energies

Review

An Assessment of Energy Flexibility Solutions from the Perspective of Low-Tech

Muhammad Salman Shahid [1,*], Seun Osonuga [1], Nana Kofi Twum-Duah [1,2], Sacha Hodencq [1], Benoit Delinchant [1] and Frédéric Wurtz [1,*]

[1] Univ. Grenoble Alpes, CNRS, Grenoble INP, G2Elab, F-38000 Grenoble, France
[2] Univ. Grenoble Alpes, CNRS, Grenoble INP, G-SCOP, F-38000 Grenoble, France
* Correspondence: muhammad-salman.shahid@g2elab.grenoble-inp.fr (M.S.S.); frederic.wurtz@g2elab.grenoble-inp.fr (F.W.)

Abstract: The energy transition is a multidisciplinary challenge that warrants solutions that are robust and sustainable. Energy flexibility, one of the key pillars of the energy transition, is an umbrella term that covers multiple innovative solutions implemented at all levels of the electric grid to ensure power quality standards, amongst other objectives. Low-tech, on the other hand, emphasizes designing, producing, and sustainably implementing solutions. Therefore, considering the multidisciplinary nature of energy transition and the existing energy flexibility solutions, the purpose of this research work is multilateral: first, it presents the concept of low-tech and its associated mechanisms; then, it addresses the misconceptions and similarities that low-tech might have with other innovation approaches; and finally, it provides an assessment of existing flexibility solutions using low-tech as a tool. The result of this assessment is presented qualitatively and indicates that indirect energy flexibility solutions rank higher on a low-tech scale relative to supply-side energy flexibility solutions and energy storage flexibility solutions.

Keywords: low-tech; energy flexibility; sustainability; technology selection criteria; socio-ecological transition

check for updates

Citation: Shahid, M.S.; Osonuga, S.; Twum-Duah, N.K.; Hodencq, S.; Delinchant, B.; Wurtz, F. An Assessment of Energy Flexibility Solutions from the Perspective of Low-Tech. *Energies* **2023**, *16*, 3298. https://doi.org/10.3390/en16073298

Academic Editor: Krushna Mahapatra

Received: 24 February 2023
Revised: 31 March 2023
Accepted: 4 April 2023
Published: 6 April 2023

1. Introduction

Faced with the ever-increasing threat of global warming and its predicted catastrophic consequences, institutions, and individuals have committed to strategies aimed at reducing their negative environmental impact. Energy use, in various forms, has been identified as the largest contributor to global warming, as illustrated in Figure 1. Many countries around the world have committed to the energy transition pathway [1,2]. For example, the EU has adopted the "European Green Deal" as an ambitious plan to transform its current fossil-fuel-dependent energy sector into a sustainable, carbon-free energy sector by the second half of this century (i.e., by 2050) [3]. However, it requires the active participation of all the stakeholders, i.e., governments, businesses, academic researchers, and society.

The active participation of the aforementioned stakeholders is generally referred to as the quadruple helix model of innovation, which was originally conceptualized by Carayannis [4] and Schutz [5]. Amongst these stakeholders, technology serves as a common commodity and, therefore, is a key ingredient for meeting the objectives of the energy transition. However, this energy transition should be implemented vigilantly without compromising the core needs of consumers (i.e., reliable energy supply). By taking into account both technology and the consumer, Illich [6] introduces the concept of a convivial society. This concept is defined as *"a society in which modern technologies serve politically interrelated individuals rather than managers"*. Illich [6] further postulates that technology can be used in two ways. The first way leads to the specialization of functions, the institutionalization of values, and the centralization of power, consequently turning people into what he termed "machines". The second approach, on the other hand, improves an individual's capability, control, and initiative, which he refers to as "conviviality".

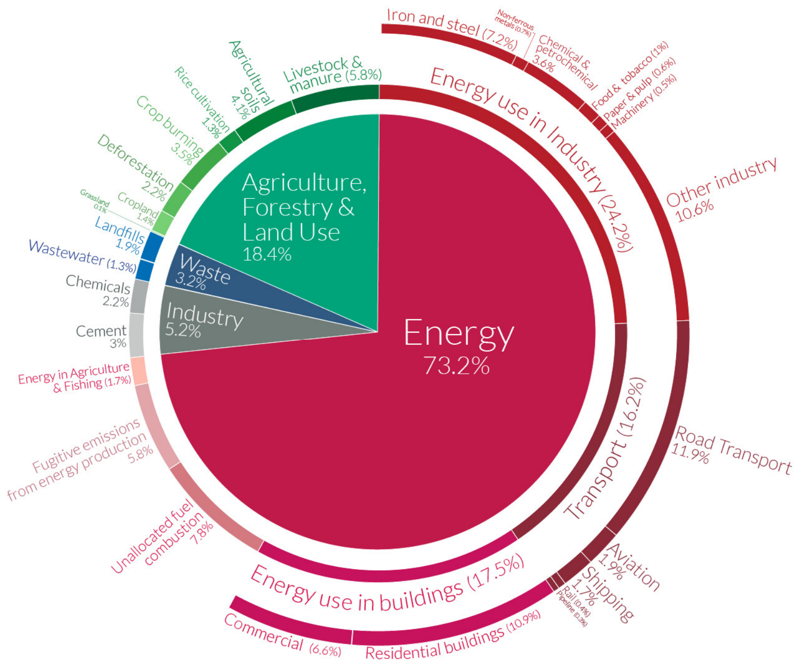

Figure 1. Global greenhouse gas emissions by sector for 2016 [7].

Schumacher [8] further built upon this idea by making a distinction between "*man-as-producer*" and "*man-as-consumer*". It is stated in his work that previous ideologies and concepts did not make this distinction and consequently resulted in the depletion of the earth's resources. To buttress this point, Schumacher [8] postulates that "*there is no escape from this confusion as long as the land and the creatures upon it are looked upon as nothing but 'factors of production*". Confusion, in this case, refers to the failure to separate "man-as-producer" and "man-as-consumer". In an attempt to address the misspecification of priorities as identified himself, Schumacher founded the "Intermediate Technology Development Group," which was a key instrument for the consequent "Appropriate Technology" movement [9].

Based on the initial works of Illich and Schumacher, some technology-innovation-related concepts have emerged over time. These concepts include, but are not limited to:

- Frugal Innovation: It is defined as a solution designed and implemented under given resource constraints, where the outcome is significantly cheaper than existing solutions and satisfies the basic needs of customers who would otherwise remain underserved or unserved [10,11]. In summary, it is an attempt to maximize the ratio of the value obtained from the solution to the resources used by the solution [12]. Proponents of this innovation approach argue that it is instrumental in meeting the needs of the human population sustainably [10]. A lot of emphasis is placed on developing economies by looking to strip non-essential elements from solutions. Whilst frugal innovation has emerged as a response to the needs of low-income markets, some frugal solutions have found their way into higher-income markets, mostly through reverse innovation [11] (innovations first developed in emerging economies and subsequently adopted by developed economies [13]). Thus, whilst the concept might stem from and have been directed towards low-income markets, it is not a far-fetched idea for all markets (irrespective of income levels) to adopt the frugal innovation approach.
- Appropriate Technology: Kaplinsky [9] defines appropriate technology by aligning it with the economics of a community (and, by extension, a country). Appropriate technologies are thus technological solutions that are simple in terms of design and operation, that can be produced on a small scale, are suited to low-income economies, and have a minimal harmful impact on the environment. In other words, it mirrors the neoclassical economic theories that suggest that developed economies would opt for capital-intensive technology, whereas developing economies would rather

choose labor-intensive techniques [14]. It has been observed that the reception of appropriate technology by developing countries is not adequate, as it faces hostility from scientists and elites in these countries. These classes of society deem appropriate technology a means of projecting their country as poor and having low productivity [9]. In this context, the appropriate technology movement was considered a deliberate attempt by developed countries to keep developing countries in a perpetual state of underdevelopment [15,16].

- Low-Tech: Arthur Keller, a notable proponent of this concept, defines Low-Tech as a category of products, services, processes, or other systems allowing, via a technical, organizational, and cultural transformation, the development of new models of society that integrate, in their fundamental principles, the requirements of strong sustainability and collective resilience [17]. Figure 2 illustrates the fundamental principles governing low-tech as expressed by Arthur Keller. More recently, Tanguy et al. [18] also defined seven key principles of low-tech systems that cut across social, organizational, and technological domains.

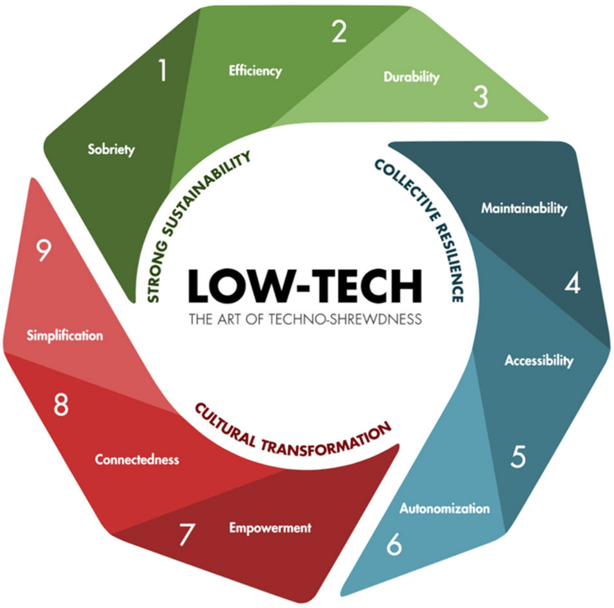

Figure 2. Fundamental principles of low-tech [19].

Just like frugal innovation and appropriate technology, other nomenclature exists for low-tech, such as slow-tech, wild-tech, easy-tech, and retro-tech. For the sake of convenience, we will use the term "low-tech" in the rest of the article. This term will also cover the terms "frugal innovation" and "appropriate technology", as the difference in the definitions is very subtle.

Low-tech has been used as a conception tool as well as an evaluation tool for simple problems. On the other hand, energy technologies have been evaluated across multiple aspects, for instance, from a technical, economical, or sustainability perspective. Considering the fact that energy flexibility is one of the key drivers for achieving the set targets of the energy transition, flexibility solutions must be conceived, built, and implemented in a sustainable manner.

It has been observed that the low-tech approach emphasizes meeting the core needs using locally available resources in the smallest possible amount (i.e., sustainability in all areas). Therefore, the importance of this article is to seek and encourage the adoption of low-tech in the energy sector (and, by extension, all other sectors). The objective of this article is to assess the low-techness of existing energy flexibility solutions. The hypothesis in this regard is that most (if not all) energy flexibility solutions have some degree of "low-techness" when assessed using the characteristics of low-tech. Thus, it leads to the following research questions:

- To what extent can an existing energy flexibility solution be considered low-tech?
- Which criteria are relevant to evaluating such solutions?

Thus, in this article, we present a qualitative assessment of existing energy flexibility solutions from a low-tech perspective. The subsequent section discusses the characteristics of low-tech. The objective of this article is to discuss and assess energy flexibility solutions from the perspective of low-tech; therefore, Section 2 presents the concept of low-tech, and Section 3 presents energy flexibility. Section 4 presents the methodology adopted for this research work, whereas Section 5 presents a discussion of energy flexibility solutions through the lens of low-tech, and Section 6 is the conclusion.

2. The Low-Tech Concept

Three characteristics have been identified by the low-tech lab [20] for a solution to be considered low-tech. The low-tech lab (existing since 2013) [20] is a community space dedicated to the fabrication and sharing of low-tech solutions in France. These three key characteristics are usefulness, accessibility, and sustainability. These characteristics are transformed in the form of a concise definition of low-tech, which states that low-tech solutions are "*the objects, systems, techniques, services, knowledge, practices, lifestyles, and ways of thinking* that *are useful, accessible (in terms of comprehension and financing), sustainable, local, and that favor autonomy*" [20,21].

2.1. Characteristics of Low-Tech

Low-tech should be based on the simplest available technology and be renewable, sustainable, repairable, and maintainable over time. Additionally, low-tech solutions should encourage and integrate the concept of a circular economy while relying on knowledge-oriented human work [22]. Therefore, the three characteristics identified by the Low-Tech Lab are extended to five by ADEME (Environment and Energy Management Agency) [21] as follows:

- Usefulness: The solution must satisfy the core need of the consumer and contribute to the moderate use of resources;
- Accessibility: The solution and knowledge related to it should be available, i.e., the barriers to entry have to be minimal or nonexistent, and the knowledge and skills required to support the technology throughout its life cycle should be easy to access and use;
- Sustainability: The solution must reduce the negative impact on the environment in terms of emissions, material and energy use, and overall adherence to the earth's physical boundaries. This is also highlighted by usage with an extended life, which reduces the need for replacement;
- Localness: The solution should be adapted to the context of local communities;
- Autonomy: The solution should contribute to the ability of the community to address its own needs, and it should only explore external resources in cases of actual local deficits.

Leaning on the characteristics of low-tech discussed in Section 2.1, this section presents the design considerations for low-tech. Phillipe Bihouix, in his book "*The Age of Low Tech: Towards a Technologically Sustainable Civilization*" [23], does a remarkable job explaining low-tech. He suggests what he calls the seven "commandments" for designing low-tech solutions, which are as follows [23]:

- The solution must address the basic need of the consumer or the problem that it seeks to address;
- It should be designed and produced in a truly sustainable way;
- It should be such that it can direct the attained knowledge toward the conservation of resources;

- It must seek a balance between performance and conviviality;
- It should be transferable without losing the right effects of scale;
- It should provide a de-mechanizing service;
- It should know how to stay modest.

A prominent example of low-tech in the domain of energy is the wind turbine made by William Kamkwamba (see Figure 3 [24]) using only repurposed and recycled materials [25]. Troullaki et al. [26] showed that locally manufactured wind turbines (such as that of William Kamkwamba; Figure 3) were particularly relevant for rural off-grid contexts and that their environmental impacts were significantly lower than those of conventional solutions (i.e., petrol generators).

