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# Semi-Systematic Literature Review on the Contribution of Hydrogen to Universal Access to Energy in the Rationale of Sustainable Development Goal Target 7.1

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**Abstract:** As part of the United Nations' (UN) Sustainable Development Goal 7 (SDG7), SDG target 7.1 recognizes universal electrification and the provision of clean cooking fuel as two fundamental challenges for global society. Faltering progress toward SDG target 7.1 calls for innovative technologies to stimulate advancements. Hydrogen has been proposed as a versatile energy carrier to be applied in both pillars of SDG target 7.1: electrification and clean cooking. This paper conducts a semi-systematic literature review to provide the status quo of research on the application of hydrogen in the rationale of SDG 7.1, covering the technical integration pathways, as well as the key economic, environmental, and social aspects of its use. We identify decisive factors for the future development of hydrogen use in the rationale of SDG target 7.1 and, by complementing our analysis with insights from the related literature, propose future avenues of research. The literature on electrification proposes that hydrogen can serve as a backup power supply in rural off-grid communities. While common electrification efforts aim to supply appliances that use lower amounts of electricity, a hydrogen-based power supply can satisfy appliances with higher power demands including electric cook stoves, while simultaneously supporting clean cooking efforts. Alternatively, with the exclusive aim of stimulating clean cooking, hydrogen is proposed to be used as a clean cooking fuel via direct combustion in distribution and utilization infrastructures analogous to Liquid Petroleum Gas (LPG). While expected economic and technical developments are seen as likely to render hydrogen technologies economically competitive with conventional fossil fuels in the future, the potential of renewably produced hydrogen usage to reduce climate-change impacts and point-of-use emissions is already evident today. Social benefits are likely when meeting essential safety standards, as a hydrogen-based power supply offers service on a high tier that might overachieve SDG 7.1 ambitions, while hydrogen cooking via combustion fits into the existing social habits of LPG users. However, the literature lacks clear evidence on the social impact of hydrogen usage. Impact assessments of demonstration projects are required to fill this research gap.

**Keywords:** Sustainable Development Goal 7; electrification; clean cooking; hydrogen; semi-systematic review

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**Citation:** Schöne, N.; Heinz, B. Semi-Systematic Literature Review on the Contribution of Hydrogen to Universal Access to Energy in the Rationale of Sustainable Development Goal Target 7.1. *Energies* **2023**, *16*, 1658. https://doi.org/10.3390/en16041658

Academic Editor: Muhammad Aziz

Received: 12 January 2023
Revised: 31 January 2023
Accepted: 2 February 2023
Published: 7 February 2023



## 1. Introduction

### 1.1. Framework and Concept

The United Nation's (UN) Sustainable Development Goals (SDGs) provide clear guidance to global society on pressing challenges for sustainable development until 2030. Energy is recognized as one distinct challenge in SDG 7. However, SDG 7 is mutually interlinked with many other SDGs and is a crucial factor to success in other dimensions of development [1]. In fact, the rudimentary access to energy is indispensable for any kind of human development, including economic and social development [2]. Accordingly, the very first and fundamental target of SDG 7, called SDG 7.1, is to ensure universal access to affordable, reliable, and modern energy services for everyone [3]. To define the goal of "energy," two dedicated indicators are introduced to measure progress within the target. SDG indicator 7.1.1 (SDG 7.1.1) determines the proportion of the population (%) with a minimum access to electricity of 100 kWh per year on a household level [4]. The complementary indicator SDG indicator 7.1.2 (SDG 7.1.2) assesses the proportion of the population (%) that primarily relies on clean fuels and technology for cooking, heating, and lighting [5]. By referencing a minimum amount of energy, these indicators set the lowest standard that must be met by the end of the SDG period in 2030.

However, in 2022, the required pace of the annual progression in electrification and provision with clean cooking fuels in order to achieve the SDG 7.1 target of universal access to energy by 2030 has not been met. In 2020, 733 million people lacked access to electricity [6]. The pace of annual growth toward access eventually slowed down from 0.8 percentage points in 2010–2018 to 0.5 percentage points in 2018–2020. This faltering progress is mainly explained by the complexity of reaching the remaining unserved populations, who are mostly located in rural regions, and the potential impacts of COVID-19 [6]. In parallel, recent improvements in universal access to clean cooking have been outpaced by population growth, particularly in sub-Saharan Africa (SSA). On a global scale, 2.5 billion people lacked access to clean cooking in 2022 [7]. In many regions, this progress has stagnated for years.

In the face of these significant challenges in the time remaining to achieve the SDGs, new and disruptive technologies could provide the impetus needed to overcome these hurdles [8]. Hydrogen-based technologies are one example of innovative technologies that have recently polarized the discussion [9]. Hydrogen is a multi-usable energy carrier with various proven possible applications. Hydrogen in its pure form is used as a substance in industrial production processes, for instance as a chemical reduction agent in steel and other metal industries [10], or as a base substance for fertilizer production [9,11]. However, in energy applications, hydrogen is proposed to be applied in power supply, heating, and mobility [9], of which the first two apply to the challenges of SDG 7.1 [12].

As a concept, the process of enabling a power supply based on hydrogen is called power-to-hydrogen-to-power (P2H2P). In P2H2P electricity, which, to meet global climate change mitigation targets must necessarily generated by renewable electricity, is used to split water in its components hydrogen and oxygen. This concept—called water electrolysis—has been known for over a century [11]. Several electrolyzer (EL) technologies have been developed to a commercial scale. Table 1 summarizes the main characteristics of the most prominent electrolyzer technologies, including alkaline electrolysis (AEL), anion exchange membrane electrolysis (AEMEL), polymer membrane electrolysis (PEMEL), and solid-oxide electrolysis (SOEL). A comprehensive review of recent advances in water electrolysis is given in [13].

**Table 1.** Technical characteristics and selected parameters of AEL, AEMEL, PEMEL, and SOEL technology according to the recent literature [13]. If not specifically indicated, the values indicate representative values in line with [13].

| Parameter | Unit | AEL | AEMEL | PEMEL | SOEL |
|---|---|---|---|---|---|
| Electrolyte | / | 10–30% KOH | Quaternary ammonia polysulfide or dilute caustic solution [14] | Perfluoro sulfonic acid | Ionic conductor consisting of $ZrO_2$ doped with 8 mol % $Y_2O_3$ [14] |
| Anode reaction [13] | / | $2OH^- \rightarrow \frac{1}{2} O_2 + H_2O + 2e^-$ | $4OH^- \rightarrow 2H_2O + O_2 + 4e^-$ | $H_2O \rightarrow \frac{1}{2} O_2 + 2H^+ + 2e^-$ | $H_2O + 2e^- \rightarrow H_2 + O^{2-}$ |
| Cathode reaction [13] | / | $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ | $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$ | $2H^+ + 2e^- \rightarrow H_2$ | $O^{2-} \rightarrow \frac{1}{2} O_2 + 2e^-$ |
| Operating temperature | °C | 70–90 | 40–60 | 50–80 | 700–900 |
| Operating pressure | bar | <30 | <35 | <70 | <10 |
| Catalyst material [15] | / | Ni-coated perforated stainless steel | High surface area nickel or NiFeCo alloys | Platinum groups/Iridium oxide | Perovskite-type/Ni/YSZ |
| Efficiency [1] (System, LHV) | % | 51–60 | 70–75 | 46–60 | 76–81 |

**Table 1.** *Cont.*

| Parameter | Unit | AEL | AEMEL | PEMEL | SOEL |
|---|---|---|---|---|---|
| Start-up time (cold [2]/warm) | / | 1–2 h<br>1–5 min | <20 min<br><<20 min | 5–10 min<br><10 s | Hours<br>15 min |
| Minimum part load | % | 20 | 5 | 0–5 | / |
| CAPEX | USD/kW | 500–1000 | / | 700–1400 | <2000 |

[1] Notably, system efficiency of PEMEL is known to be a non-linear function of the power input. Included values may refer to the efficiency reference power depending on the source consulted. [2] Defined below 50 °C temperature.

Produced hydrogen can be stored in many ways, including liquefied hydrogen, cryogenic hydrogen, hydrogen bound in metal hydrides, and hydrogen in gaseous form [16]. Compressed gaseous hydrogen storage is the most popular storage form today because of low processing requirements and costs [16]. In gaseous form, stored hydrogen can be re-electrified by a fuel cell (FC) in the opposite reaction to water electrolysis. Table 2 provides an overview of selected parameters of commercially available FC technologies. Akinyele et al. summarize the status quo of FCs and describe the system integration in complex energy systems for remote power systems [17]. Arsalis et al. present a recent update on the integration of regenerative FCs in microgrid systems [18].

**Table 2.** Technical characteristics and selected parameters of AFC, PAFC, PEMFC, and SOFC technology according to the recent literature [9,17,19]. Abbreviations: AFC = alkaline fuel cell; PAFC = phosphoric acid fuel cell; PEMFC = polymer electrolyte membrane fuel cell; SOFC = solid oxide fuel cell. If not specifically indicated, the values indicate representative values in line with [9,17,19].

| Parameter | Unit | AFC | PAFC | PEMFC | SOFC |
|---|---|---|---|---|---|
| Electrolyte [18] | / | 10–30% KOH solution in a matrix | Liquid phosphoric acid soaked in a matrix | Solid organic polymer Perfluoro sulfonic acid | Yttria stabilized zirconia |
| Anode reaction [16] | / | $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ | $H_2 \rightarrow 2H^+ + 2e-$ | $H_2 \rightarrow 2H^+ + 2e^-$ | $H_2 + O_2{}^- \rightarrow H_2O + 2e^-$ |
| Cathode reaction [16] | / | $0.5O_2 + H_2O + 2e^- \rightarrow 2OH^-$ | $0.5O_2 + 2H^+ + 2e^- \rightarrow H_2O$ | $0.5O_2 + 2H^+ + 2e^- \rightarrow H_2O$ | $0.5O_2 + 2e^- \rightarrow O_2{}^-$ |
| Operating temperature | °C | 60–120 | 150–220 | 50–100 | 800–1,000 |
| Efficiency (System, LHV) | % | 45–60 | 40–55 | 45–65 | 35–40 |
| CAPEX | USD/kW | 700–1800 | 4000–5000 | 1400–4000 | 1500–8000 |

P2H2P has been established in the power sector for different purposes. These include flexible power generation, long-term and large-scale energy storage, uninterrupted power supply schemes, as well as backup and off-grid power supplies [20]. In the latter application, P2H2P poses an alternative to predominantly diesel-based electricity supplies in off-grid areas. Historically, P2H2P in such settings was used to supply backup power to critical infrastructure, especially mobile telecommunication stations. In such crucial and sensitive-to-black-out infrastructure, the high costs of P2H2P are justifiable by the high reliability of the power supply and the long-term storability of hydrogen [21]. However, with declining costs, residential applications are becoming increasingly relevant for P2H2P. Pilot projects of the last decades have proven P2H2P's ability to serve power to residential and village loads in Norway, Japan, Sweden, Germany, Switzerland, the USA, and the UK [21]. Reflecting on the success of such projects, researchers have proposed P2H2P use for domestic electrification in countries with low electrification rates as well [12].

More recently, the utilization of hydrogen in residential applications for heating and cooking purposes has been suggested [20]. While the use of waste-heat released by FCs might serve for low-temperature heating, a substitution of natural gas and methane and direct combustion of hydrogen is discussed for heating and cooking purposes [20]. Especially in Europe and Japan, countries that rely on imports of fossil fuels for residential heating, the replacement of natural gas with hydrogen is proposed and investigated. While in such settings a well-developed infrastructure, i.e., central import hubs, pipelines, and standardized equipment, exists, valid arguments speak in favor of a transfer of the discussion to less-developed settings. The possible analogy to draw to the replacement of natural gas in well-developed infrastructures is the replacement of liquid petroleum gas (LPG) in less-developed infrastructures; LPG is already established and foreseen to become even more widely used as a cooking fuel in countries lagging behind in access to clean cooking. Reflecting on the much lower emissions of pollutants during combustion compared to conventional fuels, along with recent success stories of LPG, many African governments are promoting LPG as a clean cooking fuel for the next decade [6]. However, as LPG is still an exhaustible and fossil fuel, it is only seen as a transitional fuel to use until a renewable alternative is available [22]. Since hydrogen has very similar physical and chemical properties to LPG, it seems logical to discuss hydrogen produced from renewable energies as a future substitute for LPG.

### *1.2. Previous Literature*

Reflecting on the properties and potential utilization, the application of hydrogen in energy services in the rationale of SDG 7.1 was proposed in the previous literature. AbouSeada and Hatem [23] review the prospects of green hydrogen-production potential and usage in Africa. The authors present a status quo of initiatives, technologies, and policies. However, the authors focus on large-scale applications, i.e., in the chemical industry and the steel and iron industry. The applications of hydrogen in off-grid electrification and on-grid use for stabilization of instable power grids are proposed vaguely [12]. Mukelabai et al. reflect on how and what role hydrogen can play in the African energy landscape. The authors essentially point to exporting green hydrogen (that is, produced from renewable energy) to propel Africa´s economy, and the use of hydrogen to produce fertilizer at a large scale to meet the food demands of Africa´s fast-growing population. Grid-load balancing is proposed as an application in the power sector, while the potential use as a clean cooking fuel is seen to require the development of business, social, and techno-economic models [24]. The authors follow their previous research and conduct a political, economic, social, legal, and environmental (PESTLE) analysis to evaluate the deciding factors in the adoption of hydrogen in Africa. One critical factor to consider would be the electrification of the population without access to electricity, which should be a priority before producing hydrogen for export. Further, the authors point to the tremendous air pollution caused by and harm to the health of users who rely on traditional fuels for cooking. Therefore, the authors call hydrogen technology developers to consider the purpose of clean cooking. Interestingly, the authors find countries with a lack of clean access to electricity and cooking to be in a better position to attract hydrogen technology developers than better situated countries. This statement is justified in referring to the common thought of the hydrogen economy being an egg and chicken problem; thus, satisfying local market needs first might be a strong foundation to further expand the hydrogen technology market in a country [25]. While the aforementioned papers only broadly propose hydrogen for electrification and clean cooking purposes in Africa but do not provide details as to its application, Maestre et al. implicitly showcase examples of how a hydrogen-based power supply could improve electrification efforts in a review of stationary applications of renewable hydrogen-based power systems [13]. The extensive review includes a comprehensive overview and comparison of techno-economic analysis of off-grid power supply systems, comparing key technical and economic figures. However, including a wide geographic scope, the paper does not specifically address challenges occurring in the SDG 7.1 rationale. Further, the paper does not include the application of hydrogen for clean cooking purposes.

### *1.3. Ambition and Contribution to Research*

The review of the previous literature shows an absence of an organized analysis and concise presentation of how hydrogen may be applied in the rationale of SDG 7.1. This paper aims to close this gap by detecting relevant research contributions on hydrogen applications for electrification and clean cooking purposes. Guided by the principles of a semi-systematic literature review, this paper presents evidence from previous research and identifies applied methodologies, research foci, and proposed energy-system architectures. Relevant publications are synthetized and discussed to identify their relevance for future work. We supplement identified topics with context-related discussions from state-of-the-art literature. The specific research questions of this paper are:

- What are the predominantly proposed technical integration pathways of hydrogen for electrification and clean cooking and respective energy-system topologies?
- What are the current challenges impairing studies on the use of hydrogen in electrification or clean cooking?
- What are potential chances for the market entry of hydrogen in the Global South?
- What are the lessons learned and the way forward for studies of hydrogen application in contributing to SDG 7.1?
- Which research methods have been used in the field, and did they change over time?

The findings of this review will be useful to researchers, policymakers and regulators, NGOs, international organizations, and many other stakeholders involved in SDG 7.1. We propose a research agenda to accelerate and streamline future work in the field.

The outline of this paper reads as follows: Section 2 describes the methodology applied during our review. Section 3 presents quantitative results of a meta-analysis, before qualitatively analyzing and discussing significant contributions in technical, economic, environmental, and social aspects. We discuss the findings in Section 4.

## 2. Materials and Methods

Figure 1 illustrates the workflow applied in our paper. To guide our analysis, we adopt the principles of a semi-systematic literature review. The semi-systemic literature review is a proven concept to apply when aiming to share an overview of a thematic area, while including both quantitative and qualitative research articles [26]. The concept is useful when being confronted with heterogenous studies that are differentially conceptualized and developed by various groups of researchers within diverse disciplines, and a full systematic review process is not foreseen [27]. It differs from a systematic review, which aims to identify empirical evidence that reflects specified inclusion criteria to answer a specific research question—often but not always using a statistical meta-analysis to identify patterns that appear in different studies on the same topic [27]. While, in order to assess the quality of findings from different studies, qualitative systematic reviews have been developed [28], semi-systematic reviews are useful to capture all potentially relevant research traditions that have implications for the studied topic and to synthesize these using meta-narratives instead of by measuring effect size [26]. Semi-systematic reviews include research articles with more broad research questions as well, which are useful in identifying themes in the literature and developing a research agenda [27]. To define a transparent and replicable review, we apply the Search, Appraisal, Synthesis, and Analysis (SASA) methodology, which guides and gives protocols for the review. The SASA methodology guarantees methodological accuracy, systematization, exhaustiveness, and reproducibility [27]. To further improve the quality of our work, we lean on the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) evidence-based minimum set of items for reporting in systematic reviews and meta-analyses [29]. A flowchart summarizing the PRISMA key figures of our search is included in the Appendix A (Figure A1). In the following, we will describe the most important decisions made for each working step of SASA.

