Life Cycle Analysis (LCA) and Life Cycle Cost (LCC) Analysis model for Renewable Energy System (RES) powered Home

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Abstract

The increasing global energy demand drives the need for a sustainable energy system. Residential building consume a large amount of this energy, there renewable energy sources are increasingly employed in domestic context to reduce the CO2 emission while satisfying the energy needs. Therefore, Photo-voltaic Panels (PV) are being integrated in the energy system of houses. Moreover, energy storage and optimization techniques are used to further improve the performance of the energy system. Nevertheless, a Life Cycle Assessment (LCA) and a life cycle costing (LCC) evaluation approach is needed to assess the sustainability of the system. In this paper, we consider an Solar powered residential energy system based on three different scenarios. In the first scenario, the energy is supplied to the house through a grid and a PV. In the second scenario, a storage system is added to store excess energy for future use. The last scenario consider an optimization algorithm to control the electricity flow between the energy storage, the energy load and supply. We applied an LCA and an LCC approach integrated with Analytic Hierarchy Process (AHP). The results shows that scenario one perform better than scenario 2 and 3

Keywords: Life Cycle Assessment, Life Cycle Costing, Sustainability, Multiple criteria decision-making, Analytic hierarchy process (AHP), Biomimicry

1. Introduction

Global Energy demand is in the rise and is assumed to increase by 1.2% by 2040 [?]. A large portion of this energy is directed toward building. High energy demand from residential building drives the need for a renewable source of energy to lessen the environmental impact of green house gases emission and fossil fuel wastage. The integration of Renewable Energy System (RES) to power residential building is becoming popular. To this end, PV are frequently utilized to provide a sustainable approach to supply the energy demand of these buildings by reducing the amount of consumed fossil fuel energy. However, the stochastic nature of solar energy availability can limit the application of PV systems in this area. Therefore, a storage system is usually integrated to save excess energy for future use. Furthermore, a flow control is required to manage the flow of energy between the local energy producer systems, the appliances, and the energy system according to the energy availability.

The authors in [?] proposed an optimization solution to reduce the amount of energy consumed from the the grid, maximize energy utilization from the PV, and reduce the Financial cost of the electricity bill. The aim is to design a sustainable system at the lowest cost possible. The authors demonstrated the effectiveness of their solution . However, a thorough analytical approach is required to account for the environmental, economical, and social impact.

Although relying on a green source of energy and optimization solution is a promising approach to achieve sustainability, the introduction of the PV system and needed ICT technologies to realize the solution can have an adverse effect on the sustainability performance. Hence, a Life Cycle Assessment (LCA) is required to assess the impact of the proposed solution on the environmental. In fact, RES are usually assessed considering both LCA, Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA).

The authors in [?] conducted a review of best evaluation approaches to assess the sustainability of a system. According to the obtained results, LCA and Multi-Criteria Decision Making (MCDM) perform poorly when applied separately and an integrated approach is recommended. Moreover, the results show that the MCDM method, Analytic Hierarchy Process (AHP) is widely utilized among the academia

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due to its simplicity and robustness when applied in the context of sustainable evaluation of energy systems.

In this paper, we apply an integrated AHP and LCA evaluation performance of the proposed energy systems evaluated in [?]. In section 2, we carry a literature review of different evaluation methods to assess the performance of RES system in residential building, section 3 define the search methodology to compile the papers used for the evaluation metrics selection, section 4 introduces the different scenarios to be evaluated, section

2. literature review

The assessment of RES in residential building has been extensively studied through the literature given the significant importance of renewable energy to improve the sustainability of energy systems. In [?], the authors employed LCA and Multi-criteria Decision Analysis (MCDA) to evaluate the performance of an off-grid system to meet the electricity and heating requirement. According to the authors, three factors affect the assessment of a home energy system including the used technology, the energy demand, and the evaluation indicator. The energy demand is highly dependent on the type of appliance used in the house. Therefore, the selection of these appliance can be critical to reduce energy consumption and green house emissions. For instance, hot water is responsible for 18% of energy consumption as per paper [?]. Evaluation of the LCA performance of five heater systems based on global warming potentials showed that solar heater with electrical backup perform best. Alternatively, an approach for professionals to select the optimal thermal system for a given solar system is proposed in [?] in order to reduce energy expenditure and ensure thermal comfort.

