energies

Review

Energy Hub and Micro-Energy Hub Architecture in Integrated Local Energy Communities: Enabling Technologies and Energy Planning Tools

Mosè Rossi [1], Lingkang Jin [2], Andrea Monforti Ferrario [3], Marialaura Di Somma [4], Amedeo Buonanno [5], Christina Papadimitriou [2], Andrei Morch [6], Giorgio Graditi [3] and Gabriele Comodi [1,]*

[1] Department of Industrial Engineering and Mathematical Sciences (DIISM), UNIVPM—Marche Polytechnic University, 60131 Ancona, Italy; mose.rossi@staff.univpm.it
[2] Eindhoven Institute for Renewable Energy Systems, Eindhoven, TU/e—Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands; l.jin@tue.nl (L.J.); c.papadimitriou@tue.nl (C.P.)
[3] ENEA—Italian National Agency for New Technologies, Energy and Sustainable Economic Development, 00196 Rome, Italy; andrea.monfortiferrario@enea.it (A.M.F.); giorgio.graditi@enea.it (G.G.)
[4] Department of Industrial Engineering (DII), UNINA—University of Naples Federico II, 80125 Naples, Italy; marialaura.disomma@unina.it
[5] Department of Energy Technologies and Renewable Sources, ENEA—Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Portici, 80055 Naples, Italy; amedeo.buonanno@enea.it
[6] SINTEF Energy Research, NO-7465 Trondheim, Norway; andrei.morch@sintef.no
* Correspondence: g.comodi@univpm.it; Tel.: +39-071-220-4761

Abstract: The combination of different energy vectors like electrical energy, hydrogen, methane, and water is a crucial aspect to deal with in integrated local energy communities (ILECs). The ILEC stands for a set of active energy users that maximise benefits and minimise costs using optimisation procedures in producing and sharing energy. In particular, the proper management of different energy vectors is fundamental for achieving the best operating conditions of ILECs in terms of both energy and economic perspectives. To this end, different solutions have been developed, including advanced control and monitoring systems, distributed energy resources, and storage. Energy management planning software plays a pivotal role in developing ILECs in terms of performance evaluation and optimisation within a multi-carrier concept. In this paper, the state-of-the-art of ILECs is further enhanced by providing important details on the critical aspects related to the overall value chain for constituting an ILEC (e.g., conceptualisation, connecting technologies, barriers/limitations, control, and monitoring systems, and modelling tools for planning phases). By providing a clear understanding of the technical solutions and energy planning software, this paper can support the energy system transition towards cleaner systems by identifying the most suitable solutions and fostering the advancement of ILECs.

Keywords: energy hub; energy planning; integrated local energy community; multi-carrier energy systems; optimisation energy software

Citation: Rossi, M.; Jin, L.; Monforti Ferrario, A.; Di Somma, M.; Buonanno, A.; Papadimitriou, C.; Morch, A.; Graditi, G.; Comodi, G. Energy Hub and Micro-Energy Hub Architecture in Integrated Local Energy Communities: Enabling Technologies and Energy Planning Tools. *Energies* **2024**, *17*, 4813. https://doi.org/10.3390/en17194813

Academic Editor: François Vallée

Received: 27 July 2024
Revised: 9 September 2024
Accepted: 24 September 2024
Published: 26 September 2024

1. Introduction

This section aims to provide an extensive overview on the future deployment of integrated local energy communities (ILECs), each of them having its importance in terms of enhancing the deployment of ILECs and making a viable solution in the energy sector from both an environmental and economic point of view. The sections are structured as follows: Section 1.1 gives an insight into the motivations for pursuing sector coupling with different technologies, most of them already available, as well as providing a background of the European Union's (EU) choices to achieve determined economic and environmental targets. Section 1.2 is devoted to highlighting the main contributions to sector coupling by exploring both energy hub (EH) and micro-energy hub (mEH) concepts considering the current limitations that are slowing down the deployment of enabling technologies for sector coupling. Section 1.3 presents the current research trends related to the multi-energy systems approach.

1.1. Background and Motivation for Pushing towards Sector Coupling

Nowadays, energy and environmental contexts are closely interlinked, so their proper assessment and safeguarding are mandatory for achieving a development that meets the needs of the present without compromising the ability of future generations to meet their own needs [1–3]. In this regard, the EU has set various goals and initiatives to address these challenges, promote a sustainable and resilient energy system, reduce greenhouse gas emissions, protect the environment, and ensure a prosperous and healthy future for EU citizens [4–6].

The International Energy Agency (IEA) concluded that the energy sector has the highest contribution to carbon emissions since it accounts for 40% of the global emissions that come from power plants fired by fossil fuel-based fuels [7]. Renewables are considered the main solution for achieving 60% of carbon emissions reduction by 2030 and the net-zero emissions target by 2050 [8]. The total renewable capacity doubled in the last decade [8]; however, solar, wind, hydropower, and ocean energy need to widen their share quickly to achieve the net-zero emissions target set up to 17% by 2030. Thus, yearly renewable energy must increase by approximately 13% in the period 2022–2030, which is doubled than the one observed in the period 2019–2021. However, one of the main drawbacks of renewables is their energy production variability, which is a significant challenge associated with their integration into the electricity grid. The main key points regarding the issue of renewable production variability are:

(1) Intermittency since their production is dependent on weather conditions as well as on seasonality [9,10];
(2) Grid stability, which requires balance of real-time electricity supply and demand [11,12];
(3) Curtailment due to the excess of renewable energy generation to prevent grid overloading, or balance supply and demand [13,14].

The three previously mentioned issues can be solved by using energy storage systems (ESSs) to a great extent. Sánchez et al. [15] highlighted the need for using ESSs to satisfy the energy demand when there is an unavailability of renewables for a fixed time frame, thus storing the energy seasonally. This study is mainly focused on coupling solar and wind energy, which anyway showed an overproduction throughout the year that requires the application of energy storage solutions; furthermore, they will also lower the electricity cost considerably. Li et al. [16] dealt with the development in the field of lithium-ion battery recycling, namely those related to cathode materials. Batteries that have ended their lifetime must be evaluated for either being regenerated and reused in other sectors (e.g., second-life batteries for energy purposes) or disposed of. All battery regeneration techniques would lead to lower CO_2 emissions (e.g., 59.95 MJ/kg and 5.87 kg/kg), while the one analysed by the authors of this work achieved the lowest value of 25.62 MJ/kg and 2.14 kg/kg as well as the highest economic profit of USD 1.96/kg. Alkhalidi et al. [17] reviewed the design techniques of batteries coupled with renewables to ensure reliability and safety operations. The authors proposed important recommendations to help engineers in designing and building battery compartments, as well as maximising their operation in supporting renewable energy systems (RESs) and useful life. The increase of additional renewables capacity previously discussed, together with energy storage systems, will boost the electrification process that the EU is currently pursuing to reach a net-zero emissions target by 2050.

Since the electrification process of different sectors is growing steadily, the electricity share in the overall energy consumption will increase by 7% from 2021 to 2030 [18]. The trend is currently positive, but a booster is anyhow needed. Besides the energy sector, the electrification process will touch several sectors:

- Transportation: where internal combustion engine (ICE) vehicles (e.g., cars, buses, trucks, etc.) will be replaced with electric vehicles (EVs) [19];
- Industry: where fossil fuel-powered machinery and equipment (e.g., electric furnaces, electric boilers, electric heat pumps, and other electric-powered technologies) will be replaced by electric alternatives [20];
- Residential: where there will be the shifting from fossil fuel-based heating systems (e.g., oil or natural gas-fuelled boilers) to electric heating systems as heat pumps [21];
- Agriculture: where electric pumps will replace diesel-powered irrigation pumps, electric machinery will be used for planting and harvesting, and electric equipment will be adopted for livestock farming [22].

The electrification process will also require adequate infrastructure, policy support, and technological advancements for large-scale deployment. In such a context, Hong et al. [23] performed a study related to the benefits of fleet and infrastructure costs, electricity grid, and environment due to their electrification and automation. The results showed that only 1% of electric fleet penetration would lead to an overall cost reduction of about 18%, a fleet reduction close to 20%, and a lower peak reduction of road transportation of nearly 14%. Bauer et al. [24] focused on data related to transportation in New York City and San Francisco (USA) and found out that three/four electric charging stations per square mile, with power of at least 50 kW each, will further deploy the spread of electric transportation since the same service of ICE-based vehicles would be guaranteed. Consequently, the optimal modelling of the infrastructure is needed for properly managing increased loads as well as providing good quality services. Azin et al. [25] proposed an optimisation model for supplying integrated demands. The model allows selecting those locations where automated EV charging stations can be placed (e.g., robots take over the charging process when the car is parked autonomously without any human intervention), considering some constraints like power grid limitations for minimising power costs. Results revealed that stations will be mostly located on routes with high traffic. The low number of stations in shorter routes comes from the limited autonomous EV range. Palomino et al. [26] studied three different charging infrastructure cases (e.g., residential, public highways, and bus transportation), where each of them has different challenges to deal with and the role of decisionmakers is crucial to properly assess and guarantee EVs implementation in the future.

Although the electrification process can be a solution for decarbonising some sectors like the ones previously briefly discussed, its large-scale applicability might be trivial for other kinds of end-uses, particularly those applications where energy is used as feedstock and heavy means of transport (e.g., aeroplanes, ships, trucks, etc.). For this reason, the decarbonisation process of these end-uses requires the introduction of alternative energy vectors like carbon-neutral gases or fuels. Regarding the former, power-to-gas (PtG) technologies, which is an example of cross-vector, are considered viable solutions; in this regard, hydrogen will have an important role as an energy carrier [27]. Hydrogen will be mainly produced by water electrolysis through renewables, so-called ‘Green hydrogen’, that could be used as a fuel in the form of synthetic methane or liquid fuel, by its reaction with carbon dioxide (CO_2) or carbon monoxide (CO), to accomplish the CO_2 emissions obligations [27]. Up to now, PtG is not cost-effective since the hydrogen production cost is still high; however, in the longterm (e.g., 2030–2050), its cost would decrease to the present cost of biogas production, thus becoming more competitive [27]. In such a context, the sector coupling approach was thought to interconnect (integrate) energy-consuming sectors with the power-producing ones. The European Commission (EC) initially interpreted the term sector coupling as an interconnection of EU electricity and gas sectors’ markets and infrastructure to move further with realising a decarbonised energy system; in broader terms, this was meant as a possible way for giving more flexibility to the energy system and, at the same time, further contributing in a cleaner and more cost-effective way of energy production and usage [28]. Starting initially in Germany and mostly referring to the electrification of the end-uses such as space heating and transport to increase the share of RESs in these sectors, the process became duly recognised in Europe [27]. The concept has been recently extended to supply-side integration with a focus on the interaction of the power and gas sectors. In broader terms, sector coupling means replacing conventionally distinguished branches of the energy industry (e.g., electricity, heating and cooling, transport, and industrial consumption processes) with a rather holistic approach. Figure 1 introduces the main principles of the sector coupling concept that involves direct and indirect electrification. Indeed, renewables can directly feed heat pumps for satisfying end-users' thermal/cooling demand or be transformed into hydrogen via water electrolysis. Hydrogen together with synthetic methane, which is created by combining hydrogen and captured CO_2, can boost the decarbonisation of the hard-to-abate sectors through the power-to-heat (PtH) process in industry and transport, while the electrification process can be applied to both commercial and services, residential, and transport.

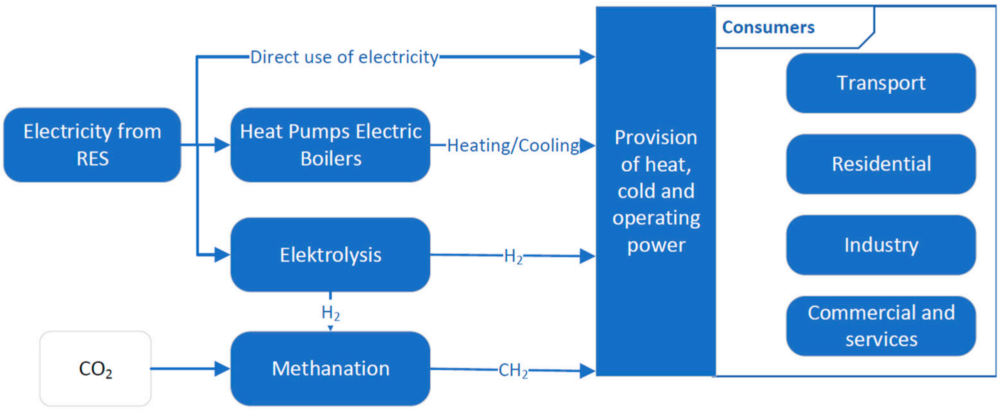

Figure 1. The main principles of sector coupling are where renewables are directly used to feed heat pumps or converted into hydrogen for being directly used in hard-to-abate sectors along with synthetic methane [29].

The European Technology and Innovation Platform Smart Networks for Energy Transitions (ETIP SNET) applied the concept of sector coupling as a technological pillar in the development of their concept of a "System of Systems", which was launched in ETIP-SNET's "Vision 2050" [29]. The concept introduced a conceptual outlook for a flexible energy system, which resides on the electric grid as its principal "backbone". Electricity has a principal role in transformation processes across several energy carriers, which employ several conversion technologies such as PtG, PtH, and power-to-liquid (PtL). This enables the transition of vast volumes of energy within Europe and thus allows interconnection among several principal hubs in the energy system. The European energy system will rely on formidable volumes of energy stored by using PtG, PtH, and PtL technologies. The seasonal long-term challenges related to energy balances will be resolved by high-efficiency conversion technologies, which will also be coupled with domestic heating and cooling demands and thereby maximise the conversion efficiency rates. In "Vision 2050", ETIP-SNET interconnects multiple energy carriers by storage technologies such as hydropower, providing long- and short-term storages, especially in some of the mountainous areas in Europe, and gas storages as key elements for ensuring the adequacy of the energy systems with low-carbon emissions by 2050 and beyond. Several European industrial associations integrated the ETIP-SNET's vision into their corporate strategies. This includes the Research, Development and Innovation (RD&I) Roadmap 2020–2030 [30] of the European Network of Transmission System Operators (ENTSO-E), where 'One System of Integrated Systems' has been defined as the first RD&I Area/Cluster and encompasses a stepwise process towards integrated energy systems in so-called Flagship 1 "Optimising cross-sector integration". Already in 2019, WindEurope published a position paper, "Wind-to-X", where they highlighted the urgent need for a legal framework that will regulate the sector coupling, which will clearly stipulate roles and responsibilities for the major market and regulated actors (as TSOs and DSOs) and rules for coupling electricity and gas infrastructures to encourage an optimal deployment and operation of the assets on all scales. Sector coupling between electricity and other networks interconnected by hydrogen is foreseen in the medium- to long-term. This will allow deployment of multiple end-uses (e.g., gas, buildings, mobility, power generation, storage).

1.2. Sector Coupling through the Integrated Local Energy Community Concept and Contribution of the Paper

In sector coupling deployment through integrated local energy communities (ILECs), enabling technologies play a crucial role. The ILEC concept stands for a set of active energy users that maximise the benefits and minimise the costs using optimisation procedures in producing and sharing energy coming from different carriers (e.g., electricity, heating/cooling, etc.). In particular, the optimal management of different energy carriers is crucial for achieving the best operating conditions of ILECs in terms of both energy and economic perspectives. So far, several energy conversion and storage technologies deal with more than two energy carriers simultaneously [31]. Nazar–Heris et al. [32] investigated the interdependencies between different energy carriers as multi-carrier energy networks consisting of power, gas, heating, and water carriers. Generation units like combined heat and power (CHP) and gas-fired boilers have been considered, as well as storage facilities like pump storage, water desalination units, heat, and gas storage. The storage units provided flexibility to the overall system, thus reducing its operation cost [33]. Furthermore, the application of multi-carrier energy networks has an important impact on the energy market, as reported by Nasiri et al. [34]. They proposed an approach to calculate the impact of renewables and energy storage coupling on local and regional markets; in particular, the minimisation of both purchase (e.g., maximisation of energy storage and wind energy production) and sell (e.g., minimisation of generation units and natural gas producers' utilisation) electricity prices has been analysed, showing that the operation cost per day lowered by 7.01% and 1.7%, respectively. Most of the technologies involved in multi-energy carrier systems have a technology readiness level (TRL) of 9, meaning that they are already mature and available in the market, while others are still under development since new energy carriers (e.g., hydrogen) are taking the field to further contribute to the decarbonisation process in different energy-intensive sectors [35,36].

However, there are still technical and non-technical (e.g., regulatory) barriers/limitations that do not allow their proper implementation in ILECs and need to be overcome quickly [36]. Technical limitations refer to those technologies involved in the definition of multi-energy carrier systems like generation, storage, and transportation. As previously said, technologies with different TRLs affect considerably the deployment of ILECs, particularly the definition and the final efficiency of the overall system in which they are installed. Apart from this, the low flexibility of some technologies has also had an important impact, and flexibility services are crucial in ILECs for adjusting generation, storage, and consumption. Most of the consolidated technologies are already available in the market and operate mainly in rated conditions, while their efficiencies are lower when operating at part-load conditions due to the end-users' demand variation. This issue can be overcome by using the same or complementary technologies, with different sizes together with energy storage ones, capable of operating efficiently while the end-users demand changes. In this case, proper control strategies allow identifying the most suitable technology to operate under certain load conditions by guaranteeing high grid stability, reliability, and main economic goals [37].

The implementation of sector coupling technologies is also facing a significant limitation related to their economic feasibility. Many of these technologies are currently not competitive in various applications and regions, impeding their widespread adoption. Given that the adoption of these solutions is still in its early stages, further technological and economic investigations must be carried out [38]. In addition to economic challenges, national and international regulations may pose restrictions on sector coupling according to [39]; for instance, in the case study of the German energy sector, renewable energies and storage solutions may encounter obstacles due to CO_2 emission restrictions. While cross-sector coupling measures that involve different energy carriers are on the rise, electrification remains a crucial approach for integrating end-use sectors [40]. Consequently, technologies such as power-to-hydrogen and power-to-heat, which enable cross-sector coupling, are not yet widely adopted. Based on the findings presented in [41], the integration of power-to-hydrogen infrastructure with other sector-coupling measures becomes vital in achieving a zero-emission energy system in Germany. Hence, the primary technical constraint impeding the implementation of sector coupling technologies lies in the lack of economic and technical competitiveness of certain technologies.

While the electrification of end-user facilities has been extensively studied, cross-sector coupling technologies still require further development both from a technological and environmental perspective due to their relatively recent adoption. Considering this, the present paper aims at providing insight into the status of ILEC implementations by considering all the previously discussed aspects and addressing them in detail. Particular attention is given to both energy conversion technologies/systems and energy system modelling tools to provide all the information required for resembling, studying, and properly analysing the design phases and operation of ILECs. Several reviews have been produced so far on multi-carrier energy systems, addressing a wide range of aspects going from technologies to modelling, optimisation, and management approaches. Most of them only focus on technical aspects, such as [42–44], that deal with the typical configurations of EHs and the conversion technologies composing them. Mohammadi–Ivatloo et al. [45] addressed the issue of the storage facilities within the EH, whereas [46] dealt with the different demand response services that can be offered by EHs. Mohammadi et al. [47] reviewed the energy management approaches used for multi-energy systems, whereas [48,49] also focused on their modelling approaches and interaction with external markets and networks.

This paper fills the gap of the state-of-the-art regarding ILECs by providing a comprehensive analysis with important details on the critical aspects of the overall value chain for constituting an ILEC (e.g., conceptualisation, technologies involved and their barriers/limitations, control and monitoring systems, and modelling tools for the ILEC planning phase). This paper first defines the EH concept as the primary architectural and operational approach for integrating various energy carriers at the local level and mEHs that represent the prosumer (e.g., industrial, tertiary, or residential sectors) within the community. The energy conversion technologies installable at mEH and EH levels are provided by also identifying the main techno-economic barriers. A detailed description of the energy planning software that can support the unification of various energy carriers and the development of ILECs is also provided. The paper also highlights the need for further development in this field, proposing possible enhancements for software and making recommendations for future investigations. The importance of this work lies in the need for sustainable integrated energy systems that can meet the increasing multi-energy demand while reducing carbon emissions cost-effectively and sustainably. By providing a clear understanding of technical solutions and energy planning software available so far, this paper can give hints on the transition to more sustainable energy systems, identify the most suitable technical solutions, and foster the advancement of ILECs.

1.3. Main Research Trends Related to the Multi-Carrier Approach

As mentioned before, the implementation of ILECs is fundamental for further deploying the sector coupling approach at different levels, but this process is being slowed down by barriers and limitations of various kinds (e.g., economical, legislative, technical, etc.). Although these factors might look independent of one another, they are strictly linked such that the consequences coming from one of them are reflected in the others and vice versa. For this reason, the present analysis collects the main contributions coming from the state-of-the-art and provides useful information on the effects of each barrier/limitation in a wider context, thus providing an overview of how they affect the ILECs deployment and tying to discuss which might be possible solutions for overcoming this. Furthermore, to the authors' knowledge, most of the available scientific papers do not deal with all the possible barriers and limitations that could be encountered in the ILECs deployment.

This subsection aims at presenting the main research trends related to the multi-carrier approach by addressing the different technical solutions for ILECs. To serve the objectives of the paper, the following methodology has been followed: (1) The key areas of focus have been identified; (2) Topics of interest have been identified under each area; (3) Review of the related documents in the literature; (4) Analysing barriers and challenges; and (5) Defining recommendations for further research. The methodology, along with the key areas of focus and topics, are shown in Figure 2.

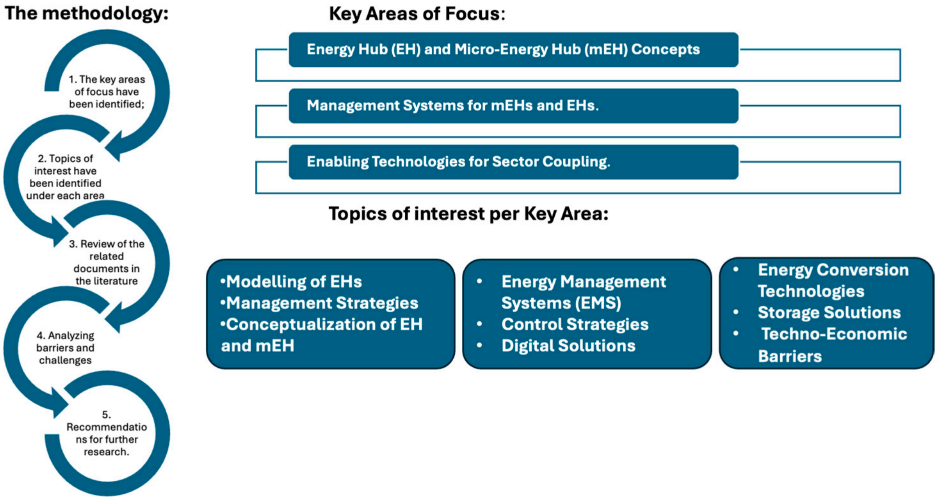

Figure 2. The methodology used in the paper for identifying the research trends related to the multi-carrier aspects under the ILEC concept.

