École Polytechnique de Bruxelles

Decision Engineering
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Multicriteria Project:
Renewable Energies on Rooftops

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Contents

Chapter 1: Introduction

Needless to say how ecology impacts today's world and certainly tomorrow's world even more. New technologies are developed, new policies are released and new actions have to be taken. On a small scale, the household scale, many eco-friendly gestures are possible. Among them, installing a system for creating its own renewable energy becomes increasingly done thanks to the technological advancements and their democratisation. In urban areas, one could think that space for installing such devices is missing. However, rooftops present an excellent opportunity as most of them are not used.

Once the rooftop selected, the question that arises is: Which device(s) to install? A first clue is the existence and use of many different systems. Thus, the best device probably doesn't exist. While including the possibility of combinations of them, multiple alternatives can be drawn, each with its benefits and drawbacks. This is the basis of multi-criteria problems.

This report will try to answer the above mentioned question by first introducing the subject of study as well as its scope in Chapter 2. Secondly, the alternatives will be presented in Chapter 3 followed by the criteria in Chapter 4. To solve the issue, a Multi-Criteria Decision Aid (MCDA) is necessary. Through the use of the D-sight software, PROMETHEE is chosen and its application is shown in Chapter 5 leading to a ranking of the alternatives. As the solution found assumes many hypothesis, a sensitivity analysis is conducted in Chapter 6 to discover how the ranking varies according to some changes in parameters. A conclusion resuming all the results found closes the report in Chapter 7.

Chapter 2: The subject

Renewable energies are gaining more and more shares of energy in Europe. To cope with the "2020-Renewable Energy Directive" of the EU aiming at fulfilling at least 20% of EU's total energy needs with renewables [3], countries are adopting new actions, ideas and technologies.

In Belgium, the goal is to reach a target of 13% of energy from renewable sources in gross final consumption of energy [4]. One of the measure established to do so is to promote the generation of energy from renewable sources through grants. As a consequence, more and more space is allocated to produce such energy. In urban areas where space is limited, rooftops are the new option.

In this report, the subject of study will be the installation of renewable energy devices on an example rooftop. The building and its associated rooftop are explained here after.

2.1 The building and its rooftop

The building considered in this report is a 4-floor building comprising eight $75m^2$-apartments of 3 people each. According to energy bills, the average consumption of energy per year for such households is 3300 kWh of electricity and 11850 kWh of thermal energy. Consequently, the building consumes 39600 kWh of electricity and 142200 kWh of thermal energy per year. The duration of the project is taken as the life span of the components, so 20 years.

The co-ownership decided to place devices that produce renewable energy on their rooftop for ecological reasons but mainly, for economical reasons. The rooftop considered is drawn in Figure 2.1. The available area is of 15 meters long and 10 meters wide. One of the long side is oriented south. On the edges, a security perimeter has been stated.

Once the surface available for the devices is fixed, it is possible to wonder what devices to place. This is done in the next section.

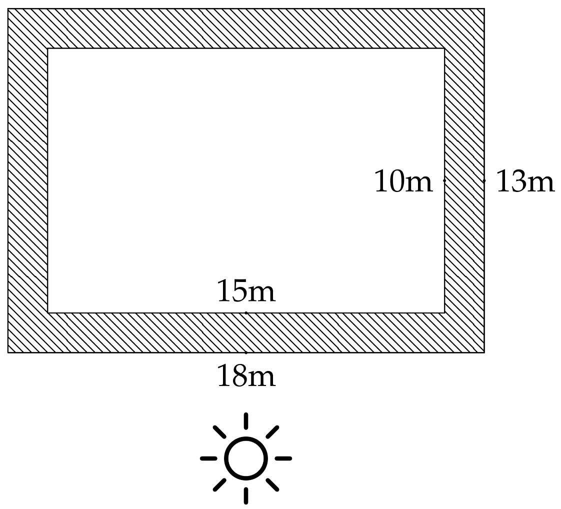


Figure 2.1: The rooftop considered

Chapter 3: The alternatives

On rooftops, multiple technologies producing renewable energy can be used. Well-known devices include thermal solar panels, photovoltaic solar panels and wind turbines. In Table 5.1, the characteristics of the devices considered in this report are stated.

Device	Name	Dimensions (mxm)	Energy Production (kWh/year)	Noise (dB)	Weight (kg)	Price (€)	Pollution (gCO2/kWh)
Wind turbine	Aeolos-V 3kW	5x5	2800	40	106	6000	12.5
Thermal panel	Vitosol 200-TM	2.25x1.2	1402	0	57	583	3.8
Photovoltaic panel	REC250	1.65x1	161	0	28	185	55

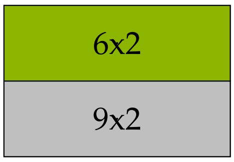
Table 3.1: Devices' characteristics

Each of them has its own properties and conditions and none is considered as the "best option". That is why, a combination of those devices is interesting thus building an equilibrium between the advantages and disadvantages of each.

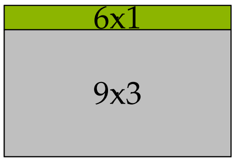
In this report, the alternatives will then consist of different combinations of solar thermal panels, solar photovoltaic panels and wind turbines. Multiple conditions need to be taken into account when drawing the different alternatives. First, due to security issues, a device must be at least 1.5 meters away from the border of the rooftop. Moreover, wind turbines must me in the middle of a $5m^2$ square. Second, for better performance, the wind turbines cannot be positioned behind each other and the panels are placed at 35°angle from the ground and facing south. Creating shade, the disposition of the panels needs to respect a certain edge distance as mentioned in [2]. Finally, the alternatives using as much space as possible on the rooftop (meaning that no more device can be added) are favoured as they dominate others.

Respecting all those conditions, the following alternatives are considered and drawn such as grey represents photovoltaic solar panels (PV), green thermal solar panels (TS) and blue wind turbines (WT). Moreover, the safety borders are removed. The numbers (.x.) indicate the number of each device on the rooftop.

