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Review

Towards future infrastructures for sustainable multi-energy systems: A review

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ABSTRACT

Integration of different energy infrastructures (heat, electricity and gas vectors) offers great potential for better managing energy sources, reducing consumption and waste as well as enabling a higher share of renewables, lower environmental impact and lower costs. This paper aims at reviewing the state-of-the-art energy system infrastructures in order to provide a comprehensive overview of technologies, operational strategies, modelling aspects and the trends towards integration of heat, electricity and gas infrastructures.

Various technological domains are taken into account, ranging from energy distribution networks (thermal, electric and gas), components for the energy vector conversion (e.g. combined heat and power, power to heat, power to gas, etc.) and energy storage. Furthermore, the aspects related to smart management in energy systems are investigated, such as integration of renewable energy sources and energy recovery systems.

Contents

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1. Introduction

Energy is produced, stored and transported over distances ranging from metres to thousands of kilometres in one of the three basic forms: thermal, electric and chemical [1]. This requires proper energy infrastructures (Fig. 1).

Traditionally, primary energy, such as natural gas,[1] is extracted, transported (Fig. 1 right) and used in energy conversion processes in two main ways: to produce electricity in large power plants (Fig. 1 centre) or to produce heat, mainly in boilers installed in buildings (Fig. 1 left). This has required the development of fuel grids and electricity grids at national and *trans*-national levels. These networks have grown mainly independently, with only simple connections between them. The introduction of cogeneration and district heating networks has caused the appearance of constraints in the energy vector conversion and established a stronger connection between the three grids.

For decades, technology has made significant advances: renewable energy technologies have gained larger shares, different types of storage systems have been proposed with the goal of increasing the system flexibility, and energy vector conversion systems are playing an increasingly large role.

Such innovations have enabled the possibility of integrating the various energy vectors, increasing the efficiency of fossil fuelled systems, increasing the share of renewable energy sources in the overall energy mix, increasing the supply security and lowering energy costs. Energy vector demands can be satisfied more efficiently when combining the use of various energy vectors in an optimal way. As an example, in Ref. [2] the case of Denmark shows that district heating and the gas network have much more capacity than the electricity grid, both in terms of distribution and storage. In this framework, energy vector conversions can contribute to overcoming peaks in the demand or in the production, or smooth cost variations of an energy vector. Furthermore, the storage of energy in a different form will enable long-term storage, as in the case of electricity transformed into heat or chemical energy, the latter enabling also long-distance transportation.

Although the three basic energy infrastructures were originally developed as independent networks, they are now evolving, exerting multiple critical influences on each other. This is true for generation and storage units, as well as for the transport systems. An overall view of the energy infrastructures is thus crucial for a global understanding of each separate system and potential for a combined management. Understanding mutual influences is fundamental in order to allow jointly optimal design and operation in terms of economic and thermodynamic efficiency and reliability operations. The growing importance of integration in the energy sector can be seen at EU level [3] as an opportunity to handle the increasing rate of renewable energy. This is true with respect to the coupling of electric and gas markets at high scale also considering the existing gas and electric infrastructures. It also applies to the expansion of district heating among others to further a better integration of renewable energy sources into the heating as well as the electricity sectors.

Multi-energy systems - sometimes referred to as smart energy systems [4] - represent a framework where various energy vectors interact with each other at various levels. The literature shows growing interest in this topic. In Ref. [5], various modelling approaches, evaluation methods and performance metrics resulting from a literature review are presented. From an industrial (or applicative) perspective, this concept has been translated into energy hubs, micro-grids and virtual power plants. Relevant examples of these applications are described in Ref. [6]. The ultimate strategic goals of the research in this field are the development of proper approaches for the optimal design and operation of the unified energy systems and the development of efficient and reliable systems able to make the infrastructures increasingly flexible. This is true at all scales: starting from an energetically self-sustainable remote village or a town where centralized district heating is fully integrated with gas and electricity supply and delivery, and extending to jointly optimal transmission of gas and electricity at regional, national and international scales.

This review paper aims at discussing the main features of three energy vector infrastructures, namely gas, electricity and heat networks. As the energy infrastructure (as shown in Fig. 1) is characterized by distribution, storage and conversion systems, the following topics are investigated for each network: general trends, network modelling, energy conversion systems and storage. The transition of energy infrastructure towards future (integrated) energy systems is discussed. The final goals of this paper are: 1) to contribute to developing a global vision and 2) to highlight the current research directions. In order to do this, various topics need to be taken into account, ranging from thermal and electric machines, distributed and non-traditional energy sources, gas and thermal pipe flows and power electronics, to expertise in theoretical engineering disciplines, such as optimization theory, control theory, computer science and machine learning.

The paper is structured as follows:

- In section 2, the characteristics of the energy infrastructures are introduced and an overview of multi-energy systems is provided.
- A description of the energy infrastructures, i.e. networks (trends and modelling), storage and conversion components, for each energy vector is provided in sections 3.1-3.4
- Management of the renewable energy sources and energy recovery system integration is discussed in section 4.

[1] Looking at energy vectors focusing on future perspectives as well as on infrastructures integration we will not discuss other fossil fuels such as oil and coal, despite the fact that synthetic gasoline could be developed utilizing electric energy overproduction; likewise, biomass will not be considered given its small impact in the overall energy mix.

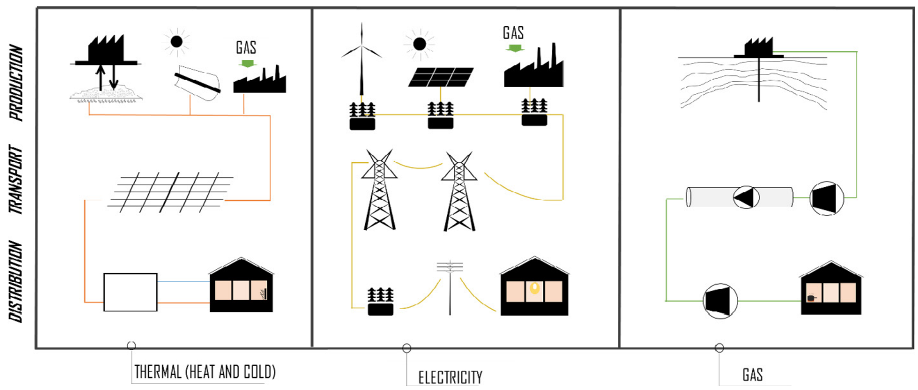

Fig. 1. Traditional energy infrastructure interconnection.

Finally, the status of integrated energy infrastructures and the scientific, industrial and policy challenges to address are discussed.

2. Defining infrastructure for multi-energy systems

The purpose of an energy infrastructure is to produce, transform and transport energy. Energy infrastructures are:

- The networks used to transport and distribute the energy vectors. These are gas pipelines, electric grids and district heating and cooling networks to transport gas, electricity and heat (and cold), respectively.
- Energy conversion units, such as heat only boilers (gas-to-heat), power plants (gas-to-power), cogeneration plants (gas-to-heat and power), heat pumps (power-to-heat) and technologies which convert electric energy into fuel such as hydrogen and methane (power-to-gas).
- Energy storages that can store gas, electricity, heat or other chemical species, for short or long periods of time.

An energy infrastructure system is schematized in Fig. 2. The energy infrastructure system is shown in the centre of the figure, the input on the right side and the output on the left side. Because of the strong correlation between the three energy vectors obtained through the conversion units, the overall system can be considered a multi-energy system.

The boundary of an energy infrastructure system depends on the area and the scale of the analysis. The area being examined could be a district, a city, a region or a country. The input quantities entering an energy infrastructure system are:

- Energy vectors imported from outside the system (entry of pipelines, import of electricity, etc.)
- Renewable energy sources convertible to energy vectors (wind, solar, hydro, ocean, geothermal, biomass).
- Reservoir of energy vectors located in the system (such as gas reservoirs).
- Waste heat obtained from other processes (usually industrial plants and in the future power-to-gas and similar conversion units).

Energy vectors are provided to industrial plants, buildings, vehicles or supplied to other energy systems which are the end-users.

This review paper describes the energy infrastructure and the connections that can enable economic and environmental benefits. The analysis mainly concerns technologies with a Technology Readiness Level (TRL) higher than 7, i.e. system prototype demonstration in operational environment [7], in order to analyse the potential of interconnected networks in the short to medium term. Therefore, technologies in the process of laboratory validation are not among the topics of the review. However, the modelling of future multi-energy systems should include many more conversion units in an integrated approach.

Natural gas is considered the only chemical energy vector in this analysis. Firstly, this is because natural gas networks are already a widespread technology worldwide, with existing infrastructures for long-distance transmission and prevalent distribution down to building level in various countries. Secondly, natural gas is one of the most used fuels for its high heating value and low environmental impact compared to other fossil fuels (in addition, its role is considered reinforced in future scenarios, since the use of natural gas is spreading worldwide, at the expense of coal and oil [8].). Thirdly, it offers the possibility of being easily transformed from and to other energy vectors, making the combined use of multi-energy networks interesting and increasing its flexibility. Furthermore, natural gas optimizes dynamic management at both the transport and distribution stages (both small- and large-scale. This occurs because transport/distribution systems are conceived to directly connect the end-users leaving them sufficiently unrestricted to adjust energy consumption. This allows for global management of these kinds of systems. For this reason most of the works available in the literature on multi-energy systems consider thermal, electricity and natural gas networks.

Further processes converting electricity into commodities ranging from electric car charging (power-to-vehicle) as well as liquid fuels to potable water will be mentioned but are beyond the scope of this paper, which is to assess comprehensive integration of the three abovementioned infrastructures (power-to-X). This is also the reason why oil networks as well as biomass and coal have not been considered in the current work, as they have a low level of integration with other energy infrastructures.

Moving towards a multi-energy system means moving towards an integrated concept of energy infrastructures. It creates higher flexibility due to the extra degrees of freedom of the integrated system, allowing minimization of the overall consumption of primary energy resources by increasing the system performance, handling a higher share of renewables, as well as better managing unexpected events. Moreover, as discussed in the following, it will allow for the use of more affordable storage solutions [9].

Fig. 3 shows two promising pathways to exploiting multi-energy systems as integrated energy infrastructures. Both cases consider management of excess electricity. In case A (Fig. 3a), mismatches between electricity production and demand are converted into thermal energy by means of power-to-heat technology

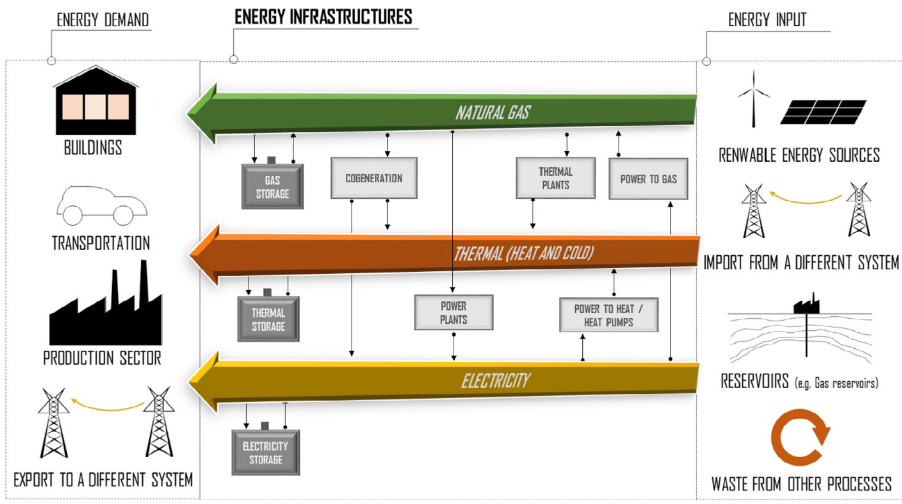

Fig. 2. Definition of main energy infrastructures.

(heat pump, described in section 3.3.3) and injected into the thermal grid. Heat can be directly used or stored. The other systems such as heat-only boilers or cogeneration plants should be adjusted according to the network control strategies, thus generally affecting gas consumption and electricity production. In case B (Fig. 3b), excess electricity is converted into gas through the use of power-to-gas technology (section 3.3.2) and injected in the gas grid. Multiple energy vectors should be considered while examining these options in order to 1) evaluate the installation potential of the energy conversion systems in each specific case, 2) select the optimal location of storage units and energy conversion systems, 3) evaluate best operations of network, storage and energy conversion systems. In particular, an investigation of the potential of case A (power-to-heat) requires: 1) modelling the electricity network to investigate where excess electricity is more significant 2) analysing effects and expenses for power-to-heat transformation 3) modelling the effects of injection of heat in the thermal network 4) evaluating the potential of storing heat in pipelines or in thermal storage. Furthermore, in case A the conversion also affects the rest of the electricity network and the cogeneration plants which should also be taken into account. Future conceptions of energy systems should consider the various energy vectors as complementary and fully integrated, not as separate units.

3. Energy infrastructures

3.1. Network trends

3.1.1. Thermal networks

District heating networks are widespread not only because of the possibility of integrating high performance plants but also due to the exploitability of renewable energy sources and waste heat. The total number of DH systems has been estimated to about 80,000 [10]. Among the largest are the networks in Moscow, New York, Paris, Warsaw, and Saint Petersburg. Two examples of low temperature networks are Otokos and Lystrup networks [11]. Large district cooling networks can be found in Hong Kong, Helsinki and Munich. The cost of the installation of a thermal network pipeline ranges from 300 to 1500 €/m [12,13].

Cogeneration provides about 56% of the heat demand of DH, as reported in Ref. [14]. Use of cogeneration plants for space heating allows significant reduction of primary energy needs and CO_2 emissions (4 million tons for a 5 MW_{el} plant) [15]; this is particularly true if the optimal cogeneration ratio is used, as shown in Ref. [16]. Integration of renewable energy sources and waste heat are discussed in sections 5.2 and 5.3, respectively. Table 1 reports the characteristics, modelling aspects and main trends for the various energy vectors, among which is district heating.

The current tendency of the district heating technology is to move towards low supply temperatures (30–70 °C), i.e. the so-called 4th generation district heating, thoroughly described in Ref. [17]. This allows a better energy exploitation, thanks to the valorisation of low exergy heat, as shown in Refs. [18,19], heat generated by renewable sources [20] (such as solar) and heat extracted at low temperature during expansion in power plants [21]. This leads to a change in the energy infrastructures because of the necessity for guaranteeing the heat provided to the users. Considering the same building request, larger pipelines are thus needed to transport higher mass flow. Indeed, investment costs for the pipeline construction may become higher in this case, but this effect decreases along with the demands of buildings (for both material, insulation and excavation). Various methods are proposed in Ref. [22] to overcome limitations on existing networks due to pipeline dimension in order to increase the number of users connected to a DH network without variation in pipeline layout.

Another tendency is on the increasing use of metering devices, as shown in Ref. [23]. The possibility of monitoring various quantities (temperature, pressure, mass flow) offers various benefits, such as the real time evaluation of energy performance, implementation of advanced control strategies and detection of possible operational anomalies (leakages, malfunctions or fouling presence). Data-driven models can typically be used for these purposes.

