Multi-energy systems: An overview of concepts and evaluation models

Pierluigi Mancarella
The University of Manchester, School of Electrical and Electronic Engineering,
Ferranti Building, M13 9PL, Manchester, UK
tel +44 (0)1613064654, fax +44 (0)1613064820
p.mancarella@manchester.ac.uk

Abstract
Multi-energy systems (MES) whereby electricity, heat, cooling, fuels, transport, and so on optimally interact with each other at various levels (for instance, within a district, city or region) represent an important opportunity to increase technical, economic and environmental performance relative to "classical" energy systems whose sectors are treated "separately" or "independently". This performance improvement can take place at both the operational and the planning stage. While such systems and in particular systems with distributed generation of multiple energy vectors (distributed multi-generation - DMG) can be a key option to decarbonise the energy sector, the approaches needed to model and relevant tools to analyze them are often of great complexity. Likewise, it is not straightforward to identify performance metrics that are capable to properly capture costs and benefits that are relating to various types of MES according to different criteria. The aim of this invited paper is thus to provide the reader with a comprehensive and critical overview of the latest models and assessment techniques that are currently available to analyse MES and in particular DMG systems, including for instance concepts such as energy hubs, microgrids, and virtual power plants, as well as various approaches and criteria for energy, environmental, and techno-economic assessment.

Keywords: cogeneration, distributed multi-generation, integrated energy systems, virtual power plant, microgrid, smart grid, smart cities, trigeneration, polygeneration, energy hub

List of Acronyms

CCHP	Combined Cooling Heat and Power
CHP	Combined Heat and Power
CO2ER	CO_2 Emission Reduction
DMG	Distribute Multi-Generation
EHP	Electric Heat Pump
EV	Electric Vehicles
FESR	Fuel Energy Saving Ratio
GHG	Greenhouse Gas
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
MES	Multi-Energy System(s)
MILP	Mixed Integer Linear Programming
NPV	Net Present Value
PES	Primary Energy Saving
PPES	Polygeneration Primary Energy Saving
RES	Renewable Energy Sources
TCO2ER	Trigeneration CO_2 Emission Reduction
TPES	Trigeneration Primary Energy Saving
VPP	Virtual Power Plant

1. Introduction

There are significant efforts worldwide at multiple levels, from research to policy initiatives, to support the integration of renewable electricity resources into the power system and particularly by deploying innovative concepts such as the Smart Grid. However, meeting challenging environmental targets and guaranteeing secure and affordable energy to present and future generations require clear strategies addressing all energy sectors, and not only electricity [1]. These refer in particular to heating and cooling as well as transport, which (i) represent major contributions to energy consumption, greenhouse gas emissions and local pollution; (ii) rely massively on fossil primary energy in most countries; and (iii) are arguably harder to decarbonise than electricity.

Traditionally, energy sectors have been de-coupled from both operational and planning viewpoints, whereas tight interactions have always taken place and are increasing. For instance, electricity, heat/cooling and gas networks interact in many cases through various distributed technologies such as combined heat and power (CHP), electric heat pumps (EHPs), air conditioning devices, trigeneration of electricity heat and cooling, and so on [2][3]. Similarly, interactions between electricity, the fuel chain, and the transport sector are more and more envisaged or already taking place by means of electric vehicles (EV) and bio-fuels and hydrogen based transport [4]. In this outlook, a key aspect to evolve towards a cleaner and affordable energy system is to better understand and develop *integrated* or *multi-energy systems (MES)*, whereby electricity, heat, cooling, fuels, transport, and so on *optimally* interact with each other at various levels (for instance, within a district, or a city, or at a country level). Electrification of heating and transport and the need to support it through Smart Grid options [5] and in case development of suitable distributed energy markets [6] are a tangible example of the need for developing a MES framework.

Multi-energy systems can feature better technical, economic and environmental performance relative to "classical" independent or *separate* energy systems and at both the operational and the planning stage, and this is now being recognized by a wealth of research being performed on related topics. However, most research focuses on specific points, and there is lack of a comprehensive view on MES as such. Therefore, the aim of this paper is to bring together some the most recent works carried out on MES and to provide a holistic overview of the issues that are associated with them, with focus on the increasingly important case of distributed multi-generation (DMG) of different energy vectors. In particular, specific objectives of this work refer to critically discussing concepts, approaches, and analysis tools that have been proposed to deal with multi-energy systems, as well as evaluation methodologies and performance metrics that are capable to properly capture costs and benefits (from an energy, environmental, and techno-economic perspective) that are relating to various types of MES.

The paper is organized as follows. Section 2 gives an introduction to multi-energy systems, outlining various analysis perspectives and general research directions. Section 3 critically analyzes modelling approaches that have been adopted to model MES, including aggregation concepts that are becoming increasingly important given the distributed nature of most MES, and describes some well known tools that are available for MES operational and planning simulation and optimization. Section 4 illustrates and discusses the major appraisal methodologies and performance assessment criteria that have been presented in the literature, taking the energy, environmental and techno-economic viewpoints as the *leitmotif* for the analysis. Section 5 contains the concluding remarks.

2. What is a multi-energy system

2.1. General aspects

Arguably, all energy systems are truly “multi-energy” from a physical perspective, in the sense that multiple energy vectors and sectors interact at different levels, from demand to generation, in case facilitated by networks. Hence, for the purposes of this work the concept of “multi-energy” rather refers to considering a whole-system approach to optimization and evaluation of the specific case under study (for instance, a building or a country). In particular, the analysis approach refers to explicitly expanding the system boundary beyond one specific sector of interest (for instance, beyond electricity only or beyond heat only, as typical study cases). Doing so allows bringing a new perspective in energy system analysis, particularly in the light of reducing the environmental burden of energy services subject to economic constraints as well as comfort level constraints. In fact, amongst the other benefits MES can play a key role to:

- Increase the conversion efficiency and utilization of primary energy sources, for instance, through DMG;
- Foster the optimal deployment of both centralized and decentralized resources at a system level through optimal market interaction, for instance by allowing small-scale heat-buffered CHP systems to respond to volatile electricity market prices in a wind-rich energy system;
- Increase the energy system flexibility, for instance by allowing thermal loads supplied by electricity (such as for EHPs), which intrinsically feature storage characteristics (*e.g.*, through the thermal inertia embedded in the building fabric), to participate in power system balancing by providing frequency response and reserve; or by exploiting flexible storage systems available in EV to support wind integration while providing clean fuel for transportation.

Following these lines, the Smart Grid conceptualization can be extended beyond electricity only [7], and indeed inclusion of other energy vectors and services within this framework is gaining interest in the form of the concepts of Smart Communities and Smart Cities, as discussed below. More specifically, four streams of categorization will be followed to highlight the manifold perspectives and complexity that typically characterize MES, namely:

- The *spatial* perspective, whereby it is pointed out how MES can be intended at different levels of aggregation in terms of components or even just conceptually. These aggregation levels may go from buildings (where for instance various types of equipment producing different energy vectors interact with each other) to districts (including the crucially important cases of district energy systems) and finally to regions and even countries.
- The *multi-service* perspective, whereby the focus is on the provision of multiple services or “outputs” (from various types of energy services to the transportation sector) by optimal integration of energy vectors particularly at the supply level. The case of combined production of multiple energy carriers is a particularly relevant case.
- The *multi-fuel* perspective, whereby it is highlighted how different types of fuels, ranging from “classical” natural gas to biomasses and Renewable Energy Sources (RES) for both electrical and thermal energy, can be integrated together for optimal supply (typically for both economic and environmental purposes) of the multi-service demand in a MES.
- The *network* perspective, whereby the critical role of energy networks (for electricity, gas, district heating and cooling, hydrogen, and so on) is discussed, particularly in terms of facilitating the development of multi-energy technologies and their interaction to minimize system cost and maximize environmental performance.