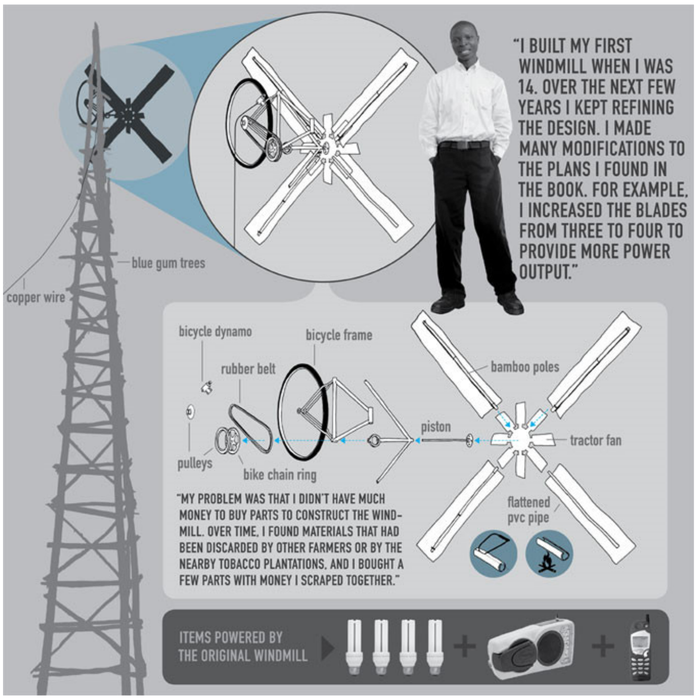

Figure 3. William Kamkwamba's windmill design and components [24].

Kamkwamba [25], who is a self-taught innovator, started his quest while studying the concept of generators in a small village library. He built an initial proof of concept using a dynamo and, subsequently, the first wind turbine using parts and components from a local waste dump. This solution is deemed low-tech since:

- It is useful as it satisfies the core need: the energy supply of the household;
- It is made using recycled and repurposed waste materials;
- The knowledge is accessible as it was locally attained through a library book;
- The product (i.e., electricity) is sustainable and renewable;
- The solution is local as it is fabricated with local components;
- Since it is the prototype, it can be considered autonomous as it nudges toward its large-scale deployment in the local community.

There is a general impression that the word low-tech implies low-cost and rudimentary solutions, or in some cases, might point to the research intensity of some sectors as described by Hirsch-Kreinsen et al. [27,28]. The history and evolution of this approach to innovation contribute to this line of thinking since both appropriate technology and frugal innovation place some emphasis on low-cost solutions. However, at the core of all these terminologies, the fundamental concept is the same, i.e., sustainable and durable solutions. Thus, low-tech solutions do not have to be basic in design and function but should be designed to meet the needs of the consumer (or solve a problem) using the lowest possible amount of natural and limited resources. In summary, low-tech is not the opposite of high-tech and is not in any way opposed to the development of complex and advanced (high-tech) solutions.

For this article and to be aligned with the insights provided above, we define low-tech as *solutions that satisfy the core need for which they are designed while remaining accessible in terms of cost, resources, and know-how, as well as minimizing their environmental impact without any significant decrease in performance*.

3. Energy Flexibility

With the increased penetration of intermittent renewable energy sources, energy flexibility has become a pertinent topic in energy research. According to Lund et al. [29], energy flexibility can be defined as the ability of an energy network to modify its generation or demand in response to external signals. This can include moving the energy consumption around in time, supplying additional energy to meet unexpected changes in demand, or varying consumption patterns according to supply conditions. It is necessary to note the difference between energy supply and energy flexibility. While energy supply can be characterized as all the processes that lead to the provision of energy for a given use case, energy demand is only concerned with the changes made to the use of these energy resources. Another aspect of energy flexibility to keep in mind is its scale, which ranges from the individual consumer/producer scale to the grid scale as discussed below:

- Building scale: At this scale, energy flexibility is mostly demand-side and presents some significance to both the buildings' users and the electric grid. To illustrate, the electricity grid equilibrium can be improved by modifying the demand profile of a building (especially with advanced building technologies) [30]. The adoption of rooftop solar systems presents an opportunity to self-consume and consequently reduce the energy cost (financial and environmental) of a building [31,32]. Local production would also imply reduced Net Energy Exchange with the Grid (NEEG) [33] and would allow for aggregated storage solutions (including vehicle to grid), which would consequently benefit stakeholders at higher levels within the grid [34];
- Community/distribution scale: With the emergence of local energy communities and the widespread adoption of renewable energy resources (RERs), it is possible to further mitigate the effects of a high RER penetration within the larger grid using methods such as collective self-consumption [35] and peer-to-peer energy trading [36]. Additionally, the presence of storage (both community scale and aggregated) coupled with RERs could imply higher resilience of the network at this scale (islanding in the event of grid fault events);
- Transmission/Utility scale: At this scale, energy flexibility is vital for ensuring that the network delivers electricity that meets regulatory standards. Energy flexibility is also key in determining and regulating the cost of electricity generation (peak shaving, valley filling, etc.) [37]. Considering the high penetration of RERs and the evolution of the existing grid towards grid 2.0, energy flexibility is a key instrument for congestion management and grid reliability improvement [38,39]. In some instances, energy flexibility reduces the need for infrastructure upgrades, implying reduced or delayed costs of infrastructure development.

Figure 4 illustrates the objectives of energy flexibility at the different scales of the grid.

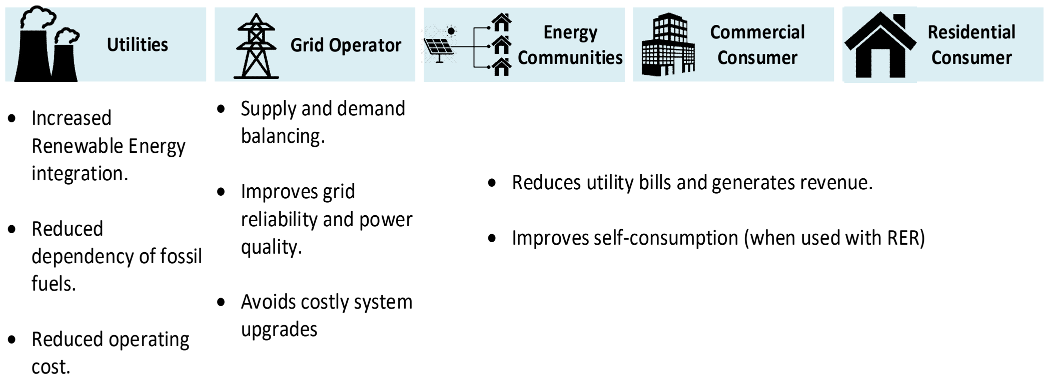

Figure 4. Objectives of energy flexibility for key stakeholders in the electric grid [40].

Low-Tech Need for Energy Flexibility

Numerous applications for low-tech have been conceived by ADEME as well as many other stakeholders, such as low-tech labs. In a recent report, The Social and Solidarity Economy Lab, a French think tank, explored the application of low-tech to certain aspects of citizen life, such as housing, transport, well-being, and work [41]. However, this work, like most other publications on low-tech, focused mostly on societal needs from an individual's perspective. Consequently, applications geared toward commercial or complex corporate goods and services were rarely discussed. To drive the adoption of low-tech as a widely accepted development philosophy for the 21st century, it is necessary that low-tech be demonstrated to not only be desirable and applicable to individual needs but also add value when used in the development of more complex and commercial systems.

Considering the low-tech approach, it is pertinent to pose questions related to the need for the grid, mainly: (i) "Is the electric grid necessary?", and (ii) "If the grid is warranted, to what extent/scale do we need it?" Bhattacharyya et al. [42] address the former question in their works and conclude that, despite not being the ideal solution, grid extension is the more sustainable alternative compared to the alternatives, i.e., off-grid solar home systems and local mini-grids. This conclusion is further highlighted by Coignard et al. [43], whose work shows that high-energy self-sufficiency (at the community scale and using energy from solar PV) has its limits. Thus, there needs to be a trade-off between the efficiency gains derived from a grid and the desire for energy self-sufficiency, especially at the lowest levels of the energy system. Although these questions are important in the broader context of low-tech, they are, however, not within the scope of this article and are therefore not addressed. Furthermore, grid infrastructure already exists in most cases, and as such, for this article, we consider electric grids (even continental-scale grids) to be warranted.

Philippe Bihouix [44] advocates that a low-tech energy transition should be guided by moderate consumption (energy sobriety [45]) and not only a technological transition. Here, moderate consumption refers to having an energy consumption that is not only reduced but also flexible, resulting from a behavioral change in the end user. Therefore, building on this established need for grids (and interconnections between grids), it is necessary that they be managed as low-tech (connected to the core need) sustainable, and socially equitable as possible.

4. Methodology of Research Work

In the context of the energy transition, it was observed through an initial literature review that the term is principally entrenched in French literature. Consequently, this warrants the introduction of low-tech in English literature. Therefore, this research work aims at using low-tech as an assessment framework for in-practice energy flexibility solutions. To carry out the evaluation, it was necessary to categorize energy flexibilities into three main types: supply-side energy flexibilities, demand-side energy flexibilities, and energy storage systems. Despite some degree of overlap between these three categories, there is enough distinction between them to present energy flexibility solutions in this manner.

Thus, Google Scholar and Web of Science were used as resource databases to search for existing energy flexibility solutions that fell within the three categories.

Although there are evaluations of energy technologies across the technical, economic, environmental, and social aspects of sustainability [46–49], using low-tech as an evaluation matrix proposes a simpler and more accessible framework that serves to apply not only to simple problems such as accommodation but also to more complex problems such as energy flexibility in this case. However, due to the lack of an evaluation metric for solutions using low-tech in the existing literature, a qualitative approach was selected to evaluate the chosen energy flexibility solutions. A five-point scale (low, low-medium, medium, medium-high, and high) was employed and applied to the criteria for evaluating energy technology solutions found in the literature.

The low-tech criteria as discussed in Section 2.1 above were adapted to the context of energy flexibility solutions, as the aforementioned criteria definitions are specific to needs at an individual scale. The *localness* and *autonomy* criteria were then used as sub-criteria for *accessibility*. Thus, the low-tech criteria for energy flexibility solutions can then be defined as:

- Usefulness: Ability to meet the core requirement of the grid, which is to provide quality electric power that meets regulatory standards (i.e., frequency, voltage, etc.). To meet this need, flexibilities with different response times, ramp powers, and ramp rates are required, depending on the application and level within the grid where the flexibility service is being applied;
- Accessibility: As with the original definition, accessibility involves cost, knowledge, and scaling. For energy flexibility solutions, we consider the levelized cost of flexibility activation, if a solution is open-access or proprietary, the ease of marginal installation, the geographical availability of the primary flexibility resource, wide-scale access to the tools used to harness the flexibility, and the precision with which flexibility can be localized;
- Sustainability: To ascertain the environmental sustainability of solutions, there is a myriad of indicators to consider. However, for this analysis, we can consider the following indicators: global warming potential per kWh (kgCO_2-eq/kWh), abiotic material depletion (kgSb-eq/kWh), human toxicity (CTU/kWh), and the average lifetime of the technology.

In the subsequent section, the energy flexibility solutions are categorized with respect to their origin of implementation, i.e., supply-side management, demand-side management, and energy storage. This is done to group solutions that are more similar together. Each of the technologies and methods is first discussed as energy flexibility solutions and then critically reviewed through the lens of the aforementioned 3 low-tech characteristics.

5. Energy Flexibility Solutions through the Lens of Low-Tech

The traditional electricity supply system constitutes a vertically integrated grid (i.e., large centralized production units upstream and consumption downstream of the grid). In this traditional system, the generation of energy follows the demand (from the consumer side) in real time. However, with the integration of distributed RERs, the advent of prosumers, and energy tariff inflation, the traditional grid is changing quickly [50]. Unlike traditional generation plants, the intermittent nature of renewable sources tends to generate variable energy. Therefore, it is exigent that the traditional approach be changed not only for production but also for consumption. This need of the hour requires not only changes to the energy supplied to the grid but also changes in behavior (consumption profiles), and energy flexibility is one such solution to keep this energy balance [51].

The term energy flexibility is often misunderstood and interchanged with demand-side management. This is because, in literature, energy flexibility solutions are usually implemented on the demand side. However, in reality, the definition of energy flexibility evolves while trickling down from the supply side to the demand side within the energy supply chain. Figure 5 [52] illustrates energy flexibility solutions at all levels of the electric grid. The geographical dispersion of renewable energy resources (i.e., distributed energy resources) is also considered part of supply-side management (as shown in Figure 5).

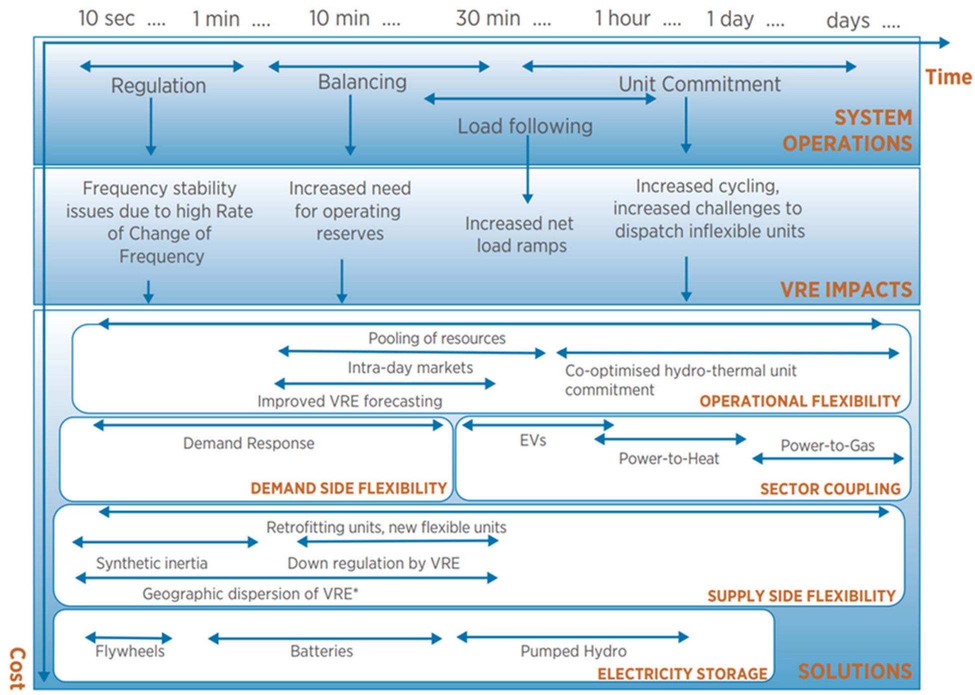

Figure 5. Flexibility solutions relevant to intermittent renewable production [52].

The following subsections will discuss in detail supply-side energy flexibility (SSEF), demand-side energy flexibility (DSEF), and energy storage systems (ESSs).

5.1. Supply-Side Energy Flexibility

In a traditional electricity supply system, the energy flexibility on the supply side is described as "the general ability to address short-run changes and imbalances between electricity supply and demand" [53–55]. This can be achieved by either switching flexible power plants (usually fossil-fuel-based power plants) or through cross-border energy trade. The former is termed system operations, while the latter is termed operational flexibility. These solutions usually function in the time range from 10 s to 30 min and, in some cases, can be quite expensive. For their operations, there are physical and technical constraints, largely based on the ramping rate of the generating station, i.e., how quickly a generator's output can be varied [56].