District cooling is also gaining popularity due to the potential higher performance (based on primary energy) with respect to individual chiller plants installed in buildings [24]. District cooling represents a solution whose deployment is continuously increasing, despite the lack of solid statistical data [14]; as an example it has been deployed in Paris (the largest in Europe), Vienna, Helsinki, Lisbon, and London. The world's largest network is in Doha, Qatar, and there are many other solutions with increasing degrees of complexity like Stockholm where free cooling from sea water is used or Barcelona where it is integrated with an LNG plant. District cooling currently dominates service sector buildings, both with vapour compression chillers and absorption chillers, often integrated with waste heat from industrial plants, cogeneration or renewables, to better exploit heat availability

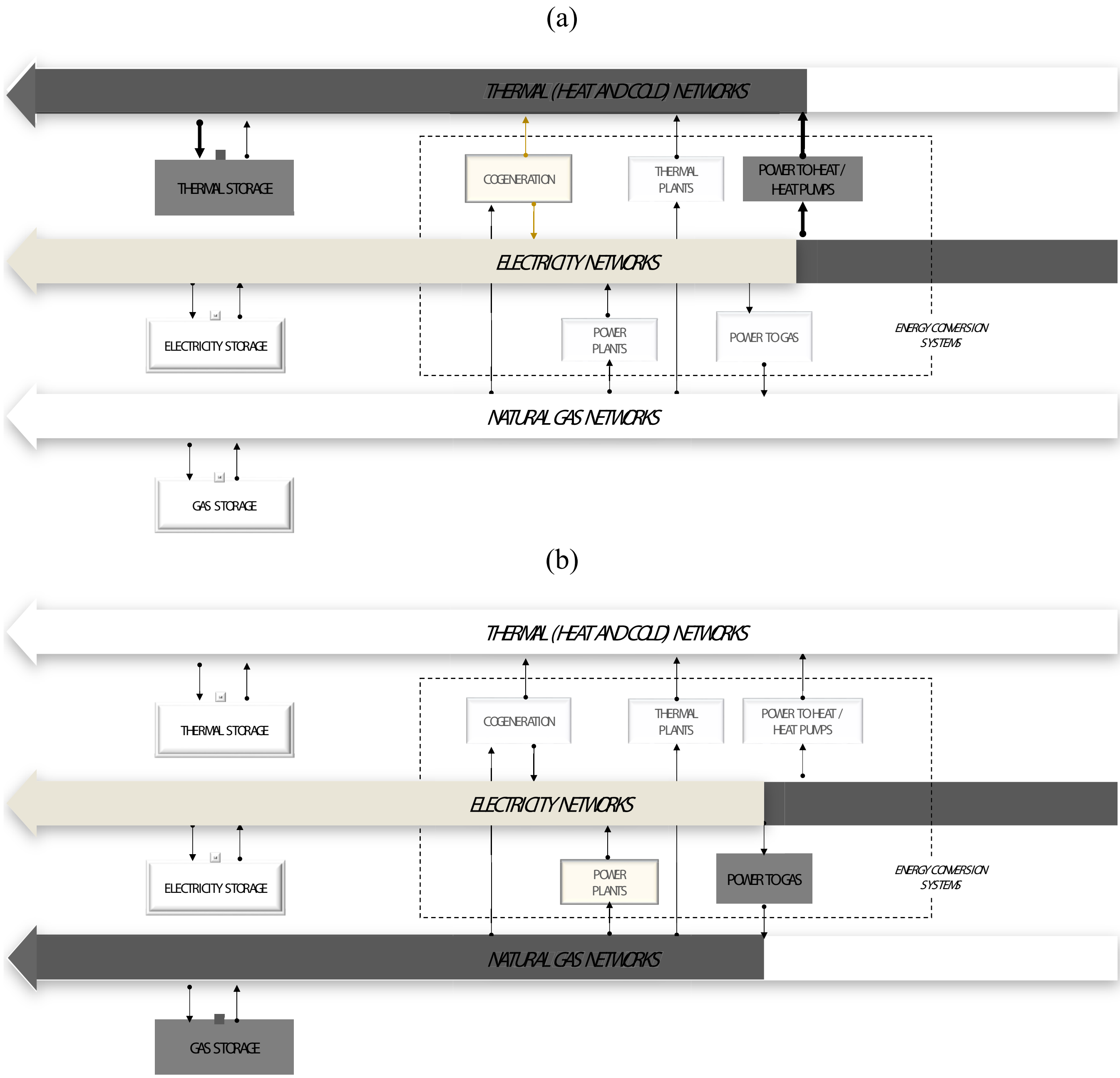

Fig. 3. Two ways to exploit a multi-energy system as an integrated energy infrastructure.

during the summer. The use of absorption chillers is well established, both in large buildings and district networks, being around 4% of the installed cooling power. Examples are reported in Refs. [10,25]. The performance of absorption chillers is improving; in Ref. [26] it is shown that single effect chillers require 80–90 °C as input temperature with 0.6–0.7 COP, but 55–60 °C is still enough to operate. This technology can thus operate even in the context of low-temperature networks.

3.1.2. Electric networks

Due to a transition in renewables and an electric grid paradigm shift [27], the main challenge in the current electric power grid is the increase in many new sources of uncertainty, as shown in Ref. [28]. Most noticeably, renewable energy generation from wind and solar, which has been introduced into the grid with an ever-increasing rate during the last two decades, is naturally uncertain. Integration of the new renewable resources forces the power grid to operate in regimes never experienced by power system operators before. The system more and more often nears boundaries of safe operation where loss of synchrony and/or voltage collapse becomes much more probable. The renewables also cause much more frequent reversals of the flows at both transmission and distribution levels, thus creating a challenge for many traditional paradigms which were developed in the past reality with fewer possible operational scenarios than today. These new criticalities have not only imposed significant stress on the system but also led to new opportunities in developing and implementing in operations new technologies and considerations at both local (devices) and system (distribution- or transmission-wide) levels. New optimization and control schemes which account for underlying

Table 1
Energy network characteristics.

	Energy vector	Driving force	Modelling	Main tendencies
Thermal (heat and cold)	Heat: Steam (in old systems), superheated water, low-temperature water (advanced systems) Cold: cold water	Pressure gap	Non-linear problem based on conservation equation	1) Low-temperature networks (for heat) 2) Technologies for data mining 3) Optimal management 4) Widespread district cooling diffusion
Electricity	Electricity at various voltage levels	Voltage gap: Transmission commonly >100 kV Distribution commonly 10–30 kV	Dynamic models Stochastic, chance constrained and robust optimization Markov decision Processes and queuing theory	1) Uncertainty due to renewables penetration 2) Demand response 3) Exploration of boundaries of safe operations close to synchrony loss and/or voltage collapse
Gas	Natural gas (characteristics)	Pressure gap	Non-linear (turbulence and high pressure) problem for a compressible flow	1) Optimal management of the compression stations 2) Best exploitation of line-pack effect 3) Supply security and security of the infrastructure

uncertainty and are capable of navigating the system closer to its operational limits are in the process of being developed and implemented. Many new market and regulatory frameworks, described in Ref. [29], as well as resources not previously used are called on to help reduce the increasing stress on the grid [30]. Demand response, reviewed in Ref. [31], is considered an important new option for efficient navigation of the system through the uncertainty as well as storage options, reviewed in Ref. [32]. Joint operations of energy system grids are also considered as a way towards more efficient operations which would also help to navigate through emergencies caused by the aforementioned (and other) uncertainties.

3.1.3. Gas networks

Many consumers worldwide depend on gas for heating. Gas is also one of the most flexible, widely available and cheapest options for power generation. More than 3 million kilometres of natural gas pipelines have been installed in the world, most in the US and Russia. The cost is usually in the range 100–150 $/km [33]. There are three main types of gas pipelines: gathering (from production wells to pre-processing plants), transmission (from pre-processing plants to distribution systems) and distribution lines [34].

Both the design and operation of the gas delivery systems are important in order to reach high performance. The design and planning procedure of gas delivery systems are presented in Refs. [35–37]. Gas delivery over long distances is done via the natural gas transmission system which is capable of transporting gas from producers (or points of transits) to consumers over thousands of kilometres; details on design procedure are provided in Refs. [38,39] for onshore and offshore projects, respectively. For this long-haul transmission, gas needs to be compressed multiple times at compressor stations, typically every 120–160 km [40]. Compression, distributed over the entire natural gas networks, is needed to maintain pressure within the pipe line sufficiently high to be able to extract gas from the system at the city gates and at the power generators connected to the system at the transmission level.

Currently optimal scheduling of the compression, minimizing compression consumption under constrained pressure bounds, summarizes the main task, which requires an online resolution to guarantee economically viable and safe operations. In Ref. [41], a geometric programming approach connected to models of real natural gas pipelines is shown to consistently outperform approaches used for optimizing compressor operations.

In various works, such as [42,43], optimization procedures are proposed for operations of steady flow gas pipelines with the aim to select the best system management in order to minimize power consumption. These include the operating compressor number and the discharge pressure for each compressing stations.

Further works aim to increase the performance of the compression stations considering their reliability. As an example, in Ref. [44], a tri-generative application (combined cooling, heating and power) has been shown to achieve a primary energy savings of about 30% when fulfilling the station needs for heating, cooling and electricity.

3.2. Network modelling

In this section, modelling of networks for the transport and distribution of energy vectors is discussed. In a multi-energy framework, modelling the various networks is crucial for proper design of the components and for optimal management, taking the topological and technical aspects into account. In the case of a power-to-heat system, for instance, installation of heat pumps in strategic locations should include a proper modelling of both the thermal and electricity networks. This allows one to investigate the effects of network dynamics and possible critical fluxes.

From a modelling viewpoint, the various networks present similarities and discrepancies. Modelling of gas and heat networks have some similarities but the dynamics are different since gas is a compressible fluid while water in a DH context can be considered uncompressible. This makes the use of pipelines as a mass storage promising for gas, while in the case of thermal networks, only the thermal capacity of the fluid can be exploited. Models of both the thermal and gas networks present issues related to computational costs, due to the non-linearity of the problem. This can be solved by different approaches, as explained in the two specific sections. The dynamics of electricity modelling are significantly different due to the different nature of the physical phenomena. In this case, the unpredictability of the production is the key issue to be modelled in order to solve problems related to the imbalance and losses. In a multi-energy framework, the modelling level depends on the control volume considered and the issue to be solved. Table 1 presents a description of various types of networks as well as a comparison between them.

3.2.1. Thermal network

District heating is managed by variation of mass flow and temperature of water produced in the various types of plants. This becomes very important in the case of multiple sources. The research conducted in Ref. [45] presents a predictive control strategy based on a mixed integer-linear problem formulation to manage the scheduling of the boilers and thermal storage operation to minimize the power generation costs. In order to optimally integrate various heat sources and find the optimal network layout, it is necessary to use network models. DH network modelling is used in order to analyse possible modification of the system performance, profit and emission by use of (for each item relevant references are provided):

a) Changes in the layout (new pipeline, different topology, new plants or storages). In Ref. [46] authors investigate various pipe configurations to minimize thermal losses and propose options for low-energy district heating. In Ref. [47] authors show the main design parameters associated with biomass district heating systems in order to optimize them from environmental and economic viewpoints. In Ref. [48], the optimal design of geothermal district heating is considered, taking into consideration pipe materials, pressure losses and installation type.
b) Modifications in the operations (change in plant operation, optimal pumping management, criteria for plant selection, and change of user scheduling). In Ref. [49], a district heating and cooling system is considered. An optimal operation strategy is obtained acting on the number of operating chillers, the supply temperature of water and the set points of the pumps. In Ref. [50], a control strategy is designed in order to minimize operational costs considering heat-only boilers and thermal storage units, taking the operational constraints of these systems into account. Pumping optimization is also considered in Refs. [51,52] where a fast modelling approach of the network is proposed in order to promptly obtain the optimal settings to react to load changes.
c) Unpredicted event occurrence (failure of pumps or plant components, leakages, unexpected demand variation, fuel supply interruption). Methodologies for the optimal management of DH network malfunctions are proposed in recent works. In Ref. [53] an optimization framework is designed in order to minimize possible discomfort to the end-users due to pipe ruptures or pump failures. In Ref. [54] a centralized optimization approach is proposed in order to adjust the thermal request of the various buildings of a network when failures occur.

Modelling can be performed by physical model or data interpolation. The latter consists of creating a function (or combination of functions) by interpolation of wide ranges of experimental data for predicting the network behaviour also in conditions not available in the dataset. Use of data interpolation may arise problems of lower accuracy when extrapolation is required. Physical models allow simulating network behaviour by a numerical solution to a thermo-fluidynamic problem. These are interesting mainly because of their potential to simulate each range of conditions, design and management. Physical model allows computing of a) pressure distribution, and b) temperature distribution along the pipelines. Mass flow accumulation can be neglected because of the small density variation of water at temperatures used for heat distribution.

Depending on the requested quantities (pressure or temperature) and on the network layout (tree or looped) two scenarios are possible:

- If only the thermal analysis is required and the network does not present loops, only mass and energy conservation equations have to be solved; this leads to a linear problem which is fast and easy to solve [55].
- When pressure values are also required or when the network is looped (making it necessary to understand the mass flow distribution within the pipelines) both fluid-dynamic and thermal problems are solved. In this case, the complete set of equations, included the momentum equation, has to be solved. This is computationally intensive, especially in case of large networks.

Because the DH networks are usually looped in order to better manage possible malfunctions or leakages, various approaches have been proposed to solve the complete set of equations.

An interesting approach is the loop method applied by Stevanovic et al. [56] to the Zenum network to solve looped networks, although no information on computational cost is provided. It has a higher performance than the Hardly Cross method [57] which was the first one built for network modelling and thus also applied to district heating networks. In order to reduce the computational costs, which are high especially in the case of large networks, two major aggregation methods have been proposed: the German aggregation method [58] and the Denmark aggregation method [59]. These approaches lead to a simplification of the network topology, by consequentially deleting nodes and branches of the network to build an equivalent network, as similar as possible to the real network from a thermo-fluid dynamic point of view. They are compared in Ref. [60]; their main limitation is connected to the use of transient problems in looped networks. Guelpa et al. proposed in Ref. [61] an approach to evaluating both pressure and temperature distribution in large networks in reasonable computational time. This is done by solving the complete set of equation in various parts of the network, consequentially, instead of considering the network as a whole system and solving the complete problem. The possibility of solving the problems in the various parts at different levels leads to a significant reduction in computational cost which makes the approach suitable for large networks.

Considering management of DH networks by varying the temperature level at the production source (typical of Nordic countries), the dynamics of the heat front has been studied in Ref. [62] where relevant physical phenomena are classified and an approach to efficiently describe network dynamics is presented. The approach has been applied to a simple example involving one producer and one consumer. Future works would include tests in a more realistic DH network.

Considering the Modelica platform, a library for the modelling of thermal-energy transport in district heating systems has been developed within the collaborative project AMBASSADOR funded by the European Commission under the 7th Framework Programme. Details are provided in Ref. [63].

3.2.2. Electricity network

The new emerging electric grid criticalities and tendencies, reviewed in Ref. [64], require an introduction of new modelling aspects. New state estimation/description models are appearing, i.e. models intended to better describe the state of the system in the presence of actors such as uncertainty of resources, new technologies and active consumers. Accounting for statistical aspects of the problems through probabilistic methods is becoming a common trend as seen in papers [65,66]. Depending on the time scales analysed and the phenomena involved, the models may be static or dynamic. More detailed analyses, and with richer models, are made of dynamics associated with power-electronics and protection (tens of milliseconds), electro-mechanical transients (seconds), primary and secondary controls (tens of seconds), voltage transients and dynamics of loads (minutes), in particular new type of loads, e.g. active and aggregated in ensembles. Richer modelling is needed to achieve system security, e.g. how far is the state from a dangerous (or unclear) regime. The state estimation models also guide new optimization and control paradigms, making the latter operations aware and intended to navigate the system optimally both in terms of economic values and safety. The optimization models take advantage of development in optimization theory and algorithms capable of efficient computations, provable bounds and relaxations [67]. New, extremely efficient and open-source simulation and optimization solvers, based on Matlab®, python and Julia have been developed. References [68,69] are relevant examples of optimization and control formulations including stochastic and robust approaches. Discussions on these types of problems are now common, for example the so-called chance-constrained and probabilistically robust type, which shows to be a practical but also mathematically sound (guaranteed) way to model uncertainty [70,71]. The control formulations involving new resources and new types of active consumers rely on advances in Markov Decision Processes and queuing theory [72,73]. Advances in optimization and control started to extend to more challenging multi-stage and multi-objective planning and extension formulations aimed at maintaining and upgrading existing systems, and designing system of principally new types in the future.