Obviously, such categorization is just a conventional one with the aim to facilitate the overview of various types of MES, as it is not easy to schematize the multiple features of a MES. In fact, as it will emerge from the discussion, there may be significant overlapping among the different categories, which further points out the complexity as well as importance of the topic under discussion.

2.2. The spatial perspective: from buildings to regions

From a spatial perspective, the concept of MES can be seen at various levels which can ideally go from individual dwellings to regions or countries. This is exemplified in Figure 1, showing how multiple energy vectors can be relevant to buildings, districts, and so on. For instance, at the building level natural gas and electricity can be the input to different pieces of equipment such as boilers, EHP, chillers, micro-CHP, and so on, for production of electricity, heat and cooling, and such equipment can be optimally coordinated for various purposes. Buildings can then also interact at the district level, for instance in typical district energy systems where networks are used to interface local generation such as from CHP or EHP and distribute energy vectors such as heat in DH. Districts can be aggregated and optimised as a next step to city and then region levels, at which point other energy vectors and services too may "enter the game", such as for instance for delivery of transport sectors. In any case, apart from the complexity and the systematic analysis of the possible options (which is outside the scope of this work), the key point is that a MES can be seen and therefore modelled at various geographical levels depending on the purpose of the study, as discussed in the sequel. In particular, while many techniques may be applied to all levels (for instance, optimization approaches based on economic assessment only), others require specific consideration for the geographical perspective (for instance, to take into account the presence of network constraints). More insights on aggregation concepts are provided in Section 3.1.

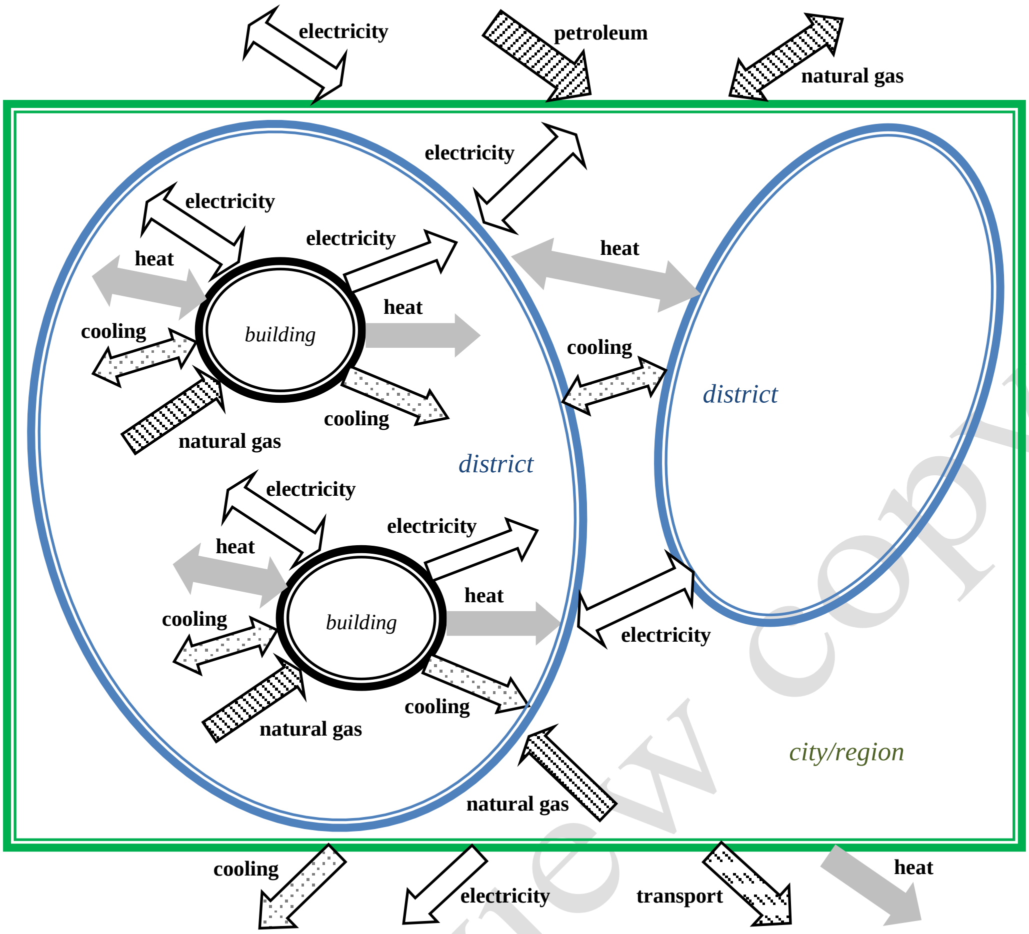

Figure 1. Schematic illustration of the spatial perspective concept.

An example of the smaller "block" in a MES, namely, a *building-level* MES, is for instance reported in [8], where an energy hub model [9] approach (see also Section 3.1.2) is proposed to describe the coupling of supply and demand in a synthetic way for design purposes aimed at minimising amongst others investment or life cycle costs.

Scaling it up from the individual building to the next spatial aggregation stage, various works have been proposed to deal with operational and planning analysis of *district-level* and *city-level* MES. In fact, multi-energy applications are particularly relevant in urban areas owing to availability and high density (which is typically one of the main drivers for cost effectiveness) of different energy loads (in case aggregated through district energy networks) as well as to the presence of developed network infrastructure for energy "inputs", particularly gas and electricity. In this respect, pioneering work on comprehensive assessment of electricity and heat supply options was carried out by Horlock in his milestone book on cogeneration [10]; in particular, various CHP supply options and district heating (DH) scheme are analysed from both energy/exergy and economic viewpoints, with introduction of specific performance indicators (still widely used today) to assess different alternatives. In another relatively early work on MES district analysis [11], the "deco" model was used as a tool for investment decision to explore potential competition and synergies of different technologies to supply heat and electricity demand in a municipality, while increasing energy efficiency and integrating RES also taking into account energy taxes and various parameters. Similar but recent studies are performed in [12], where a district energy system for an "eco-town" is optimally designed by selecting the best mix of technologies that provide the MES end-services that are required, while decreasing CO_2 emissions (up to 20% if maintaining the same level of costs as for business-as-usual) and guaranteeing resilience of supply. The optimization is performed through the specifically developed "DESDOP" tool based on mixed integer linear programming (MILP). Optimization for MES for model cities taking into account a mix of CHP systems of different sizes and electricity, gas and heat networks is also performed in the same research group in [13], with the aim of identifying the tradeoffs between limitations on CHP size and overall MES performance in urban areas and the consequent energy efficiency and cost penalties incurred because of planning restrictions. Another recent work making use of MILP models to optimize the operation and design of distributed cogeneration plants (taking into account both economic and environmental performance) connected through a heat network in a mixed residential/tertiary urban area is also reported in [14]. In a similar outlook, the paper [15] analyzes three MES alternatives in urban areas, with a mix of centralized (at district level) and decentralised (at the customer level) CHP options and with the aim of minimizing CO_2 emissions and cost to the consumers. On another note, while the previous works are focused on DMG optimization, the model proposed in [16] for optimal planning of residential DH systems has focus on heat network operation control strategies; the results indicate that larger pressure drop allowance, larger supply/return temperature difference, and variable supply temperatures and mass flow rates lead to lowering total costs. With explicit incorporation of RES in the analysis, the work [17] explores the combination of multi-energy networks with RES to improve the sustainability of urban areas, deploying in particular the potential synergies between wind and DH in heat-dominated and between PV and trigeneration in cooling-dominated urban demand scenarios. Relevant to and including MES applications, comprehensive reviews of urban energy system models can be found in [18][19].

