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Beyond Profitable Shifts to Green Energies, Towards Energy Sustainability

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Abstract: The traditional carbon-based approach towards sustainability has long caused the concepts of green and sustainable energies to be used interchangeably. Recent studies have tried to advance this archaic view by considering more aspects of sustainability. However, almost all major studies have been concerned with only the economic and environmental aspects of electricity generation, whereas the concept of sustainability is beyond these two criteria. In this paper, we seek to provide a methodology for a more comprehensive definition of electricity generation sustainability based on the lessons learned from previous studies and additional metrics suggested by them. The main characteristics of select electricity generation technologies were studied, and their environmental, economic, social, and technical criteria as well as the uncertainties associated with them were selected as the four major factors in our paper. It has also been argued that the utilization of regional resources in addition to the inherent characteristics of electricity generation technologies is vital in providing a realistic view of sustainability. Of the sustainability assessment methods previously introduced, the Relative Aggregate Footprint (RAF) method was used in conjunction with the previously selected criteria as the basis of the study due to its ability to incorporate additional criteria and regional considerations. As such, the framework for sustainability assessment presented in this research accounts for major criteria identified in the literature and takes the available regional resources that affect the feasibility of each electricity technology into account. This study paves the way for the presentation of new guidelines for the creation of more comprehensive electricity generation sustainability measures to distinguish between the concepts of green and profitable vs. sustainable energies to support the development of sustainable energy portfolios.

Keywords: energy sustainability; green energy; carbon emissions; cost of energy; energy portfolio; resource availability



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1. Introduction

The idea of tracing the footprint of the human impact on the earth is indeed one that dates back a few decades [1,2]. With renewable energies gaining popularity, the concept of how energy sources impact the environment [3] was initially only focused on carbon emissions and how they vary from one technology to the next. Initially, the lower carbon emissions of renewable energies made them synonymous with green energies. However, the concept of energy sustainability goes beyond carbon and embodies other criteria and available natural resources, in addition to their proper utilization. Hence, it is important for the key criteria that play a major role in energy sustainability to be identified and taken into consideration.

The sustainability of energies (and electricity generation in particular) has been discussed numerous times in the past decades. Each study, however, has looked at the issue of energy and its sustainability through the particular lens of the authors' area of expertise. The water–energy nexus works of [4], for example, focus on the allocation of energy to provide water, while [5–7] look at the same issue from the opposite direction: the allocation

of water for energy generation. In this regards, ref. [8] emphasizes the need for electricity generation to be reshaped based on water consumption and carbon emissions. In [9–12], the authors look at energy production with the aim of maintaining market sustainability, while [13–15] consider the technological and economic sustainability of the power plants themselves and the need for newer renewable electricity generation methods with lower carbon emissions. Other studies such as [16] look at the sustainability of energy sources in their ability to provide food or even the combined water–food–energy nexus under various scenarios [17–21]. In addition to these, other factors such as the social impact of electricity systems [22] or the risk of providing the required resources for electricity production [23,24] have been proposed as other considerations in the definition of sustainability. As a result of these disjointed studies carried out with vastly different mindsets, the definition of sustainability remains unclear, with the general public and activists still naively associating it solely with carbon emissions [25], vilifying power companies and industries for their selfishness in polluting the environment in the process. The notion of sustainability may be difficult to define as shown by these studies, but it certainly should not be limited to the environmental factors. Other criteria need to be considered to broaden its definition.

Recent studies have addressed these shortcomings by introducing numerous new sustainability indices and indicators as can be seen in the works of [26–29]. While the introduction of newer indicators seems like an improvement at first glance, they are not based on well-known previously introduced metrics in the literature. Likewise, most of these newer indices are based on the authors' definitions of sustainability with the goal of capturing as many criteria as possible as opposed to using the lessons learned from previous studies. Furthermore, these indices are based on different assumptions which make their utilization tricky and their results incomparable to each other. As such, a wise approach would have been to modify an already existing and well-established sustainability metric as opposed to introducing a new one.

Aside from the inherent uncertainties with the definition of energy sustainability, most of the previous studies fail by not considering the region where energy is to be used. As an example, the black and white approach to sustainability by looking only at carbon fails to justify the use of low-tech electricity sources in remote locations without access to other electricity sources or cleaner technologies. All the while, a proper definition of sustainability should be clear enough to consider both the environmental pollution of such older technologies, as well as the added social welfare that accompanies them. In addition, factors such as regional availability of fuel for power plants and the trade-off between using regional resources and purchasing them from neighboring states or countries are among other regional considerations that traditional definitions of sustainability have no answer for aside from economic analysis. As such, the omission of regional resources is another point where most studies fall short of reality.

Despite these shortcomings, some studies propose novel approaches such as looking at sustainability via the lens of reliability and resilience of the system [30], but perhaps the most comprehensive foundation has been laid out by [31] where a sustainability index (Relative Aggregate Footprint—RAF) has been introduced by considering the environmental and economic characteristics of electricity generation technologies. While the definition of RAF may not include a wide range of criteria, it addresses issues such as regional resource availability or uncertainty in data and decision making. As such, their approach has been chosen as the core of the sustainability definition framework presented in this paper. This research aims to look at the concept of electricity generation sustainability more broadly and define it by looking further than the environmental aspects. As such, economic, technical, and social aspects of electricity generation technologies are also taken into account, as well as the characteristics of the region where the technologies are to be used, to provide a clearer picture of available resources and how to best allocate them.

Finally, in defining sustainability, a distinction needs to be made between the use of terms such as clean, green, renewable, and sustainable energies, especially when more than 20 different definitions have been recorded for them in the literature [32]. The carbon-

based definition of sustainability has no doubt led to these words being used arbitrarily and interchangeably by many researchers [33]. Generally, clean energies are attributed to carbon-free options, whereas renewable energies are the options with naturally replenishing resources. A notable example of these terms not being equal is the case of nuclear energy and biomass, with the former being a clean energy with small carbon emissions but not renewable, and the latter being a renewable source, despite generating carbon emissions. On the other hand, green energies are a subset of renewable energies with the highest environmental benefits [34]. However, sustainability is often described as the ability to strike a balance between creating a better life for the human race on one hand and dealing with the limitations imposed by nature on the other hand [35], making it a more noble concept that is fundamentally different than the rest of the aforementioned keywords.

In practice, energy users usually define these terms based on their own goals and agendas. Most states in the United States now employ a renewable portfolio standard (RPS) as a means of diversifying electric utilities by including renewable sources. The same standard is sometimes known as the Clean Energy Standard (CES) in other locations. In the US, renewable portfolio standards were first utilized in the 2000s with the aim of allocating a portion of total energy generation to renewable energies. Despite the energy production goals, most states using renewable portfolios either have no preference towards a particular energy type at all, or only have classified select technology tiers rather than a coherent energy portfolio [36]. These issues are exacerbated by knowing that less than half of the American states have developed a renewable energy portfolio. Furthermore, the omission of heterogeneity in the development of renewable energy portfolios has led to similar characterization of energies and often identical portfolios regardless of differences [37]. As such, in practice, the need to study energy suitability based on the region, their available resources, and needs remains in place.

As a result, the goal of this study is to compile a collection of metrics based on the RAF method that states can use to compare the sustainability of electricity generation technologies and develop sustainable electricity portfolios. These metrics are spread out in various groups to account for the environmental, economic, social, and technical footprints of electricity generation technologies and are chosen per suggestions of previous research carried out in each field. Moreover, the regional characteristics and resource availability have been mentioned in addition to the specific energy-related attributes to provide a more realistic view of energy sustainability in each region by distinguishing among green, renewable, and sustainable energy technologies. In most previous studies, only the inherent characteristics of electricity generation technologies have been taken into account, and the specifics of the region are rarely a factor. The metrics mentioned in this study can be used in sustainability analysis of energy technologies for a more comprehensive vision of sustainability.

2. Chosen Energies

Next we provide a short introduction to the energy types chosen to be compared in this study. The choice of energies is important in determining what sustainability factors are to be considered. This especially affects the fuel and supply sources of the energies. Of course, the list of energies mentioned here is not exhaustive, but the majority of the commercially available technologies are considered.

2.1. Biofuels

Biomass resources are one of the oldest forms of energy production, an example of which is the burning wood, which has decreased dramatically throughout the years due to the introduction of coal, oil, and natural gas as alternative sources of energy. However, the use of biofuels comes with the ability to better manage fuel prices in case of fluctuations in the price of other available sources [38]. Currently, the main sources of biofuels are plants, genetically engineered algae, by-products from agricultural activities, methane gases from landfills, or the oil that comes from these sources [39,40]. Another advantage

of biofuels is their ability to use residues and by-products of other processes as fuel, thus reducing the overall emissions of said processes [41]. The yield of biofuels is dependent on the crop being used, with corn having the smallest yield of conventional bioenergy and cellulose having the highest. In addition, biomass energy produces carbon, nitrogen, and organic compounds and particulates as by-products that can have adverse effects on air quality and global warming in larger quantities [42]. This is also dependant on the source of energy such that using bioenergy can increase carbon emission up to 20% in the case of corn or decrease it by upwards of 120% in the case of cellulose, making the choice of crop an important consideration [43]. Overall, the sustainability of biofuels is a function of the materials used as fuel, the supply chains in place, management strategies, and policies in place [44].

