ASSESSMENT OF THE SUITABILITY OF PHOTOVOLTAIC CELL TECHNOLOGIES FOR PRODUCT DEVELOPMENT OF BUILDING INTEGRATED SOLUTIONS USING THE ANALYTICAL HIERARCHY PROCESS (AHP)

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Abstract

Photovoltaic systems integrated into the built environment can have a significant role in our pursuit to achieve the targets set by regulatory legislation with regards to nearly zero-energy buildings (nZEB). However, the share of Building Integrated Photovoltaic (BIPV) products on the market have seen a slower growth than predicted. One of the main barriers to their diffusion includes the lack of knowledge among different stakeholders. Reducing this knowledge gap between the building industry and the PV industry is of utmost importance. The project presented in this paper aims to use the multi-criteria analysis method of analytical hierarchy process (AHP) as a tool to align the preferences of architects, product developers and engineers for integrated solutions with the most suitable PV technology. This can provide product developers with the necessary information to create PV applications that will better satisfy consumer and designer preferences and reduce the knowledge gap between the different stakeholders.

Keywords: AHP, Solar energy, zero-energy buildings, BIPV, MCDM

1. Introduction

The energy sector is experiencing a structural transition from fossil energy sources to renewable energy. This is merely driven by environmental concerns to mitigate CO_2 emissions and to prevent runaway climate change and aggravated global warming. As a result, there is an urge to promote the development of new products incorporating renewable and clean energy technologies.

From all the renewable energy sources, solar energy is the most abundant, inexhaustible and clean source of energy (Parida et al., 2011). In addition, considering all the technologies for harvesting solar energy, photovoltaics and their applications in the built environment (mainly placed on rooftops or façade-integrated) receive growing attention during recent years (Farkas et al., 2013).

During the past 5 decades, photovoltaics have experienced significant growth in technological development, installed capacity and cost reduction. In terms of PV technology today, almost 20 different PV cell technologies are available (Green et al., 2017). Remarkably, the field of PV technology has the largest share (26%) in patented innovation compared to other renewable technologies (IRENA 2017). In terms of installed capacity, by the end of 2016, the total amount of solar PV installed across the globe was 320 GW; this represents a growth by a factor of 40 in only 10 years (Kurtz et al., 2017). In terms of economy, since 1980, the price of photovoltaics has been reduced by a factor of 50 (Polman et al., 2016). Last year, the world's lowest-ever bid was offered by a consortium led by Abu Dhabi's renewable energy company, for a project in Saudi Arabia, at 1.79 US dollar cent per kilowatt hour (kWh) (Bloomberg, 2018). This significant reduction is due to several reasons, mainly the economies of scale, in addition to technological progress in solar cell efficiencies, standardisation of technologies (conventional PV modules), improved module manufacturing and lower costs of production of feedstock materials (Reinders et al., 2018)

All the above-mentioned facts and figures specify, thanks to efforts of different stakeholders in the PV industry from high-level research organisations working on the multi-junction PV cell technology to the wholesalers of PV modules, PV technology is becoming mainstream in the energy sector (Kurtz et al., 2017). Today, its application varies from residential to utility scale and it is used in agriculture, construction, telecommunication, aerospace,

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transport, security, military and many other fields. With such a vast array of applications, the demand for photovoltaics is increasing every year (Parida et al., 2011).

Certain features of PV technology make it suitable for application in an urban environment, namely the possibility of integration, scalability and modularity, as well as silent operation (Reinders et al., 2018; Weller, 2010). In addition, physical properties of PV cell technology allow design flexibility for development of different modules in varied form, shape, colour and translucency (Markvart & Castañer, 2003).

All this growth, innovation and new technologies are allowing development of more and diverse applications or products incorporating PV technology. However, such variety makes the selection of the most suitable technology for a specific application a complex decision (Farkas, Probst, & Horvat, 2010).

In addition, from literature (Ritzen et al., 2013; Urbanetz et al., 2011) it is evident that there is always a trade-off between the aesthetical value that PV may offer and its functional performance. However, the interrelation between design and technical functionality is not always linear. Therefore, for smart decision making, product developers should be given an opportunity to decide how much energy output he is willing to compromise in return for flexibility in design and shape. Moreover, since the 1970s, when the possibility for the adoption of photovoltaic (PV) technologies in the built environment started to be investigated, the synergy between key stakeholders such as architects/designers and PV engineers was not productive. In time, this created an important gap in knowledge within these communities, which sometimes led to a misunderstanding of the capabilities of PV technologies and failure in product development (Wall, et al., 2012).