Moving one spatial step up from the city to the *regional level*, reference [20] develops a bottom-up MES linear programming model for planning purposes in the presence of renewable and environmental constraints, including optimal utilization of biomasses, waste, and by-products as well as integration with CHP industrial facilities and combined cycle power plants. An example of integration of energy resources at the regional level is also provided in [21], where a heat market based on DH networks is created which allows system level economic and environmental benefits to be properly allocated to the different actors. A comprehensive model of regional MES with multi-generation facilities and also including transport is discussed in [22], where ethanol is produced in Swedish regions for transportation purposes together with biogas, electricity, and heat from cereal straws; as a key result of the study, integration of transport-aimed ethanol production in CHP facilities could lead to a decrease in transportation costs by some 30%.

2.3. The multi-service perspective: from distributed multi-generation to transport

Different energy vectors can be integrated together for provision of multiple services in the MES framework, ranging from "classical" electricity and heat to hydrogen as well as transport. This concept is schematically illustrated in Figure 2, where the focus is on the multiple outputs or integrated services that a MES can provide. In particular, the possibility of integrating the production of multiple services opens the way to improving system performance from techno-economic, energy and environmental perspectives, for instance owing to the possibility of recovering otherwise wasted heat from CHP to supply local thermal demand or cooling demand (through absorption chillers in the latter case).

In this context, in fact, significantly important and widespread cases of MES are the ones based on *multi-* or *poly-generation*, which can be defined as the combined production of multiple energy vectors (e.g., electricity, heat, and cooling), from a unique source of fuel. In particular, *distributed multi-generation* refers to the concept of multi-generation units of relatively small scale (indicatively under 50 MWe) interacting with each other and with the "external world" through different forms of energy networks (see also Section 2.5), such as electricity, heat, gas, hydrogen, and so on [2][3]. As extensively discussed further below and in particular in Section 4, multi-generation has the potential to bring significant economic, energy and environmental benefits relative to the "conventional" *separate production* of the same energy vectors.

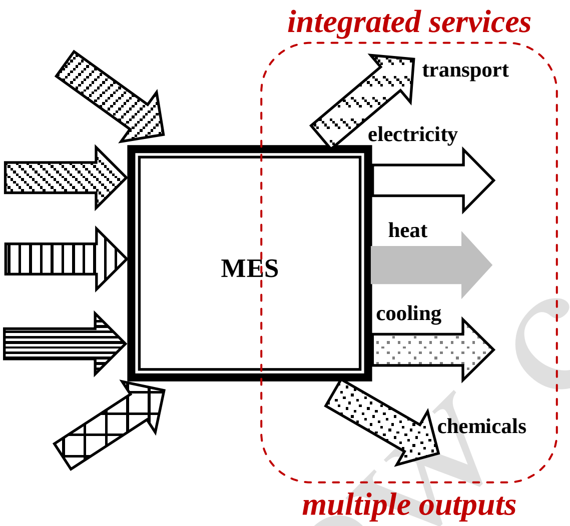

Figure 2. Schematic illustration of the multi-service perspective concept.

The simplest form of multi-generation plant is *cogeneration* or CHP, which is comprehensively analysed from an economic and energy/exergy perspective in [10], as already mentioned.

The "natural" extension of cogeneration is *trigeneration* or Combined Cooling Heat and Power (CCHP), for which comprehensive energy and environmental assessment is discussed in [3]. A review of typical trigeneration applications is reported in [23], while reference [24] focuses on micro-applications. In particular, in the "classical" trigeneration case, absorption chillers are coupled to a CHP plant to produce cooling, so making up for potential lack of thermal demand in the summertime when cooling might be required instead (seasonal trigeneration). Year-round trigeneration applications are also widespread in supermarkets, hotels, offices, and so on. A generalization of the concept of trigeneration beyond absorption chillers in a MES context is put forward in [3], where various solutions to deliver electricity, heat and cooling (including reversible heat pumps, gas-fired absorption chillers, engine driven chillers, and so on) are analysed in detail. In this respect, an example of trigeneration scheme with CHP and engine-driven compression chillers is reported in Figure 3, while a more complex schemes entailing both absorption chiller and reversible EHP and illustrating both local load supply and external network interactions is shown in Figure 4.

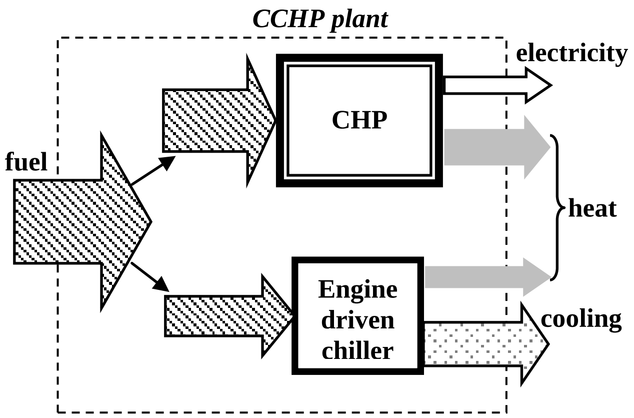

Figure 3. Example of DMG system for trigeneration of electricity, heat and cooling.

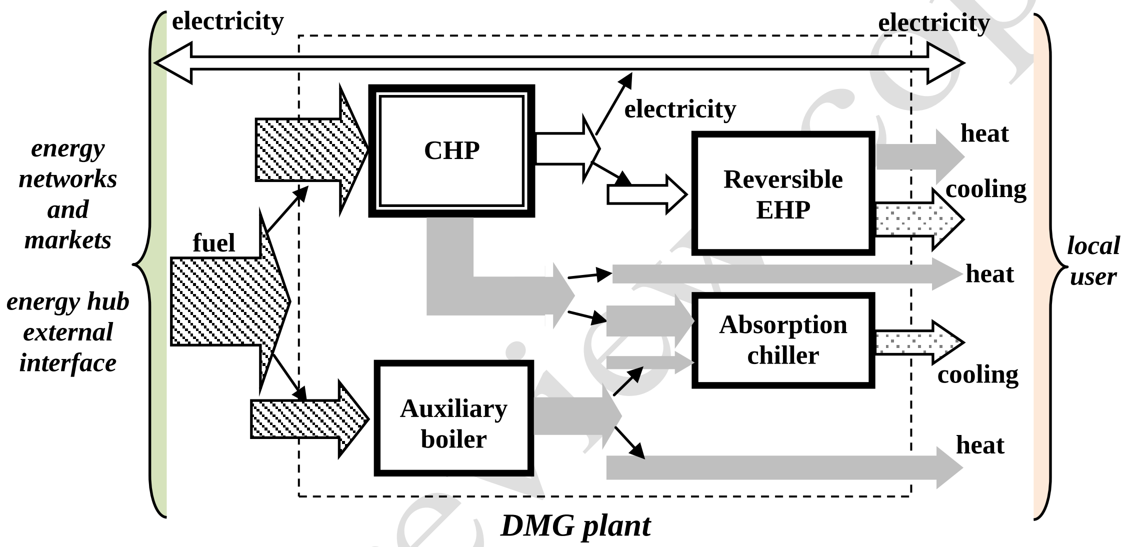

Figure 4. Example of DMG system for trigeneration of electricity, heat and cooling and local and network interactions.