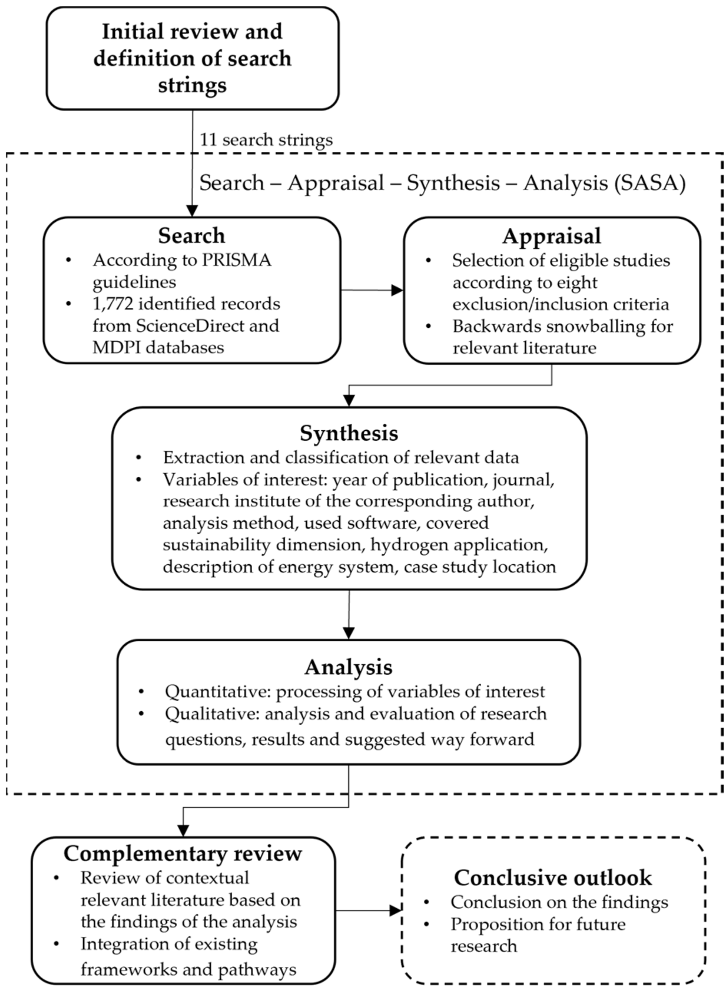



**Figure 1.** Workflow applied in the present paper, including Search–Appraisal–Synthesis–Analysis approach.

### 2.1. Search

To initialize the search for relevant papers in a structured manner, we screened two internationally recognized databases according to predefined search strings. The selected databases were the ScienceDirect [30] and the Multidisciplinary Digital Publishing Institute (MDPI) databases (https://www.mdpi.com). ScienceDirect is an online collection of published scientific research operated by the publisher Elsevier, and it is an online academic citation index at the same time. The MDPI database is a collection of 290 diverse, peer-reviewed, open-access journals operated by MDPI. We screened a wide body of related work to establish a set of search strings to be applied to the automatic filter in each of the databases. The search strings consisted of the word "hydrogen" and the keywords "Sustainable Development Goal 7," "Global South," "developing countries," "electrification," "clean cooking." "cooking," "off-grid," "off grid," "mini-grid," "minigrid," and "rural." In ScienceDirect, the combination of the search strings was entered in the advanced search field "title, abstract, keywords." In the MDPI database, the search strings were applied to the general search field. No further filters were applied (such as "subject") to avoid missing relevant work. The search was conducted in the time span between 6 July 2022 and 30 October 2022. All articles included in the search were published in peer-reviewed journals by no later than June 2022 (31 June 2022). The databank search initialized the review process, which continued with "snowballing" as described in Section 2.2.

### 2.2. Appraisal

During the appraisal stage, we selected studies eligible for our review by applying a set of inclusion/exclusion criteria to the articles:

1. Search string: Papers were only considered when including the predefined keywords as a whole or at least in combination in title, keywords, or abstract.
2. Type of paper: Only original research papers were considered. This essentially excluded reviews, patent analyses, book chapters, and proceedings.
3. Language: Only papers written in English were considered.
4. Year: To limit the scope of the databank search, we filtered for papers published (print version) from the beginning of the SDG period in 2015 until July 2022 (31 June 2022).
5. Geopolitical scope: Given the hotspots of deficit in SDG 7.1.1 and SDG 7.1.2 identified by the most recent SDG 7 progress report [6], we only consider papers essentially focusing on countries in the Global South. Notably, the term Global South is more than a geographical denotation of a geographical region. The terminus rather focuses on geopolitical relations of power, therefore essentially excluding regions in Europe and North America, but broadly including the regions of Latin America, Asia, Africa, and Oceania [31]. We relied on the United Nations' Finance Center for South–South Cooperation´s list of countries accounting for the Global South [32]. As of 2022, the list comprises 78 countries (including China).
6. Rationale: Articles included in our review had to be in alignment with the rationale of SDG 7.1.1 or SDG 7.1.2. This implies that the articles present work that directly contributes to increasing the share of people having access to electricity or clean cooking, respectively, on a household level. Notably, this excludes applications providing energy services to buildings or infrastructure, which that do not primarily serve as housing for people. Examples are telecommunication stations [33], public buildings [34], or hospitals [35]. Articles proposing an alternative energy supply to an existing, reliable, and clean status quo, such as modernization of energy services for urban buildings [36], were excluded. Further, mobility applications do not meet the rationale of SDG 7.1.
7. Specificity: Our review only includes articles that specifically address the utilization of hydrogen at the end-use. This excludes work that focuses on the production of hydrogen but insufficiently describes the foreseen utilization (e.g., [37]), and work introducing hydrogen as a broad concept only (i.e., the concept of a "hydrogen economy" such as in [38]).
8. Renewable hydrogen: SDG 7.1.1 does not specify the source of electricity supply to increase the share of the population with access to electricity. McCollum et al. [1] thereby detected negative correlations between targets and indicators of SDG 7, e.g., when electrification is enhanced via diesel generators (DGs). However, to not harm other targets of the SDGs, especially SDG 7.2 (increase the share of renewables), we only considered renewable hydrogen as eligible for our review. We further only considered the utilization of hydrogen in its pure form, but not hydrogen-rich fuels such as biomethane.

Papers meeting the criteria 1–4 were considered for abstract reading. If not excluded at this stage, the main body of the papers was studied to check for consistency with criteria 5–8. We documented the first occurring exclusion criterion only. For example, a paper entitled "Comparative assessment of zero emission electric and hydrogen buses in Australia" [39] was excluded for violating criterion 7 (rationale), even though it obviously as well violates the exclusion criterion 5 (Geopolitical scope).

Following the data bank search, we applied backward snowballing to detect more relevant literature. During snowballing, we consulted the reference sections of selected papers and searched in the citations for potentially eligible work [40]. Therefore, we screened the references according to our previously defined basic criteria. However, we excluded criterion 4 (year), as this was initially defined to limit the scope of the data bank search only.

### *2.3. Synthesis*

The synthesis step consisted of both extraction and classification of relevant data from selected papers to derive knowledge and conclusions. Documentation and categorization were performed in Microsoft Excel. The general information (variables of interest) of the articles includes year of publication, journal, geographical location of the research institute of the corresponding author, analysis method, software used, sustainability dimension covered, hydrogen application, description of energy system, and country or region where the study was conducted.

We distinguished seven discrete methods for categorization, while a single paper may combine several of these methods:

- Geospatial information system (GIS) model: Formalized representation of a real system that attempts to emulate combined processes of acquiring and using energy to satisfy the energy demands of a given area over an extended period of time [41].
- Life-cycle assessment (LCA): Assessment of the environmental impact (e.g., damages to human health, ecosystems, or resources) through all the life-cycle stages of an energy system or energy technology [42].
- Experiment: The setup of a physical experiment, i.e., manipulation of variables to establish cause-and-effect relationships.
- Optimization model: A mathematical attempt to determine the maximum or minimum value of a complex objective function that serves as a definite recommendation for the energy system.
- Simulation model: A mathematical attempt to determine an energy system´s response to different inputs, while—in contrast to optimization—not defining a clear recommendation.
- Multi-criteria decision analysis (MCDA): MCDA is an operational evaluation and decision-support approach comparing the performance of various energy system or energy technology options along multiple criteria. In contrast to the multi-objective optimization included in the method category "optimization model," the MCDA method may include qualitative aspects, such as risks, available human resources, or political drivers [42].
- Rigorous analysis: A procedure or test following a strict methodology but not included in the above-mentioned methods.

Regarding the dimensions of sustainability covered by a paper we distinguished in four dimensions:

- Technical dimension: This dimension encompasses all the technical characteristics that describe or evaluate a system, its use of resources, and its ability to meet the intended final uses [43,44].
- Environmental dimension: This dimension includes environmental impacts on the local or aggregated level. We further include effects on human health in this dimension [45].
- Economic dimension: The economic dimension covers any economic assessment on the individual, system, or aggregated level.
- Social dimension: This dimension covers the impact on, or interaction with, people, including societal structures and ethical aspects.

A dimension is seen as included when aspects of it are explicitly mentioned in the text and not only as an underlying facet.

### *2.4. Analysis*

Our analysis includes both quantitative and qualitative evaluation. For quantitative analysis, records identified, and associated variables of interest (see Section 2.3) were processed in Microsoft Excel. The data was aggregated and visualized in the same software. Qualitative evaluation included the study and analysis of the identified papers. We focused on the research questions, methods applied, results answering the research aim, and suggestions for future work. We compared papers within each application of SDG 7.1 to assess the relative contribution of a paper to the general status of research in the respective field of research.

## 3. Results and Discussion

In this section, we present the results from our literature review on hydrogen applications in the rationale of SDG 7.1. We show quantitative results of the variables of interest defined in Section 3, qualitatively assess relevant contributions, and discuss their impact. Relevant findings are supplemented with additional background and state-of-the-art contextual discussions.

We identified a total of 27 papers (out of 850 records screened) as eligible for our review during the data bank search. Another 11 papers were identified during snowballing of relevant work. According to our review, hydrogen is considered for both electrification and clean cooking purposes. Twenty-six studies focused on the application of power supply, while four studies explicitly conducted research on hydrogen as a cooking fuel. Seven studies included aspects of both; see Figure A2a of the Appendix A.

We observe an increasing trend in the number of yearly publications in the rationale of SDG 7.1.1 from 2018 (n = 2) to 2021 (n = 11); see Figure A2b of the Appendix A. The technical (n = 34) and economic (n = 31) dimensions have been investigated most extensively by far, applying optimization and simulation (see Figure A3b of the Appendix A). In contrast, the environmental dimension is included in 14 studies. Social investigations are underrepresented, with three studies considering social aspects. Of those papers investigating hydrogen-based cooking, only a single study reflected on social aspects to consider (see Section 3.4). Figure A4 of Appendix A visualizes the geographic distribution of the case-study locations.

### 3.1. Technical Integration in Energy Systems

Theoretical studies in the run-up to field studies are a useful tool to analyze optimal integration pathways of technologies and determine useful energy-system topologies. Such techno-economic feasibility studies commonly apply mathematical optimization and simulation to define optimal solutions and system configurations in dependency of variables and levers involved. The variables and levers may include:

- Setting specific variables: Load demand; seasonality influences towards load and supply.
- Economic parameters: Project parameters including weighted average cost of capital (WACC), investment costs, operation and maintenance costs, replacement costs, fuel costs.
- Availability of resources: Grid availability for interconnection, availability of renewable energy sources, availability of fossil fuels.
- System configuration: Technology availability, control algorithm, technology configuration.
- Environmental constraints: Renewable energy share, maximum emissions.
- Technical constraints: Loss of power supply probability, energy shortage, energy excess.

Only a few of the screened papers proposed and assessed large-scale hydrogen production on the regional level combined with transport to rural areas, as summarized in Table 6. Examples are found for the countries of Nepal [46], Nigeria [47], Ecuador [48], and Iran [49]. However, the majority of all screened papers (90%) proposed hydrogen production and application in smaller-sized, off-grid systems. We therefore define three popular energy-system topologies including hydrogen for SDG 7.1 focused applications: (A.a). Off-grid power supply to appliances with lower electrical needs (typically lightbulb, fan, TV, radio, phone charger [50]); (A.b) Off-grid power supply to electrical appliances including electric cooking, and (B) Separate off-grid power supply and hydrogen cooking via combustion. Figure 2 illustrates the respective energy-system topologies.

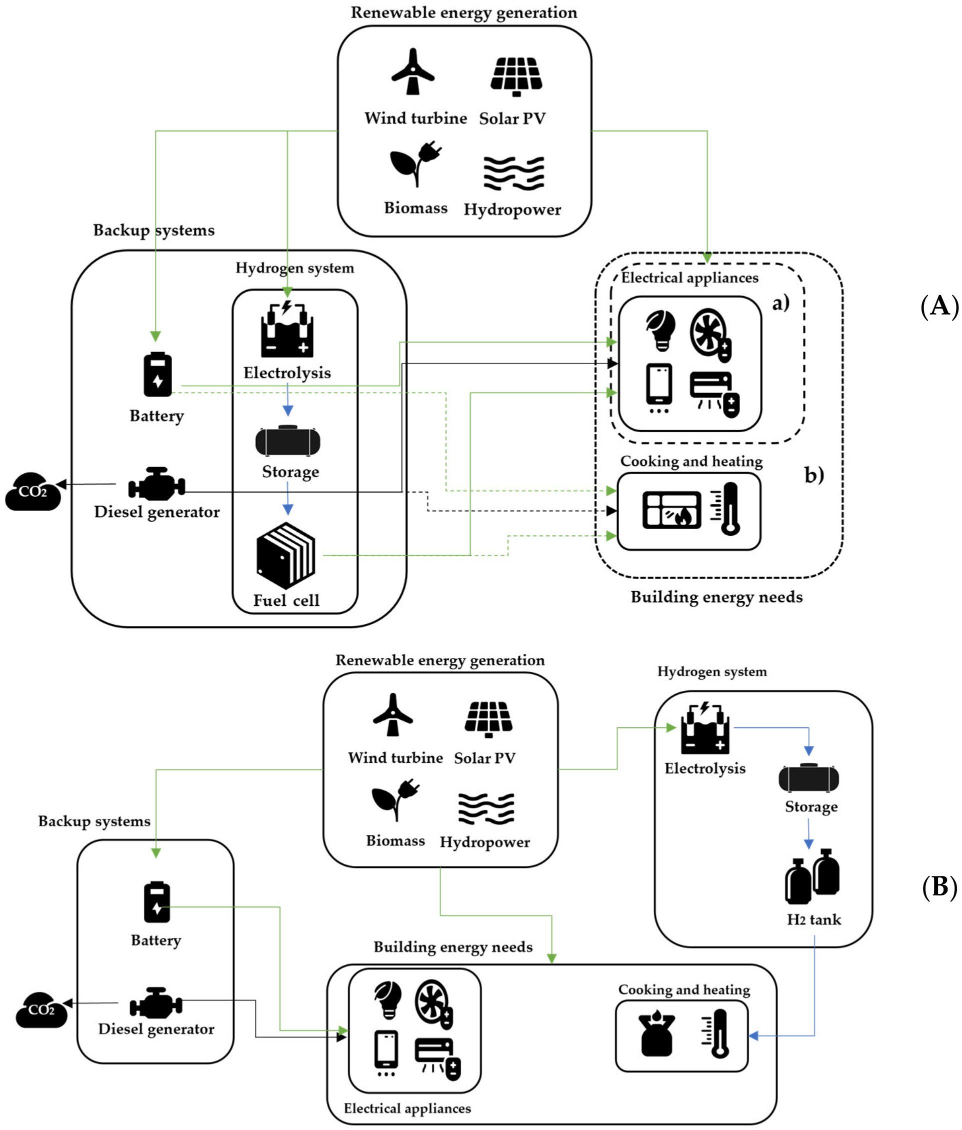



**Figure 2.** (**A**) Hydrogen integration in an off-grid renewable energy system for electrification of (**a**) lower appliances, and (**b**) additional electric cooking; and (**B**) Separate off-grid power supply and hydrogen cooking via combustion. Notably, the figures neglect the type of current supplied to the loads. Historically, alternating current (AC) loads are more common, however, efficient direct current (DC) loads are becoming more popular. While a DC supply and load is directly compatible with the EL and FC respectively, an AC/DC and DC/AC power converter is required when integrating with AC systems.

(A) Off-grid power supply:

The extension of the national grid was a significant driver of increased electrification in many countries during the last years [6]. However, for remote and sparsely populated regions, grid extension may not be a financially viable solution [51]. In such settings, off-grid hybrid renewable energy systems, combining multiple renewable generation assets and storage, are proposed as an environmentally sound alternative to the fossil counterpart of decentralized diesel generators (DGs). Integrated with such electricity systems, hydrogen can serve as an energy storage and backup power supply system to balance the intermittent renewable power generation technologies. The versatility of hydrogen makes it appropriate to be coupled with batteries or supercapacitors. While the latter two may serve for short-term storage, hydrogen may buffer for long-term storage. As the size of the FC is independent from the capacity of hydrogen energy storage, high-power devices can potentially be served without increasing the costs of storage. This eventually allows for even-power electric cooking appliances, thereby simultaneously stimulating electrification and clean cooking efforts. Table 5 comprises the identified studies proposing hydrogen usage for off-grid electrification of lower appliances (energy system-topology A.a) and additional electric cooking [energy-system topology A.b)]). It must be well-noted that some studies reporting an aggregated demand profile may also include electric cooking without our knowledge. The systems reported in the studies reviewed are mostly designed and optimized for small villages and loads. In our analysis, we find a median of peak demand in the case studies of 13 kW (average 40 kW); see Figure 3.