On top of what was mentioned about the physical aspects of PV technology and technical performance, in order to address the importance of the transition towards renewable energy and the urge for sustainable development, it is very important to consider environmental impacts of the components of a product or application during its life cycle. Not only there is public pressure for cleaner products, it is becoming mandatory within EU policies to consider environmental issues in the process of new product development (NPD) (Sinha & Anand, 2018).

Last but not least, economic aspects of each technology is a key criterion in decision making for selecting any component for product development (Kumar et al., 2017; Wang et al., 2009). And product developers are always looking for the best technical performance for the cheapest price or with the shortest payback period. However, in this field, the assumption about the cost of the product can be different when the unit varies. For example, when a product is going to be developed for the built environment, price per square meter mostly is a common unit for comparison, but in the PV sector, the unit is per W_{peak} of capacity. So, for any decision making, a uniform unit should be considered.

Multi-criteria analysis is an operational assessment method for decision support that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multiple interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems (Wang et al., 2009). It has been widely applied in social, economic, agricultural, industrial, ecological and biological decision-making process. Especially in many projects related to sustainable development and environmental impact analysis (ibid). And analytical hierarchy process (AHP) is a method for multi-criteria analysis and most preferred for tangible and intangible factors (Ozdemir & Sahin, 2018).

In this paper, the authors explain the application of the AHP method for the creation of a decision-making tool for new PV product development. In this research, AHP helps to combine user preferences (through a direct and in-direct questionnaire) and secondary data from the literature for pairwise comparison of PV cell technology (different alternatives).

2. Method:

The AHP method consists of dividing a given problem into different components and established a hierarchy, as shown in

Figure 1. The hierarchy is constructed starting from the main goal of a given decision project. At a second level, the main criteria are selected based on input from stakeholders and quantitative data. Sub-criteria can be introduced to consider further aspects and to make the model more detailed. The structure then is analysed by the selected hierarchy; this means that alternatives are studied according to each sub-criterion and weighted according to the main goal of the project.

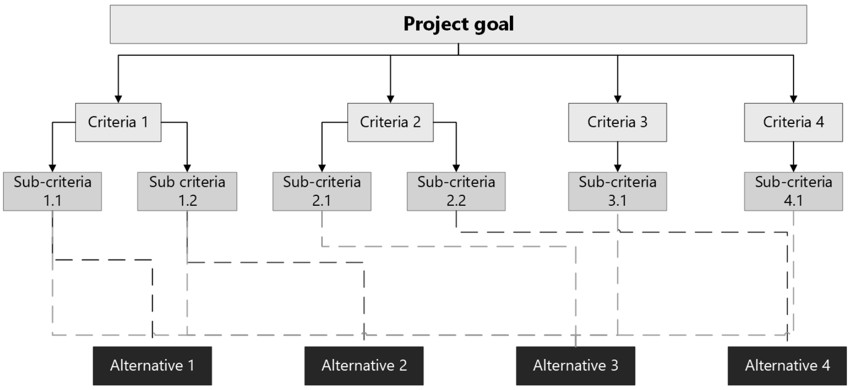

Figure 1 - Multi-level AHP structure

To weight each criterion, a so-called pair-wise comparison is used. Each alternative is compared with another for each sub-criterion, the result of this is a matrix that will be used to calculate ratios and quantify preferences. The comparison may come from a verbal preference or need that is not easily quantifiable. On these cases, the suggestion of Thomas Saaty is used and are summarised in Table

Table 1 - Saaty's fundamental scale of pairwise comparison, extracted from Saaty (1980) and San Cristóbal Mateo (2012) extracted from (Saaty, 1980) and (San Cristóbal Mateo, 2012)

Intensity of importance	Definition	Explanation
1	Equal Importance	Element 1 and 2 are equally important
3	Moderate/weak importance	Experience and judgment slightly favours 1 over 2
5	Essential or strong importance	Experience and judgment strongly favours 1 over 2
7	Demonstrated importance	1 is favourite over 2 and has been demonstrated in practice
9	Absolute importance	The evidence clearly shows that 1 is preferred over 2
2,4,6,8	An intermediate value between the judgments presented above	Compromise between 2 intensities of importance
Reciprocals	If 1 over 2 has a value of 7, then 2 over one must have a value of 1/7	

The user weights the preference of one criterion to another (e.g. the preference of design to the economy), or the preference of one technology over another, for a specific criterion, as shown in
Figure 2.