The further extension to the most general *polygeneration* case (including for instance hydrogen, chemicals, water, and so on) and relevant network interactions is extensively discussed in [2][3]. The overall benefits of increasing the utilization of natural resources and decreasing the environmental impact through process integration and DMG are further stressed in [25], with specific examples of polygeneration of sugar and energy in a sugar cane factory, gas-based DMG with district heating and cooling, and polygeneration of water and energy. Several schemes and technological options for combined production of electricity, heat/steam, cooling and water are presented in [26], with focus on the agro-food industry. Another example of flexible polygeneration of electricity, heat, and water, with process integration of the cogenerated heat and electricity with water production (from seawater desalination) through multi-stage flash/reverse osmosis is illustrated in [27]. Multi-generation and process integration is discussed in [28] too with regard to bioethanol production from biogas. A DMG plant based on a gas-fired fuel cell for combined production of electricity, heat and hydrogen, is presented in [29], with results showing potential competitiveness under certain spark-spread conditions for hydrogen production (owing to multi-generation) relative to alternative options such as natural gas reforming or electrolysis. Recent work on biomass-based multi-generation with production of hydrogen is also reported in [30], where the significant environmental benefits of multi-generation compared to both power-only and CHP cycles are pointed out. The efforts on decarbonising the *transport* sector are becoming increasingly important in recent years, and the need to incorporate transport into a MES thinking and analysis framework has recently been discussed in a number of studies (see for instance [31]). Discussions on transport in a MES context are also relevant to the interaction with hydrogen as an energy vector (with excellent characteristics of transportability, like electricity, and storability, differently from electricity) as well as fuel. In this respect, a comprehensive analysis of the synergies and interactions between electricity and hydrogen at the system level, with critical applications to transport, is available in [4], where a number of options for coproduction and inter-conversion of H_2 and electricity within an overall MES are highlighted. Again at the system level, the increasing interaction between electricity and transport but from a more "power system" perspective is illustrated in [32], with presentation of a conceptual framework for electrification of transport which covers power system technical aspects as well as electricity markets. Focusing on the production of clean fuel for transportation at the regional level, [22] MES case studies for production of electricity and heat as well as ethanol and biogas for transportation from local cereal straws are analysed, with results showing the benefits of integrating ethanol with CHP systems, as already mentioned.

2.4. The multi-fuel perspective: from waste to wind

In a MES context, the interactions with the "external" world and most noticeably the multiple *fuels* that can be used as an input to the system boundary play a key role. In fact, as also further discussed in Section 3.1.2, an effective way to look at a MES is to consider its external interactions through an input-output equivalent model, and the system inputs are particularly important in terms of economic and environmental analysis because represent the interactions with the incumbent "external world". This is schematically illustrated in Figure 5, showing some of the possible energy vector inputs to a MES which eventually could be present at the same time (also depending on the system boundary considered, as from Section 2.2).

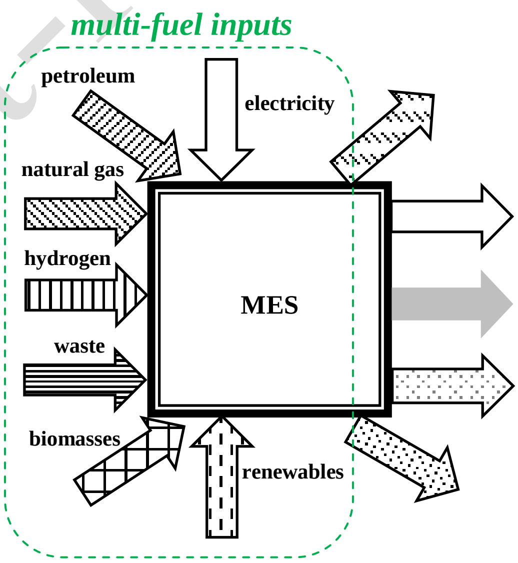

Figure 5. Schematic illustration of the multi-fuel perspective concept.

Besides classical interactions with electricity and gas network and markets, from the multi-fuel perspective of increasing interest for MES is the optimal management of *waste* in a system context. This is well argued for instance in [33], where the energy system analysis model "Balmorel" is used for cost optimization case studies in Germany and Nordic countries which highlight the crucial role played by CHP. For more details on waste-to-energy technologies, the reader can also refer to the comprehensive analysis shown in [34], where different performance techniques are illustrated to provide a like-for-like comparison among technologies.

Also relevant is the increasing use of *biomasses* to power district energy systems. In this respect, in [35] full biomass supply chain models are presented, with a formulation which is consistent with the MES network planning modelling of electricity, heat and gas infrastructure which is carried out through the "eTransport" planning tool (see also Section 3.2).

Of even higher interest in recent years is the interaction between "conventional" fossil fuel-based MES and *renewables*. For instance, a good review of CHP technologies powered by RES can be found in [36], which analyses the technical, economic, and environmental performance of different options to maintain the general structure of current energy systems with widespread use of CHP but by using renewable fuels as opposed to fossil ones. Directly related to this issue is the role of district energy systems and particularly DH [37] with increasing penetration of RES, with arguments that district energy systems will still be able to play a key role in the future, particularly in high density urban areas and with technological shift towards large scale EHPs powered by renewable electricity, centralised thermal renewables, and biofuel-based DMG, in case supported by thermal storage [38][39]. This shift would most probably occur through intermediate steps seeing an overlapping of traditional fossil-based DMG technologies and RES. In this regard, [40] discusses a model for optimal selection and sizing of a polygeneration plant for electricity, heat, cooling, and fresh water production which is fuelled by natural gas, gasified biomass, and solar power. The multi-criteria analysis for economic and environmental performance confirms how under the current framework technologies that are based on natural gas only are most profitable, while increase of RES is needed to enhance the energy and emission savings. From this point of view, a hybrid trigeneration-PV system for small scale applications is also analysed in [41], showing the environmental benefits of coordination between CHP and PV to increase PV penetration and then of coupling absorption chillers for optimal utilization of wasted heat for cooling purposes. A DH multi-fuel application with RES, including CHP and thermal storage coupled in this case to a large centralized thermal solar plant, has recently been discussed in [42], where it is highlighted how the presence of the solar plant allow reaching both environmental and economic optimization goals in a multi-objective problem.