5.1.1. Hydropower Stations

Hydropower stations have long been known to be flexible, with quick start-up and stop times and the possibility to easily adjust the amount of water that flows through the plants and hence the power output [56]. However, several types of hydropower stations offer different levels and forms of flexibility [57]. There are generally three types of hydropower plants: reservoir-based stations, pumped hydroelectric storage (PHS) stations, and diversion (run-of-river) stations. The reservoir stations are typically the largest of their kind and provide the largest individual blocks of supply flexibility. A sample schema can be found in Figure 6. PHS stations, although smaller, provide bi-directional flexibility. In a PHS plant, the turbines are reversible; they can work as turbines to generate electricity or as pumps that consume electricity by pumping water back to the reservoir. Diversion stations provide flexibility in a manner similar to that provided by reservoir stations. However, as they typically do not have the storage capacity and are not as big as reservoir stations, their flexibility is limited.

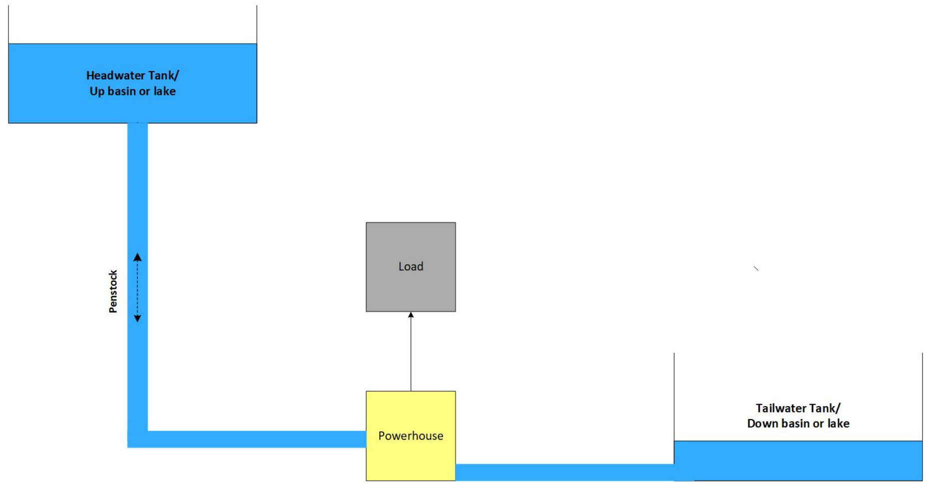

Figure 6. Working principle of pumped hydroelectric storage stations.

Small-scale (mini) pumped storage solutions have also been proposed, studied, and implemented. Oliveira Silva [58] examined the feasibility of using the rooftops of buildings to provide the needed ventilation. Similarly, Manolakos et al. [59] presented the implementation of a micro-grid system for a village that replaced conventional chemical energy storage with a small-scale pumped storage system. This concept allows PHS systems to be more accessible and sustainable. The downside is that, due to the small nature of such installations, they miss out on the financial benefits of economies of scale, thus making them financially prohibitive [60].

Although traditional (large-scale) hydro plants perform well on some of the defined low-tech criteria, they are not without their limitations, as shown below:

- Usefulness: Hydropower is one of the best energy sources to meet grid flexibility [57]. Due to the typical large installations of reservoir-based systems, they can usually vary their production over a large range. In addition, PHS plants have the ability to not only provide variable energy to the grid but also consume energy from the grid. Hydro plants have also been used for grid balancing over varying timescales, from primary reserves to even seasonal storage. Therefore, hydropower can be considered to have a high rating of usefulness for energy balancing on the grid;
- Accessibility: Large-scale hydro plants have been found to be one of the more cost-effective solutions for energy generation [61]. They are, however, constrained by their size and geographical requirements and consequently deemed less accessible. Another drawback is the long lead time to construct these structures. Although smaller pumped hydro plants have been tested and put into practice in some locations, these are often found in locations without access to the energy grid, limiting the potential for aggregation for grid balancing. Finally, although the construction of turbines and dams is based on easily accessible materials, the designs themselves are not particularly open-source. Therefore, although hydropower plants boast a rather low levelized cost of energy (LCOE), the nature of the technology and the management of the design of tools leave much to be desired from a low-tech perspective, causing them to be considered low-medium in terms of accessibility;
- Sustainability: Designated as a green energy source, hydropower plants are considered one of the most renewable classic energy generation sources [61]. With a range from 6.1 to 11 g CO_2 eq./kWh generated for an average 360 MW plant, hydro plants are low contributors to the global warming potential. Hydropower plants are also low contributors to abiotic material depletion and have a long lifespan [62]. Despite their positives, these plants have been noted to cause changes to the nutrient cycle and biotic life in the areas where they operate [63,64]. Additionally, studies indicated that hydropower plants contribute significantly to adverse changes in the surrounding

waterbodies and landscapes [65]. As such, hydropower plants can be considered to have a rating of medium-high in terms of environmental sustainability.

5.1.2. Solar PV and Wind Turbines

With the increasing integration of distributed generation on grids, numerous studies have been carried out into ways of using these technologies for self-balancing. With solar PV inverters, control algorithms have been developed to change the maximum power point on the inverters and engage in various schemes of PV curtailment to meet power flexibility demands [66,67]. Conversely, for wind turbines, frequency regulation is provided in the form of synthetic inertia used for fast frequency reserves [68,69].

As shown in Figure 7, there are two broad forms of frequency control for variable renewable energy solutions [70]. The de-loading technique involves setting the operational point of the solar PV or wind turbine plants below the optimum so that they can provide upward flexibility when required. The inertial response technique involves using the rate of change of frequency to trigger the release of kinetic energy from the blades of the wind turbine to the grid. When this happens, the speed of the rotor quickly decreases (for approximately 2–6 s) to provide the extra power needed. Using this technique, constant power is delivered to the grid for a set amount of time.

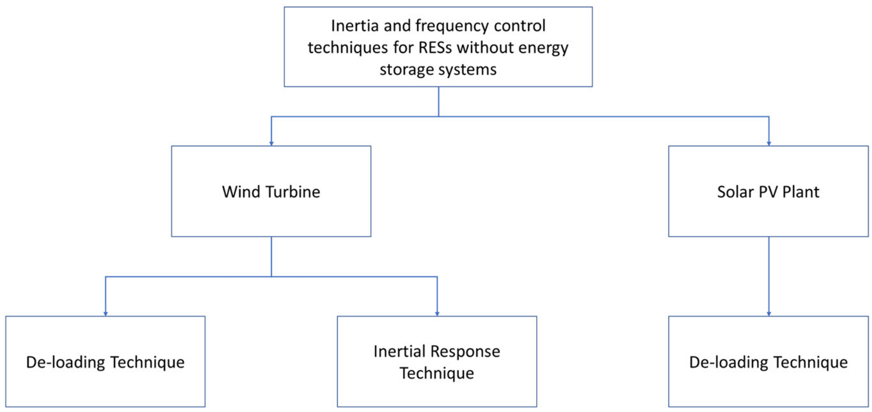

Figure 7. Frequency control techniques for variable renewable energy solutions [70].

In terms of being low-tech, the mix of wind and PV plants can be considered average, with the following ratings across the criteria:

- Usefulness: The utility of wind turbines and solar PV for grid balancing is somewhat limited. This is in part due to the inherent intermittency and uncertainty of their energy production. The application of these technologies is limited to shorter time horizons: operational reserves and primary reserves (typically milliseconds to seconds) for wind turbines, and only primary reserves for solar PV curtailment. However, as this flexibility is due to the action of power converters and controllers, when they are available for activation, they will typically be very controllable. Owing to the limitations of these technologies for grid balancing, they can be considered low-medium with regard to their usefulness for grid balancing;
- Accessibility: With a global weighted-average levelized cost of energy of \$46/MWh for solar PV and \$33/MWh for onshore wind turbines in 2021, these are some of the lowest-cost sources of energy generation available [71]. As the de-loading technique for frequency control requires these to operate in conditions outside their optimum, it has yet to be determined if the compensation from providing ancillary services can compensate for this loss [72]. Solar PV plants are one of the most geographically accessible energy solutions, as they can theoretically be deployed almost anywhere in the world and in varying sizes. On the other hand, wind turbines are not as easily installed marginally, with typical installation sizes of 4 MW [73] in 2021. The materials used to create these solutions are mostly produced in certain parts of the world due to

the complex industrial processes required in their fabrication. As such, they can be considered to have a medium-high accessibility rating.

- Sustainability: As these are renewable energy sources, they both contribute little to global warming, which occurs mostly in their manufacturing and transport. The manufacturing and disposal of materials for these technologies both contribute somewhat significantly to human toxicity and the depletion of rare earth materials [74]. Therefore, they can be considered to have a medium-high environmental rating.

5.1.3. Flexible Nuclear Plants

Nuclear plants in most parts of the world are inflexible—they cannot easily and safely be ramped up or down to balance variable outputs from renewables. However, nuclear plants used in France have been shown to provide power flexibility [75,76]. As seen in Figure 8 (which shows a nuclear reactor's operation in 2015), reactors in France can be used in load-following mode. They can be ramped from 20% to 100% of the nominal power in 30 min. However, this can only be done twice within a 24-h window and requires at least two hours between each ramp [75]. These plants can also be used for primary and secondary reserve control, for which they can change ±2% of nominal power for primary reserves and ±5% of nominal power for secondary reserves.

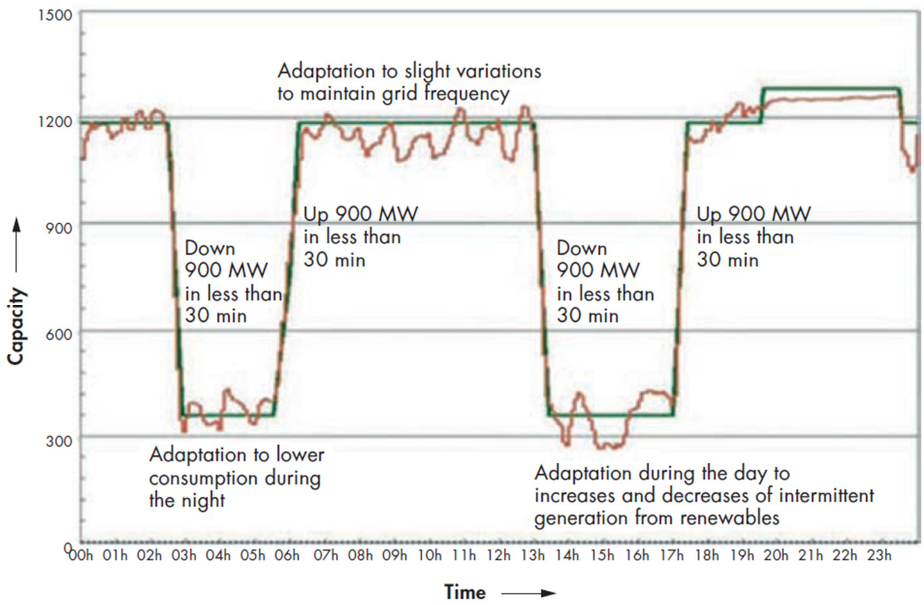

Figure 8. Power generated by a 1300 MW nuclear reactor over 24 h in response to grid variations.

Flexibility for these nuclear plants is provided in two ways. There is the change of the core power temperature to reduce the steam produced or the diversion of the steam produced away from the turbine into the atmosphere [75]. The control of the temperature core is done with the aid of "gray" control rods, a modification of the Wessington design done by Électricité de France (EDF), and the variation of the boric acid flow. The performance of nuclear plants from a low-tech perspective is discussed below:

- Usefulness: Nuclear plants have been demonstrated to be not only able to operate in load-following mode but also to provide some level of primary and secondary reserves [76]. However, the limitation in the number of times the plants can be ramped per day means that if there are uncharacteristic requirements, these plants might be unable to meet the need, resulting in a low-medium usefulness rating;
- Accessibility: With average LCOEs of \$42/MWh and \$71/MWh for Generation III nuclear plants in Russia and France, respectively, these serve as one of the financially cheaper means of supply-side energy flexibility [77]. However, this is not the case in general, as higher costs are reported in many other countries. Furthermore, LCOE

analysis from Lazard has shown that the LCOE of new nuclear plants has been increasing over the past 7 years [78]. In addition, these plants are characterized by very high capital costs, lead times on the scale of decades, and typically very huge installations [79]. The high cooling requirements of the plants often necessitate siting them on river banks, which further serve as geographic constraints on their installation. Finally, the research on nuclear plants and their operations is sensitive and, in some cases, closed for security reasons, further reducing the accessibility of nuclear as a solution for energy flexibility to a low score.

- Sustainability: Nuclear plants are a low contributor to raw material depletion, contribute very little to GHG emissions, and have a relatively long lifetime [80,81]. However, the management of the spent fuels and their radioactivity is notable (especially the risk of exposing humans to ionizing radiation), with occupational exposure being about 10 times the potential exposure to the general public [82]. Furthermore, the risks posed by nuclear plants to human health significantly increase in times of war, as can be observed in the current Ukraine-Russia conflict [79] or in times of natural disasters, as was the case in Japan (the Fukushima nuclear plant [83]). Considering all these, nuclear plants are considered to have a low-medium environmental sustainability score.

5.2. Demand-Side Energy Flexibility

Demand-side energy flexibility (DSEF) is oftentimes attributed to buildings, as they are massive consumers of electrical energy. Therefore, in the context of buildings, DSEF can be defined as "*the ability to manage a building's demand and generation according to local climate conditions, user needs, and energy network requirements*" [84]. As shown in Figure 5, the operational time range of DSEF is comparable to supply-side energy flexibility (SSEF) (synthetic inertia, down-regulation by variable renewable energy (VRE), etc.) solutions in some cases. However, DSEF solutions in general tend to be less expensive when compared to SSEF solutions of comparable scale and effect.

Demand-side energy flexibility (often alternatively called demand-side management or demand response) has been in practice for many years around the world. Ehrhardt-Martinez et al. [85] identified two notable eras of energy flexibility, the first being related to the oil crisis of the 1970s. Since oil-fired power plants dominated the energy mix of the USA, a massive campaign of energy flexibility programs was launched by energy utilities in the USA to maintain energy balance. The second era is known as the climate change era (i.e., the current era), which is being catalyzed by climate change and is the need of the hour.

The intended purpose of energy flexibility could be either upward modulation of demand (valley filling or increasing consumption during surplus RER production) or downward modulation of consumption (i.e., load curtailment during the period of peak consumption). The load shifting takes into account both upward and downward modulation (see Figure 9). Figure 10 provides a schematic diagram of the discussion on DSEF.

