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DESIGNING A SCIENTIFIC PLAN FOR ELECTRICITY GENERATION THROUGH THE SIMUS METHOD

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Abstract

In the fight for a better environment and to combat global warming, many countries are eagerly looking for ways to get rid of fossil fuels used in installations for thermal electricity generation. There is world-wide agreement about aiming at complete decarbonization by 2050; this ambitious plan consists in replacing old fossil fuel plants by renewables. This is a monumental task that involves a myriad of difficulties, which is however, reachable, perhaps not exactly at that date but possibly close enough to it.

This paper proposes a methodology or strategy, based on facts, statistics and mathematic modelling, and analysis, knowledge and experience of experts, i.e., it is a synthesis of mathematic modelling and human decision-making. This approach, to the best of this author's knowledge, has not been applied before at this scale. It is a difficult issue, because of the need to take into account future events, which entails uncertainty regarding several issues, such as demands, costs, people's reaction to new technologies, potential new developments in energy generation, new paradigms on consumption, etc.

We do not even know the risks that could appear in the future, such as the degree of global warming progress, financial risks of building new plants, new patterns for energy generation and storage, etc. In other words, uncertainty is part of the problem.

Keywords: contamination, fossil fuels, clean energy, MCDM, decarbonization, SIMUS, electric generation, transition.

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1 Introduction

Nowadays the world is threatened by global warming which results in very undesirable effects on the planet. Most researchers agree that this is due to the emissions, during decades, of two gases: carbon dioxide (CO_2) and methane (CH_4), which cause the greenhouse effect or global warming, increasing the temperature of the planet and provoking the melting of ice, which contributes to the raising of the sea level and to the flooding of land as well as increasing temperatures.

Scientists attribute the origin of these two gases and others such as sulphur oxides (SOx) and nitrogen oxides (NOx), and also of particulates, to the emissions from internal combustion engines, used especially in transportation, and in electric generation plants and which burn coal or fuel oil, as well as to the extraction of natural gas though cracking, with their large emissions of these two gases, as well as to large commercial airplanes, and ships, and to emissions from livestock digestive system (CO_2).

The United Nations and many other large organizations are worried about this contamination and their effects; they have proposed different measures to decrease these emissions. Unfortunately, this is not easy, because the energy matrix in each country is shaped by electricity generation plants using fossil fuels, as well as each country’s resources and national interest, or unions opposed to stopping coal mining, which can result in commercial and social upheaval.

However, there have been some gains, especially in the transportation sector, which is rapidly converging to more efficient and less contaminant sources such as liquid natural gas (LNG). There is also an impressive trend in personal and commercial transportation, initiated more than 20 years ago with the construction of electric cars and trucks, powered by renewable energy sources, such as hydrogen cells, batteries, and taking advantage of the deceleration of vehicles in city road traffic to recharge batteries.

There is no doubt that this has been largely helped by the introduction of policies in many countries outlawing the fabrication of vehicles burning fossil fuels soon in the near future (between 2030 and 2035). However, we are still far from solving the problem of generation of large amounts of energy to satisfy thousands of houses, factories, trains, subways, practically all type of industries, industrial furnaces, city lighting, operation of water distribution plants, as well as sewage networks, etc., that is, in all levels of life, and this is the main concern at present.

As mentioned, there are coincidental initiatives to reach total decarbonisation by 2050, which seems rather improbable at present (2024) with only 26 years to go. Fortunately, there are diverse sources of renewable and clean energy sources, mainly from the Sun, seas, rivers, biomass, winds, and from nuclear power, the latter involving about 640 reactors operating around the world.

This paper is divided in five sections and one appendix. Section 1 is the introduction. It continues in the second section with the analysis of the nature of the undertaking and considers some special characteristics of the problem to be solved.

The third section outlines the characteristics of the process, and the fourth section, the transition process, that is, the complex replacement of old and contaminant technologies by renewable and clean sources. The last one refers to the transition process which involves the consideration of many different aspects, some of them unknown, which are addressed here with a view to the future, i.e., over a quarter century from the present. There is uncertainty about demands, future contribution of each source, selection of these sources, lack of knowledge about new discoveries, etc. that make this part the most difficult one. However, we can hypothesize that such energy sources as organic PV cells (OPV), nuclear fusion reactors, or marine energy, will be used.