In this paper, we deal mainly with the choosing the best environmental, economical and social indicators to evaluate the performance of an RES that can be implemented in residential buildings/houses to optimize the sustainability of the system. Both environmental and economical factors play a critical role to evaluate the performance of a house Energy system. The authors in [?] assessed the performance of a solar stand-alone non-grid connected rooftop-mounted structure and a grid-connected rooftop-mounted structure in terms of the Levelised cost of energy (LCOE). The results shows that the grid-connected system perform relatively better. On the other hand, the results from the economical analysis presented in [?] shows that unit cost of energy production in off-grid PV system is lower than conventional powering system. However, the reliance on power from the grid has a high impact on the amount of CO2 emission.

A combined LCA and LCC approach was proposed in [?] employing a mixed integrated linear programming optimization. The results show that the integration of battery technologies is environmentally promising but can incur a higher cost compared to a grid connection scenario. The authors also concluded that PV and batteries which are environmentally optimal can significantly improve their economical performance due to the reducing cost of these technologies. In this paper, we assess the performance of residential energy system powered both by grid and a PV panel according to three scenarios: without batteries, with batteries, with optimization algorithm.

3. Search Methodology

The search Methodology adopted in this paper is divided into five steps as described below:

1. Define the search string.
2. Compile the paper.
3. Define the inclusion and exclusion criteria.
4. Select the relevant paper based on the inclusion and exclusion criteria.
5. Compile the used LCA, LCC, and SLCA metrics by selected paper.

In order to compile papers relevant to the evaluated solution and that can provide insight toward the LCA, LCC, and SLCA metrics that can be used to evaluate the RES proposed in [?], We include the following words or a variation of that to cover the technologies or tools used in the evaluated scenarios: ”Renewable Energy”, ”Energy Solar”, ”Energy Storage”, and ”optimization. We also targeted application-relevant solution so we integrate the word ”Residential” or a variation of it in our search string. We also consider the different evaluation methods to assess the performance of the solution such as: LCA, LCC, SLCA. We also rely on some references used in [?] and [?]. Table 1 presents the used search strings or the reference from which we adopted some of the cited papers, and the number of compiled papers by each string or reference.

The compiled papers are further studied to select the most relevant ones. The selection process is based the inclusion and exclusion criteria listed below:

Inclusion Criteria:

Table 1: Search String for Papers Compilation

Search String / Reference	No. Of papers
("LCA" or "LCC") & ("Renewable Energy")	3
("LCA" or "LCC" OR "SLCA") & ("Renewable Energy")	3
("LCC" or "LCA") & ("Renewable Energy") & ("Smart Home")	1
("LCC" or "LCA") & ("Renewable Energy") & ("Domestic" or "Residential")	2
("LCA" or "LCC") & ("Solar Energy")	8
("LCA" or "LCC") & ("Solar Energy") & ("Domestic" or "Residential")	26
("LCA" or "LCC" or "SLCA") & ("Sustainability Evaluation")	23
[?]	13
[?]	23
Total	**100**

1. Journal Articles.
2. Papers Covering assessments of Energy Solar Systems.
3. Papers Covering assessment of Lithium-ion batteries.
4. Papers implementing LCA, LCC and SLCA evaluation methods.
5. Papers implementing MCDM Evaluation methods.

Exclusion Criteria:

1. Papers applied in a different context (e.g. LCA, LCC and SLCA to evaluate the performance in construction building).

Applying the inclusion and exclusion criteria described above yield a total of 36 papers. These papers have been furthered examined to extract the LCA, LCC, and SLCS metrics used to assess the sustainability of the system studied in each paper. The LCA, LCC, and SLCS metrics are presented in tables 2, 3, and 4 respectively. Figure **??** showcase the steps of the research methodology adopted in our paper.