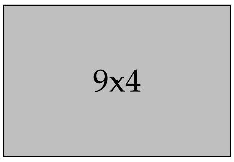
- Without any wind turbine



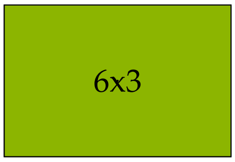
Alternative 0.1
18PV & 12TS



Alternative 0.2
27PV & 6TS

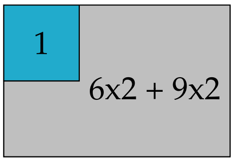


Alternative 0.3
36PV

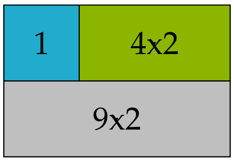


Alternative 0.4
18TS

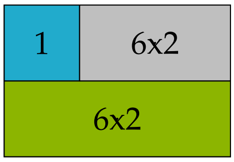
- With one wind turbine



Alternative 1.1
30PV & 1WT

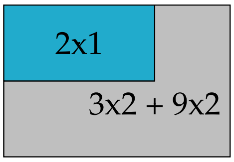


Alternative 1.2
18PV & 8TS & 1WT

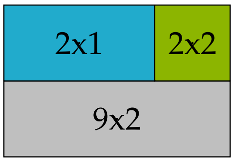


Alternative 1.3
12PV & 12TS & 1WT

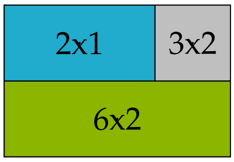
- With two wind turbines



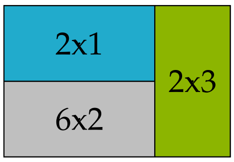
Alternative 2.1
24PV & 2WT



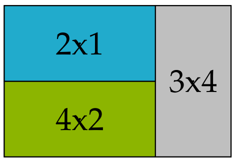
Alternative 2.2
18PV & 4TS & 2WT



Alternative 2.3
6PV & 12TS & 2WT

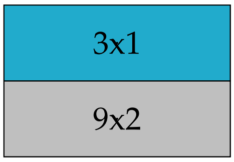


Alternative 2.4
12PV & 6TS & 2WT

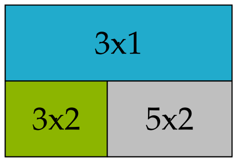


Alternative 2.5
12PV & 8TS & 2WT

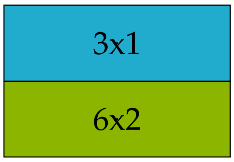
- With three wind turbines



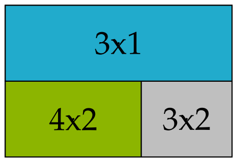
Alternative 3.1
18PV & 3WT



Alternative 3.2
10PV & 6TS & 3WT



Alternative 3.3
12TS & 3WT



Alternative 3.4
6PV & 8TS & 3WT

Of course, other alternatives exist but those will constitute the basic ones. According to the results obtained through the PROMETHEE methodology, relevant derivations will be studied.

For evaluating which alternative(s) are the best choice, criteria are considered. They are explained in the next section.

Chapter 4: The criteria

The evaluation of each alternative is made using different relevant criteria. Each of them will be described here under.

1. Purchase and installation cost
    - Alternatives are sorted according to their total cost of implementation. The lower the cost, the better the alternative as often, households cannot afford to pay a large price at once.
    - The cost of each component is taken as presented in Table 5.1.
2. Savings
    - The savings are taken as the total savings each alternative has at the end of the 20 years (average number of years of guaranty). The higher the savings, the better the alternative.
    - The savings are computed as follows:
        - The total productions (electric and thermal energy) of each alternative is computed considering 2800 kWhe/year per turbine, 161 kWhe/year per pv panel and 1402 kWht/year per thermal panel.

- Those productions are multiplied by the number of year considered (20 years).
- The productions over the 20 years is subtracted to the total consumption of energy (electric and thermal) over the 20 years.
- The differences (in kWh, which are the quantity of energy that have to be taken from the grid or gas network) are multiplied by the unit cost of electricity and gas (0.219€/kWhe and 0.054€/kWht). Those give the cost of buying energy.
- The saving are then the difference between the cost of buying energy without any renewables installation (total consumption multiplied by unit costs) and the previously computed cost of buying energy considering the installation added to the cost of purchase and installation.

3. Pollution

   - The pollution is considered as the total emissions emitted by each alternative in order to produce and recycle its components, expressed in tonnes of CO2 (tCO2).

4. Noise

   - The less noisy the alternative is, the better.
   - Only wind turbines are considered as emitting noise. PV and thermal panels are considered as noiseless.

5. Impact on the urban landscape

   - The impact on the urban landscape is taken as the visual disturbance for the neighbourhood buildings. The lower the impact, the better the alternative.
   - Only wind turbines are considered as disturbing.

6. Impact on the building infrastructure

   - The total weight of the alternative will be considered to evaluate the impact on the building infrastructure. The lower the total weight, the better the alternative.
   - The weights of each component are presented in Table 5.1.

7. Impact on fauna

   - The impact on fauna is evaluated considering the danger each alternative can have on the wildlife (mainly birds). The lower the impact, the better the alternative.
   - Wind turbines are considered as the most dangerous as birds could fly through the blades. Other devices are harmless.

8. Administrative difficulties

   - Administrative difficulties will be higher if administrative procedures have to be conducted to build the alternatives. The lower the difficulties, the better the alternative.

- Only wind turbines will play a role in the evaluation according to this criterion as they are the only ones that require a building permit.

4.1 Weights of the criteria

Assigning weights to criteria that represent their relative importance is not an easy task. Indeed, giving numbers as weights would be completely arbitrary. However, what seems more accessible is a ranking of the criteria according to their importance. Consequently, to make it more interactive, cards carrying the name of the criteria are ordered. Moreover, if the importance between 2 criteria is considered as bigger than the basic unit of importance (going from one card to the other one), a white card is introduced as shown in Figure 4.1.