Several documents related to main energy conversion technologies that apply to ILECs have been analysed. Within the development and the implementation of ILECs, the definition of EH is considered a fundamental step to further improve energy efficiency in final uses and increase the safety of energy supply since it is locally produced and consumed, as well as reduce environmental emissions due to the exploitation of local sources, mostly renewables. EH stands for local energy production through multiple energy carriers that are converted, stored, and supplied to meet the local multi-energy demand. It represents an interface between the local community and external energy infrastructures and/or loads. EHs exchange energy at their interfaces to achieve an optimal balance within the neighbouring EHs from both technical and economic points of view. Starting from this concept, the definition of both mEH and EH falls within the integrated energy system concept that consists of multi-energy generation and storage technologies for meeting the energy demand. References reported in Table 1 address the EH concept within the energy sector in various sizes and forms, starting from its modelling and moving to its optimal management considering different installed energy conversion technologies. In particular, the aim of Table 1 is to show the trends of research works addressing the EH concept over time, starting from 2002 up to now (approximately 20 years). It is worth noting that all of them provide a state-of-the-art only on the EH conceptualisation without providing detailed information about connecting technologies and possible barriers/limitations coming from their practical implementation.

Table 1. Distribution of the literature through the years addressing mEH and EH concepts (e.g., modelling and optimal management).

References	Year	# of References	Percentage of Each Paper Compared to the Overall Reviews
[50]	2002	1	4.55
[51]	2005	1	4.55
[52–55]	2007	4	18.15
[56]	2011	1	4.55
[57,58]	2013	2	9.09
[44]	2014	1	4.55
[59,60]	2015	2	9.09
[61]	2016	1	4.55
[42,62]	2017	2	9.09
[47,63]	2018	2	9.09
[64]	2019	1	4.55
[65]	2020	1	4.55
[66]	2021	1	4.55

The proper functioning of energy conversion technologies in mEHs and EHs is strictly dependent on technologies interconnected through digital solutions capable of controlling and managing them optimally and seeking to expedite the energy transition towards decentralised and bidirectional management systems. They achieve this by utilising distributed architectures, along with hardware and software systems, to monitor and operate various energy systems across different levels. A detailed description of management systems used in mEHs and EHs has been carried out by considering information coming from the current state-of-the-art, which is reported in Table 2, which lists the distribution of the literature over the years regarding mEHs and EHs management system applications.

Table 2. Distribution of literature that addresses mEHs and EHs management system applications.

References	Year	# of References	Percentage of Each Paper Compared to the Overall Reviews
[67]	2015	1	3.70
[68]	2016	1	3.70
[47]	2018	1	3.70
[69,70]	2019	2	7.41
[71,72]	2020	2	7.41
[73–81]	2021	9	33.33
[82–87]	2022	6	22.23
[88–92]	2023	5	18.52

Characteristics of enabling technologies in local multi-carrier energy systems are important to be analysed to show their pros and cons at both mEH and EH levels; indeed, this analysis is the key factor for understanding and then addressing the sector coupling approach in different sectors (energy included) to be further deployed. To the authors' knowledge, a few of them do not provide detailed information and assessment of the involved technologies (e.g., types, energy carriers involved, capital and operational & maintenance (O&M), costs, etc.), as well as potential barriers/limitations that slow down the constitution of both mEH and EH in the energy sector. Considering this, Table 3 lists the distribution of the literature that addressed the main enabling technologies for applying the sector coupling approach.

Table 3. Distribution of literature regarding the main enabling technologies for enabling the sector coupling approach.

References	Year	# of References	Percentage of Each Paper Compared to the Overall Reviews
[93,94]	2019	2	9.52
[95–97]	2020	3	14.29
[98–100]	2021	3	14.29
[101–111]	2022	11	52.38
[112,113]	2023	2	9.52

Local energy planning has been investigated for several years, mainly addressing local-scale policies to meet environmental goals. First, local energy planners and research institutions used planning tools to investigate national energy policies and contexts. Subsequently, several tools have been developed to specifically address local energy planning of DERs in well-identified areas such as districts, cities, energy islands, etc. In this regard, Table 4 lists the distribution of the literature over the years where descriptions of the most used local energy planning tools have been provided.

Table 4. Distribution of literature regarding descriptions and analyses of the local energy planning tools.

References	Year	# of References	Percentage of Each Paper Compared to the Overall Reviews
[114]	2007	1	5
[115]	2015	1	5
[116]	2017	1	5
[117–119]	2018	3	15
[120,121]	2019	2	10
[122,123]	2020	2	10
[124–128]	2021	5	25
[129,130]	2022	2	10
[131–133]	2023	3	15

2. The Concepts of Energy Hub (EH) and Micro-Energy Hub (mEH)

An energy hub (EH) is a concept that allows integration of multiple energy carriers—such as electricity, heat, gas, and cooling—in a unified system. The hub is designed to manage, convert, store, and distribute power from these energy carriers to meet the energy demands of a local community, district, or industrial area. mEH has the same underlying concept but has a different spatial scope, i.e., an apartment or a building. This leads to differentiation, e.g., in the technologies involved (sizing and conversion), their operational patterns, etc.

The energy hub (EH) concept is versatile in terms of system size, allowing the integration of any number of energy carriers and products, which offers substantial flexibility in system modelling, architecture, and operation. Since the EH concept is highly versatile, different facilities can be modelled at different layers: an EH at a higher level, like an ILEC, and an EH at a lower level (e.g., mEH as a single prosumer within the community) to capture the different levels of application. Additionally, mEHs can collaborate by sharing all energy carriers to meet the energy demands of the entire local community, which is represented by the EH. The EH is therefore regarded as a conceptual framework for managing and controlling multi-energy carrier systems across various scales, with the goal of optimising their architecture and operation. To guarantee both short- and long-term sustainability of this energy model, EH design optimisation is based on economic, reliability, and environmental factors. The inherent flexibility of EHs leads to the introduction of the mEH concept, which represents prosumers (such as industrial, commercial, or residential users) within a community. In this context, each mEH functions as an integrated energy system, incorporating multi-energy generation, conversion, and storage technologies to meet its own energy requirements. Community generation and community storage systems are also involved through dedicated community energy management systems. The energy hub (EH) facilitates local energy balancing and strategic exchanges with external electrical grids through coordinated management. This approach enables the EH to interact with larger systems, ensuring access to a broad range of external resources while maintaining the potential for local resource optimisation and offering services to other hubs or the central system. It also fosters synergies across various sectors, such as electricity, heating, cooling, and transportation (e.g., electric and hydrogen-based), as well as between different technologies.

There are some works in scientific literature dealing with the EH concept. In this regard, Tiwari et al. [134] performed a cooperative energy management approach for EHs to facilitate power exchange to achieve considerable economic and environmental goals. Indeed, they found out that individual EHs must cooperate to achieve the highest revenue instead of being confined and operating only within their boundaries. Within the EH, energy is converted and conditioned by technologies such as storage, CHP, transformers, power-electronic devices, compressors, heat exchangers, etc. The EH concept is not limited to a certain size of the system: the concept embeds different energy carriers with related technologies and products, providing significant flexibility in system modelling architecture and operation. Since the EH concept is highly versatile, various facilities can be modelled as EHs and optimised using different algorithms. Barajas–Villarruel et al. [135] worked on two optimisation models for the optimal management of EHs. The first one is based on the linear programming approach and considers one hour of operation as a temporal scale, satisfying the demands at minimum cost. The second model is a development of the first one, and it is based on the MILP approach that considers a 24-h scenario. The MILP model can also consider the connection between different energy networks outside the EHs. However, the detailed knowledge of the most used energy conversion systems, energy storage systems, and monitoring platforms is essential to properly design and constitute an EH, as well as connecting those that are close to each other according to the local sources available in a specific site. The interactions among mEHs within the EH and with the larger system under the eNeuron concept [136] are shown in Figure 3, where mEHs can exchange energy locally. mEHs can be constituted by prosumers and/or consumers only, and they can exchange/manage multiple energy carriers to satisfy the local energy demand properly as well as being aware of renewable energy production through its optimisation. The connection to the larger system addresses residual energy demands, facilitates the sale of surplus energy or the procurement of shortfalls, and enables the provision of system services to grid operators. The defining characteristics of EHs and mEHs are shown in Figure 4, where all the main features related to both the mEH and EH architectures are reported in detail.

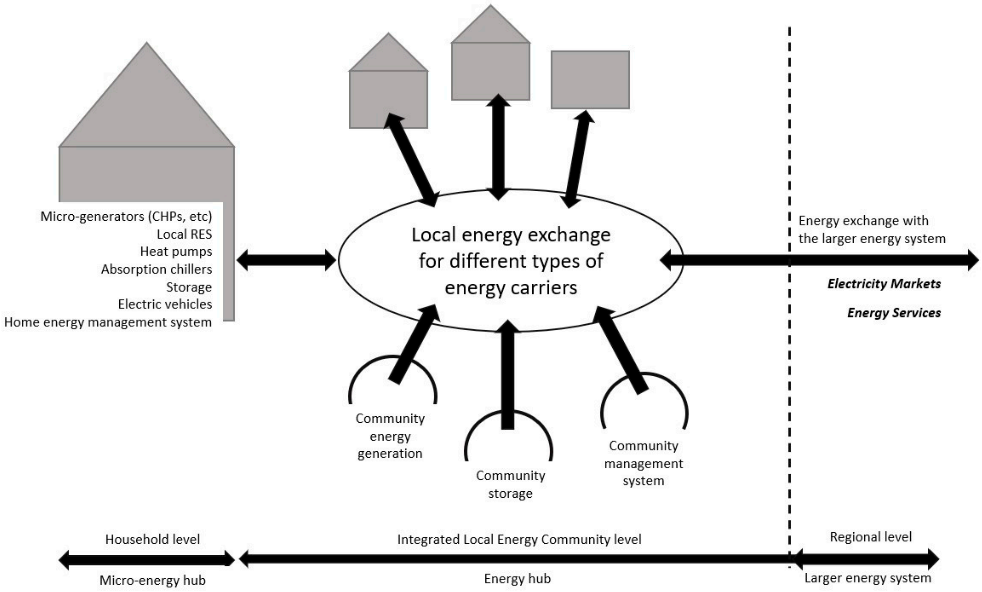

Figure 3. Representative scheme for an ILEC: several mEHs composed of prosumers and/or consumers only exchange manage multi-vector energy carriers to satisfy the local energy demand properly. mEHs are integrated within the EH, which manages residual energy demand, sells excess energy or procures shortfalls, and provides system services to grid operators [136].

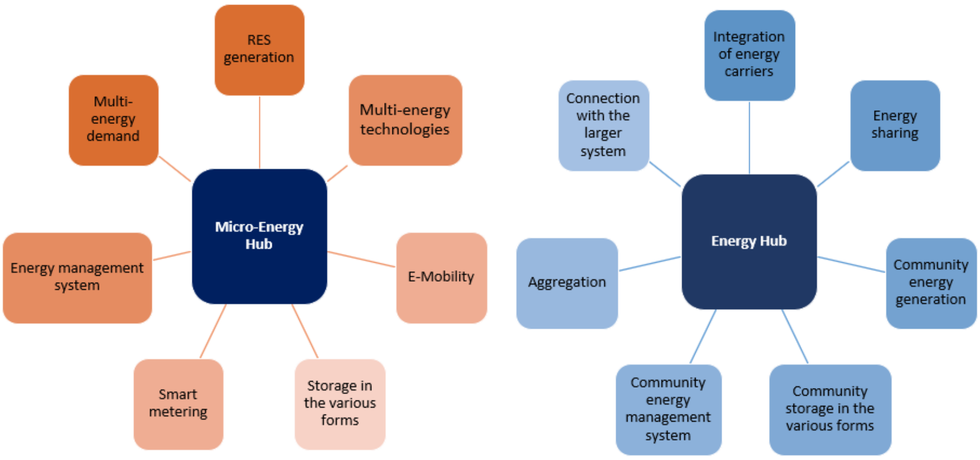

Figure 4. Main characteristics of a mEH and an EH, where all the main features related to both the mEH and EH architectures are reported in detail.

2.1. Identification of mEHs and EHs

This subsection aims to provide information on each type of infrastructure that can be identified as a mEH or as an EH according to the definitions listed in Table 5. For each identified structure/infrastructure, detailed information will be provided related to (i) technologies involved, (ii) energy carriers involved, (iii) energy networks that could be involved, (iv) level of deployment, and (v) techno-economic barriers, starting from mEH structures till the EH ones. Further details about the listed technologies are reported in Section 3. In particular, the last two items need further clarification. The level of deployment of mEHs and EHs refers to the current application of these two concepts at different energy levels by considering the TRL of the involved technologies and thus the possible interactions between at least two energy carriers involved in mEHs and EHs. The techno-economic barriers, instead, give information about what is still missing for having a complete deployment of mEHs and EHs at different energy levels, even though in some of them important steps forward have been already made.

Table 5. Structures/infrastructures that can be identified as a mEH or an EH.

mEH	EH
Apartment/house Condominium Office building Industries Campuses	Districts City Energy Islands

2.1.1. mEH—Apartment/Detached House

The apartment mEH introduces several benefits: (i) electric consumption monitoring in real-time, (ii) organising electrical billing, (iii) identifying energy efficiency measures or energy waste, and (iv) determining the cost/benefit ratio of measures or corrective actions aimed at reducing energy consumption. At the residential level, active customers can participate in the demand response programs that monitor their energy production and consumption. The demand response activity addresses the reduction of peak electricity demand and injection from/into the national grid, increasing the self-consumption of renewable sources. The optimal management of large appliances like washing machines, dishwashers, dryers, etc. can be implemented to demonstrate the load shifting and peak shaving potentials of the selected end-users. The interaction through the dedicated app allows the end-users to acquire greater awareness of their consumption and interact with other players such as the local DSOs, aggregators, ILECs, or other peers to empower final consumers/prosumers for participation in flexibility programs. For example, each time the information system detects the occurrence of the predetermined event (e.g., reaching a voltage threshold), a notification is sent to the end-users to request the increase/reduction of consumption (e.g., by switching on/off a large appliance). Table 6 lists the main information related to the apartments/detached houses in terms of technologies, energy carriers, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far [137–139].

Table 6. mEHs—apartment/detached house: technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far.

Technologies Involved	Energy Carriers Involved	Potential Energy Networks	Level of Deployment	Techno-Economic Barriers
Heat pumps Hybrid heat pumps Natural gas boilers Electric boilers Batteries Photovoltaics (PV) EV charging stations (wall box)	Electricity Hot water Chilled water Natural gas	Electricity Natural gas	High, most of them market-driven	Need for interoperable sensors and controls Need of a business model to engage final users Lack of tools to engage poorly skilled final users

2.1.2. mEH—Condominium

The main energy carriers that provide energy to condominiums are electricity and natural gas, which are withdrawn from the respective distribution grids, while water is used for district heating and cooling. The energy efficiency of the residential sector is nowadays an important goal to be achieved to reduce annual costs and minimise carbon emissions. To do this, the demand-side management program led to important improvements in terms of load control since the end-users are an active part of providing energy when needed, especially during the peak hours. Technology improvement leads to energy consumption and price reduction. Table 7 lists the main information related to condominiums in terms of technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far [140–142].

Table 7. mEHs—condominium: technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far.

Technologies Involved	Energy Carriers Involved	Potential Energy Networks	Level of Deployment	Techno-Economic Barriers
Heat pumps Hybrid heat pumps Natural gas boilers Electric boilers Batteries Thermal energy storage PV EV charging stations Centralised heating/cooling Micro-CHP	Electricity Hot water Chilled water Natural gas	Electricity Natural gas District heating/cooling	High	Governance in the decision of energy management Need for inter-operable sensors and controls Need of a business model to engage final users Lack of tools to engage poorly skilled final users

2.1.3. mEH—Office Building

The deployment of the distributed generation undoubtedly led the office buildings to improve their use of energy as it occurred for the residential sector. Different technologies can be involved for this purpose, as reported in Table 7. However, the key role in optimal energy management is performed through batteries that consider several parameters for increasing the energy efficiency of office buildings. These systems are fundamental for performing optimal scheduling of the demand-side management programs in smart cities; in particular, thermal (e.g., heating, ventilation, and air conditioning) and lighting loads are the most involved in this sector, being dependent on weather conditions. These loads present variations that occur in a quite large time frame compared to the residential ones, constituting one of the strengths of participating in demand-side management programs. Due to the quite large time frame on which the loads vary, batteries are suitable in this sector because they increase the office building efficiency when appropriate information related to both system conditions and external factors can be accurately forecasted. Table 8 lists the main information related to the technologies involved in office buildings in terms of technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far [143,144].

Table 8. mEHs—office building: technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far.

Technologies Involved	Energy Carriers Involved	Potential Energy Networks	Level of Deployment	Techno-Economic Barriers
Heat pumps Hybrid heat pumps Natural gas boilers Electric boilers Batteries Thermal energy storage PV EVs charging stations Centralised heating/cooling Micro-CHP	Electricity Hot water Chilled water Natural gas	Electricity Natural gas District heating/cooling	High	Governance in the decision of energy management Need for inter-operable sensors and controls Need of a business model to engage final users

2.1.4. mEH—Industry

The main interventions that lead to energy efficiency improvement in the industry sector are energy efficiency assessments and waste–heat recovery. A detailed overview of the consumption of each industry process where energy efficiency interventions must be performed in terms of technical/technological improvement, policymaking, internal training, and overall system management. The integration of renewables and CHP units coupled with the demand-side management program, driven by energy management systems/tools, boosted the efficiency improvement of industries in recent years mainly because the loads involved in this sector are more predictable than the ones related to other ones. Together with renewables/CHP units coupled with the demand-side management program, the demand response can also increase the benefits of the industrial sector since different energy carriers are involved. Finally, it can be concluded that the use of a proper energy management system (EMS) is anyway required for performing energy efficiency improvements in the industrial sector; indeed, the combination with smart grids and the integration with distributed energy resources can be achieved in an EH context. Table 9 lists the main information related to the industry sector in terms of technologies, energy carriers, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far [145,146].

Table 9. mEHs—industry: technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far.

Technologies Involved	Energy Carriers Involved	Potential Energy Networks	Level of Deployment	Techno-Economic Barriers
Heat pumps Hybrid heat pumps Natural gas boilers Electric boilers Batteries Thermal energy storage PV EV charging stations Centralised heating/cooling CHP Steam boilers	Electricity Hot water Chilled water Steam Natural gas	Electricity Natural gas	High in large companies Poor-medium in Smart or Medium Enterprises Highly driven by energy efficiency and cost reduction	Size Energy price

2.1.5. mEH—Campus

Campuses can be considered mEHs due to the presence of several energy carriers like electricity, natural gas, and water. Specifically, the load curves can be categorised into two groups: weekday and weekend patterns. Both curves assume a similar trend, although the numerical values are different due to the different occupancy levels of academic staff/students/workers. Table 10 lists the main information related to condominiums in terms of technologies, energy carriers, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far [147–149].

Table 10. mEHs—campus: technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far.

Technologies Involved	Energy Carriers Involved	Potential Energy Networks	Level of Deployment	Techno-Economic Barriers
Heat pumps Hybrid heat pumps Natural gas boilers Electric boilers Batteries Thermal energy storage PV EV charging stations Centralised heating/cooling CHP	Electricity Hot water Chilled water Natural gas	Electricity Natural gas	Medium (not all universities are campuses and/or mEHs)	Cost of retrofitting/refurbishment

2.1.6. EH—District

In recent years, the increasing population of the main urban areas has drastically increased energy demand. One of the most promising concepts for tackling the increase in demand is the district energy network. District energy networks consist of aggregated end-users with a shared facility that produces the required energy, such as electricity or heating or cooling, at a district level through the available local energy/waste sources. District energy networks provide benefits for (i) the environment because they have an overall better efficiency and provide the opportunity to recover waste thermal energy from cogeneration or waste-to-energy power plants; (ii) communities because they exploit local energy sources, generating job opportunities; and (iii) building owners and tenants since they reduce heating and cooling costs. The design of more complex cogeneration and tri-generation systems at a local level is expected in the upcoming future. However, these district energy networks do not supply only the electricity demand but also heating and/or cooling ones through thermal energy storage systems in a more efficient way (e.g., heat recovery systems, etc.). In this regard, Table 11 lists the main information related to districts in terms of technologies, energy carriers, potential energy networks, level of deployment, and techno-economic barriers encountered so far [150,151].

Table 11. EHs—district: technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far.

Technologies Involved	Energy Carriers Involved	Potential Energy Networks	Level of Deployment	Techno-Economic Barriers
Heat pumps Hybrid heat pumps Natural gas boilers Electric boilers Batteries Thermal energy storage PV EV charging stations Centralised heating/cooling CHP Absorption/adsorption chiller	Electricity Natural gas Hot/chilled water	Electricity Natural gas District heating and cooling EV infrastructure	Poor (districts are not yet organised as a coordinated multi-energy system)	Governance Ownership of energy networks Cost of infrastructure and connecting technologies Need for data/communication and management infrastructure Lack of funding and/or proper business models Social acceptance and citizen skills Regulatory framework

2.1.7. EH—City

Cities must act to address the growing energy demands of their populations while ensuring a healthy and sustainable living environment. Rapid urbanisation calls for innovative solutions to achieve development and climate goals. Transforming urban energy systems involves more than simply replacing one energy source with another; it requires rethinking the entire system and its interactions. The potential for renewable energy varies significantly depending on each city's unique characteristics, such as population density, growth outlook, and energy demand in different climates. Alongside energy, key focus areas for action include buildings and transportation. Decentralised renewable energy sources like solar thermal collectors, photovoltaics (PV), biomass boilers, and modern bioenergy cook stoves present viable options, but improving energy efficiency offers the greatest potential. In transportation, electrification can accelerate the adoption of renewables, while biofuels and hydrogen, though in early stages of deployment, will also play important roles. Table 12 lists the main information about cities as EHs in terms of technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far [152]. It is worth noting that, although the level of deployment is low, cities as EHs do not present techno-economic barriers up to now. This means that the current application of the EH concept in a city context is far from being applied, and this lack of techno-economic barriers means that no further studies have been made to address its deployment. This result should give pause for thoughts in the sense that there is for sure room for starting to apply the EH concept in cities to make a step forward in their transition process, but it is also important to limit the area of intervention considering the specific characteristics of the cities under investigation.

Table 12. EHs—city: technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far.

