEA-PVPS) Program [36]. This is in line with our heatmap data, which further emphasizes solar energy's lower environmental effect by demonstrating much lower emissions across all phases. The trends seen in our LCA results are supported by the Fact Sheet:

Environmental Life Cycle Assessment of Electricity from PV Systems, which was released under Task 12 (International Energy Agency Photovoltaic Power Systems (IEA-PVPS) Programme, [37]) and highlights improvements in PV technology and efficiencies that lead to these low emissions.

In another study, Asdrubali (2020) [7] reports that enhancing energy efficiency in buildings with high non-renewable energy consumption can significantly reduce both operational energy use and pollutant emissions. The study concludes that energy retrofits—such as improving thermal performance, increasing system efficiency, and integrating more renewable energy sources—can lower operational energy consumption by up to 89% and reduce pollutant emissions by up to 88%.

A recent study from the University of Exeter and the Stanford Doerr School of Sustainability highlights that global carbon emissions from fossil fuels remain at record levels, driven by continued reliance on coal, oil, and gas, with fossil fuels contributing nearly 37 billion tons of CO_2 in 2023 alone. In contrast, life-cycle emissions from renewable energy sources like wind and solar are significantly lower than those of fossil fuel power plants. Fossil fuels add massive amounts of carbon dioxide to the atmosphere through direct burning, whereas wind and solar produce no emissions during operation, resulting in far lower overall life-cycle emissions. While wind and solar power do involve initial emissions from production, installation, and maintenance, these are minimal compared to the continuous emissions from fossil fuel plants. Consequently, expanding wind and solar would contribute substantially less to global emissions over their life cycles—consistent with the patterns observed in the heatmap analysis for fossil fuels and the Cumulative Emissions Comparison discussed previously. Additionally, the report notes that 27 countries successfully reduced emissions over the past decade while experiencing economic growth, suggesting that scaling up renewable energy can support economic stability. Therefore, life-cycle emissions from renewables are not only substantially lower but also align well with sustainable growth objectives [38].

Finally, addressing potential variability and limitations in our study is crucial for understanding its applicability. While our analysis is rooted in data specific to Iran, geographical variations in resource availability, weather conditions, and energy demands can significantly influence the applicability of our findings to other regions. Future research should seek to refine the modeling assumptions, incorporating a broader array of climates and geographical contexts to enhance the generalizability of the results. Furthermore, exploring advancements in energy storage technology could provide a comprehensive understanding of how to optimize solar energy's contribution to the energy grid, particularly during peak demand periods. In general, our study reaffirms the critical need for transitioning from fossil fuels to renewable energy sources, especially solar energy, to achieve significant emissions reductions. The findings presented herein not only underscore the environmental advantages of solar energy but also advocate for concrete policy measures and technological advancements aimed at fostering a sustainable energy future.

CONCLUSION

This study highlights the difference in environmental impact between fossil fuels and solar energy, providing critical evidence to support the transition to renewable energy systems in building construction. The results demonstrate that fossil fuels consistently exhibit high emissions, particularly in electricity generation and refining phases, peaking at 120 kg CO_2 and 80 kg CO_2, respectively, during summer months. In contrast, solar energy emissions remain minimal, with installation contributing the highest emissions at only 2.5 kg CO_2 in the most intensive months. The cumulative annual emissions further reinforce this disparity, with fossil fuels surpassing 1800 kg CO_2 compared to just over 100 kg CO_2 for solar energy. This large decrease is consistent with research from the National Renewable Energy Laboratory (NREL) and the International Energy Agency (IEA), which shows that solar systems have substantially lower carbon footprints than coal, with an average of 0.05 kg CO_2 e/kWh as opposed to up to 1.8 kg CO_2 e/kWh. Solar energy is a key component of sustainable energy solutions because of its nearly negligible direct emissions, minimal life cycle impact, and significant potential to mitigate climate change. Policymakers may significantly advance the global climate goals by incorporating renewable energy sources into urban planning and developing photovoltaic technology.

Author Contributions

Conceptualization, D.S. and R.Y.K.; methodology, A.As.; software, M.G.; validation, M.G. A.An, and R.M.; formal analysis, D.S.; investigation, M.G.; resources, R.M.; data curation, A.As.; writing—original draft preparation, M.G., A.A and D.S.; writing—review and editing, A.An, R.M.; visualization, M.G.; supervision, R.Y.K. A.An. and M.G. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to ongoing collaborations.

Conflicts of Interest

The authors declare no conflicts of interest.

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