A different perspective of the relationship between energy inputs (and RES in particular) and MES can be seen in terms of demand and supply "*balancing*" provision. In fact, renewable electricity sources such as wind and PV exhibit high geographical and temporal variability, which requires additional flexible resources (at higher costs) for power system integration compared to conventional thermal power plants whose output can be more easily forecasted, scheduled, and controlled [43]. In this outlook, MES thinking can facilitate renewable integration by considering the flexibility available from transforming electricity into thermal [44][45] or transport [46][47][48] energy, or by considering the flexibility that can be provided by CHP plants buffered by thermal storage [49][50][51][52]. Such an approach is consistent with the utilization of RES for district energy systems, and requires aggregation and control concepts such as Microgrids and Virtual Power Plants (VPPs) that will be discussed in Section 3.1.

2.5. The network perspective: from electricity to CO_2

Realization of MES requires interconnections among various multi-energy plant components, multi-energy plants, or smaller multi-energy systems, depending on the boundaries and on the system size under study, as also discussed in Section 2.2. Interconnections take place through *energy networks* that carry different vectors, such as electricity, gas, heat at different enthalpy levels (for instance, steam or hot water), cooling, and so on. Energy networks can thus enable optimal management of multi-energy resource portfolios on the one hand, and introduce further complexity in the system operational and planning analysis on the other hand, for instance relevant to what energy network type is most appropriate in a given MES context.
An illustrative schematic is shown in Figure 6, highlighting the role of energy networks in facilitating possible interactions between MES as well as between MES and external networks, which go to sum up to local inputs that may be for instance based on RES (PV, solar thermal, and so forth) or storable fuels (such as biomasses).

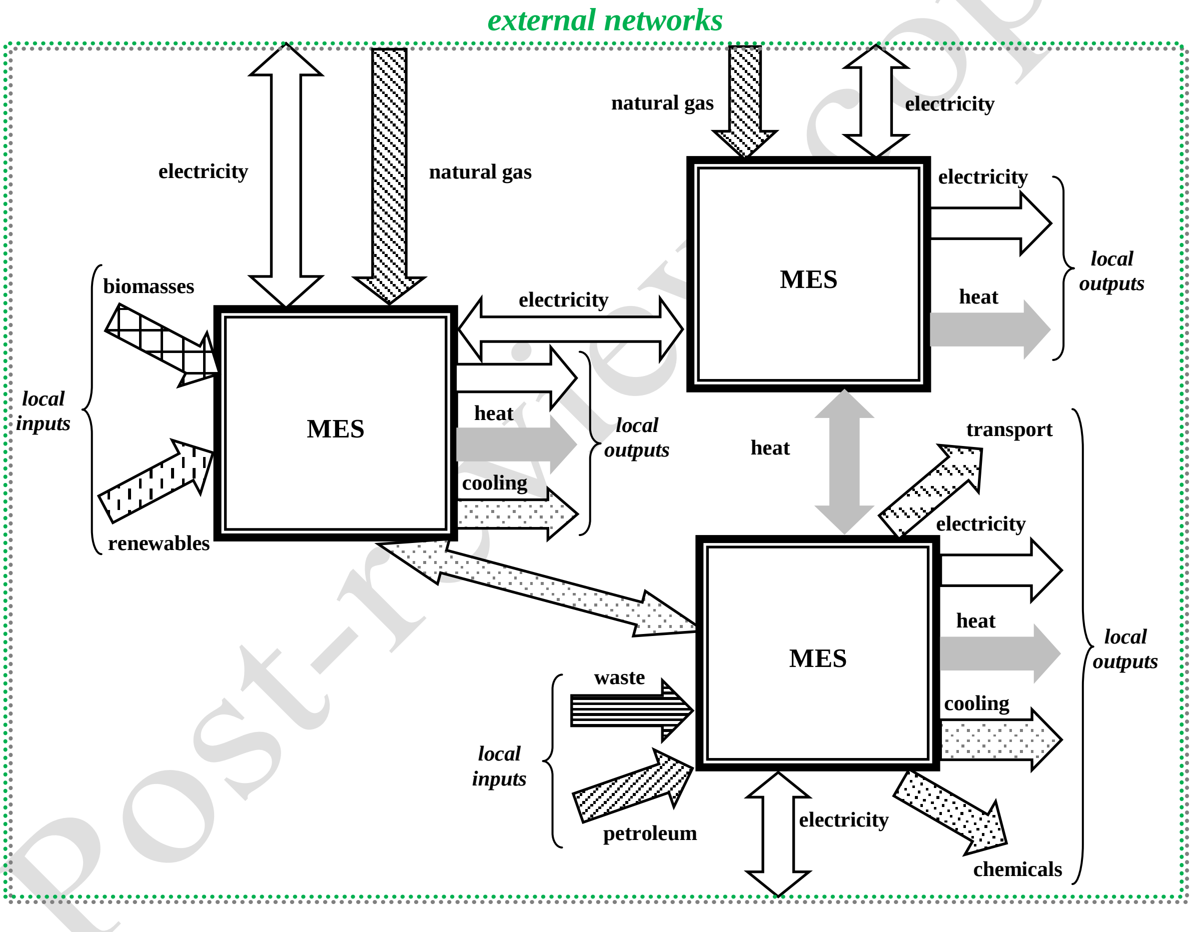

Figure 6. Schematic illustration of the network perspective concept.

Based on the above premises, network studies in the context of enabling optimal MES are performed in [53], where a Geographical Information System in integrated with a MES planning model in order to identify the best multi-energy conversion and distribution network options within urban areas; here the specific objective is to increase the overall energy efficiency performance and the utilization of local RES. In the same light, a systematic planning analysis comparing *natural gas*-based and *DH*-based district energy systems, including detailed techno-economic network aspects, is performed in [54] to identify under which conditions a solution should be preferred to the other. Potential synergies and competition between *electricity and heat* networks are on the other hand discussed by the author in [55], pointing out the main drivers in assessing the techno-economic performance of different networks to inform MES planning. In a similar perspective, the impact on the *electrical low voltage network* from electro-thermal technologies such as EHPs and micro-CHP systems is analysed in [56], where the complementarity between the two technologies to decrease network impact is highlighted. Interesting studies more oriented on the physical aspects of district energy networks are also conducted in [57], where the feasibility of substituting water with CO_2 as the network energy carrier for heat, cold and hot water is analysed, showing exergy and cost benefits for the proposed CO_2 network.

A general theoretical framework (discussed further in Section 3.1.2) for studying MES including multi-carrier energy networks and their specific physical characteristics is proposed in [9] on the basis of the *energy hub* concept. Within the same energy hub modelling context, a comprehensive model for transmission of integrated multiple carriers within a same physical system and corridor (potentially including electricity, gas, heat, cooling, hydrogen, liquid hydrocarbons, compressed air, and so on) is discussed in [58], suggesting that the most promising applications of such a multi-energy interconnector could be relevant to transporting some tens of MW of electric and chemical power over some tens of km (hence, at a medium voltage level in terms of electrical network). A relevant analysis framework is also developed in [59], where integrated planning of a MES is carried out in terms of costs and risks through the mean-variance portfolio theory and is applied to generation and transmission by including the possibility of conversion of multiple energy carriers at different levels of the energy chain.