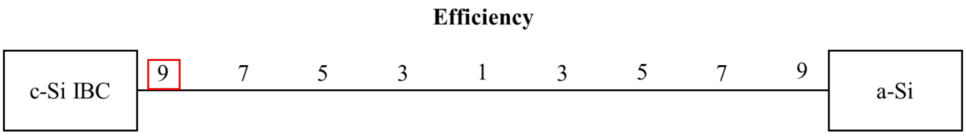

Figure 2 Pairwise comparison example

From this, matrix A is formed:

$$A = \begin{pmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{l1} & \cdots & x_{lm} \end{pmatrix} \qquad \text{Eq (1).}$$

Where x_{lm} is the evaluation of alternative l^{th} element with respect to criterion m^{th}. This produces a symmetric matrix on the form of:

$$\begin{pmatrix} 1 & x_{12} & x_{13} \\ x_{21} & 1 & x_{23} \\ x_{31} & x_{32} & 1 \end{pmatrix} \qquad \text{Eq (2).}$$

This means that if:

$$x_{12} = \beta \qquad \text{Eq (3).}$$

Then,

$$x_{21} = \frac{1}{\beta} \qquad \text{Eq (4).}$$

Since the number of alternatives greatly influences the reliability of the method, Once the evaluation matrix is complete, each element of a column is then normalised as follows:

$$x_{11n} = \frac{x_{11}}{\sum_1^l x} \qquad \text{Eq (5).}$$

This forms a normalised matrix A_n:

$$A_n = \begin{pmatrix} x_{11n} & \cdots & x_{1mn} \\ \vdots & \ddots & \vdots \\ x_{l1n} & \cdots & x_{lmn} \end{pmatrix}$$

The average of each row of the normalised matrix will yield the weight of each criterion on a vector called *W*.

Finally, the consistency of the method is assessed by performing the following steps (San Cristóbal Mateo, 2012):
1. Compute AW^T, W^T being the transpose vector *W*.
2. Calculate the value of λ_{max}

$$\lambda_{max} = \frac{1}{m} \sum \frac{ith\ value\ of\ AW^T}{ith\ value\ of\ W^T} \qquad \text{Eq (6).}$$

Consistency is then defined as:

$$CI = \frac{\lambda_{max} - m}{m - 1} \qquad \text{Eq (7).}$$

From the number of alternatives selected, a random index (*RI*) should be established following (Saaty, 1980):

Table 2– Randomness index (RI) values according to the number of alternatives used

Alternatives	2	3	4	5	6	7	8	9	10	11	12
RI	0	0.58	0.9	1.12	1.21	1.32	1.41	1.45	1.49	1.51	1.48

If *CI/RI* < 0.01 the result of the method is reliable as the consistency is considered satisfactory.

Each criterion will produce a vector W, and the values of CI/IR. An alternative matrix is then formed based on each criterion vector and then synthesised with the vector of weighted values that each main criterion has, according to the user's needs.

$$\begin{pmatrix} C_1 \\ \vdots \\ C_m \end{pmatrix} \times \begin{pmatrix} W_{11} & \cdots & W_{n1} \\ \vdots & \vdots & \vdots \\ W_{1m} & \cdots & W_{nm} \end{pmatrix} = \begin{pmatrix} A_1 \\ \vdots \\ A_m \end{pmatrix} \qquad \text{Eq (9).}$$

The resulting vector gives the final ranking, and the most suitable option is obtained.

3. Application

Figure 3 shows different stages of the application of AHP in our research. As is shown, in stage A, the main criteria are to be selected. Then the sub-criteria are chosen as a complementary analysis for each of criterion and to develop the pairwise comparison matrices. All of these criteria are selected based on scientific research. In the other words, experts from the field should have used these criteria as a factor for comparing alternatives. During the next step, alternatives for comparison should be selected, i.e. the PV cell technologies. These are known technologies, which are fully developed, and most of them are already available in the market.