Technologies Involved	Energy Carriers Involved	Potential Energy Networks	Level of Deployment	Techno-Economic Barriers
Heat pumps Hybrid heat pumps Natural gas boilers Electric boilers Batteries Thermal energy storage PV EVs charging stations Centralised heating/cooling CHP	Electricity Natural gas Hot/chilled water Water (non-energy carrier) Hydrogen	Electricity Natural gas District heating and cooling EV infrastructure Water (non-energy network)	Very low	None

2.1.8. EH—Energy Island

The rapid expansion of renewable energy production presents new and economically viable opportunities for decarbonising local energy systems. Energy islands can be defined as self-managed and self-operated local energy systems, including isolated villages, small cities, urban districts, rural areas with weak or nonexistent grid connections, and physical islands. From the perspective of electricity networks, energy islands face technological and financial challenges when integrating higher levels of renewable energy. However, they also offer opportunities to optimise electricity system operations in conjunction with other energy carriers, enhancing the capacity to host renewables not only for electricity but also for heating, cooling, transportation, and industry through a sector coupling approach. This multi-carrier energy approach enables the high penetration of renewable energy systems. Energy islands are becoming an interesting topic for the proper energy management of self-independent communities using renewable sources; in this regard, different examples have been realised so far. In Denmark, two energy islands (one artificial) have been constructed to exploit the local wind resources. The energy islands will function as hubs, enhancing the connections between energy produced from offshore wind and the regional energy systems surrounding the North Sea and Baltic Sea. This setup enables electricity generated in areas rich in wind resources to be efficiently directed to regions with the highest demand, ensuring that the energy produced by the turbines is utilised as effectively as possible in meeting electricity needs. Table 13 lists the main information related to energy islands in terms of technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far [153,154].

Table 13. EHs—energy island: technologies involved, energy carriers involved, potential energy networks involved, level of deployment, and techno-economic barriers encountered so far.

Technologies Involved	Energy Carriers Involved	Potential Energy Networks	Level of Deployment	Techno-Economic Barriers
Heat pumps Hybrid heat pumps Natural gas boilers Electric boilers Batteries Thermal energy storage PV EVs charging stations Centralised heating/cooling CHP	Electricity Natural gas Hot/chilled water Water (non-energy carrier) Hydrogen	Electricity Natural gas District heating and cooling EVs' infrastructure Water (non-energy network) Hydrogen	Poor	Governance Ownership of energy networks Cost of new infrastructure Cost for retrofitting existing infrastructure Absence of business models Social acceptance Citizen skills Cost of smart meters Need for data management infrastructure Cost of enabling technologies

To sum up, Table 14 provides an overview of the technologies, energy carriers, potential energy networks, level of deployment, and techno-economic barriers of both mEHs and EHs analysed in Section 2.1.

Table 14. General overview of the main characteristics of mEHs and EHs with technologies/energy carriers potentially involved at both the mEH and EH levels so far.

	mEH					EH		
	Apartment	Condominium	Office Buildings	Industries	Campuses	Districts	City	Energy Island
Heat pumps	✓	✓	✓	✓	✓	✓	✓	✓
Hybrid heat pumps	✓	✓	✓	✓	✓	✓	✓	✓
Natural gas boiler	✓	✓	✓	✓	✓	✓	✓	✓
Biomass boiler	✗	✗	✗	✗	✗	✗	✓	✗
Steam boiler	✗	✗	✗	✓	✗	✗	✗	✗
Electric boiler	✓	✓	✓	✓	✓	✓	✓	✓
Batteries	✓	✓	✓	✓	✓	✓	✓	✓
Thermal energy storage	✗	✓	✓	✓	✓	✓	✓	✓
PV	✓	✓	✓	✓	✓	✓	✓	✓
Solar thermal systems	✓	✓	✓	✗	✓	✓	✓	✓
EV charging station	✗	✓	✓	✓	✓	✓	✓	✓
Centralised heating/cooling	✗	✓	✓	✓	✓	✓	✓	✓
CHP	✗	✓	✓	✓	✓	✓	✓	✓
Adsorption chiller	✗	✗	✗	✗	✗	✓	✗	✗
Electricity	✓	✓	✓	✓	✓	✓	✓	✓
Water (non-energy)	✓	✓	✓	✓	✓	✓	✓	✓
Hot water	✓	✓	✓	✓	✓	✓	✓	✓
Chilled water	✓	✓	✓	✓	✓	✓	✓	✓
Steam	✗	✗	✗	✓	✗	✗	✗	✗

Table 14. *Cont.*

	mEH						EH	
	Apartment	**Condominium**	**Office Buildings**	**Industries**	**Campuses**	**Districts**	**City**	**Energy Island**
Hydrogen	✗	✗	✗	✓	✗	✓	✓	✗
Natural gas	✓	✓	✓	✓	✓	✓	✓	✓
Electricity	✓	✓	✓	✓	✓	✓	✓	✓
EV Infrastructure	✗	✗	✗	✗	✗	✓	✓	✓
Water network (non-energy)	✓	✓	✓	✓	✓	✓	✓	✓
District heating/cooling	✗	✓	✗	✗	✗	✓	✓	✓

2.2. Management Systems of mEHs and EHs

Digital energy refers to the use of digital technologies to manage energy exchanges. The digitalisation of energy is a transformative process that is reshaping the energy industry, providing solutions that enable individuals to become independent, active participants who take responsibility for their energy consumption [155]. mEHs and EHs aim at accelerating the energy transition towards decentralised and bidirectional management systems by utilising distributed architectures along with hardware and software solutions to monitor and manage various energy systems across levels. Although energy management at the micro-level can be considered State-of-the-Art since many real cases of application and implementation of energy management systems already exist in the industrial and consumer sectors, there are still open, challenging points. On the other hand, the application of commercial solutions related to EH is demanding since the coordination of several mEHs is difficult due to the constraints shown in national/international regulations, technology barriers, electrical/mechanical constraints of the assets, reliability, experimentation of new business models, and cybersecurity issues.

2.2.1. mEH Management System

As mentioned earlier, in an ILEC context, mEHs can work together by exchanging energy, ensuring that the energy requirements of the entire local community, as represented by the EH, are met more efficiently. They are equipped with energy management systems, including both software and hardware, that coordinate the operation of multiple carriers locally. This helps to accelerate the adoption of multi-energy technology and enhances the energy efficiency of mEHs. mEHs are composed of heterogeneous information and telecommunications technologies from both the industrial and consumer sectors, as shown in Figure 5, where the assets communicate with a local server via EMS. The local server is the conjunction point between the mEH and the EH. The energy management system aims at monitoring, optimising, and controlling mEHs with software (e.g., control algorithms, databases, and communication drivers) and hardware components (e.g., sensors, and actuation devices).

An EMS is a tool to supervise, manage, and optimise energy consumption within a building or enterprise. It allows mEHs to meet their goals and increase consumers' awareness of their impact on energy savings and the environment as well. EMS involves several components, such as smart meters and sensors, to monitor energy production and consumption, along with tools like supervisory control and data acquisition (SCADA) and programmable logic controllers (PLC)/distributed control systems (DCS)/embedded devices with actuators to perform control actions. Data coming from several connected devices or other mEHs needs to be properly transmitted and stored. Based on the distance in play and other design constraints, some communication technologies are employed (e.g., ZigBee, Wi-Fi mobile cellular networks, etc.), and several protocols are involved as well (e.g., Modbus TCP, Modbus RTU, ProfiNet, etc.). Regarding the managing and data logging, information gathered from the field commonly gets saved in relational databases (e.g., Oracle, MySQL, etc.), non-relational databases (e.g., InfluxDB, MongoDB, Neo4J, etc.), data lakes, or files (e.g., .csv files, .json files, etc.). EMS could be provided with several functionalities, for example, SCADA, dashboards (for analytics, reporting, and maintenance objectives), weather forecasting, demand forecasting, optimal management, etc.

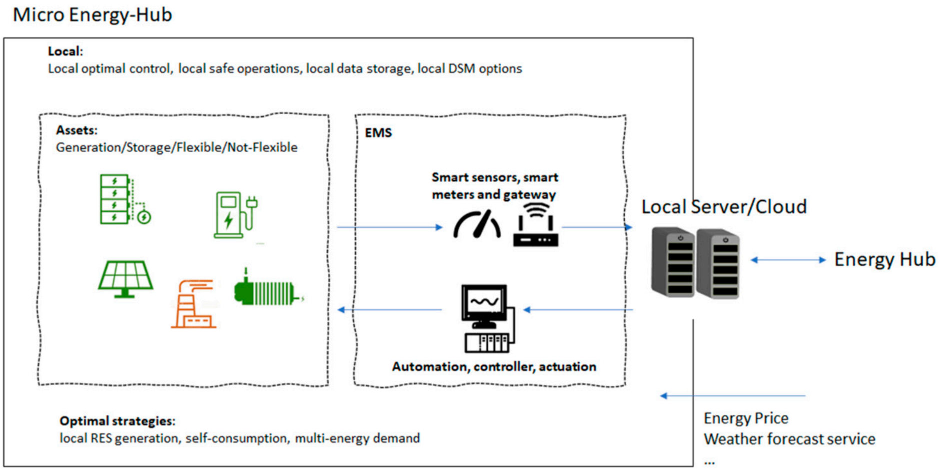

Figure 5. Scheme of a mEH management system where the assets communicate with a local server via EMS. The local server is the conjunction point between the mEH and the EH.

When the focus is primarily energy management within a specific building, the specific tool to monitor, control, and optimise energy consumption is called a building energy management system (BEMS). This is different from a building management system (BMS) that considers all the systems in a building, both the energy-related ones such as lighting, heating, ventilation, and air conditioning (HVAC) and the not -energy-related ones such as closed-circuit television (CCTV), fire, etc. Instead, BEMS considers only the energy-related systems in a building. The functionalities of BEMS are mainly four: (i) monitoring, (ii) control, (iii) optimisation, and (iv) reporting. BEMS monitors sensor measurements to modify the facility's behaviour through control algorithms, thus enabling it to achieve a particular goal. BEMS enhances energy efficiency and the occupants' comfort, assesses the building performance, generates alarms for anomalies or failures, identifies anticipated and unforeseen maintenance needs, and records energy management data for archiving purposes [156]. The EMS assists energy users in achieving their goals while promoting self-awareness of energy saving and the environmental impact of their choices. The presence of an EMS can enhance consumer awareness by providing information and feedback on energy usage patterns, energy-saving opportunities, and the associated environmental impact. It aims to manage local resources and enhance performance by utilising control strategies that consider the set points and current plant conditions. mEHs offer energy flexibility, thus allowing for the implementation of advanced demand side management (DSM) strategies that are overseen by the EH. In the event of a connection loss between local devices and smart controls, low-level controls will play a critical role in ensuring safe and secure operations. There are several types of low-level controls, such as the proportional integral derivative (PID) controller, rule-based (if-then-else), fuzzy logic based on model predictive control (MPC), and based reinforcement learning (RL) approach.

2.2.2. EH Management System

In an ILEC context, an EH aims at coordinating the different mEHs and managing multiple energy carriers. The EH management system is a high-level software solution installed in a server/cloud that collects data coming from the different mEHs and manages them for different actors to actively participate in the energy market. To have the proper operation of the EH, the communication architecture is one of the key aspects of the EH that allows the data flow among the different devices and energy assets. The communication among the different mEHs (e.g., servers/clouds of ILEC, EVs' charging stations, RES, tertiary buildings, industrial plants, and mEHs) is carried out by application programming interface representational state transfer (API REST), and then the internet-based technologies are the keys to creating an EH. Regarding the software, the EH is a web-based platform based on microservices, and a list of possible software/frameworks (free and licensed) that could be used to develop and deploy the energy hub are:

- Web-Frameworks: .Net Core, Angular, React, Vue.js, etc.;
- Database (SQL, NoSQL): Microsoft SQL Server, MySQL, PostgreSQL, Oracle, MongoDB, InfluxDB, AzureSQL, etc.;
- Event-based data ingestion: RabbitMQ, Kafka, etc.;
- Deploy: Docker, Kubernetes, etc.;
- Artificial Intelligence (AI) and Analytics: Python scripts, Tableau, Power BI, etc.

The web-based architecture considered to manage the EH should provide the following high-level features:

- Different levels of authentication are implemented to allow each different actor to access and visualise only the corresponding information and separately interact with the proper processes;
- Storage of historical data of the monitored assets and access to specific data using filters (e.g., data range, asset, geographical zone);
- Temporal aggregation of the data of the selected variables at different time resolutions for visualisation purposes: minutes, hours, days, weeks, months, and years;
- Custom import from CSV files and export to CSV or XLSX formats;
- Ability to connect via API REST and share information on resources, data for registering a new flexibility resource, etc.;
- Integrated maps for displaying meters and mEHs, read-out tours, and data concentrators;
- Dashboard for system monitoring;
- Pre-configured graphics to visualise consumption and readings;
- Built-in scheduler to automate tasks like importing, exporting, or analysis processes;
- Energy reporting;
- Energy management/control system to coordinate the whole mEHs.

The energy management and control system should be able to coordinate both energy demand and consumption. For instance, residential and industrial sectors exhibit distinct consumption patterns, allowing for coordinated control. Additionally, distributed energy resources can be used to compensate for the energy shortfalls in each sector. Furthermore, the peak demand in those two sectors does not occur simultaneously, allowing distributed generation from one sector to help meet the peak demand in the other, and vice versa. The control strategy is a big issue to face when different mEHs are linked/connected, especially when the energy flow must be optimised according to the end-users' demand and each infrastructure/architecture. One of the most used is the centralised one (see Figure 6), which collects information on the controlled areas and solves optimisation problems to find the best solution.

However, it is important to note that the centralised control method is mainly applied to small-scale systems because it is not capable of managing large-scale systems; this is due to the increase of the information that the centralised control strategy must deal with, which increases the computational time for reaching the best trade-off of the EH configuration. Indeed, multiple objectives including technical, economic, reliability, and environmental parameters need to be taken into account, constituting a multi-objective optimisation problem. For this reason, the decentralised solution (see Figure 7) and distributed controllers can be used for controlling each mEH that constitutes an EH, and each optimisation result is shared with the others. mEHs can also connected through a parallel/decentralised layout; in this way, the parallel layout lets the system operate also when failures occur.

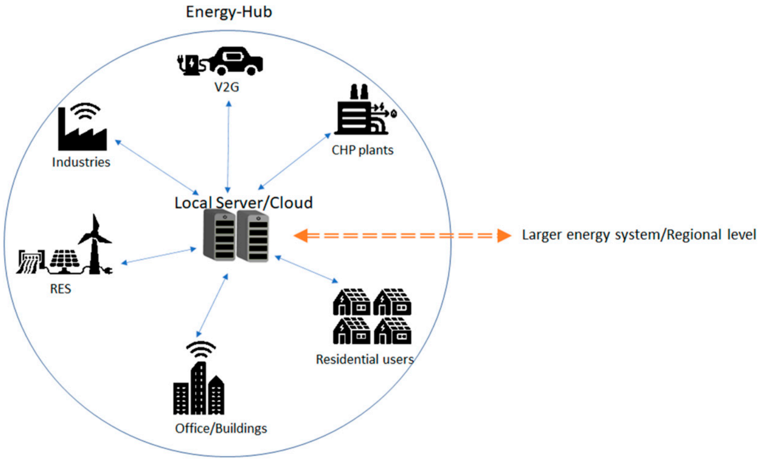

Figure 6. Scheme of an EH (centralised solution) that collects information on the controlled areas and solves optimisation problems to find the best solution.

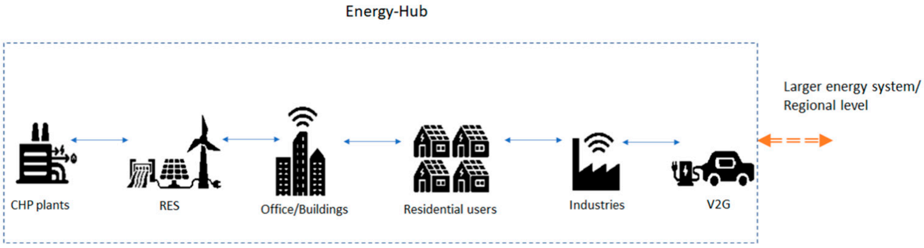

Figure 7. Scheme of an EH (decentralised solution) where each optimisation of the mEHs embedded in the EH is shared with each other.

The decentralised EH is related to the web-of-cell (WoC) concept, which is a decentralised energy architecture for energy management [157], and the control strategies are implemented in a decentralised manner based on local observations using local resources. The EH improves the reliability of the system and, at the same time, both the economic and environmental advantages. Due to the high number of connections within and between the mEHs, the use of distributed control strategies, instead of centralised ones, can enhance and speed up the optimisation procedure by finding the optimal condition locally, and then making a trade-off considering the overall EH. This configuration is useful also in case of failures of a mEH since the optimisation objective is anyway carried out due to the parallel layout of the system. The use of a control architecture leads to the main pros regarding the production and reliability of the energy system, the emissions reduction, and the share of renewables. However, all the control systems allow finding the optimal operation of a mEH and an EH as well in a short time frame; thus, long-time frame optimisation has become a big challenge in this research field. Indeed, for energy hub management, predictive controllers are required for the optimal schedule/control/coordinate of the mEHs. In this case, AI can be useful for the long-term prediction of energy consumption and production and for short-term load/demand forecast. The high-level controllers are based on a multi-objective optimisation problem that can be defined in the MPC framework and RL framework. While the MPC is a classical approach in this context, RL is a cutting-edge and scalable solution to control complex systems that, recently, have also been employed in the energy management of buildings. In the RL, the agent, which is the subsystem responsible for executing actions, learns the policy (the mapping between states and actions) through the interaction with the environment (the part of the system that is behind the agent's control). The interaction between the agent and environment can be represented in Figure 8: the agent observes the environment's state and selects an action accordingly; in the next time step, the environment transitions to a new state, and the agent receives a numerical reward.

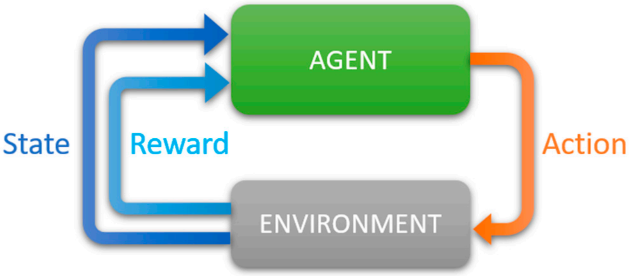

Figure 8. Agent-Environment interaction: the agent observes the state of the environment and selects an action accordingly; in the next time step, the environment transitions to a new state, and the agent receives a numerical reward.

To employ RL techniques in the decision-making process, it is essential to recognise the states, actions, and rewards involved. RL algorithms can be mainly categorised into two groups: model-based and model-free. In model-based approaches, the agent makes decisions using a model of the environment, which can be either known or learnt through experience. Differently, in model-free methods, the agent learns how to act directly [158]. The RL approaches have been tested in different areas of building energy management (HVAC control, water heater control, appliance scheduling, etc.). They showed approximately 10% savings for HVAC control, around 20% for water heaters, and greater than 20% for building energy management systems [159]. For HVAC control, RL agents usually operate using states such as time of day, indoor and outdoor temperature, occupancy, weather forecast, etc. The actions include air flow control, temperature set points, heating and cooling controls, etc. Finally, the reward is usually based on thermal comfort, energy cost, or their combination [159]. For water heaters, the states are usually the current water temperature, the time of day, and the forecast of usage; the actions are the on-off command to the heater; and the reward is related to the energy consumption. For energy management systems, RL agents use states that usually include time of day, temperature, the state of involved appliances, grid load, information related to RES production, etc. Also, in this case, the actions are related to the involved appliances (e.g., turning on/off appliances, charging/discharging batteries, etc.) [159]. One of the drawbacks of RL approaches is the necessity of a huge amount of data. Data collection is a time-consuming task, and to capture different conditions, it is necessary to collect data over multiple years. Moreover, the interaction with the real environment and the necessity to explore several settings can lead to dangerous situations [160]. For this reason, many RL applications in building energy management are based on simulated data, eventually with a fine-tuning phase done through interaction with a real physical system [159]. In such a context, Q-learning is a commonly used algorithm, but, in the presence of continuous actions or large state space, deep reinforcement learning (DRL) approaches must be considered (e.g., Deep Q-Network (DQN), Actor-critic, etc.). In the context of an energy community, where several buildings and energy resources are involved, the multiple agent reinforcement learning (MARL) perspective is a powerful approach for optimising energy management and achieving efficient resource allocation. Rather than considering each building or energy resource as an isolated entity, MARL treats them as individual agents that can interact and cooperate to achieve common goals. Although there are several challenges related to MARL (e.g., the non-stationarity of the environment, the communication overhead, scalability, privacy issues, etc.), this paradigm is very promising and effective in many situations [160].

The MPC is an advanced control strategy that is trying to replace the standard PID controllers where their performance is not satisfactory. It is the highest-impact advanced control methodology in industrial control engineering. It cannot be considered a specific control strategy. It covers several control strategies that make explicit use of a model of the process to predict its future behaviour, minimising an objective function to obtain the control inputs (see Figure 9). MPC denotes the family of controllers that predicts the future dynamics of the process with an explicit model, involves optimisation technique, and follows the receding horizon idea. Some of the most appreciated features are optimal control: metavariable systems are treated straightforwardly, and system constraints are easily considered and can be successfully implemented for simple or very complex processes. It can be handled by people with limited control knowledge, it does not have a fixed structure; it does not need modifications; and new features are easily included. The primary disadvantage of MPC is tied to the quality of the identified model. A model that does not represent the real process might heavily affect the control performance. Stability is not often easily proven (finite horizon). The online computational effort is high, but in the process industry it is weakly affected, and the sampling time is in the order of seconds or even higher. MPC, or receding horizon control, has been widely used as a high-level controller in microgrids with multiple types of RES and BEMS. In the context of microgrids, the standard MPC is extended to a MILP formulation for the optimal control of hybrid systems such as microgrids and RES.

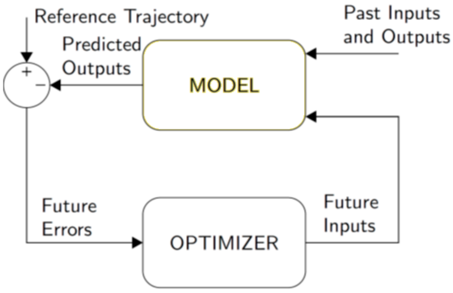

Figure 9. Control scheme of MPC: this closed-loop architecture allows the control system to anticipate future behaviour and adjust proactively, rather than just reacting to past errors.

3. Connecting Technologies for ILECs Implementation and Deployment

To realise the ILEC concept, the implementation of several energy technologies—that can convert energy in different forms—as well as interoperability with different energy carriers is required. Such technologies are known as connecting technologies, and they allow increasing the energy systems' flexibility [161]. Connecting technologies can consist of both energy conversion systems (e.g., distributed units) and energy-related infrastructure (e.g., centralised infrastructure) that can be involved at both mEH and EH levels, as displayed in Figure 10.