2.2. Solar

Solar energy started becoming a major source of electricity in the past decade, and its usage is projected to grow slowly but steadily. In reality, however, the energy from the sun has been taken advantage of even in the past century due to the simplicity of the process with its most dominant use being for heating water. Using the energy from the sun to heat water is currently popular in many countries including Germany [45].

For electricity production, solar energy can be used in two forms: Solar thermal and solar photovoltaic (PV). Solar thermal technologies employ the heat from the sun to run electric generators. The fact that the United States is the second largest producer of solar thermal energy in the world [46], shows that the US understands the potential for solar power. In these systems, the sun bounces off parabolic mirrors and is directed to a central tube that is filled with air, vapor, synthetic oil, molten salt, or liquid sodium, heating it in the process [47]. As such, this system is called Concentrated Solar Power (CSP). The hot contents of the central tube later transfer their heat to a source of water to generate steam and drive a turbine. One of the advantages of using molten salt or synthetic oil over water is that they can hold more thermal energy and enable the power plant to keep producing power even when the sun is not shining. For example, the Gemasolar power plant in Spain, which uses molten salt, is capable of producing uninterrupted electricity for 24 h. However, if these systems remain idle for a long time, heating them back up takes a considerable amount of time and energy. Another issue with solar thermal energy is the effects it can have on wildlife, threatening the habitats of desert creatures and scorching birds that fly in the vicinity. Finally, the output of solar thermal plants relies on sunshine. Therefore, due to cloudy days and bad weather, their production seldom reaches its ideal peak. Lastly, for the solar thermal plants to work, large areas of land are required, which increases their land-use footprint.

Solar PV is the other form of solar energy that uses solar cells to convert solar radiation directly to DC electric energy and is the type of solar power with considerable growth in the past decade. The US, South America, North and South Africa, the Middle East, and Australia are some of the regions with the highest PV potential [48]. In the US, the Southwest has the highest solar PV potential, and the northern areas have the lowest potential. Currently, the manufacture of panels and batteries are the two items that drive up the cost of solar panels. Some countries such as Germany choose to install solar panels next to highways on land that is otherwise unsuitable for farming or other uses to save on the land footprint. The obvious problem with solar PV is its inability to generate power at night, which makes it an unsuitable choice to provide the baseload. In addition, just like CSP, the actual electricity generation of PV energy is reliant on the sunshine.

2.3. Wind

Wind energy is probably the fastest growing renewable energy source worldwide, with its commutative capacity having been multiplied by a factor of 10 since the 1990s [49]. Wind is also one of the cheapest renewable energy sources available on the market today, especially in the long run. China has the largest installed wind capacity in the world,

followed by the US. The fastest growth in wind energy can also be seen in China. In the US, the central regions have the highest onshore wind capacity, and the northeastern and northwestern coasts have the highest offshore wind capacity [50]. About 0.5 percent of solar energy ends up forming winds, so wind ultimately can be considered an alternative form of solar energy. The minimum wind speed required for wind turbines to be feasible is 7 mph at an altitude of 80 m, but in practice, wind farms are constructed in areas with an average wind speed of 12 mph. Because of the slow-moving speed of wind turbines, some of them come with transmissions to adjust the speed of the generator, but the lubricant in these transmission can sometimes be a fire hazard at higher speeds. More modern wind turbines also have the ability to adjust the pitch of their blades towards wind to increase efficiency [51].

In addition to onshore wind, offshore wind is also another alternative that offers a higher potential of power production than its terrestrial counterpart [52]. Sadly, the US is completely missing from the list of major offshore wind farms in the world with most major offshore wind farms being located in the North Sea. Offshore wind turbines are in constant danger of corrosion by seawater that can cause both structural and electrical disruptions. The requirement of large transmission lines is also another disadvantage of offshore wind turbines.

Perhaps the most dominant disadvantage of wind farms is their disruption of the natural landscape. In addition, making room for onshore wind farms sometimes requires the felling of trees which has its own environmental consequences. Furthermore, the general issue with all types of wind turbines is their low capacity factors that often lie in the 25 to 50 percent range [53]. In addition, due to the fluctuations of the wind in different hours of the day and in different seasons, the actual production of wind turbines is much lower than their nominal capacity. This requires huge capacities to be installed, with only a small percentage of which is used to the full potential at any given time.

2.4. Hydropower

While hydropower is a rather clean source of energy, it is not considered a green energy by many sources [54–56]. This is due to the reservoir changing the sediment structure of the bed surface, jeopardizing terrestrial and aquatic species in the vicinity, as well as its high water demand. In particular, the construction of dams has the potential to displace a large number of people and comes with social ramifications. Hydropower is one of the oldest sources of energy with watermills dating back hundreds of years. In 2018, 9 out of the 10 largest power plants in the world were hydropower plants [57], which shows hydropower's high potential for electricity generation. The Three Gorges Dam in China with a capacity of 22,500 MW, for example, is the equivalent of about 32 regular coal power plants. However, US energy generation data in the past decade shows that the share of hydropower in the total electricity production has not grown considerably. At the same time, Chinese hydropower has almost doubled. Globally, the increase in hydropower electricity production has almost been increasing on a linear basis. Overall, hydropower plants have the potential to replace many of the older greenhouse-gas emitting power plants and save considerably on noxious gases and fossil fuels.

In short, hydropower is an almost carbon-emission-free [58] and renewable source of energy with high electricity conversion efficiencies of up to 80% [53] which can be used to supply the baseload of electricity. It is also versatile and can be scaled from as low as 10 kW to 20,000 MW. The operating and maintenance cost of hydropower plants are lower than most other competitors, and they have the advantage of long lifetimes [59]. On the other hand, using hydropower requires a large water footprint [60] and causes the inundation of large portions of land which can have social impacts due to people being displaced. Hydropower's output can vary due to rainfall, and therefore, a level of flooding risk is associated with it. Due to disruptions in natural water flow, hydropower plans can impact aquatic ecology and oxygen depletion in water. Hydropower generation often requires high capital costs and construction can take long amounts of time. The limiting

factor of hydropower in many countries, however, is the limited available land and not enough valleys to flood, which hampers its implementation.

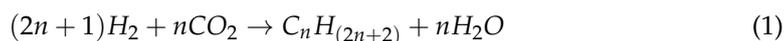
2.5. Coal

Coal is a rather old means of electricity production, and only a small percentage of today's largest power plants operate on coal; however, the high use of coal in developing countries is still noticeable [61]. The US is rich in coal reserves and more than half of the states have recoverable reserves [62]. The use of coal is still noticeable in the US, but it is on the decline with the introduction of newer technologies. Less emphasis on coal production in recent years and more automated extraction processes have resulted in the drop of the number of people working in the coal industry [63].

Among the greenhouse gases emitted by the coal power plants are sulfur dioxide, nitrogen oxides, carbon monoxide, carbon dioxide, particulate matters, mercury, lead, selenium and fly ash [64–66]. However, these emissions have seen a considerable decline in the past 30 years due to the improvements of technology. Integrated gasification combined cycle (IGCC) is the newer version of coal power plants that uses a gasifier to turn coal into syngas, a synthetic gas consisting primarily of hydrogen [67]. The carbon in the syngas can be shifted to hydrogen which can result in a carbon free-fuel. Furthermore, the resulting carbon dioxide can be compressed for easier storage. However, the high cost of IGCCs which can drive up the electricity prices is a hindrance to their use.

2.6. Oil

Oil is mostly used directly for the transportation sector rather than for electricity generation. However, the conventional internal combustion engines using oil products lack high efficiencies. Unlike the suggestions made by [68] that the rate of petroleum production follows a bell-shaped curve, the discovery of newer sources of oil and newer extraction technologies has kept the oil industry growing. Aside from the conventional sources of oil, unconventional sources such as oil shales, oil sands, coal-based liquid supplies, biomass-based liquid supplies, and gas to liquid (GTL) have become possibilities [69]. In addition to using oil as fuel, the Fischer–Tropsch synthesis process can be used as shown in Equation (1) to convert carbon monoxide and hydrogen into liquid hydrocarbons as an additional source of fuel.



While these new sources provide additional oil, they also impact the environment because of acid drainage, introduction of metals into groundwater, erosion, sulfur emissions, and air pollution, as well as disposal problems, greenhouse gas emissions, and water usage. This adds a layer of uncertainty to the emissions of these new technologies [70].