In stage B and C, the weighting process will be conducted. In this process, there are 3 methods for weighting each criterion and sub-criterion. First and second are through a user input (stage B). The tool comprises of the graphical user interface (GUI), where users are directly and indirectly asked to express their preference, according to the type of application for which they want to develop a product. Those values will be used directly in the matrices. Indirect questions are those that will be asked in a way that helps to produce matrix values in connection with other information, which was given earlier. In this questionnaire, the personal and professional information of the users will be documented, which allows further investigation of the preference of a specific group of experts. The other method is the rational weighting method. Here, alternatives are ranked according to their quantitative values. For example, it is obvious and rational to sort the PV cell efficiencies according to the hierarchy of their values. On such a sub-criterion, the users will not be asked whether they want the tool to include the results of the most efficient technology or not. We include them in the weighting process by default. However, if the user gives a low weight on the 'functional performance', for example, which is one of the main criteria, the influence of efficiency on the outcome will be lower.
In stage D, the pair-wise comparison based on sub-criteria and alternatives will be developed and then normalised and averaged, and the criterion vectors will be developed. Later all vectors will be multiplied by the index coming from first user input on main criteria and final ranking will be attained. However, before arriving at final ranking, consistency evaluation should be done to validate the method that leads to final ranking.

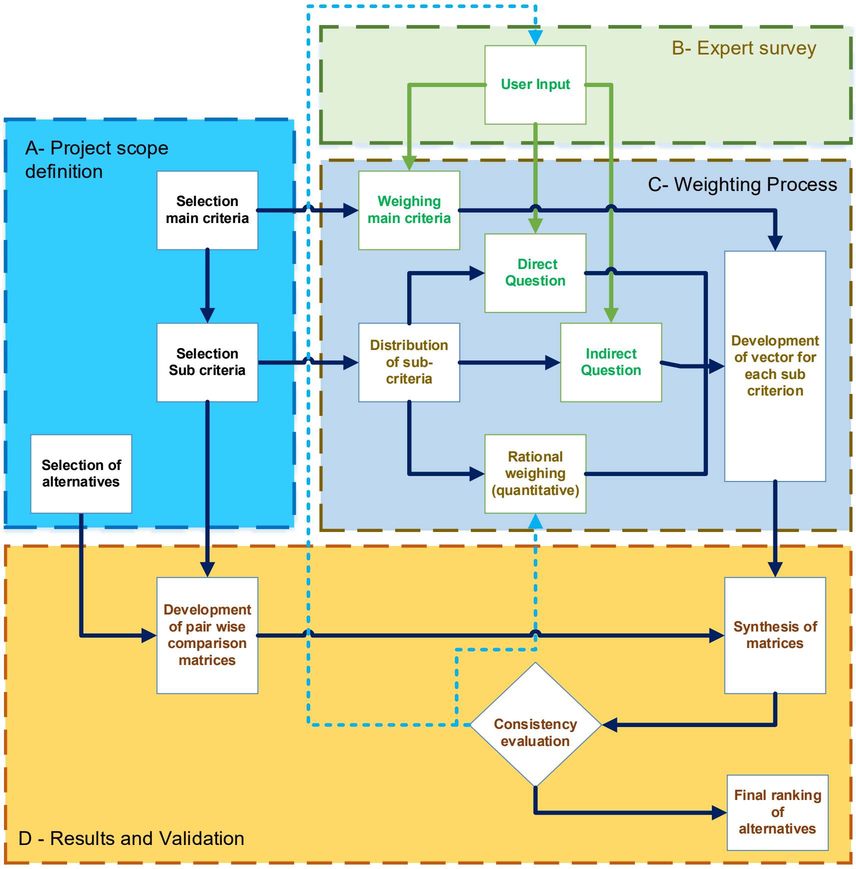

Figure 3: AHP application Process

4. Example (with sample alternative and Criteria)

A potential use for this tool, for example, is that of a 'product developer' who wants to design a solar infotainment spot. His device will be placed in different parts of the city, and its aim is to improve the overall experience tourists have when visiting the city. Additionally, it will serve as a means for promoting the use and application of sustainable energy technologies.

The tool for such an example will start by asking the user´s (here the product developer) most relevant information, i.e. their professional profile (engineer, architect, designer, developer). In this part, the location, orientation, tilt and other relevant information must be provided by the user to the tool.