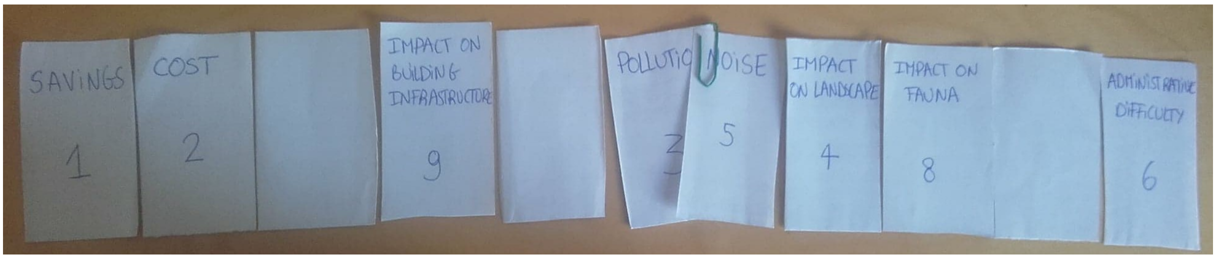


Figure 4.1: Order of importance of the criteria

This procedure is called the Simos' procedure and is described in [5]. Through this interaction with cards, it is possible to assign weights to criteria. After applying the methodology, weights are assigned as shown in the next section.

At first, the most important criterion is naturally the savings made by the people living in the building. Moreover, installing such devices is a big investment that is why, the cost is in the second position. Even though the cost is included in the savings, people could have reticence to invest in expensive units by lack of money, even if this solutions could get them more money at the end. In the third place after a white card, the impact on the building infrastructure is considered as such devices are heavy. After that, pollution (including recycling) and noise can be found at the same ranking position followed by the impact on landscape and fauna. Finally, the administrative difficulty to get the permits is the least important criterion traducing only a small effort from the owners.

Chapter 5: Application of PROMETHEE

5.1 PROMETHEE

PROMETHEE was introduced by J.P. Brans in 1982 [1]. It consists of a series of methods based on pairwise comparison. They all require the decision makers to directly assign weights but also preference functions to the criteria. The latter represent the deviation between the evaluations of two alternatives on that particular criterion [1].

Once all the information is provided, it is possible to compute degrees of preference among each pair of alternatives. Outranking flows are then calculated as a sum of the degrees of preferences: they represent how an alternative is outranking all the others for an outgoing flow $\phi^+(.)$ or how an alternative is outranked by all the others for an ingoing flow $\phi^-(.)$.

For using PROMETHEE, many software's exist. Among them, D-Sight has been chosen to run the analysis of the "Renewable Energies on Rooftops" project. The modelling part is explained here after.

5.2 Modelling in D-Sight

The modelling in D-Sight of each criterion will be described one by one in this section.

In order to measure the importance of one criterion compared to another, weight were assigned to each one of them. Criteria with higher weights will have a bigger impact on the evaluation of each alternative while criteria with lower weights will have less impact.

Also, each criterion must be either maximise or minimise. In this practical case, all of them must be minimise except for the savings that represents the economy save over 20 years and thus must be maximise.

Finally, for each criterion, a preference function must be defined. The role of this preference function is to compare two alternatives according to a criterion by computing the absolute difference and to assign a score to this comparison. The preference function evolves between 0 and 1 where 0 means that no preference at all can be expressed and 1 means that there is an indisputable preference for the best alternatives. The three preference functions presented below were used.

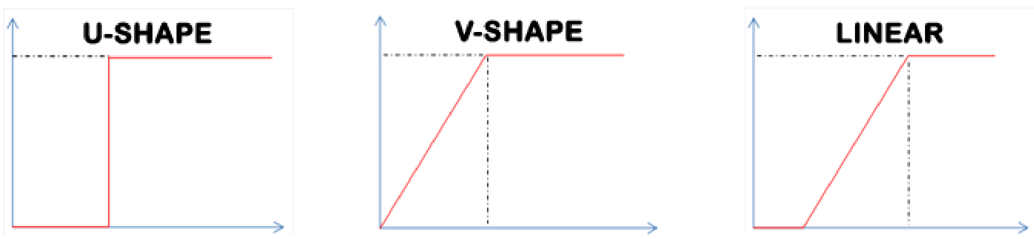


Figure 5.1: Preference functions.

The U-shape function is simply a binary preference. Below a certain threshold, called the indifference threshold, no preference can be made. Over this indifference threshold, the best alternative is indisputably preferred.

The V-shape function has zero as indifference threshold, but has a non-zero preference threshold, which is the point at which the best alternative is indisputably preferred. Between zero and this indifference threshold, the function evolves linearly.

The linear function is the same as the V-shape function but with a non-zero indifference threshold.

Knowing the previously mentioned tools, all the criterion have the following characteristics:

Criterion	Type of values	Unit	Minimise/ Maximise	Weight	Type of function	Indifference threshold	Preference threshold
Savings	Cardinal	€	Maximise	22.92%	Linear	500	8000
Cost	Cardinal	€	Minimise	20.83%	Linear	1000	5000
Infrastructure impact	Cardinal	kg	Minimise	16.67%	Linear	50	300
Pollution	Cardinal	tCO2	Minimise	11.46%	V-shape	/	4
Noise	Cardinal	dB	Minimise	11.46%	V-shape	/	45
Urban impact	Ordinal	1: low 2: average 3: high 4: very high	Minimise	8.33%	~~V-shape~~	/	3
Fauna impact	Ordinal	1: low 2: average 3: high 4: very high	Minimise	6.25%	~~V-shape~~	/	3
Administrative effort	Binary	Yes No	Minimise	2.08%	U-shape	0	/

Table 5.1: Criteria's characteristics

5.3 Analysis

A first analysis will present the results according to the alternatives presented in chapter 3. In the following part, a deeper analysis of the best alternatives will be conducted bringing new combinations of devices.