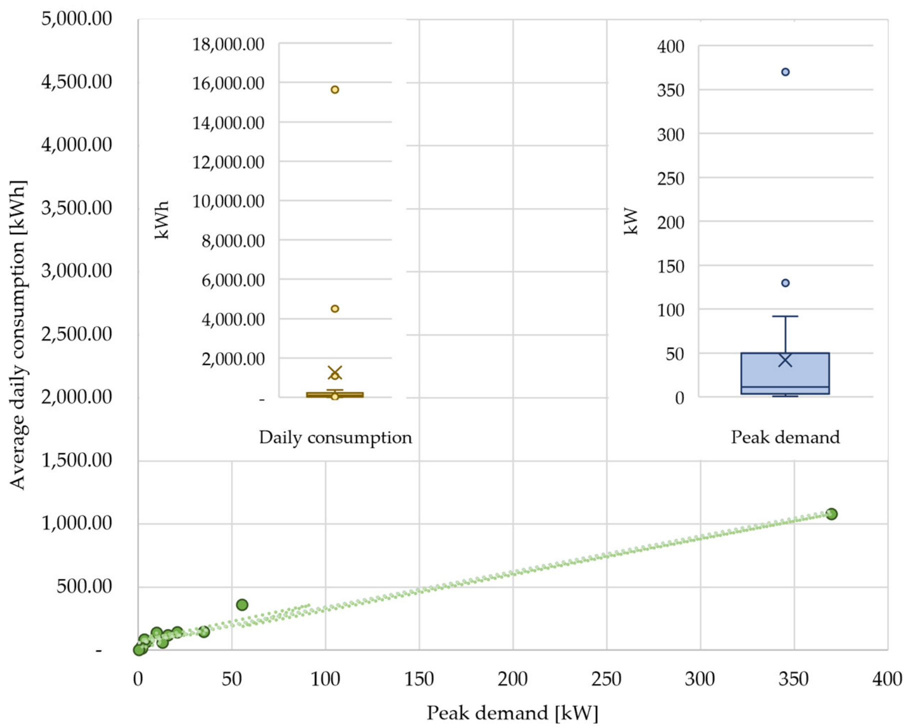



**Figure 3.** Peak demand and average daily electricity consumption in off-grid systems.

The median of the average daily electricity consumption is 84 kWh (average 408 kWh). However, in the few studies that explicitly report electric cooking to be included in the demand profile [52–54], average per capita peak demand and per capita electricity demand are substantially higher compared to the overall median of the larger sample group (60% and 1160% positive deviation respectively).

Most techno-economic feasibility studies analyzed propose photovoltaic (PV) as the primary electricity source to power water electrolysis, with a median of 40 kW, followed by wind turbines (WTs) (median 16 kW). The median optimal sizes of common backup DGs are 8 kW and 166 Ah, in the case of battery storage. While the studies reveal a competition between the DG and the hydrogen system—i.e., usually only one of the two backup systems is included in the optimal system design—the battery storage and hydrogen system are commonly combined. This is because the hydrogen system serves the same operational niche as DGs, which is to buffer for long-term energy storage, while the battery fills short-term storage demand. Thus, battery storage and hydrogen storage are complementary but not competitive in energy-system operation. Median sizes of the hydrogen systems are reported as 10 kW FC, 14 kW EL, and 15 kg hydrogen storage.

Notably, all studies reviewed except one propose PEMFC and PEMEL technologies, justified by technical advantages against competitive technologies (including dynamic behavior and efficiency). Cross-checking this proposition with actual current market shares shows that PEMFCs indeed record the most sales today (manufacturing capacities for PEMFCs exceeded 1100 MW in 2020, which at that time was more than ten times higher than the manufacturing capacities of competitive technologies [9]). However, the predominant suggestion of PEMEL in the literature may be surprising, considering the current market status in EL technologies. Here, AEL is the most mature EL technology with currently the lowest investment costs and largest application [13]. However, stagnation in efficiency improvement and cost reductions, as well as limitations in dynamic behavior might have motivated the search for alternatives at the expense of increased costs due to lower maturity [55].

The studies [52–54] explicitly include electric cooking in the assumed electric demand profile, simultaneously addressing electrification and clean cooking. Today, electric cooking in off-grid systems is not popular due to the high-power requirements of electric stoves that can usually only be satisfied by the electrical grid. However, recent advances in stove design (e.g., electric pressure cookers) and increased energy efficiency may facilitate the increased application of electric cooking in off-grid systems [56]. The studies reviewed suggest hydrogen systems to be a suitable alternative to grid extension to satisfy such loads. This is due to their high reliability and power output, which offer a grid-like electricity supply [52]. Due to the decoupling of energy storage in hydrogen tanks and power supply via FC, hydrogen systems—in contrast to battery storage—can be flexibly designed for higher power demands without necessarily increasing costly energy storage. Such application of FCs, facilitating electric cooking in off-grid systems, may offer significant opportunities to accelerate access to clean cooking. By mutually linking the cooking system to the electricity supply system and sharing assets, energy efficiency and economic synergies could be unlocked. Furthermore, from an institutional perspective, the complexity of the stakeholders involved might be reduced. Stakeholders seeking clean cooking may co-use the infrastructure and arrangements established in the electrification sector. For example, minigrid operators that, at the moment, can rely on clear regulations assuring clear financial planning in the long-term in many African countries could become responsible for the rollout of clean cooking projects via electric cooking, avoiding the time-intensive development of similar structures for clean cooking agents.

(B) Separate power supply and hydrogen cooking via combustion

Table 7 summarizes studies reviewed that propose the use of hydrogen for cooking via combustion, in separated infrastructures to the electricity supply system. Young et al. [57] and Topriska et al. [58] propose hydrogen cooking fuel production systems for rural villages separate from the electricity infrastructure (note that Figure 2B suggests at least to share the primary electricity generation assets). While the renewable power generation systems serve electricity to the village and simultaneously feed an electrolyzer in [57], Ref. [58] considers a standalone PV system dedicated to produce hydrogen via a PEMEL. In contrast to utilizing electricity supplied by FCs for cooking purposes, the direct combustion of hydrogen for cooking and heating purposes is suggested.

The physical and chemical properties of hydrogen allow for conventional combustion in oxygen-fuel mixing burners. In fact, hydrogen has very similar properties to popularly known cooking fuels, such as LPG or methane. Table 3 presents selected key characteristics of hydrogen, propane, and methane as reference gases. Key characteristics and advantages of hydrogen against its fossil counterparts are:

- The higher hydrogen-air flame temperature allows for quick and flexible heating.
- The high diffusion coefficient is a great safety advantage.
- Hydrogen can be ignited within a wide flammability range with low ignition energy required.
- Hydrogen has a high (gravimetric) energy density, offering great potential for storage and transport.

**Table 3.** Selected properties of hydrogen, propane, and methane. As the main compound of LPG and natural gas, the properties of propane and methane approximate LPG and natural gas properties, respectively.

| Property | Unit | Hydrogen ($H_2$) | Propane ($C_3H_8$) | Methane ($CH_4$) |
|---|---|---|---|---|
| Molecular weight | u | 2.01594 [59] | 44.1 | 16.4 |
| Gravimetric energy content | MJ/kg | 120 [60] | 46.4 [60] | 50 [60] |
| Higher heating value (HHV) | MJ/Nm$^3$ (MJ/l Propane) | 12.75 [61] | 26.5 [62] | 39.82 [61] |
| Flammability range (Equivalence ratio) | | 0.1 ∼ 7.1 [60] | 0.51 ∼ 2.5 [60] | 0.5 ∼ 1.7 [60] |
| Max. laminar burning velocity | m/s | 2.91 [60] | 0.43 [60] | 0.37 [60] |
| Adiabatic flame temperature in air | °C | 2.110 [60] | 2.000 [60] | 1.950 [60] |
| Diffusion coefficient in air | Cm$^2$/s | 0.61 [59] | 0.1318 | 0.221 |
| Minimum auto ignition temperature | °C | 520 [60] | 450 [60] | 630 [60] |

Pointing to the similarities of hydrogen and LPG (>95% propane), Young et al. [57] and Topriska et al. [58] propose decentralized hydrogen production, and a distribution model and utilization of pure hydrogen similar to LPG (notably, Grové et al. propose the same for hydrogen-based dimethyl ether [63]). Hydrogen is proposed to be produced via small-scale decentralized water electrolysis and supplied to households in portable containers, refilled on a monthly basis. In the households, the hydrogen is burned in hydrogen stoves or modified LPG burners [58]. With this, the downstream process of hydrogen cooking is in fact analogous to established LPG cooking schemes.

Therefore, it is an obvious question to explore the actual co-usage of LPG infrastructures and search for synergies. In fact, a reasonable integration pathway of hydrogen as a cooking fuel could be via existing LPG distribution channels, i.e., in regions in which LPG is already popularly used as cooking fuel [57]. Hydrogen could either replace the LPG, or, as a bridge solution, be blended with LPG, reducing emissions. To our best knowledge, no studies explore the technical possibility to use relevant LPG technologies with hydrogen. However, the findings from studies on gas blends in other settings might be transferable. Makaryan et al. [64] conducted a review on studies investigating the opportunities and challenges of blending hydrogen in European natural gas infrastructures. The authors differentiate individual assets of the energy infrastructure. Material corrosion, safety issues, and volumetric energy density are the main restriction factors to hydrogen admixture to the natural gas grid. For such energy infrastructure assets relevant to the case considered in this paper, i.e., meters, (compressed natural gas) storage tanks, house installs, and home gas burners/stoves, the authors summarize sensitivity thresholds as cited in Table 4:

**Table 4.** Sensitivity of selected natural gas infrastructure assets to hydrogen admixture as reported in [64].

| Asset | $H_2$ Blending Uncritical | Adjustment Needed | Further Research Required |
|---|---|---|---|
| Meters | <30% | 30%–70% | >70% |
| CNG storage tank | <30% | 30%–50% | >50% |
| House installs | <30% | 30%–50% | >50% |
| Home gas burner/stove | <10% | 10%–50% | >50% |

As a critical end-use appliance for domestic use, De Vries et al. [61] further detail the analysis of impact the of hydrogen mixing on cookstove appliances. According to the authors, the Wobbe index (indicator of the interchangeability of fuel gases), probability of a flashback, and fuel-air ratio of the burner are decisive for the maximum fraction of hydrogen possible to mix to a reference gas without requiring any modifications. While the Wobbe index is a matter of thermal comfort, the flashback probability is a severe security risk. A flashback occurs when the burning velocity in the primary flame front exceeds the velocity of the unburned mixture leaving the burner exit to such an extent that the flame will propagate upstream into the burner, "flashing back" into the appliance [65]. A flashback can cause damage to the burner or flame extinction, which, in the absence of a flame safety device, can result in spillage of the combustible mixture. As hydrogen increases the laminar burning velocity of a potential blend (Table 3), it increases the probability of flashbacks. De Vries et al. find that higher Wobbe index gases can take more hydrogen before harming safety concerns. For a gas with a high Wobbe index according to the European Union natural gas standards (14.7 kWh/m$^3$ ≤ WNG ≤ 16 kWh/m$^3$), a 20% admix of hydrogen is found to be the maximum threshold [61]. As LPG has an even higher Wobbe index than such natural gas (20.3 kWh/m$^3$ ≤ WNG ≤ 24 kWh/m$^3$), we conclude that we may conservatively adopt the 20% admixture threshold but propose a dedicated investigation on hydrogen–LPG admixtures for future work. However, with this, the option to blend hydrogen with LPG is only possible up to a limited amount of hydrogen. Modifications to the LPG burner as shown in [66] are required to enable increased hydrogen amounts.

### *3.2. Economic Prospective*

Hydrogen integration in off-grid energy systems for electrification remains an economic challenge. This circumstance has been reported for off-grid systems in developed economies [21] but might be even more critical in settings in the Global South with lower purchasing power of users. The capital expenditure (CAPEX) of hydrogen components is high, compared to other energy-system components. Figure 4 comprises the CAPEX of prominent components as reported in the reviewed literature. With a median of 3000 USD/kW and 1,500 USD/kW the fuel cell and electrolyzer respectively are the most expensive energy-system assets. Notably, the fossil-based DG has the lowest CAPEX, with a median of 510 USD/kW.

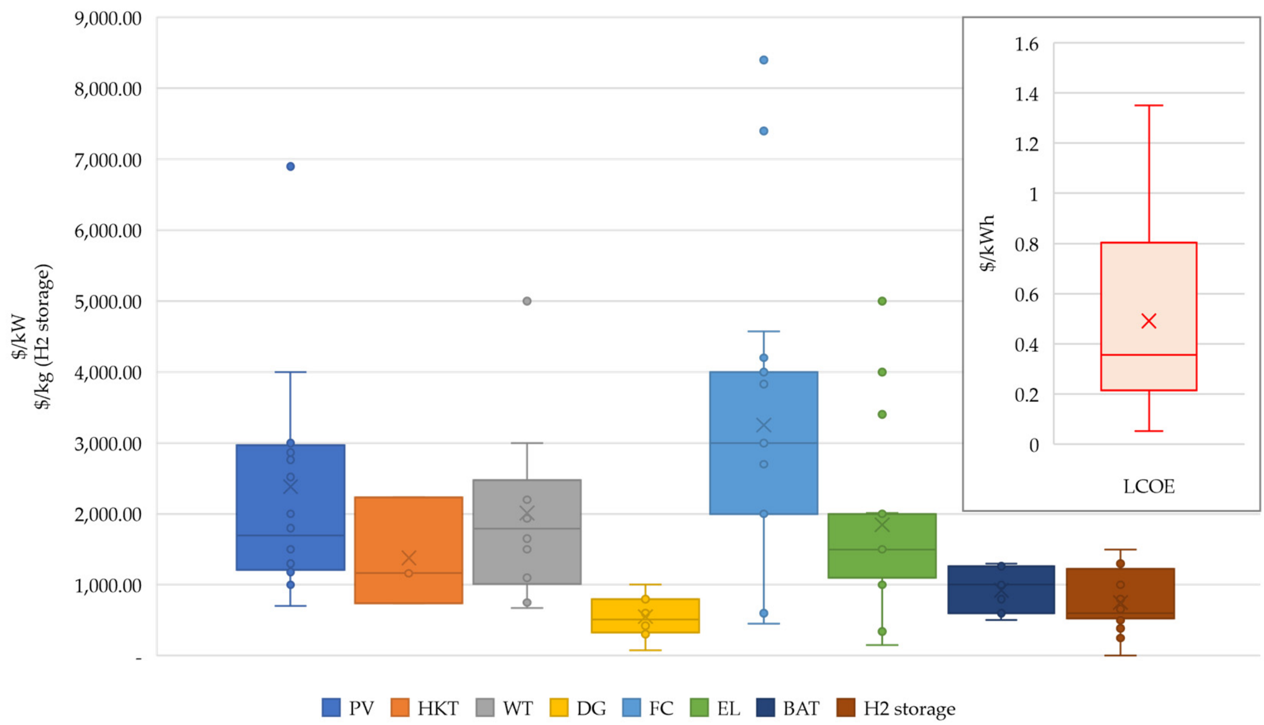



**Figure 4.** CAPEX of main components and LCOE reported in the literature. Abbreviations: PV = photovoltaic; HKT = hydrokinetic turbine; WT = wind turbine; DG = diesel generator; FC = fuel cell; EL = electrolyzer; BAT = battery; $H_2$ storage = hydrogen storage.

However, the Levelized Costs of Electricity (LCOE) of systems including renewable energy and hydrogen backup reported in the techno-economic studies reviewed (median

0.355 USD/kWh) are in a similar range as conventional renewable off-grid systems in comparable settings [67,68]. We must further note that with advancing technology and market maturity, the CAPEX of hydrogen components is likely to drop. For example, the International Renewable Energy Agency (IRENA) proposes a decline in EL CAPEX by 40% until 2030, and by >80% by 2050 (notably for large-scale systems) [15]. Maestre et al. propose the substitution of expensive noble metal–based catalysts by non-Platinum Group Metals (PGM) materials to reduce the system costs [21]. In addition, efficiency improvements of both ELs and FCs are foreseen with increasing commercialization [69]. As the efficiency of the EL and FC influences both the investment costs—as impacting the required installed power—and operating costs—determining the required energy input—additional economic benefits can be expected when increasing efficiency. A potential decline of EL and FC CAPEX would have a great impact on the economic competitiveness of hydrogen in off-grid energy systems. [54,70–72] include a sensitivity analysis on FC and EL CAPEX. Each study's results show a steep decline in the hydrogen-based system costs when assuming a relative reduction of EL and FC CAPEX compared to the initial assumptions. [52,72] additionally show the impact of hydrogen storage costs on the system results, which show less impact.

In contrast to high CAPEX, operational expenditures (OPEX) of hydrogen systems are low [66]. The fossil counterpart of the DG, in contrast, is characterized by low CAPEX but substantially high OPEX. Refs. [71,73,74] show the economic advantages of low OPEX of hydrogen-based systems over the lifetime of a project [71], for example, shows that a potential increase in diesel fuel costs of 2 USD/L to 3 USD/L leads to the hydrogen-based system being economically advantageous against the DG in a case study of a village in the Gulf of Guinea. Sensitivity analysis in [74] show the diesel fuel price to be the most influential parameter on the economic competitiveness of hydrogen-based power supply against a DG.