The first step begins via the survey. The developer is asked about the overall goals of the project. For the solar infotainment spot, for example, he might want to select specific characteristics, such as performance, recycling of materials, a long life-span for the device, low price, etc. This defines the main criteria of the project and the second stage in the hierarchical approach.

The second step of the survey will be based on the main criteria. It will help the developer to build a third stage of the hierarchy: the sub-criteria. Regarding performance, for example, the developer will assess the importance of the project of power output per unit of area, by asking about area limitations and desired output, whether the recycling should be performed by specialised labour or be as simple as possible. Other characteristics to be determined are, for instance, transparency, colour and flexibility. The step ends with a hierarchy chart as shown in Figure 4. The user can then confirm that such a selection of criteria and sub-criteria perfectly describes what is wanted for the project. Subsequently, the software pre-selects the alternative technologies for analysis.

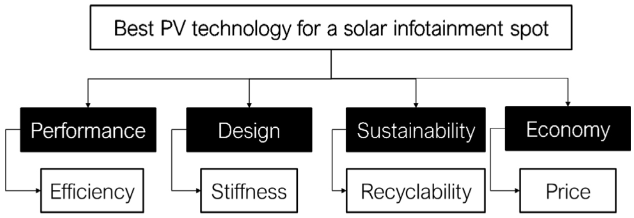

Figure 4 Hierarchy of criteria and sub-criteria developed after the user survey

This pre-selection is done based on those technologies that have the most potential to suit all such criteria. For example, if a long life-span of the project is needed, then technologies that do not fulfil this criterion are ruled out (such as perovskites). If the application is terrestrial, and low price is the main objective, then III-V technologies[1] are ruled out. All these are currently under development, and with greater expert input (step B) this preselection will be more accurate as the tool progresses.

Afterwards, the professional information of the user input is documented. This allows further improvement of the tool by analysing the preference of specific professions and applications. The user is asked about the type of product or application they are working on. In time, users will be able to choose the type of application to get a specific survey to weight their preferences. Applications such as urban integrated solutions, e-mobility, solar facades, BIPV-T, etc. are under development now.

During the last step, the tool combines the methods used in the two previous one with a more quantitative method. Here, the user will weight each criterion with respect to the overall goal of the project. Each criterion will be compared with the others to determine the intensity of importance for the developer. The values assigned will be in accordance to those explained on Table . The developer might feel it is more important for the device to be recyclable than flexibility in design (therefore, sustainability is preferred to aesthetics). If economic and functional aspects are desired more than aesthetic, the latter will be ranked below everything else, as shown in Figure 5.

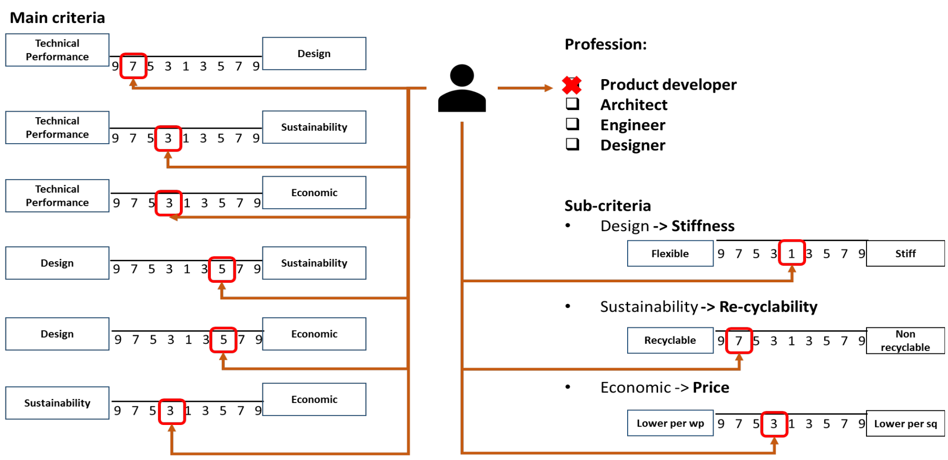

Figure 5 Pair-wise comparison scheme. Based on the answers provided by the developer, the main criteria is weighted with respect to the overall goal of the project.

[1] "III-V" semiconductor technologies are elements belonging to groups III and V of the periodic table of chemical elements.