3. Multi-energy system modelling approaches, aggregation concepts, and tools

3.1. Modelling and aggregation concepts

3.1.1. General aspects

The variety of potential MES types that can be envisaged and the complexity of the relevant issues for their operational and planning optimization call for the use and development of advanced modelling techniques and tools. In particular, there is a simultaneous need for modelling the complexity of the multi-energy interactions taking place "inside" the MES as well as for capturing the main aspects and parameters of the interactions with the "outside" world. In this respect, it is recognised that DMG and multi-energy loads that have been traditionally considered as "passive" by power system operators need to be incorporated into the power system operation in order to deliver a more sustainable energy system at minimum cost. Given the small- and even micro-scale level of many DMG systems (for instance, micro-CHP generators installed in individual houses), a number of general aggregation concepts have been put forward for integration of distributed energy resources into power system operation and planning [60], most noticeably, Microgrids [61] and virtual power plants (VPP) [62][63]. Many of these concepts can be applied in particular to multi-energy systems too, while on the other hand the already mentioned "energy hub" concept [9][64] has been specifically developed to model from a technical perspective generic MES. The importance of such aggregation concepts from an economic perspective is highlighted in [62], pointing out to the need for moving beyond the conventional approach of building up large-scale power plants with regulated rate of return and to the challenge of creating new business models for these innovative distributed systems.

3.1.2. Energy hubs and input-output models

The idea of input-output relationships to provide synthetic information and optimization basis to complex system dates back to the milestone work of Leontief on economics [65].
In a MES context, the *energy hub* framework was introduced in [9][66] for analysing multi-energy conversion from an input-output perspective and for modelling the interactions among hubs through different energy vectors and networks. Further discussions are provided in [67] in terms of energy hub aggregation modelling throughout the whole system chain, from production to consumption, while [68] focuses on the production side and in particular the concept of multi-source multi-products energy systems, including chemicals beyond more "traditional" energy vectors such as gas, electricity, and heat. An example of energy hub with inclusion of hydrogen networks is provided in [69], while in [70] it is shown how EV can also be included in the general energy hub framework and how synergies between CHP, controllable loads, and electric transport can be optimally deployed to provide power system services in a MES context. Related to the issues discussed in Section 2.2, while most papers on energy hubs focus on theoretical applications to district or regional energy systems, an interesting example of building-level energy hub is provided in [8], where it is shown how this concept can also be used to aggregate individual pieces of equipment on a small-scale.
The *black-box modelling* framework developed in [3] for DMG systems is consistent with the energy hub model, and an algorithm to automatically aggregate any energy hub component and plant in a MES was developed in [71] and exemplified through hierarchical aggregation of multi-energy components to make up and optimize the operation of a CCHP system. Also, similar to the energy hub model, a comprehensive approach with optimization of the multi-energy plant components and the superstructure that describes the input-output connections over these components was proposed in [72] and solved as a large-scale MILP problem through decomposition techniques. In particular, with respect to the energy hub model, this

concept has the advantage of being mathematically treatable in an easier way (see also the discussion in Section 3.1.5). Following up on [72] and similarly to [71], the reference [73] has recently proposed an automated process to describe the plant superstructure through a connection matrix, from which the optimal plant configuration and component mix is derived, also taking into account multiple redundant units and for application to both Greenfield and Brownfield[1] designs of trigeneration systems.

3.1.3. Microgrids

A Microgrid can be interpreted as a low voltage or medium voltage distribution system with various distributed energy resources (distributed generation, storage, and controllable loads), which is controlled in a coordinated way and can in case operate in *islanded mode* (particularly to guarantee a certain level of power quality and reliability in the case of failure of the grid mains) [74][61]. Specific cases of Microgrids designed to operate in islanded mode may also occur, for instance in scarcely electrified areas such as in developing countries. Microgrids have grown in the last years as a powerful aggregation concept to integrate distributed energy resources and also recently including EVs [75]. The control architecture is based on a central controller that schedules the Microgrid resources in a coordinated way according to predefined objective functions while guaranteeing that internal network constraints are not breached [76] or by making use of automatic iterative feedback signals that also allow for the setup of distributed markets [77]. In a MES context, advanced control strategies based on model predictive control have been applied in [78], where a Microgrid including CHP and EHP is operated and designed taking into account different aggregation levels, namely, local level, multiple buildings, and the power grid. Extension of electricity-only Microgrids to MES is also being discussed in a few recent publications in order to capture the benefits that a multi-energy focus might bring from an environmental perspective. For instance, Microgrids with trigeneration applications are optimally designed and operated at a building-level in [79]. Microgrids for supply of electricity and heat loads are also discussed in [80], where after a review of the main relevant models and research challenges a specific polygeneration Microgrid installed at the University of Genoa and used as a test-bed facility is presented. In fact, an idea of increasing interest is to deploy the heat rejected from small scale thermal generators to supply local communities so as to create district energy Microgrids with DMG and controllable multi-energy loads. In this respect, a set of studies [81][82][83][84] have been performed for optimal sizing (through particle swarm optimization) and management (through fuzzy logic control techniques) of a Microgrid for remote areas, including RES and polygeneration of electricity, space heating and cooling, potable water from desalination, and hydrogen for transport (the latter two also functioning for seasonal storage purposes). A relevant tool for optimal operation and design of polygeneration Microgrids, based on MILP, has recently been illustrated in [85][86], whereby the electricity, heat and cooling demand of a cluster of buildings can be optimally satisfied taking into account power grid exchanges, tariff structure, and normative constraints. As well argued in those papers, such flexible tools prove to be of increasing importance in MES applications, particularly to consider the robustness of optimal operation and design variables to changing boundary conditions such as market prices or regulatory environment.

3.1.4. Virtual power plants

The FENIX project [87] has defined the VPP concept as a flexible aggregation of distributed energy resources that are coordinated in an optimal way, are capable to play in the energy market, and offer services in the same way as conventional large-scale power plants. The

[1] By "Greenfield" and "Brownfield" it is meant here a new project and an upgrade of an existing project, respectively.

definition also considers a Commercial VPP (with economic focus only and no need for specific geographical proximity of the aggregated resources) and a Technical VPP (where the VPP aggregated resources are geographically close and their coordinated control also considers electrical network constraints, differently from the Commercial VPP). While the original focus is on electrical resources, it is beneficial to extend the concept to considering MES and deploy the synergies between electricity and other energy vectors (above all heat) particularly for system balancing purposes in the presence of fluctuating RES, as already mentioned earlier. In this respect, in [88] an equivalent VPP model for cogeneration from combination of CHP and EHP is presented, highlighting the flexibility to supply the multi-energy load as well as enhanced energy saving and emission reduction potential. A schematic illustration of such a concept is shown in Figure 7. In the same light, the value of thermal storage in providing system flexibility in a MES is analysed in [89], where a cluster of CHP plants are optimally controlled in a VPP configuration through a MILP model. The potential for providing balancing resources to the power system through multi-energy VPP in district energy systems is discussed too in [90], with focus on the role of such schemes in a future dominated by renewables. In a similar context of provision of power system services, a multi-energy VPP model with demand-side resources only is presented in [91], where heat pumps, electric vehicles, and electrolyzers are aggregated to participate in the provision of spinning reserve, showing benefits in terms of increased techno-economic efficiency of the overall power system, reduction of operational costs and emissions, and integration of additional volumes of RES. Recent contribution from the author in the outlook of power system services from multi-energy systems aggregated in an equivalent VPP configuration is also shown in [92] and [93], where the novel concept of multi-energy price arbitrage is explored for the provision of demand response and ancillary services, respectively. Similarly, VPP models in a MES context with focus on the role of gas are discussed in [51], where the synergies between electricity and gas to produce electricity and heat are optimally exploited through local market-driven optimization of micro-CHP plants and hybrid electricity-gas heat pumps. Recognizing in an analogue way the importance of aggregation concepts from a market and commercial standpoint, an analysis of the economics, business cases, and policy framework to support development of distributed fuel cells is presented in [94], where it is also shown that the VPP coordination could lead to a more stable operation of the individual plants.