Hydrogen technologies offer the potential to harness economic benefits of sector-coupling. An innovative approach to further decrease the costs of hydrogen systems is presented by Baldinelli et al. [75]. The authors propose the integration of a reversible solid oxide cell (rSOC) in a PV-hybrid energy storage minigrid. Aside from fulfilling the purpose of electricity generation, the rSOC can be used in seawater desalination, as desalted water is released as a byproduct during reconversion of hydrogen to electricity (desalinated water co-production is on average 0.28 $L/kWh_{SOFC}$). The authors demonstrate the proof-of-concept on a single cell in an experimental setup, before simulating the operation of a minigrid on an archetypal community in sub-Saharan Africa, optimizing energy and environmental objectives [75]. The authors propose to include the cross-sectoral integration (water desalination) as economic value. Therefore, water co-production is monetized in the study. By this method, the LCOE can be reduced by approximately. 25% under today´s conditions. As the amount of water desalinated is inherently coupled to the amount of electricity generated by the rSOC, greater impact is seen in scenarios of higher per capita electricity consumption.

However, the economic competitivity of hydrogen in clean cooking applications is even more challenging than in power supply. Conventional cooking fuels, especially firewood and charcoal, are inexpensive in many Global South countries. A standalone energy system dedicated to decentralized hydrogen generation and use as cooking fuel is not economically competitive with such traditional fuels [66]. Therefore, Topriska et al. [66] propose upfront subsidies to finance such system solutions. However, the authors remember the failure of historic aid-giving interventions in cooking projects. Previous solar cooking projects have shown that distributing technologies to the very poor for free may jeopardize the uptake of the technologies. Solar cooker projects in the past targeted extreme energy poverty. The persons of concern, however, have associated such aids with social discrimination, which in turn created criticism and reluctance in the uptake by the local communities [76]. Solution uptake by the market is therefore preferred. However, suitable business models to enable a market uptake of hydrogen cooking must be explored to achieve economic competitiveness with traditional fuels. While the studies reviewed considered the separate energy system for electricity supply and hydrogen cooking fuel production [66,77], the integration of both should be explored. Increasing the cost effectiveness by triggering synergies in the shared assets (i.e., PV, converter) is likely. Further, when considering cooking fuel production as a byproduct of an electricity supply system analogous to water as a byproduct reported in [75], economic benefits could be achieved. Generally, the average revenue per use, a prominent economic performance indicator in off-grid systems, linearly correlates with increasing system utilization [68]. Harnessing excess electricity generated by renewable energies to produce hydrogen cooking fuel via water electrolysis could hence improve the economic system performance of the electricity supply system [68]. Further, operational benefits may be unlocked when co-utilizing energy infrastructures. An economic assessment of the effects of combining electricity and hydrogen cooking services is suggested for future work.

Especially for costly cooking fuels, the purchase modalities are a crucial factor that influence the affordability of the fuel for the end-user. While historically, gaseous fuels traded in standardized containers, including LPG, confronted the user with high unit costs, recent developments allow for incremental payments, as established for fuelwood and charcoal. As the hydrogen cooking system proposed by Topriska et al. [66] builds on a similar (in parts identical) infrastructure as LPG cooking, we assume the same payment methods to be adoptable for hydrogen cooking.

One example of a recent success story in clean cooking is the rollout of LPG in Kenya. In Kenya, LPG is a fundamental pillar to reach national targets in clean cooking [78]. The Kenyan government is targeting an expansion of LPG use from 20% of the population in 2016 to 35% by 2030 [79]. However, cash-based models, requiring upfront payments for stoves and fuel, are still the most popular business model for LPG (98%) [22]. The high upfront investments pose a significant barrier to low-income households [80]. Therefore, innovative business models including pay-as-you-go and layaway models evidently reduce this barrier [80]. The pay-as-you-go business model allows the user to buy fuel in small portions and to the extent they can afford. The providers supply the user with branded LPG cylinders and a monitoring system, remotely controlling a valve. Consumers only pay for the valve and monitoring system as an upfront investment and can make prepayments for the gas via mobile money. The valve only releases as much gas as is paid for before shutting down via the smart monitoring system. Thus, a user can decide to purchase small units of gas [80,81]. Enabling such incremental payments has triggered the large uptake of LPG as a cooking fuel in Kenya [80].

### 3.3. Environmental Performance

Today, approximately 95% of global hydrogen is produced from hydrocarbons (48% methane reforming, 30% oil reforming, 18% coal gasification) [9]. The production of hydrogen from hydrocarbons releases significant amounts of $CO_2$. Production methods based on renewable energy sources, avoiding $CO_2$ emissions, are promoted by governments around the globe [11].

An environmental assessment of renewable a hydrogen-based power supply is conventionally performed by comparing the emissions occurring from the proposed hydrogen-based power supply to the emissions occurring from the status quo of power supply. Ayodele et al. therefore propose ecological efficiency as an indicator to evaluate the power supply performance according to pollutants emissions by hypothetically comparing the integrated pollutants emissions $CO_2$-equivalent ($CO_2$-eq.) with existing air quality standards [82]. Ranging from 0 to 1, the indicator quantifies the potential of a system to conduct a desired process as a least-polluting option, i.e., the most environmentally friendly situation (in the specific case of hydrogen production via waste-based biogas and hydrogen utilization by a PEMFC, the process yields an ecological efficiency of 94.33%) [82].

More commonly, a measure to evaluate the environmental benefit of a hydrogen-based power supply is to estimate the amount of air pollutants avoided by displacing currently used fossil fuels (see, e.g., [47,54,75]). In the electrification context, diesel fuel is usually assumed to be the benchmark. While the amount of diesel fuel replaced is calculated based on the heating value of diesel and respective DG efficiency, international standards for emission factors of specific fuels are cited to determine the emissions savings. For example, the Intergovernmental Panel on Climate Change frequently publishes emission factors for greenhouse gas inventories [83]. While such inventories usually include several pollutants associated with a fuel (i.e., $CO_2$, $CH_4$, $N_2O$), studies mostly convert all occurring emissions to $CO_2$ equivalents by multiplying each emission type with its global warming potential. With this, replacing a typical DG in off-grid power supply may save approximately 270 g$CO_2$-eq. per kWh produced [83].

While the aforementioned procedure assesses emissions at the point-of-use, Galvez et al. [84] propose to include emissions ($CO_2$-eq.) released over the life cycle of the component in a case study of a small village in Cuba. The authors report specific emissions of 0.045 kg $CO_2$-eq./kWh for mono-Si PV modules, 0.88 kg $CO_2$-eq./kWh for a DG, 0.011 kg $CO_2$-eq./kWh for an electrolyzer, 0.02 kg $CO_2$-eq./kWh for a fuel cell, and 0.028 kg $CO_2$-eq./kWh for a Pb-acid battery. Multiplying the specific emissions with an optimized system (Homer), the authors find the hydrogen-based system to outperform even the battery storage on environmental metrics [84].

However, common EL and FC technologies use significant amounts of rare-earth elements and noble metals as catalysts, transport layers, and bipolar plates [15]. When scaling up the production of ELs and FCs, the mining of such scarce resources will require additional efforts, and potentially increase the environmental impact. To ensure positive environmental impacts in the future, alternatives to the current use of noble catalysts and titanium must be explored. A promising technology might be AEMEL. AEMEL allows the use of non-noble catalysts and titanium-free components, but instead uses high-surface nickel or NiFeCo as catalysts and transport layers. However, at present, AEMEL technologies must still overcome chemical and mechanical stability problems [15].

Studies on hydrogen-based cooking are motivated by developing an alternative to harmful traditional cooking fuels [48,57,66]. Indoor air pollution caused by the use of traditional fuels is the fourth most common cause of death after malnutrition, HIV/AIDS, and lack of clean water [85]. Therefore, the studies reviewed propose hydrogen as a non-polluting cooking fuel to substitute for traditional fuel woods and minimize emissions at the point-of-use. Topriska et al. evaluate the amount of local $CO_2$ emissions saved by hydrogen cooking compared to conventional cooking with fuelwood, charcoal, and LPG in case studies in Jamaica, Ghana, and Indonesia. Depending on the fuel stacking mix of the respective case study, hydrogen cooking could save between 8.75 and 12.8 tons of $CO_2$ per household per year [66].

As discussed in Section 3.1, the blending of hydrogen in LPG could be an entry point for hydrogen-based cooking in energy systems. We therefore discuss the potential impact of hydrogen–LPG blends on the point-of-use emissions. We rely on practical estimations provided by [61], who experimentally blended hydrogen with methane. As discussed in Section 3.1, we can adopt the findings to hydrogen–LPG blends. The authors in [61] show that the $CO_2$ emissions saved by substituting methane (or LPG) with hydrogen when blending does not linearly correlate with the amount of gas substituted, given that the use maintains a constant thermal throughput and temperature. This is due to the lower volumetric heating value of hydrogen compared to methane and LPG. Therefore, when increasing the level of the hydrogen mixture, more fuel use of LPG would be required. For the case of hydrogen–methane blends, de Vries et al. show that at fractions below $\sim$30% hydrogen, the $CO_2$ reduction is only 1/3 of the hydrogen fraction, tempering the expected impact of hydrogen addition to natural gas on $CO_2$ emissions [61]. Even less $CO_2$ reduction could be expected when blending hydrogen with LPG, given the higher heating value of LPG compared to methane. However, no $CO_2$ emissions occur when completely replacing LPG.

Schmidt-Rivera et al. [77] extend the environmental evaluation of the system proposed by Topriska et al. in [58] and demonstrated in Jamaica [86,87]. The authors follow clear guidelines as stated in the ISO 14040/44 to estimate the cradle-to-grave life-cycle environmental impacts of hydrogen produced in a solar-powered PEMEL and used as a fuel for domestic cooking. Hydrogen fuel is compared to other cooking fuels including LPG, firewood, and charcoal. The authors can build on primary data of the hydrogen cooking system deployed under the ACP Science and Technology Programme [88]. The results show that the PV system dominates the environmental impacts of the hydrogen system by far in every considered impact category. Recycling of material and PV efficiency can significantly improve environmental performance. Compared to other fuels, the authors find the hydrogen system to be the best option for avoiding fossil fuel depletion, climate change, ozone depletion, and summer smog (the last, jointly with LPG). Specifically, hydrogen would reduce the climate-change impact to 0.04 kg $CO_2$ eq./MJ compared to firewood (0.10 kg $CO_2$ eq./MJ) and LPG (0.57 kg $CO_2$ eq./MJ). Additionally, considering the point-of-use, local health and environmental benefits can be significantly improved when using hydrogen as cooking fuel, compared with traditional fuels. However, the hydrogen-based cooking system is the worst option considering the depletion of metals, freshwater eutrophication, and freshwater and marine ecotoxicity. As mentioned, this is mainly due to the solar photovoltaic panels used to generate power for the electrolyzer. This highlights the importance of the choice of the primary electricity source in the environmental evaluation of the overall system.

### 3.4. Social Considerations

With the overarching aim of improving people's quality of life, energy systems for electrification or clean cooking must fit into the social habits of individuals and communities. Energy technologies must ensure an equitable distribution of the benefits along the value chain. Vice-versa, the support and desire for energy technologies by individuals and the community is crucial for the uptake and longevity of the solution itself. Zhang et al. [49] therefore propose to consider social aspects as constraints in the initial search for the location of energy systems. Defining the optimal location for a hybrid renewable hydrogen system in an off-grid context in Iran via GIS, the authors limit the search to buffer distances to the villages to respect the perceived degradation of the visual aesthetics by the local community. Furthermore, appropriate distance from religious sites, cultural heritage sites, and other places sensitive to the population is suggested.

As any communities' and individual´s values, habits, and preferences vary with the local context, measuring the social impact of energy technologies remains challenging. Hernández Galvez et al. propose community acceptance as a criterion to compare hydrogen in electrification against the fossil counterpart of a diesel generator aside from CAPEX and life-cycle emissions [89]. Community acceptance should measure the degree of acceptance by the residents regarding the different technologies involved, as a factor that may affect the sustainability of a self-sufficient energy system. However, the study does not explore the reasons why participants had this preference.

It is known that supply reliability is one critical factor to ensure high acceptance for energy technologies [90]. Robert et al. show a vicious cycle of power supply reliability and the willingness to pay for electricity. The authors observed that with decreasing reliability of supply, people tended to either invest in their own power supply systems or refuse to pay their electricity bills, decreasing the revenue of the system operator. Confronted with less revenue, the operator could not sustain sufficient maintenance of the assets, which caused asset failure and further decreased the reliability of the power supply system [90]. The versatility of hydrogen in this context might ensure a required high reliability of power supply. Firstly, the production techniques of hydrogen are flexible, ensuring a high reliability of the primary power source. Electricity for water electrolysis can be served from any renewable energy source, unlocking the potential of any renewable source available in the local context. In addition, other production techniques could diversify the hydrogen supply. In Nigeria, for example, hydrogen produced from biogases using food waste is proposed [82]. Secondly, the storability of hydrogen guarantees a high availability of power supply when integrating hydrogen energy storage. Thirdly, sizing the FC independently from the storage capacity allows to flexibly adjust to required capacities. With this, hydrogen-based technologies are suitable for higher power supply [9,52], and higher quality of energy access provision. Referring to the Multi-Tier framework defined by the Energy Sector Management Assistance Program (ESMAP) to measure energy access on seven distinct attributes [91], a hydrogen-based power supply is capable to provide access beyond Tier 3 (e.g., >200 W and 1 kWh per day). This ability is important when considering future prospects of energy access. It must be noted that providing electricity access in the context of SDG 7 foresees access to at least 100 kWh of supply per individual per year. While this threshold may ensure an absolute minimum of energy services possible, energy services enabling higher economic development opportunities are hardly possible. Approaching the closing of the SDG period, discussions on follow-up targets have evolved. In the modern energy minimum, it is postulated to extend the availability of electricity to people from domestic purposes to other purposes of the wider economy, which include higher-powered devices and energy availability for longer durations (Tier 3 and higher) [92]. Including such upcoming future ambitions in today´s energy-system planning forcibly includes highly reliable backup systems, such as hydrogen-based systems. The argumentation in Babatunde et al. [50] underpins the ability of a hydrogen-based power supply to guarantee a high reliability of supply, increasing the likelihood to be integrated into future energy systems. Conducting an economic optimization, the authors find a PV/battery storage system to be the least-cost system to power a residential load of a low-income household in Nigeria. A subsequent MCDA, in contrast, suggests a PV/WT/FC/BAT system to be the best option. Including the reliability of supply as an evaluation criterion, as the authors advise for decision makers in the future, substantially improves the performance of the hydrogen-based system.

As a central community activity, cooking is sensitive to novelties and any disruptions of the present habits. When introducing a new cooking fuel and technology, it is suggested that a successful alternative cooking system should be easy to adopt and should not pose disruption to the daily habits and cooking schedule of local residents that traditionally cook with stoves [93]. In countries and settings in which LPG is already a widely known and used cooking fuel, such as India, Kenya, Ghana, and South American countries, hydrogen cooking via combustion could meet these requirements. As Topriska et al. [66] and Young et al. [57] propose, a distribution scheme of hydrogen fuel similar to LPG using existing distribution channels (e.g., local kiosks or last-mile delivery) could be adopted. Furthermore, the hydrogen cookstove system meets the criteria of ease of use during utilization, which is a combination of direct ignition, systematic heat regulation, systematic fuel use, allowance for partial fuel refill, non-smoking clear flame/heat, and fuel level detection [22]. Notably, the ease-of-use criterion is recognized as the second most important factor affecting the choice of cooking fuel in the Kenyan population [22], as an example for a sub-Saharan context.

Topriska et al. [66] conducted country case studies for Jamaica, Ghana, and Indonesia to assess the potential of hydrogen-based cooking. The system is sized via numerical modeling to supply hydrogen cooking fuel to meet the demand of 20 households. Aside from consumption and expenditure patterns, the authors assessed the preferences and perceptions of different traditional fuels and LPG using a survey at the household level. The respondents indicated their willingness to switch from their current fuel to the innovative hydrogen fuel, if cheaper and safer than the current fuel [66]. Especially the users relying on firewood as a primary cooking fuel saw a potential increase in safety as a driver to switch to hydrogen fuel [66].

Aiming to identify safety risks occurring from decentralized hydrogen systems, Ogbonnaya et al. [94] assess engineering risks, failure modes, and their effects. Hydrogen leakage from pressurized tanks is seen as a severe risk and danger to users. The authors see a moderate probability of such failure and moderate chance that the design control will detect such failure, but potentially hazardous risks (e.g., explosion) in case of occurrence. However, when compared to other gases, such as LPG, hydrogen presents fewer risks due to its non-toxic characteristics and low volatility. Since hydrogen is, for instance, 57 times lighter than gasoline vapor, it will typically rise and disperse rapidly when leaked, reducing the risk of ignition close to the user [11]. Nevertheless, Topriska et al. [66] explicitly suggest metal hydride hydrogen storage as an alternative to pressurized containers to reduce the safety threats of the system. However, metal hydride containers are still under development at the moment and not yet cost competitive [16].

## 4. Concluding Remarks

Achieving universal electrification and access to clean cooking until 2030 is envisaged in SDG 7.1. However, pace in the rate of progression in both targets and potential impacts of the COVID-19 pandemic and the crisis in Ukraine create doubt that the final target can be reached by 2030. International organizations and governments call for innovative technologies to be developed and embedded into existing structures to accelerate electrification and access to clean cooking. Therefore, hydrogen has been proposed as a versatile energy carrier to stimulate electrification efforts and clean cooking fuel provision.