Here, as shown in figure 5, the product developer has given his preference thought the survey as follows. In the main criteria, he *wants functional* performance but also looking at sustainability and economic factors. Both latter aspects *have importance with respect to* design, but - among them - sustainability is *a bit more important.* In the sub-criteria, he *does not extremely* care for the trade-off between stiffness *vs* flexibility but is interested in *relatively* low cost (in €/Wp) and *rather passionate* about recyclability. From this, the pair-wise comparison matrix is then created for each main criterion and sub-criteria.

Pair-wise comparison matrix for the main criteria based on the results of the survey

	Performance	Design	Sustainability	Economic
Performance	1	7	3	3
Design	1/7	1	1/5	1/5
Sustainability	1/3	5	1	3
Economic	1/3	5	1/3	1

Then, in accordance with Eq (5), we get the normalised matrix

Normalised matrix

	Performance	Design	Sustainability	Economic
Performance	0.55	0.39	0.66	0.42
Design	0.08	0.06	0.04	0.03
Sustainability	0.18	0.28	0.22	0.42
Economic	0.18	0.28	0.07	0.14

By averaging each row, the weighting vector is obtained. This establishes the overall preference of the criteria with respect to the main goal. For this case, Performance and Sustainability account for 78% of the total weight, meaning that technologies that have a leading edge on these aspects will be most suitable.

Weighting vector

Weighting vector
0.51
0.05
0.27
0.17

The weighting vector shows the overall preference of each criterion with respect to the main goal. For this case, Performance and Sustainability account for 78% of the total weight, meaning that technologies that have a leading edge on these aspects will have higher chances of being selected by the tool. The same process is carried out for the main criterion that has more than one sub-criterion. In such a case, the importance or preference of each sub-criterion is weighted with respect to the main criterion.

Pair-wise comparison of alternatives for the sub-criterion of Efficiency

	c-Si	CdTe	CIGS	a-Si
c-Si	1	7	7	9
CdTe	1/7	1	1	7
CIGS	1/7	1	1	7
a-Si	1/9	1/7	1/7	1

Each alternative is analysed for every sub-criterion (or criterion that do not have sub-criteria). A pair-wise comparison is built based on scientific research, market research and expert insights. In this case, for example, crystalline silicon technologies have a commanding lead compared to other alternatives. It is possible to find solar cells on the market, based on crystalline silicon, which has an efficiency greater than 20%. Although similar efficiency values are reported on lab-scale devices of CdTe and CIGS, readily available products with such technologies are still around 16%. Given that this is not an application intended for research, but rather to develop a product ready for sale, the preference for c-Si technologies is very strong. This is even more evident against a-Si cells, that even on lab-scale devices cannot reach an efficiency above 14% (Polman, et al, 2016).

Complete pair-wise comparison for all the alternatives for each sub-criterion

Criterion		Pair-wise comparison matrix: c-Si	CdTe	CIGS	a-Si	Normalized: c-Si	CdTe	CIGS	a-Si	Weighting vector
Efficiency	c-Si	1	7	7	9	0.72	0.77	0.77	0.38	0.66
	CdTe	1/7	1	1	7	0.10	0.11	0.11	0.29	0.15
	CIGS	1/7	1	1	7	0.10	0.11	0.11	0.29	0.15
	a-Si	1/9	1/7	1/7	1	0.08	0.02	0.02	0.04	0.04
Stiffness	c-Si	1	1	1	1	0.25	0.25	0.25	0.25	0.25
	CdTe	1	1	1	1	0.25	0.25	0.25	0.25	0.25
	CIGS	1	1	1	1	0.25	0.25	0.25	0.25	0.24
	a-Si	1	1	1	1	0.25	0.25	0.25	0.25	0.25
Recyclability	c-Si	1	9	7	3	0.63	0.35	0.63	0.68	0.57
	CdTe	1/7	1	1/7	1/9	0.07	0.04	0.01	0.03	0.04
	CIGS	1/7	7	1	1/3	0.09	0.27	0.09	0.08	0.13
	a-Si	1/3	9	3	1	0.21	0.35	0.27	0.23	0.26
Price	c-Si	1	2	2	3	0.20	0.40	0.40	0.50	0.43
	CdTe	1/2	1	1	1	0.10	0.20	0.20	0.17	0.20
	CIGS	1/2	1	1	1	0.10	0.20	0.20	0.17	0.20
	a-Si	1/3	1	1	1	0.10	0.20	0.20	0.17	0.18

Error! Reference source not found. shows all the pair-wise comparison matrices in which the alternatives are studied for each sub-criterion. The developer prefers a sturdy and durable module for the product. Every technology selected can be built into a rigid module, and such products are easily obtained on the market; therefore, there is no quantifiable preference of one technology over the other. Hence, all the values of the matrix are 1.