2.7. Natural Gas

Natural gas can be used for power generation, as well as for transportation, hydrogen production, and the manufacture of fabrics, glass, steel and many other products. The burning of natural gas produces 20 percent less carbon dioxide compared to burning gasoline and 40 percent less compared to coal [71]. In addition, due to the similar nature of natural gas and coal power plants, older coal power plants can be retrofitted to operate on natural gas. The efficiency of natural gas turbines is rather high and can range from 30 percent to 60 percent for the variants with heat recovery. Of course, single cycle power plants are less efficient and therefore more suitable as peaking power plants that operate only a few hours a day. Currently, combined cycle power generation using natural gas is the cleanest source of energy using hydrocarbon fuels in terms of carbon emissions [72]. Another advantage of these power plants is their ability to be turned on and off very quickly which makes them suitable for supplying power over peak demands. The use of natural gas as a replacement for petroleum is also viable as the efficiency of natural gas engines is comparable to that of gasoline engines.

Natural gas can be found in associated (along with oil) or non-associated (isolated) fields. Newer gas resources such as sour gas, tight gas, shale gas, and coalbed gas also exist, but using them can be costly and challenging at the current time. The most common form of natural gas today is probably liquid natural gas (LNG). The energy density of LNG is 2.4 times that of compressed natural gas which makes it an ideal solution for long-distance transport and in situations where pipelines are not available. The liquid form of gas also makes it possible to store the natural gas [73], usually in underground storage facilities; however, leakages in natural gas storage tanks (for example, the Aliso Canyon incident) are still one of the main concerns [74]. Despite natural gas being regarded as one of the greener energies, the losses of up to nine percent of stored methane in storage tanks have a considerable environmental impact, not to mention wasted resources. The issue is not limited to storage facilities and can be witnessed even in urban areas.

2.8. Nuclear

In nuclear power, exothermic nuclear processes create heat which generates electricity. In 2016, nuclear fission powered roughly 10 percent of the world's electricity as well as numerous naval vessels [75]. France and the United States are the leading producers of nuclear power in the world, with the Netherlands and Armenia following as the countries least reliant on nuclear energy [76]. In the southeast US, the state of South Carolina is the main user of nuclear power and the home to four nuclear plants with the Virgil C. Summer Nuclear Station being the most important one. This is partly due to the fact that South Carolina suffers from a lack of gas pipeline infrastructure. Oddly enough, Australia despite being one of the largest producers of uranium in the world, has no nuclear power plants in service.

Most conventional nuclear plants are either of the Boiling Water Reactor (BWR) or Pressurized Water Reactor (PWR) types [77]. In older PWR types, the coolant water also acts as a moderator and goes past the control rods. Therefore, the water becomes contaminated, and in case of leaks, the leaking steam will be dangerous. To remedy this, in newer PWR reactors, boron and control rods are used to maintain system temperature, but the water that goes through the turbine is not directly in contact with nuclear materials and will not be radioactive.

With increased awareness towards probable nuclear catastrophes, Germany and Japan are among countries trying to decommission their nuclear plants [78]. In addition to the direct catastrophes that may be caused by nuclear plants, disposal of nuclear waste is another direct issue of nuclear power as it requires the provision of land and specialized storage grounds and cooling pods.

More optimistically, nuclear energy is rather affordable, with the total fuel costs (including the fuel itself, enrichment, manufacturing, and disposal) being about 5 to 10 cents per kilowatt-hour [79]. Fuel contributes to about 10 percent of this price, so the changes in the price of fuel have minimal impact on the final cost of energy.

2.9. Geothermal

Geothermal energy is the energy stored in the Earth's core in the form of heat. This thermal energy manifests itself in the form of steam and hot water and has been used as a source of electricity for decades. Based on [80], the total geothermal capacity of the Earth has been estimated at 7974 MW_e, but as of year 2000, only 0.3% of this amount was exploited. Extraction of geothermal energy occurs by drilling a hole in the Earth's crust in regions where the geothermal gradient is higher than the average of 30 °C/km in depth. The heat is transferred from the sub-surface regions to the surface via conduction and convection processes through geothermal fluids in underground aquifers. These hot fluids (or steam) are then extracted, and depending on their pressure and temperature, they can be used for electricity generation or heating.

The shortcoming of geothermal energy is the need for three conditions: a thermal anomaly, a productive geothermal source, and a closed reservoir in an accessible depth

that is not covered by impenetrable rocks. This greatly limits the viability of geothermal energy despite its potential. On the positive side, when all the aforementioned conditions are met, extraction of geothermal energy can be achieved using conventional technologies. Geothermal energy is generally cleaner than fossil fuels in terms of carbon emissions, but in reality, its use is dependent on the cost of fossil fuels and carbon taxes.

3. Electricity Generation Footprint and Impact

More often than not, studies focus only on one aspect of electricity generation or on many aspects of one technology which does not provide the bigger picture for comparing different electricity generation types [81]. There is more to the concept of sustainability than carbon emissions and costs. Sustainability is looking at the Earth as a whole and using its resources efficiently while considering the limitations. Therefore, not all green energies are necessarily sustainable.

As pictured in Figure 1 based on the data by [82], the current electricity portfolios in the southeast United States are mostly based on hydrocarbon and nuclear sources with renewable sources only contributing a negligible amount to total electricity production. To overcome this shortcoming, some states have incorporated renewable portfolio standards with the goal of improving the sustainability of electricity generation. However, firstly, not all states have such standards in place with the states of North and South Carolina being the only examples with renewable portfolio goals in the southeast United States [83]. Secondly, these portfolios are almost exclusively based on increasing the share of renewable energies and whether said energies are actually green is not mentioned. This shows that the states are mostly concerned with lowering their carbon footprints, and other criteria are not a major deciding factor of their definition of sustainability.

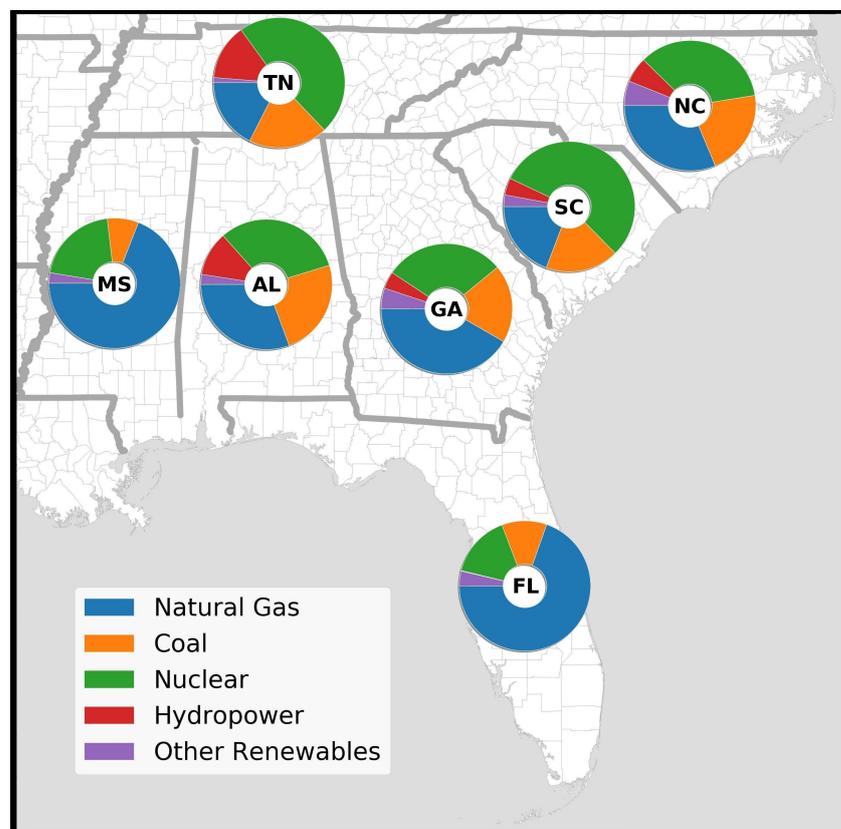


Figure 1. Current energy portfolios in the southeast United States.

As such, the energy impact indexes in the literature are bound by the factors included in them and may not be all-inclusive. These indexes are usually custom-tailored to consider one or a few aspects of electricity production in a very detailed manner. Instead, our

paper tries to include more factors to obtain a more coherent look at benefits and drawbacks of electricity generation methods and their sustainability. The considered factors are categorized in four groups of environmental, economic, social, and technical, thus enhancing the traditional way of viewing only the environmental and economic properties of energies. Figure 2 shows the conceptual framework of how sustainability is defined, and the major factors that play a role in defining and measuring sustainability, and forming the energy portfolio. Some of these criteria had been suggested before in the works of [84–86], but a broader range of possible metrics are collected in Figure 2. This enhances the view on sustainability which was based on environmental and economic factors in the past. Since different experts have different priorities in terms of factors they deem important, additional criteria and factors can be added or removed to the list presented here. In addition, different weights can be specified for each criteria to consider the importance of each one based on the experts’ opinions.