5.2.1. Incentive-Based Energy Flexibility

Generally, DSOs (distribution system operators) or aggregators directly control incentive-based energy flexibility; therefore, it can also be placed under the category of direct energy flexibility. The terms "direct" and "indirect" are used with respect to the degree of control by an aggregator or DSO. Usually, the purpose of direct energy flexibility is to attain load curtailment during peak consumption hours. Direct load control enables the aggregator or DSO to control the consumption loads remotely while being aware of the degree of flexibility of the respective consumer [86]. The consumers commit certain loads to be interrupted remotely by the grid in case of need. This commitment provides incentives to consumers, either in the form of energy discounts or bonuses.

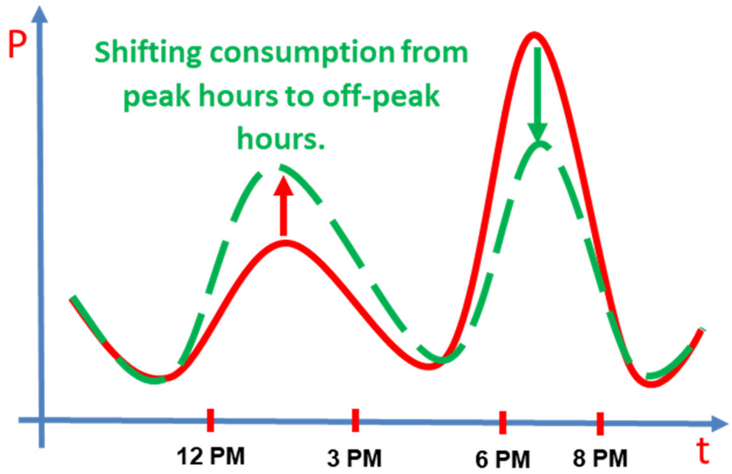

Figure 9. Load shifting using demand-side energy flexibility [51].

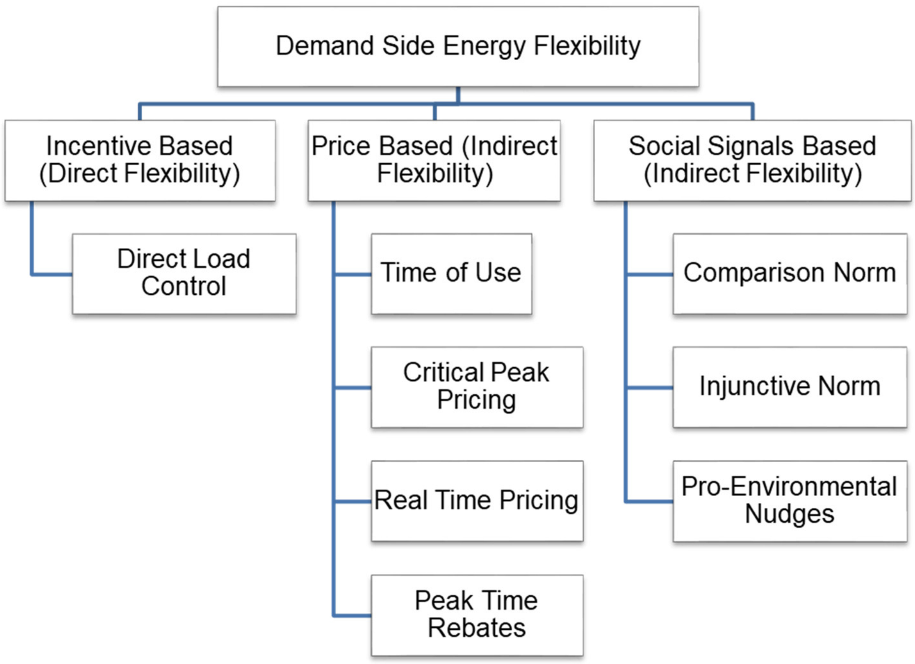

Figure 10. Types of Demand Side Energy Flexibility (DSEF).

Direct energy flexibilities are usually employed (though not exclusively) by industrial (large-scale) energy consumers and energy aggregators. For instance, energy pool [87] is an aggregator of industrial loads, data centers, and hospitals in France. With an available capacity of 1500 MW for energy flexibility, an energy pool offers load adjustment in multiple energy markets following the identification of the flexibility potential of its clients [88]. The clients of the energy pool receive specific payments for each intervention made for energy flexibility, a portion based on activated energy and the other on provisioned capacity [89]. Besides energy pools, Voltalis [90] is another aggregator of energy flexibility that has clients in the residential sector. According to ADEME, electric heating accounts for 36% of the annual electricity consumption in French residential buildings [91]. Therefore, Voltalis trades the aggregated load curtailment of electric heating in energy balancing markets [88]. An assessment of incentive-based energy flexibility through the lens of low-tech is given below:

- Usefulness: The grid operator/aggregator is required to commit the resources that will participate in the flexibility action ahead of time. Usually, this type of DSEF can be activated in a time scale of a few seconds. Additionally, it gives a high degree of remote load control to the grid operator/aggregator. Thus, it is evident that this type of energy flexibility is highly useful for the grid but has limited usefulness (usually financial) for the end-user; thus, this solution is assigned a medium score for the usefulness sub-criterion;

- Accessibility: The switches and circuit breakers used in this energy flexibility approach could be manufactured at a local site; however, it might not be possible to manufacture them using only the primary resources within the geographical vicinity of the application. The availability of information is not limited; therefore, the grid operator can outsource the work of installation to an SME (small and medium enterprise). In terms of information regarding a prospective intervention, the grid operator (or aggregator) informs the energy consumer ahead of the intervention. The ease of marginal installation depends on the complexity of the switching scheme. Besides, it also depends upon the acceptance of this solution by the energy consumer, since the energy consumers show certain concerns about the privacy and balanced use of direct load control [92]. Therefore, this solution can be considered to have a medium score in terms of accessibility;
- Sustainability: Usually, high-voltage circuit breakers use SF_6 gas for arc quenching, which has a global warming potential 23,500 times that of CO_2 [93]. On medium-voltage circuit breakers, it is preferable to replace the SF_6 gas with a low-toxic gas [94]. However, on the low-voltage side, mechanical and power electronics circuits preferably operate the circuit breakers. The circuit breakers on the low-voltage side offer a higher degree of reparability and are less toxic as compared to high-voltage circuit breakers. Besides, abiotic material depletion is also a concern, especially when one considers the lifecycle (production, use, and disposal/recycling) of the various components (particularly circuit breakers) used for this solution. Considering the aforementioned pros and cons, the solution gets a low-medium score for sustainability.

5.2.2. Price-Based Energy Flexibility

Price-based energy flexibility is a type of indirect energy flexibility that puts the burden of implementation on the consumer. Generally, it is expected to be implemented by the consumer in response to a signal. The consumer can benefit by changing their energy consumption in response to the variation in price. Alternatively, the consumer might have to pay a high electricity bill for not following up on the price signal and acting accordingly. This type of energy flexibility is non-intrusive and does not require any intervention via switching devices by the DSO or aggregator. The price signals can be used for load curtailment and load shifting. They can also be complemented with a message for valley filling. A brief overview of types of price-based energy flexibility is given as follows:

- Time of Use (TOU): It fixes the energy tariff for a certain period of the day, which is higher than the rest of the day [95];
- Critical Peak Pricing (CPP): It fixes certain days in a calendar year when the energy tariff is higher as compared to the normal tariff for other days [96,97];
- Real-Time Pricing (RTP): It tends to inform the consumer regarding the evolving real-time price of energy provision in accordance with grid conditions and peak consumption. "*For RTP, the price of electricity is defined for shorter periods, usually 1 h [98], reflecting the changes in the wholesale price of electricity. Customers usually have the information about prices on a day-ahead or hour-ahead basis*" [99];
- Peak Time Rebates (PTR): The "*peak time rebate (PTR) relies on rewarding the customers during the peak time based on their load reduction*" [100].

An assessment of price-based energy flexibility through the lens of low-tech is given below.

- Usefulness: The price-based energy signal is dispatched ahead of the hour of energy flexibility intervention. These signals are publicly accessible to all stakeholders in the energy supply chain. However, the solution is not directly controllable by the grid operator. It is executed by the energy consumer and is subject to their level of motivation. The predictability of the solution can be viewed in two regards: as the

prediction of network congestion that serves as the basis of the price signal and as the prediction of potentially achieved energy flexibility in response to the price signal. For the former, we can say that the solution is useful, whereas the latter depends upon the level of motivation of the energy consumer, which needs to be predicted through carefully performed social experiments. Besides, literature indicates that consumers may have cognitive limitations while acting upon the price signal [51,101,102]. Therefore, price-based energy flexibility can be considered useful at a medium level;
- Accessibility: The dispatch and reception of price signals make use of local resources, i.e., communication media like mobile phones, the internet, etc. A price-based signal is generated by a grid-level computer and is received by the energy consumer via mobile phone, etc. As the price-based signal is diffused to the public, the information can be considered open. Additionally, this type of energy flexibility is very scalable, i.e., anybody who subscribes to this service receives the price-based signal. Therefore, we can say that the price-based energy flexibility solution is accessible at a high level;
- Sustainability: The solution has an extremely low (almost negligible) impact in terms of global warming potential. Similarly, it is easier to do maintenance on the server; therefore, it is easily repairable. The electronics used for this solution (meters, network devices, etc.) generate e-waste at the end of their life cycles. "*Many case studies from e-waste recycling plants confirmed that toxic chemicals such as heavy metals and POPs (persistent organic pollutants) have and continue to contaminate the surrounding environment. This results in the considerable accumulation of hazardous substances in the ecosystem, which can adversely impact human health*" [103]. Thus, the solution is considered sustainable at a medium level.

5.2.3. Social Signals-Based Energy Flexibility

Over the past two decades, a new lateral of indirect energy flexibility has been gaining popularity. This lateral is based on social signals, which are usually aimed at residential consumers. Like other types of DSEF, the general purpose of these social signals is found to be load curtailment. However, the impact of these social signals on load shifting has also been studied over the past few years [104]. This type of energy flexibility is also termed indirect energy flexibility, since the burden of implementation is on the consumers. Thus, it can be conceptualized as the indirect control of devices and systems using humans in the loop, which usually relies on influencing human behavior [105]. Additionally, it is also non-intrusive and is normally complemented with feedback on energy consumption to the consumer. A brief overview of some types of social signals based on energy flexibility is given as follows:

- Comparative Norm: To give a social push to an energy consumer, their energy consumption over a defined period is compared using either:
    - a social comparison, in which the comparison is done with the energy consumption of a similar household during the same defined period; or;
    - a historical comparison, in which the comparison is done with consumers' own historical energy consumption for the same defined period, e.g., with the previous month's consumption or the previous year's consumption of the same period, etc. [106,107];
- Injunctive Norm: This is part of the indirect feedback given to the consumer after a period of energy consumption. For this type of feedback, the energy consumption for the defined period is given in the form of an "efficiency standing". e.g., [108];
- Pro-Environmental Nudges: Unlike price signals, social comparisons, and self-comparison, pro-environmental nudges are social signals that take into account the environmental impact of energy production. It might be the environmental hazards of fossil fuel power plants or the environmental benefits of clean energy from renewable energy production. These nudges can also be framed by only giving information about forecasted peak production and forecasted network congestion [109]. It is found that these types of social signals are effective with a set of pre-defined commitments

made by the consumer to attain energy flexibility at the requested time interval [51]. However, the impact of indirect feedback is not quantified yet in the case of pro-environmental nudges.

An assessment of social signal-based energy flexibility through the lens of low-tech is given below.

- Usefulness: The usefulness of a social signal-based energy flexibility solution equates to that of price-based energy flexibility. The only difference is that where price-based signals cause extrinsic motivation, the use of social and injunctive norms can be motivating as well as demotivating. This is a result of some energy users' dislike for comparison, whether socially or historically. Therefore, this solution attains a medium usefulness classification.
- Accessibility: Like the price-based energy flexibility signals, the dispatch and reception of these signals satisfy the criterion of using local resources. These signals are typically generated from computers at the grid operator or aggregator and subsequently transmitted via SMS or the internet. Also, like price-based signals, these signals are open and available to the public. For example, the diffusion of ecoWatt signals in France is for the public, and it does not require a subscription to a special tariff. *Based on a signal from RTE (the French distribution system operator), the Ecowatt smartphone application encourages the end consumer to adopt a citizen-friendly behavior by reducing their power demand* [110]. As such, social signal-based energy flexibility has a high accessibility score.
- Sustainability: With regard to social signals, the only infrastructure that is needed would be computer algorithms to forecast load curves and send out alerts. Rather than implementing new infrastructure for these signals, the algorithm can be self-executed on the existing hardware infrastructure of the grid or aggregator. On the consumer side, it relies on the traditional means of communication (sms, email, app notifications, etc.) with the human in the loop (i.e., the consumer). Therefore, in essence, this energy flexibility solution is capitalizing on existing hardware structures with no (or low) environmental cost. Therefore, this solution has a high sustainability score.

5.3. Energy Storage Systems

With the introduction of more renewable energy resources (and largely distributed energy resources (DERs)), the evolution of the electrical grid to a "smart grid" is inevitable. Energy Storage Systems (ESSs) are a key component of this smart grid. Katie Fehrenbacher [111] describes any next-generation smart grid without energy storage as being severely limited. Rodriguez et al. [112] further point out that ESSs facilitate the integration of renewable/intermittent generation resources, improve grid reliability and power quality, provide ancillary services (including flexibility), and enable energy arbitrage and the reduction or deferral of transmission and distribution investments.

The Impact of energy flexibility can be observed in isolated local energy communities, where demand and supply need to be in perfect synergy. To address this problem of having perfect synergy, local energy communities often require some form of storage technology, especially if there is a high penetration of DERs. In this regard, energy storage systems (ESSs) provide energy flexibility services at all levels of the grid. On the other hand, grid-connected energy communities rely less on energy flexibility since they can sell any unused energy back to the grid.

There are many energy storage technologies employed in the electricity sector. These include battery (electro-chemical) energy storage (BES) [113], supercapacitor energy storage (SCES) [114], superconducting magnetic energy storage (SMES) [115], hydrogen energy storage systems (HESS) [116], flywheel energy storage systems (FESS) [117], compressed-air energy storage (CAES) [118], and pumped hydro storage (PHS) [119]. The technology behind these ESSs is at various stages of maturity, as depicted in Figure 11 [120].