In the Appendix there is a brief description of the present-day technologies and alternatives for electricity generation, with and without contamination.

2 Characteristics of the undertaking

- It is necessary to identify which generation plants will be decommissioned, and when they will be replaced by new renewable ones. This is a process dragging perhaps for years, because it needs to be done gradually, i.e., it involves reducing progressively the participation of a contaminating generation plant until it is shut down and decommissioned.
- Once the type of technology is identified, e.g. coal and fossil fuels power plants that contribute heavily to the actual demand, it must be decided which type of technology will be used for replacement, and how long will it take to construct and test it.
- The main problem is probably the selection of the new technology, since an old plant must be substituted by another that fulfils the conditions of the old one, not only in its output **plus estimated future demand**, but also in its function.

  That is, a generation plant that is used for base load, i.e., the minimum or lowest level of continuous demand in a period, needs to be replaced by another one of the same characteristics, such as nuclear, hydro, biomass, etc., because all of them must work 24/7, and for long periods. This condition automatically excludes photo voltaic (PV), solar or thermal PV and wind generators, because of their low-capacity factor, or their intermittent operation. This results in very few options, unless new developments, such as nuclear fusion, may allow this replacement. Nevertheless, these plants can be used to absorb peak demand (increase of demand over the minimum) usually during

short periods, in periods of high temperatures and due to intensive use of air conditioners and refrigeration equipment, or usual demand occurring twice a day in winter and once a day in summer (Fedkin, 2025). Fedkin poses a very important and intriguing question: *"Can the base load power be entirely provided by renewable energy sources? Or we cannot avoid coal altogether?"*
and adds:
"While some of the components of the grid are subject to renovation, it is not the physical structure of the grid that is the focus of current redesign efforts; it is the informatics component that is supposed to bring the grid to a new level of intelligence".
In this author's opinion this points out a difficult problem. Of course, usually, we can operate a combination of plants such as nuclear fusion with biomass, geothermal and hydro power, thanks to the national electricity distribution grid, which can be perhaps reinforced with solar thermal plants and battery storage. **The latter are nowadays envisioned as a fundamental contribution to decarbonization**; they are not generators, but a support for the efficient operation similar to those working as base load.
The selection of the replacement equipment is a critical issue. This author believes that it cannot be solved just by selecting at random the type of renewable plant that will replace the old one, since the replacement must consider that all different alternatives for generation must satisfy a set of criteria evaluation, in many different aspects and involving demand, investments, maintenance, job generation, public health, global warming, environment, sustainability, reliability, safety, risks, cost to the user per kWh, the grid, life cycle, etc. For instance, it could be convenient to disconnect small and isolated populations from the grid and service them instead by portable 1 MW hydrogen cells packages (see Ballard, 2025).
Therefore, selection and replacement are indeed a complex undertaking, impossible to manage at the individual human level, and consequently requiring mathematical modelling aid. A widely used methodology known as Multi Criteria Decision-Making (MCDM) can do the job. This paper presents a very simplified example, of how an MCDM method, called Sequential Iterative Modelling for Urban Systems (SIMUS) (Munier, 2011), is capable of addressing this problem.

2.1 Brief explanation of the SIMUS method

The method is fundamentally an application of Linear Programming, which is a branch of Operations Research, and it was created by L. Kantorovich (1939) to maximize Soviet resources against the German forces during the WWII. It was complex and labor-intensive, but was made easier to use in 1948 by G. Dantzig (1963) who introduced the simplex algorithm which could solve efficiently largescale LP problems, and was latter recognized by the Society for Industrial and Applied Mathematics (SIAM) as one of the top 10 algorithms of the 20th century.

The simplex algorithm is the computational engine used by SIMUS and has been available as an Excel add-on since 1993. However, classical LP is limited to single-objective problems with quantitative criteria, which restricts its applicability in real-world, multi-dimensional decision contexts. These limitations were overcome by the development of SIMUS in 2014 by N. Munier. SIMUS extends LP to handle up to 100 objectives simultaneously, accommodating any mix of quantitative and qualitative criteria.

At its core, Linear Programming involves a series of matrix-based transformations that iteratively optimize a linear objective function subject to linear inequalities.