4. Scenarios Definition

As a case study, our sustainability assessment methodological approach was applied on three different scenarios for RES powered residential house, we considered the lifetime of our case study is 50 years. The general idea is installing a building integrated PV system to locally generate electricity for the house, the house is also connected to the national electricity grid so that when the solar electricity doesn't meet all the house appliances demands, the house gets additional electricity from the grid. The PV can also generate more electricity than the house needs, this excess amount of power is sent back to the grid.

The first Scenario as shown in Figure 1:is composed of a PV system, a battery to store the excess amount of the generated watts for later usages in night when PVs are not working or to store electricity from grid when its needed, and also composed of an ICT equipments to run an optimization algorithm (green house gas reduction System is shown in [**?**]) that will schedule the energy flows between the national grid and the batteries only on times which correspond to lower carbon emissions. (Reference)

The second Scenario differs from the previous one in the absence of the optimization algorithm and the ICT components. Figure 2: clearly demonstrates this scenario.

In Figure 3: The last scenario is shown, it is only composed of PV system. In this scenario no batteries are installed to store the excess generated energy and all residual watts are sent back to the grid.

Table 2 shows the monthly readings for CO2 emissions, Electricity Bills and the PV fed back into grid for the three scenarios. Note that Appliances are not considered same for different scenarios.

5. System Model

The scope and parameters of the system model were defined under the following categories: selection of the LCC, LCA metrics and values per scenario, definition of the AHP algorithm and the normalization and CR calculation of the AHP matrix. The system model was based on the following assumptions:

1. The model was evaluated over a period of 50 years, given that the warranties of the battery, PV array and PV inverter are 10 years, 25 years and 5 years respectively.

2. The value of the environmental impact of these components are calculated monthly over the 50 year period.

3. The monthly replacement cost over 50 years of the model components are calculated, assuming replacement once the warranty expires.

5.1. Selected Metrics

As defined in the methodology, the 36 filtered papers were reviewed and the LCC, LCA and SLCA metrics used in each paper were tabulated. After merging the duplicates, there were 24 environmental parameters identified under the LCA category. The final parameters were selected based on frequency of

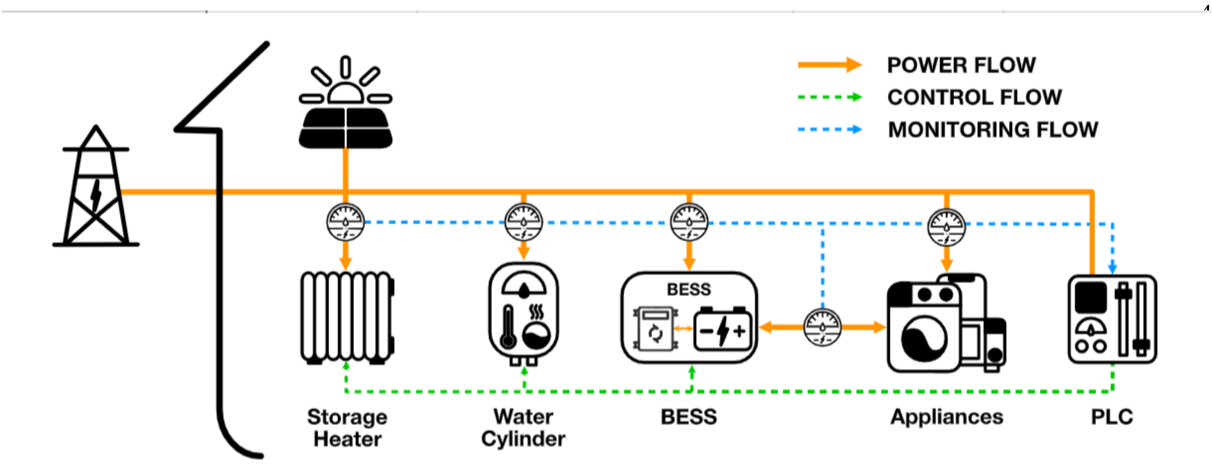

Figure 1: Scenario 1: The optimized scenario of building Integrated PV system with battery