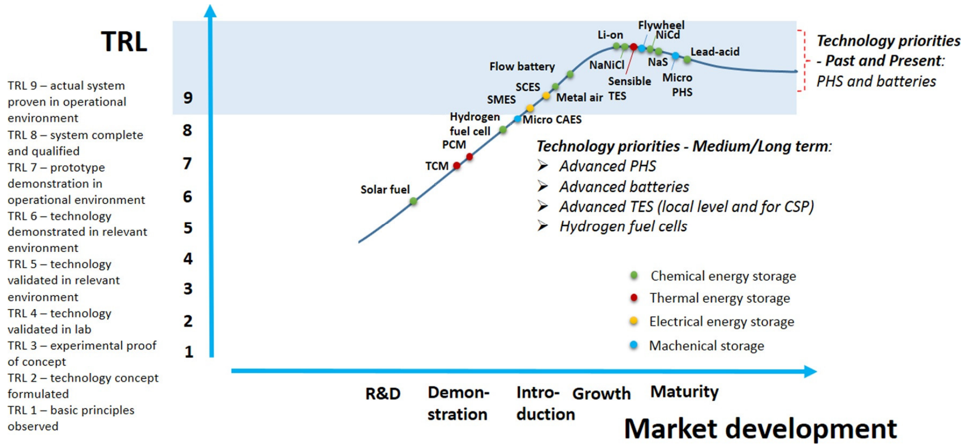

Figure 11. Overview of the maturity of energy storage technologies (Thermo-Chemical Materials (TCMs), phase change materials (PCMs), superconducting magnetic energy storage (SMES), super capacitor energy storage (SCES), sodium nickel chloride (NaNiCl) batteries, thermal energy storage (TES), nickel cadmium (NiCd) batteries, sodium sulphur (NaS) batteries, and pumped hydro storage (PHS)) as of 2017 with technology readiness level (TRL) on the y-axis and market development on the x-axis [120].

5.3.1. Battery Energy Storage

BESs are one of the most commonly employed storage technologies and have applications at all levels of the grid, particularly at the consumer (building or community) scale, despite being expensive (financial and environmental impact). At the grid scale, large-scale batteries (typically larger than 1 MW [121]) are deployed within the network and are used by network operators to provide ancillary services, amongst others. It is, however, possible to aggregate smaller batteries distributed at different levels within the network to serve the same purpose as a grid-scale battery.

With the recent developments in lithium-ion battery technology and consequently battery-electric vehicles (BEVs), there is an increasing appetite for second-life batteries in the market. For this article, we define second-life battery usage as repurposing batteries that may no longer be considered viable for their originally intended purpose for alternative and usually less demanding operations [122]. The use of second-life batteries reduces the entry barriers of financial cost and availability of raw materials. However, there are still concerns related to the safety of these batteries (particularly lithium-ion batteries).

Lithium-ion-based batteries (which have a high energy density) are used in a variety of applications, most notably electric vehicles and personal portable electronics. Due to the high uptake of electric-mobility applications, Skarvelis-Kazakos et al. [123] estimate that eVs alone could provide between 3.6 GWh and 17.6 GWh of waste battery capacity by 2030. In addition, this waste battery capacity, if not used for alternative (second-life) applications, will either go to landfills or have to be recycled. However, although recycling is currently technically feasible, it is not economically viable as the energy requirements of recycling are far higher than those required for sourcing new materials [124,125].

There are currently several initiatives to take advantage of second-life batteries by EV manufacturers such as Renault [126] and Nissan [127]. There is an active community of do-it-yourselfers (DIYers) who have taken a low-tech approach to repurposing these otherwise end-of-life batteries. Jehu Garcia [128,129], an influential member and possibly one of the pioneers of this community, has shared extensively on the subject matter (sourcing end-of-life batteries, testing and classifying cells, and building battery packs). The community developed an interesting approach for building lithium-ion battery packs. Their solution is composed of a modular, stackable, and easy-to-use (and assemble) kit; see Figure 12 [128].

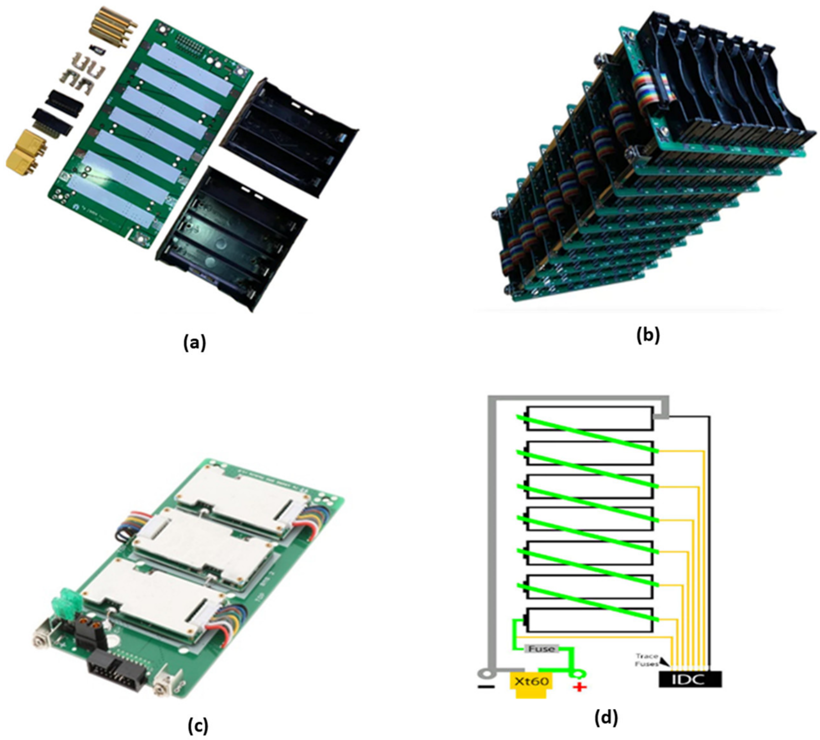

Figure 12. Open-source, Do-it-yourself modular battery storage kit: (**a**) exploded view; (**b**) assembled and stacked; (**c**) battery management module; (**d**) simplified circuit representation of the battery module [128].

Additionally, the Gerber files related to all the developed PCBs are open-access and available for others to improve and modify. Although the community boasts a large number of technically astute individuals, there are still some concerns regarding the safety of the 18,650 cells used, particularly related to the thermal runaway (fire and explosion risk) [130,131]. Despite these concerns, Hossain et al. posit that the extension of battery life using the second-life approach is necessary and argue that a standardized framework for categorizing, modeling, testing, and repurposing batteries for second-life applications needs to be put in place [132].

BESs have the advantage of being highly scalable and highly responsive (i.e., high ramp rate and low ramp time), and as such have applications on every level of the grid. At the building scale, they can be used as emergency energy reserves, especially for critical infrastructure. Additionally, when combined with RERs, BESs are useful for peak shaving and valley filling services [37,133]. At the local energy community level, batteries can be applied to increase the self-consumption of local energy resources and can increase the resilience of the community by reducing its dependence on the larger grid. Finally, at the utility scale, batteries represent a directly controllable flexibility source that can be harnessed to maintain equilibrium (and provide ancillary services) using either aggregated storage devices from lower levels of the network [134] or utility-scale storage devices [135].

Using the low-tech lens to evaluate second-life BESs, the following assessments can be made:

- Usefulness: As the core need is to provide flexibility services, BESs would typically score higher on this scale since they have a very fast reaction time (typically in the order of milliseconds) and are able to deal with variations quite well. Additionally, they can be used at all levels of the grid (residential, commercial, and utility scales) to provide different services (power quality, peak shaving, etc.). Thus, from a low-tech perspective, BESs can be considered to have a high usefulness rating;
- Accessibility: BESs, especially those using lithium-ion cells, are rather expensive (approximately $345/kWh in 2020 [136]). However, considering second-life applications

(especially in the DIY space), cells that have been deemed waste from their primary use are relatively cheaper (estimated at 116 $/kWh [137]) when compared to new cells. In terms of reparability, BESs require a certain level of technical expertise and can be complex to repair, depending on their underlying chemistry. Although information about lead-acid battery technology is readily available (as its technology is very mature and relatively simple), this is not the case for lithium-based cells, as they require a battery management system (BMS) and other mechanisms to ensure their safe operation. These additional features are usually proprietary and not typically available to the public. Finally, BES solutions are modular, and as such, their capacities can be increased or decreased to meet demand as and when needed. As such, BESs have a medium-high accessibility ranking;

- Sustainability: Lithium-based BESs, according to Gutsch et al. [138], have a GWP of 9–135 g CO_2 eq./kWh. There are also issues of resource depletion as well as high human and environmental toxicity largely associated with cobalt, copper, nickel, thallium, and silver [139]. These issues are further compounded by the relatively short life of BES (up to 15 years owing to both cyclic and calendar fade); however, the second-life use of BES has the potential of extending their life span to approximately 30 years depending on their use [140]. Extending the life of these cells through second-life applications, therefore, ensures optimal use of these cells before they are dispatched for recycling (and, unfortunately, in some cases, landfills). BESs are thus considered to have a low-medium sustainability score (influenced by the extra use associated with second-life applications).

5.3.2. Compressed-Air Energy Storage

Compressed air energy storage (CAES) systems were first developed in Germany by Nordwestdeutsche Kraftwerke in 1960 [118] based on the fundamental concept proposed by F.W. Gay in his US patent [141]. The fundamental concept of CAES is to 'charge' a storage vessel with air using electrical-driven compressors; the stored air is then released upon demand and used to generate electricity using air expansion through an air turbine [118] (see Figure 13 [142]).

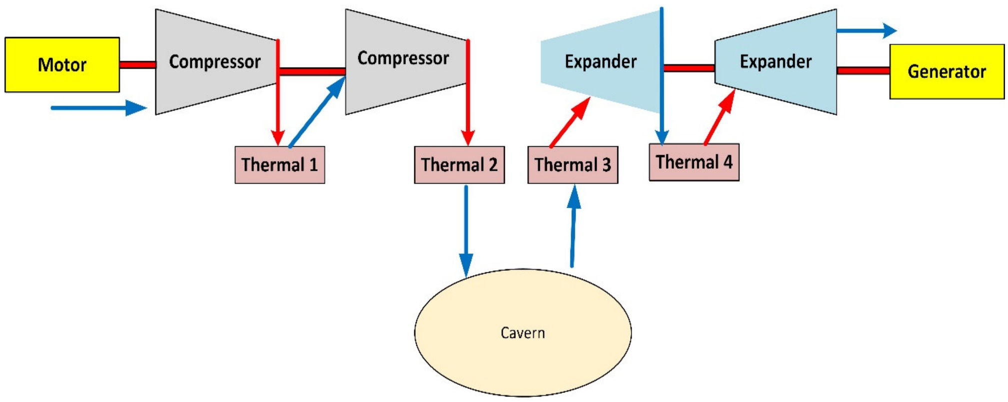

Figure 13. Working principle of compressed air energy storage systems [142].

Wang et al. [143] posit that the main driving factor for developing CAES is sustainability (reduced environmental impact), and as such, current efforts at developing this technology try to avoid fossil fuels. The development of this technology has, however, focused on large-scale applications, largely due to the space requirements of CAES. Despite this, there has been a growing interest in micro-CAES systems, focused on two key areas: (i) reducing the volume of storage required (for high-pressure and low-pressure applications), and (ii) improving the efficiency of compressors and expanders [144,145].

Similar to the BES example discussed above, Alami et al. [146] have proposed a low-pressure, modular micro-CAES system (Figure 14) that makes use of multiple small tanks instead of one large one, allowing for the system to ramp up (using aggregated pressure from the tanks) or ramp down when required. Interestingly, since this system is low pressure (i.e., it operates isothermally), it can achieve a maximum global efficiency of 97.6% and a maximum mechanical efficiency of 97.6% with a space requirement of approximately 0.6 m^3 [146].

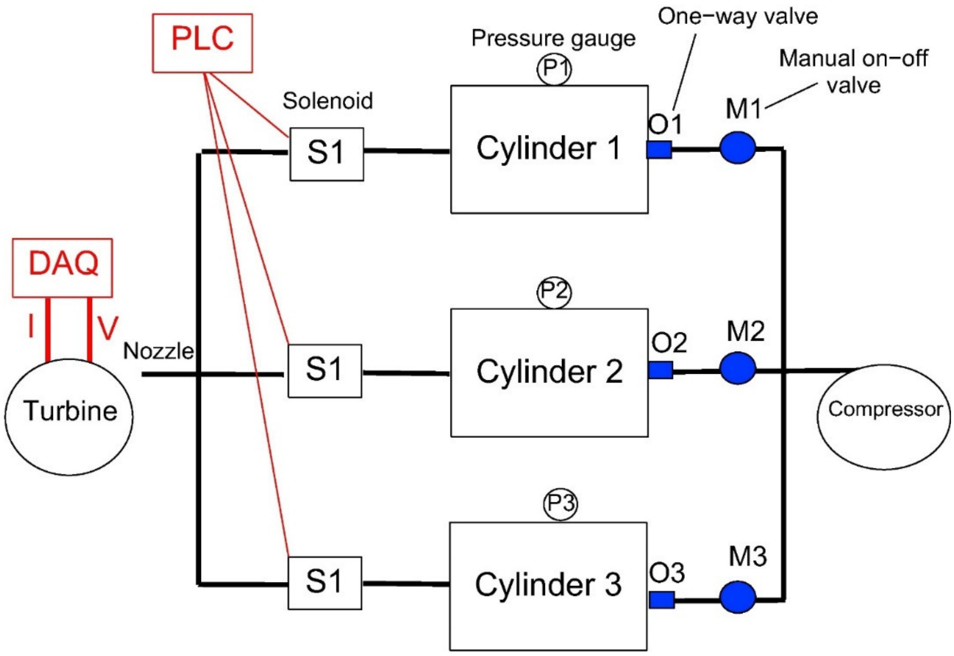

Figure 14. Main components of the modular low-pressure micro-CAES [146].

Segula Technologies [147] has also developed a CAES solution for undersea energy storage, REMORA, which is made up of a 15 MW floating platform coupled with undersea storage tanks with a capacity of 90 MWh. Their proposed system has an overall efficiency of 70%, which is achieved by avoiding the heating cycle (for compression) and using water and compression chambers. REMORA can be used at depths between 70 and 200 m [147], thus making it suitable for most coastal areas. A land-based pilot program, OdySEA, has been in operation in France since 2020, and the initial results indicate it is working as expected [148].

CAES (especially micro-CAES) are particularly interesting for low-tech applications as their Energy Stored On Invested (ESOI), defined by J. Barnhart [149] as "the ratio of electrical energy stored over the lifetime of a storage device to the amount of primary embodied energy required to build the device", which stands at 240, is significantly higher than that of BES at 10. Implying that, on average, a typical CAES system would store approximately 240 times its embodied energy, whereas BES systems, in the best-case scenario, would only store 10 times their embodied energy. CAES applications in the grid are similar to those of pumped hydro storage systems presented in Section 5.1.1.