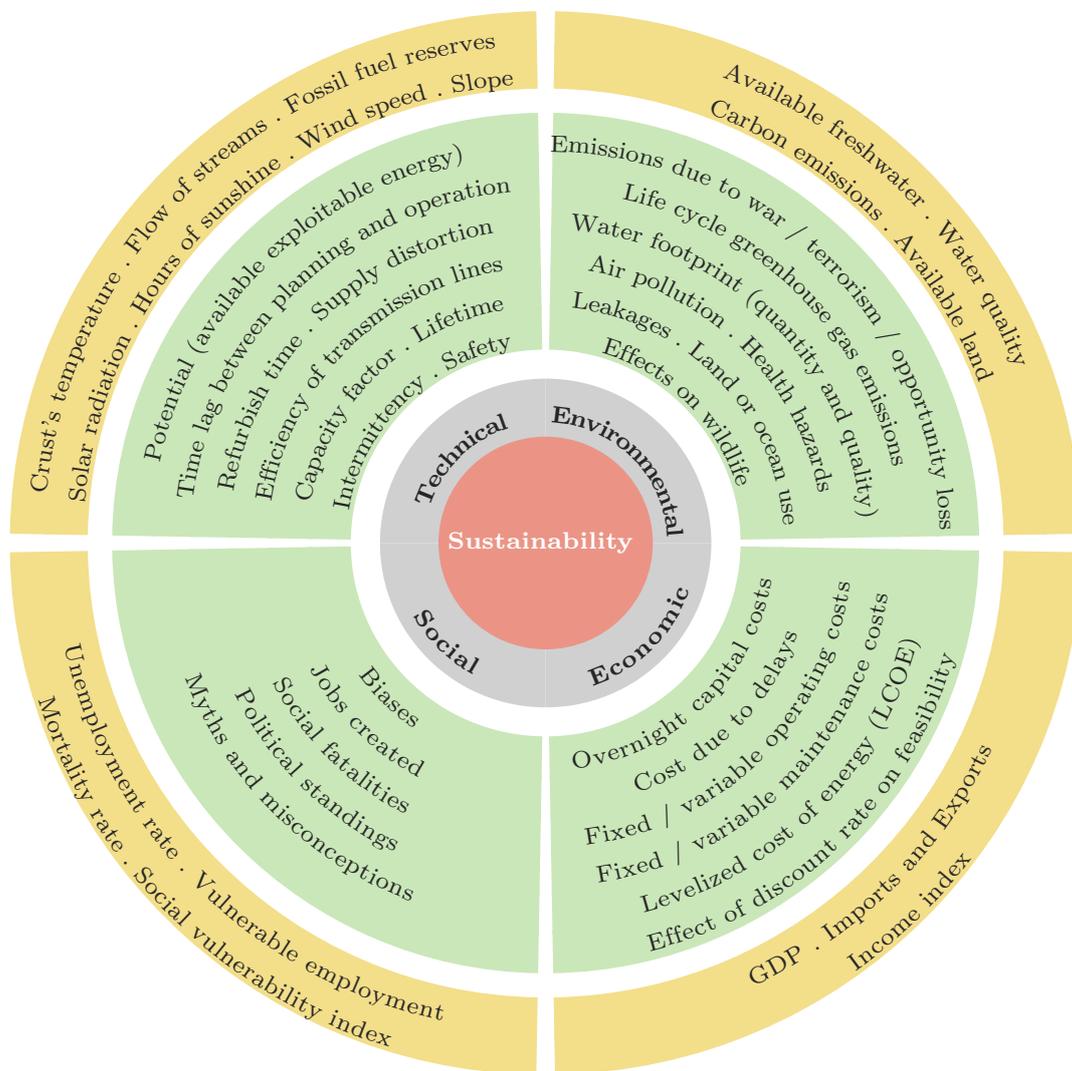


Figure 2. The four main criteria for sustainability: environmental, economic, social, and technical sustainability. The inner layer shows the sustainability factors, while the outer layers depict the corresponding regional and portfolio factors.

To describe the sustainability of each electricity generation technology, the main chosen indicator groups (hereafter referred to as criteria) represent the environmental, economic, social and technical aspects involved in each electricity generation option. Furthermore, special care was taken to make certain each of these criteria are described by using life

cycle indicators whenever possible, as these are the most inclusive and therefore capture a better picture of what is involved in electricity production. Of course, as mentioned, all the criteria and indicators presented here can be replaced by other factors or removed entirely based on the discretion of the user.

To complement previous research, in addition to the usual environmental and economic criteria, the social and technological aspects of electricity sources are considered here. For each criteria, an exhaustive list of factors mentioned in the literature was collected, and those that were measurable with available databases were chosen. When studying energy impact, it is important to consider both sustainability and regional factors together. This helps put the numbers in perspective and helps with the decision-making process. Aside from the inherent advantages and disadvantages of each electricity generation technology that dictates their performance, the use of each technology is also dependent on the availability of required resources in a given area. These resources range from the availability of the fuel source (from sunshine to fossil fuels), to the availability of water, land, social acceptance, and many more. For example, even if one generation method is identified as the absolute best choice, as long as the technology for its implementation or the required fuel is not available in a region, that technology will be rendered ineffective.

Some of the most important of these factors are introduced in this paper, each of which is directly related to one of the sustainability factors discussed before. Therefore, the resource availability along with the resource requirements of each electricity generation technology in a location defines the weight of each criteria in that location. As such, the chosen factors are a mix of variables that are directly a result of electricity generation (impact or footprint variables) as well as variables that describe the state of the location where the electricity generation will take place (resource availability or state variables). Special care has been taken to make certain that for each footprint variable, there exists a corresponding variable. These factors are discussed here in more detail.

3.1. Environmental Impact

When studying the environmental factors, the most defining of the factors is the level of life cycle greenhouse gas emissions. Aside from the direct and indirect greenhouse gas emissions caused by the operation and construction of power plants, auxiliary emissions are caused due to opportunity losses (i.e., the emissions caused by older technologies that could have been circumvented had a greener energy been used instead) and also because of damages caused to the power plants as a result of accidents or wars. Water and land footprints are also the staples of environmental sustainability analysis. When analyzing the water footprint, aside from the quantity of water needed, the changes in the quality should also be kept in mind. These quality factors include chemical, radioactive, and thermal pollutants. Emitting greenhouse gases also has adverse effects on the air quality and increases the air-pollution-related mortality rates. Another source of contamination is the leakages of fuel from the storage depots or transportation pipelines. Finally, it is important for the effects of each technology on wildlife and the environment to be taken into consideration. Unfortunately, not all these factors can be quantified, and of the ones that can, few have usable databases. As a result, what we describe below is a list of factors that have the potential to be part of the sustainability analysis.

3.1.1. Life Cycle Greenhouse Gas Emissions

Due to the different nature of electricity generation methods, different types of greenhouse gases are emitted. To better quantify the effects of all these greenhouse gases, the CO₂-equivalent (CO_{2e}) values for emissions are used in this study. This is the sum of the amounts of each greenhouse gas emitted in the process multiplied by the global warming potential of each. In addition to the greenhouse gas emissions from the process of electricity generation, emissions due to the planning, construction, and decommissioning phases are also accounted for in the data. The data used in this research are in terms of gCO_{2eq}/kWh for all electricity generation methods. The data for life cycle analysis of greenhouse gas

(GHG) emissions have been presented before in the works of [53,85]. This study suggests the data by [72] as they seem to be the most comprehensive in terms of including most of the processes.

The data show that renewable energies generally emit less greenhouse gases, with the exception of nuclear energy which is on a par with its non-renewable counterparts. The lowest and highest emissions both belong to hydropower which stresses the importance of the scale of the power plant.

3.1.2. Carbon Emissions due to Opportunity Losses

As suggested by [85], some electricity generation methods require a rather short time between their planning and implementation phases, while the same period for others can take much longer. In the meantime, the existing power plants that are assumed to be generating more GHGs are still in operation, and the longer the time before newer technologies are implemented, the longer older technologies generate more GHGs. Therefore, the technologies with lower implementation times are preferable to their counterparts with longer implementation times. The delays in this period are caused by the time it takes for the site permit to be issued, financial sources to be found, permits to be issued, and the construction phase to be completed. In addition, retrofitting a plan after its lifetime ends can further add to the delays and emissions resulting from them.

This time is actually not a constant number as plants of the same type are expected to take less time to reach their operational phases. Furthermore, the more cleaner energy sources are in operation, the lower the emissions of GHGs will be over time. This makes the calculation of this metric a complicated matter. The data in this research come from [85], where opportunity losses are defined as the subtraction of the downtime emissions of each technology from the downtime emissions of the technology with the least emissions. Taking into account the emissions in the downtime rather than the actual downtime, is a more reliable method to account for how clean the current systems of electricity production are. Since the available data only give the minimum and maximum values, the median is calculated by taking the arithmetic mean of the two available numbers. In addition, it is implied that the data for coal extend to other fossil fuels as well. Thus, unless otherwise noted by [85], the same numbers are used for oil, natural gas, and coal. It should be noted, however, that some fossil fuels such as natural gas are cleaner than the other ones, and the approach mentioned above can be improved with better data. As shown in the data, the opportunity cost emissions of most renewable energies are either zero or close to it, with the exception once again being hydropower.