SIMUS begins with an initial decision matrix and selects an alternative based on the opportunity cost principle. Using a mathematically chosen pivot, it transforms the entire matrix to yield an optimal or Pareto-efficient solution. It then evaluates whether this solution is the best; if not, it iterates the process, generating new solutions that may improve upon the previous ones. Since there is no guarantee that any intermediate solution is optimal, the method continues iterating until it reaches the optimal solution, defined by the tangency between the constraint set and the objective function.

SIMUS applies the simplex algorithm once for each alternative, producing a set of Pareto-efficient scores. For each alternative, it calculates a weight, defined as the ratio of the number of optimal scores it achieves to the total number of criteria satisfied. By weighting the sum of scores accordingly, it determines the relative importance of each alternative.

Importantly, this is only one of two procedures. SIMUS also performs an outranking procedure over the same weighted matrix. When the results of the weighted sum and outranking procedures are compared, they yield identical rankings, a convergence that underscores the mathematical rigor and reliability of the method.

This is the method applied to solve the complex energy problem addressed in this paper.

3 Capacity factor

The transition from the present-day energy matrix which uses fossil fuels involves its replacement by an energy matrix utilizing renewable and clean sources. As mentioned, this is a labor of decades since it means replacing contaminant technologies and equipment by renewable and carbon-free electricity generators, which is a complex undertaking. The concept of capacity factor is here of paramount significance.

The electricity factor is a ratio that measures the actual energy production of a piece of equipment in a certain period, and the theoretical maximum in this period. This is important because the actual generation in a period, for instance, a day, may be different from the theoretical energy it can deliver in the same period. This applies to installations where the fuel cannot be supplied continuously as in the case of fossil fuels or hydropower plants, but only in certain subperiods, and sometimes with large variations, as in the case of solar or wind power.

This is the case of PV cells which generate power only when the sun shines and even on cloudy days, or of wind turbines which can generate power day and night, provided that there is enough wind. Therefore, they cannot serve as base load generators, but can be used advantageously in peak periods or for charging batteries, which is one of their most promising and reliable uses.

At present, generators that satisfy the 24/7 condition are thermal plants, nuclear reactors, geothermal and biomass, diesel generators, and, to some extent, hydropower plants (since they may be subject to variations and even shortages due to insufficient precipitation or ice melting). Hydrogen cells meet the 24/7 condition, but they cannot work as base load, at least at present time.

Table 1 shows the capacity factor values for different kinds of energy generators (Statista, 2022).

Table 1: Capacity factors

Type of generator	Capacity factors (%)
Nuclear fission	92.7
Geothermal	69
Natural gas – Combined cycle	65
Other gas	61.6
Other biomass	60.2
Wood	57.9
Coal	48.4
Hydroelectricity	36.3
Wind	35.9
Solar PV	24.4
Solar thermal	23.1
Natural gas internal combustion	18.1
Natural gas – Steam turbine	15.6
Petroleum – Steam turbine	13.2
Natural gas turbine	12.9
Pumped storage	11.1
Batteries	6.4
Petroleum internal combustion	1.8
Petroleum gas turbine	1.6

Source: Statista (2022).

The very low-capacity factors of the last two categories is noticeable. It may be due to the fact that since about 1980, boilers were fueled with petroleum (liquid fuel). Since nowadays they are fueled by natural gas, these installations are currently used for brief periods only.

4 The transition processes

As mentioned in the Introduction, an MCDM method can be applied to work out a plan to progressively decommission the existing fossil fuel plants. The methodology involves the following steps (Munier, 2023):

Researchers point at 2050 as the date to decarbonize electricity generation entirely, and this is the date used here. It is convenient to partition the intervening time – the 26 years from 2024 through 2050 – into four periods of five years each, and a fifth one of six years. This partition logic is based on the unreliability and guesswork involved in predictions of what will happens 26 years from now regarding costs, energy demands, new developments, people's reaction, etc., with no added information in between about demands, new discoveries, more advanced equipment, etc. Thus, partitioning reduces vagueness, considering that experts will have more information about what has happened in the previous five years, which will allow them to extract trends and make more accurate predictions for the next five-year period.

In addition, in many laboratories around the world research is being conducted on new developments for electricity generation at high TRL levels (see NASA, 2010), related to using organic solar cells, with lower cost, more adaptability and considerably less contamination, which can change the scenario, and which may be in commercial operation about 2035-2040 or even before.