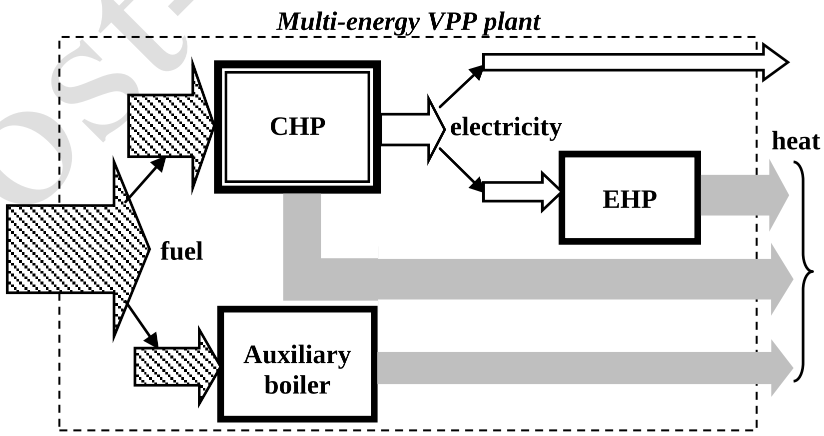

Figure 7. Schematic example of multi-energy VPP plant based on CHP and EHP.

3.1.5. Discussion on MES aggregation models

Although the focus of the *energy hub* concept is on modelling the MES internal and external energy flows, it can be regarded as a general case of aggregation model of MES. In particular, it is suitable for modelling of distributed MES with inclusion of network constraints and has proven itself to be flexible for manifold applications. However, its mathematical tractability may be complicated as the model formulation itself, based on the concept of "aggregating" energy flows within a synthetic matrix representation, is intrinsically nonlinear due to the multiplication of decision variables. In order to deal with this drawback, the work [95] has proposed to "disaggregate" energy flows, leading to a more treatable problem and in case linear models. However, while it is arguable that such an approach still maintains the energy hub "philosophy" (in the sense that equation aggregation is the main core of the model, allowing the synthetic generalization of the Karush-Kuhn-Tucker conditions from the electrical-only optimal power flow problem to the multi-carrier domain [9]), linearization of the physical behaviour of networks such as the gas one may lead to large errors. In any case, this is a general issue that applies to all models trying to linearise nonlinear network behaviours. If problem linearization is accepted, the energy hub formulation is an elegant way to describe energy flows in a synthetic way, and other aggregation concepts such as input-output representations, Microgrids, and VPP can all be modelled through it.

The *Microgrid* concept has been widely used in the last years also because it reflects real world implementations in low and medium voltage distribution networks, with a central controller of the distributed energy resources typically located at the electrical substation level. The main characteristic and benefit of the approach is to take network constraints into account so that the feasibility of various control options is technically validated too. However, the extension of MES case is in most cases limited to considering provision of heat from local CHP generators and in case cooling from absorption chillers, but without a real "MES thinking". From this perspective, there is certainly room for research into "multi-energy Microgrids", whereby the synergy between electricity and other energy vectors (and in particular the control flexibility that other energy vectors can provide [93]) can be captured even if the focus of the study and the application is on the electrical network.

The main characteristic of the *VPP* approach is to "emulate" the behaviour of centralised resources and power plants in general for wholesale market participation. To some extent, the VPP concept appears to be more general than the Microgrid. In particular, a Microgrid can be interpreted as a Technical VPP (in which network constraints are taken into account), once the focus is on the coordinated control of the resources internal to the Microgrid and on the interaction with the external network/markets. Obviously, an isolated Microgrid cannot be interpreted as a VPP, and *vice versa*. The VPP concept lends itself well to multi-energy applications and generalization of the electricity-only domain. As discussed above, in fact, a few works on VPP already take into account the interactions with other energy vectors and particularly gas on the input side and heat on the output side, although comprehensive multi-energy VPP models are still missing. MES applications, in particular, have focused on commercial VPP aspects, while network constraints and in general network issues (particularly for networks other than the electrical one) have been neglected. An energy hub model or similar input-output models could be used to merge technical and commercial aspects of a VPP in a MES context.

3.2. Operation and planning tools for multi-energy system analysis

Given the complexity to deal with MES, powerful simulation tools are needed for both operational and planning analysis and considering different objectives, including technical, economic, energy efficiency, and environmental aspects. Various tools have therefore been developed to deal with different aspects of MES. Comprehensive reviews can be found for instance in [96] for regional-level tools and focus on RES integration and in [97] for community-level tools and focus on DMG. Below there is some example of MES tools that are available (mostly free of charge, although some may require to purchase an optimization solver).

The "RETScreen" tool [98] is capable to support decision making relevant to MES operation (and planning starting from the operational studies). The tool is scenario-based and compares a base case against a study case, and economic as well as environmental indices are used to assess the performance of the proposed system relative to the reference one. Applications [99] range from individual buildings and district energy systems to regional applications, and can include a number of electricity, heat, and cooling fossil-based (including trigeneration) and renewable technologies as well as energy efficiency measures. Since the time step employed in the analysis is monthly, it is less effective for studying issues such as integration of RES in terms of close-to-real-time balancing as well as new technologies such as storage or demand response. The tool is thus more suitable for screening scenario analysis and high level planning before possibly resorting to more advanced operational tool such as the ones below.

The MES analysis model "EnergyPLAN" [100] is discussed in a number of papers and for instance in [101] with regard to studying the integration of wind power in the Danish systems (to optimally interact with CHP plants) and to inform national energy planning strategies, with focus on economics, markets, and consequent regulatory aspects. The tool is being developed since 1999 and takes into account electricity, heat, and transport supply options on a national/regional level, with deterministic hourly operational optimization (based on heuristic rules) performed over a one year window. The various studies that have been carried out with this tool include modelling of national energy systems [102] and smaller regions such as cities [103] amongst the others. EnergyPLAN is an operational optimization tool and investment planning needs to be performed starting from the annual operational results. Treatment of complex aspects such as involving the role of distributed storage at the system level may be difficult, also because the tool does not model network constraints.