When analysing an energy system, the entire energy supply chain should always be addressed; for instance, a natural gas boiler providing domestic hot water can be schematised as reported in Figure 11. Considering the objective of covering the same energy end-use, the energy supply chain can be optimised in each step, such as reducing the energy demand, implementing alternative energy carriers, improving the efficiency of the energy conversion system, either acting on the energy infrastructure or reducing the primary energy demand related to the primary energy resource. Therefore, covering the same energy demand with different connecting technologies (e.g., energy conversion systems and/or energy infrastructures) influences the whole energy supply chain.

In the following, two main macro-categories of sector coupling are analysed in Section 3.1:

- End-use sector coupling, which is driven by the final energy use and energy utilisation streams at a lower level, mainly at the single user and/or mEH level, that are affected by the local energy conversion systems;
- Cross-carrier sector coupling, which depends on the energy carriers used at high levels (e.g., energy network and EH level) that are affected by the energy infrastructure networks.

Each specific connecting technology is introduced, focussing mainly on its capability of enabling system integration and providing flexibility to the energy network.

Section 3.2 is devoted to the analysis of energy infrastructures that can be affected by sector coupling.

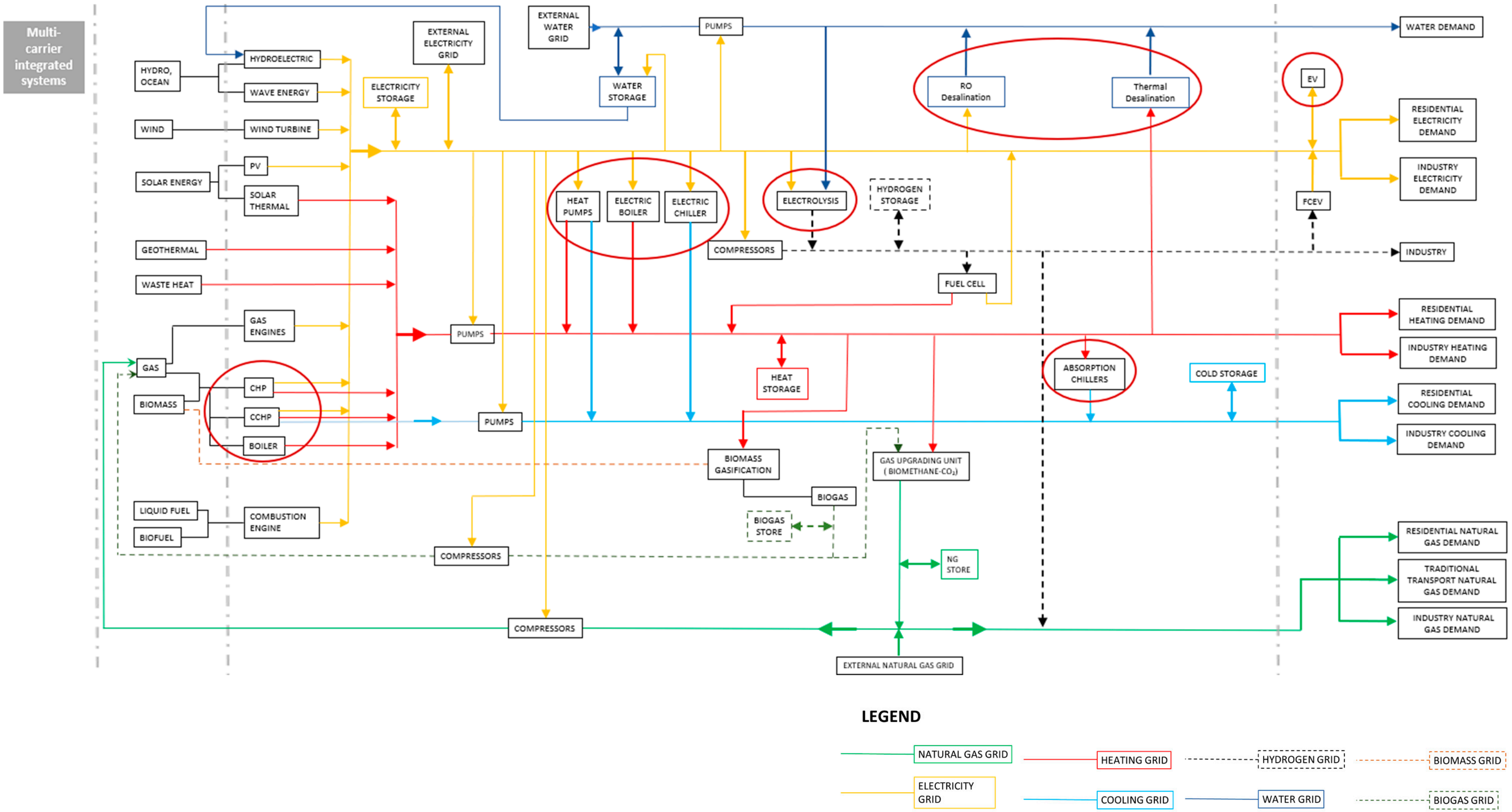

Figure 10. A holistic view of connecting technologies (energy conversion systems and infrastructure) in an EH. Different energy carriers are involved and managed simultaneously to optimally operate an EH.

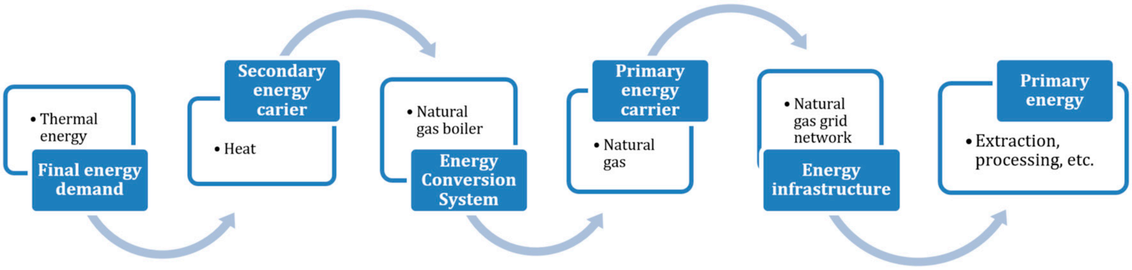

Figure 11. A complete view of the energy supply chain—example of natural gas boiler to produce domestic hot water moving backward from the final energy demand to the primary energy used to obtain the energy source.

3.1. End-Use and Cross-Carrier Sector Coupling Technologies

3.1.1. Heat Pump

A heat pump is an electricity-driven solution for space heating and cooling, as well as for generating domestic hot water. It operates based on the established reverse vapour compression cycle and can harness ambient heat for both heating and cooling applications [162]. Heat pumps are an essential and decisive technology considering the electrification that the heating sector is currently undergoing, in particular, both the small residential applications and the large industrial users (from a few kW to hundreds of kW) [163–165]. Although small-scale heat pumps have seen the strongest development, large-scale ones can also be implemented in different types of final uses (e.g., commercial or industrial), as well as in distribution network applications [166,167]. From a technology point of view, heat pumps are mainly categorised according to the primary-secondary operating fluids that act as heat source-sink, whose properties determine the heating/cooling capacity and performance together with the characteristics of the heat distribution network components (e.g., heat exchangers, fan coils, radiant systems, etc.) [168]. Different combinations of heat source-sink can be implemented using external air, internal air, groundwater, domestic hot water, cooling water from industrial processes, process water before chilling, etc. Performances generally range between a coefficient of performance (COP) of 2–5 (heating mode) and an energy efficiency ratio (EER) of 2–4 (cooling mode), measured based on EN1451 and EN16147. One of the main issues with heat pumps is that the performance depends on the external temperature; therefore, both sizing and operation should be carefully considered concerning external temperature trends. A requirement for the implementation of heat pumps is typically the refurbishment of the heating system, which can sometimes represent a limitation due to the unwillingness of users to purchase a new heating system, albeit the generally short time of the economic return on the initial investment. The payback period depends on the electricity and natural gas consumption of the end-user and their respective prices. Other possible limitations of heat pumps are related to the characteristics of the used source water and working fluid (e.g., geothermal fluid) that might increase the operating costs. Heat pumps can actuate demand response schemes at a single household level with various control strategies and thermal comfort monitoring methods [169].

3.1.2. Hybrid Heat Pump

A hybrid heat pump includes a combined heating system composed of a heat pump and a boiler (e.g., gas or electrical boiler) installed in parallel [170]. In this way, the heating demand is covered by the two technologies, differentiating the operating regions. The heat pump is typically used to supply the baseload thermal energy demand (e.g., cover thermal losses and building envelope thermal inertia), while the boiler is used to cover the peak demand (e.g., domestic hot water, space heating peaks, low external temperatures at night, etc.). Hybrid heat pump systems are especially useful in colder climates, considering the de-rating of COP and EER concerning low external temperatures. By fine-tuning the operation strategy, it is advisable to manage the heating system in a way that the natural gas boiler only covers a limited portion of the thermal top energy load related to the peaks to maximise the benefits of the efficiency related to the heat pump implementation. With the hybridisation concept, the heat pump-rated power can be downsized, and the overall flexibility and energy management of the heating system can be improved as well [171].

3.1.3. Electric Boiler

An electric boiler converts electricity into heat by dissipating electrical energy through resistors into thermal energy, which is absorbed by a heat transfer fluid (e.g., hot water tank in insulated tanks of around 10–300 L in buildings/apartments that operate between 15–25 °C and 70 °C for domestic hot water purposes). The energy conversion efficiency from electricity to heat through dissipation is nearly unitary (>97%). Although the conversion of electricity into heat is not convenient for primary energy usage, electric boilers may represent, in some cases, a convenient option in EHs. For instance, it can be sometimes convenient to shift energy volumes from electricity to heat to decouple the energy production and use from a temporal point of view. Indeed, the heat can be stored for longer periods when hot water tanks are properly insulated, thus covering the thermal energy demands that are shifted in time concerning the electricity production profiles. The implementation of thermal energy storage (TES) in a mEH and EH can also provide an additional degree of flexibility. Another convenient case regards renewables (e.g., excess electricity that is not used for electric self-consumption) so that the primary energy consumption of both the heat and the domestic hot water is null. Furthermore, electric boilers can consist of dispatchable loads that can be implemented in demand–response concepts, consuming electricity based on energy or price signals, or managing predictable heat demand patterns by dynamically regulating the hot water temperature [172].

3.1.4. Electric Chiller

An electric chiller works as an electric boiler in terms of EH implementation, where electricity is used in cooling circuits for space or process cooling applications. Their function is typically based on the reverse vapour compression cycle (e.g., opposite of heat pumps) and is classified similarly. Different technologies entail different requirements in terms of working fluids (e.g., refrigerants). Refrigerants are regulated by laws according to their greenhouse gas emissions and ozone depletion impact. Some refrigerants are being phased out or have been banned due to their considerable impact in case of leakages. Like heat pumps, electric chillers achieved a high maturity and economy of scale, so electric chillers are available at cheaper prices for most of the endusers [173]. Similarly, electric chillers can be used as controlled loads in demand response concepts to supply flexibility to buildings through a dedicated energy management system control strategy.

3.1.5. Home Electrical Appliances

Although home electrical appliances are usually passive devices, they can be seen as flexibility providers by using such appliances in an active and controllable manner in connection with the energy management system of the household. Indeed, controllable and dispatchable loads (e.g., washing machines, dishwashers, electrical heating, tumble dryers, electric boilers, multimedia devices, small appliances, lighting, etc.) can be aggregated and implemented in demand response concepts for which the electricity consumption is managed as a function of load control logics or price signals. In this way, the electricity consumption patterns can be better synchronised with the electricity production profiles (e.g., from local renewables), smoothing the demand profile and reducing the dependency on the power grid network. Home energy management systems are required to actively manage controllable home electrical appliances, which can be operated by the end-users or third-party service providers that can act both at a single-home level or aggregate multiple customers [174].

3.1.6. CHP Technology

CHP technology is an energy conversion system capable of obtaining simultaneously electric and thermal power output, the latter intended as a useful effect, from the processing of a fuel with a reduced primary energy consumption (at equal energy output). Heat is obtained either from the hot exhaust streams or from the process heat and it is conveyed to a heat, transfer fluid in the form of sensible heat (e.g., hot water) or latent heat (e.g., steam). Heat is subsequently used locally or distributed to nearby users via district heating networks. The local use of heat can be an important issue, especially in warm climates or summer months without heating requirements, hindering the benefits of implementing a CHP unit concerning separated power and heat generators. This should be carefully considered when dimensioning and operating a CHP unit. Any technology that can provide power and heat outputs simultaneously can be considered CHP technology. The main CHP technologies applied on both large- and small-scale are the following:

- ICE is based on an internal combustion cycle of a fuel. This technology is typically used in small-scale applications (between 1–50 kW), but it can also scaled up and used in medium- and large-scale ones (up to the MW scale). ICE presents low electric efficiency (around 20–30%) and medium thermal efficiency (around 50–60%), which may differ depending on both the operating temperature and the pressure as well as the used fuel. In all cases, noise and vibrations are relevant, and local emissions are relatively high due to the internal combustion process and performances that are strongly derated at partloads [175,176];
- Gas turbines and micro-gas turbines (GTs and mGTs) are based on the Brayton cycle fuelled by natural gas or other fuels. GTs present a higher efficiency concerning ICEs (around 30–40%), with a similar thermal efficiency at the expense of a higher complexity concerning ICEs. While GTs are generally used in large-scale applications (MW scale), mGTs are more suitable in smaller applications (10–100 kW) despite some technological fluid dynamic limitations and maintenance/reliability issues [177]. Like ICEs, the performance is dependent on both the temperature and the pressure, and it is strongly derated at partloads;
- Steam turbines (STs) are based on the Hirn or Rankine cycle. The steam is produced in a steam generator fired by solid or liquid fuels. STs are typically used for utility-scale stationary power plants (multi-MW) with large and centralised configurations. The electric efficiency is quite low (around 30–40%), and it requires a complex plant design and preferable stationary operations [178];
- Combined cycles (CCs) are based on coupled top–bottoming cycles, recycling the high temperature of exhausts coming from a top cycle and used as a heat source for the bottoming one, improving the energy efficiency of the system (an electric efficiency of 40–55% and a thermal efficiency of 35–40%). A typical CC configuration at a largescale (MW level) consists of a GT as a top cycle and an ST as a bottoming cycle with a heat recovery steam generator (HRSG). Considering the required temperature levels, the two cycles are thermally compatible; indeed, the exhausts exit the GT cycle at around 500 °C, and the HRSG requires heat at 100–200 °C for water vaporisation and up to 400 °C for its superheating. At lower scales (kW level), an organic Rankine cycle (ORC) can be used as a further bottoming cycle to recover the waste heat from the ST cycle, thus exploiting the low boiling point of the ORC working fluids (<100 °C). CCs are highly dependent on the thermal integration between top/bottom cycles, which is typically designed in rated operating conditions and thus not well suited for flexible operations [179];
- Fuel cells (FCs) are electrochemical devices that convert the chemical energy of a fuel gas directly into electrical energy (typically hydrogen, but also other fuel gas mixtures according to the FC technology) [180]. For this reason, FCs have the highest electrical efficiency (up to 40–70%, above the Carnot limit) and lower thermal efficiency (20–30%), reaching exceptionally high total efficiency values with a high power-to-heat ratio. Being based on an electrochemical conversion process, FCs are modular

units that make them suitable for flexible operation and do not present noises or vibrations. On the downside, FCs present lower technological maturity concerning other CHP technologies (e.g., ICE and GT), higher cost, and depend on the level of the fuel infrastructure development (e.g., hydrogen) [181]. According to the used materials, FCs are mainly categorised into low-temperature FCs and high-temperature FCs. Low-temperature FCs like alkaline and proton exchange membranes operate with a temperature range of 60–100 °C. They have an electric efficiency of 40–50% and present a lower efficiency than high-temperature FCs like solid oxide or molten carbonate technology; indeed, the two last ones operate in a temperature range of 500–900 °C with an electric efficiency of 60–70%. In addition, high-temperature FCs present a high-grade heat output thanks to the higher process temperature, which can be used for a wider range of thermal end uses (e.g., space heating, district heating, process heat, etc.) concerning low-temperature FC (e.g., domestic hot water due to the low-temperature of exhaust heat). On the other hand, high-temperature FCs present larger thermal inertia than low-temperature FCs, thus the flexible operation is more limited [182].

All CHP systems, if operated on alternative low-carbon energy carriers/carriers (e.g., hydrogen, natural gas + Hydrogen blends, ammonia, biofuels, synfuels, etc.), can further reduce the emissions over the produced energy volumes. Together with energy production, CHP systems are dispatchable generators that can support the grid by providing power capacity. Since high-temperature FCs can be operated reversibly (see the following electrolyser subsection), they can be implemented as high-efficiency electric energy storage systems.

3.1.7. Combined Cooling, Heat, and Power (CCHP) Technology

Combined cooling, heat, and power (CCHP) technology is like CHP with the addition of an energy conversion step to convert all/part of the thermal energy to cold [183]. The main CCHP technology is based on a CHP device coupled to a refrigerant system, which exploits waste heat to provide chilled water for cooling purposes [184]. Similarly, cold energy can either be used locally or distributed to nearby users. The main refrigerant systems used in CCHP concepts are:

- Absorption chiller that is based on the absorption process of a binary solution of a refrigerant and an absorbent, operating cyclically. The most common refrigerant/absorbent working pairs are water-lithium bromide and ammonia-water, respectively. This kind of system is modular and can cover cooling demands on small-(kW) and large-(MW) scales;
- Adsorption chiller that is based on an adsorbent capturing and releasing the adsorbate vapour in different steps. The working pair consisting of silica gel (adsorbent) and water (adsorbate) is often applied. This kind of system is modular and can cover cooling demands on small-(kW) and large-(MW) scales;
- Desiccant humidifier that is based on the dehumidification of a substance. Desiccant systems need to be regenerated periodically for continuous operation. This kind of system is typically used in small-scale applications [185,186].

Such devices present high cost, low COP performance, and moderate flexibility capabilities together with possible complications related to issues caused by the operating fluids (e.g., corrosion, contamination, leaks, fouling of pipes, filtering, etc.) [187]. Despite the penalties in terms of performance, converting heat into cold energy can be advantageous to improve the operational flexibility of the EH, thus diversifying the energy outputs of the system. Furthermore, they can mitigate the problem of waste heat for CHP systems since the cold energy might be more easily usable in these contexts.

3.1.8. Electrolyser

Electrolysers are electrochemical conversion systems that use electrical energy to divide water into hydrogen and oxygen in an electrochemical assembly. Being based on an electrochemical conversion process, electrolysers are modular, scalable (from a few kW to multi-MW systems by assembling multiple stacks and modules), and can be operated flexibly with limited performance derating at part loads and with high hydrogen purity [188]. Electrolysers operate with water (feedstock) and oxygen (by-product) that, despite not being energy carriers, could be considered and valorised. Contrarily to FCs, recent trends are pushing for the deployment of large-scale systems (multi-MW scale) for cross-vector carrier coupling. Indeed, electrolysers are considered a key technology for cross-carrier sector coupling since the electrolysis process shifts electric energy to chemical energy. Large-scale electrolysers can support the penetration of large volumes of renewable electricity into the energy system through hydrogen, especially in sectors that are challenging to be directly electrified, like the hard-to-abate one [189]. Electrolysers are mainly divided into low-temperature Electrolysis (LTE), which operates between 60 and 100 °C, and high-temperature electrolysis (HTE), which operates between 600 and 850 °C. LTE electrolysers are the most widespread and mature technology and consume around 50–60 kWh/kg of the produced hydrogen. Conversely, HTE electrolysers can supply a portion of the energy needed for electrolysis as heat, significantly lowering the specific energy consumption to below 40 kWh/kg of hydrogen produced and increasing the integration capabilities, especially when coupled to processes or systems that have wasteheat/steam. The main technical challenges of electrolysers are mainly related to the limitedservice life (60,000–80,000 h for LTE, 40,000 h for HTE with degradation of about 1%/year for LTE and <1%/1000 h for HTE) and high costs since the HTE ones have not reached a completed maturity so far, although some research on novel industrial magnetically enhanced hydrogen production electrolysers is being carried out as reported in [190]. From the perspective of demand–response, electrolysers can be seen as dispatchable loads that can be controlled based on global energy management strategies. In addition, LTE in dynamic operation can be used to provide grid support services, while HTE ones can be used reversibly as local electricity storage systems. Despite a strong increase in interest due to the recent policies that foster hydrogen as a possible future energy carrier, the commercial deployment of electrolysers is still limited.

3.1.9. EVs and Charging Equipment

EVs are gradually replacing fossil-fuel-based ICE powertrains to achieve the zero-emission target in the mobility sector [191,192]. Different mobility segments are responding to electrification with different speeds; for instance, small and medium-sized vehicles for short distances (e.g., automotive sector, lightweight vehicles for urban mobility, last-mile delivery, etc.) can be directly powered by batteries (up to 180–300 kWh). However, heavy-duty vehicles for long-distance transportation require a higher battery and charging capacity (>1000 kWh, ultra-fast high power charging station capacity), for which shifting to other carriers (e.g., hydrogen, sustainable fuels, or other carriers) could be a more viable alternative [193]. For railway transportation. In the case of non-electrified lines, it can be more convenient to run trains with hydrogen FCs rather than covering the high investment cost of railway electrification. In the maritime sector, it is difficult to directly electrify the ships (except for short-range shuttle ferries); thus, maritime transport can be decarbonised mostly with energy efficiency measures, alternative propulsion systems, or with low-carbon shore connections [194]. The aviation sector is like the maritime one. Together with technical constraints, the electricity price and CO_2 taxation policy are key drivers for EV implementation, which can shift the competitiveness of one solution concerning the other. Charging stations represent the set of elements and supply equipment (e.g., hardware and software) required to connect the EVs for charging purposes. The connection between the electric vehicle (EV) charging point and the grid is usually hard-wired directly to a control device and a protection box for individual users (such as a wall box or charging post). However, it can also be configured as charging islands designed to accommodate multiple EVs, such as charging hubs that can service up to 10–12 vehicles simultaneously. The power output is constrained by the charge acceptance of each specific EV's batteries, the nominal ratings of the charger, as well as the specifications of the connector and the cable connecting the vehicle to the charger. High charging currents require larger cable diameters to avoid overheating [191]. The power output is mostly defined by local regulation and utilities procedures (IEC61851) [195], as well as a local distribution network, power supply characteristics, and constraints of the electrical equipment. The charging supply equipment is mainly repartitioned into slow-charging and low-power systems (Mode 1 and Mode 2—<22 kW), which use existing alternating current (AC) connections (220–230 V single-phase, 380–400 V three-phase), and fast-charging high-power systems (Mode 3 and Mode 4—50–400 kW capacity) that can be operated in AC (Mode 3—up to 1000 V and 50 kW) or directly in direct current (DC) (Mode 4—up to 1500 V and >100 kW). According to the charging mode, hardware (e.g., converters, cables, standardised sockets, control systems, etc.) must be installed on-board/off-board, and the charging equipment must be connected to the low voltage (LV) or medium voltage (MV) power grid with different configurations (e.g., common LV-AC link and independent rectifiers for each EV, or common rectifier and common DC link) [196,197]. In general, household charging is operated in Mode 1 and Mode 2 using existing electric cables/sockets or wall-boxes, while public charging points (approximately 1 charging point for every 10 EVs) are operated in Mode 3 (fast charging 1–2 h) or in Mode 4 (ultra-fast opportunity charging <1 h) [198]. Wireless charging is also available, but it is less used due to lower efficiency and reliability issues, as well as other concepts like batteryswapping due to the extra cost required for doubling the battery packs and the service management.