This extensive review provides a status quo on prominent technical integration pathways, economic challenges, environmental comparison, and social considerations of hydrogen applications in the rationale of SDG 7.1. Initializing the review with a semi-systematic literature search and snowballing in relevant publications, this paper presents quantitative metadata and a qualitative analysis of identified contributions. Relevant findings are supplemented with contextual discussions from relevant associated research.

Theoretical techno-economic analysis has identified three dominant integration pathways of hydrogen in energy systems: as a backup technology in small-scale off-grid villages to power (A a) lower electrical appliances and (A b) additional electric cooking/heating appliances, and (B) direct utilization of hydrogen as a cooking fuel via combustion, independent from electricity supply. The downstream infrastructure of the latter hydrogen cooking system is analogous to established LPG cooking systems. The co-utilization of existing LPG infrastructures is therefore a likely market entry point.

However, in both electrification and clean cooking the high initial investment costs required for FCs and ELs pose a challenge in competing with alternative technologies and especially fossil fuels, the latter of which are still cheap in most settings observed. The future likely developments of declining CAPEX and increasing technology efficiencies will significantly improve the economic performance of the hydrogen system. However, economic competition against traditional cooking fuels especially will require the development of cost-efficient business models. We suggest the investigation of exploitable cost-efficiency improvements when integrating hydrogen-based cooking (via electric cooking or combustion) in electricity supply systems.

When fostering the production of hydrogen from renewable sources, a hydrogen-based energy supply can significantly improve the environmental impact compared to the status quo of prevailing fossil fuel–based energy supplies. Hydrogen releases no carbon point-of-use emissions in both power supply and combustion as clean cooking fuel. However, to prospectively decrease the life-cycle emissions and extend the environmental benefits beyond climate-change impact and point-of-use emissions only, EL and FC technologies avoiding noble metals and rare resources must be fostered. As the production of hydrogen via water electrolysis depends on a primary source of electricity, the choice of the primary source significantly impacts the environmental performance of the overall system.

Studies investigating the social impact of hydrogen-based energy supplies in the rationale of SDG 7 are underrepresented. However, arguably the potential fit to supply sustainable, growing energy services at levels even beyond the minimum requirements manifested in SDG 7.1 is likely according to the literature. The literature highlights the reliability and availability of supply as crucial to electricity customers. The versatile production pathways and renewable resources exploitable for its production, and the storability of hydrogen can satisfy the need for such reliable power supply. The consideration of recent postulations to increase the standards and thresholds for electricity supply beyond the SDG period strengthens the arguments for backup power supply technologies in general, and hydrogen-based power supply in particular.

In the sensitive-to-changes activity of cooking, hydrogen cooking via combustion fits for the uptake in settings where LPG, notably recognized as transitional clean cooking fuel due to its fossil origin only, is or will become an established cooking fuel. Building on a similar, or even the same, distribution and utilization infrastructures, the introduction of hydrogen as a clean cooking fuel may avoid any disruptions in the user behavior in settings with LPG predominance, while meeting crucial ease-of-use criteria. However, safety issues are vital for the perception of users to adopt hydrogen cooking and should be elaborated upon.

**Table 5.** Variables of interest for the literature considering hydrogen applications for off-grid power supply to lower electrical appliances and electric cooking.

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [84] | 2012 | Cuba | • Optimization<br>• Simulation | • HOMER<br>• HOGA | • Technical<br>• Economic<br>• Environmental | • Evaluation of a PV/WT/BAT/FC/DG system for electrification of a rural community in Cuba<br>• Multi-objective optimization for economic and environmental objective functions<br>• Optimal solutions propose $H_2$ storage instead of storage in batteries<br>• Results obtained via HOMER were compared to those obtained by means of the HOGA model | • Community with 200 inhabitants (40 dwellings)<br>• Average daily load is 120 kWh, with a peak power of 16 kW |
| [89] | 2013 | Cuba | • Optimization<br>• Simulation<br>• MCDA | • HOMER | • Technical<br>• Economic<br>• Environmental<br>• Social | • Techno-economic optimization of a PV/WT/DG/FC hybrid system for a rural community in Cuba<br>• MCDA conducted applying the criteria: Capital costs, community acceptance, and equivalent emissions in the life cycle<br>• When applying low weight on the capital cost criteria, the hydrogen-based system is preferential to a diesel-based power supply | • As in [84]<br>• Average daily load is 140 kWh, with a peak power of 35 kW<br>• Optimal solution including hydrogen: 15 kW PV; 50 kW WT; 30 kW DG; 10 kW FC; 15 kW EL; 10 kg $H_2$ storage |
| [70] | 2013 | Brazil | • Optimization<br>• Simulation | • HOMER | • Technical<br>• Economic | • Techno-economic evaluation of a PV/FC/BAT system to supply power in an isolated community in the Amazon region<br>• PV/BAT system is economically advantageous against the FC<br>• Sensitivity analysis on FC and EL capital costs, interest rates, load, and global solar irradiation | • Average load of 23.8 kWh/d<br>• Load profile according to five houses, a community left, a school, and a health left<br>• PEMEL, PEMFC (50–60% efficiency); Aluminum pressure hydrogen tanks |
| [95] * | 2014 | Iran | • Simulation | • Carrier (for computing the cooling and heating load)<br>• Simulation: Not mentioned | • Technical<br>• Economic | • Techno-economic evaluation of a WT/$H_2$-hybrid system in a household size for standalone off-grid location in Iran<br>• Electric heating considered<br>• Exergy analysis of the system | • Cooling and heating load of the building and required hot water are calculated for four people's consumption<br>• PEMEL (GenHy1000) and fuel cell (BCS); compressed hydrogen storage |

**Table 5.** *Cont.*

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [71] | 2015 | Gulf of Guinea | • Optimization<br>• Simulation | Odyssey (CEA) | • Technical<br>• Economic | • Development of a power-management strategy for a standalone PV/BAT/FC system and size optimization<br>• Performances degradation of the EL and FC has a limited impact on the economic results<br>• Sensitivity analyses on BAT and hydrogen chain costs show that the PV/BAT/$H_2$ solution is more profitable than the PV/BAT configuration<br>• Sensitivity analyses on diesel cost show that PV/BAT/$H_2$ solution becomes more competitive than PV/DG when diesel price moves from 2 €/L to 3 €/L | • 130 kW maximum load<br>• PEMEL and PEMFC considered |
| [96] | 2015 | India | • Optimization<br>• Simulation | • HOMER<br>• Unspecified software for modeling of the anaerobic digester | • Technical<br>• Economic | • Techno-economic comparison of different Integrated Renewable Energy Systems with multiple generation technologies for an unelectrified rural village in West Bengal<br>• $H_2$-based system decreases excess electricity but is the most expensive option considered | • Electrical demand of the village containing around 1000 residents; total energy demand of 60.27 kWh/year<br>• PV, BG, combined heat and power (CHP), vanadium-redox flow BAT, water electrolysis (unspecified, 85% efficiency), FC (unspecified), hydride hydrogen storage |
| [73] | 2016 | Ethiopia | • Optimization<br>• Simulation | • HOMER | • Technical<br>• Economic<br>• Environmental | • Techno-economic optimization of hybrid and integrated approaches of 16 different combinations of generation mix configurations to electrify a rural village in Ethiopia (Mehakelegnaw Zone of the Tigray Region)<br>• Sensitivity variables: Solar radiation, diesel fuel price, BAT prices, PV prices, converter prices have been used as sensitivity variables<br>• $H_2$ integration is a little more expensive than the optimal PV/WT/HKT/BAT system | • Village with 21,450 members (3575 households)<br>• 15,640 kWh average daily energy consumption |

**Table 5.** *Cont.*

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [53] * | 2016 | Iran | • Optimization<br>• Simulation | • HOMER | • Technical<br>• Economic<br>• Environmental | • Techno-economic feasibility study of a PV/WT/DG/FC hybrid system for a residential, not grid-connected household in Teheran, Iran<br>• Electric cooking explicitly considered<br>• WT/$H_2$/BAT hybrid system is the most economical solution | • Average daily energy demand of 17 kWh/d with 1.5 kW peak<br>• Devices powered: Lighting, a color television set, a refrigerator, an air conditioner, a washing machine, a water heater, an electric cooker, and small power appliances |
| [97] | 2017 | India | • Optimization<br>• Simulation | HOMER | • Technical<br>• Economic | • Techno-economic feasibility study of a PV/FC/BAT hybrid system for Jhiriya Kheda, a small unelectrified village located in Huzur Tahsil<br>• Sensitivity analysis on the initial tank level relative to the tank size expressed in percentage | • Energy demand includes domestic, agricultural, commercial, and street lighting<br>• Peak load of the system is 4.7 kW<br>• Optimal solution: PV (5 kW), PEMFC (4 kW), Battery, electrolyzer (0.1–0.3 kW); pressurized hydrogen storage |
| [98] | 2017 | Malaysia | • Optimization<br>• Simulation | HOMER | • Technical<br>• Economic<br>• Environmental | • Techno-economic feasibility study of a renewable hybrid system to electrify a residential long-house in rural Malaysia<br>• PV/FC system is 12% more expensive than a PV/BAT system<br>• Sensitivity analysis performed to assess the impact of variation in solar irradiation and load profile | • The average load consumption is 140.75 kWh/day, and the peak demand is 20.85 kW and average load is 5.81 kW<br>• Optimized system including hydrogen: PV (71 kW), FC (5 kW), EL (3 kW), BAT |
| [99] | 2018 | United Arab Emirates | • Optimization<br>• Simulation | Not mentioned. | • Technical<br>• Economic | • Techno-economic analysis of an off-grid hybrid solar PV/FC power system for a residential community in a desert region in the UAE<br>• Dust accumulation and temperature effects on the PV system were analyzed | • 150 houses with 4500 kWh average daily electricity demand<br>• PEMFC (70% efficiency HHV); generic EL (90% efficiency HHV); pressurized hydrogen tank<br>• Optimal topology: 517 kW PV; 750 kW FC; 250 kW EL 900 kg hydrogen tank) |

**Table 5.** *Cont.*

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [54] * | 2018 | Ethiopia | • Optimization<br>• Simulation | HOMER | • Technical<br>• Economic | • Techno-economic feasibility study (using HOMER) of emission-free hybrid power system of PV/WT/FC/BAT, for a rural village in Ethiopia called Nifasso<br>• The least-cost system under today´s conditions includes PV and BAT<br>• Reducing the PV CAPEX by less than 10% or reducing the FC CAPEX by 20% leads to integration of the FC in the optimal system topology | • Daily power demand and energy needs for the community of 289 households are estimated by considering basic domestic appliances such as television (70 W), CFLs of 11 W and 15 W for lighting, radio/tape (5 W), VCD/DVD player (15 W), refrigerator (70 W), "electric mitad" (2.5 kW), cell phone (2.5 W), and stove (1.5 kW); and public loads including hospital, church, school, water pumps, miller<br>• Least-cost system (NPV) including hydrogen: 150 kW PV, 100 kWh BAT, 10 kW PEMFC, 40 kW PEMEL |
| [100] | 2018 | Ecuador | • Simulation<br>• Optimization | • Simulation of the river energy potential:<br>HEC-RAS<br>System Optimization: HOMER | • Technical<br>• Economic | • Evaluation of an optimal location of an HKT in a cross-section of the river<br>• Techno-economic study of a PV/HKT/FC/BAT hybrid system for electricity supply to Santay Island, Ecuador | • Island village with 235 persons in 46 houses<br>• Average load of 4.18 kW with 5.6 kW peak<br>• HKT/PV/FC/BAT hybrid system<br>• PEMFC (50% efficiency), PEMEL (85% efficiency); compressed hydrogen storage<br>• Optimal system topology (at COE 0.254$/kWh): PV (36 kW), HKT (15 kW), FC (6 kW), EL (10 kW), hydrogen tank (10 kg), BAT (25 kWh) |

**Table 5.** *Cont.*

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [52] * | 2018 | South Africa | • Optimization<br>• Simulation | • HOMER | • Technical<br>• Economic | • Optimization to determine the least-cost pathway to supply energy to an off-grid farming village<br>• The load profile includes lighting, cooking, and hot-water demands<br>• The $H_2$ storage enables for high reliability and grid-like electricity supply<br>• The off-grid system is financially beneficial against grid extension at >4000 km distance | • Napier farming village (4214 inhabitants)<br>• Annual average energy requirement of 1080.60 kWh per day at 370.08 kW of peak load<br>• 1026 kWp PV, 497 kW WT, 300 kW FC, 110 kW EL, 90 kg $H_2$ tank |
| [74] | 2019 | Iran | Optimization | • MATLAB | • Technical<br>• Economic<br>• Environmental | • Multi-objective crow-search optimization of PV/DG/FC system for an off-grid community in Kerman<br>• Total net present costs and loss of power supply probability are considered as decision variables<br>• Integration of hydrogen energy technology will reduce the total cost of the hybrid energy systems | • Residential load with peak demand of 55 kW<br>• PEMFC, PEMEL, pressurized hydrogen tank<br>• Optimal sizes at 0% loss of power supply probability: 443 kW PV, 30 kW DG, 7 kW FC, 26 kW EL |
| [101] | 2019 | Iran | • Optimization<br>• Simulation | HOMER | • Technical<br>• Economic | • Techno-economic optimization on the provision of electricity and hydrogen with renewable grid-connected and off-the-grid systems for Bandar Abbas City<br>• Four types of commercially available vertical axis WT are compared<br>• $H_2$ considered to replace a DG | • Annual average electricity requirement is 13.9 kWh/day (hourly maximum 2.12 kW)<br>• Annual average hydrogen requirement is 85 kg/day (maximum 11.5 kg/h) |

**Table 5.** *Cont.*

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [102] | 2019 | Iran | • Optimization<br>• Simulation<br>• MCDA | HOMER | • Technical<br>• Economic | • Techno-economic comparison of energy systems for electrification of a rural village in off-grid and grid-connected scenario followed by MCDA on economic and technical criteria<br>• Grid-connected scenarios perform better than off-grid cases<br>• Adding a FC to costs by 33–37% compared to a biogas system, but also improve system reliability in off-grid scenarios | • Rural village with 360 people and total average electricity demand of 361 kWh/day; 55.47 kW peak load<br>• Hybrid PV/WT/Biogas (BG)/PEMEL/PEMFC renewable energy system in off-grid and grid-connected scenario |
| [103] | 2019 | Egypt | • Optimization<br>• Simulation | MATLAB | • Technical<br>• Economic | • Techno-economic optimization of a PV/WT/FC hybrid system to electrify a small-scale countryside area in Egypt<br>• Results from firefly algorithm compared to those obtained from the shuffled frog-leaping algorithm and particle swarm optimization<br>• FC has major impact on the system reliability | • 445 houses with mean demand of 35 kW (maximum demand 92 kW)<br>• Village is grid-connected but with low reliability and limited supply<br>• PEMEL (efficiency 90%), PEMFC (efficiency 50%); compressed hydrogen storage<br>• Optimal solution: 41 kW PV; 30 kW FC, 64 kW EL, 182 kWh hydrogen storage |
| [104] | 2020 | Archetype rural community in sub-Saharan Africa | • Experiment<br>• Simulation | MATLAB | • Technical<br>• Environmental<br>• Economic | • Experimental study of an rSOC for simultaneous electricity generation and seawater desalination<br>• Simulation of the rSOC integration into an archetypal minigrid in sub-Saharan Africa and optimization for energy and environmental objectives<br>• The rSOC system shows increased energy performance and lower emissions compared to a PV/DG system, while producing 20–25 L desalted water per capita each year | • Community with 410 inhabitants and 17% electrification rate<br>• Annual electricity demand per capita of 75 kWh/y/p and average electric power of 3.5 kW<br>• Best energy performance solution: PV (39 kW), DG (5 kW), hydrogen storage (125 kWh), rSOC (11 kW), flywheel (58 kW) |

**Table 5.** *Cont.*

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [105] | 2020 | Saudi Arabia | • Optimization<br>• Simulation | HOMER | • Technical<br>• Economic | • Techno-economic feasibility study of a hybrid PV/FC/BAT system to supply a small community close to NEOM in Saudi Arabia<br>• Sensitivity analysis on PV (200 kW–280 kW) variation of the tilt angle of the PV array and the derating factor<br>• Hybrid PV/FC/BAT system is economically advantageous against grid extension or a DG | • Small community with a daily load demand is 500 kWh, with a peak of 35 kW<br>• Optimal solution: 200 kW PV array, 40 kW PEMFC (50% efficiency), 96 batteries, 50 kW converter, 110 kW PEMEL (85% efficiency), and 50 kg hydrogen tank |
| [75] | 2021 | Tanzania | • Simulation<br>• Optimization | MATLAB | • Technical<br>• Economic<br>• Environmental | • Economic impact analysis of integration of an rSOC in a rural community for electricity supply and simultaneous water desalination<br>• A novel evaluation method is proposed to measure to what extent cross-sectoral integration favors economic competitiveness (LCOE decline in ~25%)<br>• Scenarios according to future increase in per capita consumption show valuable economic benefits of water desalination on the overall system performance | • Community with 410 inhabitants and 17% electrification rate<br>• Annual electricity demand per capita of 75 kWh/y/p and average electric power of 3.5 kW<br>• Scenarios of increased per capita consumption according to STEPS |
| [106] | 2021 | Iran | Optimization | MATLAB | • Technical<br>• Environmental | • Improved optimization algorithm (global dynamic harmony search) of an off-grid hybrid WT/FC energy scheme<br>• Case study on a remote area located in Southern Khorasan Province, Iran<br>• Global dynamic harmony search algorithm finds better fitting results than harmony search algorithm | • Peak load of the system 7.5 kW<br>• Generic FC (50% efficiency), generic EL (74% efficiency), compressed hydrogen tank |