Evaluating CAESs through the lens of low-tech, the following assessment was made:

- Usefulness: CAESs are capable of ramping up at a rate of 10% every 3 s [150,151], thus making them suitable for providing flexibility services within a timeframe of a few seconds. These plants are, in addition, very controllable and capable of providing both upward and downward flexibility. Barring unforeseen technical issues, CAESs have a high degree of predictability, and their operations are usually scheduled. Therefore, CAES systems are considered to have a medium-high usefulness score;
- Accessibility: Considering the traditional concept of CAESs, accessibility would be considered low. This is because these CAES require specific geographical and topographical features to be technically feasible. Additionally, the capital cost related to such plants is high: 650–1500 $/kW [152,153]. Considering newer technologies, however, the geographical constraints are reduced, as demonstrated by [146,147]. Since

these newer approaches for implementing CAES also improve efficiency while reducing the cost associated with storage, it can be inferred that the levelized cost of storage would be lower than that of a traditional CAES plant. Although the underlying concept of CAES is itself quite old and can be considered open, new modifications of the concept are not exactly openly available, as in the case of the REMORA solution [147]. Accessibility is thus considered to be low-medium;

- Sustainability: CAESs, like most mechanical storage solutions, are designed to last a long time (typically 40 years or more). Literature shows that the GWP of large-scale (traditional) CAES could range from 117 to 293 g CO_2 eq./kWh [154,155] depending on the energy mix of the input power source. Further, Alshafi et al. [155] show that CAES has a low human toxicity potential (approx. 0.00161 kg DCB eq./kWh). Lastly, CAES has a high reparability index and can be retrofitted with modern, more efficient parts to improve their efficiency. As such, the sustainability of CAES systems is considered to be medium-high (especially if the long lifespan is taken into account).

5.4. Summary of Energy Flexibility Evaluations and Discussion

In this section, we presented and evaluated some existing flexibility solutions using three characteristics of low-tech: usefulness, accessibility, and sustainability. Table 1 below provides a summary of this evaluation. Generally, flexibility solutions, which require large-scale infrastructure (usually the direct flexibilities), scored lower, especially for accessibility and sustainability. On the other hand, indirect flexibility solutions generally scored higher, owing to the distributed nature of the flexibility and the requirement of little to no infrastructure for their development. It can also be observed that no single technology had the maximum ranking (high) for all three criteria. This points towards the need for a plurality of solutions for a generic, balanced system based on low-tech principles.

Table 1. Summary of assessment of energy flexibility solutions through the lens of low-tech.

SN	Energy Flexibility Solution	Assessment through the Lens of Low-Tech		
		Usefulness	**Accessibility**	**Sustainability**
	Supply-Side Energy Flexibility			
1	Hydropower Stations	High	Low-Medium	Medium-High
2	Solar PV and Wind Turbines	Low-Medium	Medium-High	Medium-High
3	Flexible Nuclear Plants	Low-Medium	Low	Low-Medium
	Demand Side Energy Flexibility			
4	Incentive-Based Energy Flexibility	Medium	Medium	Low-Medium
5	Price-Based Energy Flexibility	Medium	High	Medium
6	Social Signals-Based Energy Flexibility	Medium	High	High
	Energy Storage Systems			
7	Battery Energy Storage	High	Medium-High	Low-Medium
8	Compressed-Air Energy Storage	Medium-High	Low-Medium	Medium-High

This assessment is one of the first applications of low-tech to such a complex issue, and as such, it can be useful as a guide for different stakeholders. The following stakeholders will find these results especially relevant:

- Low-tech enthusiasts;
- Energy researchers;
- Innovators as a new criterion to take into account;

- Policy experts as they look to select climate change mitigation strategies.

First, these results validate the utility and explanatory power of the low-tech concept. Low-tech enthusiasts can be satisfied that the concept is indeed scalable and applicable to more complex topics and does not need to be relegated to issues like cycling and solar ovens. Next, it is also relevant to energy researchers. As we look to employ multi-criteria decision models for the selection of technologies, the low-tech framework here can serve as a starting point for relevant criteria to consider. Furthermore, relevant to developers of novel technologies for energy and otherwise, this can serve as additional design requirements that should be taken into consideration. Finally, for policy experts and public officials, this can serve as a more accessible way to think about technology selection, project commissioning, and the management of common goods.

6. Conclusions

Low-tech is a term that has been popularized for a few years. The term, however, has been bundled with other terminologies such as frugal innovation, which emphasize low-cost solutions. However, the gist of low-tech is to develop, implement, and use innovative solutions that are easy to develop within the given constraints of resources. Therefore, the fundamental criterion for a solution to be low-tech is not its financial cost but rather a mix of satisfying the core needs of the local community (usefulness), using local resources, being easily replicable (accessibility), and being environmentally sustainable (sustainability).

Existing energy flexibility solutions have been evaluated in this article from the perspective of low-tech, demonstrating that low-tech can be applied to complex systems and should not be restricted to simple problems (or solutions). The use of low-tech as an evaluation framework has been shown not only to be accessible but also scientifically pertinent. In the above sections, we have carried out a detailed discussion of the benefits and pitfalls of numerous energy flexibility solutions, highlighting some novel innovations to classic flexibility, notably for second-life battery use and synthetic inertia provided by distributed renewable energy resources. Such initiatives would benefit immensely from more support from academia and the scientific community at large.

In this article, a qualitative assessment of energy flexibility solutions was made on a 5-point scale from low to high. As no weights were assigned to the criteria, all the criteria were assumed to be of equal importance to the low-techness of the solutions. Overall, it can be concluded that different classes of flexibility solutions provide their own advantages and that a mix of the different classes of flexibility will be required in the future. Demand-side energy flexibility (DSEF) solutions have been presented as one of the more desirable means of energy flexibility. This conclusion is in contrast with the classic scheme for energy flexibility, which was based primarily on variations in power supply (typically through gas turbines) to meet imbalances in the power grid. This assessment sheds light on some of the barriers that limit the appropriateness of different energy flexibility resources and can serve as a guide for the innovation required in the design and implementation of future energy flexibility solutions.

6.1. Limitations

The work presented in this article is not without limitations, one of which is its generic outlook. Although it is clear that the results may be different in specific contexts, the authors assessed the discussed solutions from a global perspective (i.e., comparing the energy flexibility solutions within specific geographical boundaries would make them more relatable and comparable). As one of the first forays into the evaluation of technology using low-tech criteria, it seemed beneficial to the authors to favor a more generic assessment. Another limitation was the lack of qualitative ratings of various energy flexibility solutions based only on literature. This can be built upon using quantitative methods and other qualitative methods, such as a Delphi study, if possible. Finally, all the solutions assessed are mature means of providing grid flexibility. Emerging grid flexibility solutions such as hydrogen, bio-fuels, and sector coupling applications were not covered in this evaluation; however, it will be interesting to look at them as well.

6.2. Future Directions

Future work can be done to address some of the limitations highlighted in the sub-section above. Further work needs to be done to develop a framework for defining relevant (and comparable) sub-criteria, based on which a quantitative low-tech scoring matrix can be developed that incorporates weighting of the different sub-criteria. In addition to this, localized assessments can be carried out at the scale of countries and sub-country regions that will support technology selection and deployment at these scales. Subsequently, sensitivity analyses can be performed (using different geographic locations, for example) using the developed quantitative method.

We also invite other researchers to apply this low-tech framework to other applications in their respective domains. In the energy domain, evaluating emerging grid flexibility solutions such as sector coupling solutions as well as new energy generation solutions purely from a supply perspective would be useful directions to use this low-tech framework. In line with evaluating complex systems from a low-tech perspective, it might also be interesting to investigate other systems such as space exploration, telecommunications, and applied artificial intelligence. Finally, side-by-side comparisons can be made between this framework and other technology selection frameworks to highlight the explanatory power behind this work.

Author Contributions: All authors contributed to the conceptualization and methodology used in this review. M.S.S., S.O. and N.K.T.-D. performed the data search, analyzed the literature, and drafted the paper. S.H., B.D. and F.W. supervised and directed the research and provided a formal analysis of the review. All authors have read and agreed to the published version of the manuscript.

Funding: This work was partially supported by the ANR project ANR-15-IDEX-02, the eco-SESA program (https://ecosesa.univ-grenoble-alpes.fr/, accessed on 3 April 2023), the Observatory of Transition for Energy (https://ote.univ-grenoble-alpes.fr/, accessed on 3 April 2023), and a grant from the French government under the PIA, IRT Nanoelec, bearing the reference ANR-10-AIRT-05.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Balibar, S. Energy transitions after COP21 and 22. *Comptes Rendus Phys.* **2017**, *18*, 479–487. [CrossRef]
2. United Nations. *The Paris Agreement*; United Nations: Paris, France, 2015; pp. 1–25.
3. IRENA. Energy Transition. Available online: https://www.irena.org/energytransition (accessed on 21 September 2022).
4. Carayannis, E.G.; Campbell, D.F.J. "Mode 3" and "Quadruple Helix": Toward a 21st century fractal innovation ecosystem. *Int. J. Technol. Manag.* **2009**, *46*, 201–234. [CrossRef]
5. Schütz, F.; Heidingsfelder, M.L.; Schraudner, M. Co-shaping the Future in Quadruple Helix Innovation Systems: Uncovering Public Preferences toward Participatory Research and Innovation. *J. Des. Econ. Innov. She Ji* **2019**, *5*, 128–146. [CrossRef]
6. Illich, I. *Tools of Conviviality*; Harper & Row: New York, NY, USA, 1973; ISBN 9780714509730.
7. Sector by Sector: Where Do Global Greenhouse Gas Emissions Come from? Our World in Data. Available online: https://ourworldindata.org/ghg-emissions-by-sector (accessed on 14 October 2022).
8. Schumacher, E.F. *Small is Beautiful: A Study of Economics as if People Mattered*; Blond & Briggs: London, UK, 1973.
9. Kaplinsky, R. Schumacher meets schumpeter: Appropriate technology below the radar. *Res. Policy* **2011**, *40*, 193–203. [CrossRef]
10. Prabhu, J. Frugal innovation: Doing more with less for more. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **2017**, *375*, 20160372. [CrossRef] [PubMed]
11. Hossain, M.; Simula, H.; Halme, M. Can frugal go global? Diffusion patterns of frugal innovations. *Technol. Soc.* **2016**, *46*, 132–139. [CrossRef]
12. Navi, R.; Prabhu, J. *Frugal Innovation: How to Do More with Less*; Profile Books Limited: London, UK, 2015; ISBN 9781781253755.
13. Trimble, C. Reverse innovation and the emerging-market growth imperative. *Ivey Bus. J.* **2012**, *76*, 19–21.
14. James, D.D. The Political Economy of Science and Technology. *J. Econ.* **1987**, *2*, 921–923. [CrossRef]
15. Emmanuel, A. *Appropriate Technology and Underdevelopment*; John Wiley: Chichester, UK, 1982.
16. Eckaus, R.S. Appropriate technology: The movement has only a few clothes on. *Issues Sci. Technol.* **1987**, *3*, 62–71.

17. Émilien Bournigal Low-Tech: Définition et Exemples de la Démarche d'Innovation. Available online: https://lowtechnation.com/low-tech/ (accessed on 19 October 2022).
18. Tanguy, A.; Carrière, L.; Laforest, V. Low-tech approaches for sustainability: Key principles from the literature and practice. *Sustain. Sci. Pract. Policy* **2023**, *19*, 2170143. [CrossRef]
19. Wikipedia Contributors Low Technology. Available online: https://en.wikipedia.org/w/index.php?title=Special:CiteThisPage&page=Low_technology&id=1112854573&wpFormIdentifier=titleform (accessed on 8 October 2022).
20. Low-Tech Lab. What Are Low-Techs. Available online: https://lowtechlab.org/en/low-techs (accessed on 21 September 2022).
21. Bloquel, M.; Bonjean, A.-C.; Fangeat, E.; Marry, S.; Forget, A.; Fustec, A.; Habe, C.; Jaeger, R.; Moiroud, L.; Morales, E.; et al. *État des Lieux et Perspectives des Démarches «Low-Tech» Synthèse*; ADEME: Angers, France, 2022; 13p.
22. La Fabrique Ecologique. *Vers des Technologies Sobres et Résilientes—Pourquoi et Comment Développer l'Innovation «Low-Tech»?* La Fabrique Ecologique: Paris, France, 2017.
23. Bihouix, P.; McMahon, C. *The Age of Low Tech*, 1st ed.; Bristol University Press: Bristol, UK, 2014; ISBN 9781529213263.
24. Moving Windmills: The William Kamkwamba Story. Available online: https://thekidshouldseethis.com/post/william-kamkwamba-moving-windmills (accessed on 18 October 2022).
25. Kamkwamba, W.; Mealer, B. *The Boy Who Harnessed the Wind: Creating Currents of Electricity and Hope*; HarperCollins: New York, NY, USA, 2010; ISBN 9780061730337.
26. Troullaki, A.; Latoufis, K.; Marques, P.; Freire, F.; Hatziargyriou, N. Life Cycle Assessment of Locally Manufactured Small Wind Turbines and Pico-Hydro Plants. In Proceedings of the International Conference on Smart Energy Systems and Technologies (SEST), Porto, Portugal, 9–11 September 2019; Institute of Electrical and Electronics Engineers Inc.: Porto, Portugal, 2019; pp. 1–6.
27. Hirsch-Kreinsen, H.; Jacobson, D.; Robertson, P.L. "Low-tech" industries: Innovativeness and development perspectives—A summary of a European research project. *Prometheus* **2006**, *24*, 3–21. [CrossRef]
28. OCED. *OECD Science, Technology and Industry Scoreboard*; OECD Publishing: Paris, France, 2005; ISBN 92-64-01055-6.
29. Lund, P.D.; Lindgren, J.; Mikkola, J.; Salpakari, J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew. Sustain. Energy Rev.* **2015**, *45*, 785–807. [CrossRef]
30. Li, R.; Satchwell, A.J.; Finn, D.; Christensen, T.H.; Kummert, M.; Le Dréau, J.; Lopes, R.A.; Madsen, H.; Salom, J.; Henze, G.; et al. Ten questions concerning energy flexibility in buildings. *Build. Environ.* **2022**, *223*, 109461. [CrossRef]
31. Musolino, V.; Alet, P.-J.; Regamey, Y.-J.; Stauffer, Y.; Hutter, A.; Perret-Aebi, L.-E.; Ballif, C. Multi-occupancy buildings as micro-grids: An asset for integrating photovoltaics in power systems. In Proceedings of the 3rd Renewable Power Generation Conference (RPG 2014), Naples, FL, USA, 24–25 September 2014; pp. 1–6.
32. Roberts, M.B.; Bruce, A.; MacGill, I. Impact of shared battery energy storage systems on photovoltaic self-consumption and electricity bills in apartment buildings. *Appl. Energy* **2019**, *245*, 78–95. [CrossRef]
33. Simoiu, M.S.; Fagarasan, I.; Ploix, S.; Calofir, V. Modeling the energy community members' willingness to change their behaviour with multi-agent systems: A stochastic approach. *Renew. Energy* **2022**, *194*, 1233–1246. [CrossRef]
34. Jain, P.; Das, A.; Jain, T. Aggregated electric vehicle resource modelling for regulation services commitment in power grid. *Sustain. Cities Soc.* **2019**, *45*, 439–450. [CrossRef]
35. Frieden, D.; Tuerk, A.; Neumann, C.; D'Herbemont, S.; Roberts, J. *Collective Self-Consumption and Energy Communities: Trends and Challenges in the Transposition of the EU Framework*; ReScoop.eu: Brussels, Belgium, 2020. [CrossRef]
36. Soto, E.A.; Bosman, L.B.; Wollega, E.; Leon-Salas, W.D. Peer-to-peer energy trading: A review of the literature. *Appl. Energy* **2021**, *283*, 116268. [CrossRef]
37. Zheng, Y.; Wang, C.; Ju, P. Study on peak cutting and valley filling based on flexible load. In Proceedings of the 2020 5th Asia Conference on Power and Electrical Engineering (ACPEE), Chengdu, China, 4–7 June 2020; pp. 2188–2192.
38. Prajapati, V.K.; Mahajan, V. Reliability assessment and congestion management of power system with energy storage system and uncertain renewable resources. *Energy* **2021**, *215*, 119–134. [CrossRef]
39. Hu, J.; Saleem, A.; You, S.; Nordström, L.; Lind, M.; Ostergaard, J. A multi-agent system for distribution grid congestion management with electric vehicles. *Eng. Appl. Artif. Intell.* **2015**, *38*, 45–58. [CrossRef]
40. Background—Clean Energy Group. Available online: https://www.cleanegroup.org/ceg-projects/energy-storage/background/#toggle-id-1 (accessed on 14 October 2022).
41. Le Labo de L'economie Sociale et Solidaire Pour des Métropoles Low-Tech et Solidaires. For Low-Tech and Solidarity-Based Metropols. Available online: https://www.lelabo-ess.org/system/files/2022-02/2021%20EUCO%20eng_Low-tech_VF%20WEB.pdf (accessed on 27 February 2023).
42. Bhattacharyya, S.C. Energy access programmes and sustainable development: A critical review and analysis. *Energy Sustain. Dev.* **2012**, *16*, 260–271. [CrossRef]
43. Coignard, J.; Hodencq, S.; Twum-Duah, N.K.; Rigo-mariani, R. Solar panels—Is more always better? Assessing the carbon footprint of communities. *TATuP Z. Tech. Theor. Prax.* **2022**, *31*, 25–31.
44. Bihouix, P. La transition énergétique peut-elle être low-tech? *Rev. Int. Strat.* **2019**, *113*, 97. [CrossRef]
45. Bourban, M. Ethics, Energy Transition, and Ecological Citizenship Michel. In *Comprehensive Renewable Energy*; Letcher, T., Ed.; Elsevier: Amsterdam, The Netherlands, 2022; p. 31, ISBN 978/0/12/819727/1.
46. Wang, J.-J.; Jing, Y.-Y.; Zhang, C.-F.; Zhao, J.-H. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2263–2278. [CrossRef]