3.1.10. Desalination

A desalination system uses energy to obtain water for different purposes. Although it is not strictly an energy conversion system, it is wellknown that water is a key element in the industrial network considering its use in many different processes and applications. Desalination technologies are mainly divided between electricity- and thermal-driven technologies, and their characteristics strongly depend on the input/output water quality requirements [199,200]:

- Reverse osmosis (RO) is the main electricity-driven desalination technology, and it is based on a selective semi-permeable membrane that separates a solution based on a concentration gradient. Although it consumes electricity (1–15 kWh/m^3 per day), which is usually a more valuable form of energy, RO has the advantage of being modular, more suitable for small-scale applications (from 20 m^3/day), and can be operated flexibly also at part loads [201];
- Multi-effect distillation (MED) is based on the thermal distillation process, and it operates between 60 and 95 °C in cells at decreasing steps of pressure for water evaporation driven by heat (14–22 kWh/m^3 per day). As a thermal-driven technology, MED has a large thermal inertia, and it is usually designed for large, centralised systems (up to 500,000 m^3/day) with little or no operation flexibility, thus limiting the coupling with variable renewables [202];
- Multi-flash distillation (MSF) is also based on the thermal distillation process, but by flash separation of water in multiple steps at increasing temperature and pressure levels (18–29 kWh/m^3 per day). MSF shares the limitations of MED systems in terms of difficult down-scalability, flexibility, and compatibility with variable renewables [203].

3.2. Energy Infrastructure

3.2.1. Power Network

The European electricity grid today is a well-established and highly reliable infrastructure residing on many decades of experience, technological development, and supporting regulatory documents. This electrical grid has been called ‘the world’s largest machine’ in popular literature. It has been designed to provide electricity from generation to end-use customers and, conventionally, includes three main sections: generation, transmission, and distribution networks. The electricity network is a fundamental component of the energy infrastructure, continuously balancing power flow between connected consumers and producers to ensure the stability of the network. One of the main advantages of the electricity infrastructure is its ability to transfer substantial volumes of energy over long distances by using high-voltage AC or high-voltage DC lines with fairly low losses and low operational costs. Electricity is highly versatile, as it can be easily tailored for a wide array of end-use applications, including direct heating, lighting, different forms of mechanical energy, and industrial processes. There are also several limitations related to the physical nature of electricity and the necessity to maintain the momentary balance between generation and consumption at any time. It is also difficult and expensive to convert and store substantial volumes of electricity, at least at the present level of technological development. To enhance the comprehension of direct and indirect electrification, Figure 12 illustrates examples primarily related to transport and heating. It depicts the flow of electricity utilised for direct electrification and the flow of chemical energy, such as hydrogen for indirect electrification. In addition to electricity use that relies on the grid, a decentralised PV system can directly electrify the transport sector through EVs or indirectly electrify heating via a decentralised heat pump. Furthermore, hydrogen or natural gas can be stored long-term in chemical storage or injected into the natural gas grid.

The presence of electricity infrastructure in Europe is ubiquitous today; however, the foreseen electrification will substantially increase the electric load of the existing networks. This will likely require a considerable upgrade of the existing infrastructure and corresponding expenditure. A dedicated study accomplished by Eurelectric, European Distribution System Operators (E.DSO), and Monitor Deloitte, where different electrification scenarios have been developed and assessed, concludes that electricity is a critical part of the backbone of the European modern society and grid resilience will be key to climate change adaptation [204] and will require total investment of 375–425 billion€ in distribution grid between 2020 and 2030, where approximately 50% of investment needs are related to the electrification and introduction of renewables.

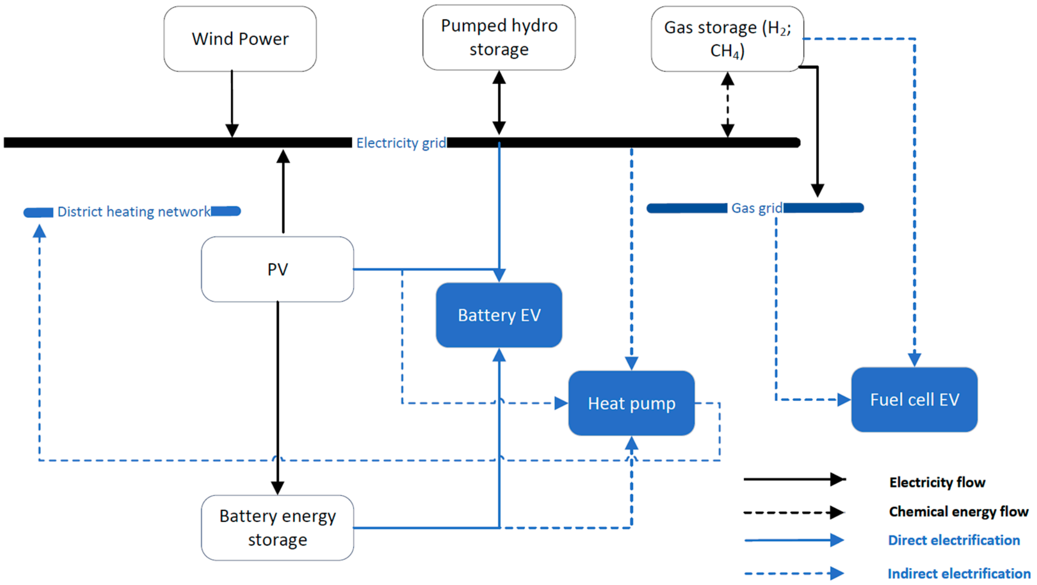

Figure 12. Direct and indirect electrification of transport and heating is illustrated, showcasing the flow of electricity used for direct electrification and the chemical energy flow, such as hydrogen, for indirect electrification [205].

3.2.2. Gas Network

The gas network is one of the main energy infrastructures that can reach multiple applications such as stationary applications (e.g., fuel for CHP plants/boilers), mobility applications (e.g., transport fuels), or industries (e.g., fuel/feedstock). Many studies have suggested that the natural gas grid could be repurposed to hydrogen, in blends or pure, to decarbonise the final users. In this way, all the downstream end-use applications (e.g., CHP systems, boilers, mobility, etc.) are affected by the change of energy carrier without building new pipeline infrastructure or having to implement substantial modifications for end-users. In addition, the large gas volume contained in the gas grid represents an intrinsic form of energy storage, leveraging the inter-operability between chemical storage (e.g., long-term and high energy density) and electricity storage (e.g., short-term and low energy density) for cross-carrier sector coupling [206]. Hydrogen can be blended with natural gas up to around 5–15%vol without safety and reliability issues of end-use technologies as well as continuing to assure the durability and integrity of the existing pipeline infrastructure. Beyond this concentration, the material compatibility of steel and polyethylene pipes could be a limiting factor (e.g., hydrogen leakages, diffusion, embrittlement) as well as safety-related issues for the end-users (e.g., burner and combustor designs, safety protocols, etc.) considering that hydrogen has different thermophysical properties than natural gas. Alternatively, pure hydrogen gas networks could exist with new or repurposed pipeline infrastructure and operate in parallel to in substitution of the natural gas or blended grid network [207]. In the case of blending, considering the high energy density on a mass basis and added value of hydrogen, it is interesting to implement downstream hydrogen separation technologies (HSTs) to re-separate pure hydrogen from the blended mixture. The advantage of the HST is that the natural gas network is only used as a transport medium, but hydrogen is not limited to blend applications (e.g., process gas, thermal uses, etc.) and can be used as pure hydrogen in higher-value applications (e.g., mobility, feedstock for industry, fuel in FC CHP systems, etc.) [208,209]. The main HST technologies are:

- Pressure swing adsorption (PSA), which is based on materials used to absorb the non-hydrogen component at high pressure. It is the most developed HST, but it also presents high energy intensity (20 kWh/kg from a 10%vol blend mixture) and high cost due to the need for two compressors, one to reach the absorption pressure and the other to reinject the gas [209];
- Temperature swing adsorption (TSA) is based on a thermal-driven cycle composed of four steps (e.g., adsorption, preheating, desorption, and precooling). It has similar characteristics and maturity to the PSA technology [210,211];
- Electrochemical separation occurs through proton exchange electrolysers that can separate hydrogen from a gas mixture feedstock. Proton -conductive electrolysers (e.g., polymer membranes or proton -conductive ceramics) are suitable for hydrogen separation/concentration. Electrochemical separation is an improvement concerning PSA/TSA, and it is less energy-intensive, although the separated hydrogen might have a lower purity [209,211];
- Amine-based separation uses an aqueous amine solution to capture hydrogen. It is a very mature and commercialised technology, but has several disadvantages, as the amine solution is corrosive and harmful due to significant losses (e.g., volatility) and degradation issues;
- Cryogenic distillation is a low-temperature separation technique that utilises the varying boiling points of different components in a gas mixture to achieve separation. This technology has the advantage of being deployed on a largescale but requires high investment costs for the cryogenic equipment;
- Membrane separation uses membranes that are selective to hydrogen for physical separation (e.g., organic or inorganic membranes; the most promising material today is palladium (Pd)). Membrane separation technologies are energy-efficient, lightweight, and have lower investment costs compared to other HST technologies; however, they lack maturity at the industrial level [212,213].

3.2.3. Mobility Infrastructure

Today, EVs represent only a limited part of the vehicle fleet, and most of the EVs (around 90%) are charged overnight with low-power charging systems (Mode 1 and Mode 2—<22 kW—charging time > 8 h), while only 10% are charged with fast-charging high-power systems (Mode 3 and Mode 4—charging time 1–2 h or less). However, EVs and the related EV infrastructure should be seen as part of the energy infrastructure. Considering the prospected increase in EVs' sales, the number of charging points, and charging power capacity (up to 150 kW for passenger cars and 500 kW for heavy-duty vehicles) [214], EVs will represent the highest electricity demands in the future, especially in the case of multi-vehicle charging islands, thus deeply affecting the power grid capacity requirements (e.g., imbalances, fluctuations, etc.), power quality standards (e.g., current and voltage distortions, power factor, harmonics, etc.), and electricity market price mechanisms [197]. In this sense, EVs can represent the link between the power and transport network and represent active participants of the power grid [196] (vehicle-to-grid (V2G) concept). In the V2G concept, the battery capacity of each EV is used during non-utilisation periods (e.g., parking time or overnight) to support the grid while providing revenues to the car owners. V2G is a powerful tool used to balance the power and mobility sectors and requires detailed long-term planning as well as dedicated policymaking considering the impact that the EVs' charging/discharging capacity can have on the grid capacity and market mechanisms [215]. Dedicated mobility/storage hubs coupled with dedicated local renewables would provide even more flexibility options for grids and EH in general, thus allowing to charge the EVs with zero-emission electricity and, at the same time, provide grid services at relevant capacity. An evolution of V2G is the vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), and vehicle-to-pedestrian (V2P) concepts, which are encompassed into what is called cellular-vehicle-to-everything (C-V2X) [216]. Apart from the V2G and C-V2X concepts, which are more relevant from an energy point of view, the presence of many EVs can also used for communication, control, and navigation purposes in different concepts such as shared autonomous mobility (SAM) [217], dedicated short-range communications (DSRC), etc. The interaction between EVs and the mobility infrastructure requires the development of specifically designed communication protocols, such as the IEEE 802.11p and LTE-V2V standards, and support facilities to manage the services [218].

4. Energy Planning Tools and Framework

Local-scale energy planning research has been a research topic over the last decades, addressing local-scale energy policies orientated to environmental goals. Initially, local energy planners and researchers focused mainly on national energy policies and context; subsequently, a wide number of planning tools have been developed over the recent years, specifically addressing local energy planning of DERs in specific areas such as districts, cities, and energy islands (both geographical and technological ones). Chang et al. [219] reviewed 54 energy planning tools dedicated to energy transition planning. When it comes to ILEC energy planning, the main constraint of the research is to have a comprehensive overview of the interactions and synergies among different types of DERs, energy carriers, and energy distribution networks. In the last decades, wider deployment of intermittent renewable energy production increased the need for flexibility both in the supply and demand side of the energy systems. This entailed the growing interest in technologies enabling flexibility strategies such as energy storage or the connecting technologies already discussed previously. Klemm et al. [220] reviewed 145 modelling tools, finding that only 13 were suitable for ILEC planning. According to this work, the main features of a planning tool should (i) implement optimisation algorithms, (ii) address multi-energy districts, (iii) operate with an at least hourly temporal resolution, and (iv) follow a bottom-up or hybrid analytical approach. Several planning tools could also used to optimise the operation of energy systems.

The most suitable energy planning tools for ILECs are investigated in detail below [221]. The common ground for these tools is that they are commercially available and can be considered the most adapted for the EH scale. To sum up, Table 15 lists the differences between the analysed energy planning tools and their scope of application.

Table 15. A comparison of the main characteristics and functionalities of the investigated energy planning tools.

Origin	Type	Users	Community	End-Use	Networks	Customisable	Cost Functions	Energy Carriers	Functionalities	Scale	Temporal Resolution	Time Horizon	Modularity
Energyplan	Free	Worldwide users	No	Adapted from national planning tools	Electricity, heating, fossil resources	No	Economic, environmental, energy efficiency, social	Electricity, heating, cooling, hydrogen, fossil fuels	Operation, no smart options	National	Hours	Year	No
DER-CAM	Open	Academic researcher	Yes	ILEC	Electricity, heating, cooling, fossil fuels	Yes	Financial and environmental	Electricity, heating, cooling, fossil fuels	Design and scheduling	Local	Year	Max. 20 years	Yes
Calliope	Open	Worldwide	Yes	ILEC	Electricity, heating, fossil resources, hydrogen	Yes	Economic	User-defined	Design and scheduling	User-defined	User-defined	User-defined	Possible
HOMER	Commercial	Worldwide users	Community tools	ILEC	Electricity, heating, fossil and renewable sources	Yes	Economic, environmental, energy efficiency	Electricity, heat, hydrogen, biomass, fuel	Operation	Local to regional	User-defined	User-defined	Yes
EnergyPro	Commercial	Worldwide	No	ILEC	Electricity, heating, fossil resources	No	Economic	Electricity, heating, fossil resources	Operation	Local to regional	Minutes	Max. 40 years	No
eTransport (Integrate)	Commercial	Energy systems' planners	No	ILEC	Electricity, district heating/cooling, gas, hydrogen	N.A.	Economic	Electricity, district heating/cooling, gas, hydrogen	Design and scheduling	Local	Hours	Max. 50 years	Yes

4.1. Energyplan

EnergyPlan 16.22 is a software tool available for free that models the functioning of national energy systems on an hourly scale. It covers sectors such as electricity, heating, cooling, industry, and transportation. The tool was created and is managed by the Sustainable Energy Planning Research Group at Aalborg University in Denmark. Overall speaking, Energyplan is a user-friendly software that allows obtaining the optimal design easily and efficiently. It is widely adopted in the research field, namely in 315 journal literature (until July 2022) [222]. However, it does not permit the customisation of the energy carriers involved. It was originally designed for national scale planning instead of local energy community therefore some details of local scale could be omitted.

4.2. DER-CAM

The approach used in DER-CAM is fully technology-neutral and can include energy purchases, on-site conversion, both electrical and thermal on-site renewable harvesting, and partly end-use efficiency investments. It allows finding the best combination of equipment and its operation over a typical year (e.g., average over many historical years) that minimises the site's total energy bill or CO_2 emissions, typically for electricity plus natural gas purchases as well as amortised equipment purchases. Another key output is the hourly operating schedule, as well as the resulting costs, fuel consumption, and CO_2 emissions. Given its optimisation nature and technology-neutral approach, DER-CAM can capture both direct and indirect benefits of dealing with multi-energy systems. Moreover, a wide range of generation, conversion, and storage technologies is included in the database. Another pro to be considered is that it is user-friendly and free to access. The drawbacks of such a tool are listed below:

- It does not allow dealing with the optimal design of district heating networks;
- Although it allows making environmental assessments, it does not rely on a multi-objective approach to the optimisation problem;
- In a multi-node configuration, the optimal design approach is centralised, and not distributed;
- It does not allow simulating peer-to-peer energy transactions;
- It does not consider uncertainties related to renewable energy output;
- It is not possible for the user to include new custom components;
- Energy market interaction is not addressed.

The distributed energy resources-consumer adoption model (DER-CAM) is a mixed-integer optimisation tool designed to support investment and planning decisions in microgrids. It is developed in the general algebraic modelling system (GAMS) and has been continuously updated by the Lawrence Berkeley National Laboratory since 2000. Recently, two new versions have been introduced: a web-based version known as the DERs Web Optimisation Service (WebOpt) and an advanced version called DER-CAM+.

Users of DER-CAM provide various inputs, such as:

- Hourly load profiles for a typical year, including electricity, cooling, refrigeration, space heating, hot water, and natural gas usage;
- Electricity tariffs, natural gas prices, and other relevant pricing information;
- Capital and O&M costs, fuel expenses, and interest rates on investments for different technologies;
- Physical attributes of different generation, heat recovery, and cooling technologies, including the thermal-electric ratio, which indicates residual heat based on the generator's electric output;
- Details on site layout and heating infrastructure (for multi-node models only).

The output provided by DER-CAM includes:

- The optimal choice and sizing of distributed energy resources (DER) to be installed;
- The best placement of DERs within the microgrid (for multi-node configurations);

- Dispatch strategies for DERs to maximise economic outcomes while maintaining reliability and resilience;
- A detailed cost breakdown for meeting end-use loads;
- A comprehensive breakdown of carbon emissions associated with energy consumption.

DER-CAM has become widely used for optimising DER investment, scheduling, and conducting economic and environmental assessments in local energy systems. The model is technologyneutral, allowing it to account for energy purchases, on-site conversion, renewable energy harvesting, and energy efficiency improvements. It identifies the optimal combination of equipment and its operational schedule to minimise the total energy cost or carbon emissions over a typical year, providing outputs such as hourly operating schedules, costs, fuel consumption, and emissions.

Despite its strengths, DER-CAM has some limitations, including:

- It does not support optimal district heating network design;
- While environmental assessments are possible, multi-objective optimisation is not;
- In multi-node configurations, the optimal design is centralised rather than distributed;
- Peer-to-peer energy transactions cannot be simulated;
- Renewable energy output uncertainties are not accounted for;
- Users cannot add custom components;

The model does not consider interactions with energy markets.

Although the tool has some limitations, it remains a powerful, user-friendly, and freely accessible solution for optimizing DERs in microgrids.

4.3. HOMER

Hybrid optimisation of multiple electric renewables (HOMER) can simulate and optimise stand-alone and grid-connected local energy systems consisting of wind turbines, PV, hydropower, biomass, conventional generators, energy storage, etc. For the optimal design problem, it allows identifying what components are required to be included in the system as well as the number and size of each component, according to the objective function selected. Power sources that can be modelled include PV, wind turbines, hydropower, diesel, gasoline, biogas, alternative, co-fired, and custom-fuelled generators, electric utility grids, microturbines, and FCs. Storage options include battery banks and hydrogen. HOMER can be defined as a regional system -scale tool, originally developed to support the design of off-grid community-scale electrical energy systems but expanded to model grid-connected and thermal systems. HOMER takes into account investment and operating costs, along with techno-economic factors and emission constraints, to determine the optimal sizing for hybrid renewable energy systems and community microgrids. HOMER was originally developed by National Renewable Energy Laboratories (NREL) in 1992 and further enhanced by HOMER energy. User inputs include load curves (electrical and thermal) up to the 1-min resolution, technology efficiencies and features, O&M costs, emission constraints, and sensitivity parameters. The software output includes optimisation and sensitivity analysis of the system involving energy production, fuel consumption, emissions, and costs with graphs and detailed data reports. One of the main pros related to HOMER is that it is user-friendly and does not need users' specific engineering skills. Moreover, it is based on a modular architecture, giving the possibility to include customised modules. It can also count on a supply profile generator, generating the supply profile from the resource input (e.g., climate) and the device specifications. The main drawbacks are listed below:

- It does not rely on a wide range of heat and cooling technologies, since the focus is on the electrical sector;
- It does not allow analysing district heating network configurations;
- It allows mainly the optimisation of studies from the financial point of view, and it does not rely on a multi-objective approach considering environmental objectives in the optimisation problem;

- In a multi-node configuration, the optimal design approach is centralised and not distributed;
- It does not allow simulating peer-to-peer energy transactions;
- It does not consider cooling loads;
- The user is required to pre-define the technologies and their sizes or capacities, and HOMER evaluates and ranks these combinations based on their outcomes. As a result, the financial analysis is limited to the technology combinations specified by the user in advance.
- Energy market interaction is not addressed.

4.4. Calliope

Calliope is an open-source, community-driven framework for building energy system models. It is designed to analyze systems with highly customizable spatial and temporal resolutions, using a scale-independent mathematical approach that allows for analysis at scales ranging from individual urban districts to entire countries or continents. The basic process of modelling with Calliope is based on three steps:

- Building a model;
- Running a model;
- Analysing a model.

It provides both a command-line interface and an API for programmatic use, to be useful both for users experienced with Python and those with no Python knowledge. The Calliope model is made of .yaml and .csv files, where the first ones describe the technologies, locations, and constraints while the latter ones are input demand data, once created the model Calliope passes the model through Pyomo 6.8.0 for constructing the optimisation problem, back-end interface which can use both open and commercial solvers. Calliope v0.6.10, being an open software, is highly a community-driven software with prompt support and improvement by its community. Its design clearly separates the general framework (code) from the problem-specific model (data). The user has a very large freedom in the modelling (e.g., time resolution, technologies, networks involved, etc.) which enables the ability to have high temporal and spatial resolution and permits the execution of several runs on the same model. The main con is that it does not have a graphic interface and requires some basic skill in programming to handle properly the modelling. As a continuing improvement of software, guided by the community, different bugs can occur.

4.5. EnergyPro

EnergyPro 9.3.1 is a comprehensive software package designed for the combined techno-economic analysis and optimization of cogeneration and trigeneration projects, as well as other complex energy systems that supply both electricity and thermal energy (such as steam, hot water, or cooling) from various energy-producing units. It is typically applied to projects like district heating cogeneration plants with gas engines, industrial cogeneration systems providing electricity, steam, and hot water, and trigeneration plants with absorption chilling. Additionally, it can be used for projects involving biogas-fueled CHP plants, biomass cogeneration, and other renewable energy systems like geothermal, solar collectors, PV, and wind farms.