**Table 5.** *Cont.*

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [107] | 2021 | India | • Optimization<br>• Simulation | HOMER | • Technical<br>• Economic | • Techno-economic feasibility assessment and optimal sizing of PV/FC energy system based on simulation results for the application of off-grid electricity generation for NE India states<br>• Hydrogen-based power supply is found to be a feasible option for NE India states considering costs and reliability of power supply | • Typical AC electrical load profile of 10 kWp is assumed; scaled daily annual mean value equal to 138 kWh/d<br>• Optimal system design: 110–120 kW PV array, 10–15 kW PEMFC, 30–60 kW PEMEL, 40–60 kg compressed hydrogen tank capacity |
| [108] | 2021 | Iran | • Optimization<br>• Simulation | • HOMER | • Technical<br>• Economic<br>• Environmental | • Techno-economic feasibility study to investigate several hybrid renewable systems for power supply of a remote village in Iran<br>• Sensitivity analysis on component costs, changes in solar irradiation and wind speed, fuel price and discount rate<br>• The hydrogen-based system increases the system costs compared to the optimal solution by 50% but reduce the excess electricity significantly | • Village with 2000 inhabitants<br>• Maximum consumption of each household is 13.68 kWh/day by 2.16 kW peak<br>• PEMFC, PEMEL |
| [109] | 2021 | Brazil | Experiment | / | Technical | • Experimental investigation of the effects on the performance and combustion process of a diesel generator set operating with addition of hydrogen in the air intake<br>• Proposed fuel blending scheme for isolated diesel generators in Brazil<br>• Results show an increase in the engine performance and decrease in $CO_2$, CO, and HC emissions proportional to the increase of $H_2$ | • Genset: BRANCO BD-6500 CF3E (a typical engine used in the amazon region)<br>• Different fuel compositions |

**Table 5.** *Cont.*

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [72] | 2021 | Tibet/China | • Optimization (Amended Water Strider Algorithm)<br>• Simulation | MATLAB | • Technical<br>• Economic | • Techno-economic analysis of an off-grid PV/FC system to provide electricity to a remote Tibetan village<br>• Improved metaheuristic, Amended Water Strider Algorithm, is applied to optimize for the least net present value of the system and compared to particle swarm optimization algorithm, flower pollination optimization algorithm and original Water Strider Algorithm<br>• Sensitivity analysis shows FC and EL costs to have the greatest impact on the overall result | • Jiaju Tibetan Village with 140 houses<br>• PEMFC (85% efficiency); PEMFC; compressed hydrogen storage |
| [94] | 2021 | Unspecified Africa, Middle east, Asia | Rigorous analysis | MATLAB | Technical | • Analysis of failure modes, effects, and critical analysis of failure modes of components of an integrated PV/FC system to supply power and thermal energy to off-grid areas in developing countries<br>• Lack of solar radiation, $H_2$ leakage, failure of photovoltaic module, leakage of oxygen have the highest risk priorities<br>• Generating power with both battery and FC may improve the overall reliability of the system | • System including photovoltaic-thermal (PV/T) module, a cold-water source and hot-water storage tank; inverter, a PEMEL, a $H_2$ and oxygen storage tanks, PEMFC, and a BAT and ancillary components (pumps, compressors, reheater, tanks) |
| [50] | 2022 | Nigeria | • Optimization<br>• Simulation<br>• MCDA | HOMER | • Technical<br>• Economic<br>• Environmental | • Techno-economic optimization and MCDA (COPRAS method) analysis of a hybrid PV/WT/FC/BAT system to power a residential load in Nigeria<br>• While a PV/BAT system is the least-cost solution, MCDA suggests a PV/WT/FC/BAT system<br>• MCDA criteria applied are total capital costs, total net present costs, cost of energy, capacity shortage, excess electricity, total electrical production, NOx emission | • Residential load of a low-income household in Nigeria<br>• Peak demand of 0.53 kW with average daily electricity consumption of 2.71 kWh<br>• Optimal hydrogen-based system: PV (2 kW), WT (0.4 kW), FC (0.4 kW), EL (3 kW) $H_2$ tank (2 kg), BAT (800 Ah) |

* Estimated demand explicitly includes electric cooking appliances.

**Table 6.** Variables of interest for the literature considering hydrogen applications for power supply with large-scale hydrogen production or large-scale power production.

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [49] | 2020 | Iran | • Optimization (improved harmony search)<br>• Geographical information system | • Optimization: MATLAB<br>GIS: Not mentioned | • Technical<br>• Economic<br>• Environmental<br>• Social | • Improved heuristic approach of combining improved harmony search and geographic information system to assess the viability of an off-grid PV/$H_2$ system for rural electrification in Iran<br>• The GIS solution respects technical, economic, environmental, and social parameters in defining the optimal site | • Birjand County region in Iran with 75,000 people living in rural areas and 185,000 in urban areas |
| [46] | 2021 | Nepal | Rigorous analysis | Not mentioned | • Technical<br>• Economic | • Evaluation of the potential of green hydrogen production from surplus hydropower energy and its application in electricity regeneration in off-grid areas in Nepal<br>• Complete diesel-powered thermal plant production can be replaced by electricity generated from hydrogen in 2022 when utilizing 60% of the surplus electricity available | • Surplus from existing hydropower stations (mostly run-of-river types) as primary electricity source<br>• EL energy consumption: 50 kWh per kg $H_2$<br>• FC with 60% efficiency for re-electrification |
| [47] | 2021 | Nigeria | • Simulation | • EnergyPLAN<br>• MATLAB | • Technical<br>• Economic<br>• Environmental | • Evaluation of sustainable electrification pathways for the country case study of Nigeria<br>• Integration of RE technologies in the existing non-RE energy mix<br>• $H_2$ production and storage can significantly increase the share of RE in the power mix | • National power plant mix<br>• Large-scale PEM considered (0.019 kg/kWh) |

**Table 7.** Variables of interest for literature considering separate power supply and hydrogen utilization as clean cooking fuel via combustion.

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [57] | 2007 | Bhutan | • Rigorous analysis | Not mentioned | • Technical<br>• Economic | • Techno-economic feasibility study of a PV/$H_2$-based energy system for supplying power and clean cooking fuel for two case-study villages in rural Bhutan<br>• $H_2$ used as energy storage for power supply and combustion fuel for cooking and space heating<br>• The analysis suggests the technical feasibility for both power supply and clean cooking, while financial viability is likely in regions far of the electricity grid | • Electricity system as described in Table 4<br>• 150 households considered<br>• 112.65 kWh/month cooking energy requirement for an average 5 members household; Estimated 40 Nm3 hydrogen requirement<br>• 5 Nm3 H2/month space-heating requirement for a catalytic space heater<br>• Portable hydrogen cylinder with size providing a week's supply |
| [58] | 2015 | Jamaica | • Experiment<br>• Simulation model | TRYNSYS | • Technical | • Laboratory experimental measurements of a PEMEL, controls, gas management, and metal hydride storage<br>• A semi-empirical numerical model of a solar-powered PEMEL is developed<br>• The hydrogen produced is proposed to be used for cooking applications in a Jamaican village | • The daily cooking demand of the community (20 households) is 39.6 kWh (1.7 kg) hydrogen<br>• The proposed system consists of a 1.14 $Nm^3$ PEMEL operating at 3–13.8 bar metal hydride storage ($LaNi_5$) and 100.8 kW PV |
| [48] | 2016 | Ecuador | • Rigorous analysis | Not specified | • Technical | • Assessment of the hydrogen-production potential to substitute firewood as cooking fuel (and mobility fuel) in rural Ecuador per province<br>• Sufficient hydrogen-production potential in 22 of 23 provinces<br>• Surplus of hydrogen-production potential could be used to additionally supply electricity vie fuel cell to 10% of the national rural households | • Renewable energy sources considered are large-scale PV, WT, HKT, and geothermal power plants<br>• Hydrogen production via PEMEL with 75% based on HHV of $H_2$, and an availability of the electrolytic plant of 95%<br>• Additional PEMFC for electricity supply with average efficiency of 50% |

**Table 7.** *Cont.*

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [66] | 2016 | • Ghana<br>• Jamaica<br>• Indonesia | • Simulation model | TRYNSYS | • Technical<br>• Social<br>• Environmental | • Cooking demand profiles for rural villages (20 households) in Jamaica, Ghana, and Indonesia are evaluated via statistical analysis<br>• Sizing of a hydrogen cooking supply system via numerical modeling<br>• Solar hydrogen potential maps are created for Jamaica, Ghana, and Indonesia<br>• Comparing TMY and recent weather data shows marginal effects on the results<br>• Responses to a survey show great willingness to change from current fuel use to hydrogen fuel in the population, if it was cheaper and safer than current fuels | • Central production of hydrogen via PV supplied PEMEL<br>• Ghana: 77.4 kW PV; 2 × 2 $Nm^3/h$ PEM; 3.35 $kgH_2$ storageJamaica: 63 kW PV; 2 × 2 $Nm^3/h$ PEM; 2.65 kg $H_2$ storageIndonesia: 54 kW PV; 2 × 2 $Nm^3/h$ PEM; 2.7 kg $H_2$ storage<br>• $H_2$ in metal hydride cylinders for distribution to households on a monthly basis<br>• Modified LPG gas stoves for hydrogen combustion |
| [77] | 2018 | Jamaica | LCA | GaBi V6.110 | Environmental | • Environmental LCA of a solar hydrogen-based cooking system in Jamaica<br>• Comparison to other traditional fuels and LPG<br>• Hydrogen-based cooking would mitigate climate-change impacts at the expense of other impact categories<br>• LPG is still environmentally a better option than hydrogen for most of the impacts<br>• The PV modules are by far the greatest contribution to life-cycle emissions of the system | • Rural village with 20 households<br>• PV 100.8 kWp<br>• Cascade high-pressure hydrogen steel storage (13.8 bar)<br>• Low-pressure (3 bar) portable hydrogen cylinders |

**Table 7.** *Cont.*

| Source | Year | Study Location | Methods | Software | Dimensions of Sustainability | Highlights | System Description |
|---|---|---|---|---|---|---|---|
| [63] | 2017 | India | • Rigorous analysis<br>• Simulation | Aspen Plus | • Economic<br>• Technical | • Economic evaluation of DME based on hydrogen produced via water electrolysis as cooking fuel in rural households<br>• Combustion of DME in LPG stoves proposed<br>• DME blending into existing LPG infrastructures proposed (up to 20% by volume) | • Large-scale HKT and PEM with electricity consumption of 49.2 kWh per kg $H_2$ and BOP electricity consumption of 5.1 kWh per kg $H_2$<br>• $CO_2$ capture from ethanol production |

**Author Contributions:** Conceptualization, N.S.; methodology, N.S.; software, N.S.; formal analysis, N.S.; investigation, N.S.; data curation, N.S.; writing—original draft preparation, N.S.; writing—review and editing, N.S. and B.H.; visualization, N.S.; supervision, B.H.; project administration, B.H.; funding acquisition, B.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Horizon 2020 research program under the grant agreement No. 101037428 (ENERGICA). The outcomes will feed into full reports submitted to the European Commission and available on www.energica-h2020.eu.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors express their gratitude to Raluca Dumitrescu for iterative discussions, and Anne van Leeuwen, Lukas Otte, and Tim Ronan Britton for proofreading.

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

## Nomenclature

| Abbreviation | |
|---|---|
| AEL | Alkaline electrolysis |
| AFC | Alkaline fuel cell |
| AEMEL | Anion exchange membrane electrolysis |
| BAT | Battery |
| BG | Biogas |
| CAPEX | Capital expenditure |
| CHP | Combined heat and power |
| DG | Diesel generator |
| EL | Electrolysis |
| FC | Fuel cell |
| GIS | Geospatial information system |
| HECRAS | Hydrologic Engineering Center's River Analysis System |
| HKT | Hydrokinetic turbine |
| HOGA | Hybrid Optimization by Genetic Algorithms |
| HOMER | Hybrid Optimization of Multiple Energy Resources |
| $H_2$ | Hydrogen |
| LCA | Life-cycle assessment |
| LCOE | Levelized costs of electricity |
| MCDA | Multi-criteria decision analysis |
| OPEX | Operational expenditure |
| PAFC | Phosphoric acid fuel cell |
| PV | Photovoltaic |
| PEMEL | Polymer membrane exchange electrolysis |
| PEMFC | Polymer membrane exchange fuel cell |
| PGM | Platinum group metals |
| PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |
| P2H2P | Power-to-hydrogen-to-power |
| rSOC | Reversible solid oxide fuel cell |
| SASA | Search, Appraisal, Synthesis, and Analysis |
| SDG | Sustainable Development Goal |
| SOEL | Solid oxide electrolysis |
| SOFC | Solid oxide fuel cell |
| SSA | Sub-Saharan Africa |
| WT | Wind turbine |

## Appendix A

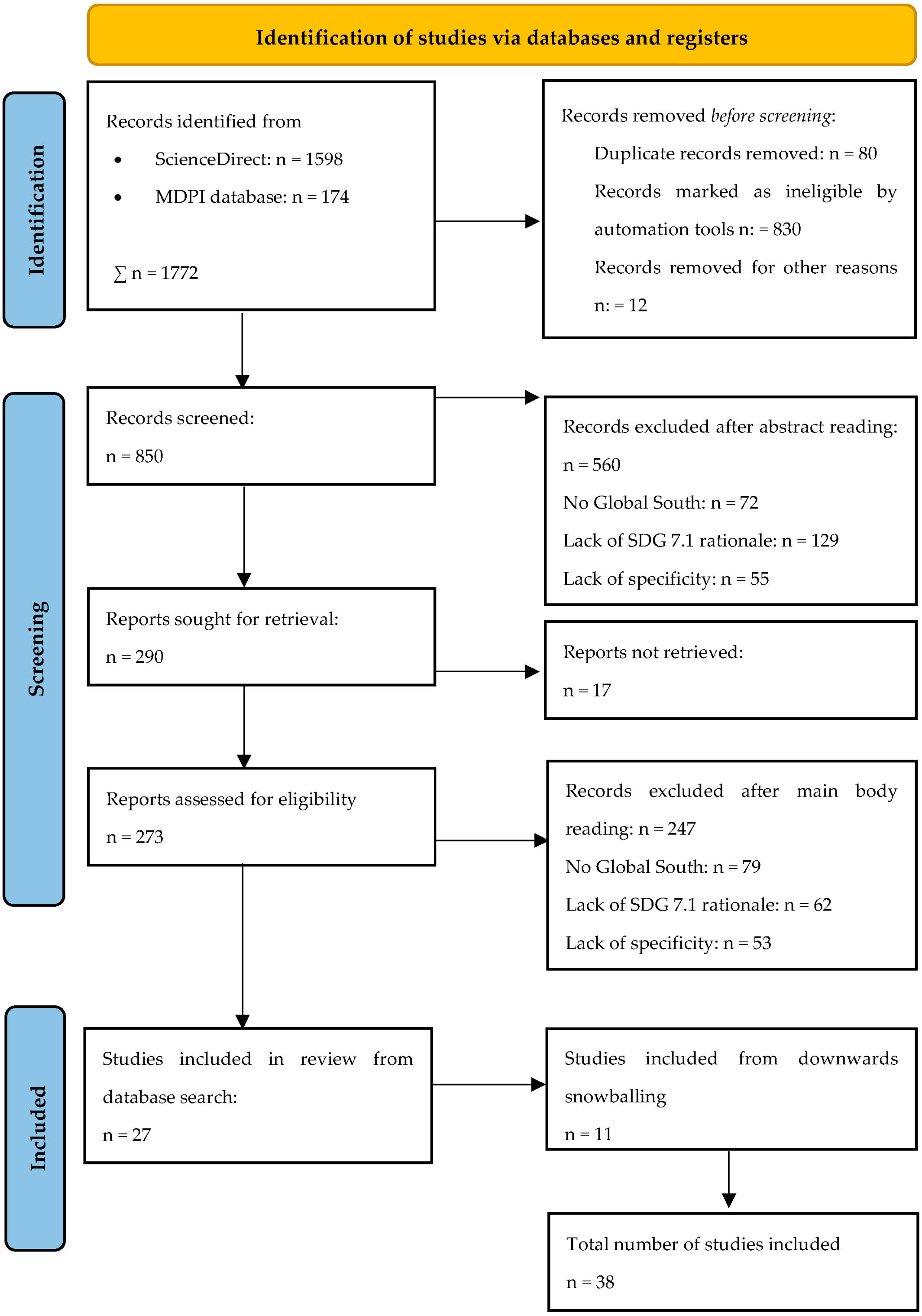
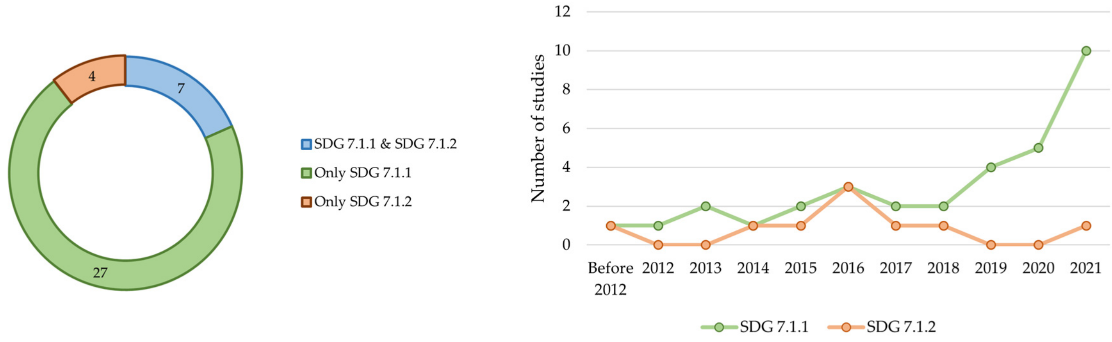
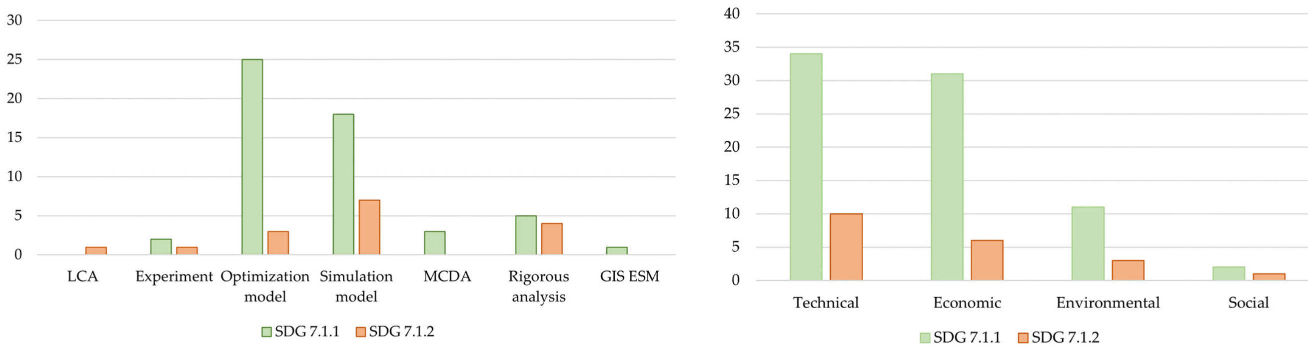



**Figure A1.** PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers, and other sources [110]. Notably, during the initial search on "Hydrogen" + "off-grid" conducted in ScienceDirect, we cross-screened full texts to validate the methodology and exclusion criteria. This reduced the number of records screened for abstract reading only by approximately 50–90.