3.2.3. Gas network

Various approaches can be found in the literature for gas line modelling. Concerning analysis in steady state conditions, dynamic programming has been widely used because it allows solving nonlinear problems and guarantees a global optimum in both tree shaped and looped networks, as shown in Refs. [74,75], respectively. Other interesting papers using different approaches in the literature are: gradient based procedure [76–78], geometric approach [79] and non-linear programming [80–82]. Concerning unsteady conditions the most widespread techniques are: hierarchical control [83–85] and nonlinear programming [86–88].

Compressibility of the gas flows results in the operational ability to use the natural gas system in a dynamic, unbalanced way. One significant consequence of gas compressibility is the so-called line-pack effect – the gas can be stored in pipes, allowing injection and consumption to be balanced not instantaneously but with a delay, often extendable to tens of hours. The line-packing in gas pipelines consists of injecting more gas into the pipelines when it is at disposal (off-peak time) in order to make it available when the request is high. This is done by increasing the gas pressure, using an upstream compressor and closing a downstream valve. The line-packing issue has been studied in decades by using mathematical programming, as done in Refs. [89,90]. Optimization of line-packing is discussed in Refs. [90–92]; this allows evaluating the best timetable and pressures of compressor stations. Limits of the line-packing and for a single pipeline are discussed in Ref. [89] by considering the aim of matching variation of demands and supplies. In Ref. [93], a model for the optimal control problem of large-scale gas systems is proposed, also taking into account line-packing in modelling.

Similar to power systems, natural gas systems are undergoing revolutionary development. Many criticalities and tendencies and new modelling aspects introduced in power systems apply, at least at the principle level, to natural gas systems. Modelling operational uncertainty in the natural gas system is complicated due to the fact that in order to resolve pipe flow one needs to account for the spatio-temporal evolution. This is modelled through the system of coupled partial differential equations representing dynamics of gas flows, pressures and other relevant characteristics within pipes, and not solely in the lump, nodal-only way justified in the case of power systems. Therefore, many efforts to estimate the state of the natural gas systems have focused on designing better, more accurate, and more efficient simulation methods and solvers which can provide guarantees.

Optimization and control schemes in the modelling of natural gas have also become more advanced [34]. Many principal advances in theory, algorithms and implementations already developed and emerging in power system engineering are expected to extend, with proper adjustment, modification and improvements, to natural gas engineering very soon. There are also developments in optimization and planning of the natural gas systems, which are case specific, i.e. linked to special features of the natural gas systems. As an example, recently discovered monotonicity [94] of the principal equations of the gas dynamics (also coined Aquarius theorem) allow reducing robust optimization of the natural operations. This can e.g. consist of system-wide optimal tuning of compressors) to a standard (deterministic) optimization which requires evolution of only two extreme scenarios, most and least loaded, with guarantees that any other configuration of the natural gas production-consumption input laying strictly between the two extremes will be bounded in terms of the output by pressures and flows of the extreme configurations.

Other important topics connected to gas transport pipelines are security of the infrastructures [95,96] and supply security [97,98]. Concerning the security of the gas transport line, in Ref. [96] a list of critical facilities in Russia's gas transport system is provided; the work also proposes a way to minimize the negative effects of emergency situations. Concerning security supply, various stochastic approaches for simulating the security level for the supply are provided in the literature. Examples related to Europe's and China's supply can be found in Refs. [98,99]. In this framework, the individuation of bottleneck is an important aspect, discussed in Refs. [100,101] as well as the uncertainty related to the available information ranging from demand to pipe state and characteristics continuously evolving [102].

3.3. Energy vector conversion

There are many possible ways to convert energy vectors from one form to another within the multi-energy systems framework, thus enabling interconnections between different energy infrastructures. The energy vector conversion ranges from well-known and highly deployed, so to say traditional, units to recent ones gaining momentum. Among the most widespread are conversion of natural gas into heat and power, electricity into heating and cooling, heat into cooling, and the latter aiming at converting renewable excess electric power into gas or even other kinds of commodities. In this way, the usage of the excess electric energy is shifted, anticipated or postponed, in different time intervals depending on the adopted solution. The higher the number of energy conversion units and typologies involved (input-output energy vectors and performance curves), the higher the overall integrated energy system flexibility; this is due to the higher number of independent variables allowing to reach a more efficient system, improving the overall objective function e.g., savings of primary energy, economic or related to the stability of the system. Proper knowledge and modelling of these devices is crucial in order to exploit the potential of multi-energy systems. In the following subsections, the gas to heat, power to heat and power to gas potential is discussed to provide a state-of-the-art for energy vector conversion.

3.3.1. Gas to heat, cooling and power

This section presents a set of technologies which have been commercially deployed in the last decades for generating heat, power and cooling [103] and whose performance has been continuously improved in terms of efficiency, flexibility and reliability [104].

On the one hand, below are listed the conventional units converting chemical energy of fuels into heat and/or electric power, with focus on natural gas due to its possible transmission and distribution via gas network infrastructures:

- Heat only boilers: converting fuel chemical energy into heat at different temperatures depending on the customers' needs.
- Electricity generators: converting fuel chemical energy into electric energy. Examples of such units are reciprocating internal combustion engines, gas turbines, steam plants or Natural Gas Combined Cycles (NGCC), with the first being the more common solution in the small scale and the last in the large scale (both manage to provide high electric efficiency).
- Combined Heat and Power (CHP) units: converting fuel chemical energy simultaneously into heat and electricity, with a large variety of correlations between heat and power production and fuel consumption. As an example, volumetric internal combustion engines and gas turbines have plenty of thermal energy available in their exhausts considering only a minor share of primary energy can be converted into electric energy. This can range from above 20% of kW-sized micro-gas turbines to about 50% of MW-sized volumetric internal combustion engines heavily depending on size and many other design features. In this case both useful effects depend on one independent variable, which is the fuel consumption.

On the other hand, whether more complex prime movers such as NGCCs are adopted and heat could be extracted from the steam turbine at high temperature by means of a valve, it will be possible to play both with fuel as the first independent variable and with the ratio between the two useful effects using the valve opening rate as second independent variable [105]. The number of independent variables could be increased to three or more.

Several less conventional energy conversion units could be identified such as Stirling engines, especially at the kW-sized scale, or boilers coupled with bottoming Organic Rankin Cycles (ORC). The latter is gaining increasing importance due to its capability to convert unexploited heat into electric energy [106]. Higher electric efficiency could be reached by fuel cells which can convert chemical energy into electricity directly and by means of cogeneration. High temperature fuel cells, such as Solid Oxide Fuel Cells, could be directly fed with natural gas produced by internally reforming the required hydrogen and reaching commercial development at about 60% electric efficiency [107]. This said, it should be emphasised that gaseous biofuels [108] could also be burned to generate heat and power either alternately to natural gas or, if insufficient, complementary with it, but affecting the natural gas Lower Heating Value (LHV).

Furthermore, cooling could be taken into account in connection with Combined Cooling, Heat and Power (CCHP). This is realized at commercial scale by means of dedicated units generating cooling either by absorption chillers utilizing waste heat produced by cogenerative prime movers or by utilizing electrically driven vapour compression chillers. Both could also be driven by gas; one by gas-fired engines and the other by gas-fired absorption units as well as heat generated by gas combustion. A conversion from fuel to cooling, bypassing electricity generation, is thus possible although still less common. The district heating network could be utilized to feed absorption chillers converting heat into cooling at the users. This may imply a different temperature drop at the users but can allow them to use heat also during summer when the request is lower but the heat still available, e.g. one degree-of-freedom cogenerative prime movers by-product. Another option is to feed a small-scale cooling grid or a dedicated district cooling network directly by large absorption chillers or by vapour compression chillers. The performance of the latter, as well as that of the vapour compression heat pumps discussed in Section 3.2.4, are very sensitive to the ambient conditions and could also be deployed at very small scale per single family. In such a case it should be considered as an ensemble clustering the input and output energy fluxes whether connected to the same network, such as the electric one. Fully integrated tri-generative technologies capable of providing the three effects at the same time by means of more complex thermodynamic cycles are still object of research [109].

3.3.2. Power-to-gas

Power-to-gas technologies facilitate interconnection between the electric and the gas networks in a bidirectional fashion, utilizing the excess electric energy to generate hydrogen via water electrolysis. Several technologies could be utilized, the more common are alkaline electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis. The hydrogen produced can be either stored locally and reconverted into electric energy when needed or injected into the natural gas grid up to a small percentage of the total volumetric composition, e.g. 0–12 vol% depending on the country specific regulations [110]. Another option is to transport the hydrogen. Green hydrogen has proven to be an interesting option for decarbonisation of the mobility sector [111], especially for large vehicles going through fixed routes such as trains. The challenges related to hydrogen handling can be avoided dealing with, and via biological or catalytic methanation reaction with carbon dioxide it could be utilized to produce synthetic methane. This creates further energy penalty and process complexity but it enables the utilization of the generated methane in the gas network. P2G challenges are related to the high costs and low electrolysis efficiency improvements, which are needed especially during transient operation. Optimal technology will also depend on the size and transient management of the full chain including methanation as well as the need for temporary hydrogen storage which is also costly [110]. A large number of P2G studies were carried out in the last decade as well as pilot and demonstration projects [112]. Furthermore, the heat management of such kinds of technologies needs to be optimized paving the way for cogeneration possibilities further tightening the infrastructure interconnections. System level studies of power-to-gas have also been carried out highlighting the impact on the electric and gas transmission networks. This is not only to ensure long-term chemical storage of renewable overproduction reducing curtailment and decarbonizing natural gas, but also to reduce congestion in both the gas and electric networks [113].

Power-to-gas is currently costly, however gaining momentum with about 50 projects comprising carbon dioxide methanation, biogas and syngas upgrading to generate methane via three step reactions under development, as reported in Ref. [112].

3.3.3. Power-to-heat/heat pumps

Power-to-heat is another possibility to further integrate energy systems, utilizing electric energy for heating purposes either via direct heat generation at the customer or by feeding a heating network. Heat generation by use of electric heaters and boilers has always been considered inefficient, while it can lead to primary energy savings if done by heat pumps and at a low temperature suitable for floor heating or 4th generation district heating [114]. The performance increases further by use of groundwater heat pumps [115,116]. In this way it represents an extra interconnection between the two systems, electric and thermal. Heat pumps can also be utilized to produce high temperature heat, possibly in a centralized manner, to feed even third generation district heating systems via high temperature heat pumps or electric boilers in presence of peaks of electric generation from renewables, with the latter having far lower costs of investment. Power-to-heat has also been investigated, providing good results, as an indirect form of electricity storage when the heat at about 100 °C is converted back to electricity by means of heat engines [117]. However, the power-to-heat solution can be utilized in a distributed fashion as a cluster of several heat pumps, which can behave as a virtual large consumer consuming in a more or less sophisticated manner, e.g. integrated with local heat storage [118]. Finally, distributed solutions are also a relevant option because they have both an impact on the electric system, clustering all of them, as well as on the thermal system such as district heating in these countries where people are connected to district heating while also having an individual heat pump which could be utilized jointly or alternatively to the district heating; same hybrid mechanism could be developed with cooling as mentioned in Section 3.2.1 [119].

Based on Bloes et al., 2018 [118] it is possible to argue that about 1.5% of heat is electricity based. At a European level, this figure increases to about 12%, as shown in Ref. [120]. This means that the path towards electrification of heating from a global perspective is still long and heat pumps as well as other power-to-heat systems are quantitatively still small but continuously growing.

3.3.4. Power-to-commodities

Further possible usages of excess electric energy are related to the production of a list of commodities, so called power-to-X schemes, starting from liquid fuels which will help to decarbonize mobility, including the fulfilment of aviation requisites [121], to desalination [122]. In general, looking at isolated micro-grids we can speak of multigood microgrids [123] where ice production for food storage as well as potable water pumped from dwells or water desalination in desert areas are also taken into account. Among the more recent frontiers we can consider energy intensive blockchain and bitcoin generation, which is currently exponentially growing [124]. A detailed review of blockchain activities, which are relevant for the energy sector, together with the opportunities, challenges and limitations, are presented in Ref. [125].

3.4. Storages

Storing energy is becoming more and more interesting in a framework of high efficiency energy systems. Storage allows better management of energy systems since this mitigates the imbalances between demand and production. For this reason research on storage opportunities is increasingly widespread. In the following subsections, storage is discussed for each type of energy vector. Furthermore, the opportunities related with storage in multi-energy systems are discussed in Section 3.3.4. Main storage characteristics for each type of energy vector are reported in Table 2.

3.4.1. Thermal storage

Storage is an essential technology for wisely managing energy vectors; overviews can be found in Refs. [148,149]. Benefits of thermal storage in thermal networks are mainly related to the increasing flexibility offered by storage installation. These lead to various consequences, such as:

- reduction of generation unit size and pipeline diameters;
- when DH is connected to different heat sources, storage allows selecting more flexibly the plant to be used, by reducing usage of low-efficiency plants, such as boilers, and increasing use of RES relieving the effects of their intermittent characteristics;
- in DH systems, when fed by CHP plants, they enable the shifting of electrical production when electric costs are high, and allow a reduction of the unit size of the generation component. Moreover, it furthers the integration of solar thermal power.
- Concerning the infrastructure design, it is possible to reduce the dimension of the pipeline or, at constant pipe dimension, to increase the number of connected users; it also leads to a pumping cost reduction
- When electricity and heat grids are connected by power-to-heat technologies, the overall efficiency can be increased by transforming electricity into heat and storing heat as discussed in Section 3.3.4.

Storage connected to DH networks can be divided into two main families: short-term storages and long-term storages. The first is the daily storage, used in order to move the daily thermal peak to fill the daily thermal lows. For this aim, water tank storages are usually located along the network. Long-term storage concerns the possibility of storing energy in the season when it is available (heat in summer and cold in winter) in order to use it when the request is high (heat in winter and cold in summer). Seasonal storages are particularly suitable in the case of solar power or waste heat exploitation. Long-term storages can be divided into various types depending on the construction, location and heat storage medium. These can be tank, pit, aquifer or borehole storages; a review can be found in Ref. [150]. The main difficulty of using storage systems in DH is the necessity of large spaces for the installation of both the storage itself and its components. This can be challenging in densely populated areas, where DH networks are usually located. In case of seasonal storages, another drawback concerns thermal losses, which are not negligible (energy and exergy efficiencies of the order of 60% and 19%, respectively, are expected [151]), due to the long storage period. Heat in long-term thermal storages is usually stored at low temperature because of the lower thermal losses [152]. This usually requires the installation of additional components to increase the temperature of the stored heat in order to reach the heat transfer fluid within the network. Heat pumps are particularly suitable to increase the temperature of the heat transfer fluid [153]. In case of low-temperature DH, the installation of heat pumps should be avoided, as shown in Refs. [154,155]. If the benefit of seasonal storage is undisputed, as shown among others in Refs. [156,157], because it allows using heat that otherwise would be lost, they should be further investigated in order to minimize the thermal losses.