EnergyPro outputs results in a format suitable for submission to the World Bank and international investment banks. Its flexible and generic design enables the modeling of virtually any type of energy plant. However, it lacks modularity, meaning users cannot integrate custom modules to develop new functionalities within the software.

4.6. eTransport/Integrate

Integrate, formerly known as eTransport, is a software system designed for optimizing integrated energy systems. It helps in initial planning development of existing energy systems by accounting for energy demand forecasts, various technological options for energy supply, conversion between energy carriers, distribution, storage, end-use measures, and CO_2 emission constraints. The software uses a combination of linear programming (LP) and dynamic programming (DP/SDP) to generate a cost-effective development plan and provides a detailed operational model of the system for representative time period on an hourly basis across different seasons. Integrate is particularly suited for analyzing local energy systems, such as those for housing associations or districts, and also includes a model for the entire European energy system, known as Integrate Europe. Modularity allows to introduce of new components, which can be very specific, and refine the existing ones, but the model does not consider physical constraints in details (e.g., congestion or/and voltage violations in electric grid).

5. Key Findings and Conclusions

This paper aims to provide a deep insight into technological solutions that could better enable the establishment of local energy systems by achieving synergies among different energy conversion and storage technologies to achieve energy self-sufficiency. These solutions have been contextualised within the 'EH' and 'mEH' contexts, which are the basis for the future development and deployment of ILECs. This paper highlights the importance of system integration considering the sector coupling approach, which is thought of as one of the main pathways for achieving the full decarbonisation process by 2050 (e.g., the net-zero emission target goal set by the EU). However, a good understanding of the enabling technologies for pursuing sector coupling is needed to address limitations and both technical and non-technical barriers that lower the deployment of ILECs. Main enabling technologies have been critically analysed and divided in terms of size, applications (e.g., EH and/or mEH), energy carrier used, costs, etc., showing the current level of development and what is needed/required for use optimally in ILECs. Besides the hardware, software integration is also another aspect to deal with; indeed, the proper and optimal management of all the technologies within an ILEC is mandatory to foresee and apply energy efficiency measures that will lead to both economic and economic advantages, locally but also to a wider area. Due to current limitations and barriers, the use of energy planning tools is considered a viable solution for assessing the feasibility of multi-carrier ILECs; however, their validation is strongly required to have reliable results. The paper also reports an insight into the existing planning tools, providing specific information about their potential and current limitations. All the information reported in this document might be used by researchers and experts in the energy systems field to evaluate possible project outcomes to choose the best technologies according to their own specific needs.

To provide a further highlight on the current real applications where both the EH and mEH structures can be applied, a few pilot projects have been realised so far in Italy (e.g., Osimo town located in the centre of Italy) and Singapore [223]. In Osimo, both the EH and mEH architectures are applied, which have been developed in the two H2020 EU projects [224,225] to coordinate local energy communities, aggregators, and large consumers. Up to now, the architecture is currently being used by ASTEA S.p.A., the local utility (EH), to monitor and coordinate four assets (mEHs). As a result, mEHs provide flexibility services for the electricity market through a 1.2 MW-CHP plant, congestion management, and/or PV energy self-consumption increase with 105 kW-batteries that allowed ASTEA S.p.A. to save almost 150 k EUR. In Singapore, a novel district-scale demonstrator for Nanyang Technological University acts as a mEH consisting of a distributed cryo-polygeneration system composed of a 5.2 MW-GT plant, a 200 kW of liquid natural gas (LNG) regasification unit, a 9 MW-absorption chiller, and a 2.8 MW-vapour compression chiller. The scope was to use cold energy from LNG and waste heat for power generation along with renewables [226]; indeed, the integration of both a 5 MWh-cold thermal energy storage (CTES) and a 2.5 MW-PV system into the cryo-polygeneration system led to 38.3% cost savings of overall annualised with a positive net present value (NPV) of 45.4 MUSD over 30 years. From an environmental perspective, this action led to a 19% carbon dioxide (CO_2) reduction by increasing the primary energy saving (PES) up to 17.5%.

Finally, the broad overview of ILECs provided by this paper leads to valuable lessons learned which revolve around sustainability, community engagement, technology, and policy. These lessons learned might be also considered as a roadmap to follow for deploying the implementation of ILECs further. However, it must be kept in mind that the field of energy, and particularly ILECs, is continuously evolving. In particular, the main lessons learned are:

- Empowering local communities by incentivising the end-users in decision-making processes. Engaging the community early on and involving them in planning, implementing, and managing energy projects leads to a sense of ownership and increased support for sustainable initiatives;
- RES integration to adopt and integrate solar, wind, hydropower, biomass, etc. These clean energy sources will reduce carbon emissions and enhance the community's energy resilience and independence;
- Smart grid and energy storage implementation to efficiently manage the energy flows, through different energy carriers, within the community. These technologies allow for better utilization of renewable energy and help balance supply and demand;
- Encouraging energy efficiency through various measures, such as energy audits, energy-efficient appliances, and home retrofits, to significantly reduce energy consumption and costs for community members.
- Stimulating local economies. Investments in renewable energy projects and energy efficiency initiatives can create jobs, attract businesses, and foster local entrepreneurship;
- Creating a supportive policy environment is crucial for the success of local energy communities. Governments should develop policies that encourage community-based renewable energy projects, remove regulatory barriers, and provide fair compensation mechanisms for energy production and sharing;
- Transparency on data and information sharing among community members, local authorities, and energy providers are essential for building trust, understanding energy patterns, and making informed decisions;
- Enhancing their resilience by having backup energy systems and emergency plans in place. This is especially important during extreme weather events or other disruptions to the grid;
- Raising awareness about the benefits of local energy communities, renewable energy, and energy conservation is crucial for encouraging widespread adoption and support; and
- Scaling up and replicability to identify factors that contributed to their success. These insights can be used to replicate and scale up similar initiatives in other communities.

It is worth noting that the effectiveness of these lessons may vary depending on the specific contexts and characteristics of each community; therefore, tailoring solutions to local needs and circumstances is essential for creating successful ILECs, and this is the specific purpose of the eNeuron project by developing a toolbox capable of evaluating the performance of an ILEC and evaluating strategies to achieve economic and environmental benefits from their implementation.

Author Contributions: Conceptualization, M.R. and G.C.; methodology, M.R., M.D.S., C.P. and G.C.; formal analysis, M.R., A.M.F., A.B. and A.M.; data curation, M.R. and L.J.; writing—original draft preparation, M.R., L.J., A.M.F., M.D.S., A.B., C.P., A.M., G.G. and G.C.; writing—review and editing, M.R., L.J., A.M.F., M.D.S., A.B., C.P., A.M., G.G. and G.C.; visualisation, M.R., L.J., A.M.F., M.D.S., A.B., C.P. and A.M.; supervision, M.D.S., C.P., G.G. and G.C.; project administration, M.D.S. and C.P.; funding acquisition, M.D.S. and C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union Horizon 2020 Research and Innovation Programme, grant number 957779.

Data Availability Statement: Data sharing is not applicable.

Acknowledgments: This work has been carried out within the eNeuron project that has received funding from the European Union Horizon 2020 Research and Innovation Programme under Grant Agreement No. 957779.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Acronyms

AC	Alternating Current
AI	Artificial Intelligence
API REST	Application Programming Interface Representational State Transfer
BEMS	Building Energy Management System
BMS	Building Management System
C-V2X	Cellular-Vehicle-to-Everything
CC	Combined Cycle
CCTV	Closed-Circuit Television
CHP	Combined, Heat, and Power
COP	Coefficient Of Performance
CTES	Cold Thermal Energy Storage
DC	Direct Current
DCS	Distributed Control System
DER-CAM	Distributed Energy Resources-Consumer Adoption Model
DP/SDP	Dynamic Programming
DQN	Deep Q-Network
DRL	Deep Reinforcement Learning
DSM	Demand Side Management
DSO	Distribution System Operator
DSRC	Dedicated Short-Range Communications
E.DSO	European Distribution System Operators
EC	European Commission
EER	Energy Efficiency Ratio
EH	Energy Hub
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators
ESS	Energy Storage System
ETIP SNET	European Technology and Innovation Platform Smart Networks for Energy Transition
EU	European Union
EV	Electric Vehicle
FC	Fuel Cell
GAMS	General Algebraic Modelling System
GT	Gas Turbine
HOMER	Hybrid Optimisation of Multiple Electric Renewables
HRSG	Heat Recovery Steam Generator
HST	Hydrogen Separation Technology
HTE	High-Temperature Electrolysis
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
ICE	Internal Combustion Engine
ILEC	Integrated Local Energy Community
LNG	Liquid Natural Gas
LP	Linear Programming
LTE	Low-Temperature Electrolysis

LV	Low Voltage
MARL	Multiple Agent Reinforcement Learning
MED	Multi-Effect Distillation
mEH	Micro-Energy Hub
MFD	Multi Flash Distillation
mGT	Micro-Gas Turbine
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
MV	Medium Voltage
NPV	Net Present Value
NREL	National Renewable Energy Laboratories
ORC	Organic Rankine Cycle
O&M	Operation & Maintenance
PES	Primary Energy Saving
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PSA	Pressure Swing Adsorption
PtG	Power-to-Gas
PtH	Power-to-Heat
PtL	Power-to-Liquid
P	Photovoltaics
RD&I	Research, Development, and Innovation
RES	Renewable Energy System
RL	Reinforcement Learning
RO	Reverse Osmosis
SAM	Shared Autonomous Mobility
SCADA	Supervisory Control and Data Acquisition
ST	Steam Turbine
TRL	Technology Readiness Level
TSA	Temperature Swing Adsorption
TSO	Transmission System Operator
V2I	Vehicle-to-Infrastructure
V2G	Vehicle-to-Grid
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
WebOpt	Web Optimisation Service
WoC	Web-of-Cell

References

1. Chen, W.; Alharthi, M.; Zhang, J.; Khan, I. The need for energy efficiency and economic prosperity in a sustainable environment. *Gondwana Res.* **2024**, *127*, 22–35. [CrossRef]
2. Du, W.; Li, M.; Wang, Z. The impact of environmental regulation on firms' energy-environment efficiency: Concurrent discussion of policy tool heterogeneity. *Ecol. Indic.* **2022**, *143*, 109327. [CrossRef]
3. Wu, Q.; Li, C. Economy-environment-energy benefit analysis for green Hydrogen based integrated energy system operation under carbon trading with a robust optimization model. *J. Energy Storage* **2022**, *55*, 105560. [CrossRef]
4. Hodzic, S.; Sikic, T.F.; Dogan, E. Green environment in the EU countries: The role of financial inclusion, natural resources, and energy intensity. *Resour. Policy* **2023**, *82*, 103476. [CrossRef]
5. Zhu, Y.; Yang, F.; Wei, F.; Wang, D. Measuring environmental efficiency of the EU based on a DEA approach with fixed cost allocation under different decision goals. *Expert Syst. Appl.* **2022**, *208*, 118183. [CrossRef]
6. Tutak, M.; Brodny, J. Renewable energy consumption in economic sectors in the EU-27. The impact on economics, environment, and conventional energy sources. A 20-year perspective. *J. Clean. Prod.* **2022**, *345*, 131076. [CrossRef]
7. IEA—International Energy Agency. CO_2 Emissions in 2022. Available online: https://www.iea.org/reports/co2-emissions-in-2022 (accessed on 26 July 2024).
8. IEA—International Energy Agency. Renewables 2022. Available online: https://www.iea.org/reports/renewables-2022 (accessed on 26 July 2024).

9. Johnathon, C.; Agalgaonkar, A.P.; Planiden, C.; Kennedy, J. A proposed hedge-based energy market model to manage renewable intermittency. *Renew. Energy* **2023**, *207*, 376–384. [CrossRef]
10. Cosgrove, P.; Roulstone, T.; Zachary, S. Intermittency and periodicity in net-zero renewable energy systems with storage. *Renew. Energy* **2023**, *212*, 299–307. [CrossRef]
11. Adetokun, B.B.; Muriithi, C.M. Application and control of flexible alternating current transmission system devices for voltage stability enhancement of renewable-integrated power grid: A comprehensive review. *Heliyon* **2021**, *7*, E06461. [CrossRef]
12. Li, C.; Huang, Y.; Deng, H.; Zhang, X.; Zhao, H. A novel grid-forming technology for transient stability enhancement of power system with high penetration of renewable energy. *Int. J. Electr. Power Energy Syst.* **2022**, *143*, 108402. [CrossRef]
13. Mirzapour, O.; Rui, X.; Sahraei-Ardakani, M. Transmission impedance control impacts on carbon emissions and renewable energy curtailment. *Energy* **2023**, *278*, 127741. [CrossRef]
14. Saboori, H.; Jadid, S. Capturing curtailed renewable energy in electric power distribution networks via mobile battery storage fleet. *J. Energy Storage* **2022**, *46*, 103883. [CrossRef]
15. Sánchez, A.; Martin, M.; Zhang, Q. Optimal design of sustainable power-to-fuels supply chains for seasonal energy storage. *Energy* **2021**, *234*, 121300. [CrossRef]
16. Li, Y.; Zhao, P.; Shen, B. A review of new technologies for lithium-ion battery treatment. *Sci. Total Environ.* **2024**, *951*, 175459. [CrossRef]
17. Alkhalidi, A.; Alrousan, T.; Ishbeytah, M.; Abdelkareem, M.A.; Olabi, A.G. Recommendations for energy storage compartment used in renewable energy project. *Int. J. Thermofluids* **2022**, *15*, 100182. [CrossRef]
18. IEA—International Energy Agency. Electrification. Available online: https://www.iea.org/energy-system/electricity/electrification (accessed on 26 July 2024).
19. Zhou, Y.; Ong, G.P.; Meng, Q. The road to electrification: Bus fleet replacement strategies. *Appl. Energy* **2023**, *337*, 120903. [CrossRef]
20. Son, H.; Kim, M.; Kim, J.-K. Sustainable process integration of electrification technologies with industrial energy systems. *Energy* **2022**, *239*, 122060. [CrossRef]
21. Hong, T.; Lee, S.H.; Zhang, W.; Sun, K.; Hooper, B.; Kim, J. Nexus of electrification and energy efficiency retrofit of commercial buildings at the district scale. *Sustain. Cities Soc.* **2023**, *95*, 104608. [CrossRef]
22. Dell, S.; Menconi, M. Off-grid Approach to Support the Small Scale Food Producers in Rural Areas. *Agric. Agric. Sci. Procedia* **2016**, *8*, 516–526. [CrossRef]
23. Hong, W.; Jenn, A.; Wang, B. Electrified autonomous freight benefit analysis on fleet, infrastructure, and grid leveraging Grid-Electrified Mobility (GEM) model. *Appl. Energy* **2023**, *335*, 120760. [CrossRef]
24. Bauer, G.S.; Phadke, A.; Greenblatt, J.B.; Rajagopal, D. Electrifying urban ridesourcing fleets at no added cost through efficient use of charging infrastructure. *Transp. Res. Part C Emerg. Technol.* **2019**, *105*, 385–404. [CrossRef]
25. Azin, B.; Yang, X.; Markovic, N.; Liu, M. Infrastructure enabled and electrified automation: Charging facility planning for cleaner smart mobility. *Transp. Res. Part D Transp. Environ.* **2021**, *101*, 103079. [CrossRef]
26. Palomino, A.; Parvania, M. Advanced charging infrastructure for enabling electrified transportation. *Electr. J.* **2019**, *32*, 21–26. [CrossRef]
27. Van Nuffel, L.; Dedecca, J.G.; Smit, T.; Rademaekers, K. *Sector Coupling: How Can It Be Enhanced in the EU to Foster Grid Stability and Decarbonise?* PE 626.091; European Parliament's Committee on Industry Research and Energy: Maastricht, The Netherlands, 2018. Available online: https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf (accessed on 26 July 2024).
28. European Commission; Directorate-General for Energy; Galano, C.; Grinsven, A.; Kampman, B.; Scholten, T.; Veen, R.; Balachandar, V.; Jenssen, Å.; Riechmann, C.; et al. *Potentials of Sector Coupling for Decarbonisation—Assessing Regulatory Barriers in Linking the Gas and Electricity Sectors in the EU—Final Report*; Publications Office of the European Union: Luxembourg, 2019. Available online: https://data.europa.eu/doi/10.2833/000080 (accessed on 26 July 2024).
29. ETIP SNET VISION 2050, Integrating Smart Networks for the Energy Transition: Serving Society and Protecting the Environment. Available online: https://smart-networks-energy-transition.ec.europa.eu/etip-snet-vision-2050 (accessed on 26 July 2024).
30. ENTSO-E Research. Development & Innovation Roadmap 2020–2030. 2020. Available online: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/RDC%20publications/entso-e-rdi_roadmap-2020-2030.pdf (accessed on 26 July 2024).
31. Nasiri, T.; Moeini-Aghtaie, M.; Foroughi, M.; Azimi, M. Energy optimization of multi-carrier energy systems to achieve a low carbon community. *J. Clean. Prod.* **2023**, *390*, 136154. [CrossRef]
32. Nazari-Heris, M.; Mohammadi-Ivatloo, B.; Asadi, S. Optimal operation of multi-carrier energy networks with gas, power, heating, and water energy sources considering different energy storage technologies. *J. Energy Storage* **2020**, *31*, 101574. [CrossRef]
33. Chicco, G.; Di Somma, M.; Graditi, G. Chapter 1—Overview of distributed energy resources in the context of local integrated energy systems. In *Distributed Energy Resources in Local Integrated Energy Systems, Optimal Operation and Planning*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 1–29. [CrossRef]
34. Nasiri, N.; Sadeghi Yazdankhah, A.; Mirzaei, M.A.; Loni, A.; Mohammadi-Ivatloo, B.; Zare, K.; Marzband, M. A bi-level market-clearing for coordinated regional-local multi-carrier systems in presence of energy storage technologies. *Sustain. Cities Soc.* **2020**, *63*, 102439. [CrossRef]

35. Raimondi, G.; Spazzafumo, G. Exploring Renewable Energy Communities integration through a Hydrogen Power-to-Power system in Italy. *Renew. Energy* **2023**, *206*, 710–721. [CrossRef]
36. Bashi, M.H.; De Tommasi, L.; Le Cam, A.; Relano, L.S.; Lyons, P.; Mundo, J.; Pandelieva-Dimova, I.; Schapp, H.; Loth-Babut, K.; Egger, C.; et al. A review and mapping exercise of energy community regulatory challenges in European member states based on a survey of collective energy actors. *Renew. Sustain. Energy Rev.* **2023**, *172*, 113055. [CrossRef]
37. Choudhury, S. Review of energy storage system technologies integration to microgrid: Types, control strategies, issues, and future prospects. *J. Energy Storage* **2022**, *48*, 103966. [CrossRef]
38. ETIP SNET—European Technology and Innovation Platform Smart Networks for Energy Transition. Sector Coupling: Concepts, State-of-the-art and Perspectives. 2020. Available online: https://smart-networks-energy-transition.ec.europa.eu/sites/default/files/news/ETIP-SNEP-Sector-Coupling-Concepts-state-of-the-art-and-perspectives-WG1.pdf (accessed on 26 July 2024).
39. Nebel, A.; Cantor, J.; Salim, S.; Salih, A.; Patel, D. The Role of Renewable Energies, Storage and Sector-Coupling Technologies in the German Energy Sector under Different CO_2 Emission Restrictions. *Sustainability* **2022**, *14*, 10379. [CrossRef]
40. IRENA—International Renewable Energy Agency. Sector Coupling in Facilitating Integration of Variable Renewable Energy in Cities. 2021. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Sector_Coupling_in_Cities_2021.pdf (accessed on 26 July 2024).
41. Gils, H.C.; Gardian, H.; Schmugge, J. Interaction of Hydrogen infrastructures with other sector coupling options towards a zero-emission energy system in Germany. *Renew. Energy* **2021**, *180*, 140–156. [CrossRef]
42. Mohammadi, M.; Noorollahi, Y.; Mohammadi-Ivatloo, B.; Yousefi, H. Energy hub: From a model to a concept—A review. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1512–1527. [CrossRef]
43. Guelpa, E.; Bischi, A.; Verda, V.; Chertkov, M.; Lund, H. Towards future infrastructures for sustainable multi-energy systems: A review. *Energy* **2019**, *184*, 2–21. [CrossRef]
44. Mancarella, P. MES (multi-energy systems): An overview of concepts and evaluation models. *Energy* **2014**, *65*, 1–17. [CrossRef]
45. Mohammadi-Ivatloo, B.; Jabari, F. *Operation, Planning, and Analysis of Energy Storage Systems in Smart Energy Hubs*; Springer: Cham, Switzerland, 2018; 456p. [CrossRef]
46. Papadimitriou, C.N.; Anastasiadis, A.; Psomopoulos, C.S.; Vokas, G. Demand Response schemes in Energy Hubs: A comparison study. *Energy Procedia* **2019**, *157*, 939–944. [CrossRef]
47. Mohammadi, M.; Noorollahi, Y.; Mohammadi-Ivatloo, B.; Hosseinzadeh, M.; Yousefi, H.; Khorasani, S.T. Optimal management of energy hubs and smart energy hubs—A review. *Renew. Sustain. Energy Rev.* **2018**, *89*, 33–50. [CrossRef]
48. Lasemi, M.A.; Arabkoohsar, A.; Hajizadeh, A.; Mohammadi-Ivatloo, B. A comprehensive review on optimization challenges of smart energy hubs under uncertainty factors. *Renew. Sustain. Energy Rev.* **2022**, *160*, 112320. [CrossRef]
49. Papadimitriou, C.; Di Somma, M.; Charalambous, C.; Caliano, M.; Palladino, V.; Borray, A.F.C.; Gonzalez-Garrido, A.; Ruiz, N.; Graditi, G. A Comprehensive Review of the Design and Operation Optimization of Energy Hubs and Their Interaction with the Markets and External Networks. *Energies* **2023**, *16*, 4018. [CrossRef]
50. Yokoyama, R.; Nasegawa, Y.; Ito, K. A MILP decomposition approach to large scale optimization in structural design of energy supply systems. *Energy Convers. Manag.* **2002**, *43*, 771–790. [CrossRef]
51. Favre-Perrod, P. A vision of future energy networks. In Proceedings of the 2005 IEEE Power Engineering Society Inaugural Conference and Exposition in Africa, Durban, South Africa, 11–15 July 2005; pp. 13–17. [CrossRef]
52. Geidl, M.; Koeppel, G.; Favre-Perrod, P.; Klockl, B.; Andersson, G.; Frohlich, K. The Energy Hub—A Powerful Concept for Future Energy Systems. In Proceedings of the 3rd Annual Carnegie Mellon Conference on the Electricity Industry, Pittsburgh, PA, USA, 13–14 March 2007. Available online: https://research.ece.cmu.edu/electriconf/2007/2007%20Conf%20Papers/Andersson%20Paper%20final.pdf (accessed on 26 July 2024).
53. Geidl, M.; Koeppel, G.; Favre-Perrod, P.; Klockl, B.; Andersson, G.; Frohlich, K. Energy hubs for the future. *IEEE Power Energy Mag.* **2007**, *5*, 24–30. [CrossRef]
54. Hajimiragha, A.; Canizares, C.; Fowler, M.; Geidl, M.; Andersson, G. Optimal Energy Flow of integrated energy systems with Hydrogen economy considerations. In Proceedings of the 2007 iREP Symposium—Bulk Power System Dynamics and Control—VII. Revitalizing Operational Reliability, Charleston, SC, USA, 19–24 August 2007; pp. 1–11. [CrossRef]
55. Geidl, M. Integrated Modeling and Optimization of Multi-Carrier Energy Systems. Ph.D. Thesis, ETH Zurich, Zurich, Switzerland, 2007. [CrossRef]
56. Galus, M.D.; Koch, S.; Andersson, G. Provision of Load Frequency Control by PHEVs, Controllable Loads, and a Cogeneration Unit. *IEEE Trans. Ind. Electron.* **2011**, *58*, 4568–4582. [CrossRef]
57. Voll, P.; Klaffe, C.; Hennen, M.; Bardow, A. Automated superstructure-based synthesis and optimization of distributed energy supply systems. *Energy* **2013**, *50*, 374–388. [CrossRef]
58. Kostevsek, A.; Petek, J.; Cucek, L.; Pivec, A. Conceptual design of a municipal energy and environmental system as an efficient basis for advanced energy planning. *Energy* **2013**, *60*, 148–158. [CrossRef]
59. Clegg, S.; Mancarella, P. Integrated Modeling and Assessment of the Operational Impact of Power-to-Gas (P2G) on Electrical and Gas Transmission Networks. *IEEE Trans. Sustain. Energy* **2015**, *6*, 1234–1244. [CrossRef]
60. Maroufmashat, A.; Elkamel, A.; Fowler, M.; Sattari, S.; Roshandel, R.; Hajimiragha, A.; Walker, S.; Entchev, E. Modeling and optimization of a network of energy hubs to improve economic and emission considerations. *Energy* **2015**, *93*, 2546–2558. [CrossRef]