47. Wimmler, C.; Hejazi, G.; Fernandes, E.D.O.; Moreira, C.; Connors, S. Multi-Criteria Decision Support Methods for Renewable Energy Systems on Islands. *J. Clean Energy Technol.* **2015**, *3*, 185–195. [CrossRef]
48. Abdel-Basset, M.; Gamal, A.; Chakrabortty, R.K.; Ryan, M.J. Evaluation approach for sustainable renewable energy systems under uncertain environment: A case study. *Renew. Energy* **2021**, *168*, 1073–1095. [CrossRef]
49. Maxim, A. Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis. *Energy Policy* **2014**, *65*, 284–297. [CrossRef]
50. Birman, K.; Ganesh, L.; van Rennessee, R. Running Smart Grid Control Software on Cloud Computing Architectures. In Proceedings of the Computational Needs for the Next Generation Electric Grid, New York, NY, USA, 19–20 April 2011; pp. 1–33.
51. Shahid, M.S. Nudging Electricity Consumption in Households: A Case Study of French Residential Sector. Ph.D. Thesis, Université Grenoble Alpes, Grenoble, France, 2022.
52. Taibi, E.; Nikolakakis, T.; Gutierrez, L.; Fernandez, C.; Kiviluoma, J.; Rissanen, S.; Lindroos, T.J. *Power System Flexibility for the Energy Transition: Part 1, Overview for Policy Makers*; International Renewable Energy Agency IRENA: Abu Dhabi, United Arab Emirates, 2015; Volume 48.
53. Palensky, P.; Dietrich, D. Demand side management: Demand response, intelligent energy systems, and smart loads. *IEEE Trans. Ind. Inform.* **2011**, *7*, 381–388. [CrossRef]
54. Huber, M.; Dimkova, D.; Hamacher, T. Integration of wind and solar power in Europe: Assessment of flexibility requirements. *Energy* **2014**, *69*, 236–246. [CrossRef]
55. Heffron, R.; Körner, M.F.; Wagner, J.; Weibelzahl, M.; Fridgen, G. Industrial demand-side flexibility: A key element of a just energy transition and industrial development. *Appl. Energy* **2020**, *269*, 115026. [CrossRef]
56. Shivakumar, A.; Taliotis, C.; Deane, P.; Gottschling, J.; Pattupara, R.; Kannan, R.; Jakšić, D.; Stupin, K.; Hemert, R.V.; Normark, B.; et al. Need for Flexibility and Potential Solutions. In *Europe's Energy Transition*; Welsch, M., Pye, S., Keles, D., Faure-Schuyer, A., Dobbins, A., Shivakumar, A., Deane, P., Howells, M., Eds.; Academic Press: Cambridge, MA, USA, 2017; pp. 149–172, ISBN 978/0/12/809806/6.
57. Huertas-Hernando, D.; Farahmand, H.; Holttinen, H.; Kiviluoma, J.; Rinne, E.; Söder, L.; Milligan, M.; Ibanez, E.; Martinez, S.M.; Gómez-Lázaro, E.; et al. Hydropower Flexibility for Power Systems with Variable Renewable Energy Sources. In *Advances in Energy Systems*; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2019; pp. 385–405.
58. de Oliveira Silva, G.; Hendrick, P. Pumped hydro energy storage in buildings. *Appl. Energy* **2016**, *179*, 1242–1250. [CrossRef]
59. Manolakos, D.; Papadakis, G.; Papantonis, D.; Kyritsis, S. A stand-alone photovoltaic power system for remote villages using pumped water energy storage. *Energy* **2004**, *29*, 57–69. [CrossRef]
60. De Guilherme, O.E.S. Pumped storage—How small can you go? *Int. Water Power Dam Constr.* **2017**, *69*, 8–10.
61. Lorenczik, S.; Kim, S.; Wanner, B.; Bermudez Menendez, J.M.; Remme, U.; Hasegawa, T.; Keppler, J.H.; Mir, L.; Sousa, G.; Berthelemy, M.; et al. *Projected Costs of Generating Electricity 2020 Edition*; International Energy Agency: Paris, France, 2020.
62. Youdeowei, P.O.; Nwankwoala, H.O.; Desai, D.D. Dam structures and types in Nigeria: Sustainability and effectiveness. *Water Conserv. Manag.* **2019**, *3*, 20–26. [CrossRef]
63. Costea, G.; Pusch, M.T.; Bănăduc, D.; Cosmoiu, D.; Curtean-Bănăduc, A. A review of hydropower plants in Romania: Distribution, current knowledge, and their effects on fish in headwater streams. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111003. [CrossRef]
64. Soukhaphon, A.; Baird, I.G.; Hogan, Z.S. The Impacts of Hydropower Dams in the Mekong River Basin: A Review. *Water* **2021**, *13*, 265. [CrossRef]
65. de Almeida, A.T.; Moura, P.S.; Marques, A.S.; de Almeida, J.L. Multi-impact evaluation of new medium and large hydropower plants in Portugal centre region. *Renew. Sustain. Energy Rev.* **2005**, *9*, 149–167. [CrossRef]
66. Kraiczy, M.; Siegl, S.; Schütt, J.; Arnold, G.; Wende von Berg, S.; Mende, D.; Braun, M.; Bründlinger, R.; Heilscher, G.; Chen, S.; et al. PV as an ancillary service provider—Laboratory and field experiences from IEA PVPS countries. In Proceedings of the 11th Solar & Storage Power System Integration Workshop (SIW 2021), Hybrid Conference, Germany, 28 September 2021; Institution of Engineering and Technology (IET): Stevenage, UK; pp. 19–29.
67. Fang, X.; Tan, J.; Yuan, H.; Yin, S.; Wang, J. Providing Ancillary Services with Photovoltaic Generation in Multi-Timescale Grid Operation. In Proceedings of the 2020 52nd North American Power Symposium, NAPS 2020, Tempe, AZ, USA, 11–13 April 2021; Institute of Electrical and Electronics Engineers Inc.: Piscataway Township, NJ, USA, 2021.
68. Eriksson, R.; Modig, N.; Elkington, K. Synthetic inertia versus fast frequency response: A definition. *IET Renew. Power Gener.* **2018**, *12*, 507–514. [CrossRef]
69. Fernández-Bustamante, P.; Barambones, O.; Calvo, I.; Napole, C.; Derbeli, M. Provision of frequency response from wind farms: A review. *Energies* **2021**, *14*, 6689. [CrossRef]
70. Dreidy, M.; Mokhlis, H.; Mekhilef, S. Inertia response and frequency control techniques for renewable energy sources: A review. *Renew. Sustain. Energy Rev.* **2017**, *69*, 144–155. [CrossRef]
71. REN21. *Renewables 2022 Global Status Report*; REN21: Paris, France, 2022; ISBN 9783948393045.
72. Schittekatte, T.; Pototschnig, A. *Distributed Energy Resources and Electricity Balancing: Visions for Future Organization*; European University Institute: Fiesole, Italy, 2022. [CrossRef]
73. Ivan, K.; Brindley, G.; Fraile, D.; Ramirez, L. *2021 Statistics and the Outlook for 2022–2026*; Wind Energy in Europe; Wind Europe: Brussels, Belgium, 2022.

74. United Nations Economic Commission for Europe. *Carbon Neutrality in the UNECE Region: Integrated Life-Cycle Assessment of Electricity Sources*; United Nations Economic Commission for Europe: New York, NY, USA, 2021.
75. Morilhat, P.; Feutry, S.; Le Maitre, C.; Favennec, J.M.; Melaine, J.; Nuclear, F.; Plant, P. Nuclear Power Plant flexibility at EDF. *VGB PowerTech* **2019**, *99*, 32–41.
76. Cany, C.; Mansilla, C.; Mathonnière, G.; da Costa, P. Nuclear power supply: Going against the misconceptions. Evidence of nuclear flexibility from the French experience. *Energy* **2018**, *151*, 289–296. [CrossRef]
77. Nuclear Energy Agency (NEA) and International Energy Agency (IEA). *Projected Costs of Generating Electricity—2020 Edition*; OECD Publishing: Paris, France, 2020.
78. Lazard Lazard's Levelized Cost of Energy Analysis—Version 15.0 2021. Available online: https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/ (accessed on 7 February 2023).
79. Schneider, M.; Froggatt, A. *The World Nuclear Industry Status Report 2022*; World Scientific: Singapore, 2022; p. 385. [CrossRef]
80. Sartori, I.; Napolitano, A.; Voss, K. Net zero energy buildings: A consistent definition framework. *Energy Build.* **2012**, *48*, 220–232. [CrossRef]
81. Hondo, H. Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy* **2005**, *30*, 2042–2056. [CrossRef]
82. UNECE. *Life Cycle Assessment of Electricity Generation Options*; United Nations Economic Commission for Europe: Geneva, Switzerland, 2021; p. 107.
83. Akahane, K.; Yonai, S.; Fukuda, S.; Miyahara, N.; Yasuda, H.; Iwaoka, K.; Matsumoto, M.; Fukumura, A.; Akashi, M. The Fukushima Nuclear Power Plant accident and exposures in the environment. *Environmentalist* **2012**, *32*, 136–143. [CrossRef]
84. Jensen, S.Ø.; Henrik, M.; Lopes, R.; Junker, R.G.; Aelenei, D.; Li, R.; Metzger, S.; Lindberg, K.B.; Marszal, A.J.; Kummert, M.; et al. Annex 67: Energy Flexible Buildings—Energy Flexibility as a Key Asset in a Smart Building Future—Contribution of Annex 67 to the European Smart Building Initiatives. 2017. Available online: https://annex67.org/media/1470/position-paper-energy-flexibility-as-a-key-asset-i-a-smart-building-future.pdf (accessed on 27 February 2023).
85. Ehrhardt-Martinez, K.; Donnelly, K.A.; Laitner, J.A. *Advanced Metering Initiatives and Residential Feedback Programs: A Meta-Review for Household Electricity-Saving Opportunities*; American Council for an Energy-Efficient Economy: Washington, DC, USA, 2010.
86. Tahersima, F.; Madsen, P.P.; Andersen, P. An intuitive definition of demand flexibility in direct load control. In Proceedings of the IEEE International Conference on Control Applications, Hyderabad, India, 28–30 August 2013; pp. 521–526.
87. Energy Pool Home. Available online: https://www.energy-pool.eu/en/ (accessed on 10 November 2022).
88. Eid, C.; Codani, P.; Chen, Y.; Perez, Y.; Hakvoort, R. Aggregation of demand side flexibility in a smart grid: A review for European market design. In Proceedings of the International Conference on the European Energy Market, EEM, Lisbon, Portugal, 19–22 May 2015; Volume 2015, pp. 1–5.
89. Energy Pool. Unlocking energy market flexibility and demand side response. In Proceedings of the CEER 2015 Annual Conference, Brussels, Belgium, 29 January 2015; pp. 1–12.
90. Voltalis. La Solution d'Economies d'Energie Gratuite. Available online: https://www.voltalis.com/ (accessed on 10 November 2022).
91. ADEME. *Climat, Air et Energie*; ADEME: Angers, France, 2018.
92. Haque, A.N.M.M.; Nijhuis, M.; Ye, G.; Nguyen, P.H.; Bliek, F.W.; Slootweg, J.G. Integrating Direct and Indirect Load Control for Congestion Management in LV Networks. *IEEE Trans. Smart Grid* **2019**, *10*, 741–751. [CrossRef]
93. Wang, Y.; Huang, D.; Liu, J.; Zhang, Y.; Zeng, L. Alternative Environmentally Friendly Insulating Gases for SF6. *Processes* **2019**, *7*, 216. [CrossRef]
94. Hyrenbach, M.; Zache, S. Alternative insulation gas for medium-voltage switchgear. In Proceedings of the Petroleum and Chemical Industry Conference Europe Conference Proceedings, PCIC Europe, Berlin, Germany, 14–16 June 2016; Volume 2016.
95. Forouli, A.; Bakirtzis, E.A.; Papazoglou, G.; Oureilidis, K.; Gkountis, V.; Candido, L.; Ferrer, E.D.; Biskas, P. Assessment of Demand Side Flexibility in European Electricity Markets: A Country Level Review. *Energies* **2021**, *14*, 2324. [CrossRef]
96. Albadi, M.H.; El-Saadany, E.F. Demand response in electricity markets: An overview. In Proceedings of the 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 24–28 June 2007. [CrossRef]
97. Bivas, P. La production d'effacement: Comment offrir des économies d'électricité à des millions de foyers. *J. Ecole Paris Manag.* **2011**, *90*, 8–14. [CrossRef]
98. Sioshansi, R. Evaluating the impacts of real-time pricing on the cost and value of wind generation. *IEEE Trans. Power Syst.* **2010**, *25*, 741–748. [CrossRef]
99. Faria, P.; Vale, Z. Demand response in electrical energy supply: An optimal real time pricing approach. *Energy* **2011**, *36*, 5374–5384. [CrossRef]
100. Mohajeryami, S.; Schwarz, P.; Baboli, P.T. Including the behavioral aspects of customers in demand response model: Real time pricing versus peak time rebate. In Proceedings of the 2015 North American Power Symposium, NAPS 2015, Charlotte, NC, USA, 4–6 October 2015; Institute of Electrical and Electronics Engineers Inc.: Charlotte, NC, USA, 2015.
101. de Bartolome, C.A.M. Which tax rate do people use: Average or marginal? *J. Public Econ.* **1995**, *56*, 79–96. [CrossRef]
102. Ito, K.; Anderson, M.; Auffhammer, M.; Berck, P.; Borenstein, S.; Bushnell, J.; Chong, H.; Courty, P.; Davis, L.; Faruqui, A.; et al. Do Consumers Respond to Marginal or Average Price? Evidence from Nonlinear Electricity Pricing. *Am. Econ. Rev.* **2014**, *104*, 537–563. [CrossRef]