For transition, including replacement and selection of new alternatives in each period, and a reduction of fossil fuels participation in every five-year period, this author uses SIMUS, which is a proved and reliable MCDM method; but it is possible that a new and more powerful method appears in some of the periods which may also be used for comparisons with SIMUS results.

As can be seen, the reason for partitioning is that it facilitates the decision-making at reasonable intervals, which allows for a set of reviews based on the past five-year performances. That is, the problem is approached dynamically, based on the immediate past and projected for the distant future. The past information permits making a comparison of what was done with what should have been done regarding usage of different alternatives and extracting conclusions.

The projection for the future is performed by experts, based on what was learnt from the past and aiming at determining which is the best mix of technologies for the future, and at reducing contamination as much as possible by decreasing outputs in fossil fuel installations, supported by extensive simulations to select the best candidates. From there, the experts can build the matrix for the incoming periods. The proposed method is a synthesis of a mathematical analytical procedure and a further testing and analysis by experts who decide about the best policy.

The periods are:
First: 2024/2029
Second: 2029/2034
Third: 2034/2039
Fourth: 2039/2044
Fifth: 2044/2050

Table 2 illustrates the procedure in a simple and only demonstrative case. These data have been processed by SIMUS, and the result is seen in the solid row. Data for the present period are valuable and verifiable, and, starting with 2029 it is impossible to predict what can happen until 2050, and for this reason data are not shown. Table 2 has been generated by AI, but it can also be built using information from Google. The justification for using AI is:

- Google gives only **partial information,** while AI builds the **whole picture.**
- In Google, the DM needs to read **many publications and find the average**, while **AI compares and synthesises everything at once.**
- AI may discover **hidden problems,** while Google **can miss them.**
- AI considers **all the existing data base**, while Google selects **only some papers from general queries.** Google responds to general queries from the DM, while **AI needs precise guiding.** This implies that the DM must have a deep knowledge of the problem.

The DM must give the following parameters to AI:

- Costs,
- Capacity factor,
- O&M Cost,
- Job generation,
- People approval.

AI fills the cells with average unit values.

Modelling must be made by the DM, who has to design activities and criteria, as well as instructions to the chatbot including a 1-10 scale for ‘job generation’, using a Linguistic Rating Scale such as ‘Low’, ‘Moderate’, ‘High’.

From this point on, SIMUS operates using this table as the initial Decision Matrix, and thus its starting point and base. It is worth mentioning that instead of asking for averages, we can work with intervals, that is, lows and highs for each criterion, thus reducing uncertainty.

The solid row in Table 3 gives the results using the SIMUS method for the period 2024-2029:
Fossil: 45%
Nuclear: 7%
Solar PV: 21%
Hydro power: 0
Biomass: 7%

Table 2: Initial decision matrix for the period 2024-2029

	Types of electricity generators (Alternatives)				
	Fossil fuel	Nuclear	Solar PV	Hydropower	Biomass
Objectives (Criteria)					
Capital cost ($)	2000	9000	1250	2250	3500
Capacity factor (%)	60	85	20	50	75
Operation and maintenance ($)	30	15	15	10	30
Job generation (#)	3	2	9	6	8
People approval (%)	30	40	80	70	60

Normalization is automatically performed by SIMUS, once the DM has selected one of the four methods offered by the software. After normalization, the matrix was electronically loaded into SIMUS. The results are in Table 3.

Table 3: SIMUS results for the period 2024-2029

SIMUS Result	**45**	**7**	**21**	**68**	**7**

Let us now examine the next period (2029-2034). Table 4 shows the new matrix:

Table 4: Initial decision matrix for the period 2029-2034

	Types of electricity generators (Alternatives)					
	Fossil fuel	Nuclear	Solar PV	Hydropower	Biomass	**Wind**

Table 5: SIMUS results for the period 2029-2034

SIMUS Result	**29**	**8**	**25**	**46**	**7**	**27**

In this new result it is worth noting that:
There are now six alternatives since **wind power is included**, with a score of 27, because new ways to treat used blades have been found instead of dumping them in landfills.
Fossil fuel score decreased from 45 to 29, a large decrease indeed.
Nuclear increased from 7 to 8, because a nuclear reactor under construction will enter service in 2031.