5.3.1 Base Case

The final ranking is presented in Figure 5.2. The higher the score, the better the alternative. The best alternative according to the PROMETHEE method and the different parameters taken into account (weights and preference functions characteristics) is the Alternative 0.3 comprising only solar PV panels (36 of them as presented above). A second interesting result to mention is that the four first alternatives are the ones without any wind turbine, which shows clearly that they are not economically viable for now. A further assessment of the contribution of each criteria will be made in the next subsection.

does not show it

As explained in Section 3, not all possible alternatives are displayed in the base case. New alternatives will then be created in the next section based on the best alternatives

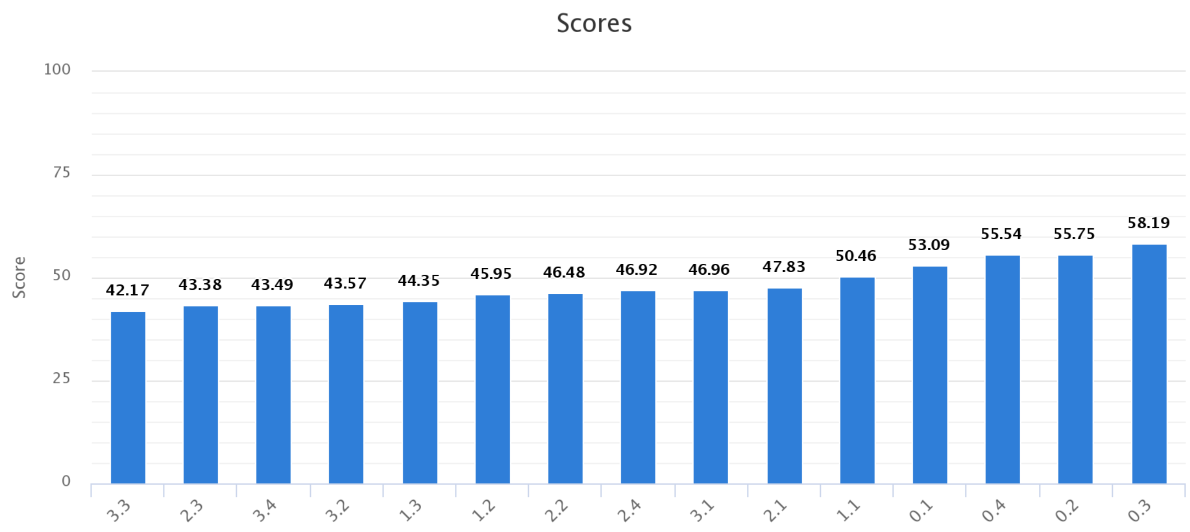


Figure 5.2: Ranking of the base case.

from the base case.

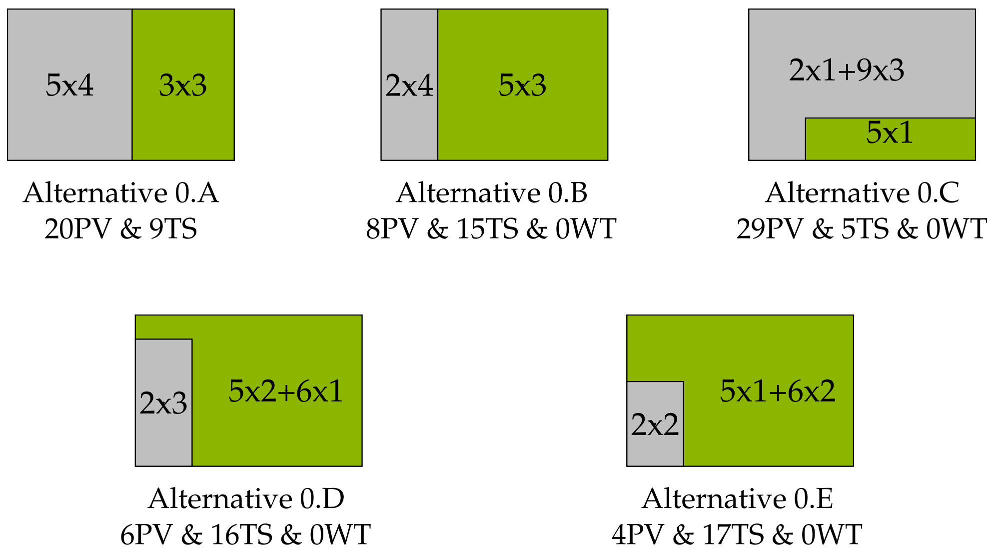
5.3.2 Deeper analysis

The three best alternatives from the base case are

- Alternative 0.3: 36PV & 0TS & 0WT
- Alternative 0.2: 27PV & 6TS & 0WT
- Alternative 0.4: 0PV & 18TS & 0WT

As all three best alternatives don't have any wind turbine, this device is definitely not a good one to place on this rooftop. The next combinations will then consist of a mix between photovoltaïc and thermal solar panels.

Five new alternatives are built as described here under:



When running the new comparison, it is important to keep all the alternatives. Indeed, due to the characteristic of the dependence to the third alternative of PROMETHEE, the results will lead to different outcomes otherwise.

A new analysis with the above mentioned alternatives has been conducted. The new ranking is shown in Figure 5.5. The Alternative 0.3 meaning 36PV remains the best one. However, the new alternatives are quite well ranked with the alternative 0.C (29PV & 5TS) as the second best combination and 0.A (20PV & 9TS) as the fourth one.

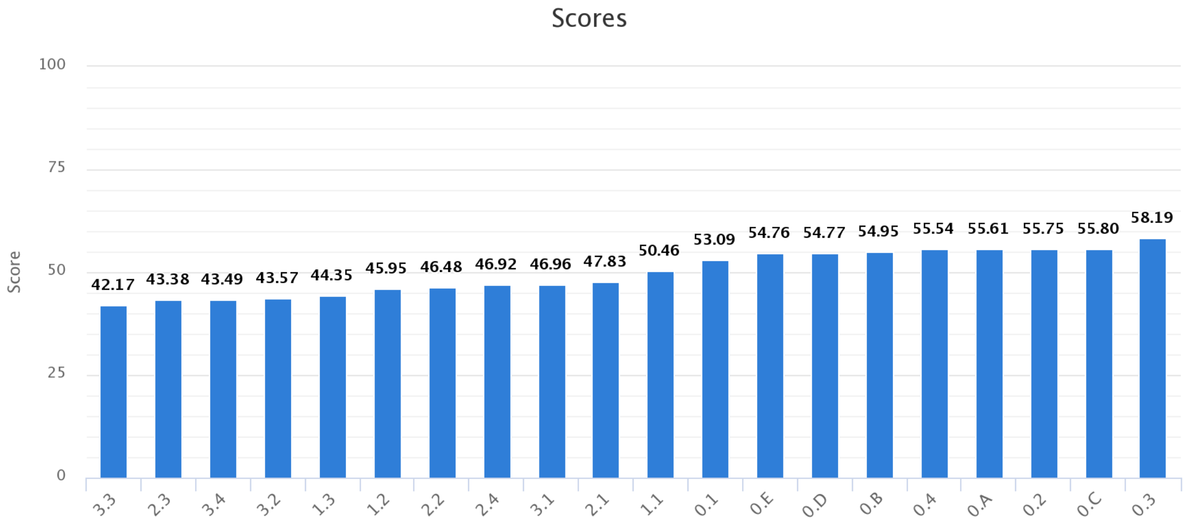


Figure 5.5: Ranking of the deeper analysis.