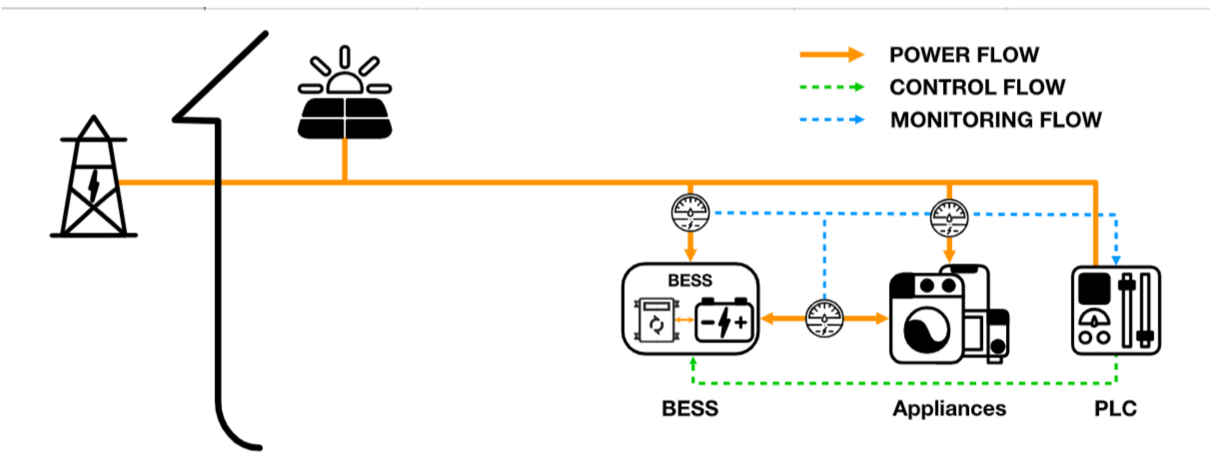

Figure 2: Scenario 2: Building Integrated PV system with battery

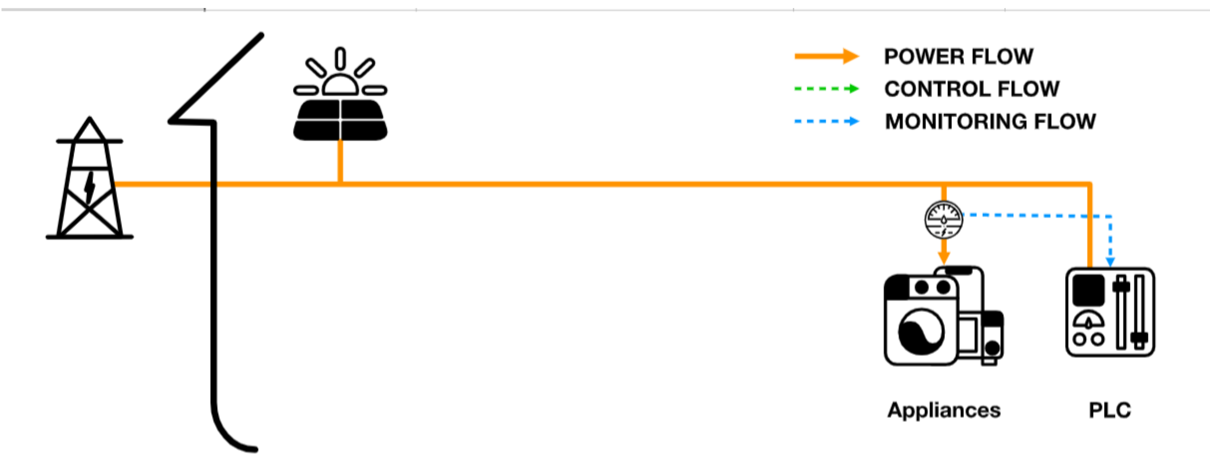

Figure 3: Scenario 3: Building Integrated PV system without battery

Table 2: Complied LCA Metric and their Utilization Frequency

Metrics	Refrences																																SUM
Ecosystem Quality	1																																1
Noice Impact	1																																1
Global Warming		1	1				1	1	1	1	1	1		1	1		1	1		1	1	1	1		1		1						18
Acidification		1	1	1			1	1	1	1	1	1					1	1	1	1		1		1	1								16
Eutrophication		1		1			1	1	1	1	1	1					1	1	1	1		1	1		1								15
Ozone Depletion		1					1		1	1	1	1					1	1				1	1										10
Abiotic Depletion of Elements	1	1	1	1	1			1	1								1	1	1														10
Abiotic Depletion of Fossil Fuels		1		1	1		1				1				1			1	1						1								9
Fresh-Water Aquatic Ecotoxicity		1							1			1					1		1			1	1		1								8
Human Toxicity	1	1		1					1		1						1	1							1								8
Marine Aquatic Ecotoxicity		1							1			1					1		1			1		1	1								8
Photochemical Oxidant Creation		1							1			1					1					1											5
Terrestric Ecotoxicity		1							1								1																3
Green House Gas Emission			1		1	1	1			1					1	1			1		1		1				1	1	1	1	1	1	16
Waste Generation			1							1																							2
Bio Diversity Impact			1																														1
Land Use Change			1	1								1						1	1			1	1										7
Aggregated Environmental Indicator			1																														1
Air Quality			1																				1			1							3
Cumulative Energy Demand					1			1								1				1													4
Fresh Water Consumption					1		1	1							1																		4
Photochemical Ozone Creation Potential										1																							1
Input Material Recyclability												1										1											2

Table 3: Compiled LCC Metrics and their Utilization Frequency

Metrics	References																													SUM
	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]			[?]	[?]	[?]	[?]		[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]		[?]
Installation Cost	1	1				1		1	1	1		1							1				1				1			10
Maintenance cost - failure rate	1	1	1	1		1		1		1	1	1	1	1		1			1	1	1		1	1						17
Operating cost	1		1			1		1			1	1	1	1		1			1	1	1	1	1	1						15
Disposal	1											1	1										1							4
Assembly		1																												1
Transportation		1			1													1									1			4
Fossil Fuel Consumption		1									1										1									3
Material Cost (PV, battery, inverter)		1						1		1				1			1		1											6
Investment Cost			1	1			1				1			1		1	1			1	1			1						10
Energy Supply cost			1	1																			1		1					4
Payback period/internal rate of return			1		1				1						1			1	1							1	1	1	1	10