Solar PV increased from 21 to 25, due to the construction of new PV farms and of a large Solar PV plant.
Hydro decreases from 68 to 46, due to global warming and the melting of some glaciers.
Biomass stays constant. There is a strong opposition from environmentalists, because biomass harvesting can produce deforestation. Moreover, environmental researchers strongly doubt that the amount of CO_2 generated is compensated by the amount of this gas captured in the photosynthesis process by green leaves.

A similar examination and process will follow in 2039, when the nuclear-fusion reactors that were in testing since 2024, enter service (which may happen in the late 2037). In this case, it is envisioned that by 2039 the energy matrix will be as shown in Table 6.

There is complete uncertainty about the type of alternatives that will constitute the initial matrix, since we are looking at ten years from 2024, but according to present-day developments of emergent technologies such as OPV, D-T, Marine generation, etc., these are the most advanced, especially D-T and batteries. Table 6 shows the SIMUS results for the period 2034-2039.

Table 6: SIMUS results for the period 2034-2039

SIMUS result	**29**	**7**	**25**		**59**	**12**

However, it is also probable that in this period the use of hydrogen-oxygen thermal plants, where this mix, instead of fossil fuels, is burnt in boilers, will prevail. Also, hydrogen fuel cells may be widely used. That is, we need to assume that everything can change with time, including the energy matrix, just as the energy matrices of the twenties were different to the current ones.

By designing the energy matrix for the period 2034-2039 (Table 7), it could very well be that a new actor enters into this energy generation scenario: the nuclear fusion reactor (or D-T Deuterium-Tritium). Some governments are against the current nuclear fission reactors (uranium reactor), because of their risk, construction, and maintenance cost. If the D-T becomes commercially applied in 2037, for example, it is quite possible that the experts, pressed by governments and the age of the existing uranium reactors, will start shutting them down and replacing them by the new reactors. In this case uranium reactors will have decrease from 7% to 4% and the loss in output will be absorbed by the new reactors.

Table 7: Initial matrix for the period for 2034-2039

Types of electricity generators (Alternatives)					
Batteries	Nuclear	Solar PV	Hydropower	Biomass	**Nuclear fusion (D-T)**

Table 8: SIMUS results for the period 2034-2039

SIMUS result	**40**	**4**	**28**	**15**	**5**	

Notice that at the end of 2039, the **fossil fuel plant will no longer exist**, and most of the lost energy will be delivered by **new hydro plants and by a set of batteries**, with a very large capacity, which will provide hundreds of MW/hr during long hours and which will be loaded by solar PV and very possibly by Organic PV cells (OPV). Note that **hydro is declining** due to scarcity of water in rivers and because many plants may be decommissioned because of their low output and high maintenance costs.

Wind turbines will be no longer used. They will be left out due to their elevated cost as well as for environmental reasons, since the recycling of used blades is linked to **higher production of fumes from the blades.** Also, due to the **death of birds** and for **economic reasons**, since at present it appears that they, with their length of up to 108 metres, have reached the structural limit of materials, and because **their transportation is** very difficult and **costly**, and **the erection costs, high.**

From the case analysed, the author believes that the complexity of the scenario can be understood, but that it is also possible to solve to solve the problem scientifically through an adequate procedure.

In reality, this is a simplified scheme, because we are not considering changes in the set of criteria, with new and updated values, deleting or adding criteria, etc.

As a bottom line the steps of the process are:

1. Considering that the **main objective is total decarbonization by 2050**, divide the time from the date of the study to that date.
2. Based on statistics and trends, the analyst **can forecast electricity demand** during the first period.
3. Find the **available alternatives** for electricity generation.
4. Determine the **criteria** for the evaluation of alternatives and the **goal or target** for each one.
5. Using public information, the Web, and **AI find the actual contribution (in percent) of each alternative to each objective.**
6. **Build the initial decision matrix** with alternatives in columns and criteria in rows.
7. Apply MCDM to this initial matrix, using the **SIMUS method.** The result will indicate the most convenient **energy technology**, that is, that which **best satisfies the largest number of objectives,** and will determine the ranking by decreasing order of excellence of the other technologies.
8. At the end of the first period the experts may proceed to define:

- The **most contaminant fossil fuel plants to be shut down** by progressively decreasing their output demand. The shutting down may take more than one period, hence, at the beginning, a plant may continue operating for many years until it is decommissioned. For this reason, the analyst must **instruct the software to keep this plant in operation in the next period**.
- **Life Cycle** of all installations to determine their remaining useful life. The software will use this value when considering the importance of the criterion.
- **Construction time and testing of new generation plants**. It is therefore necessary to develop a tentative schedule as a guide.
- Experts can **add new technologies** that comply with the **Technologies Readiness Levels (TRL) (NASA, 2010), > 10, as in a commercial stage.**
- Using **simulation**, experts can reach a conclusion regarding the decrease of a contaminant technology and the increase of renewables.