61. Clegg, S.; Mancarella, P. Storing renewables in the gas network: Modelling of power-to-gas seasonal storage flexibility in low-carbon power systems. *IET Gener. Transm. Distrib.* **2016**, *10*, 566–575. [CrossRef]
62. Moeini-Aghtaie, M.; Farzin, H.; Fotuhi-Firuzabad, M.; Amrollahi, R. Generalized Analytical Approach to Assess Reliability of Renewable-Based Energy Hubs. *IEEE Trans. Power Syst.* **2017**, *32*, 368–377. [CrossRef]
63. Wild, E.; Jacobs, T.; Schwabeneder, D.; Nicolas, S.; Basciotti, D.; Henein, S.; Noh, T.-G.; Terreros, O.; Schuelke, A.; Auer, H. Studying the potential of multi-carrier energy distribution grids: A holistic approach. *Energy* **2018**, *153*, 519–529. [CrossRef]
64. Sadegi, H.; Rashidinejad, M.; Moeini-Aghtaie, M.; Abdollahi, A. The energy hub: An extensive survey on the state-of-the-art. *Appl. Therm. Eng.* **2019**, *161*, 114071. [CrossRef]
65. Ma, B.; Tian, X. Research progress to energy system model and application of Energy Hub concept model to Sustainable manufacturing. In Proceedings of the 2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC), Chongqing, China, 12–14 June 2020; pp. 1482–1486. [CrossRef]
66. Aljabery, A.A.M.; Mehrjerdi, H.; Mahdavi, S.; Hemmati, R. Multi carrier energy systems and energy hubs: Comprehensive review, survey and recommendations. *Int. J. Hydrogen Energy* **2021**, *46*, 23795–23814. [CrossRef]
67. Brahman, F.; Honarmand, M.; Jadid, S. Optimal electrical and thermal energy management of a residential energy hub, integrating demand response and energy storage system. *Energy Build.* **2015**, *90*, 65–75. [CrossRef]
68. Najafi, A.; Falaghi, H.; Contreras, J.; Ramezani, M. Medium-term energy hub management subject to electricity price and wind uncertainty. *Appl. Energy* **2016**, *168*, 418–433. [CrossRef]
69. Gholinejad, H.R.; Loni, A.; Adabi, J.; Marzband, M. A hierarchical energy management system for multiple home energy hubs in neighborhood grids. *J. Build. Eng.* **2020**, *28*, 101028. [CrossRef]
70. Dini, A.; Pirouzi, S.; Norouzi, M.; Lehtonen, M. Grid-connected energy hubs in the coordinated multi-energy management based on day-ahead market framework. *Energy* **2019**, *188*, 116055. [CrossRef]
71. Zhang, K.; Zhou, B.; Li, C.; Voropai, N.; Li, J.; Huang, W.; Wang, T. Dynamic modeling and coordinated multi-energy management for a sustainable biogas-dominated energy hub. *Energy* **2021**, *220*, 119640. [CrossRef]
72. Wang, X.; Liu, Y.; Liu, C.; Liu, J. Coordinating energy management for multiple energy hubs: From a transaction perspective. *Int. J. Electr. Power Energy Syst.* **2020**, *121*, 106060. [CrossRef]
73. Bahmani, R.; Karimi, H.; Jadid, S. Cooperative energy management of multi-energy hub systems considering demand response programs and ice storage. *Int. J. Electr. Power Energy Syst.* **2021**, *130*, 106904. [CrossRef]
74. Azimi, M.; Salami, A. A new approach on quantification of flexibility index in multi-carrier energy systems towards optimally energy hub management. *Energy* **2021**, *232*, 120973. [CrossRef]
75. Khorasany, M.; Najafi-Ghalelou, A.; Razzaghi, R.; Mihammadi-Ivatloo, B. Transactive energy framework for optimal energy management of multi-carrier energy hubs under local electrical, thermal, and cooling market constraints. *Int. J. Electr. Power Energy Syst.* **2021**, *129*, 106803. [CrossRef]
76. Mansouri, S.A.; Javadi, M.S.; Ahmarinejad, A.; Nematbakhsh, E.; Zare, A.; Catalao, J.P.S. A coordinated energy management framework for industrial, residential and commercial energy hubs considering demand response programs. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101376. [CrossRef]
77. Reza, M.; Zadeh, A.; Niknam, T.; Kavousi-Fard, A. Adaptive robust optimization for the energy management of the grid-connected energy hubs based on hybrid meta-heuristic algorithm. *Energy* **2021**, *235*, 121171. [CrossRef]
78. Shahrabi, E.; Mehdi-Hakimi, S.; Hasankhani, A.; Derakhshan, G.; Abdi, B. Developing optimal energy management of energy hub in the presence of stochastic renewable energy resources. *Sustain. Energy Grids Netw.* **2021**, *26*, 100428. [CrossRef]
79. Bidgoli, M.M.; Karimi, H.; Jadid, S.; Anvari-Moghaddam, A. Stochastic electrical and thermal energy management of energy hubs integrated with demand response programs and renewable energy: A prioritized multi-objective framework. *Electr. Power Syst. Res.* **2021**, *196*, 107183. [CrossRef]
80. Poursmail, B.; Najmi, P.H.; Ravadanegh, S.N. Interconnected-energy hubs robust energy management and scheduling in the presence of electric vehicles considering uncertainties. *J. Clean. Prod.* **2021**, *316*, 128167. [CrossRef]
81. Nosratabadi, S.M.; Jahandide, M.; Guerrero, J.M. Robust scenario-based concept for stochastic energy management of an energy hub contains intelligent parking lot considering convexity principle of CHP nonlinear model with triple operational zones. *Sustain. Cities Soc.* **2021**, *68*, 102795. [CrossRef]
82. Zhang, G.; Hu, W.; Cao, D.; Zhang, Z.; Huang, Q.; Chen, Z.; Blaabjerg, F. A multi-agent deep reinforcement learning approach enabled distributed energy management schedule for the coordinate control of multi-energy hub with gas, electricity, and freshwater. *Energy Convers. Manag.* **2022**, *255*, 115340. [CrossRef]
83. Ahrarinouri, M.; Rastegar, M.; Karami, K.; Seifi, A.R. Distributed reinforcement learning energy management approach in multiple residential energy hubs. *Sustain. Energy Grids Netw.* **2022**, *32*, 100795. [CrossRef]
84. Lefebure, N.; Khosravi, M.; de Badyn, M.H.; Bunning, F.; Lygeros, J.; Jones, C.; Smith, R.S. Distributed model predictive control of buildings and energy hubs. *Energy Build.* **2022**, *259*, 111806. [CrossRef]
85. Seyfi, M.; Mehdinejad, M.; Mohammadi-Ivatloo, B.; Shayanfar, H. Scenario-based robust energy management of CCHP-based virtual energy hub for participating in multiple energy and reserve markets. *Sustain. Cities Soc.* **2022**, *80*, 103711. [CrossRef]
86. Thang, V.V.; Ha, T.; Li, Q.; Zhang, Y. Stochastic optimization in multi-energy hub system operation considering solar energy resource and demand response. *Int. J. Electr. Power Energy Syst.* **2022**, *141*, 108132. [CrossRef]

87. Cao, J.; Yang, B.; Zhu, S.; Chung, C.Y.; Guan, X. Multi-level coordinated energy management for energy hub in hybrid markets with distributionally robust scheduling. *Appl. Energy* **2022**, *311*, 118639. [CrossRef]
88. Cheng, Y.; Zheng, H.; Juanatas, R.A.; Golkar, M.J. Profitably scheduling the energy hub of inhabitable houses considering electric vehicles, storage systems, revival provenances and demand side management through a modified particle swarm optimization. *Sustain. Cities Soc.* **2023**, *92*, 104487. [CrossRef]
89. Bao, M.; Hui, H.; Ding, Y.; Sun, X.; Zheng, C.; Gao, X. An efficient framework for exploiting operational flexibility of load energy hubs in risk management of integrated electricity-gas systems. *Appl. Energy* **2023**, *338*, 120765. [CrossRef]
90. Akbari, E.; Shabestari, S.F.M.; Pirouzi, S.; Jadidoleslam, M. Network flexibility regulation by renewable energy hubs using flexibility pricing-based energy management. *Renew. Energy* **2023**, *206*, 295–308. [CrossRef]
91. He, Q.; Wu, M.; Liu, C.; Jin, D.; Zhao, M. Management and real-time monitoring of interconnected energy hubs using digital twin: Machine learning based approach. *Sol. Energy* **2023**, *250*, 173–181. [CrossRef]
92. Khouzestani, L.B.; Sheikh-El-Eslami, M.K.; Salemi, A.H.; Moghaddam, I.G. Virtual smart energy Hub: A powerful tool for integrated multi energy systems operation. *Energy* **2023**, *265*, 126361. [CrossRef]
93. Boblenz, K.; Frank, V.; Meyer, B. Energy system analysis for evaluation of sector coupling technologies. *Fuel* **2019**, *254*, 115658. [CrossRef]
94. Steinmann, W.-D.; Bauer, D.; Jockenhofer, H.; Johnson, M. Pumped thermal energy storage (PTES) as smart sector-coupling technology for heat and electricity. *Energy* **2019**, *183*, 185–190. [CrossRef]
95. Munster, M.; Sneum, D.M.; Bramstoft, R.; Elmegaard, B.; Buhler, F.; Losa, I.; Iliceto, A.; Oudalov, A.; Elsaesser, D.; Giannellos, S.; et al. Sector Coupling: Concepts, Potentials and Barriers. In Proceedings of the 2020 AEIT International Annual Conference (AEIT), Catania, Italy, 23–25 September 2020; pp. 1–6. [CrossRef]
96. Technischen Universität Darmstadt (Ed.) *PESS 2020—IEEE Power and Energy Student Summit, Conference Proceedings 5–7 October 2020 | Online, Technical University of Darmstadt*; Slimlinebox, CD-Rom; Technische Universität Darmstadt: Darmstadt, Germany, 2020; 252p, ISBN 978-3-8007-5337-6. e-book ISBN 978-3-8007-5338-3.
97. O'Malley, M.J.; Anwar, M.B.; Heinen, S.; Kober, T.; McCalley, J.; McPherson, M.; Muratori, M.; Orths, A.; Ruth, M.; Schmidt, T.J.; et al. Multicarrier Energy Systems: Shaping Our Energy Future. *Proc. IEEE* **2020**, *108*, 1437–1456. [CrossRef]
98. Bohm, H.; Moser, S.; Puschnigg, S.; Zauner, A. Power-to-Hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials. *Int. J. Hydrogen Energy* **2021**, *64*, 31938–31951. [CrossRef]
99. Rehman, O.A.; Palomba, V.; Frazzica, A.; Cabeza, L.F. Enabling Technologies for Sector Coupling: A Review on the Role of Heat Pumps and Thermal Energy Storage. *Energies* **2021**, *14*, 8195. [CrossRef]
100. He, G.; Mallapragada, D.S.; Bose, A.; Heuberger-Austin, C.F.; Gencer, E. Sector coupling via Hydrogen to lower the cost of energy system decarbonization. *Energy Environ. Sci.* **2021**, *14*, 4635–4646. [CrossRef]
101. Meschede, E.; Schlachter, U.; Diekmann, T.; Hanke, B.; Von Maydell, K. Assessment of sector-coupling technologies in combination with battery energy storage systems for frequency containment reserve. *J. Energy Storage* **2022**, *49*, 104170. [CrossRef]
102. Huckebrink, D.; Bertsch, V. Decarbonising the residential heating sector: A techno-economic assessment of selected technologies. *Energy* **2022**, *257*, 124605. [CrossRef]
103. IRENA—International Renewable Energy Agency. *Sector Coupling: A Key Concept for Accelerating the Energy Transformation*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2022; ISBN 978-92-9260-487-5. Available online: https://www.irena.org/Publications/2022/Dec/Sector-coupling-A-key-concept-for-accelerating-the-energy-transformation (accessed on 26 July 2024).
104. Hua, W.; Chen, Y.; Qadrdan, M.; Jiang, J.; Sun, H.; Wu, J. Applications of blockchain and artificial intelligence technologies for enabling prosumers in smart grids: A review. *Renew. Sustain. Energy Rev.* **2022**, *161*, 112308. [CrossRef]
105. Wei, H.; Zhang, Y.; Wang, Y.; Hua, W.; Jing, R. Planning integrated energy systems coupling V2G as a flexible storage. *Energy* **2022**, *239*, 122215. [CrossRef]
106. Sandberg, E.; Krook-Riekkola, A. The impact of technology availability on the transition to net-zero industry in Sweden. *J. Clean. Prod.* **2022**, *363*, 132594. [CrossRef]
107. Bovera, F.; Schiavo, L.L. From energy communities to sector coupling:a taxonomy for regulatory experimentation in the age of the European Green Deal. *Energy Policy* **2022**, *171*, 113299. [CrossRef]
108. McGregor, N.; Yeung, G. Strategic coupling, path creation and diversification: Oil-related development in the 'Straits Region' since 1959. *Extr. Ind. Soc.* **2022**, *11*, 101085. [CrossRef]
109. Makitie, T.; Hanson, J.; Steen, M.; Hansen, T.; Andersen, A.D. Complementarity formation mechanisms in technology value chains. *Res. Policy* **2022**, *51*, 104559. [CrossRef]
110. Mimica, M.; Percic, M.; Vladimir, N.; Krajacic, G. Cross-sectoral integration for increased penetration of renewable energy sources in the energy system—Unlocking the flexibility potential of maritime transport electrification. *Smart Energy* **2022**, *8*, 100089. [CrossRef]
111. Jayachandran, M.; Gatla, R.K.; Rao, K.P.; Rao, G.S.; Mohammed, S.; Milyani, A.H.; Azhari, A.A.; Kalaiarasy, C.; Geetha, S. Challenges in achieving sustainable development goal 7: Affordable and clean energy in light of nascent technologies. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102692. [CrossRef]
112. Fernqvist, N.; Broberg, S.; Toren, J.; Svensson, I.-L. District heating as a flexibility service: Challenges in sector coupling for increased solar and wind power production in Sweden. *Energy Policy* **2023**, *172*, 113332. [CrossRef]

113. Bukhari, M.H.; Javed, A.; Kazmi, S.A.A.; Ali, M.; Chaudhary, M.T. Techno-economic feasibility analysis of Hydrogen production by PtG concept and feeding it into a combined cycle power plant leading to sector coupling in future. *Energy Convers. Manag.* **2023**, *282*, 116814. [CrossRef]
114. Terrados, J.; Almonacid, G.; Hontoria, L. Regional energy planning through SWOT analysis and strategic planning tools.: Impact on renewables development. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1275–1287. [CrossRef]
115. Oregi, X.; Roth, E.; Alsema, E.; Van Ginkel, M.; Struik, D. Use of ICT Tools for Integration of Energy in Urban Planning Projects. *Energy Procedia* **2015**, *83*, 157–166. [CrossRef]
116. Tzanes, G.T.; Zafirakis, D.; Papapostolou, C.; Kavadias, K.; Kaldellis, J.K. PHAROS: An Integrated Planning Tool for Meeting the Energy and Water Needs of Remote Islands using RES-based Hybrid Solutions. *Energy Procedia* **2017**, *142*, 2586–2591. [CrossRef]
117. Gacitua, L.; Gallegos, P.; Henriquez-Auba, R.; Lorca, A.; Negrete-Pincetic, M.; Olivares, D.; Valenzuela, A.; Wenzel, G. A comprehensive review on expansion planning: Models and tools for energy policy analysis. *Renew. Sustain. Energy Rev.* **2018**, *98*, 346–360. [CrossRef]
118. Valente, C.; Soldal, E.; Johnsen, F.M.; Verdu, F.; Raadal, H.L.; Modahl, I.S.; Hanssen, O.J. Methodological accounting tool for Climate and Energy Planning in a Norwegian municipality. *J. Clean. Prod.* **2018**, *183*, 772–785. [CrossRef]
119. Yan, X.; Abbes, D.; Francois, B. Development of a tool for urban microgrid optimal energy planning and management. *Simul. Model. Pract. Theory* **2018**, *89*, 64–81. [CrossRef]
120. Ferrari, S.; Zagarella, F.; Caputo, P.; Bonomolo, M. Assessment of tools for urban energy planning. *Energy* **2019**, *176*, 544–551. [CrossRef]
121. Mroue, A.M.; Mohtar, R.H.; Pistikopoulos, E.N.; Holtzapple, M.T. Energy Portfolio Assessment Tool (EPAT): Sustainable energy planning using the WEF nexus approach—Texas case. *Sci. Total Environ.* **2019**, *648*, 1649–1664. [CrossRef] [PubMed]
122. Cabrera, P.; Lund, H.; Thellufsen, J.Z.; Sorknaes, P. The MATLAB Toolbox for EnergyPLAN: A tool to extend energy planning studies. *Sci. Comput. Program.* **2020**, *191*, 102405. [CrossRef]
123. Rosales-Asensio, E.; de la Puente-Gil, A.; Garcia-Moya, F.-J.; Blanes-Peiro, J.; de Simon-Martin, M. Decision-making tools for sustainable planning and conceptual framework for the energy–water–food nexus. *Energy Rep.* **2020**, *6*, 4–15. [CrossRef]
124. Lyden, A.; Flett, G.; Tuohy, P.G. PyLESA: A Python modelling tool for planning-level Local, integrated, and smart Energy Systems Analysis. *Orig. Softw. Publ.* **2021**, *14*, 100699. [CrossRef]
125. Saad, S.; Lahoud, C.; Brouche, M.; Hmadi, M.; Ghandour, M.; Mourtada, A. Advanced tool for elaborating a sustainable energy and climate action plan at municipalities level. *Energy Rep.* **2021**, *7*, 51–69. [CrossRef]
126. Schenone, C.; Delponte, I. Renewable energy sources in local sustainable energy action PLANs (SEAPs): Analysis and outcomes. *Energy Policy* **2021**, *156*, 112475. [CrossRef]
127. Bouw, K.; Jan Noorman, K.; Wiekens, C.J.; Faaij, A. Local energy planning in the built environment: An analysis of model characteristics. *Renew. Sustain. Energy Rev.* **2021**, *144*, 111030. [CrossRef]
128. Taheri, S.; Jooshaki, M.; Moeini-Aghtaie, M. Long-term planning of integrated local energy systems using deep learning algorithms. *Int. J. Electr. Power Energy Syst.* **2021**, *129*, 106855. [CrossRef]
129. Ligardo-Herrera, I.; Quintana-Gallardo, A.; Stascheit, C.W.; Gomez-Navarro, T. Make your home carbon-free. An open access planning tool to calculate energy-related carbon emissions in districts and dwellings. *Energy Rep.* **2022**, *8*, 11404–11415. [CrossRef]
130. Gonzalez, A.; Connell, P. Developing a renewable energy planning decision-support tool: Stakeholder input guiding strategic decisions. *Appl. Energy* **2022**, *312*, 118782. [CrossRef]
131. Wirtz, M. nPro: A web-based planning tool for designing district energy systems and thermal networks. *Energy* **2023**, *268*, 126575. [CrossRef]
132. Deng, Z.; Chen, Y.; Yang, J.; Causone, F. AutoBPS: A tool for urban building energy modeling to support energy efficiency improvement at city-scale. *Energy Build.* **2023**, *282*, 112794. [CrossRef]
133. Ren, Z.; Jian, A.; Law, A.; Godhani, A.; Chen, D. Development of a benchmark tool for whole of home energy rating for Australian new housing. *Energy Build.* **2023**, *285*, 112921. [CrossRef]
134. Tiwari, S.; Singh, J.G. Optimal energy management of multi-carrier networked energy hubs considering efficient integration of demand response and electrical vehicles: A cooperative energy management framework. *J. Energy Storage* **2022**, *51*, 104479. [CrossRef]
135. Barajas-Villarruel, L.R.; Rico-Ramirez, V.; Castrejon-Gonzalez, E.O. Optimization models for the generation, distribution and transmission of electricity in a macroscopic system: Representation of operational regions as energy hubs. *Chem. Eng. Res. Des.* **2022**, *187*, 645–661. [CrossRef]
136. Morch, A.; Di Somma, M.; Papadimitriou, C.; Saele, H.; Palladino, V.; Ardanuy, J.F.; Conti, G.; Rossi, M.; Comodi, G. Technologies enabling evolution of Integrated Local Energy Communities. In Proceedings of the 2022 IEEE International Smart Cities Conference (ISC2), Pafos, Cyprus, 26–29 September 2022; pp. 1–6. [CrossRef]
137. Tonnellato, G.; Heidari, A.; Pereira, J.; Carnieletto, L.; Flourentzou, F.; De Carli, M.; Khovalyg, D. Optimal design and operation of a building energy hub: A comparison of exergy-based and energy-based optimization in Swiss and Italian case studies. *Energy Convers. Manag.* **2021**, *242*, 114316. [CrossRef]
138. Najafi-Ghalelou, A.; Zare, K.; Nojavan, S. Risk-based scheduling of smart apartment building under market price uncertainty using robust optimization approach. *Sustain. Cities Soc.* **2019**, *48*, 101549. [CrossRef]