To understand better how the new alternatives compare to the 3 best ranked alternatives from the base case, let's draw a spider chart as in Figure 5.6.

The criteria such as urban and fauna impact, noise and administrative effort indeed contribute the same way to the score of the alternatives as no wind turbine is installed. The main discriminating criterion seem to be the pollution. Indeed, the PV panels are extremely polluting compared to the thermal solar panels as seen in Table 5.1. As a consequence, the alternative comprising only TS panels is the best performing according to this criterion. However, this does not compensate its really bad performance (the worst one) in respect of the "Savings" criterion which is actually considered as the most important criterion. By contrast, the Alternative 0.3 containing only PV panels outrank all the others on two quite important criteria: cost and infrastructure impact. It is then sufficient enough to remain at the first position of the ranking.

If one takes a look at the contribution of all criteria on each alternative score, represented in Figure 5.7, one sees that the "Cost" criterion is the bigger part of the score of the best alternatives. For all the alternatives without any wind turbine, only the cost, the pollution, the savings and the infrastructure impact will make the difference as confirmed here above. Even though the savings is a priori the most important parameters, it does not play a big role in the ranking of the top alternatives as they are all varying between 17899€ and 19736€ (with the exception of Alternative 0.4 which is below the other), so less than 10% difference over 20 years. In order to decide the first place of the ranking, cost is the determinant parameter, and as PV panels are cheaper than solar

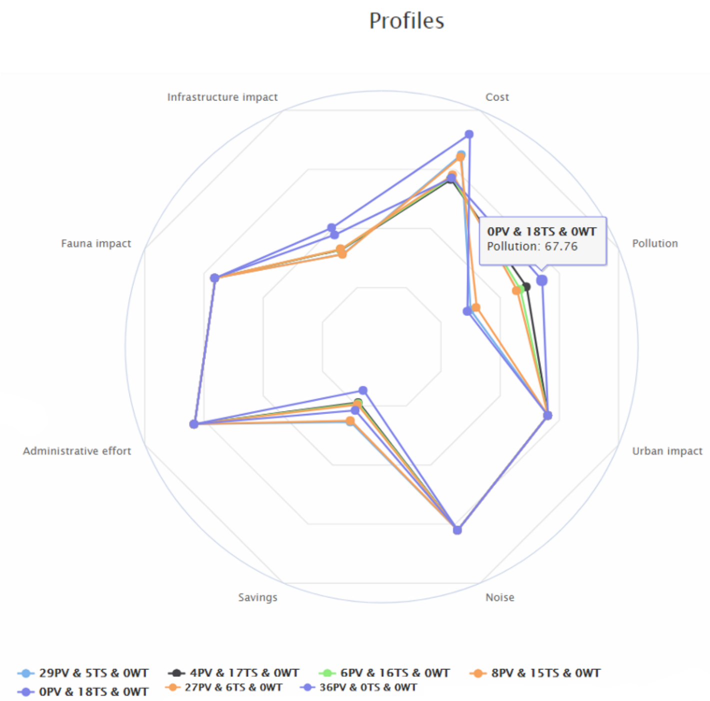


Figure 5.6: Comparison of the best ranked alternatives according to the criteria.

thermal panels, it is quite logic to find the full PV panels solution at the top position. Moreover, the price of gas is much more lower than the price of electricity, and thus it is more economically profitable to produce its own electricity instead of heat. If one takes a look at the worst alternatives, the savings play the major role. However, those alternatives are really poor in term of cost (they cost up to 4 times the cost of the best alternative). This is due to the still high cost of domestic wind turbines and thus it proves well that they are still too expensive to be counted as a "good domestic device".

To see the similarities between criteria on the one hand and alternatives on the other hand, Figure 5.8 is used. The green axis represent the criteria, and when those are expressing similar preferences, they are aligned in quite the same direction. For example, cost and savings are completely opposed. Indeed, an increase in cost leads naturally to a decrease in total savings. It can be confirmed by looking at Figure 5.7 where the savings contribute the most to the score of the worst alternatives while the cost contributes to only a small portion. For the best alternatives, the opposite happens.

The blue dots represent the alternatives. Similar alternatives are close to each other. For example, Alternative 0.C is opposed to 3.4 as the contribution of most of the criteria to the scores is completely opposite. Interestingly, the alternatives are grouped according to the number of wind turbines thus forming clusters. Indeed, adding a wind turbine changes substantially the contribution of all criteria to the scores. The score of an alternative according to one criterion is the projection of this alternative on the axis of the criterion. The red axis is the decision stick which corresponds to direction of the best solutions. Therefore, it points out to the cluster of alternatives that do not comprise any wind turbine and more specifically to the Alternative 0.3 which is indeed the best one.