This information will allow them to **build the energy matrix for the next period.**

Due to the uncertainty of information and future events, it is advisable to perform a **sensitivity analysis to** determine the strength of the solution found. For instance, it could happen that a certain installation or plant is scheduled to enter the system; this selection, however, depends to a large extent on the subset of criteria used for the evaluation of the plant. It may depend heavily on the regular supply of the fuel.

As an example, if a hydrogen cell is selected, its fuel (hydrogen), may come from another country, and if the hydrogen production is erratic in that country, this choice is very risky. Other problems, related to a high variability in the cost of hydrogen, such as regular quality, transportation delays, etc., may occur, too. On the other hand, a criterion may vary widely without affecting the plant.

This criterion may be stable, variable or unpredictable. If its variation is large, but it does not affect the best selection, we say that the result is strong. If the criterion depends on external aspects such as international fuel prices, and if it is rather volatile, this can cause the best alternative to lower its position. A recent example is the suspension of delivery of Russian gas to Europe; many generation projects had to be cancelled because of this.

Analysis at the end of each period

In an energy matrix the criteria are also objectives to be met, thus they have a **goal or target.** A result must indicate the extent of the achievement of a certain objective. This is invaluable information for the experts, which can reset goals or lead them to a more in-depth study to determine why that objective didn’t reach its goal. It could also be that the goal in period (n – 1) was not as important as previously thought and its importance was lowered, thus allowing for an increase in importance of another objective. For instance, if a goal consisted in job generation and it was not met, perhaps its importance should be preserved or decreased.

Another important issue is related to the life cycle of each installation. For instance, a hydropower plant built 30 years ago cannot be decommissioned because it is expected to be many more decades in service, unless the water supply is greatly reduced. **That is, the software must incorporate an objective related exclusively to the life cycle of each equipment piece**, by changing the performance value taking into account its remaining useful life. This means that if at the end of the period (n – 1) an installation is at its half-life, it must remain in service in the next period (n), unless technical or economic risk aspects suggest the opposite.

At this point the proposed methodology creates a symbiosis with experts, giving them important information to take decisions based on new developments in energy generation.

Thus, the experts know which are the best renewable sources to keep, but also which should be decommissioned because they are at the end of their useful life. This is one of the criteria to be satisfied, as mentioned in the Introduction. This is very important, since if a solar thermal plant was commissioned e.g. in 2025, is does not make economic sense to shut it down and tear down four years later (EIA, 2025a).

Suppose that in 2029, the contribution from renewables including nuclear, hydro, PV cells, solar thermal, wind, biomass and geothermal account for 50% of total demand of base and peak load. Assume that there are coal and oil fuel plants that satisfy the other 50%. The experts, using the SIMUS method, can perform **hundreds of simulations runs,** varying the amount of contamination among the different still contaminating units, by reducing their output. At the end, they will have a solution stating that with all factors taken into consideration, it is more convenient to decrease the contribution of a coal plant, for example.

With this data for the next period 2029-2034 the experts can decide, on the basis of data from the previous SIMUS results, which of the plants (or both) contribution should be decreased; they can also make a projection for the next periods starting in 2034.

5 Conclusion

This paper has analyzed the critical issue of transition of an actual energy matrix, based on a mix of conventional sources of electricity generation, mostly composed by plants burning fossil fuels, as well as renewable sources of electricity generation installations, aiming at developing a plan of conversion of the initial matrix into a new one composed entirely of renewable sources for electricity generation.

The analysis is divided into two parts. The first one brings general information on the issue, as well as enumerates and comments on an array of currently available alternatives, detailed in the Appendix. The second part outlines the proposed methodology to be used to plan for an uncertain future, since it considers the period up to 2050, and aims at achieving a total decarbonisation of electricity generation by this date.