Affordability			1																											1
Competitiveness			1																											1
Replacement Cost - also degradation				1		1		1		1			1										1							6
Gas energy consumption cost				1																										1
Degradation					1	1		1		1														1						5
Levelised Const of energy							1				1				1						1									4
Total Annualized cost							1																							1

appearance over the 36 papers, relevance to the scenarios and the ease of measurement of each parameter. The frequency of each parameter is recorded in Table 2.

Out of the 24 environmental parameters, the selected metrics are displayed in Table 7. Global Warming Potential was discarded in favour of the Greenhouse Gas Emission parameter. The majority of reviewed papers focused on the CO2 emissions and it was a major contributor to the total environmental impact of each scenario. The Depletion Potential for Elements and Fossil Fuels were deemed important metrics as they have significant impact during the manufacturing and raw material extraction phase of the life cycles for each component. Similarly, Human Carcinogenic Toxicity and Terrestric Ecotoxicity was particularly potent during the early stages of the life cycles. During the literature review, it was understood that the manufacturing and raw material extraction phase have the lion's share of the environmental impact across life cycle phases. This is why the LCA parameters with significant impact in the early stages were prioritized.

There were 20 LCC parameters identified post the literature review, which were once again sorted based on the frequency of appearance. After filtering based on relevance to the scenarios defined and ease of measurement, four LCC parameters were selected as shown in Table 7. Many of the reviewed papers focused on the LCC analysis of power grids or renewable energy power plants and hence the cost factors differed greatly from the residential PV systems in the scenario. For this reason, the parameters such as Maintenance cost and Investment cost were discarded in preference of measurable parameters such as the Monthly Operating Cost, the Payback Period and Replacement Cost of the battery, PV array and the PV inverter.

The SCLA parameters were tabulated and filtered, however, they were not included in the final AHP calculations as they were not relevant to the residential PV system scenario. Most of the reviewed literature that utilized these parameters focused on regional Economic Development, Social Acceptance, Injuries and Fatalities. These parameters are more relevant to large scale power systems like plants and renewable energy grids.