Latent heat storage and chemical storage for DH are still used at a laboratory level. Latent storage, reviewed in Ref. [158], has great potential because of the higher thermal density compared to sensible storage but low thermal conductivity is a limiting aspect for its use [159,160]. Applications in DH are provided in Refs. [161,162]. In particular, it has been shown in Ref. [162] through a CFD model that latent heat storage is particularly suitable to be used in building substations at the secondary sides because of the lower temperature differences compared to the primary side. From an economic viewpoint, a techno-economic investigation [161] shows that LH-TES cost 4 times as much as a water tank TES (about 10 €/kWh), but the cost become only 1.5 times higher in case of low-temperature networks.

Chemical storages have the advantage of high thermal density and very low thermal losses, but they require further research before being commercialized. Applications of chemical storage for DH can be found in Refs. [163–166].

Several TES installations can be found worldwide in DHC networks. In Turin, a capacity of 15,000 m^3 is installed as centralized TES, while in Saint Paul, Minnesota more than 15,000 m^3 are installed [167]. Various installations are located in campuses; among them the Alamo Colleges [167], Cornell University [168] and University of Nebraska-Lincoln [169]. Some of the largest

Table 2
Storage system characteristics.

		Types	Main characteristics	Typical size [m3]	Energy density [kWh/ m3]	Ref.
Thermal	Long-term	Aquifer, Pit, Tank, Borehole	Requires large space or particular morphological characteristics of ground High investment cost	Magnitude of 10^3–10^4 m^3	15–50	[126–129,126]
	Short-term	Sensible	Mature and widespread technology	From 1 to 10^3 each	50	
		Latent	More complex structure than the sensible type Requires further investigation to become more competitive	Mainly laboratory scale	40–150	
		Chemical	Mainly laboratory scale Requires further investigation to become more competitive	Laboratory scale	60–300	
Electricity	Mechanical energy storage	Pumped Hydro Storage (PHS)	Mature Deployed worldwide Long lifetime Innovative smaller scale solutions are under development avoiding geographical constraints	From pilot scale for innovative to GWs size for consolidated	1–2	[130,131]
		Compressed Air Energy Storage (CAES)	Commercially mature technology High power of charge/discharge. Many different typologies, from Diabatic (external heat source required) to Adiabatic (thermal storage integrated), Isothermal (not heating during compression), Underwater (using hydrostatic water pressure).	From 10^5 to 10^6	1–10	[131–134]
		Flywheel	Good solution for high power density, release in short time periods and frequent	From small scale to 100 kW s fleets clustered in large scale of 10 s MW size	20–100	[131,135]
		Liquid Air Energy Storage (LAES)	High energy densities	Hundreds kW pilot plant up to 5 MW	30–300	[136,137]
		Pumped Thermal Energy Storage (PTES)	Electricity is stored indirectly as thermal storage and temperature difference is used to drive a heat engine generating mechanical, then electric energy.	Laboratory scale	50–60	[138–140]
	Electrochemical	Conventional (i.e. lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion)	Mature and widespread technology	From small scale to large MWs or clustered up to 100 MWs currently under construction	50–400	[141,142]
		High temperature (such as sodium-sulphur and sodium-nickel chloride)	Molten salts are used as electrolyte enabling high energy density and power density	From laboratory scale up to MW size	100–300	[131]
		Flow batteries	Ions moving through an electrochemical cell, with membrane selective to active ions, and contained in liquid electrolytes stored in tanks, decoupling energy from power	From laboratory scale to MW	20–30	[143,144]
		Metal air batteries	High potential for large energy density but requires further investigation to become more competitive	Laboratory scale	200–800	[145]
	Electrical	Supercapacitors	Accumulating positive and negative charges, being faster than electrochemical technologies	Commercially deployed for transport, up to MWs size	10–30	[183]
		Superconductors	Current passing through a superconducting coil generates a magnetic field	MW size integrated with wind generators	10	[146]
Gas	Depleted cavern, aquifer, salt cavern		Mature, low cost and long lifetime	10^4–10^6	11	[147]

installations of long-term TES can be found in Marstal [170] (tank and pit, more than 15,000 m^3), Friedrichshafen (tank 12,000 m^3) [171], Rockstock (aquifer) [172], and Alberta (borehole) [173]. Costs are about 30 €/m3 for water storages, while chemical and latent have so far been more expensive, and further research activity is required to make them more competitive.

3.4.2. *Electric storages*

When looking at aggregated numbers, electric energy storage is by far dominated by traditional pumping hydro technology with about 97% of the overall stored energy capacity. Nevertheless, considering the role of electric energy storage in the decarbonisation of the electric energy market, there will be a large increase in other technologies; a number of operational projects are ongoing [174] and installations are expected to grow significantly, being tightly related to the renewable energy trend. Electrochemical storage is leading this improvement both with its rapidly improving performance and costs reduction, expected to fall by 50% and more by 2030 [175].

Storage can be applied to a wide range of services depending on the adopted technology performance. On the one hand, there is grid-connected storage for services ranging from large-scale bulk, e.g. time shift and capacity supply, to ancillary services, e.g. regulation, reserves, and voltage support, to distribution and transmission infrastructure services as well as smaller scale helping consumers manage their energy, e.g. increasing renewables self-consumption. On the other hand, there are off-grid applications which need batteries, as well as the transport sector.

Many of the storage technologies can be synthetized as [176].[2] The most widespread technologies are described in Table 2.

Given the high number of services which can be provided with electric energy storage, as mentioned above, there will likely be a role for many of the listed technologies depending on the way their technical specifications match the market requirements. Studying them from the viewpoint of integrating energy infrastructures, the

[2] Chemical storage, namely power-to-gas or other commodities (power-to-X), has been discussed separately especially because of its impact on the infrastructure interconnection.

following key aspects are listed:

- Size; both in terms of potential energy stored and potential power instantly released; this means that, on the one hand, some technologies are suitable for being integrated at distribution or even at transmission level, and some large-scale facilities have been deployed up to 100 MW size, possibly in a very short time (as 100 days for Tesla in Australia [177]). On the other hand, small-scale batteries could be deployed at small consumer/prosumer level that could be clustered to create a large storage capacity as a virtual power plant. This could also be done clustering electric vehicles and using them as storage when parked, vehicle-to-grid, and commercial solutions have already been deployed with electric companies joining forces with electric vehicle manufacturers [178].
- Energy and power density; these are important, respectively, to save space, as in mobility, and to ensure high power quality providing large discharge currents and fast response time, as for frequency control application.
- Lifetime; some electrical storage systems, such as the electrochemical ones, have a performance decay faster than others, like the mechanical storage. Therefore, their performance curves, charging and discharging, vary continuously as a function of the charge/discharge cycles. After a number of cycles they may not be able to fulfil certain performance requirements but they can still comply with others, e.g. used electric car batteries that could be recycled for static application of load shifting.
- Storage efficiency and duration; in this case the amount of energy taken from the grid is higher than what is actually stored and such efficiency often depends on the state of charge of the energy storage systems. The same happens at discharge level where the released electric energy is less than the stored energy and depends on the state of charge. Furthermore, duration is also an issue because stored energy will decrease over time.
- Electric energy storage; this can also be applied as a hybrid solution where batteries guaranteeing complementary performance are coupled to provide the best feature of each one, such as flywheel, supercapacitors [179] or superconducting magnetic energy storage for fast response [180] coupled with another type, such as lithium-ion batteries, in order to sustain the response for longer, depending on market needs. In addition, hybrid configurations are an option where thermo-mechanical solutions like CAES or LAES could be integrated with power cycles like natural gas combined cycles [181].

Finally it is worth highlighting the importance of thermal management in electric energy storage systems; depending on the temperature of the processes taking place it may be needed to remove or provide heat. Looking at this solution, and not only focusing on electric energy storage perspectives but on the overall integration of energy systems, e.g. when thermo-mechanical processes such as CAES and LAES are involved, waste heat [182] or cold, e.g. Liquefied Natural Gas [193], could be integrated or the electric storage system could be considered for heat/cooling loads fulfilments [184].

Among the largest electrical storage installations are two CAES systems, McIntoch and Huntorf [185], in the US and Germany, respectively, and various battery fields [186,187] (Dalian, Jemgum, Jamestown, Modesto). Pumped hydro storage is very widespread; China, US and Japan are the countries with the highest installed capacity, with a total capacity of 80 GW [188].

3.4.3. Gas storage

Gas storage has various advantages:

- It is usually built as a security reservoir. It represents a surplus of gas that can be used in case of supply problems, such as upstream or downstream failures.
- It allows balancing the demand evolution, i.e. the difference in consumption over the seasons
- It makes a country or company able to better negotiate prices.

Concerning long-term storage, natural gas stored in the gaseous phase is considered the most economical way to store it [34]. The most widespread type of gas storage is the depleted caverns. These are empty natural gas or oil fields and are usually of large volumes [189]. Another possibility consists in using aquifers that have particular morphological characteristics [42]. In the US, salt caverns can also be used for this purpose. In order to make them available, salts must be removed by using wells to inject (and afterwards extract) water where salts dissolve [37]. These are often used to bridge the gap between the demands in different seasons. Several installations are present worldwide for all the types cited [190]. Depending on the type, the cost of gas storage ranges from 0.15 to 1 $\$/m^3$ [191].

Short-term storage is exploited in connection with the trading possibilities. Among the various options are liquefied gas tanks [192], hydrate-based technology [193] and the line-pack effect.

3.4.4. Storage towards integration of energy networks

In a framework of multi-energy systems, an important point concerns the selection of the energy vector for the storage. When energy vectors must be converted into another type, it is possible to choose to store energy before or after the conversion. Furthermore, it may be useful to convert one energy vector into another just to increase the storage performance. In this framework it is interesting to make a comparison of various kinds of storage: heat, electricity and fuel.

Thermal energy storage has various advantages compared to other storage systems which makes it attractive. Indeed it is generally less expensive [194] (investment for electricity storage 170 €/kW for thermal 0.5–3 €/kW [195]).

Another important point is to avoid round trip conversion losses typical of PHES and CAES [196]. Nevertheless, electrical storage has high flexibility [197].

Conversion of electricity into thermal energy can be appealing to increase the storage efficiency. Heat pump energy storage (HPES) can be used with this aim (technology cost is about 35 €/kWh [198]). Electricity surplus can be converted into heat (and cold); when electricity is required, heat is transformed into electricity by using the reverse cycle used for the charging process (as discussed in Section 3.2.4).

Alternative energy storage consists of modifying the network request, i.e. demand response. The concept of demand response was coined in the electric field representing a promising option to meet renewables fluctuations due to the progress on information technology, control and data science; it allows a better use of transmission and distribution networks, increasing overall system efficiency [199]. However, some recent works show the interest of demand response in thermal networks [200–203]. Demand response in DH systems (also called virtual storage) consists of modifying the settings of the heating systems in buildings: the time the heating systems are switched on and off or the set point temperature. This leads to a modification in the thermal request evolution; peak cuts from 5% to 25% and primary energy savings of 3.5%–5%, respectively, in cases of small and more advanced changes, as shown in Refs. [200–203]. Clearly, it implies the presence of a proper tool for the evaluation of the user thermal consumption evolution; recent proper models for large thermal networks are provided in Refs. [204–206], while the generic topic is reviewed in Ref. [207]. At the level of energy infrastructure integration, interactions between electric and thermal/cooling demand response could play a crucial role. A combination of thermal and electric demand response represents a further variable that could be utilized to reduce primary energy consumption and/or operating costs, linking the two infrastructures in addition to the connections they already have to gas. It should also be noted that shifting the requested load from one network to the other implies an intrinsic increasing degree of inertia related to the possibility to postpone the energy vector usage. In order to do so, intelligence in the electric grid and in the building management system is required and ad hoc control techniques need to be developed to ensure comfort while shifting the load. This should also include the legacy of old control systems, both radiators and HVAC systems [208].

4. Future energy systems

4.1. Renewable energy penetration

Exploitation of RES has been increasing in the last 15 years, thanks to both research advances and tax incentives. The trend is +5% per year [209]. The main issue related with the integration of RES into multi-energy systems is the unpredictable and intermittent characteristics of this kind of source. For this reason, proper considerations have to be made while designing the network because of the need for solid base load supply. An important point for optimal integration of RES in the networks is the use of storage to take advantage of excess production during times of additional demand as discussed in Section 3.3.1.

RES can be used to produce electricity, heat and gas.

- Electricity: solar sources (converted using photovoltaics and solar thermodynamic technologies), wind energy, hydroelectricity, geothermal sources, ocean energy, biomass and biofuel. RES are generally highly variable with time, non-dispatchable with limited control and have low capacity credit in particular on the power system planning [210]. It has been demonstrated in Ref. [211] how combinations of the sources will decrease the problem. Adoption of energy storage systems or controllable dispatch loads [212] can be used in order to balance electricity generation. In smart grids, the integration of control, communication and metering are crucial for RES integration. This enables the connection of heterogeneous types of energy sources with AC or DC grid by converters, by achieving an optimal extraction of power from the sources, operational scheduling of demand and request and control of transients [213].
- Thermal energy: thermal solar, geothermal heat (with or without use of heat pumps), heat from bodies of water, biomass and biofuel. The integration of RES in DH networks results in low-grade energy in the supply line. A review of the integration of RES in DH is provided in Ref. [214]. Intelligent control of RES is fundamental in order to avoid over-generation that would lead to a higher return temperature with consequent lower overall performance [215].
- Gas: biogas from various types of vegetables and wastes. Some examples are food waste, biomass waste, biomass, algae, animal and breeding waste.

In terms of smart energy system planning, the high cost of RES plants can make them non-competitive when selecting technology compared to traditional plants, such as cogeneration plants [216]. However, when emissions are taken into account when choosing generation units, renewable energy sources are found among the suitable technologies [217].

A further point concerning RES's integration deals with the potential of the users to also become producers, i.e. the so-called prosumers. The integration of prosumers in energy infrastructure need proper control systems. In the case of electricity, integration of prosumers is common, while in thermal networks this is less common, with two exceptions. The first one concerns industrial plants fed by thermal networks which may release waste heat. The second one concerns buildings with solar collectors installed on the roofs, which in certain conditions can supply the DHC network.

4.2. Waste energy exploitation

In industrial plants, fossil fuels are usually burned in furnaces in order to produce high-temperature heat. This heat is used only partially, at high temperatures, while a percentage is wasted. The potential recovery of heat in industrial plants that otherwise would be wasted has been estimated at 420 trillion BTU [218]. In China, it is believed that about 50% of the total energy used in industrial plants is wasted, frequently in the form of low-temperature waste heat [219]. In Europe, the current excess heat potential from electricity production and industrial processes exceeds the total heating demand of all of Europe [220]. Integration of waste heat in DH systems is discussed in various papers, such as [221,222]. Generally speaking waste heat with medium to high exergy content can be conveniently recovered for electricity production, while lower exergy waste heat can be used for covering a heat demand typically combined with DH.

The fist DH demonstration project using multiple sources of waste heat from a copper smelter is presented in Ref. [223], where waste heat can be considered a suitable technology for providing base load. In Ref. [223] Fang et al. also discussed the potential of usage of two or more low-grade waste heat flows from industry, at a temperature between 20 °C and 90 °C. A key issue is the distance from the heat sources and the consumers. Other types of industries that are particularly suitable for integrating with DH are [224]: mineral manufacturing (20–50% of the energy consumed in this sector in the United States is lost as waste heat [225]) and cement production (a research study on a cement plant shows that about 50% of the heat used in the process had been wasted [226]). Examples of use of waste heat from mineral manufacturing and cement production can be found in Refs. [227,228].

A holistic approach for an efficient integration of low-grade industrial waste heat in DH systems is shown in Ref. [221]. Results show the increase in energy efficiency of the plants and the reduction of pollutant emissions. Integration of system design and land use has been studied in Ref. [229] to develop a network by including a cost-benefit assessment considering both an inventory survey and a geographic database. This allows evaluating the potential of waste heat exploitation by reducing pipeline length (and therefore investment costs) and decreasing CO_2 emissions.