The paper analyzes all currently available alternatives, as well as potential alternatives. It divides the 26-year interval between 2024 and 2050 in five periods and uses an example to illustrate the process using an MCDM tool, the SIMUS method. From this, and considering other patterns from simulation, the experts can decide the most convenient mix of technologies for the next period. The same procedure is followed in each period.

Appendix

Description of present-day technologies for energy generation

There are many ways for electricity generation: coal and fossil fuel plants, which have been in use for more than 100 years, as well as hydro and nuclear installations. This category includes typical thermal plants, including a boiler, a steam turbine driving an electrical generator, and a condenser, as well as internal combustion engines such as diesel engines and gas turbines.

All of them burn fossil fuels, and consequently, in view of the absolute necessity to reduce the emission of noxious gases, they are considered for decommissioning and replacement by renewable sources. In fact, we are seeing the beginning of the end of these installations. In these days it is mandatory to replace these installations by others that fulfill two fundamental requisites: Using only renewable resources and being zero contaminant.

This paper is aimed at establishing a plan, program or strategy, to complete the decarbonisation by about 2050. Why then, it is addressing and explaining present-day installations that do not comply with them? Because the transition process, i.e., the conversion to renewable sources may take, decades to complete, and in consequence, it will be still necessary to live with some of these old installations until they are replaced. In addition, there are plants that were built or refurbished recently, and thus, it would be uneconomical to decommission them. Just as it took decades to replace horse-drawn carriages by cars, which in turn are being replaced by electric cars, so it will take decades to switch from coal fueled steam locomotives to ones burning liquid fuels, and from these, to diesel units which are being replaced by electric trains.

Biomass

This refers to generating electricity by burning vegetal matter. Since it is burned in the presence of oxygen its exhaust contains CO_2 from the combustion, but it is considered a renewable resource. Many researchers agree with this; despite of the production of CO_2, under the assumption that an equivalent amount of CO_2 that was formerly taken from it by green leaves through the photosynthesis process, is returned to the atmosphere. This hypothesis is challenged by many researchers because, among other reasons, there is no certainty that the CO_2 exhausted is equivalent to the CO_2 absorbed.

Its defenders maintain that using biomass is dependable, which is true, and that it can also help in reducing waste, which is also correct. In fact, in some large cities, about 20% of the domestic garbage is re-used; for instance, in Portland it is used in cement kilns, thus reducing fossil fuels consumption.

Other researchers, even acknowledging these advantages, point out that this process produces contamination – directly or indirectly – other than the alleged surplus of CO_2. For instance, it happens that a forest is logged to produce timber to be burnt, adding the issue of transportation costs, by trucks which also contaminate with their exhausts. From this author's point of view, logging creates deserted areas that are quickly eroded, which constitutes an externality, or cost to the society without market values, that most of the times, and universally, are not considered as a cost in the GDP. Nevertheless, this procedure is extremely popular in some countries. Carrier Process Equipment Group (2025) sustains that biomass provides 5% of energy consumption in the United States.

Average life span: About 20 years
Environmental pollution: Emissions from the plant may be loaded with contaminants
Investment: US$ 3000-4000 per kW installed
Load factor: Full, at 24/7
Output: These plants operate in a range of about 50 MW, there are installations with outputs as high as 1000 MW, e.g., in Florida (Biomass Magazine, 2025)
People: This is a big issue, since people are, in general, reluctant to see biomass plants installations in their neighborhoods, not only because of the gases, but also because of the intense truck traffic required by the supply, and most importantly, because of loss in property values near the plant
Risk: Risk is related mostly to the environment, for reasons already listed
Additional relevant information: **EIA (2025b)**

Hydrogen cell

This is a device to generate electricity, based on the electrochemical action of oxygen and hydrogen, using a catalyzer to facilitate the process. The cell produces electricity as well as heat and water without any contamination; it is used in the car industry. Hydrogen – the fuel – enters the anode while the oxygen, used for the reduction or oxidation, is fed to the cathode. The electrons of the hydrogen flow as electricity which charges batteries. After that, the electrons meet the protons of the hydrogen and, when combined, produce water. Fuel cells do not have any moving parts, and due to its simple configuration are extremely dependable. They can increase their efficiency using the heat in many other applications.