(**a**) (**b**)

**Figure A2.** (**a**) Total number of studies on SDG 7.1.1 and SDG 7.1.2, and (**b**) Historic trend in publications on SDG 7.1.1 and SDG 7.1.2.




(**a**) (**b**)

**Figure A3.** (**a**) Methods applied in studies on SDG 7.1.1 and SDG 7.1.2, and (**b**) Dimensions covered in studies on SDG 7.1.1 and SDG 7.1.2.

(**a**)

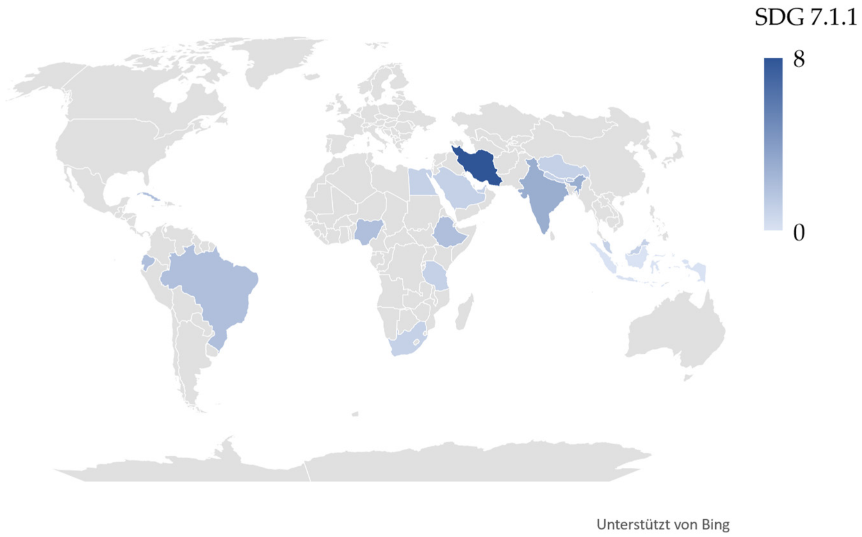



**Figure A4.** *Cont.*

(**b**)

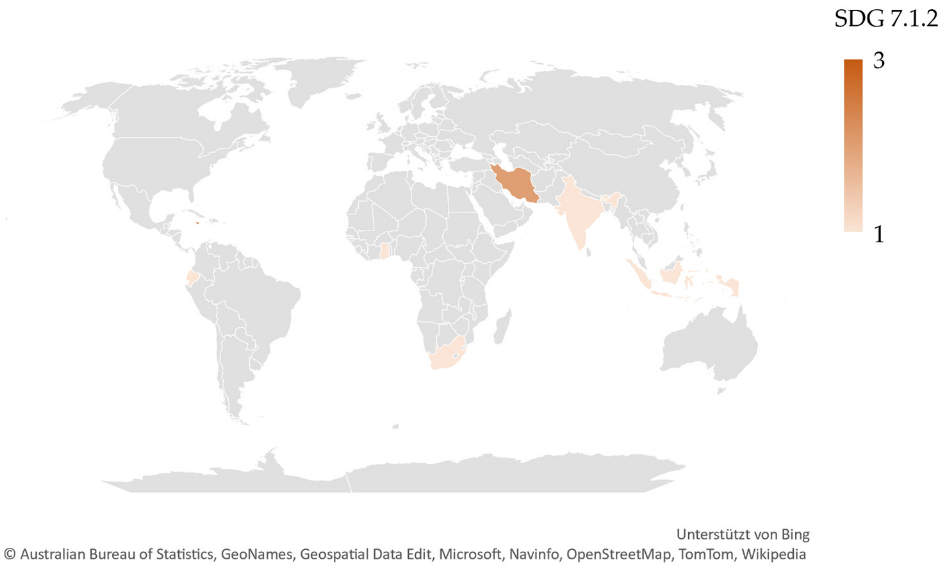



**Figure A4.** Geographic location of the case studies in (**a**) hydrogen in the rationale of SDG 7.1.1. Maximum = Iran (8), India (3), Cuba, Ecuador, Brazil, Ethiopia (2 respectively). Notably, three studies did not specify the country; and (**b**) hydrogen in the rationale of SDG 7.1.2. Maximum = Jamaica (3), Iran (2), others (1 respectively).

## References

1. McCollum, D.L.; Echeverri, L.G.; Busch, S.; Pachauri, S.; Parkinson, S.; Rogelj, J.; Krey, V.; Minx, J.C.; Nilsson, M.; Stevance, A.-S.; et al. Connecting the Sustainable Development Goals by Their Energy Inter-Linkages. *Environ. Res. Lett.* **2018**, *13*, 033006. [CrossRef]
2. González-Eguino, M. Energy Poverty: An Overview. *Renew. Sust. Energ. Rev.* **2015**, *47*, 377–385. [CrossRef]
3. United Nations Sustainable Development Goals Knowledge Platform. Available online: https://sustainabledevelopment.un.org (accessed on 11 July 2022).
4. United Nations SDG Indicator Metadata Indicator 7.1.1. Available online: https://unstats.un.org/sdgs/metadata/ (accessed on 17 October 2022).
5. United Nations SDG Indicator Metadata Indicator 7.1.2. Available online: https://unstats.un.org/sdgs/metadata/ (accessed on 17 October 2022).
6. IEA; IRENA; UNSD; WB; WHO. *Tracking SDG7: The Energy Progress Report 2022*; IEA: Washington, DC, USA, 2022.
7. International Energy Agency. *Access to Electricity—SDG7: Data and Projections*; IEA: Washington, DC, USA, 2022.
8. IRENA. *Innovation Outlook Minigrids*; IRENA: Abu Dhabi, United Arab Emirates, 2016.
9. ESMAP; World Bank Group. *Green Hydrogen in Developing Countries*; The Energy Sector Management Assistance Program: Washington, DC, USA, 2022.
10. Roeben, F.; Schöne, N.; Bau, U. Decarbonizing Copper Production by Power-to-Hydrogen: A Technoeconomic Analysis. *J. Clean. Prod.* **2021**, *306*, 127191. [CrossRef]
11. Hydrogen Europe. *Hydrogen Report 2022*; Hydrogen Europe: Bruxelles, Belgium, 2022.
12. Duran, A.; Sahinyasa, F. An Analysis of Renewable Mini-Grid Projects for Rural Electrification. *Socio-Econ. Plan. Sci.* **2020**, *34*, 106739. [CrossRef]
13. Buttler, A.; Spliethoff, H. Current Status of Water Electrolysis for Energy Storage, Grid Balancing and Sector Coupling via Power-to-Gas and Power-to-Liquids: A Review. *Renew. Sust. Energ. Rev.* **2018**, *82*, 2440–2454. [CrossRef]
14. Li, C.; Baek, J.B. The Promise of Hydrogen Production from Alkaline Anion Exchange Membrane Electrolyzers. *Nano Energy* **2021**, *87*, 106162. [CrossRef]
15. IRENA. *Green Hydrogen Cost Reduction—Scaling Up Electrolysers to Meet the 1.5 °C Climate Goal*; IRENA: Abu Dhabi, United Arab Emirates, 2020.
16. Danish Energy Agency. *Technoloy Data Energy Storage*; Technology descriptions and projections for long-term energy system planning; Danish Energy Agency: København, Denmark, 2018.
17. Akinyele, D.; Olabode, E.; Amole, A. Review of Fuel Cell Technologies and Applications for Sustainable Microgrid Systems. *Inventions* **2020**, *5*, 42. [CrossRef]
18. Arsalis, A.; Georghiou, G.E.; Papanastasiou, P. Recent Research Progress in Hybrid Photovoltaic–Regenerative Hydrogen Fuel Cell Microgrid Systems. *Energies* **2022**, *15*, 3512. [CrossRef]

19. Besha, A.T.; Tsehaye, M.T.; Tiruye, G.A.; Gebreyohannes, A.Y.; Awoke, A.; Tufa, R.A. Deployable Membrane-Based Energy Technologies: The Ethiopian Prospect. *Sustainability* **2020**, *12*, 8792. [CrossRef]
20. International Energy Agency. *The Future of Hydrogen—Seizing Today's Opportunities*; IEA: Paris, France, 2019.
21. Maestre, V.M.; Ortiz, A.; Ortiz, I. Challenges and Prospects of Renewable Hydrogen-Based Strategies for Full Decarbonization of Stationary Power Applications. *Renew. Sustain. Energy Rev.* **2021**, *152*, 111628. [CrossRef]
22. Ministry of Energy Kenya. *Kenya Cooking Sector Study Compressed*; Ministry of Energy Kenya: Nairobi, Kenya, 2019.
23. AbouSeada, N.; Hatem, T.M. Climate Action: Prospects of Green Hydrogen in Africa. *Energy Rep.* **2022**, *8*, 3873–3890. [CrossRef]
24. Mukelabai, M.D.; Wijayantha, U.K.G.; Blanchard, R.E. Renewable Hydrogen Economy Outlook in Africa. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112705. [CrossRef]
25. Mukelabai, M.D.; Wijayantha, K.G.U.; Blanchard, R.E. Hydrogen Technology Adoption Analysis in Africa Using a Doughnut-PESTLE Hydrogen Model (DPHM). *Int. J. Hydrog. Energy* **2022**, *47*, 31521–31540. [CrossRef]
26. Wong, G.; Greenhalgh, T.; Westhorp, G.; Buckingham, J.; Pawson, R. RAMESES Publication Standards: Meta-Narrative Reviews. *J. Adv. Nurs.* **2013**, *69*, 987–1004. [CrossRef] [PubMed]
27. Snyder, H. Literature Review as a Research Methodology: An Overview and Guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [CrossRef]
28. Greenhalgh, T.; Robert, G.; Macfarlane, F.; Bate, P.; Kyriakidou, O. Diffusion of Innovations in Service Organizations: Systematic Review and Recommendations. *Milbank Q.* **2004**, *82*, 581–629. [CrossRef] [PubMed]
29. PRISMA PRISMA Transparent Reporting of Systematic Reviewas and Meta-Analysis. Available online: https://www.prisma-statement.org (accessed on 17 October 2022).
30. Elsevier Science Direct. Available online: https://www.sciencedirect.com (accessed on 18 November 2022).
31. Dados, N.; Connell, R. The Global South. *Contexts* **2012**, *11*, 12–13. [CrossRef]
32. Finance Center for South-South Cooperation Global South Countries. Available online: http://www.fc-ssc.org/en/partnership_program/south_south_countries (accessed on 25 November 2022).
33. Jansen, G.; Dehouche, Z.; Corrigan, H. Cost-Effective Sizing of a Hybrid Regenerative Hydrogen Fuel Cell Energy Storage System for Remote & off-Grid Telecom Towers. *Int. J. Hydrog. Energy* **2021**, *46*, 18153–18166. [CrossRef]
34. Okundamiya, M.S. Size optimization of a hybrid photovoltaic/fuel cell grid connected power system including hydrogen storage. *Int. J. Hydrog. Energy* **2021**, *46*, 30539–30546. [CrossRef]
35. Ayodele, T.R.; Mosetlhe, T.C.; Yusuff, A.A.; Ogunjuyigbe, A.S. O Off-Grid Hybrid Renewable Energy System with Hydrogen Storage for South African Rural Community Health Clinic. *Int. J. Hydrog. Energ.* **2021**, *46*, 19871–19885. [CrossRef]
36. Al Moussawi, H.; Fardoun, F.; Louahlia, H. 4-E Based Optimal Management of a SOFC-CCHP System Model for Residential Applications. *Energy Convers. Manag.* **2017**, *151*, 607–629. [CrossRef]
37. Inayat, A.; Shahbaz, M.; Khan, Z.; Inayat, M.; Mofijur, M.; Ahmed, S.F.; Ghenai, C.; Ahmad, A.A. Heat Integration Modeling of Hydrogen Production from Date Seeds via Steam Gasification. *Int. J. Hydrog. Energy* **2021**, *46*, 30592–30605. [CrossRef]
38. Chantre, C.; Eliziáro, S.A.; Pradelle, F.; Católico, A.C.; Dores, A.; Serra, E.; Tucunduva, R.; Cantarino, V.; Braga, S. Hydrogen Economy Development in Brazil: An Analysis of Stakeholders' Perception. *Sustain. Prod. Consum.* **2022**, *34*, 26–41. [CrossRef]
39. Hensher, D.A.; Wei, E.; Balbontin, C. Comparative Assessment of Zero Emission Electric and Hydrogen Buses in Australia. *Transp. Res. Part D Transp. Environ.* **2022**, *102*, 103130. [CrossRef]
40. Wohlin, C. Guidelines for Snowballing in Systematic Literature Studies and a Replication in Software Engineering. In Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering—EASE '14;, London, UK, 13–14 May 2014; ACM Press: London, UK, 2014; pp. 1–10.
41. Alhamwi, A.; Medjroubi, W.; Vogt, T.; Agert, C. GIS-Based Urban Energy Systems Models and Tools: Introducing a Model for the Optimisation of Flexibilisation Technologies in Urban Areas. *Appl. Energy* **2017**, *191*, 1–9. [CrossRef]
42. Blanco, H.; Codina, V.; Laurent, A.; Nijs, W.; Maréchal, F.; Faaij, A. Life Cycle Assessment Integration into Energy System Models: An Application for Power-to-Methane in the EU. *Appl. Energy* **2020**, *259*, 114160. [CrossRef]
43. Ilskog, E. Indicators for Assessment of Rural Electrification—An Approach for the Comparison of Apples and Pears. *Energy Policy* **2008**, *36*, 2665–2673. [CrossRef]
44. Katre, A.; Tozzi, A. Assessing the Sustainability of Decentralized Renewable Energy Systems: A Comprehensive Framework with Analytical Methods. *Sustainability* **2018**, *10*, 1058–1076. [CrossRef]
45. Shrestha, R.M.; Acharya, J.S. *Sustainable Energy Access Planning—A Framework*; Asian Development Bank: Mandaluyong, Philippines, 2015.
46. Thapa, B.S.; Neupane, B.; Yang, H.; Lee, Y.-H. Green Hydrogen Potentials from Surplus Hydro Energy in Nepal. *Int. J. Hydrog. Energy* **2021**, *46*, 22256–22267. [CrossRef]
47. Bamisile, O.; Babatunde, A.; Adun, H.; Yimen, N.; Mukhtar, M.; Huang, Q.; Hu, W. Electrification and Renewable Energy Nexus in Developing Countries; an Overarching Analysis of Hydrogen Production and Electric Vehicles Integrality in Renewable Energy Penetration. *Energy Convers. Manag.* **2021**, *236*, 114023. [CrossRef]
48. Posso, F.; Sánchez, J.; Espinoza, J.L.; Siguencia, J. Preliminary Estimation of Electrolytic Hydrogen Production Potential from Renewable Energies in Ecuador. *Int. J. Hydrog. Energy* **2016**, *41*, 2326–2344. [CrossRef]
49. Zhang, G.; Shi, Y.; Maleki, A.; Rosen, M.A. Optimal Location and Size of a Grid-Independent Solar/Hydrogen System for Rural Areas Using an Efficient Heuristic Approach. *Renew. Energy* **2020**, *156*, 1203–1214. [CrossRef]