Another point related to the use of the waste for energy production concerns the use of municipal solid waste as a fuel. This can be used in both a DH context and for electricity production. A review is proposed in Ref. [222] to clarify the perspectives in terms of heat recovery from waste in Europe. Among the works related to the use of various types of waste materials (municipal waste, wastewater, farming waste) for electricity production it is worth considering [230–234].

This resource is particularly suitable in DH, particularly in low-temperature DH, where also poor exergy heat can be significantly exploited. In fact, a reduction in the supply temperature can give a significant increase in the performance. Energy and exergy assessment of a DH system is performed in Ref. [235] by changing supply temperatures. Results show that when the supply temperature is reduced from 95 to 60 °C, the final exergy efficiency of the systems increases significantly from 32% to 39.3% in the proposed application. It has been quantified how these benefits of low temperature exceed the cost of such a transformation by a safe margin [236].

Similarly, small reductions in DH return temperatures make the exergy performance increase by various percentage points (e.g. 3.7% through a reduction of 3 °C in the proposed application). In particular, a decrease in the water temperature on the return DH network pipeline is particularly suitable for the long-distance delivery that can be a crucial problem while integrating waste heat [223]; indeed usually industrial sites are located in different areas than the urban centres.

4.3. Towards multi-energy systems

Multi-energy systems, whose networks (Section 3.1), energy conversion units (Section 3.2), and energy storage (Section 3.3), have already been discussed, face large challenges related to their optimal management and design. The energy conversion units should be coordinated with the transmission and distribution networks of energy vectors (gas, heat/cooling and electricity) in order to meet the demand. The latter keeps increasing its intelligence and capabilities to be controlled in a demand response fashion and actively add energy as a prosumer, becoming itself an energy conversion unit, at either small or large scale such as in the case of industrial facilities. The above-mentioned chain should be designed and operated in a way that the overall primary energy and/or economics are optimal while maintaining system stability and fulfilling all these constraints deemed fundamental for the overall system integrity.

In this way, there are many possible elements to optimize and they depend on which part of the overall system is taken into consideration, as well as the chosen point of view, and whose revenues to maximize. Once the objective function has been defined, constraints will be introduced accordingly such as accounting for energy vector balances and curves of the characteristics of energy conversion units [237]. Energy network balances and constraints also need to be formalized in order to provide stability to the system and avoid inconveniences such as overload in certain network regions [238]. In addition to optimizing the management there could be a need to add extra constraints related to national policies, to electricity and gas prices as well as fiscal incentives. The combination of these elements along with the presence of long-term storage and other kinds of inertia will help to solve large problems at once without focusing only on the single time step [239]. The problem is often non-linear because of the performance curves of conversion systems, which are often complex systems, or the regulatory and fiscal constraints (often non-linear and non-convex) as well as the inertia which implies non-linear time dependence, making the optimization problems difficult to solve, e.g. seasonal storages which bind a long period of time to be solved at once [240]. Moreover, as further explained below, the uncertainties related to future fuel prices play an important role in any attempt to identify an optimal solution. State-of-the-art tackles such challenging Mixed Integer Non Linear Problems (MINLP) by means of convexification and linearization techniques, piecewise discretizing the performance curves or dividing the problem into small time steps to deal with transients and more generally formulating the problem in such a way that it resembles the problem with a satisfactory degree of accuracy while ensuring feasible solutions [241]. Such a solution should be found within a time frame allowing the implementation of the results into production plans consistent with the actual needs. In addition to optimal design, yearly optimization problems need to be solved to determine the yearly costs, which are needed to determine the cash flow of the design solutions. The latter will vary with the number and typology of conversion units which are discrete and vary non-linearly depending on size. The overall design problem is therefore highly non-linear, non-smooth and non-continuous [242], thus a master-slave approach with a meta-heuristic algorithm, e.g. genetic, could be utilized to call optimization problems for each different design and assess the optimal configuration [243]. Furthermore, when making decisions related to optimal design, the K-best near-optimal solutions could also be assessed to help the decision makers by providing an overview of the best alternatives [244].

Uncertainty has largely increased its impact on the overall integrated energy system due to the growing renewable energy sources affecting first and foremost the electric system, and as a consequence the thermal and gas systems. The last two have so far been less affected by renewables, e.g. some solar thermal and biogas, so their connection to the electric system brings further uncertainty consequently influencing the demand. This paper has so far discussed the so-called deterministic problem. The level of complexity for the solution of the same problem under uncertainty is surely higher and an increasing number of researchers are working on such topics. A comprehensive overview is provided by Ref. [245] where the uncertainty is dealt with by “tweaking” heuristically the deterministic formulation so that uncertainty can be handled, e.g. via stricter constraints than needed, in a conservative fashion thus reaching a sub-optimal solution. The three families of optimization methods utilized to deal with uncertainty are:

- Stochastic optimization (scenario tree), which discretizes the continuous stochastic parameters into a tree of scenarios, in whose nodes uncertainty is assumed to be known. This approach means de facto solving a very large deterministic problem and the main challenge consists of defining a scenario tree which represents properly the underlying uncertainty and its compliance with the accuracy of the deterministic model approximations,
- Robust optimization, which defines the more adverse scenarios provided by the uncertain parameters and determines the solution accordingly, regardless of the probability of them occurring. Therefore it is often too conservative because it aims at covering also too unlikely events. Many robust optimization approaches thus introduce parameters aiming at controlling such degree of protection,
- Chance constrained optimization deals with a trade-off between objective function optimal value, e.g. cost, and robustness of the solution with the introduction of probabilistic constraints.

All these techniques have traditionally been applied to electric infrastructure and generation due to their less predictable nature and faster dynamics compared to thermal and gas networks with their slower dynamics and intrinsic capability of being stored, possibly by the network inertia. A deeper integration of the three energy infrastructures will on the one hand help smoothen them and on the other hand increase the computational effort due to larger deterministic problems.

When it comes to the design of long-term strategies and scenarios such as identifying pathways to affordable 100% renewable energy solutions, all the uncertainties mentioned above relevantly question the scientific relevance of searching for one optimal solution. Such theoretical considerations are discussed in Ref. [246] leading to the conclusion that a simulation approach makes more sense. Additionally, in Ref. [247] it is discussed how to tackle the huge long-term uncertainties in the inclusion of fuel prices as well as electricity prices regarding exchange of electricity between countries and/or regions. Any kind of modelling must include all relevant sectors and storage types in order to be able to identify suitable and affordable solutions [248].

As shown in Fig. 4, in addition to the multiple interconnections between the infrastructures, each of them is currently facing an evolution which goes towards multigrid interconnection solutions also involving vectors of the same type. A multi-microgrid power system is a well-accepted paradigm and the scientific community is currently exploring the possible architecture of effective and reliable micro-grid clusters [249]. This is due to the massive deployment of renewable energy sources which inject electricity in the grid in a distributed fashion. The same shift from hierarchical large scale towards small infrastructures can happen at thermal side, often when pre-existing infrastructure allows such micro-grid interconnections to compensate over- and under-production of heat or when establishing a market starting from bi-lateral ones [250]. This is also true in a green field scenario with lower district heating temperature and an increasing rate of distributed generation of heat and the prosumer's role [251], via small CHP or HP, where the micro grid could also be utilized as indirect storage of renewable energy both thermal and electric. The same concept is still far from being deployed in the natural gas network because of its intrinsic centralized nature, which will need a massive deployment of power-to-gas units and/or bio-methane production plants. The last level of interconnection would be at a higher level and at an international scale. It depends on the nature of the energy vector; for example it is intrinsic in the current nature of the natural gas grid where thousands of kilometres of gas pipelines are utilized to balance the primary energy demand with offers [252].

It is also true for the electric energy where electric grids in countries balance in real time the whole continent frequency enhancing the overall reliability of the system where several hundred megawatts of power outage in an extremely restrained region could be handled at continental level and large inter-area frequency oscillation in phase opposition could be measured at the other extreme [253]. Interconnection is very important to avoid extreme events such as blackouts [254] and to the challenges related to increasing shares of non-controllable renewables in the energy mix but could also be developed to transfer electricity from one region to the other on a market basis. For this reason underwater (High Voltage Direct Current) HVDC cables have been deployed in several regions of the world with case studies even pointing at connecting North America with Europe and the socio-economic benefits of more than 100 M€ they could bring [255]. The overall integration could also include the thermal networks at town level where each

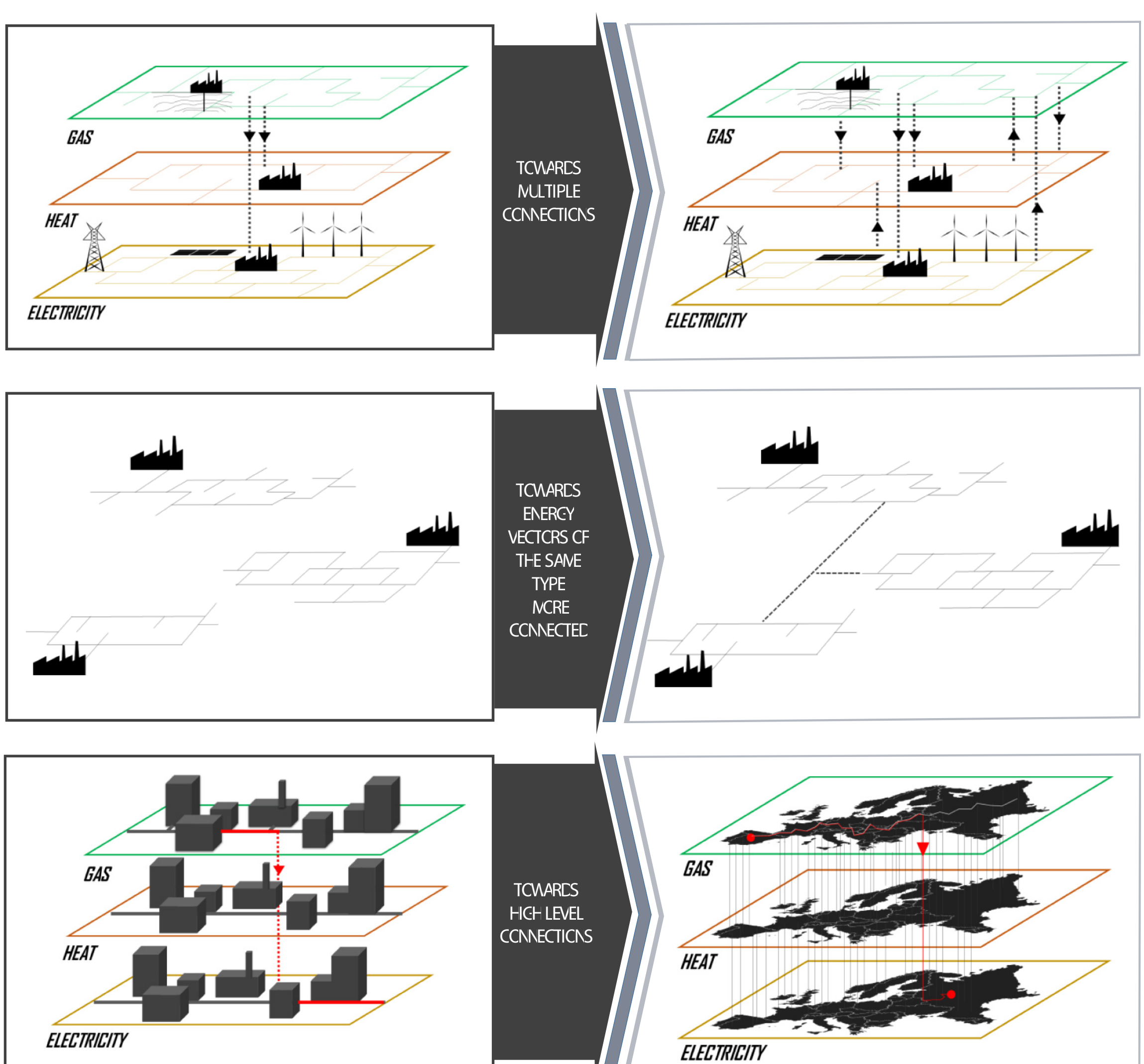

Fig. 4. Towards future multi-energy systems.

of these networks could be interconnected to the electric grid via power-to-heat devices and CHP units that could shift from electricity to heat generation and vice-versa. A fully integrated system would then require the development of solutions capable of tackling such challenging and large problems ranging from the need for dealing with large pipeline systems, heat and gas [256], to the need for finding effective aggregation methodologies while mapping energy district loads [257]. The impact on the security [258] and the energy consumption at national level have already been studied [1,206] with promising results such as 75% carbon emission reduction and more than 20% peak shaving.

5. Conclusions

This paper aims at reviewing the current status of energy infrastructures, considering electricity, thermal and gas systems. The following aspects are investigated:

- Description of the energy infrastructure from a technological and modelling point of view:
  o Networks: gas pipelines, electric grids and district heating networks.
  o Components used to convert the energy vectors: gas-to-heat, gas-to-power, power-to-heat and power-to-gas technologies.
  o Energy storages.
- Integration of renewable sources and energy recovered into the energy systems
- Evolution of energy infrastructures towards multi-energy systems for pushing energy decarbonisation. Multi-energy systems is a fully multi-disciplinary research topic requiring a definition of a common basis for achieving problem solution. Current research trends are investigated, showing the opportunities for enhancing the results at all scales.

The analysis shows that despite various similarities, electricity, thermal and gas networks have different characteristics and face different technical challenges, and therefore the technological aspects and the modelling approaches are different. From a modelling point of view approaches are significantly different since non-linearities are due to different phenomena. Multi-energy modelling should focus on methodologies that effectively tackle transients coupled problems. This represents one of the main goals for future research in multi-energy systems.

The manuscript also highlights that energy infrastructures, when interconnected, allow increasing efficiency by reducing primary energy consumption and pollutant substances emissions, enhancing energy storage exploitation. In order to reach optimality of scheduling and design of such integrated energy systems, furthermore under uncertainty, the mathematical problem results challenging; the more accurate and comprehensive the model is the more the non-linear, non-convex as well as high number of variables is.

The proposed review revealed various research lines that should be taken into account in the future:

- Analysis of network integration into multi-energy models with the aim of understanding the effects of dynamics on sudden conversion of energy from one form to another. For instance, effects of conversion of electrical energy into thermal energy should be analysed by considering the network dynamics.
- Investigation of potential for using combined strategies for the management of different energy vector infrastructures in order to achieve efficient multi-energy systems. For instance, joint optimization of district heating network with electric and gas network, interconnected via flexible power plants.
- Study of the possible interaction between agencies managing various energy vectors to promote combined management of multi-energy systems.
- Investigation of design techniques for new energy infrastructure (or expansion of existing) by also taking into account the infrastructure related to other energy vectors.
- Large scale mixed integer non-linear optimization problems under uncertainty, ranging from mathematical methods to simplification approaches.