5.2. The LCA and LCC values

When estimating the LCA values for the BESS battery, special attention was paid to the environmental impact of each chemical component of the battery. 15 individual chemical components and the impact per kg of the material was identified. The impact per kg was weighted by the percentage of composition in a battery. The summation of the impact per chemical component was taken as the final LCA parameter values for the BESS battery. Credits were also applied for recycling and the fossil fuel displacement for a chemical component. The values thus contain the environmental impact from the manufacturing, operation and disposal.

The LCA impact of the PV array and inverter was measured together across the manufacturing, transportation and disposal stages of the life cycle. The data was modelled on a 3 kW PV system comprised of single-crystalline silicon. It is assumed that 20 percent of the total PV modules are imported to Europe. Similar to the BESS, the major contribution to the environmental impact occurs from the production phase of the solar cell, panel and inverter. The environmental impact values have been calculated and presented per kWh produced by the PV system.

The LCC parameter Payback Period takes the Feed In Tariff of 0.25 euros/kWh. The amount of electricity returned to the grid by the PV system monthly has been defined for each scenario. Payback Period has been defined as the number of years taken to cover the initial Material Cost of the PV and battery system.

The Replacement Cost accounts for the cost of replacing a module (PV array, inverter or battery) once the warranty expires over a 50 year time-frame.

Table 8 shows the values for the metrics considered for each scenario.

5.3. The AHP algorithm

The selected LCA and LCC parameters were assigned weights based on the frequency of appearance during the literature review. The weights were assigned values from Saaty's scale of relative importance 1,3,5,7,9. Parameters with equal or similar frequencies - a difference of 1-2 appearances - were assigned the value 1. Parameters with a higher difference in frequency were assigned values of 5 and 7. The Consistency Ratio was calculated to ensure a value less than 0.1.

The weighting and normalizing procedure was repeated for the LCC and LCA values of each scenario, so as to obtain a final comparison between the three scenarios. Figure 4: shows the weights and values used in AHP tree.

The preferences of one scenario compared to the other were determined for each metric considered for LCA and LCC, whereby the ratio of the two compared scenarios was taken to populate the matrix for each evaluation metric. the adopted general matrix is shown below.

Table 4: Compiled S-LCA Metrics and their Utilization Frequency

Metrics	References												SUM
	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]	[?]	
People developement	1												1
Green Product and Renewable Resources	1												1
Economic Developement	1												1
Job creation		1	1	1					1	1	1	1	7
Injury		1	1	1		1			1				5
Fatalities		1	1	1		1			1				5
Social Acceptance		1				1	1			1			4
Imported Fossil Fuel Potentially Avoided			1	1					1				3
Diversity of fuel supply mix			1	1					1				3
Fuel storage capabilities				1					1				2
Human toxicity potential	1			1				1	1	1			5
Average wage of female workers					1								1
Average wage of male workers					1								1
Disabled workers					1								1
Male workers					1								1
Female Workers					1								1
Participation of Local People in Generated Jobs												1	1