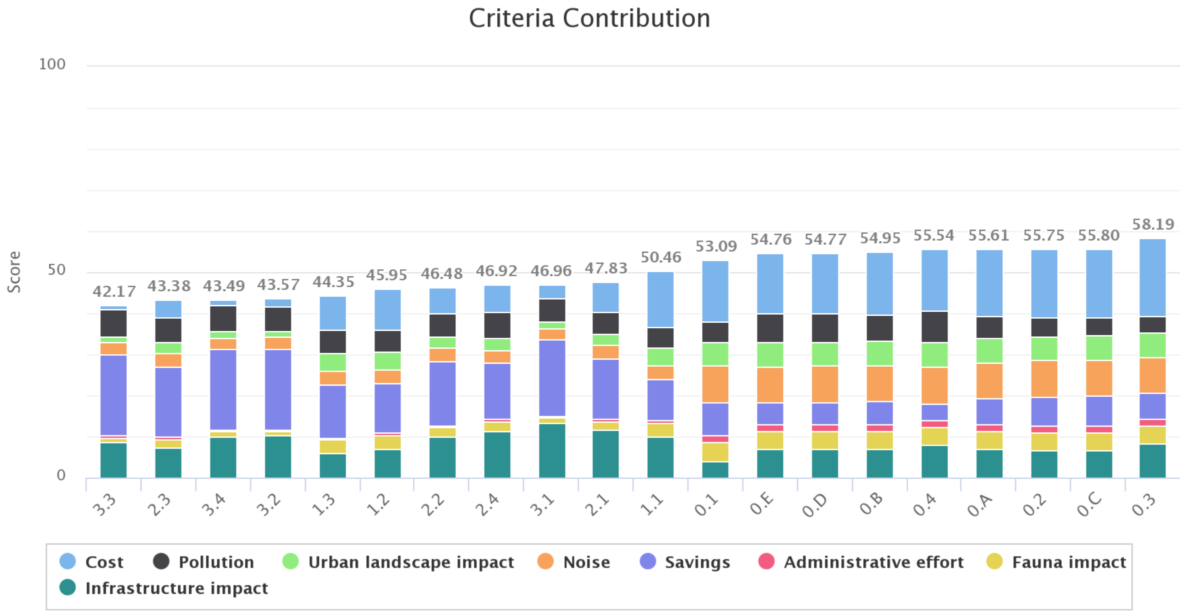


Figure 5.7: Criteria contribution to the ranking of the deeper analysis.

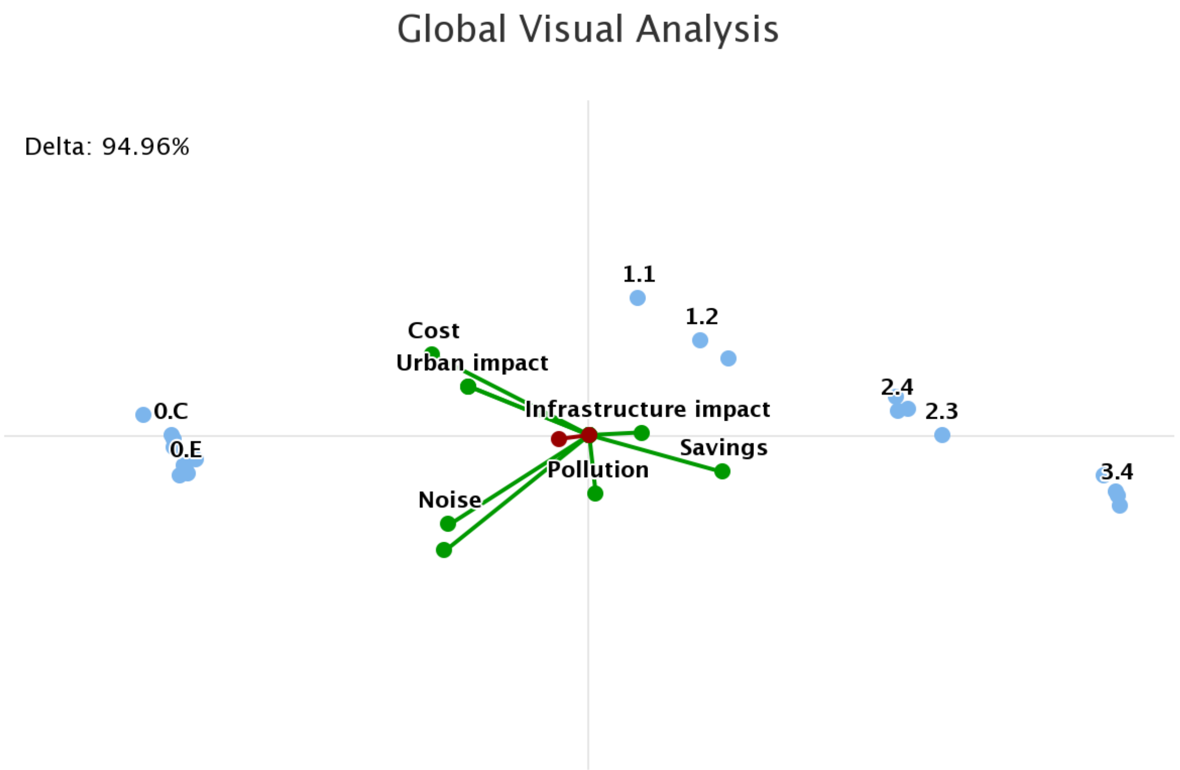


Figure 5.8: GAIA visual analysis for the deeper analysis.

Chapter 6: Sensitivity Analysis

All the previous analysis were considering two assumptions. The first one is that the electricity produced by wind turbines and solar panels is either consumed directly (and thus totally free) or is send to the electrical grid by making the electrical counter turn backwards, and thus this exact amount of electricity, when needed, is also totally free. The second assumption is that people have a strong reticence to invest in very expensive systems, even if it is more profitable on the long term, which made the cost criteria high. This chapter will present the analysis of the modification of those two assumptions.

6.1 Analysis 1: New cost of electricity

As mentioned, the base case assumed that all the non-directly consumed electricity could be sent to the electrical grid and be used later at no cost. The electrical grid plays thus the role of a giant battery. The cost of buying electricity is in this case approximated by:

$$\text{Cost}_{\text{elec}} = (E_{\text{cons}} - E_{\text{prod}}) \times P_{\text{bought}} \tag{6.1}$$

where E_{cons} and E_{prod} are respectively the total electricity consumption and production, and P_{bought} is the price of electricity taken as 0.219€/kWh.

In many electricity policy, electricity can not be sent to the electrical grid by making turn the electrical counter backwards, and thus the latter expression of the cost of buying electricity becomes more complicated. In that case, one has to consider the part of electricity that is directly consumed (and thus is free) and the part that is sent to the electrical grid (assumed to be sold at a price of 0.12€/kWh). The parts of the solar and wind electricity that are directly consumed are respectively of 37% and 50% and thus 63% and 50% are sold to the grid. The cost of buying electricity becomes:

$$\text{Cost}_{\text{elec}} = (E_{\text{cons}} - E_{\text{prod}}) \times P_{\text{bought}} + (0.63E_{\text{solar}} + 0.5E_{\text{wind}}) \times (P_{\text{bought}} - P_{\text{sold}}) \tag{6.2}$$

This new formulation increases for sure the total cost of buying electricity, and thus decreases the total savings.