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References

[1] Clegg S, Mancarella P. Integrated electricity-heat-gas modelling and assessment, with applications to the Great Britain system. Part II: transmission network analysis and low carbon technology and resilience case studies. Energy 2018.
[2] Lund H. Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach. Energy 2018;151:94–102.
[3] Olczak M, Piebalgs A. Sector coupling: the new EU climate and energy paradigm. Florence School of Regulation, European University Institute, Robert Shuman cEnter for advanced Studies; 2018. Policy Brief: Gas http://fsr.eui.eu/publications/.
[4] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65.
[5] Mancarella P. MES (multi-energy systems): an overview of concepts and evaluation models. Energy 2014;65:1–17.
[6] Siemens, Arup. Distributed energy systems: flexible and efficient power for the new energy era. 2016. Available online at: . [Accessed 19 February 2019]. https://new.siemens.com/global/en/products/energy/topics/distributed-energy-systems.html#Study.
[7] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf.
[8] Annual energy outlook 2014 early release della EIA.
[9] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F,, Sorknæs P. Energy storage and smart energy systems. Inter J Sustain Energy Plan Manag 2016;11:3–14.
[10] Frederiksen S, Werner S. District heating and cooling lund studentlitteratur. 2013.
[11] Castro Flores JF, Lacarrière B, Le Corre O, Martin V. Study of a district heating substation using the return water of the main system to service a low-temperature secondary network. In: The 14th international symposium on district heating and cooling; 2014 Sep 7-9. Stockholm, Sweden: Swedish District Heating Association; 2014.
[12] Kapil A, Bulatov I, Smith R, Kim JK. Process integration of low grade heat in process industry with district heating networks. Energy 2012;44(1):11–9.
[13] https://www.euroheat.org/wp-content/uploads/2016/04/UP RES_M6_District_Heating_and_Cooling.pdf.
[14] Werner S. International review of district heating and cooling. Energy 15 October 2017;137:617–31. https://doi.org/10.1016/j.energy.2017.04.045.
[15] Soltero VM, Chacartegui R, Ortiz C, Velázquez R. Evaluation of the potential of natural gas district heating cogeneration in Spain as a tool for decarbonisation of the economy. Energy 2016;115:1513–32.
[16] Ziębik A, Gładysz P. Optimal coefficient of the share of cogeneration in district heating systems. Energy 2012;45(1):220–7.
[17] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, Mathiesen BV. 4th Generation District Heating (4GDH): integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11.
[18] Østergaard PA, Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Appl Energy 2011;88(2):479–87.
[19] Fang H, Xia J, Zhu K, Su Y, Jiang Y. Industrial waste heat utilization for low temperature district heating. Energy Policy 2013;62:236–46.
[20] Brand M, Svendsen S. Renewable-based low-temperature district heating for existing buildings in various stages of refurbishment. Energy 2013;62:311–9.
[21] Prato AP, Strobino F, Broccardo M, Giusino LP. Integrated management of cogeneration plants and district heating networks. Appl Energy 2012;97:590–600.
[22] Guelpa E, Mutani G, Todeschi V, Verda V. Reduction of CO2 emissions in urban areas through optimal expansion of existing district heating networks. J Clean Prod 2019;204(10):117–29.

[23] Brundu FG, Patti E, Osello A, Del Giudice M, Rapetti N, Krylovskiy A,, Acquaviva A. IoT software infrastructure for energy management and simulation in smart cities. IEEE Trans. Industrial Informatics 2017;13(2): 832–40.

[24] Chan AL, Chow TT, Fong SK, Lin JZ. Performance evaluation of district cooling plant with ice storage. Energy 2006;31(14):2750–62.

[25] http://www.sea-energia.eu/en/plants/malpensa-plant.

[26] Hüls Güido W, Lanser W, Petersen S, Ziegler F. Performance of absorption chillers in field tests. Appl Therm Eng 2018;134:353–9.

[27] Lavoine O. Thoughts on an electricity system and grid paradigm shift in response to the EU energy transition and the clean energy package. Policy Briefs; 2018/19; Florence School of Regulation; 2018. 2467-4540.

[28] Vu TL, Turitsyn K. A framework for robust assessment of power grid stability and resiliency. IEEE Trans Autom Control 2016;62(3).

[29] Roberts C. Review of international grid codes. USA: Lawrence Berkeley National Laboratory; 2018.

[30] Kuhn P, Huber M, Dorfner J, Hamacher T. Challenges and opportunities of power systems from smart homes to super-grids. Ambio 2016;45(1): S50–62.

[31] Chen S, Liu CC. From demand response to transactive energy: state of the art. Journal of Modern Power Systems and Clean Energy 2017;5(1):10–9.

[32] Yao L, Yang B, Cui H, Zhuang J, Ye J, Xue J. Challenges and progresses of energy storage technology and its application in power systems. Journal of Modern Power Systems and Clean Energy 2016;4:519–28.

[33] Bernard JT, Bolduc D, Hardy A. The marginal cost of natural gas distribution pipelines: the case of Societé en Commandite Gaz Métropolitain, Quebec. Cahiers de recherché; 1998. 9824.

[34] Ríos-Mercado RZ, Borraz-Sánchez C. Optimization problems in natural gas transportation systems: a state-of-the-art review. Appl Energy 2015;147: 536–55.

[35] Ruan Y, Liu Q, Zhou W, Batty B, Gao W, Ren J, Watanabe T. A procedure to design the mainline system in natural gas networks. Appl Math Model 2009;33(7):3040–51.

[36] Hübner M, Haubrich H-J. Long-term pressure-stage comprehensive planning of natural gas networks. In: Sorokin A, Rebennack S, Pardalos PM, Iliadis NA, Pereira MVF, editors. Handbook of networks in power systems II. Energy systems. Berlin Heidelberg: Springer; 2012. p. 37–59.

[37] Li X, Armagan E, Tomasgard A, Barton PI. Long-term planning of natural gas production systems via a stochastic pooling problem. In: American control conference (2010-ACC). IEEE; 2010, ISBN 978-1-4244-7426-4. p. 429–35.

[38] Handbook of natural gas transmission and processing: principles and practices di saeid mokhatab, William A. Poe, John Y. Mak.

[39] Rothfarb B, Frank H, Rosenbaum DM, Steiglitz K, Kleitman DJ. Optimal design of offshore natural-gas pipeline systems. Oper Res 1970;18(6):992–1020.

[40] Ruan Y, Liu Q, Zhou W, Batty B, Gao W, Ren J, Watanabe T. A procedure to design the mainline system in natural gas networks. Appl Math Model 2009;33(7):3040–51.

[41] Misra S, Fisher MW, Backhaus S, Bent R, MC, Pan F. Optimal compression in natural gas networks: a geometric programming approach. IEEE Trans Contr Netw Syst 2015;2(1):47–56.

[42] Bautz R. Natural gas storage. GWA. Gas, Wasser, Abwasser 2009;5:373–80.

[43] Aalto H. April). Simplified real-time optimization of the gas pipeline network saves compression energy. In: *PSIG annual meeting*. Pipeline simulation interest group; 2013.

[44] Silva P, Bischi A, Lamberti M, Campanari S, Macchi E, Tacchinardi D. Trigenerative solution for natural gas compressor stations: a north Italian test case. Energy 2018.

[45] Verrilli F, Srinivasan S, Gambino G, Canelli M, Himanka M, Del Vecchio C,, Glielmo L. Model predictive control-based optimal operations of district heating system with thermal energy storage and flexible loads. IEEE Trans Autom Sci Eng 2017;14(2):547–57.

[46] Dalla Rosa A, Li H, Svendsen S. Method for optimal design of pipes for low-energy district heating, with focus on heat losses. Energy 2011;36(5): 2407–18.

[47] Vallios I, Tsoutsos T, Papadakis G. Design of biomass district heating systems. Biomass Bioenergy 2009;33(4):659–78.

[48] Yildirim N, Toksoy M, Gokcen G. Piping network design of geothermal district heating systems: case study for a university campus. Energy 2010;35(8): 3256–62.

[49] Jing ZX, Jiang XS, Wu QH, Tang WH, Hua B. Modelling and optimal operation of a small-scale integrated energy based district heating and cooling system. Energy 2014;73:399–415.

[50] Gambino G, Verrilli F, Canelli M, Russo A, Himanka M, Sasso M,, Glielmo L. Optimal operation of a district heating power plant with thermal energy storage. In: American control conference (ACC), 2016. IEEE; 2016, July. p. 2334–9.

[51] Guelpa E, Toro C, Sciacovelli A, Melli R, Sciubba E, Verda V. Optimal operation of large district heating networks through fast fluid-dynamic simulation. Energy 2016;102:586–95.

[52] Sciacovelli A, Guelpa E, Verda V. November). Pumping cost minimization in an existing district heating network. In: ASME 2013 international mechanical engineering congress and exposition. American Society of Mechanical Engineers; 2013. V06AT07A066-V06AT07A066.

[53] Guelpa E, Verda V. Model for optimal malfunction management in extended district heating networks. Appl Energy 2018;230:519–30.

[54] Pizzolato A, Sciacovelli A, Verda V. Centralized control of district heating networks during failure events using discrete adjoint sensitivities. Energy 2017.

[55] Guelpa E, Verda V. Compact physical model for simulation of thermal networks. Energy 2019;175(15):998–1008.

[56] Stevanovic VD, Prica S, Maslovaric B, Zivkovic B, Nikodijevic S. Efficient numerical method for district heating system hydraulics. Energy Convers Manag 2007;48(5):1536–43.

[57] Cross H. Analysis of flow in networks of conduits or conductors. University of Illinois at Urbana Champaign, College of Engineering. Engineering Experiment Station; 1936.

[58] Larsen HV, Pálsson H, Bøhm B, Ravn HF. Aggregated dynamic simulation model of district heating networks. Energy Convers Manag 2002;43(8): 995–1019.

[59] Loewen A, Wigbels M, Althaus W, Augusiak A. A RenskiStructural simplification of complex DH-networks euroheat & power. 2001. p. 46–50.

[60] Larsen HV, Bøhm B, Wigbels M. A comparison of aggregated models for simulation and operational optimisation of district heating networks. Energy Convers Manag 2004;45(7–8):1119–39.

[61] Guelpa E, Sciacovelli A, Verda V. Thermo-fluid dynamic model of large district heating networks for the analysis of primary energy savings. Energy 2017.

[62] Chertkov M, Novitsky NN. Thermal transients in district heating systems. Energy 2018.

[63] del Hoyo Arce I, López SH, Perez SL, Rämä M, Klobut K, Febres JA. Models for fast modelling of district heating and cooling networks. Renew Sustain Energy Rev 2018;82:1863–73.

[64] Syranidis K, Robinius M, Stolten D. Control techniques and the modeling of electrical power flow across transmission networks. Renew Sustain Energy Rev 2018;82:3452–67.

[65] Aien M, Rashidinejad M, Firuz-Abad M. Probabilistic optimal power flow. In: Proceedings of the 1998 11th Canadian conference on electrical and computer engineering, CCECE, vol. 1; 1998. p. 385–8. Part 1 (of 2).

[66] Shargh S, ghazani BK, Mohammadi-ivatloo B, Seyedi H, Abapour M. Probabilistic multi-objective optimal power flow considering correlated wind power and load uncertainties. Renew Energy 2016;94:10–21.

[67] Lavaei J, Low SH. Zero duality gap in optimal power flow problem. IEEE Trans Power Syst February 2012;27(1):92–107.

[68] Lorca A, Sun XA. Adaptive robust optimization with dynamic uncertainty sets for multi-period economic dispatch under significant wind. IEEE Trans. Pwr. Sys. July 2015;30(4):17021713.

[69] Vu TL, Turitsyn K. A framework for robust assessment of power grid stability and resiliency. IEEE Trans Autom Control 2017;62:1165–77.

[70] Roald L, Misra S, Krause T, Andersson G. Corrective control to handle forecast uncertainty: a chance constrained optimal power flow. IEEE Trans Power Syst March 2017;32(2):16261637.

[71] DallAnese E, Baker K, Summers T. Chance-constrained AC optimal power flow for distribution systems with renewables. IEEE Trans Power Syst Sept 2017;32(5):34273438.

[72] Chen Yue, Hashmi Md Umar, Mathias Joel, Busic Ana, Meyn Sean. Distributed control design for balancing the grid using flexible loads. IMA Volume on the Control of Energy Markets and Grids 2019;162:1–26.

[73] Chertkov Michael, Vladimir Y. Chernyak, deepjyoti deka, ensemble control of cycling energy loads: Markov decision approach. IMA Volume on the Control of Energy Markets and Grids 2019;162:363–82.

[74] Wong PJ, Larson RE. Optimization of natural-gas pipeline systems via dynamic programming. IEEE Trans Autom Control 1968;AC-13(5):475–81.

[75] Carter RG. Pipeline optimization: dynamic programming after 30 years. In: Proceedings of the 30th PSIG annual meeting; October 1998. Denver.

[76] Percell PB, Ryan MJ. Steady-state optimization of gas pipeline network operation. In: Proceedings of the 19th PSIG annual meeting; October 1987. Tulsa.

[77] Villalobos-Morales Y, Ríos-Mercado RZ. Preprocesamiento efectivo de un problema de minimización de combustible en sistemas de transporte de gas natural. Revista Ingeniería Sistemas 2005;19:79–103.

[78] Flores-Villarreal HJ, Ríos-Mercado RZ. Computational experience with a GRG method for minimizing fuel consumption on cyclic natural gas networks. In: Mastorakis NE, Stathopulos IA, Manikopoulos C, Antoniou GE, Mladenov VM, Gonos IF, editors. Computational methods in circuits and systems applications. Athens, Greece: WSEAS Press; 2003. p. 90–4.

[79] Misra S, Fisher MW, Backhaus S, Bent R, Chertkov M, Pan F. Optimal compression in natural gas networks: a geometric programming approach. IEEE transactions on control of network systems 2015;2(1):47–56.

[80] Martin A, Möller M, Moritz S. Mixed integer models for the stationary case of gas network optimization. Math Program 2006;105(2–3):563–82.

[81] Chebouba A, Yalaoui F, Smati A, Amodeo L, Younsi K, Tairi A. Optimization of natural gas pipeline transportation using ant colony optimization. Comput Oper Res 2009;36(6):1916–23.

[82] Wu X, Li C, Jia W, He Y. Optimal operation of trunk natural gas pipelines via an inertia-adaptive particle swarm optimization algorithm. J Nat Gas Sci Eng 2014;21:10–8.

[83] Larson RE, Wismer DA. Hierarchical control of transient flow in natural gas pipeline networks. In: Proceedings of the IFAC symposium on distributed parameter systems; 1971. Banff, Alberta, Canada.