3.1.3. Emissions due to Natural Hazards, War, and Terrorism

Due to nuclear energy becoming more common, ref. [85] suggest considering the damages caused in case of accidents, war, terrorist attacks, or even natural disasters involving these facilities. Depending on the priorities of decision makers, these adverse effects can either be described by the potential casualties or by the carbon emissions due to the destruction of facilities and the long-term warming that they cause, the former of which is recommended by [85]. To estimate the carbon emissions, the countries with nuclear capability and their nuclear facilities in the vicinity of habitable areas are first identified. Then, the damages caused by the potential destruction of each of these facilities (which is proportional to their size) is multiplied by a risk factor. The carbon content of the nearby cities is finally used to estimate the total carbon emissions caused by a nuclear explosion. The final results are reported as the grams of equivalent emitted CO₂ per each kilowatt of released energy.

3.1.4. Storage and Transmission Losses

The emissions caused by storage losses due to leakages has been studied by [85] as well. However, he only considers the leakages associated with carbon capture and sequestration (CCS) on coal plants. As mentioned by [74], leakage in natural gas storage

facilities is another important source of emissions that is also considered in the estimations. Leakage are defined as the amount of CO₂ that escapes underground formations or storage facilities due to earthquakes. From the given description, it is apparent that accidents, storage tank malfunctions, and natural leakages from crevices in the structures are not considered in this estimation (as is normally the case in natural gas storage tanks and pipelines). For the estimation of this factor, ref. [85] first estimated the total amount of CO₂ in a geological formation, and then multiplied it by the leakage rates 1% and 18% as lower and higher estimates. He then compared the amount of leaked carbon with the amount of emissions caused by the same mass of carbon in a power plant with CCS equipment to estimate the mass of released carbon per each kilowatt of energy. While this method is not flawless and fails to take into account other sources of leakages, its results are used in this research mainly because more accurate data are not available.

3.1.5. Adjusted Carbon Footprint

To obtain a better and more generalized metric of the carbon footprint, the emissions due to opportunity losses, war and terrorism, and storage losses were added to the life cycle greenhouse gas emissions to adjust it for the aforementioned cases. The resulting metric is named adjusted carbon footprint and will be the main metric in this research for considering greenhouse gas emissions. Equation (2) shows how this new metric was calculated. The result of Equation (2) offers a slight improvement to the general values of carbon emissions often found in the literature and are given in the Appendix A as part of Table A1.

$$\begin{aligned} \text{Adjusted carbon footprint} = & \text{life cycle carbon footprint} + \\ & \text{Opportunity losses emissions} + \\ & \text{War or terrorism emissions} + \text{Leakage emissions} \end{aligned} \quad (2)$$

3.1.6. Regional Carbon Emissions

The use of energies with a high carbon footprint is particularly undesirable if the regional emission rates are already high. As such, carbon dioxide emissions in each location were also considered as an additional factor to scale the carbon emissions of each technology. As a measure of greenhouse gas emissions, the per capita carbon emissions (tons/cap) within the area was selected. Higher values of this number usually indicate that an area is more industrial and can benefit more from the addition of green energies. Other areas with less emissions, on the other hand, are less sensitive to air-quality-related issues. [87] has studied per capita carbon emissions in the US for different sectors. Total carbon dioxide emissions on the state levels have been published by [88]. For carbon emissions to be comparable over a variety of different locations, the emission numbers were divided by the population of each state as given by the US Census Bureau to find the per capita carbon emissions. Naturally, regions with higher carbon emissions find renewable energies more desirable.

3.1.7. Water Footprint

Many parts of the world are currently struggling with water shortages, and with the passing of time, providing safe water sources will become a more prominent issue as a result of global warming. The water footprint of power plants comes from the water used to process the fuels (irrigation of crops, mining operations, etc.), transportation, construction of the facilities, evaporated water in the process of cooling, and, in the case of hydropower, direct water usage.

The water footprint is one of the reliable metrics for quantifying water consumption and is defined in the literature as the total volume of water required for a unit of energy to be generated. Estimates for the water footprint of different electric technologies are given in the works of [60,85,89,90], the latter of which is used in the current study where

water consumption is given in units of m^3/GJ . The data for biomass are from [91] as it was missing from the previous study.

3.1.8. Regional Freshwater Withdrawal

To address the state of water availability, the percentage of freshwater withdrawal over the total available fresh water was chosen. This index shows how much each area is stretching its available water resources. The lower the value of this index, the less of a concern water supply would be. Regions with higher water availability are less sensitive to energies with a higher water footprint, and it is important for current regional freshwater availability, renewable water sources, freshwater withdrawal, and water demand to be considered. While there are regional documents on water consumption that describe the resources in detail, such as the report by [92], the more comprehensive but lower level data given by [93] were used in this study. Using the available data, annual freshwater withdrawal rates in each region were found. Available annual renewable water sources in each region were also found. Finally, the percentage ratio of freshwater withdrawal to freshwater availability was found for each location. Higher withdrawal numbers show more stress on available water supplies, and such regions prefer technologies with lower water footprints.

3.1.9. Land Use

One of the important factors in the sustainability of energy sources is their land footprint (or sea and ocean usage for offshore technologies). The land used by power plants could have been used more productively by other activities such as farming or building accommodations. In many cases, the potential construction site for power plants used to contain vegetation and various types of wildlife. Any construction work in these areas disrupts the natural habitat. In addition, aside from the land directly occupied by the power plant, the spacing required around it should also be considered in the figures. In the literature, different methods of estimating the spacing for different electricity production methods have been noted. One advantage of aquatic technologies over their terrestrial counterparts is the fact that the turbines are usually spaced more closely together, reducing the land footprint. Aside from the land directly used by the power plant, the additional land that it renders inhabitable or otherwise unusable should be included in the land footprint as well. For example, growing crops to be used as biofuels contributes to the food crisis, and continuous cultivation of a similar crop can have adverse effects on soil health. In the case of hydropower, the large areas behind the reservoir that are flooded become uninhabitable. As another example, nuclear reactors require storage facilities, which add to their land use. In [94], the authors found that although renewable energies may require more direct land, their life cycle land footprint can be lower than their non-renewable counterparts. The authors in [95] have also looked at land usage (in the unit of M^2/GWh) as part of their studies on the effects of climate policy on natural habitats. Since their data have been measured firsthand, and they give the lower and higher bounds, their research has been the basis of the land-use data used here. In addition, due to the unavailability of data, it was assumed that the land usage of onshore and offshore wind turbines is the same. In practice, offshore wind turbines are more efficient but require more elaborate transmission lines. In addition, the median was once again assumed to be the arithmetic mean of the minimum and maximum values. Land footprint is where renewable energies fall short of fossil fuels as their impact on land is usually considerably larger.

3.1.10. Regional Available Land

The availability of land (km^2) is also another environmental factor considered in portfolio analysis. Usually, to find the available land to be utilized by power plants, first, the total available land not occupied by cities and industries should be estimated. Next, the smaller areas and the ones with inappropriate slopes should be eliminated for the total usable land to be found. This is clearly not an easy task and providing the data can prove

difficult. For this reason, in this study, the available land is defined as the total available land, whether occupied or not, and land slope has not been accounted for.

The availability of land per region has been documented in many research projects such as [96] where the land use has been reported per each US state. Based on this data, the percentage of available land that can be used for construction of power plants was calculated by subtracting the percentage of urban areas and croplands. This number was then multiplied by the total land area of the region given in [97] to find the total available land.

3.2. Economic Impact

When comparing the newer renewable energies to non-renewables, it should be noted that renewable energies often have higher upfront costs, but their annual costs are cheaper. For this reason, in addition to the capital cost of technologies, their annual operation and maintenance costs should also be taken into account. In addition to these costs, the cost of the power plant's fuel should also be considered. Overall, to calculate the levelized cost of energy, the overnight investment costs, recovery costs, tax rates, depreciation, capacity factor of plants, operation and maintenance costs, discount rates, and operation times should all be taken into consideration. Furthermore, the changes in the discount rates should also be studied as some technologies might not be economically feasible in the case of lower discount rates. Finally, the costs incurred because of delays in construction, interruptions in the operation, and profit losses when the plant is non-operational is another economic factor worthy of consideration. For the purpose of this study, the levelized cost of energy (LCOE) was chosen as the main factor as it incorporates most of the items described above.

3.2.1. Levelized Cost of Energy

In [59], the authors provide one of the most comprehensive publicly available databases on levelized cost of energy (LCOE) in the US and is the main source of prices in this study. However, not all the data in this database include every type of operation and maintenance costs. Furthermore, the major limitation with this price database is the fact that its raw data were obtained from multiple sources, and therefore, not all the assumptions are necessarily consistent. Unless studies on levelized cost of energy become more transparent, these issues will continue to persist in the databases.