The new ranking considering this formulation is presented in Figure 6.1. Again, the alternatives without any wind turbine are the best ones. However, the ranking of the best alternatives has changed. The previous best alternative made of only PV panels (Alternative 0.3) looses a lot of positions in the ranking and now occupies the 8th position. The new best alternatives are the ones with a gradual increase of solar thermal panels (from 6TS to 17TS) or in other words, a gradual increase of thermal energy production until reaching the best one which is the Alternative 0.4, corresponding to thermal solar panels only. Indeed, the PV panels are not profitable anymore due to the small part of electricity that can be directly consumed and thus be free. The rest of the produced electricity will not be bought at an advantageous price per kWh.

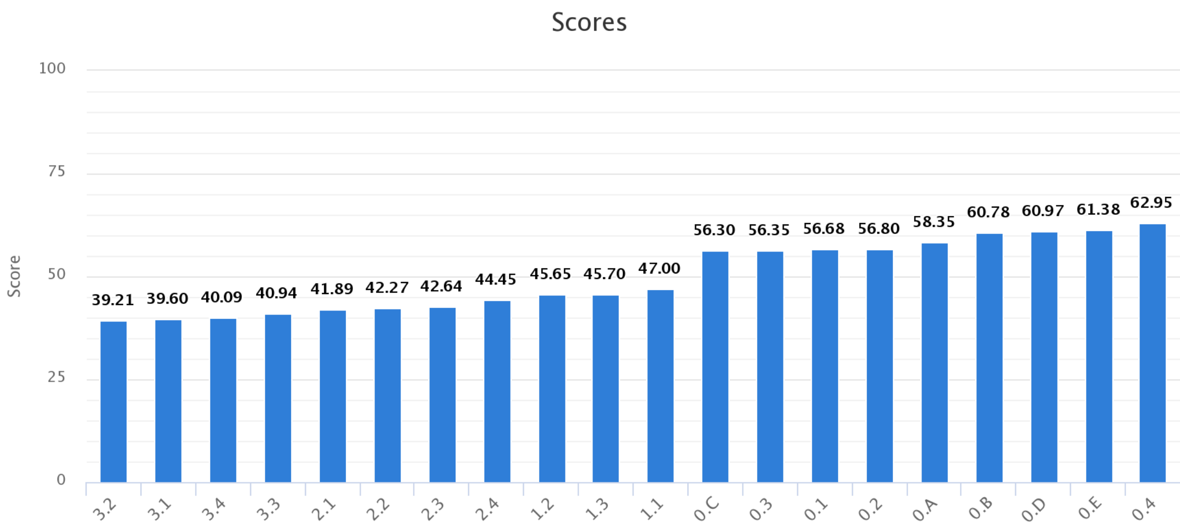


Figure 6.1: Ranking of the new cost of buying electricity formulation.

Moreover, if one takes a look at Figure 6.2 representing a visual analysis of the alternatives and by comparing it to Figure 5.8, one sees that the alternatives differ much more within a cluster. They are spread along the "Savings" axis, which means that the savings play now a more important role since this criterion contributes differently to the score of the alternatives within a same cluster as opposed to the previous case as shown in Figure 5.7. Consequently, the ranking changes.

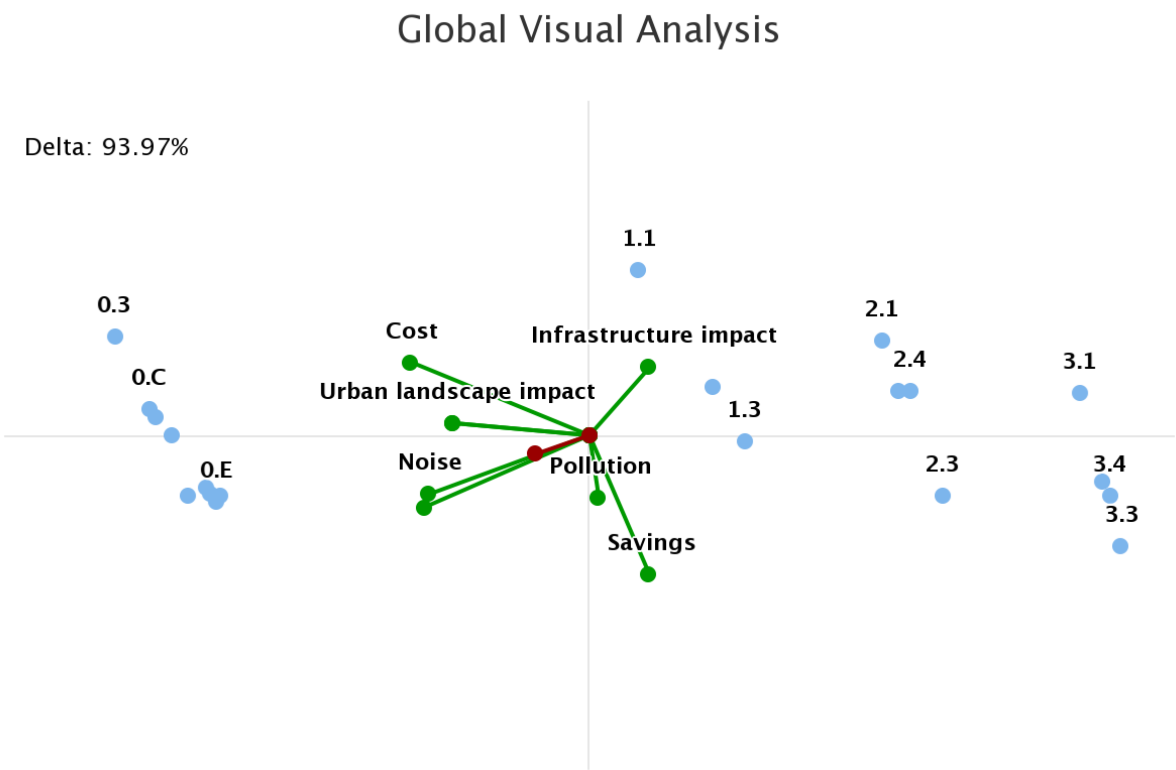


Figure 6.2: GAIA visual analysis of the new cost of buying electricity formulation.