103. Kiddee, P.; Naidu, R.; Wong, M.H. Electronic waste management approaches: An overview. *Waste Manag.* **2013**, *33*, 1237–1250. [CrossRef]
104. Shahid, M.S.; Delinchant, B.; Roussillon, B.; Frederic, W.; Llerena, D.; Fadhuile, A.; Artiges, N. Designing and experimenting nudge signals to act on the energy signature of households for implementing indirect energy flexibility. In Proceedings of the Building Simulation 2021, Bruges, Belgium, 1–3 September 2021; International Building Performance Simulation Association: Verona, WI, USA, 2021.
105. Wurtz, F.; Delinchant, B. "Smart buildings" integrated in "smart grids": A key challenge for the energy transition by using physical models and optimization with a "human-in-the-loop" approach. *C. R. Phys.* **2017**, *18*, 428–444. [CrossRef]
106. Allcott, H. Social norms and energy conservation. *J. Public Econ.* **2011**, *95*, 1082–1095. [CrossRef]
107. Henry, M.L.; Ferraro, P.J.; Kontoleon, A. The behavioural effect of electronic home energy reports: Evidence from a randomised field trial in the United States. *Energy Policy* **2019**, *132*, 1256–1261. [CrossRef]
108. Jachimowicz, J.M.; Hauser, O.P.; O'Brien, J.D.; Sherman, E.; Galinsky, A.D. The critical role of second-order normative beliefs in predicting energy conservation. *Nat. Hum. Behav.* **2018**, *2*, 757–764. [CrossRef]
109. Jorgensen, B.S.; Fumei, S.; Byrne, G. Reducing Peak Energy Demand among Residents Who Are Not Billed for Their Electricity Consumption: Experimental Evaluation of Behaviour Change Interventions in a University Setting. *Int. J. Environ. Res. Public Health* **2021**, *18*, 8460. [CrossRef] [PubMed]
110. Percebois, J. Le numérique au service de la modernisation des réseaux d'électricité. *Enjeux Numér.* **2021**, *15*, 6–11.
111. Facts & Figures—Energy Storage Association. Available online: https://energystorage.org/facts-figures/ (accessed on 15 October 2022).
112. Rodriguez, G.D. A utility perspective of the role of energy storage in the smart grid. In Proceedings of the IEEE PES General Meeting, PES 2010, Minneapolis, MN, USA, 25–29 July 2010; pp. 4–5.
113. Hannan, M.A.; Wali, S.B.; Ker, P.J.; Rahman, M.S.A.; Mansor, M.; Ramachandaramurthy, V.K.; Muttaqi, K.M.; Mahlia, T.M.I.; Dong, Z.Y. Battery energy-storage system: A review of technologies, optimization objectives, constraints, approaches, and outstanding issues. *J. Energy Storage* **2021**, *42*, 103023. [CrossRef]
114. Yang, Y.; Han, Y.; Jiang, W.; Zhang, Y.; Xu, Y.; Ahmed, A.M. Application of the supercapacitor for energy storage in China: Role and strategy. *Appl. Sci.* **2022**, *12*, 354. [CrossRef]
115. Zhou, X.; Lu, B.; Ma, Y. Superconducting magnetic energy storage. *IEEE Power Eng. Rev.* **2000**, *5*, 16–20. [CrossRef]
116. Koohi-Fayegh, S.; Rosen, M.A. A review of energy storage types, applications and recent developments. *J. Energy Storage* **2020**, *27*, 101047. [CrossRef]
117. Mousavi G, S.M.; Faraji, F.; Majazi, A.; Al-Haddad, K. A comprehensive review of Flywheel Energy Storage System technology. *Renew. Sustain. Energy Rev.* **2017**, *67*, 477–490. [CrossRef]
118. Budt, M.; Wolf, D.; Span, R.; Yan, J. A review on compressed air energy storage: Basic principles, past milestones and recent developments. *Appl. Energy* **2016**, *170*, 250–268. [CrossRef]
119. Blakers, A.; Stocks, M.; Lu, B.; Cheng, C. A review of pumped hydro energy storage. *Prog. Energy* **2020**, *3*, 022003. [CrossRef]
120. Nguyen, T.-T.; Martin, V.; Malmquist, A.; Silva, C.A.S. A review on technology maturity of small scale energy storage technologies. *Renew. Energy Environ. Sustain.* **2017**, *2*, 36. [CrossRef]
121. Chen, T.; Jin, Y.; Lv, H.; Yang, A.; Liu, M.; Chen, B.; Xie, Y.; Chen, Q. Applications of Lithium-Ion Batteries in Grid-Scale Energy Storage Systems. *Trans. Tianjin Univ.* **2020**, *26*, 208–217. [CrossRef]
122. Martinez-laserna, E.; Gandiaga, I.; Sarasketa-zabala, E.; Badeda, J.; Stroe, D. Battery second life: Hype, hope or reality? A critical review of the state of the art. *Renew. Sustain. Energy Rev.* **2018**, *93*, 701–718. [CrossRef]
123. Skarvelis-Kazakos, S.; Daniel, S.; Buckley, S. Distributed energy storage using second-life electric vehicle batteries. In Proceedings of the IET Conference on Power in Unity: A Whole System Approach, London, UK, 16–17 October 2013; pp. 1–6.
124. Idjis, H.; da Costa, P. Is electric vehicles battery recovery a source of cost or profit? In *The Automobile Revolution*; Springer: Cham, Switzerland, 2016; pp. 117–134. [CrossRef]
125. Bowler, M. Battery Second Use: A Framework for Evaluating the Combination of Two Value Chains. Ph.D. Thesis, Clemson University, Clemson, SC, USA, 2014.
126. A Second Life for Batteries: From Energy Usage to Industrial Storage—Renault Group. Available online: https://www.renaultgroup.com/en/news-on-air/news/a-second-life-for-batteries-from-energy-usage-to-industrial-storage/ (accessed on 20 September 2022).
127. xStorage by Nissan—Clean Power Energy. Nissan. Available online: https://www.nissan.ie/experience-nissan/electric-vehicle-leadership/xstorage-by-nissan.html (accessed on 20 September 2022).
128. Garcia, J. Jehu Garcia Diy University. Available online: https://jag35.com/blogs/jehu-garcia-battery-university/ (accessed on 21 September 2022).
129. Garcia, J. Jehugarcia—YouTube. Available online: https://www.youtube.com/user/jehugarcia (accessed on 21 September 2022).
130. Waldmann, T.; Soc, J.E.; Waldmann, T.; Quinn, J.B.; Richter, K.; Kasper, M.; Tost, A.; Klein, A.; Wohlfahrt-mehrens, M. Electrochemical, Post-Mortem, and ARC Analysis of Li-Ion Cell Safety in Second-Life Applications Safety in Second-Life Applications. *J. Electrochem. Soc.* **2017**, *164*, 13. [CrossRef]
131. Liu, J.; Duan, Q.; Ma, M.; Zhao, C.; Sun, J.; Wang, Q. Aging mechanisms and thermal stability of aged commercial 18,650 lithium ion battery induced by slight overcharging cycling. *J. Power Sources* **2020**, *445*, 227263. [CrossRef]

132. Hossain, E.; Murtaugh, D.; Mody, J.; Faruque, H.M.R.; Sunny, M.S.H.; Mohammad, N. A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers Potential Solutions, Business Strategies, and Policies. *IEEE Access* **2019**, *7*, 73215–73252. [CrossRef]
133. Setlhaolo, D.; Xia, X. Optimal scheduling of household appliances with a battery storage system and coordination. *Energy Build.* **2015**, *94*, 61–70. [CrossRef]
134. Sun, S.; Dong, M.; Liang, B. Real-time power balancing in electric grids with distributed storage. *IEEE J. Sel. Top. Signal Process.* **2014**, *8*, 1167–1181. [CrossRef]
135. Luo, W.; Stynski, S.; Chub, A.; Franquelo, L.G.; Malinowski, M.; Vinnikov, D. Utility-Scale Energy Storage Systems: A Comprehensive Review of Their Applications, Challenges, and Future Directions. *IEEE Ind. Electron. Mag.* **2021**, *15*, 17–27. [CrossRef]
136. Vignesh, R.; Feldman, D.; Desai, J.; Margolis, R.U.S. *Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2021*; Technical Report NREL/TP-7A40-80694; National Renewable Energy Laboratory: Sacramento, CA, USA, 2021.
137. Wu, W.; Lin, B.; Xie, C.; Elliott, R.J.R.; Radcliffe, J. Does energy storage provide a profitable second life for electric vehicle batteries? *Energy Econ.* **2020**, *92*, 105010. [CrossRef]
138. Gutsch, M.; Leker, J. Global warming potential of lithium-ion battery energy storage systems: A review. *J. Energy Storage* **2022**, *52*, 105030. [CrossRef]
139. Kang, D.H.P.; Chen, M.; Ogunseitan, O.A. Potential environmental and human health impacts of rechargeable lithium batteries in electronic waste. *Environ. Sci. Technol.* **2013**, *47*, 5495–5503. [CrossRef]
140. Casals, L.C.; Amante García, B.; Canal, C. Second life batteries lifespan: Rest of useful life and environmental analysis. *J. Environ. Manag.* **2019**, *232*, 354–363. [CrossRef] [PubMed]
141. Gay, F.W. Means for Storing Fluids for Power Generation. U.S. Patent US2433896A, 6 January 1948.
142. Pickard, W.F.; Hansing, N.J.; Shen, A.Q. Can large-scale advanced-adiabatic compressed air energy storage be justified economically in an age of sustainable energy? *J. Renew. Sustain. Energy* **2014**, *1*, 033102. [CrossRef]
143. Wang, J.; Lu, K.; Ma, L.; Wang, J.; Dooner, M.; Miao, S.; Li, J.; Wang, D. Overview of compressed air energy storage and technology development. *Energies* **2017**, *10*, 991. [CrossRef]
144. Villela, D.; Kasinathan, V.V.; De Valle, S.; Alvarez, M.; Frantziskonis, G.; Deymier, P.; Muralidharan, K. Compressed-air energy storage systems for stand-alone off-grid photovoltaic modules. In Proceedings of the 2010 35th IEEE Photovoltaic Specialists Conference, Honolulu, HI, USA, 20–25 June 2010; pp. 962–967.
145. Maisonnave, O.; Bernard, N.; Moreau, L.; Aubree, R.; Benkhoris, M.F.; Neu, T. Optimal design of a converter-machine system on a load profile applied to a caes system. *IEEE Trans. Energy Convers.* **2019**, *34*, 1839–1847. [CrossRef]
146. Alami, A.H.; Aokal, K.; Abed, J.; Alhemyari, M. Low pressure, modular compressed air energy storage (CAES) system for wind energy storage applications. *Renew. Energy* **2017**, *106*, 201–211. [CrossRef]
147. REMORA. Segula Technologies. Available online: https://www.segulatechnologies.com/en/innovation_project/remora/ (accessed on 24 October 2022).
148. Remora, the Innovative Storage System for Offshore Wind Energy—SeaTitan. Available online: https://seatitan.eu/remora-the-innovative-storage-system-for-offshore-wind-energy/ (accessed on 24 October 2022).
149. Barnhart, C.J.; Benson, S.M. On the importance of reducing the energetic and material demands of electrical energy storage. *Energy Environ. Sci.* **2013**, *6*, 1083–1092. [CrossRef]
150. Electric Power Research Institute (EPRI). *Wind Power Integration Technology Assessment and Case Studies*; Electric Power Research Institute (EPRI): Washington, DC, USA, 2004.
151. Fertig, E.; Apt, J. Economics of compressed air energy storage to integrate wind power: A case study in ERCOT. *Energy Policy* **2011**, *39*, 2330–2342. [CrossRef]
152. Electric Power Research Institute. *Compressed Air Energy Storage System Cost Analysis*; Electric Power Research Institute, Palo Alto: Santa Clara, CA, USA, 2008.
153. Viswanathan, V.; Mongird, K.; Franks, R.; Li, X.; Sprenkle, V.; Baxter, R. *Grid Energy Storage Technology Cost and Performance Assessment*; Technical Report Publication, No. DOE/PA-0204; U.S. Department of Energy: Washington, DC, USA, 2020.
154. Kapila, S.; Oni, A.O.; Gemechu, E.D.; Kumar, A. Development of net energy ratios and life cycle greenhouse gas emissions of large-scale mechanical energy storage systems. *Energy* **2019**, *170*, 592–603. [CrossRef]
155. AlShafi, M.; Bicer, Y. Life cycle assessment of compressed air, vanadium redox flow battery, and molten salt systems for renewable energy storage. *Energy Rep.* **2021**, *7*, 7090–7105. [CrossRef]