[84] Osiadacz AJ, Bell DJ. A simplified algorithm for optimization of large-scale gas

networks. Optim Contr Appl Methods 1986;7(1):95–104.
[85] Anglard P, David P. Hierarchical steady state optimization of very large gas pipelines. In: Proceedings of the 20th PSIG annual meeting; October 1988. Toronto.
[86] Ehrhardt K, Steinbach MC. Nonlinear optimization in gas networks. In: Bock HG, Kostina E, Phu HX, Rannacher R, editors. Modeling, simulation and optimization of complex processes. Springer; 2005. p. 139–48. Berlin.
[87] Aalto H. Optimal control of natural gas pipeline networks: a real-time, model-based, receding horizon optimisation approach. Saarbrücken, Germany: VDM Verlag; 2008.
[88] Mahlke D, Martin A, Moritz S. A simulated annealing algorithm for transient optimization in gas networks. Math Methods Oper Res 2007;66(1):99–115.
[89] de Nevers N, Day A. Packing and drafting in natural gas pipelines. J Pet Technol 1983;35(3):655–8.
[90] Carter RG, Rachford Jr HH. Optimizing line-pack management to hedge against future load uncertainty. In: Proceedings of the 35th PSIG annual meeting. Switzerland: Bern; October 2003. Paper 0306.
[91] Frimannslund L, Haugland D. Line pack management for improved regularity in pipeline gas transportation networks. In: Martorell S, Guedes-Soares C, Barnett J, editors. Safety, reliability and risk analysis: theory, methods and applications. vol. 4. London, UK: CRC Press; 2008. p. 2963–9.
[92] Krishnaswami P, Chapman KS, Abbaspour M. Compressor station optimization for linepack maintenance. In: Proceedings of the 36th PSIG annual meeting. Palm Springs; October 2004.
[93] Sukharev MG, Kosova KO, Popov RV. Mathematical and computer models for identification and optimal control of large-scale gas supply systems. Energy 2018.
[94] Vuffray M, Misra S, Chertkov M. Monotonicity of dissipative flow networks renders robust maximum profit problem tractable: general analysis and application to natural gas flows. In: 2015 54th IEEE conference on decision and control (CDC). IEEE; 2015. p. 4571–8.
[95] Augutis J, Jokšas B, Krikštolaitis R, Urbonas R. The assessment technology of energy critical infrastructure. Appl Energy 2016;162:1494–504.
[96] Senderov SM, Edelev AV. Formation of a list of critical facilities in the gas transportation system of Russia in terms of energy security. Energy 2017.
[97] Dieckhöner C. Simulating security of supply effects of the Nabucco and South Stream projects for the European natural gas market. Energy J 2012;33(3):155–83.
[98] Monforti F, Szikszai A. A MonteCarlo approach for assessing the adequacy of the European gas transmission system under supply crisis conditions. Energy Policy 2010;38(5):2486–98.
[99] Zhang M, Su M, Lu W, Su C. An assessment of the security of China's natural gas supply system using two network models. Energies 2015;8(12):13710–25.
[100] Voropai NI, Senderov SM, Edelev AV. Detection of “bottlenecks” and ways to overcome emergency situations in gas transportation networks on the example of the European gas pipeline network. Energy 2012. https://doi.org/10.1016/j.energy.2011.07.038.
[101] Vorobiev SV, Edelev AV. A methodology for detection of “bottlenecks” in operation of large-scale pipeline systems. Software and systems 2014;(3):174–7.
[102] Sukharev MG, Kulikc VS. The impact of information uncertainty on the problems of medium and long-term planning of the operation modes of gas transport systems. Energy 2019. https://doi.org/10.1016/j.energy.2017.08.099. In Press, Corrected Proof.
[103] Wu DW, Wang RZ. Combined cooling, heating and power: a review. Prog Energy Combust Sci 2006;32:459–95.
[104] Al Moussawi H, Fardoun F, Louahlia-Gualous H. Review of tri-generation technologies: design evaluation, optimization, decision-making, and selection approach. Energy Convers Manag 2016;120:157–96.
[105] Consonni S, Lozza G, Macchi E. Optimization of cogeneration systems operation. Part A. Prime movers modelization American Society of Mechanical Engineers. International Gas Turbine Institute (Publication) IGTI 4 1989:313–22.
[106] Tartiere T, Astolfi M. A world overview of the organic rankine cycle market. Energy Procedia 2017;129:2–9. https://doi.org/10.1016/j.egypro.2017.09.159.
[107] https://www.solidpower.com/.
[108] Gaurava N, Sivasankari S, Kiranc GS, Ninawe A, Selvin J. Utilization of bioresources for sustainable biofuels: a Review. Renew Sustain Energy Rev 2017;73:205–14. https://doi.org/10.1016/j.rser.2017.01.070.
[109] Briola S, Di Marco P, Gabbrielli R. Thermodynamic sensitivity analysis of a novel trigeneration thermodynamic cycle with two-phase expanders and two-phase compressors. Energy 2017;127:335–50.
[110] Götz M, Lefebvre J, Mörs F, McDaniel Koch A, Graf F, Bajohr S, Reimert R, Kolb T. Renewable Power-to-Gas: a technological and economic review. Renew Energy 2016;85:1371–90. https://doi.org/10.1016/j.renene.2015.07.066.
[111] Colbertaldo P, Guandalini G, Campanari S. Modelling the integrated power and transport energy system: the role of power-to-gas and hydrogen in long-term scenarios for Italy. Energy 2018;154:592–601. https://doi.org/10.1016/j.energy.2018.04.089.
[112] Bailera M, Lisbona P, Romeo LM, Espatolero S. Power to Gas projects review. Lab, pilot and demo plants for storing renewable energy and CO_2 Renewable and Sustainable Energy Reviews 2017;69:292–312. https://doi.org/10.1016/j.rser.2016.11.130.
[113] Clegg S, Mancarella P. Integrated modeling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks. IEEE Transactions on sustainable energy 2015;6(4):1234–44. https://doi.org/10.1109/TSTE.2015.2424885.
[114] David A, Mathiesen BV, Averfalk H, Werner S, Lund H. Heat roadmap Europe: large-scale electric heat pumps in district heating systems. Energies 2017;10(4):578.
[115] Arat H, Arslan O. Exergoeconomic analysis of district heating system boosted by the geothermal heat pump. Energy 2017;119:1159–70.
[116] Sciacovelli A, Guelpa E, Verda V. Multi-scale modeling of the environmental impact and energy performance of open-loop groundwater heat pumps in urban areas. Appl Therm Eng 2014;71(2):780–9.
[117] Frate GF, Antonelli M, Desideri U. A novel Pumped Thermal Electricity Storage (PTES) system with thermal integration. Appl Therm Eng 2017;121:1051–8. https://doi.org/10.1016/j.applthermaleng.2017.04.127.
[118] Bloess A, Schill W-P, Zerrahn A. Power-to-heat for renewable energy integration: a review of technologies, modeling approaches, and flexibility potentials. Appl Energy 2018;212:1611–26. https://doi.org/10.1016/j.apenergy.2017.12.073.
[119] https://www.euroheat.org/wp-content/uploads/2018/05/Digital-Roadmap_final.pdf.
[120] https://heatroadmap.eu/wp-content/uploads/2018/09/STRATEGO-WP2-Background-Report-4-Heat-Cold-Demands.pdf.
[121] Schmidt P, Batteiger V, Roth A, Weindorf W, Raksha T. Power-to-Liquids as renewable fuel option for aviation: a review. Chem Ing Tech 2018;90(1–2):127–40. https://doi.org/10.1002/cite.201700129.
[122] Østergaard PA, Lund H, Mathiesen BV. Energy system impacts of desalination in Jordan. Inter J Sustain Energy Plan Manag 2014;1:29–40.
[123] Mazzola S, Astolfi M, Macchi E. A detailed model for the optimal management of a multigood microgrid. Appl Energy 2015;154:862–73. https://doi.org/10.1016/j.apenergy.2015.05.078.
[124] de Vries A. Bitcoin's growing energy problem. Joule 2018;2(5):801–5. https://doi.org/10.1016/j.joule.2018.04.016.
[125] Andonia M, Robu V, Flynn D, Abram S, Geach D, Jenkins D, McCallum P, Peacock A. Blockchain technology in the energy sector: a systematic review of challenges and opportunities. Renew Sustain Energy Rev 2019;100:143–74.
[126] Flores JFC, Espagnet AR, Chiu JN, Martin V, Lacarrière B. Techno-economic assessment of active latent heat thermal energy storage systems with low-temperature district heating. Inter J Sustain Energy Plan Manag 2017;13:5–18.
[127] He B. High-capacity cool thermal energy storage for peak shaving-A solution for energy challenges in the 21st century. Doctoral dissertation. 2004. Kemiteknik.
[128] Xu J, Wang RZ, Li Y. A review of available technologies for seasonal thermal energy storage. Sol Energy 2014;103:610–38.
[129] Weber R, Dorer V. Long-term heat storage with NaOH. Vacuum 2008;82:708–16.
[130] Bueno C, Carta JA. Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands. Renew Sustain Energy Rev 2006;10(4):312–40.
[131] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy 2015;137:511–36.
[132] Chen H, Zhang X, Liu J, Tan C. Compressed air energy storage. In: Energy storage-technologies and applications. InTech; 2013.
[133] Vosburgh KG. Compressed air energy storage. J Energy 1978;2(2):106–12.
[134] Wang J, Lu K, Ma L, Wang J, Dooner M, Miao S,, Wang D. Overview of compressed air energy storage and technology development. Energies 2017;10(7):991.
[135] Amiryar M, Pullen K. A review of flywheel energy storage system technologies and their applications. Appl Sci 2017;7(3):286.
[136] Morgan R, Nelmes S, Gibson E, Brett G. Liquid air energy storage—analysis and first results from a pilot scale demonstration plant. Appl Energy 2015;137:845–53.
[137] http://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Mechanical_LAES.pdf.
[138] Abarr M, Geels B, Hertzberg J, Montoya LD. Pumped thermal energy storage and bottoming system part A: concept and model. Energy 2017;120:320–31.
[139] Abarr M, Hertzberg J, Montoya LD. Pumped thermal energy storage and bottoming system Part B: sensitivity analysis and baseline performance. Energy 2017;119:601–11.
[140] McTigue JD, White AJ, Markides CN. Parametric studies and optimisation of pumped thermal electricity storage. Appl Energy 2015;137:800–11.
[141] Erol SALIM. Electrochemical impedance spectroscopy analysis and modeling of lithium cobalt oxide/carbon batteries. Doctoral dissertation, Ph. D. Thesis. Gainesville, FL, USA: University of Florida; 2015. 2015. Available online: http://www.che.ufl.edu/orazem/pdf-files/Erol-PhD-2015.pdf.
[142] Andriollo M, Benato R, Sessa SD, Di Pietro N, Hirai N, Nakanishi Y, Senatore E. Energy intensive electrochemical storage in Italy: 34.8 MW sodium—sulphur secondary cells. Journal of Energy Storage 2016;5:146–55.
[143] Ding C, Zhang H, Li X, Liu T, Xing F. Vanadium flow battery for energy storage: prospects and challenges. J Phys Chem Lett 2013;4(8):1281–94.
[144] San Martín JI, Zamora I, San Martín JJ, Aperribay V, Eguia P. April). Energy

storage technologies for electric applications. In: International conference on renewable energies and power quality; 2011. No. 2.

[145] Iannuzzi D, Lauria D, Tricoli P. Optimal design of stationary supercapacitors storage devices for light electrical transportation systems. Optim Eng 2012;13(4):689–704.

[146] Buckles W, Hassenzahl WV. Superconducting magnetic energy storage. IEEE Power Eng Rev 2000;20(5):16–20.

[147] Evans DJ, Chadwick RA, editors. Underground gas storage: worldwide experiences and future development in the UK and Europe. Geological Society of London; 2009.

[148] Alva G, Lin Y, Fang G. An overview of thermal energy storage systems. Energy 2017.

[149] Arce P, Medrano M, Gil A, Oró E, Cabeza LF. Overview of thermal energy storage (TES) potential energy savings and climate change mitigation in Spain and Europe. Appl Energy 2011;88(8):2764–74.

[150] Xu J, Wang RZ, Li Y. A review of available technologies for seasonal thermal energy storage. Sol Energy 2014;103:610–38.

[151] Rezaie B, Reddy BV, Rosen MA. Exergy analysis of thermal energy storage in a district energy application. Renew Energy 2015;74:848–54.

[152] Xu J, Wang RZ, Li Y. A review of available technologies for seasonal thermal energy storage. Sol Energy 2014;103:610–38.

[153] Hesaraki A, Holmberg S, Haghighat F. Seasonal thermal energy storage with heat pumps and low temperatures in building projectsea comparative review. Renew Sustain Energy Rev 2015;43:1199e213.

[154] Snijders AL, van Aarssen MM. Big is beautiful?: application of large-scale energy storage in The Netherlands. Futurestock. In: Proceedings of the 9th international conference on thermal energy storage; 2003. Warsaw, Poland.

[155] Andersson O, Sellberg B. Swedish ATES applications: experiences after ten years of development. In: Jenne EA, editor. Aquifer thermal energy (heat and chill) storage: proceedings of the 27th intersociety energy conversion engineering conference; 1993. p. 1–9. San Diego, CA.

[156] Ciampi G, Rosato A, Sibilio S. Thermo-economic sensitivity analysis by dynamic simulations of a small Italian solar district heating system with a seasonal borehole thermal energy storage. Energy 2018;143:757–71.

[157] Desmedt J, Hoes H. Monitoring results of aquifer thermal energy storage system in a Belgian hospital. In: Proceedings of 2nd PALENC conference and 28th AIVC conference on building low energy cooling and advanced ventilation technologies; 2007. Crete Island, Greece.

[158] Sharma SD, Sagara K. Latent heat storage materials and systems: a review. Int J Green Energy 2005;2(1):1–56.

[159] Mettawee EBS, Assassa GM. Thermal conductivity enhancement in a latent heat storage system. Sol Energy 2007;81(7):839–45.

[160] Sciacovelli A, Guelpa E, Verda V. Second law optimization of a PCM based latent heat thermal energy storage system with tree shaped fins. Int J Thermodyn 2014;17(3):145–54.

[161] Techno-economic assessment of active latent heat thermal energy storage systems with low-temperature district heating.

[162] Colella F, Sciacovelli A, Verda V. Numerical analysis of a medium scale latent energy storage unit for district heating systems. Energy 2012;45(1):397–406.

[163] HauerThermal A. Energy storage with zeolite for heating and cooling applications 2nd Int heat powered cycles conf - cool heat power gener syst. 2001. p. 343–8. Paris.

[164] Hauer A. Adsorption systems for TES—design and demonstration projects. In: Therm energy storage sustain energy consum. IOS Press, Springer, NATO; 2007. p. 409–27. https://doi.org/10.1016/0378-7788(89)90020-0.

[165] Taube M. A duplex chemical system for the storage and container transport of heat for district heating. Nucl Technol 1978;38(1):62–8.

[166] Basciotti D, Pol O. February). A theoretical study of the impact of using small scale thermo chemical storage units in district heating networks. In: Proceedings of the international sustainable energy conference 2011; 2011. Belfast, Ireland.

[167] http://www.bwbr.com/portfolio/district-energy-water-storage-tank-chiller/.

[168] https://energyandsustainability.fs.cornell.edu/util/cooling/production/thermal.cfm.

[169] https://news.unl.edu/newsrooms/today/article/tank-projects-help-cut-campus-energy-costs/.

[170] Raab S, Mangold D, Heidemann W, Müller-Steinhagen H. Solar assisted district heating system with seasonal hot water heat store in Friedrichshafen (Germany). In: The 5th ISES Europe solar conference; 2004. Freiburg, Germany (20–23 June).

[171] Gadd H, Werner S. 18 - thermal energy storage systems for district heating and cooling. In: Cabeza Luisa F, editor. Advances in thermal energy storage systems. Woodhead Publishing; 2015, ISBN 9781782420880. p. 467–78. 2015, https://doi.org/10.1533/9781782420965.4.467.

[172] Schmidt T, Mangold D, Müller-Steinhagen H. Central solar heating plants with seasonal storage in Germany. Sol Energy 2004;76(1–3):165–74.

[173] Wong B, Snijders A, McClung L. Recent inter-seasonal underground thermal energy storage applications in Canada. In: EIC climate change technology. IEEE; 2006. 2006.

[174] Aneke M, Wang M. Energy storage technologies and real life applications – a state of the art review. Appl Energy 2016;179:350–77. https://doi.org/10.1016/j.apenergy.2016.06.097.

[175] IRENA. Electricity storage and renewables: costs and markets to 2030. Abu Dhabi: International Renewable Energy Agency; 2017, ISBN 978-92-9260-038-9.

[176] Gallo AB, Simões-Moreira JR, Costa HKM, Santos MM, Moutinho dos Santos E. Energy storage in the energy transition context: a technology review. Renew Sustain Energy Rev 2016;65:800–22. https://doi.org/10.1016/j.rser.2016.07.028.

[177] Peters R. Battery storage is growing up on the grid. 3 Nat Gas Electr 2018;34(8):1–8 [Online]. Available: doi:wiley.com/10.1002/gas.22039.