In order for the LCOE to be calculated, first, the capital recovery factor (CRF) must be calculated using Equation (3). CRF is the conversion factor of the capital expenditures to annual payments and is dependent on the discount rate (D) and the lifetime of investment (N), which are assumed to be 7% and 30 years, respectively.

$$CRF = \frac{D(1+D)^N}{(1+D)^N - 1} \quad (3)$$

LCOE in \$/kWh is next determined by Equation (4). Aside from the capital costs (\$/kW) and the fixed and variable operation and maintenance costs (\$/kW and \$/MW), LCOE depends on CRF, tax rate ($\tau = 39.2\%$), depreciation value of each technology (D_{PV}), fuel price (\$/MMBtu), and heat rate (\$/MMBtu) if applicable. Heat rate is defined here as the efficiency of the power plant to generate energy from electricity. LCOE is the minimum price that the electricity companies need to charge in order to cover all their expenses.

$$\begin{aligned} LCOE = & \frac{\text{Capital Cost} \times CRF \times (1 - \tau D_{PV})}{8760 \times \text{Capacity Factor} \times (1 - \tau)} + \frac{\text{Fixed O\&M}}{8760 \times \text{Capacity Factor}} \\ & + \frac{\text{variable O\&M}}{1000 \frac{\text{kWh}}{\text{MWh}}} + \frac{\text{Fuel Price} \times \text{Heat Rate}}{1000000 \frac{\text{BTU}}{\text{mmBTU}}} \end{aligned} \quad (4)$$

3.2.2. Regional GDP

Economic factors are important to show if the location in question is capable of funding the projects or not. GDP is the first and most comprehensive economic index that comes to mind which includes factors such as income, imports, and exports. GDP also helps put the cost of energy production into perspective. The use of GDP gives more insight about how economically affordable each alternative may seem to each region based on their level of economic power. Regions with higher GDPs will have more freedom in choosing energy technologies regardless of the associated costs. The authors in [98] give the annual GDP by state in millions of dollars in 2020 prices. When vastly different locations are compared, the use of GDP alone can be misleading as larger states or countries are likely to have higher GDPs. To eliminate the size, the index of economic power can also be defined as per capita GDP (\$/cap).

3.2.3. Average Age of Power Plant Before Retirement

Another important aspect in the economic analysis of a project is its lifespan. In [99], the authors list the average age of power plants in years in the United States based on their fuel type. Naturally, longer lifespans reduce the effects of initial costs over time and are more desirable in terms of economics.

3.2.4. Regional APR Rates

Just like GDP for LCOE, the APR rate in each region makes it easier to decide about the lifespan of each alternative. Regions with higher APRs indicate higher investment risks and normally prefer shorter project time frames as a result. In [100], the authors offer a comprehensive list of APR rates by state in the United States.

3.2.5. Additional Economic Factors

Aside from what was mentioned before, additional factors can also be considered to better convey the stability of markets in a given region. Circularity of goods is one of these factors that shows the percentage use of locally sourced commodities to total commodities used in a certain industry. Higher circularities show higher levels of self-sufficiency and can be important in sourcing fuel for power plants. Resilience of supply chains towards disruption can be another potential factor. A region that relies on multiple supply providers is more resilient, and the industries using those supplies will be more desirable. The Shannon Diversity Index can be used to describe the level of resilience. The importance of a state in the economic market can also be shown through the dependence of other regions on that market. This can be shown by finding what percentage of the resources are being supplied by each source. Likewise, the number of regions that supply a resource is the perfect complement to the dependency. In the electricity market in particular, if a region is the main supplier of electricity to the neighboring areas, the stakeholders are more likely to prioritize production and economic, and technical factors over their environmental or social counterparts. If closer analysis of market prices is needed, factors such as maximum interest rates, average regional electricity prices, land value, minimum wage salary, and the cost of fuel for different types of power plants can also be considered as additional factors. This study however, has omitted these factors entirely for the benefit of an easier data collection process.

3.3. Social Impact

When studying the sustainability of electricity sources, the social aspect is often overlooked in favor of more mainstream issues such as emissions and finances. As a result, few articles have considered the social factors. Even the best of technologies have to be accepted in a society before being implemented, hence the importance of considering people's beliefs about certain electricity generation technologies, the urban myths and misconceptions regarding them, and the biases. This level of preparedness in each community in case of a hazardous event is partially determined by the social conditions governing that community,

which itself is affected by the industries and technologies present in the region. Politically, the use of some technologies might yield other long- or short-term advantages for certain individuals or societies which can be one of the deciding factors in policy making and in determining which electricity generation technologies are to be used. Finally, the operation of power plants creates direct and indirect jobs which are an income source to the society. However, at the same time, the operation of plants is inherently hazardous, causing injuries or fatalities to workers at times. Since the opinion of people towards each electricity generation technology is not easy to scientifically quantify, the chosen social factors in this paper are the ones that were easier to define and measure.

3.3.1. Fatalities

To calculate the fatalities associated with each electricity generation technology per each GW of electricity, ref. [53] divided the yearly fatality rates given in [101] by the net-rated power capacity given by [59] (TCD). Since TCD directly includes the fatality rates per each GigaWatt of energy per year, instead of the method described in the literature, this research uses the TCD data. However, the majority of this data is the average for all OECD countries and using it for the US can be inaccurate. That said, the results are more comprehensive than other similar research. This is the basis for the choice of using them in the current article. The other area where this data fall short is that it does not consider sub-technologies. As such, the results are more or less the average across all sub-technologies. Furthermore, due to the lack of data, as suggested by [53], it was assumed that the fatality rates of CSP are similar to that of geothermal. Just as before, the data for fuel cells are also assumed to be similar to natural gas.

Overall, while the fatality rates of renewable energies are generally lower than the other technologies, the overall fatality rates seem to be mainly directed to the size of the power plant rather than the technology being used. In addition, the minimum and median fatality rates for nuclear power are relatively small, making it look like a safe alternative, but in the case of a nuclear catastrophe, the maximum mortality rate of nuclear energy is higher than the other technologies by at least two orders of magnitude.

3.3.2. Regional Social Vulnerability Index (SVI)

The vulnerability of a community towards natural hazards and its ability to prevent or subdue suffering in case of disasters is summarized in the Social Vulnerability Index (SVI). Social vulnerability is also a measure of a community's preparedness to respond to a hazardous event such as outbreaks, droughts, chemical and nuclear spills, and power plant failures. SVI can also be used to determine the amount of emergency supplies that need to be allocated to a region after a disaster or to help plan evacuation routes. One of the most well-known of these indexes, is the SVI index developed jointly by the Centers for Disease Control and Prevention (CDC) and the Agency for Toxic Substances and Disease Registry (ATSDR) based on 15 US Census variables such as income levels, education, disability, housing types, vehicle access, race and age groups among other variables [102]. The data for the SVI index is available online for the US states on county and census tract levels [103]. SVI is measured by ranking the performance of each location in each theme and constructing its percentile rank [104]. To improve the index, ref. [105] expanded SVI by considering more factors, using principal component analysis based on the influence of each of the factors, and proposing the improved SoVI index at county levels. In this study, the weighted average of these numbers as a function of county area was calculated to construct the overall SoVI of a state. The numbers were then scaled to the 0 to 1 range with higher numbers showing more social vulnerability. It must be noted that SoVI values are comparative, and single values cannot be used on their own.

3.3.3. Jobs Created

Recently, the number of jobs created was listed in studies as a tangible social metric for each technology. It is widely agreed that the technologies with a higher number of created

jobs are more acceptable both socially and politically. In [106], the authors employ a model proposed by NREL to estimate the ranges of full-time equivalent (FTE) employment rate of each technology. The only exception to this was the employment rate of nuclear technology that was taken from [107]. The employment rates account for direct jobs as the result of construction and operation of facilities, as well as indirect jobs along the supply chain as third-party individuals or companies produce services, goods, and resources beneficial to the power plant. In addition, induced jobs as the result of the money from direct and indirect jobs being spent locally are also considered in the data. The final numbers are reported in terms of the number of jobs created per each GWh of generated electricity. Due to the unavailability of data, the number of created jobs for oil and fuel cells was assumed to be equal to that of natural gas.

3.3.4. Regional Unemployment Rate

The unemployment rate was chosen to put the job creation data in each region into perspective as regions with a higher unemployment rate will be more concerned with the social aspects of energy technologies and the number of new jobs they create rather than the environmental aspects of power generation. The unemployment rate was found based on the data reported by [103].

3.3.5. Regional Politics

While the social repercussions of electricity generation technologies are an important factor in how attractive they are perceived to be, in the end the general policies involving their utilization is set by the political parties in power. As such, the percentages of House and Senate legislators belonging to each of the major political parties in each state as reported by [108] were recorded. This has been included because each of these parties has its own definition of sustainable energies which in turn will be reflected in the policies and regulations they pass. Furthermore, the statewide comprehensive energy plans [109] and the existing capacities of traditional and renewable electricity generation [110] were noted as additional factors of social preference, and as additional evidence of regional electricity generation preferences.