50. Babatunde, O.M.; Munda, J.L.; Hamam, Y. Hybridized Off-Grid Fuel Cell/Wind/Solar PV /Battery for Energy Generation in a Small Household: A Multi-Criteria Perspective. *Int. J. Hydrogen Energy* **2022**, *47*, 6437–6452. [CrossRef]
51. Morrissey, J. *The Energy Challenge in Sub-Saharan Africa: A Guide for Advocates and Policy Makers: Part 2: Addressing Energy Poverty*; Oxfam Research Backgrounder: Boston, MA, USA, 2017; pp. 23–44.
52. Luta, D.N.; Raji, A.K. Decision-Making between a Grid Extension and a Rural Renewable off-Grid System with Hydrogen Generation. *Int. J. Hydrog. Energy* **2018**, *43*, 9535–9548. [CrossRef]
53. Fazelpour, F.; Soltani, N.; Rosen, M.A. Economic Analysis of Standalone Hybrid Energy Systems for Application in Tehran, Iran. *Int. J. Hydrog. Energy* **2016**, *41*, 7732–7743. [CrossRef]
54. Hailu Kebede, M.; Bekele Beyene, G. Feasibility Study of PV-Wind-Fuel Cell Hybrid Power System for Electrification of a Rural Village in Ethiopia. *J. Electr. Comput. Eng.* **2018**, *2018*, 4015354. [CrossRef]
55. Grigoriev, S.A.; Fateev, V.N.; Bessarabov, D.G.; Millet, P. Current Status, Research Trends, and Challenges in Water Electrolysis Science and Technology. *Int. J. Hydrogen Energ* **2020**, *45*, 26036–26058. [CrossRef]
56. A2EI. *Clean Cooking Data Release Report*; A2EI: Germany, Berlin, 2021.
57. Young, D.; Mill, G.; Wall, R. Feasibility of Renewable Energy Storage Using Hydrogen in Remote Communities in Bhutan. *Int. J. Hydrog. Energy* **2007**, *32*, 997–1009. [CrossRef]
58. Topriska, E.; Kolokotroni, M.; Dehouche, Z.; Wilson, E. Solar Hydrogen System for Cooking Applications: Experimental and Numerical Study. *Renew. Energy* **2015**, *83*, 717–728. [CrossRef]
59. Singh, V.K.; Chauhan, N.S. Fundamentals and Use of Hydrogen as a Fuel. *J. Mech. Eng.* **2015**, *6*, 63–68.
60. Kobayashi, H.; Hayakawa, A.; Somarathne, K.; Okafor, E.C. Science and Technology of Ammonia Combustion. *Proc. Combust. Inst.* **2019**, *37*, 109–133. [CrossRef]
61. de Vries, H.; Mokhov, A.; Levinsky, H. The Impact of Natural Gas/Hydrogen Mixtures on the Performance of End-Use Equipment: Interchangeability Analysis for Domestic Appliances. *Appl. Energy* **2017**, *208*, 1007–1019. [CrossRef]
62. The Engineering ToolBox Fuels—Higher and Lower Calorific Values. Available online: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html (accessed on 23 January 2023).
63. Grové, J.; Greig, C.R.; Smart, S.; Lant, P.A. Producing a CO2-Neutral Clean Cooking Fuel in India—Where and at What Cost? *Int. J. Hydrog. Energy* **2017**, *42*, 19067–19078. [CrossRef]
64. Makaryan, I.A.; Sedov, I.V.; Salgansky, E.A.; Arutyunov, A.V.; Arutyunov, V.S. A Comprehensive Review on the Prospects of Using Hydrogen–Methane Blends: Challenges and Opportunities. *Energies* **2022**, *15*, 2265. [CrossRef]
65. Jones, H.R.N. *The Applications of Combustion Principles to Domestic Gas Burner Design*; Taylor and Francis: Oxford, UK, 1990.
66. Topriska, E.; Kolokotroni, M.; Dehouche, Z.; Novieto, D.T.; Wilson, E.A. The Potential to Generate Solar Hydrogen for Cooking Applications: Case Studies of Ghana, Jamaica and Indonesia. *Renew. Energy* **2016**, *95*, 495–509. [CrossRef]
67. Agenbroad, J.; Carlin, K.; Ernst, K.; Doig, S. *Minigrids in the Money: Six Ways to Reduce Minigrid Costs by 60% for Rural Electrification*; Rocky Mountain Institute: Basalt, CO, USA, 2018.
68. AMDA. *Benchmarking Africa ´s Minigrids*; AMDA: New York, NY, USA, 2020.
69. Smolinka, T.; Wiebe, N.; Sterchele, P.; Palzer, A.; Lehner, F.; Jansen, M.; Kiemel, S.; Miehe, R.; Wahren, S.; Zimmermann, F. *Studie IndWEDe—Industrialisierung Der Wasser Elektrolyse in Deutschland: Chancen Und Herausforderungen Für Nachhaltigen Wasserstoff Für Verkehr, Strom Und Wärme*; NOW GmbH: Berlin, Germany, 2018.
70. Silva, S.B.; Severino, M.M.; de Oliveira, M.A.G. A Stand-Alone Hybrid Photovoltaic, Fuel Cell and Battery System: A Case Study of Tocantins, Brazil. *Renew. Energy* **2013**, *57*, 384–389. [CrossRef]
71. Guinot, B.; Champel, B.; Montignac, F.; Lemaire, E.; Vannucci, D.; Sailler, S.; Bultel, Y. Techno-Economic Study of a PV-Hydrogen-Battery Hybrid System for off-Grid Power Supply: Impact of Performances' Ageing on Optimal System Sizing and Competitiveness. *Int. J. Hydrog. Energy* **2015**, *40*, 623–632. [CrossRef]
72. Xu, Y.-P.; Ouyang, P.; Xing, S.-M.; Qi, L.-Y.; Khayatnezhad, M.; Jafari, H. Optimal Structure Design of a PV/FC HRES Using Amended Water Strider Algorithm. *Energy Rep.* **2021**, *7*, 2057–2067. [CrossRef]
73. Brenna, M.; Foiadelli, F.; Longo, M.; Abegaz, T.D. Integration and Optimization of Renewables and Storages for Rural Electrification. *Sustainibility* **2016**, *8*, 982. [CrossRef]
74. Jamshidi, M.; Askarzadeh, A. Techno-Economic Analysis and Size Optimization of an off-Grid Hybrid Photovoltaic, Fuel Cell and Diesel Generator System. *Sustain. Cities Soc.* **2019**, *44*, 310–320. [CrossRef]
75. Baldinelli, A.; Barelli, L.; Bidini, G. Sustainable Water-Energy Innovations for Higher Comfort of Living in Remote and Rural Areas from Developing Countries: From Seawater to Hydrogen through Reversible Solid Oxide Cells. *J. Clean. Prod.* **2021**, *321*, 128846. [CrossRef]
76. Otte, P.P. Solar Cookers in Developing Countries—What Is Their Key to Success? *Energy Policy* **2013**, *63*, 375–381. [CrossRef]
77. Schmidt Rivera, X.C.; Topriska, E.; Kolokotroni, M.; Azapagic, A. Environmental Sustainability of Renewable Hydrogen in Comparison with Conventional Cooking Fuels. *J. Clean. Prod.* **2018**, *196*, 863–879. [CrossRef]
78. Ambition to Action. *The Kenyan Cooking Sector Opportunities for Climate Action and Sustainable Development*; New Climate Institute: Cologne/Berlin, Germany, 2021.
79. Shupler, M.; Menya, D.; Sang, E.; Anderson de Cuevas, R.; Mang'eni, J.; Lorenzetti, F.; Saligari, S.; Nix, E.; Mwitari, J.; Gohole, A.; et al. Widening Inequities in Clean Cooking Fuel Use and Food Security: Compounding Effects of COVID-19 Restrictions and VAT on LPG in a Kenyan Informal Urban Settlement. *Environ. Res. Lett.* **2022**, *17*, 055012. [CrossRef]

80. Shupler, M.; O'Keefe, M.; Puzzolo, E.; Nix, E.; Anderson de Cuevas, R.; Mwitari, J.; Gohole, A.; Sang, E.; Čukić, I.; Menya, D.; et al. Pay-as-You-Go Liquefied Petroleum Gas Supports Sustainable Clean Cooking in Kenyan Informal Urban Settlement during COVID-19 Lockdown. *Appl. Energy* **2021**, *292*, 116769. [CrossRef] [PubMed]
81. Acar, C.; Dincer, I. Comparative Assessment of Hydrogen Production Methods from Renewable and Non-Renewable Sources. *Int. J. Hydrogen Energ.* **2013**, *13*, 1–12. [CrossRef]
82. Ayodele, T.R.; Alao, M.A.; Ogunjuyigbe, A.S.O.; Munda, J.L. Electricity Generation Prospective of Hydrogen Derived from Biogas Using Food Waste in South-Western Nigeria. *Biomass Bioenergy* **2019**, *127*, 105291. [CrossRef]
83. EPA Emission Factors for Greenhouse Gas Inventories. Available online: https://www.epa.gov/sites/default/files/2018-03/documents/emission-factors_mar_2018_0.pdf (accessed on 24 January 2022).
84. Galvez, G.H.; Probst, O.; Lastres, O.; Rodríguez, A.N.; Ugás, A.J.; Durán, E.A.; Sebastian, P.J. Optimization of Autonomous Hybrid Systems with Hydrogen Storage: Life Cycle Assessment. *Int. J. Energy Res.* **2012**, *36*, 749–763. [CrossRef]
85. IEA—International Energy Agency. *World Energy Outlook 2018*; IEA: Washington, DC, USA, 2019; p. 661.
86. Jamaica information service Utech Launches Project to Develop Hydrogen Gas for Cooking. Available online: https://jis.gov.jm/utech-launches-project-to-develop-hydrogen-gas-for-cooking/ (accessed on 25 November 2022).
87. University of Technology Jamaica Sustainable Hydrogen Cooking Gas. Available online: https://www.utech.edu.jm/cseii/event-3.html (accessed on 25 November 2022).
88. ACP Science and Technology Programme. The Application of Solar-Powered Polymer Electrolyte Membrane (PEM) Electrolysers for the Sustainable Production of Hydrogen Gas as Fuel for Domestic Cooking. Available online: http://www.acp-st.eu/content/application-solar-poweredpolymer-electrolyte-membrane-pem-electrolysers-sustainable-product (accessed on 25 November 2022).
89. Hernández Galvez, G.; Dorrego Portela, J.R.; Núñez Rodríguez, A.; Lastres Danguillecourt, O.; Ixtlilco Cortés, L.; Juantorena Ugás, A.; Sarracino Martínez, O.; Sebastian, P.J. Selection of Hybrid Systems with Hydrogen Storage Based on Multiple Criteria: Application to Autonomous Systems and Connected to the Electrical Grid: Hybrid Systems with Hydrogen Storage. *Int. J. Energy Res.* **2014**, *38*, 702–713. [CrossRef]
90. Robert, F.C.; Sisodia, G.S.; Gopalan, S. Sustainable Trade-Offbetween Reliability and Electricity Prices for Geographically Isolated Communities. *Enrgy Proced* **2019**, *5*, 1399–1407. [CrossRef]
91. ESMAP; SE4All. *Beyond Connections: Energy Access Redefined*; The Energy Sector Management Assistance Program: Washington, DC, USA, 2016.
92. Moss, T.; Bazilian, M.; Blimpo, M.; Culver, L.; Kincer, J.; Mahadavan, M.; Modi, V.; Muhwezi, B.; Mutiso, R.; Sivaram, V.; et al. The Modern Energy Minimum: The Case for a New Global Electricity Consumption Threshold, Energy for Growth Hub. Available online: https://www.rockefellerfoundation.org/wp-content/uploads/2020/12/Modern-Energy-Minimum-Sept30.pdf (accessed on 4 November 2022).
93. Foell, W.; Pachauri, S.; Spreng, D.; Zerriffi, H. Household Cooking Fuels and Technologies in Developing Economies. *Energy Policy* **2011**, *39*, 7487–7496. [CrossRef]
94. Ogbonnaya, C.; Abeykoon, C.; Nasser, A.; Ume, C.S.; Damo, U.M.; Turan, A. Engineering Risk Assessment of Photovoltaic-Thermal-Fuel Cell System Using Classical Failure Modes, Effects and Criticality Analyses. *Clean. Environ. Syst.* **2021**, *2*, 100021. [CrossRef]
95. Rahimi, S.; Meratizaman, M.; Monadizadeh, S.; Amidpour, M. Techno-Economic Analysis of Wind TurbinePEM (Polymer Electrolyte Membrane) Fuel Cell Hybrid System in Standalone Area. *Energy* **2014**, *67*, 381–396. [CrossRef]
96. Castellanos, J.G.; Walker, M.; Poggio, D.; Pourkashanian, M.; Nimmo, W. Modelling an Off-Grid Integrated Renewable Energy System for Rural Electrification in India Using Photovoltaics and Anaerobic Digestion. *Renew. Energy* **2015**, *74*, 390–398. [CrossRef]
97. Khemariya, M.; Mittalb, A.; Baredarb, P.; Singh, A. Cost and Size Optimization of Solar Photovoltaic and Fuel Cell Based Integrated Energy System for Un-Electrified Village. *J. Energy Storage* **2017**, *14*, 62–70. [CrossRef]
98. Das, H.S.; Tan, C.W.; Yatim, A.H.M.; Lau, K.Y. Feasibility Analysis of Hybrid Photovoltaic/Battery/Fuel Cell Energy System for an Indigenous Residence in East Malaysia. *Renew. Sust. Energ. Rev.* **2017**, *76*, 1332–1347. [CrossRef]
99. Ghenai, C.; Salameh, T.; Merabet, A. Technico-Economic Analysis of off Grid Solar PV/Fuel Cell Energy System for Residential Community in Desert Region. *Int. J. Hydrogen Energ* **2018**, *45*, 11460–11470. [CrossRef]
100. Lata-García, J.; Jurado, F.; Fernández-Ramírez, L.M.; Sánchez-Sainz, H. Optimal Hydrokinetic Turbine Location and Techno-Economic Analysis of a Hybrid System Based on Photovoltaic/Hydrokinetic/Hydrogen/Battery. *Energy* **2018**, *159*, 611–620. [CrossRef]
101. Jahangiri, M.; Haghani, A.; Alidadi Shamsabadi, A.; Mostafaeipour, A.; Pomares, L.M. Feasibility Study on the Provision of Electricity and Hydrogen for Domestic Purposes in the South of Iran Using Grid-Connected Renewable Energy Plants. *Energy Strategy Rev.* **2019**, *23*, 23–32. [CrossRef]
102. Rad, M.A.V.; Ghasempour, R.; Rahdan, P.; Mousavi, S.; Arastounia, M. Techno-Economic Analysis of a Hybrid Power System Based on the Cost-Effective Hydrogen Production Method for Rural Electrification, a Case Study in Iran. *Energy* **2020**, *190*, 116421. [CrossRef]
103. Samy, M.M.; Barakat, S.; Ramadan, H.S. Techno-Economic Analysis for Rustic Electrification in Egypt Using Multi-Source Renewable Energy Based on PV/ Wind/ FC. *Int. J. Hydrogen Energy* **2020**, *45*, 11471–11483. [CrossRef]

104. Baldinelli, A.; Barelli, L.; Bidini, G.; Cinti, G.; Di Michele, A.; Mondi, F. How to Power the Energy–Water Nexus: Coupling Desalination and Hydrogen Energy Storage in Mini-Grids with Reversible Solid Oxide Cells. *Processes* **2020**, *8*, 1494. [CrossRef]
105. Rezk, H.; Kanagaraj, N.; Al-Dhaifallah, M. Design and Sensitivity Analysis of Hybrid Photovoltaic-Fuel-Cell-Battery System to Supply a Small Community at Saudi NEOM City. *Sustainability* **2020**, *12*, 3341. [CrossRef]
106. Zhang, W.; Maleki, A.; Pourfayaz, F.; Shadloo, M. An Artificial Intelligence Approach to Optimization of an Off-Grid Hybrid Wind/Hydrogen System. *Int. J. Hydrogen Energy* **2021**, *46*, 12725–12738. [CrossRef]
107. Pal, P.; Mukherjee, V. Off-Grid Solar Photovoltaic/Hydrogen Fuel Cell System for Renewable Energy Generation: An Investigation Based on Techno-Economic Feasibility Assessment for the Application of End-User Load Demand in North-East India. *Renew. Sust. Energ. Rev.* **2021**, *149*, 111421. [CrossRef]
108. Razmjoo, A.; Gakenia Kaigutha, L.; Vaziri Rad, M.A.; Marzband, M.; Davarpanah, A.; Denai, M. A Technical Analysis Investigating Energy Sustainability Utilizing Reliable Renewable Energy Sources to Reduce $CO_2$ Emissions in a High Potential Area. *Renew. Energy* **2021**, *164*, 46–57. [CrossRef]
109. Rocha, H.M.Z.; Nogueira, M.F.M.; Guerra, D.R.D.S.; Hernández, J.J.; Queiroz, L.S. Improving the Usage of Vegetable Oils in Generator Sets Used for Off-Grid Power Generation by Hydrogen Addition. *Int. J. Hydrogen Energy* **2021**, *46*, 35479–35494. [CrossRef]
110. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [CrossRef]