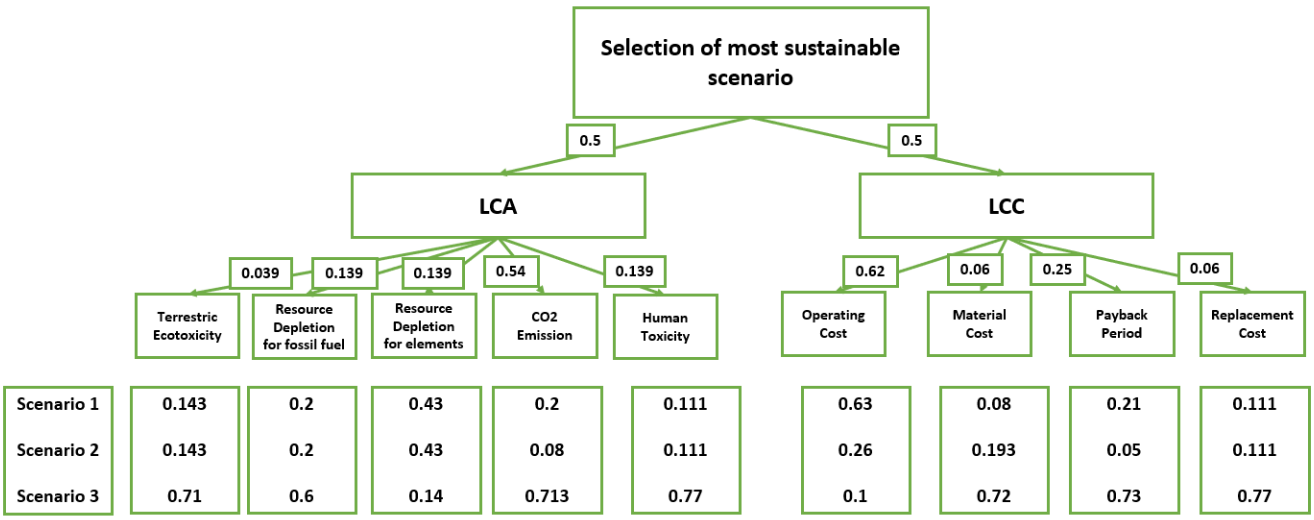

Figure 4: AHP Tree

Table 5: Monthly Values for CO2 emission, Electricity Bills and PV to grid for the scenarios

Monthly Data	Scenario 1	Scenario 2	Scenario 3
CO2 /Kg CO2	80	136	40
Electricity Bill/€	115	173	281
PV to grid / KW	3300	530	3300

Table 6: Selected Metrics

Categories	Indicators
Environmental Indicators	Human Toxicity Potential
	Carbon dioxide emission
	Resource Depletion Potential for elements
	Resource Depletion Potential for fossil fuel
	Terrestric Ecotoxicity Potential
Economic Indicators	Operating Cost
	Material Cost
	Payback Period
	Replacement Cost

$$(C)_{z\times z} = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_z \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \dots & C_z \end{array} \\ \begin{bmatrix} c_{11} & c_{12} & \dots & c_{1z} \\ c_{21} & c_{22} & \dots & c_{2z} \\ \vdots & \vdots & \vdots & \vdots \\ c_{z1} & c_{z2} & \dots & c_{zz} \end{bmatrix} \end{array} \tag{1}$$

6. Results and Conclusion

This section includes the discussions on the Life cycle assessment of our scenario and the indications of the overall results.

Adopting LCA, LCC and SLCA models in our scenario was not easy due to the difficulty of choosing suitable metrics and collecting data since most of the papers we collected throughout our research methodology were discussing LCA, LCC and SLCA for large scale power generation schemes such as plants, not many papers discussed Building Integrated Solar Systems in details. However the strength of making LCA is that its one of the most efficient tools to give a hint on the environmental impact and sustainability of a given project.

The Results in Figure 5 shows the Relative Sustainability Index for the three scenarios per Sub-Criteria. for the environmental impact, Scenario 3 is the most sustainable solution since the amount of the Carbon Dioxide -which considered the most important metric in environmental aspect- emitted using this solution is the lowest, followed by scenario 1 and then scenario 2. However for the economical impact, Scenario 1 is considered the most profitable scenario because the operating costs - the operating cost has the highest weight among other metrics in LCC Sub-Criteria- for it it the lowest.

When Considering the Overall Relative Sustainability Index, and by giving equal weights to environmental and economical aspects, scenario 1 is considered the most sustainable solution as it shown in Figure 6