3.3.6. Additional Social Factors

Leakage risk can be considered by compiling a list of oil and gas leakage incidents in the region. Additionally, a list of accidents related to power plants can provide a vision on the overall safety of the technologies and the threat they pose to the society. Finally, the pollution rate of the power plants can optionally be considered. This is important due to the fact that in most studies, only the carbon emissions are considered which results in other forms of pollution such as deterioration of water supplies, air pollution, or disfiguring natural landscapes, being omitted. Of course, in these factors, the number of incidents and their intensity, rather than the amount of pollution, are the main point.

3.4. Technical Impact

Technical factors are mainly concerned with the efficiency and reliability of each technology to deliver electricity. One of the major technical disadvantages of renewable energies as is discussed below is their intermittency and lack of ability to match generation at the time of demand. The capacity factor of plants is another method of evaluating the reliability of each technology. Other factors that can potentially be included in future research when reliable data for them are released include the fluctuations in the fuel price to show the distortions in the supplies, the lifetime of plants, the need for periodic repairs and refurbishments, the time lag between planning and the operation of each plant, and the safety of each technology. The efficiency of transmission lines (in addition to the efficiency of the plant) is also another potential factor that can be considered in future studies.

To address the technical side of energy usage, the available resources in each location were chosen as the most important factor in the analysis. In [111], the authors provide an

excellent resource availability study that highlights the most vital factors determining the potential of green energies in a region. Available regional technology is another factor that has been considered through various tech and science indexes. In addition, for widespread energies, the existing infrastructure was considered a resource as it can influence further decision making about energy portfolios. While factors such as intermittency and capacity are important, they are secondary issues if the technology or resources for energy generation are not available in a region.

3.4.1. Resource Availability

When it comes to the resources required for electricity generation, due to inherent differences of energy technologies, various variables need to be considered depending on the electricity type.

- **Solar PV and CSP:** For solar energy, the availability of regional silicon, gold, copper, and lithium reserves [112] were considered to show how reliant on raw materials a region is in order to locally manufacture solar panels. In terms of generation potential, average temperature [113], daily solar radiation [114] and annual sunshine hours, and mean elevation were chosen. Finally, for the specific case of CSP, the number of regional commercial and private airports [115] was also considered to account for the possible blinding effect of the mirrors in these installations.
- **Onshore and Offshore Wind:** The potential of wind energy generation is mainly a function of onshore and offshore wind speed [50,116]. The minimum and maximum wind speeds that a wind turbine can capture effectively were also considered, and all locations met these requirements. For the particular case of offshore wind, the length of coastlines [117] were also considered.
- **Geothermal:** For the generation of geothermal energy, the main resources are the earth's crust's temperature and the availability of a proper aquifer. For this reason, the favorable range of geothermal reservoirs [118], regional freshwater withdrawals, and available renewable water sources [93] were considered.
- **Hydropower:** Dam elevation, stream flow discharge, and land slope are the main driving factors of hydropower. Aside from the size of the largest regional dams as well as annual, and seasonal stream flows [119], the elevation range of the region was also considered as a measure of the land slope. Elevation range was used since calculation of slope needs to be carried out in a specific direction, whereas elevation is a relative measure. Additionally, the number of notable prior dam failures [120] were recorded as a measure of how safe hydropower can be in the face of natural disasters.
- **Nuclear Power:** For nuclear power, an inventory of regional uranium and plutonium reserves was compiled [112]. However, none of the southeastern US states house any of these repositories. In addition, the number of nuclear materials storage sites [121] and spent fuel disposal sites [122] were also considered.
- **Coal:** With the technology of coal power plants being widely available, the main restriction in their use is the availability of coal itself as the fuel. For this reason, the actual recoverable reserves at production mines, estimated recoverable reserves, and demonstrated potential reserve base [62] were taken into account as measures of resources.
- **Oil:** With the southeast US deprived of oil reserves and near zero current production rates, the undiscovered onshore and offshore technically recoverable oil resources [123] were noted as the oil fuel resources.
- **Natural Gas:** Similar to oil, with the absence of prominent natural gas fields in the southeast US, the discovered shale gas repositories, as well as existing natural gas processing plants [124] were considered as available resources.
- **Biomass:** While technically a wide range of biofuels can be used in biomass plants, the sources of energy were limited to wood and dead plants. Thus, the available regional wood stocks as the percentage of forest cover [125], the percentage of land used for plantation crops [96], as well as per capita waste generation and composition [126]

were recorded. For a more in-depth study, Ref. [43] gives a comprehensive list of crops that can be used for bioenergy generation and the level of emission abatement that each one offers. On the other hand, Ref. [127] provides a list of acreage of each crop per US state. As such, a metric of total potential emissions abatement can be found by taking the weighted average of possible abatement with respect to the percentage of each crop available to a specific region.

3.4.2. Science and Technology Index

Aside from the availability of fuel and resources, the availability of each technology should also be considered. This has been achieved by documenting state technology and science indexes and state research and development index, as well as the state technology and science workforce indexes [128]. Additionally, the number of local colleges and universities [129] were also considered as institutions that work towards scientific advancement of energy technologies.

3.4.3. Capacity Factor

In addition to the availability of resources and technologies needed for energy generation, the intermittency of the existing power network can potentially be considered. One of the issues with green energies is that at a single location and at a given time, it is not possible to guarantee their power production. Some green energy sources are more predictable than others. Tidal energy is more predictable than solar for instance. The higher the intermittency of a technology, the more the need for backup generators or alternate sources of energy. However, with all the green energies combined over a larger geographical region, their intermittency drastically decreases as each energy can cover for the other ones. Therefore, intermittency is dependent both on the energies being used and the electricity mix in a power grid. Intermittency can be reduced by geographically dispersing energy sources, load smoothing, energy storage, and reliable weather forecasting.

Since it is complicated to quantify intermittency, reliability or capacity factors of power plants can be used instead. The capacity factor of each power plant is described as the ratio of its actual power production to its nominal capacity. The capacity factor is dependent on the down-time of the power plant due to reliability issues, maintenance, weather conditions, fuel availability, and electricity conversion mechanisms. Since the capacity factor is not a constant number, its annual average is usually reported. The capacity factors of different power plants can range from 18% for solar PV up to 95% for geothermal and nuclear energies. Generally, based on the data provided in [53], renewable energies have lower capacity factors and as such they are not suitable for peak-time electricity generation and need to be used along with non-renewable types.

3.5. Summary of Chosen Factors

Table 1 shows the summary of all the final quantifiable factors and their data sources across different electricity generation technologies. Of all the mentioned criteria, some had to be omitted due to lack of reliable data or subjectivity of the chosen criteria. For the environmental criteria, the adjusted carbon footprint, water footprint, and land footprint are chosen as the deciding factors. The levelized cost of energy, as well as the average age of plant retirement, are candidates from the economics criteria. Additionally, for the social criteria, factors such as fatality rates of each electricity generation technology and jobs created by each energy were chosen. Finally, for the technical criteria, the capacity factor of each technology was considered as the main factor. Example data for these factors have been given in Appendix A.

Table 1. Energy-related sustainability criteria.

Energy Factor	Unit	Criteria	Data Source
Environmental			
Adjusted carbon footprint	gCO _{2eq} /kWh	L	[72,85]
Water footprint	m ³ /GJ	L	[60]
Land footprint	m ² /GWh	L	[95]
Economic			
Levelized cost of energy	\$ ₂₀₁₉ /kWh	L	[59]
Plant retirement age	Yr	H	[99]
Social			
Fatality rate	#/GW _{eq} Yr	L	[59]
Job creation	#/GWh	H	[106]
Technical			
Capacity factor	%	H	[53]

L: Lower is better, H: Higher is better.

Although the intrinsic properties of energy technologies are important, it is also vital to consider the regional characteristics as well. Of all the criteria mentioned before, those that can be expressed either in quantitative or qualitative ways are summarized in Table 2. Since some of the qualitative data are essential in understanding the state of an energy's usage in a certain area, it is suggested that the regional factors be graded by the experts in the field, rather than via mathematical means. Among the environmental factors, carbon emissions, freshwater withdrawal, and available land were chosen. Regional GDP and APR rates are the indicators for the economic criteria. In terms of social aspects, the social vulnerability index and unemployment rate are the indicators of choice. In addition, the political standing and the previous policies have been considered as well. Finally the regional technical characteristics are captured by looking at the available regional resources, as well as various science and technology indexes. Resource availability ranges from the availability of raw materials and fuels, to the existing infrastructure.

Table 2. Location-Related Sustainability Criteria.

Energy Factor	Unit	Criteria	Data Source
Environmental			
Carbon emissions	ton/cap	L	[88]
Freshwater withdrawal	%	L	[93]
Available land	km ²	H	[97]
Economic			
Regional GDP	M\$	H	[98]
Regional APR	Yr	L	[100]
Social			
Social Vulnerability	-	L	[105]
Unemployment rate	%	L	[103]
Technical			
Regional resource availability	Varies	Varies	See Section 3.4
Tech and science index	%	H	[128]
R&D index	%	H	[128]
Technology workforce index	%	H	[128]
Number of universities	#	H	[129]

L: Lower is better, H: Higher is better.