139. Setlhaolo, D.; Sichilalu, S.; Zhang, J. Residential load management in an energy hub with heat pump water heater. *Appl. Energy* **2017**, *208*, 551–560. [CrossRef]
140. Fina, B.; Auer, H.; Friedl, W. Profitability of active retrofitting of multi-apartment buildings: Building-attached/integrated photovoltaics with special consideration of different heating systems. *Energy Build.* **2019**, *190*, 86–102. [CrossRef]
141. Rahimzadeh, A.; Christiaanse, T.V.; Evins, R. Optimal storage systems for residential energy systems in British Columbia. *Sustain. Energy Technol. Assess.* **2021**, *45*, 101108. [CrossRef]
142. Perera, A.T.D.; Mauree, D.; Scartezzini, J.-L. The energy hub concept applied to a case study of mixed residential and administrative buildings in Switzerland. *Energy Procedia* **2017**, *122*, 181–186. [CrossRef]
143. Ghorab, M. Energy hubs optimization for smart energy network system to minimize economic and environmental impact at Canadian community. *Appl. Therm. Eng.* **2019**, *151*, 214–230. [CrossRef]
144. Roustai, M.; Rayati, M.; Sheikhi, A.; Ranjbar, A. A scenario-based optimization of Smart Energy Hub operation in a stochastic environment using conditional-value-at-risk. *Sustain. Cities Soc.* **2018**, *39*, 309–316. [CrossRef]
145. Halmschlager, V.; Hofmann, R. Assessing the potential of combined production and energy management in Industrial Energy Hubs—Analysis of a chipboard production plant. *Energy* **2021**, *226*, 120415. [CrossRef]
146. Taqvi, S.; Almansoori, A.; Elkamel, A. Optimal renewable energy integration into the process industry using multi-energy hub approach with economic and environmental considerations: Refinery-wide case study. *Comput. Chem. Eng.* **2021**, *151*, 107345. [CrossRef]
147. Kourgiozou, V.; Commin, A.; Dowson, M.; Rovas, D.; Mumovic, D. Scalable pathways to net zero carbon in the UK higher education sector: A systematic review of smart energy systems in university campuses. *Renew. Sustain. Energy Rev.* **2021**, *147*, 111234. [CrossRef]
148. Al-Ghussain, L.; Ahmad, A.D.; Abubaker, A.M.; Mohamed, M.A. An integrated photovoltaic/wind/biomass and hybrid energy storage systems towards 100% renewable energy microgrids in university campuses. *Sustain. Energy Technol. Assess.* **2021**, *46*, 101273. [CrossRef]
149. Liu, H. WITHDRAWN: Smart campus student management system based on 5G network and Internet of Things. *Microprocess. Mycrosystems* **2020**, 103428. [CrossRef]
150. Rismanchi, B. District energy network (DEN), current global status and future development. *Renew. Sustain. Energy Rev.* **2017**, *75*, 571–579. [CrossRef]
151. Revesz, A.; Jones, P.; Dunham, C.; Davies, G.; Marques, C.; Matabuena, R.; Scott, J.; Maidment, G. Developing novel 5th generation district energy networks. *Energy* **2020**, *201*, 117389. [CrossRef]
152. IRENA—International Renewable Energy Agency. *Renewable Energy in Cities*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2016; ISBN 978-92-95111-32-5. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Renewable_Energy_in_Cities_2016.pdf (accessed on 26 July 2024).
153. Herencic, L.; Melnjak, M.; Capuder, T.; Androcec, I.; Rajsl, I. Techno-economic and environmental assessment of energy vectors in decarbonization of energy islands. *Energy Convers. Manag.* **2021**, *236*, 114064. [CrossRef]
154. Krajacic, G.; Martins, R.; Busuttil, A.; Duic, N.; Da Graca Carvalho, M. Hydrogen as an energy vector in the islands' energy supply. *Int. J. Hydrogen Energy* **2008**, *33*, 1091–1103. [CrossRef]
155. Ciavarella, R.; Di Somma, M.; Graditi, G.; Valenti, M. Congestion Management in distribution grid networks through active power control of flexible distributed energy resources. In Proceedings of the 2019 IEEE Milan PowerTech, Milan, Italy, 23–27 June 2019; pp. 1–6. [CrossRef]
156. Miguel, F.J.; Sanz, R.; Correda, A.; Serna, V.; Hernandez, J.L.; Garcia, J.; Madero, V.; Palomar, R.; Martin, D.; Inaner, G.; et al. Building Energy Management System (BEMS) Definition, BREakthrough Solutions for Adaptable Envelopes in Building Refurbishment EeB-02-2014 RIA. 2016. Available online: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5a596c494&appId=PPGMS (accessed on 26 July 2024).
157. Morch, A.; Caerts, C.; Mutule, A.; Merino, J. Chapter 2—Architectures and concepts for smart decentralised energy systems. In *Distributed Energy Resources in Local Integrated Energy Systems, Optimal Operation and Planning*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 31–61. [CrossRef]
158. Sutton, R.S.; Barto, A.G. *Reinforcement Learning: An Introduction*, 2nd ed.; Adaptive Computation and Machine Learning Series; MIT Press: Cambridge, MA, USA, 2018; 552p, ISBN 9780262039246.
159. Mason, K.; Grijalva, S. A review of reinforcement learning for autonomous building energy management. *Comput. Electr. Eng.* **2019**, *78*, 300–312. [CrossRef]
160. Weinberg, D.; Wang, Q.; Timoudas, T.O.; Fischione, C. A Review of Reinforcement Learning for Controlling Building Energy Systems From a Computer Science Perspective. *Sustain. Cities Soc.* **2023**, *89*, 104351. [CrossRef]
161. EU—European Commission, Directorate-General for Energy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Powering a Climate-Neutral Economy: An EU Strategy for Energy System Integration, OM/2020/299 Final. 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52020DC0299 (accessed on 26 July 2024).
162. Arpagaus, C.; Bless, F.; Uhlmann, M.; Schiffmann, J.; Bertsch, S.S. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. *Energy* **2018**, *152*, 985–1010. [CrossRef]

163. Kozarcanin, S.; Hann, R.; Staffell, I.; Gross, R.; Andresen, G.B. Impact of climate change on the cost-optimal mix of decentralised heat pump and gas boiler technologies in Europe. *Energy Policy* **2020**, *140*, 111386. [CrossRef]
164. Marina, A.; Spoelstra, S.; Zondag, H.A.; Wemmers, A.K. An estimation of the European industrial heat pump market potential. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110545. [CrossRef]
165. Fisher, D.; Madani, H. On heat pumps in smart grids: A review. *Renew. Sustain. Energy Rev.* **2017**, *70*, 342–357. [CrossRef]
166. Jesper, M.; Schlosser, F.; Pag, F.; Walmsley, T.G.; Schmitt, B.; Vajen, K. Large-scale heat pumps: Uptake and performance modelling of market-available devices. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110646. [CrossRef]
167. Schlosser, F.; Jesper, M.; Vogelsang, J.; Walmsley, T.G.; Arpagaus, C.; Hesselbach, J. Large-scale heat pumps: Applications; performance, economic feasibility and industrial integration. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110219. [CrossRef]
168. Aditya, G.R.; Mikhaylova, O.; Narsilio, G.A.; Johnston, I.W. Comparative costs of ground source heat pump systems against other forms of heating and cooling for different climatic conditions. *Sustain. Energy Technol. Assess.* **2020**, *42*, 100824. [CrossRef]
169. Terreros, O.; Spreitzhofer, J.; Basciotti, D.; Schmidt, R.R.; Esterl, T.; Pober, M.; Kerschbaumer, M.; Ziegler, M. Electricity market options for heat pumps in rural district heating networks in Austria. *Energy* **2020**, *196*, 116875. [CrossRef]
170. Elementenergy. Hybrid Heat Pumps Final Report for Department for Business, Energy & Industrial Strategy. 2017. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700572/Hybrid_heat_pumps_Final_report-.pdf (accessed on 26 July 2024).
171. Uytterhoeven, A.; Deconinck, G.; Arteconi, A.; Helsen, L. Hybrid heat pump scenarios as a transition towards more flexible buildings. In Proceedings of the 10th International Conference on System Simulation in Buildings, Liege, Belgium, 10–12 December 2018; Available online: https://lirias.kuleuven.be/retrieve/532608 (accessed on 26 July 2024).
172. Ciabattoni, L.; Comodi, G.; Ferracuti, F.; Foresi, G. A Methodology to Enable Electric Boiler as a Storage for Residential Energy Management. In Proceedings of the 2020 IEEE International Conference on Consumer Electronics (ICCE), Las Vegas, NV, USA, 4–6 January 2020; pp. 1–2. [CrossRef]
173. Arteconi, A.; Mugnini, A.; Polonara, F. Energy flexible buildings: A methodology for rating the flexibility performance of buildings with electric heating and cooling systems. *Appl. Energy* **2019**, *251*, 113387. [CrossRef]
174. Ciabattoni, L.; Comodi, G.; Ferracuti, F.; Foresi, G. AI-Powered Home Electrical Appliances as Enabler of Demand-Side Flexibility. *IEEE Consum. Electron. Mag.* **2020**, *9*, 72–78. [CrossRef]
175. Diangelakis, N.A.; Panos, C.; Pistikopoulos, E.N. Design optimization of an internal combustion engine powered CHP system for residential scale application. *Comput. Manag. Sci.* **2014**, *11*, 237–266. [CrossRef]
176. Onovwiona, H.I.; Ugursal, V.I.; Fung, A.S. Modeling of internal combustion engine based cogeneration systems for residential applications. *Appl. Therm. Eng.* **2007**, *27*, 848–861. [CrossRef]
177. Pilavachi, P.A. Mini- and micro-gas turbines for combined heat and power. *Appl. Therm. Eng.* **2002**, *22*, 2003–2014. [CrossRef]
178. Negreanu, G.-P.; Oprea, I.; Berbece, V. Some design characteristics of micro steam turbines for agricultural biomass energy conversion. *E3S Web Conf.* **2020**, *180*, 01017. [CrossRef]
179. Ordys, A.W.; Grimble, M.J.; Kocaarslan, I. Combined Cycle and Combined Heat and Power Processes, Control Systems, Robotics, and Automation—Vol. XVIII. Available online: https://www.eolss.net/sample-chapters/C18/E6-43-33-06.pdf (accessed on 26 July 2024).
180. Pachauri, R.K.; Chauhan, Y.K. A study, analysis and power management schemes for fuel cells. *Renew. Sustain. Energy Rev.* **2015**, *43*, 1301–1319. [CrossRef]
181. EG&G Technical Services, Inc. *Fuel Cell Handbook*, 7th ed.; Under Contract No. DE-AM26-99FT40575; U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory: Morgantown, WV, USA, 2004. Available online: https://www.netl.doe.gov/sites/default/files/netl-file/FCHandbook7.pdf (accessed on 26 July 2024).
182. McPhail, S.J.; Aarva, A.; Devianto, H.; Bove, R.; Moreno, A. SOFC and MCFC: Commonalities and opportunities for integrated research. *Int. J. Hydrogen Energy* **2011**, *36*, 10337–10345. [CrossRef]
183. Ebrahimi, M.; Keshavarz, A. *Combined Cooling, Heating and Power Decision-Making, Design and Optimization*; Elsevier: Amsterdam, The Netherlands, 2015; ISBN 978-0-08-099985-2. [CrossRef]
184. Shi, Y.; Liu, M.; Fang, F. *Combined Cooling, Heating, and Power Systems: Modeling, Optimization, and Operation*; John Wiley & Sons: Hoboken, NJ, USA, 2017; ISBN 9781119283362. [CrossRef]
185. Mei, V.C.; Chen, F.C.; Lavan, Z.; Collier, R.K.; Meckler, G. *An Assessment of Desiccant Cooling and Dehumidification Technology*; Oak Ridge National Lab. (ORNL): Oak Ridge, TN, USA; USDOE: Washington, DC, USA, 1992. [CrossRef]
186. Liu, X.; Qu, M.; Liu, X.; Wang, L. Membrane-based liquid desiccant air dehumidification: A comprehensive review on materials, components, systems, and performances. *Renew. Sustain. Energy Rev.* **2019**, *110*, 444–466. [CrossRef]
187. Roman, K.K.; Azam, M.H.H. CCHP System Performance Based on Economic Analysis, Energy Conservation, and Emission Analysis. In *Energy Systems and Environment*; IntechOpen: London, UK, 2018. [CrossRef]
188. Zhao, P.; Wang, J.; He, W.; Sun, L.; Li, Y. Alkaline zero gap bipolar water electrolyzer for hydrogen production with independent fluid path. *Energy Rep.* **2023**, *9*, 352–360. [CrossRef]
189. Azadnia, A.H.; McDaid, C.; Awari, A.M.; Hosseini, S.E. Green Hydrogen supply chain risk analysis: A european hard-to-abate sectors perspective. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113371. [CrossRef]
190. Zhao, P.; Wang, J.; Xia, H.; He, W. A novel industrial magnetically enhanced hydrogen production electrolyzer and effect of magnetic field configuration. *Appl. Energy* **2024**, *367*, 123402. [CrossRef]

191. Martinez-Lao, J.; Montoya, F.G.; Montoya, M.G.; Manzano-Agugliaro, F. Electric vehicles in Spain: An overview of charging systems. *Renew. Sustain. Energy Rev.* **2017**, *77*, 970–983. [CrossRef]
192. Gonul, O.; Duman, A.C.; Guler, O. Electric vehicles and charging infrastructure in Turkey: An overview. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110913. [CrossRef]
193. Ferrario, A.M.; Cigolotti, V.; Ruz, A.M.; Gallardo, F.; Garcia, J.; Monteleone, G. Role of Hydrogen in Low-Carbon Energy Future. In *Technologies for Integrated Energy Systems and Networks*; Wiley-VCH GmbH: Weinheim, Germany, 2022. [CrossRef]
194. Xing, H.; Stuart, C.; Spence, S.; Chen, H. Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives. *Sustainability* **2021**, *13*, 1213. [CrossRef]
195. Habib, S.; Khan, M.M.; Abbas, F.; Sang, L.; Shahid, M.U.; Tang, H. A Comprehensive Study of Implemented International Standards, Technical Challenges, Impacts and Prospects for Electric Vehicles. *IEEE Access* **2018**, *6*, 13866–13890. [CrossRef]
196. Das, H.S.; Rahman, M.M.; Li, S.; Tan, C.W. Electric vehicles standards; charging infrastructure, and impact on grid integration: A technological review. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109618. [CrossRef]
197. Shareef, H.; Islam, M.M.; Mohamed, A. A review of the stage-of-the-art charging technologies, placement methodologies, and impacts of electric vehicles. *Renew. Sustain. Energy Rev.* **2016**, *64*, 403–420. [CrossRef]
198. Tu, H.; Feng, H.; Srdic, S.; Lukic, S. Extreme Fast Charging of Electric Vehicles: A Technology Overview. *IEEE Trans. Transp. Electrif.* **2019**, *5*, 861–878. [CrossRef]
199. Nassrullah, H.; Anis, S.F.; Hashaikeh, R.; Hilal, N. Energy for desalination: A state-of-the-art review. *Desalination* **2020**, *491*, 114569. [CrossRef]
200. Feria-Diaz, J.J.; Correa-Mahecha, F.; Lopez-Mendez, M.C.; Rodriguez-Miranda, J.P.; Barrera-Rojas, J. Recent Desalination Technologies by Hybridization and Integration with Reverse Osmosis: A Review. *Water* **2021**, *13*, 1369. [CrossRef]
201. Sayed, E.T.; Olabi, A.G.; Elsaid, K.; Al Radi, M.; Alqadi, R.; Abdelkareem, M.A. Recent progress in renewable energy based-desalination in the Middle East and North Africa MENA region. *J. Adv. Res.* **2023**, *48*, 125–156. [CrossRef]
202. Signorato, F.; Morciano, M.; Bergamasco, L.; Fasano, M.; Asinari, P. Exergy analysis of solar desalination systems based on passive multi-effect membrane distillation. *Energy Rep.* **2020**, *6*, 445–454. [CrossRef]
203. Zhao, Y.; Li, M.; Long, R.; Liu, Z.; Liu, W. Advanced adsorption-based osmotic heat engines with heat recovery for low grade heat recovery. *Energy Rep.* **2021**, *7*, 5977–5987. [CrossRef]
204. Eurelectic. Connecting the Dots: Distribution Grid Investment to Power the Energy Transition. Union of Electricity Industry—Eurelectric Aisbl. Available online: https://www.eurelectric.org/publications/connecting-the-dots/ (accessed on 26 July 2024).
205. Ramsebner, J.; Haas, R.; Ajanovic, A.; Wirtschel, M. The sector coupling concept: A critical review. *WIREs Energy Environ.* **2021**, *10*, e396. [CrossRef]
206. Jentsch, M.; Trost, T.; Sterner, M. Optimal Use of Power-to-Gas Energy Storage Systems in an 85% Renewable Energy Scenario. *Energy Procedia* **2014**, *46*, 254–261. [CrossRef]
207. Jin, L.; Ferrario, A.M.; Cigolotti, V.; Comodi, G. Evaluation of the impact of green hydrogen blending scenarios in the Italian gas network: Optimal design and dynamic simulation of operation strategies. *Renew. Sustain. Energy Transit.* **2022**, *2*, 100022. [CrossRef]
208. Adhikari, S.; Fernando, S. Hydrogen Membrane Separation Techniques. *Ind. Eng. Chem. Res.* **2006**, *45*, 875–881. [CrossRef]
209. Nordio, M.; Wassie, S.A.; Van Sint Annaland, M.; Tanaka, D.A.P.; Sole, J.L.V.; Gallucci, F. Techno-economic evaluation on a hybrid technology for low hydrogen concentration separation and purification from natural gas grid. *Int. J. Hydrogen Energy* **2021**, *46*, 23417–23435. [CrossRef]
210. Jiang, L.; Wang, R.Q.; Gonzalez-Diaz, A.; Smallbone, A.; Lamidi, R.O.; Roskilly, A.P. Comparative analysis on temperature swing adsorption cycle for carbon capture by using internal heat/mass recovery. *Appl. Therm. Eng.* **2020**, *169*, 114973. [CrossRef]
211. Ohs, B.; Abduly, L.; Krodel, M.; Wessling, M. Combining electrochemical hydrogen separation and temperature vacuum swing adsorption for the separation of N_2, H_2 and CO_2. *Int. J. Hydrogen Energy* **2020**, *45*, 9811–9820. [CrossRef]
212. Ockwig, N.W.; Nenoff, T.M. Membranes for Hydrogen Separation. *Chem. Rev.* **2007**, *107*, 4078–4110. [CrossRef]
213. Shahbaz, M.; Al-Ansari, T.; Aslam, M.; Khan, Z.; Inayat, A.; Athar, M.; Naqvi, S.R.; Ahmed, M.A.; McKay, G. A state of the art review on biomass processing and conversion technologies to produce hydrogen and its recovery via membrane separation. *Int. J. Hydrogen Energy* **2020**, *45*, 15166–15195. [CrossRef]
214. TRANSPORT & ENVIRONMENT. *Recharge EU: How Many Charge Points Will EU Countries Need by 2030*; EU Transparency Register Number 58744833263-19, 2020; European Federation for Transport and Environment AISBL: Brussels, Belgium, 2023. Available online: https://www.transportenvironment.org/discover/recharge-eu-how-many-charge-points-will-eu-countries-need-2030/ (accessed on 26 July 2024).
215. Deb, S.; Tammi, K.; Kalita, K.; Mahanta, P. Review of recent trends in charging infrastructure planning for electric vehicles. *WIREs Energy Environ.* **2018**, *7*, e306. [CrossRef]
216. Garcia, M.H.C.; Molina-Galan, A.; Boban, M.; Gozalvez, J.; Coll-Perales, B.; Sahin, T.; Kousaridas, A. A Tutorial on 5G NR V2X Communications. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 1972–2026. [CrossRef]
217. Masini, B.M.; Silva, C.M.; Balador, A. The Use of Meta-Surface in Vehicular Networks. *J. Sens. Actuator Netw.* **2020**, *9*, 15. [CrossRef]
218. Moradi-Pari, E.; Tian, D.; Bahramgiri, M.; Rajab, S.; Bai, S. DSRC Versus LTE-V2X: Empirical Performance Analysis of Direct Vehicular Communication Technologies. *IEEE Trans. Intell. Transp. Syst.* **2023**, *24*, 4889–4903. [CrossRef]

219. Chang, M.; Thellufsen, J.Z.; Zakeri, B.; Pickering, B.; Pfenninger, A.; Lund, H.; Ostergaard, P.A. Trends in tools and approaches for modelling the energy transition. *Appl. Energy* **2021**, *290*, 116731. [CrossRef]
220. Lemm, C.; Vennemann, P. Modeling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110206. [CrossRef]
221. Di Somma, M.; Graditi, G.; Yan, B. Cost-Sustainability Trade-Off Solutions for the Optimal Planning of Local Integrated Energy Systems from Nanogrids to Communities. In *Handbook of Smart Energy Systems*; Living Reference Work Entry; Springer: Berlin/Heidelberg, Germany, 2022. [CrossRef]
222. EnergyPLAN. Advanced Energy System Analysis Computer Model. Available online: https://www.energyplan.eu/ (accessed on 26 July 2024).
223. Comodi, G.; Rossi, M.; Romagnoli, A.; Tafone, A.; Tuerk, A. Validation of Energy Hub Solutions Through Simulation and Testing in a Lab Environment and Real World. In *Integrated Local Energy Communities: From Concepts and Enabling Conditions to Optimal Planning and Operation*; Chapter 10; Wiley-VCH GmbH: Weinheim, Germany, 2024; pp. 323–352. [CrossRef]
224. H2020 Project, Multi Utilities Smart Energy GRIDS (MUSE GRIDS), 01/11/2018–31/10/2022. Available online: https://muse-grids.eu/ (accessed on 26 July 2024).
225. H2020 Project, TSO-DSO-Consumer INTERFACE aRchitecture to Provide Innovative Grid Services for an Efficient Power System (INTERRFACE), 01/01/2019–31/12/2022. Available online: https://www.interrface.eu/ (accessed on 26 July 2024).
226. Tafone, A.; Thangavelu, S.R.; Morita, S.; Romagnoli, A. Design Optimization of a novel cryo-polygeneration demonstrator developed in Singapore—Techno-economic feasibility study for a cooling dominated tropical climate. *Appl. Energy* **2023**, *330*, 119916. [CrossRef]