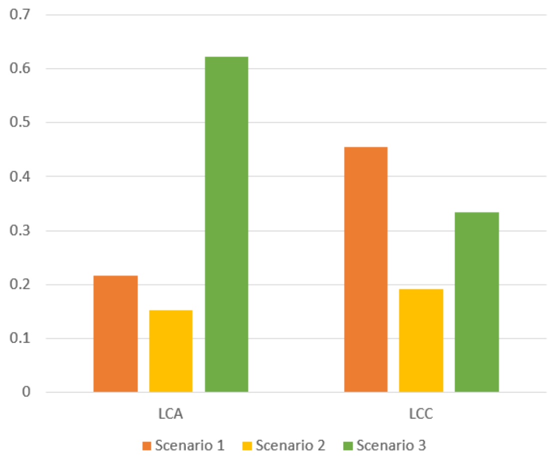

Figure 5: AHP Tree

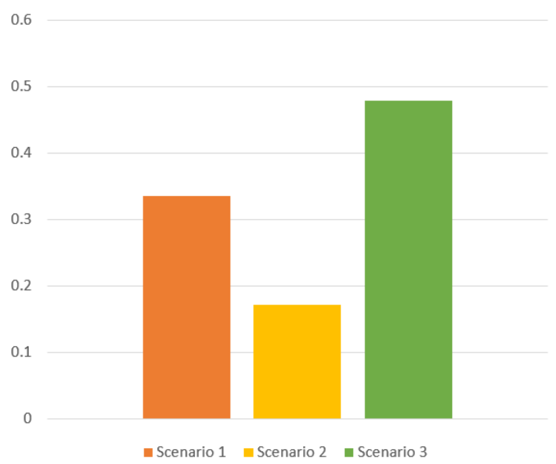

Figure 6: AHP Tree

In Conclusion, to reduce the environmental impact of a project, we should be able to make qualitative and quantitative measures to assess the project sustainability. The aim of this paper was to implement these different assessments to consider environmental and economic consequences for three different Renewable

Energy System powered house scenarios. The main gap was the scarcity of the scenario related research work to select more related metrics and get more realistic values, in future work this gap is considered by working on more specific search strings.

References

[1] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, Y.-J. A. Zhang, The roadmap to 6g: Ai empowered wireless networks, IEEE Communications Magazine 57 (2019) 84–90. doi:10.1109/MCOM.2019.1900271.

Table 7: Metrics Values for All Scenarios

		LCA					LCC			
		Human Toxicity Potential / kg1,4-DBC	**Green House gas emission / kg Co2**	**Abiotic Resource Depletion Potential for elements /kg Cu**	**Abiotic Resource Depletion Potential for Fossil Fuels / kg oil**	**Terrestric Ecotoxicity Potential / kg1,4-DBC**	**Operating cost / monthly euros**	**Material Cost / euros**	**Payback period / years**	**Replacement Cost / monthly euros**
Scenario 1	PV Array	0.00433	0.0524	0.000542	0.0127	1.13	-	3250		10.8
	PV Inverter						-	1049		17.4
	BESS	0.022	0.0477	-0.042	0.00255	2.24	-	10000		83.3
	Storage Heater	-	-	-	-	-	-	950		-
	Water Cylinder	-	-	-	-	-	-	923		-
	Appliances	-	-	-	-	-	-	-		-
	PLC	-	-	-	-	-	-	860		-
	Electrical Meter	-	-	-	-	-	-	3000		-
	ICT part		10.1	-	-	-	-			-
	whole scenario	-	80	-	-	-	115	-	2	-
	Total	**0.02633**	**90.2001**	**-0.041458**	**0.01525**	**3.37**	**115**	**20032**	**2**	**111.5**
Scenario 2	PV Array	0.00433	0.0524	0.000542	0.0127	1.13	-	3250		10.8
	PV Inverter							1049		17.4
	BESS	0.022	0.0477	-0.042	0.00255	2.24	-	10000		83.3
	Appliances	-	-	-	-	-	-	-		-
	PLC	-	-	-	-	-	-	860		-
	Electrical Meter	-	-	-	-	-	-	1080		-
	whole scenario	-	136	-	-	-	173		10.2	-
	Total	**0.02633**	**136.1001**	**-0.041458**	**0.01525**	**3.37**	**173**	**16239**	**10.2**	**111.5**
Scenario 3	PV Array	0.00433	0.0524	0.000542	0.0127	1.13	-	3250		10.8
	PV Inverter							1049		17.4
	Appliances	-	-	-	-	-	-	-		-
	PLC	-	-	-	-	-	-	860		-
	Electrical Meter	-	-	-	-	-	-	360		-
	whole scenario	-	40	-	-	-	281		0.6	-
	Total	**0.00433**	**40.0524**	**0.000542**	**0.0127**	**1.13**	**281**	**5519**	**0.6**	**28.2**

[1]