4. Conclusions

In this research, a collection of criteria was compiled to study the sustainability of energy technologies. Previous research studies have only looked at a few of these criteria. Thus, the concept of sustainability can still be improved by looking at energy technologies more comprehensively. Still, the use of all the facets of the aforementioned criteria is not possible in practice due to gaps in data availability, uncertainties in the quantification of data, regional characteristics not being included in sustainability studies, and sustainability indexes having been designed with only a few of the aforementioned criteria in mind. This research aims to provide a list of the criteria that needs to be included in the definition of sustainability to elevate it from the traditional carbon-based view. It also serves to identify RAF as a solid basis for a sustainability index for definitions of sustainability.

4.1. Data Availability and Gaps

Upon studying the literature on the sustainability of energy sources, the first visible issue with creating a more comprehensive sustainability index is the databases not sharing the same assumptions. As such, in many occasions, further assumptions were made or part of the data was estimated based on other technologies. Next, some of the parameters mentioned in the studies are extremely difficult, if not impossible, to quantify. Variables such as energy mix intermittency, biases, myths and misconceptions, and wildlife diversity are examples of these that cannot be expressed in numbers due to their nature or the ambiguity in their definition. Of course, the inclusion of such variables in sustainability studies can be greatly beneficial.

Finally, the lack of a comprehensive index or framework for studying sustainability is noticeable. Most sustainability indexes are concerned only with environmental and economic aspects of electricity generation, and almost no framework considers other criteria such as social and technical aspects. Even then, to date, only the RAF index [31] includes regional resource availability. The omission of such important aspect from sustainability studies is puzzling.

4.2. Future of Sustainability

Based on the review of sustainability factors presented in this paper, the need for change in the future of sustainability studies is evident. The previous studies defined sustainability using only a limited number of criteria that were chosen for their specific case study. We argue that the definition of sustainability needs to be broader than confining it to typical criteria such as emissions or cost. In this research, a review of the previous methods was given, and the criteria presented in them was summarized under the main four categories of environmental, economic, social, and technical criteria, improving the previous viewpoint on sustainability as a result. In doing so, only the aspects that could be quantified were kept. In addition, it was argued that most studies miss the regional characteristics of the location in which electricity is to be generated. This step is important as regional characteristics indicate the feasibility of each technology for the specific location in which they are to be used. Thus, proper location-based factors were also given to complement each of the electricity generation criteria. Finally, instead of creating a new index, this study suggests using the RAF index as a basis to build a more comprehensive definition of sustainability to keep the results relevant and comparable. To improve the definition of energy sustainability, the following actions are suggested:

- Studies need to consider additional criteria aside from environmental and economic factors. Even then, the definition of environmental factors can be enhanced by looking beyond carbon emissions and considering other environmental factors such as wildlife. Almost no global standards exist for the inclusion of additional criteria and the variables that need to be considered in each. Thus, it is hoped that the information provided in this paper is useful for other researchers.

- Some of the variables can be placed in different categories depending on the point of view. For example, damages caused due to natural hazards to the power plants can be looked at from the point of view of environmental emissions, economic costs that arise from the repairs or outages, or even the social consequences of them. It is inevitable to include similar variables in each of the criteria; however, caution should be exercised to keep these variables from skewing the final direction of the sustainability analysis. Furthermore, it is suggested that a similar number of variables be used in each criteria to make certain no aspect of electricity generation receives more attention than the other parts.
- The same can be said about the technical resource availability of different energy technologies. Some technologies share the same resources, thus duplicate items will be present. Additionally, the researchers need to make certain that either the life-cycle variables are used, or if not, the variables are not biased towards a certain technology or a certain resource.
- To date, the most comprehensive sustainability indexes are based only on environmental and economic aspects. Ideally, a more comprehensive metric needs to be developed that considers other aspects of electricity generation as well. The outdated view of sustainability being analogous to carbon emissions is not the best approach, and a better index can help change this mentality.
- Except for the RAF index, almost no other study takes into account the regional characteristics of where the electricity technologies are to be used. Naturally, the sustainability of energy sources are not static and can change based on the regional and environmental status. As such, studying the concept of sustainability without considering the regional aspects will not be realistic. The authors suggest treating the regional values as weights that change the importance of each sustainability criteria. However, other approaches can also be taken.
- Finally, with the plethora of sustainability indexes that are constantly being introduced via the literature, it is vital for the new works to be based on previous studies. When possible, they should augment and complete the current indexes, and when not possible, they should be built based on one of the existing indexes. This way, recording the assumptions of each method will become much easier, and the findings of each method can be taken advantage of, while the shortcomings of a method are addressed.

Throughout this paper, a summary of different approaches towards capturing the essence of energy sustainability was given. Still, no single study manages to present an all-inclusive approach towards sustainability. It is evident that despite all the recent studies, a better framework for defining sustainability needs to be developed. The change in approach towards sustainability can help enhance the understanding of sustainability, which in turn leads to the design of a better energy portfolio. The current sustainability studies are limited in their scopes, and the authors hope the provided materials will be beneficial in future policy-making and sustainability analysis endeavors. However, the most important outcome of this comprehensive review of sustainability is perhaps to inform the energy managers, planners, and stakeholders that a renewable energy is not always green; a green energy is not always sustainable; one energy that may be sustainable in one location may not necessarily be so in another location.

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Abbreviations

The following abbreviations are used in this manuscript:

ATSDR	Agency for Toxic Substances and Disease Registry
CCS	Carbon Capture and Storage\Sequestration
CDC	Center for Disease Control
CRF	Capital Recovery Factor
FTE	Full-Time Equivalent
GDP	Gross Domestic Product
LCOE	Levelized Cost of Energy
RAF	Relative Aggregate Footprint
SVI	Social Vulnerability Index
TCD	Transparent Cost Dataset

Appendix A. Sustainability Criteria Values for Different Electricity Generation Technologies

Tables A1 and A2 list the numeric values of environmental, economic, social, and technical sustainability values as expressed in Section 3.5. These numbers describe the inherent characteristics of electricity generation technologies under the aforementioned four criteria. Of these, the environmental criteria has been broken down into three sub-criteria. The values presented in Tables A1 and A2 can be used to calculate the RAF index. It should be noted that in some criteria, smaller numbers indicate a better value, while for others, larger numbers are preferable. RAF has the ability of using both of these data types without further need for standardization. Of course, for a real case study, these tables should be matched with a corresponding table of regional characteristics (criteria presented in Table 2) for the weight and importance of each criteria to be determined. As such, no general advisement can be given just by considering the inherent characteristics of electricity generation technologies alone, and the results of regional RAF metrics should be the main source of comparison.

Table A1. Environmental sustainability criteria values.

Technology	Carbon Footprint gCO _{2eq} /kWh Lower Is Better			Land Footprint m ² /GWh Lower Is Better			Water Footprint m ³ /GJ Lower Is Better		
	Min	Median	Max	Min	Median	Max	Min	Median	Max
	Biomass	130	230	420	4433	13,116.5	21,800	20	42
Conc. Sol. P.	8.8	27	63	340	510	680	0.118	1.149	2.18
Solar PV	18	48	180	704	1232	1760	0.00064	0.1518	0.303
Wind: Onshore	7	11	56	2168	2404	2640	0.0002	0.0007	0.0012
Wind: Offshore	8	12	35	2168	2404	2640	0.0002	0.0007	0.0012
Hydropower	32	39.5	2200	538	1803	3068	0.3	425.15	850
Coal	792.8	910.9	1039	83	325	567	0.079	1.0895	2.1
Oil	708	831	953	1490	1490	1490	0.214	0.702	1.19
Natural Gas	461	559	737	623	623	623	0.076	0.658	1.24
Nuclear	62.7	96.55	220.1	63	78	93	0.018	0.734	1.45
Geothermal	7	41.5	85	33	248	463	0.0073	0.3832	0.759

Table A2. Economic, Social, and Technical sustainability criteria values.

Technology	Economic		Social		Technical
	LCOE \$/kWh L	Avg. Lifespan yr H	Job Creation Jobs/GWh H	Fatality Fatality/GW _{eq} yr L	Capacity Factor % H
Biomass	0.08	41	2.06	0.0149	84
Conc. Sol. P.	0.18	40	2.02	0.0017	50
Solar PV	0.27	10	1.47	0.0002	22
Wind: Onshore	0.07	15	0.33	0.0019	41
Wind: Offshore	0.13	15	0.62	0.0064	43
Hydropower	0.07	70	0.96	0.0027	87
Coal	0.07	54	0.66	0.1200	85
Oil	0.09	38	0.48	0.0932	85
Natural Gas	0.05	38	0.48	0.0721	85
Nuclear	0.08	35	0.47	0.0069	90
Geothermal	0.09	40	0.91	0.0017	90

H: Higher is better, L: Lower is better.

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