[178] https://corporate.enel.it/en/stories/a/2017/05/V2G-the-car-of-the-future-is-a-battery.

[179] Kouchachvili L, Yaïci W, Entchev E. Hybrid battery/supercapacitor energy storage system for the electric Vehicles. J Power Sources 2018;374:237–48.

[180] Li J, Xiong R, Yang Q, Liang F, Zhang M, Yuan W. Design/test of a hybrid energy storage system for primary frequency control using a dynamic droop method in an isolated microgrid power system. Appl Energy 2017;201:257–69.

[181] Wojcik JD, Wang J. Feasibility study of combined cycle gas turbine (CCGT) power plant integration with adiabatic compressed air energy storage (ACAES). Appl Energy 2018;22:477–89.

[182] Peng X, She X, Cong L, Zhang T, Li C, Li Y, Wang L, Tong L, Ding Y. Thermodynamic study on the effect of cold and heat recovery on performance of liquid air energy storage. Appl Energy 2018;221:86–99.

[183] Peng X. Liquid air energy storage: process optimization and performance enhancement. Ph.D. thesis. University of Birmingham; 2018.

[184] Tafone A, Romagnoli A, Li Y, Borri E, Comodi G. Techno-economic analysis of a Liquid Air Energy Storage (LAES) for cooling application in hot climates. Energy Procedia 2017;105:4450–7.

[185] Nakhamkin M, Chiruvolu M, Daniel C. Available compressed air energy storage (CAES) plant concepts. Energy 2010;4100(0):81.

[186] https://www.ewe-gasspeicher.de/en/home/b4p.

[187] http://www.energystorageexchange.org/projects.

[188] IRENA. Electricity storage and renewables: costs and markets to 2030. Abu Dhabi: International Renewable Energy Agency; 2017. p. 30.

[189] De Jong C. Gas storage valuation and optimization. J Nat Gas Sci Eng 2015;24:365–78.

[190] https://www.eia.gov/todayinenergy/detail.php?id=7930.

[191] http://www.energymarketers.com/Documents/report-oct21conf.pdf.

[192] Pospíšil J, Charvát P, Arsenyeva O, Klimeš L, Špiláček M, Klemeš JJ. Energy demand of liquefaction and regasification of natural gas and the potential of LNG for operative thermal energy storage. Renew Sustain Energy Rev 2019;99:1–15.

[193] Veluswamy HP, Kumar A, Seo Y, Lee JD, Linga P. A review of solidified natural gas (SNG) technology for gas storage via clathrate hydrates. Appl Energy 2018;216(C):262–85.

[194] Lund H, Alberg Østergaard P, Connolly D, Ridjan I, Vad Mathiesen B, Hvelplund F. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016;11:3–14.

[195] Rong A, Lahdelma R. Role of polygeneration in sustainable energy system development challenges and opportunities from optimization viewpoints. Renew Sustain Energy Rev 2016;53:363–72.

[196] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B,, Hvelplund FK. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54.

[197] Ostergaard PA. Comparing electricity, heat and biogas storages' impacts on renewable energy integration. Energy 2012;37:255–62.

[198] Macnaghten J. Utility scale pumped heat electricity storage. Fareham: Isentropic Ltd; 2009.

[199] O'Connell N, Pinson P, Madsen H, O'Malley M. Benefits and challenges of electrical demand response: a critical review. Renew Sustain Energy Rev 2014;39:686–99. https://doi.org/10.1016/j.rser.2014.07.098.

[200] Guelpa E, Deputato S, Verda V. Thermal request optimization in district heating networks using a clustering approach. Appl Energy 2018;228:608–17.

[201] Guelpa E, Barbero G, Sciacovelli A, Verda V. Peak-shaving in district heating systems through optimal management of the thermal request of buildings. Energy 2017;137:706–14.

[202] Verda V, Capone M, Guelpa E. Optimal operation of district heating networks through demand response. Int J Thermodyn 2019;22(1):35.

[203] Sipila K, Karkkainen S. Demand side management in district heating systems. Euroheat Power/Fernwarme Int 2000;29(3):36–45.

[204] Guelpa E, Marincioni L, Capone M, Deputato S, Verda V. Thermal load prediction in district heating systems. Energy 2019;176(1):693–703.

[205] Clegg S, Mancarella P. Integrated electricity-heat-gas modelling and assessment, with applications to the Great Britain system. Part I: high-resolution spatial and temporal heat demand modelling. Energy 2018.

[206] Guelpa E, Marincioni L, Verda V. Towards 4th generation district heating: prediction of building thermal load for optimal management. Energy 2019;171(15):510–22.

[207] Yildiz B, Bilbao JI, Sproul AB. A review and analysis of regression and machine learning models on commercial building electricity load forecasting. Renew Sustain Energy Rev 2017;73:1104–22.

[208] Lawrence TM, Boudreau MC, Helsen L, Henze G, Mohammadpour J, Noonan D, Patteeuw D, Pless S, Watson RT. Ten questions concerning integrating smart buildings into the smart grid. Build Environ 2016;108:273–83. https://doi.org/10.1016/j.buildenv.2016.08.022. 2016.

[209] http://www.irena.org/publications/2015/Jun/Renewable-Energy-Capacity-

Statistics-2015.
[210] Mwasilu F, Justo JJ, Kim EK, Do TD, Jung JW. Electric vehicles and smart grid interaction: a review on vehicle to grid and renewable energy sources integration. Renew Sustain Energy Rev 2014;34:501–16.
[211] Lund H. Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply. Renew Energy 2006;31(4):503–15.
[212] Battke B, Schmidt TS, Grosspietsch D, Hoffmann VH. A review and probalistic model of lifecycle costs of stationary batteries in multiple applications. Renew Sustain Energy Rev 2013;25:240–50.
[213] Reddy KS, Kumar M, Mallick TK, Sharon H, Lokeswaran S. A review of Integration, Control, Communication and Metering (ICCM) of renewable energy based smart grid. Renew Sustain Energy Rev 2014;38:180–92.
[214] Olsthoorn D, Haghighat F, Mirzaei PA. Integration of storage and renewable energy into district heating systems: a review of modelling and optimization. Sol Energy 2016;136:49–64.
[215] Gustafsson J, Delsing J, van Deventer J. Improved district heating substation efficiency with a new control strategy. Appl Energy 2010;87(6):1996–2004.
[216] Pina EA, Lozano MA, Serra LM. Optimal design of polygeneration systems supported with renewable energy sources and energy storage for a Brazilian hospital. Proc. ECOS 2018. Guimaraes, Portugal: 2018.
[217] Pina EA, Lozano MA, Serra LM. Opportunities for the integration of solar thermal heat, photovoltaics and biomass in a Brazilian hospital. Proc. EuroSun 2018. Rapperswil, Switzerland: 2018.
[218] Kreith F, Krudmdieck S. Principle of sustainable energy systems. Boca Raton: CRC Press, Taylor & Francis Group; 2014. p. 28–71. 200.
[219] Lian H, Y. Li, G. Shu, C. Gu. An overview of domestic technologies for waste heat utilization Energy Conserv Technol 2011;29(2):123–8. 133.
[220] Connolly D, Lund H, Mathiesen BV, Werner S, Möller B, Persson U,, Nielsen S. Heat Roadmap Europe: combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89.
[221] Fang H, Xia J, Zhu K, Su Y, Jiang Y. Industrial waste heat utilization for low temperature district heating. Energy Policy 2013;62:236–46.
[222] Persson U, Münster M. Current and future prospects for heat recovery from waste in European district heating systems: a literature and data review. Energy 2016;110:116–28.
[223] Fang H, Xia J, Jiang Y. Key issues and solutions in a district heating system using low-grade industrial waste heat. Energy 2015;86:589–602.
[224] Fang H, Xia J, Jiang Y. Key issues and solutions in a district heating system using low-grade industrial waste heat. Energy 2015;86:589–602.
[225] Johnson I, Choate B, S.. Dillich Waste heat recovery: opportunities and challenges TMS annual meeting. 2008. p. 47–52.
[226] Sogut Z, Oktay Z, Karakoc H. Mathematical modeling of heat recovery from a rotary kiln. Appl Therm Eng 2010;30(8–9):817–25.
[227] Konigs K, Eisenbauer G, Eisenburger H. The use of industrial surplus heat in the district heat supply at. Duisburg – Rheinhausen FernwaermeInternational 1982;11(2):60–4.
[228] Belaz C. From concept to implementation of a district heating system using waste heat from an industrial plant. Bull de l'Association Suisse des Electr (Organe Commun de l'Association Suissedes Electr (ASE) de l'Union des Centrales Suisses d'Electricite (UCS) 1986;77(10):587–90.
[229] Dou Y, Togawa T, Dong L, Fujii M, Ohnishi S, Tanikawa H, Fujita T. Innovative planning and evaluation system for district heating using waste heat considering spatial configuration: a case in Fukushima, Japan. Resour Conserv Recycl 2018;128:406–16.
[230] Rocco MV, Di Lucchio A, Colombo E. Exergy life cycle assessment of electricity production from waste-to-energy technology: a hybrid input-output approach. Appl Energy 2017;194:832–44.
[231] Nordi GH, Palacios-Bereche R, Gallego AG, Nebra SA. Electricity production from municipal solid waste in Brazil. Waste Manag Res 2017;35(7):709–20.
[232] Zou S, Kanimba E, Diller TE, Tian Z, He Z. Modeling assisted evaluation of direct electricity generation from waste heat of wastewater via a thermoelectric generator. Sci Total Environ 2018;635:1215–24.
[233] Arshad M, Bano I, Khan N, Shahzad MI, Younus M, Abbas M, Iqbal M. Electricity generation from biogas of poultry waste: an assessment of potential and feasibility in Pakistan. Renew Sustain Energy Rev 2018;81:1241–6.
[234] Zakaria IH, Ibrahim JA, Othman AA. Development of oil palm fiber waste inventory system for optimal electricity grid supply: biomass briquette. Int J Supply Chain Manag 2018;7(2):228–36.
[235] Torio H, Schmidt D. Development of system concepts for improving the performance of a waste heat district heating network with exergy analysis. Energy Build 2010;42(10):1601–9.
[236] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P,, Bojesen C. The status of 4th generation district heating: research and results. Energy 2018.
[237] Bischi A, Taccari L, Martelli E, Amaldi E, Manzolini G, Silva P, Campanari S, Macchi E. A detailed MILP optimization model for combined cooling, heat and power system operation planning. Energy 2014;74:12–26. https://doi.org/10.1016/j.energy.2014.02.042.
[238] Gonzalez-Castellanos A., Guha Thakurta P., Bischi A., Flexible unit commitment of a network-constrained combined heat and power system, arXiv: 1809.09508.
[239] Bischi A., Taccari L., Martelli E., Amaldi E., Manzolini G., Silva P., Campanari S., Macchi E., A rolling-horizon optimization algorithm for the long term operational scheduling of cogeneration systems, Energy, Available online 6 December 2017, In Press, current Special Issue: doi:10.1016/j.energy.2017.12.022.
[240] Gabrielli P, Gazzani M, Martelli E, Mazzotti M. Optimal design of multi-energy systems with seasonal storage. Appl Energy 2018;219:408–24. https://doi.org/10.1016/j.apenergy.2017.07.142.
[241] Sahraoui Y., Bendotti P., D'Ambrosio C., Real-world hydro-power unit-commitment: dealing with numerical errors and feasibility issues, Energy, Available online 15 November 2017, In Press, current Special Issue: doi: 10.1016/j.energy.2017.11.064.
[242] Martelli E, Amaldi E. PGS-COM: a hybrid method for constrained non-smooth black-box optimization problems: brief review, novel algorithm and comparative evaluation. Comput Chem Eng 2014;63:108–39. https://doi.org/10.1016/j.compchemeng.2013.12.014.
[243] Elsido C, Bischi A, Silva P, Martelli E. Two-stage MINLP algorithm for the optimal synthesis and design of networks of CHP units. Energy 2017;121: 403–26. https://doi.org/10.1016/j.energy.2017.01.014.
[244] Yokoyama R, Shinano Y, Taniguchi S, Wakui T. Search for K-best solutions in optimal design of energy supply systems by an extended MILP hierarchical branch and bound method. Energy 2019. https://doi.org/10.1016/j.energy.2018.02.077. In Press, Corrected Proof.
[245] van Ackooij W, Danti Lopez I, Frangioni A, Lacalandra F, Tahanan M. Large-scale unit commitment under uncertainty: an updated literature survey. Ann Oper Res 2018:1–75. https://doi.org/10.1007/s10479-018-3003-.
[246] Lund H, Arler F, Østergaard PA, Hvelplund F, Connolly D, Mathiesen BV, Karnøe P. Simulation versus optimisation: theoretical positions in energy system modelling. Energies 2017;10(7):840.
[247] Lund H, Sorknæs P, Mathiesen BV, Hansen K. Beyond sensitivity analysis: a methodology to handle fuel and electricity prices when designing energy scenarios. Energy Research & Social Science 2018;39:108–16.
[248] Lund H, Mathiesen BV, Connolly D, Østergaard PA. Renewable energy systems - a smart energy systems approach to the choice and modelling of 100 % renewable solutions. Chemical Engineering Transactions 2014;39.
[249] Bullich-Massagué E, Díaz-González F, Aragüés-Peñalba M, Girbau-Llistuella F, Olivella-Rosell P, Sumper A. Microgrid clustering architectures. Appl Energy 2018;212:340–61. https://doi.org/10.1016/j.apenergy.2017.12.048.
[250] Im Y-H, Liu J. Feasibility study on the low temperature district heating and cooling system with bi-lateral heat trades model. Energy 2018;153:988e999. https://doi.org/10.1016/j.energy.2018.04.094.
[251] Tereshchenko T, Nord N. Future trends in district heating development. Current Sustainable/Renewable Energy Reports 2018;5(2):172–80. https://doi.org/10.1007/s4051.
[252] Entso G. website, last page access 09/11/2018, https://www.entsog.eu/public/uploads/files/maps/transmissioncapacity/2015/ENTSOG_CAP_MAY2015_A0FORMAT.pdf.
[253] The effects of system extension on inter-area oscillations, UCTE Annual Report. 2002. https://www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/report_2002_6.pdf.
[254] Andersson G, Donalek P, Farmer R, Hatziargyriou N, Kamwa I, Kundur P, Martins N, Paserba J, Pourbeik P, Sanchez-Gasca J, Schulz R, Stankovic A, Taylor C, Vittal V. Causes of the 2003 major grid blackouts in north America and Europe, and recommended means to improve system dynamic performance. IEEE Trans Power Syst 2005;20(4):1922–8.
[255] Purvins A, Sereno L, Ardelean M, Covrig C-F, Efthimiadis T, Minnebo P. Submarine power cable between Europe and North America: a techno-economic analysis. J Clean Prod 2018;186:131–45.
[256] Novitsky NN, Alekseev AV, Grebneva OA, Lutsenko AV, Tokarev VV, Shalaginova ZI. Multilevel modeling and optimization of large-scale pipeline systems operation. Energy 2019. https://doi.org/10.1016/j.energy.2018.02.070. In Press, Corrected Proof.
[257] Good N, Martínez Ceseña EA, Heltorpa C, Mancarella P. A transactive energy modelling and assessment framework for demand response business cases in smart distributed multi-energy systems. Energy 2019. https://doi.org/10.1016/j.energy.2018.02.089. In Press, Corrected Proof.
[258] Dokic SB, Rajakovic NL. Security modelling of integrated gas and electrical power systems by analyzing critical situations and potentials for performance optimization. Energy 2019. https://doi.org/10.1016/j.energy.2018.04.165. In Press, Corrected Proof.