Average life span: Depends on applications. For instance, for stationary units it may be about 40,000 hours (see US Department of Energy, 2025a)
Environmental pollution: None
Investment: Hard to define, but a 120-kW fuel cell, in large agricultural machinery, may cost about US$ 200,000
Load factor: 24/7
Output: At present the highest output is 1MW and there are portable packages of cells stacks that can work unattended, providing electricity to remote or isolated areas
People: It has benefited many people and industry e.g., forklift manufacturing and construction
Risk: The hydrogen is stored until it is used. It is a highly explosive gas and maximum caution must be exerted when handling and storing
Additional relevant information: Ballard (2025) and US Department of Energy (2025b)

Geothermal

These plants, which use water steam at hot temperatures (182°C) from underground sources of heat, constitute a valuable renewable source of energy. When the hot high-pressure water reaches the surface, it evaporates due to the lower pressure, and the steam is used to drive a turbine or an electricity generator.

Average life span: About 20-25 years, after which time the turbines are usually affected by corrosion
Environmental pollution: Water from underground sources may release toxic gases into the atmosphere
Investment: About 3.5 US$ per KW installed
Load factor: 90%
Output: Large, about 1800 MW
People: 196,000 jobs worldwide in 2022 (Statista, 2022)
Risk: Risk occurs in the exploration and drilling stage when searching for an adequate source
Additional relevant information: JUMO (2025)

Nuclear fission or D-T reactors

This is the newest technology for electricity generation and it is still in development. As opposed to nuclear reactors, which have been in service from decades and use uranium bars as fuel, using the principle of fission, D-T reactors use the principle of fusion of two chemical elements (two hydrogen isotopes: deuterium and tritium). Experiments on such reactors have been conducted since the 1970s and even before earlier, but the main problem encountered is that the energy input exceeded the energy produced.

At present, a large-scale D-T reactor is almost complete in southern France (ITER, 2025), as a joint effort of several countries and the European Union. Tests will start in 2024, and it is expected that the energy output will be ten tines the energy input. This reactor, however, is designed not for commercial but for experimental use. If tests are successful, some units can be in service by 2050, and many researchers believe that it will be the source of energy generation for centuries to come.

It works on the same principle as the Sun, but since it is not possible to replicate on the Earth the pressure conditions existing in our star, fusion must be produced not by pressure (as in the sun), but by temperatures ten times higher, that is, at 150,000,000 degrees.

Average life span: Unknown
Environmental pollution: It does not produce greenhouse gases
Investment: Extremely high. It is estimated that ITER will cost more than 12 billion euros
Load factor: Unknown
Output: 500 MW with an input of 50 MW
People: Since there is no radiation, it is assumed that there will be no risk for people
Risk: Neutron release produces radiation that can last between 50 and 100 years, which is low in comparison with fission reactors, whose radiation may persist for several centuries
Additional relevant information: ITER (2025)

Batteries (BESS)

This an acronym for Battery Energy Storage System.

A park of packs of lithium-ion batteries with a power of 750/3000 MW has been built in Moss Landing in Monterey County, California, allowing for powering houses and businesses by supplying 750 MWh for four hours; larger plants are also being built (Lewis, 2023).

These battery storage plants are used in peak loads to allow base load plants to continue working uniformly or at constant speed, and are managed by sophisticated software. Generation by large load base plants is most efficient when they work continuously and at the same rate. For that reason it is convenient to have peak load generation units. It is in this segment that batteries can be used, for as long as four hours or more, to absorb the peak demand.

Such batteries can be charged by renewable sources such as PV, solar, thermal and wind; they contribute to present-day decarbonisation, mitigating the pollution produced by plants using fossil fuels. From this author's point of view, they offer a solution to the process of gradual decommissioning of currently existing plants, and can be considered as partial energy generators, essential in the decarbonisation process. According to Shah (2022), "Some of the largest Battery Energy Storage Systems worldwide can even power thousands of homes for hours or even days", and adds: "Intelligent battery software uses algorithms to coordinate energy production and computerised control systems are used to decide when to store energy or to release it to the grid".

Battery storage systems are not the only way to store electricity. EIA (2022) proposes other four systems and provides valuable information.

Additional relevant information: Shah (2022), Siemens Energy (2025)

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