Since the product needs to be easily recyclable, c-Si and a-Si have a lead in this aspect compared to CdTe and CIGS. It has been shown that c-Si and a-Si modules can be recycled by relatively simple processes, and furthermore, the c-Si cells can be reused (Lee, et al., 2017) (hence, the values of 3 compared to a-Si, and 7 and 9 compared to the remaining technologies). CdTe and CIGS modules require specialized handling, which could increase the costs (Tao & Yu, 2015). Furthermore, the toxicity potential of CdTe modules puts the technology at a disadvantage when compared to others on the ease of recycling perspective (Monteiro Lunardi et al 2018).

Regarding price, the developer stated that a technology with the best value of €/Wp should be preferred. Even though a-Si and other thin-film technologies present cheaper products, their lower overall performance puts them at a slight disadvantage compared to c-Si: analysis of large-scale production has demonstrated a small advantage of mc-Si in this area (Horowitz et al 2017).

Once all these pair-wise comparison matrices are normalised and their rows averaged. The weighting vectors for each of them are produced. These vectors indicate the dominance of the technology for that given sub-criterion. In this case, c-Si technologies are by far the better choice, since they dominate on each analysis. The last step, however, is to create a matrix with all the weighting vectors of the alternatives and multiply it with the weighting vector of the criteria, as stated on Eq. (9).

$$\begin{array}{c} \\ \text{c-Si} \\ \text{CdTe} \\ \text{CIGS} \\ \text{a-Si} \end{array} \begin{array}{c} \begin{array}{cccc} \text{c-Si} & \text{CdTe} & \text{CIGS} & \text{a-Si} \end{array} \\ \begin{pmatrix} 1 & 2 & 2 & 3 \\ 1/2 & 1 & 1 & 1 \\ 1/2 & 1 & 1 & 1 \\ 1/3 & 1 & 1 & 1 \end{pmatrix} \end{array} \text{X} \begin{array}{c} \text{Criteria} \\ \begin{bmatrix} 0.51 \\ 0.05 \\ 0.27 \\ 0.17 \end{bmatrix} \end{array} = \begin{array}{c} \text{Ranking} \\ \begin{bmatrix} 0.547 \\ 0.134 \\ 0.160 \\ 0.158 \end{bmatrix} \end{array}$$

The result is the final ranking for the best PV technology to be used on the solar infotainment spot. As stated, c-Si is way above the other alternatives for this application, thanks to its high efficiency, low price, and ease of recycling. This last aspect puts CdTe last, even when, performance wise, has a significant advantage compared to a-Si.

If, for example, the design had been the most important aspect of the product, and flexibility was a must, the ranking could change dramatically, and technologies such as CIGS could be the most appropriate. If transparency was preferred, with energy performance not being an important aspect, then c-Si would possibly be last. The idea of the tool is to guide the user in finding what better suits the need of the project in question, with the aid of a substantial research analysis of the technical aspects of the PV industry.

5. Conclusion

AHP allows numerical rating of criteria that might be *subjective*. Here, an example of how a product developer can use the main stakeholder subjective preferences into *objective* comparison. As shown in the example, AHP can be a very helpful method for decision making on complex problems. Especially if somehow interrelation between the criteria can be found. In this research, compared to other applications of AHP to answer other questions, we have the intention to present an open outcome based on user preference and not to limit the outcome based on the quantitative survey and preference of a majority in certain professions. There we need to develop a GUI (graphical user interface) for the tool in which the user can freely use the algorithm and ready-made matrices to find the most suitable technology for his application.

In addition, going deep into the application of AHP method and process of product development in the PV sector, we noticed some of the physical aspects of a PV product are not only depended on the suitable PV cell technology and can be later achieved through the selection of different module manufacturing technologies. Therefore, for further development, we should also consider the selection of these technologies to confirm whether one PV technology can be suitable for one application or not.

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