6.2 Analysis 2: No "Cost" criterion considered

In this new analysis, the modification of the economic criterion will be assessed. One will consider that the purchase and installation cost have now no impact as it is already considered in the "Savings" criterion. It is the case for people that have the possibility to invest in expensive equipment and who are only looking for the long-term savings. With this new configuration, the "Cost" criterion is simply not considered thus carrying a weight of 0 and the weights of the remaining criteria are computed according to a re-normalisation, which gives the weights shown in Table 6.1.

Criterion	Weights
Savings	28.95%
Infrastructure impact	21.05%
Noise	14.47%
Pollution	14.47%
Urban landscape impact	10.53%
Fauna impact	7.89%
Administrative effort	2.63%

Table 6.1: Weights with no consideration of "Cost".

As one can see in Figure 6.3, the four alternatives with a maximum of wind turbines occupy the top positions of the ranking. Indeed, the "Cost" dominance that could be found in Figure 5.7 does no longer appear, and "Savings" become the dominant criterion as indicated in Figure 6.4.

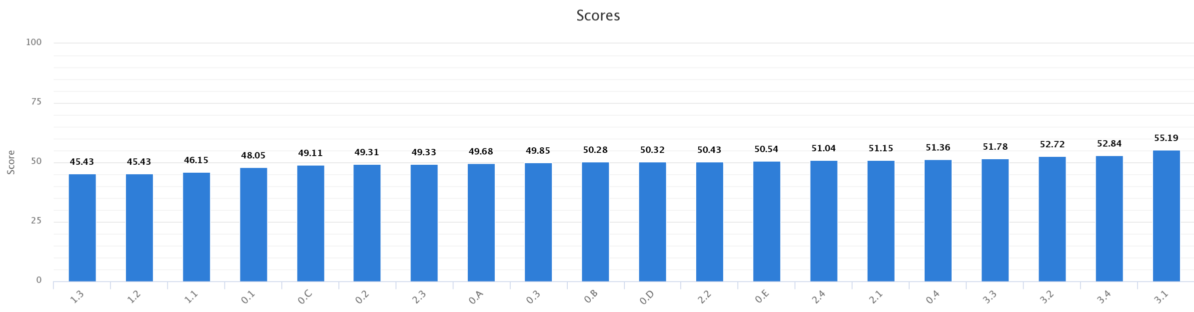


Figure 6.3: Ranking with no consideration of "Cost".

It is thus quite normal to find wind turbines in the best alternatives as the savings with wind turbines are substantially higher than without (28154€ for the new best alternative which is Alternative 3.1 and 18725€ for the old one, Alternative 0.3). In addition to a maximum of wind turbines, the best alternative presents a maximum of solar panels, which is quite logic according to the deeper analysis in Section 5.3.2 which has shown that PV panels were more optimal than solar thermal panels.

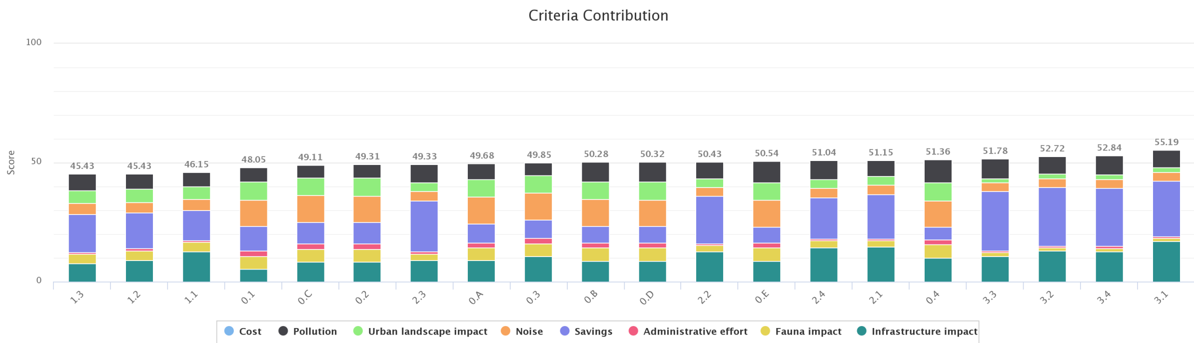


Figure 6.4: Criteria contribution with no consideration of "Cost".

Chapter 7: Conclusion

In this report, a multicriteria decision aid methodology has been used in order to assess a practical multiobjective optimisation problem. This problem consisted of finding the best combination of renewable energy sources on a rooftop, composed of wind turbines, solar PV panels and solar thermal panels, among a predefined set of alternatives. Those alternatives were evaluated according to given criteria, and the PROMETHEE methodology, through the D-Sight software, was used to compute a ranking of those alternatives.

The base case results have shown that wind turbines were not economically viable due to their high investment costs and that PV panels were preferred to solar thermal panels due to their low investment costs and the difference in price of electricity and gas. A much deeper analysis was performed introducing new alternatives without any wind turbine. The results of this simulation confirmed the previously obtained outcome, that is PV panels are the best solution.

Two sensitivity analysis were conducted in order to assess the impact of changes in the assumptions and parameters on the final ranking. The first modification was the introduction of a new formulation for the savings, which previously considered that all electricity produced could be used freely when needed. The new pricing considered that only a part of solar and wind electricity could be used instantaneously, and thus freely, and the remaining part should be sold to the electrical grid at a lower price that it is bought, and thus increasing the cost of buying electricity and decreasing the savings. This modification led to a change in the final ranking, bringing full solar thermal panels at the top position. The second sensitivity analysis was considering that the cost criterion did not play a role anymore, and that people only looked to the final savings. This led to a maximum of wind turbines as the best solution as they are the most producing source of electricity and thus maximise the savings, which becomes the most important criterion.

All of the previously mentioned analysis have allowed us to determine the best combination depending on different situations. Energy generation being an increasingly bigger concern, this work could be a first draft for people willing to jump ahead in the domestic renewable generation.

- very good analysis
- very good modeling
- just lack of justificat° sometimes and sources should be included in the text more clearly

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