While the above models are suitable for optimal operational analysis, "DER-CAM" is a tool suitable for design analysis of polygeneration Microgrids [79]. The model is capable to select the best technologies and then simulate optimal operational patterns (on an hourly or even finer basis) to supply the electricity, heat, and cooling requirements of a Microgrid given certain economic and price conditions. The model uses a MILP approach for optimization, and can be used for both operation and planning analysis of Microgrids (and community-level MES in general) from an economic as well as environmental point of view [104].

Differently from the previous tools that focus on an equivalent single bus bar model of the energy system, "eTransport" [105] is suitable for optimal investment planning in local energy supply systems for both supply technologies as well as energy networks. In particular, the tool is capable to model geographical and topological ("where") characteristics of the multi-carrier energy system, as well as investment timing ("when"), as key features of the investment analysis besides "typical" techno-economic characteristics of different planning options. The model optimizes the life cycle cost of supplying given energy requirements in a certain geographical area and over a certain planning horizon (typically 20-30 years), and considers both optimal hourly operation for typical days as well as optimal expansion plan.

A comparative synthesis of some of the characteristics of the tools discussed above is provided in Table 1. From the Table and the previous discussion, it emerges how the RETScreen tool may be viable for a preliminary techno-economic, environmental, and financial viability assessment of energy projects that do not require fine time resolution (for instance, balancing issues in integration of RES, storage and demand response). Input for the

design analysis of district energy networks are considered too. EnergyPlan is instead more suitable for operational analysis of alternative energy systems, whereby a mathematical cost-based heuristic optimization is performed which allows assessment of hourly interaction between for instance RES and CHP. Although initially built for regional studies, the tool is flexible enough to model different aggregation levels. Investment analysis needs to be performed “offline” following up on the operational results. In contrast, the DER-CAM tool allows for investment analysis over the lifetime of the project, although its focus is on electrical Microgrids that are relatively confined from a geographically point of view. Finally, although eTransport is not suitable for operational studies, it is the only tool capable to perform optimal system expansion also explicitly including networks and considering network development for district/region energy systems. It can thus be used for optimal system design, while operational studies could be performed with other tools.
For further and systematic reviews of relevant tools, the reader can also for instance see [18] for urban energy systems, [96] for RES integration, and [97] for integrated community energy systems.

Table 1. Summary of analysis features for different MES tools.

	RETScreen	*EnergyPlan*	*DER-CAM*	*eTransport*
Operation	Yes	Optimization	Optimization	No
Planning	Yes	No	Optimization	Optimization
Network	Yes	No	No	Optimization
Resolution	Monthly	Hourly	Hourly/Variable	Hourly
Time scale	Annual	Annual	Lifetime	Lifetime

4. Evaluation methodologies and performance assessment criteria

4.1. Generalities on assessment methodologies

In addition to suitable models and simulation/optimization tools to perform MES analysis, it is critically important to have at disposal robust assessment methodologies and indicators that are capable to evaluate the energy system performance according to specific objectives, for instance from an economic or environmental rather than technical perspective.

While some assessment methodologies may in case be of qualitative nature, quantitative metrics are fundamental to perform engineering analysis and formulate optimization problems for MES. Different categorization of performance indicators can refer for instance to different temporal horizons (e.g., from hourly to annual studies), different objectives (e.g., from economic to emission reduction assessments or from operational to investment studies), absolute or relative value (in the latter case it is crucial to select the reference energy system the comparison is made with), multi-objective or single-objective approaches, deterministic or probabilistic (with in the latter case the inputs/outputs being for instance represented by probability distribution functions rather than deterministic values), and so on. An analysis of relevant assessment criteria, approaches, and indicators that have been considered in the literature for MES and particularly DMG analysis is provided below with reference to energy, environmental, and techno-economic characteristics (the latter with consideration of both deterministic and probabilistic approaches). The selection of these categories is of course arbitrary and other approaches could have been followed. However, the rationale of the choice is linked to real world discussions and applications. In particular, *energy* indicators are being considered more and more from a regulatory point of view to boost the utilization of MES, and hence a critical analysis of them proves to be fundamental. This to some extent stems from classical fossil-fuel dominated energy systems. However, in a fast-changing energy world with increasing volumes of RES, energy indicators might not be any longer suitable or sufficient, and other *environmental* impact approaches and criteria may be needed. Finally, *techno-economic* and financial assessment of any energy system is of course always crucial, particularly in the presence of budget constraints and increasing uncertainties on energy prices, demand levels and patterns, technologies, and so on. In addition, the merge of economic considerations with energy and environmental ones is becoming common practice, which justifies the focus on these aspects as categorised below.

4.2. Energy assessment criteria

Base indicators at an individual component level for energy efficiency characterization are typically relating to the *input-output efficiency* definitions such as electrical and thermal efficiencies in CHP plants, thermal efficiency in boilers, Coefficient of Performance (*COP*) for electric, absorption/adsorption, and mechanical heat pumps as well as chillers, and so on [3][106]. Such input-output indicators can be evaluated on the basis of different time resolutions, from minutes (addressing power-like issues) to a whole year or even the whole lifetime (addressing the time-integral performance of the component under consideration). Such indicators can then be generalized to an entire plant or system, for instance considering the energy first-law energy performance of a cogeneration plant [10] or of a trigeneration system for electricity, heat and cooling [3]**Error! Reference source not found.**. However, such *"absolute"* efficiency indicators may be not sufficient or even adequate to provide enough information with respect to the role and performance of the MES in an overall energy system level context because lacking of comparative terms.

Most indicators used for regulatory purposes are therefore based on *"relative"* energy efficiency indicators that assess the MES system performance compared to a *reference* case. In the case of *cogeneration*, for instance, one of the most used indicators is the Fuel Energy

Saving Ratio (*FESR*), defined and discussed in [10] for a number of practical cases. The *FESR* indicates the primary energy saving that a CHP system can bring with respect to the "separate production" of electricity and heat in reference production technologies, namely, electricity in conventional power plants and heat in fuel boilers (or EHPs, in case). The *FESR* and similar types of indicators and relevant pitfalls when used for applications in regulatory contexts in different countries are for instance extensively discussed in [107], and the paper [108] has recently carried out a comprehensive analysis of the requirements to comply with the cogeneration directives and guidelines of the European Union. The *FESR* is also known as Primary Energy Saving (*PES*) and has also been discussed in [109] with various parametric studies. Alternative indicators relevant to energy analysis could also be *exergy-based* [110]. In this respect, [111] carry out a comparison of energy-based indicators used for regulatory purposes of cogeneration in different countries with exergy-based ones and again highlight the inconsistencies that sometimes arise. As a general comment, in real applications for energy system assessment it can be appreciated how energy indicators are still widespread with respect to exergy ones, most probably because of the ease to deal with energy (which is eventually what is "paid" for) rather than exergy.Given the fundamental issue to understand the role of MES in a system context and following the same rationale as the primary energy saving assessment in cogeneration, generalization of the *FESR* indicators has been proposed for *trigeneration* plant too. In this respect, [112] discusses the *primary energy rates* of the separate production of different energy vectors (electricity in power plants, heat in boilers, and cooling in electric chillers) and of a trigeneration plant, and uses these rates to assess the potential energy saving in CCHP. A parametric analysis based on the same type of indicators (called "*quality index*") is carried out in [113], highlighting how the energy saving in trigeneration changes with the recovered heat that is used for cooling. Interesting mathematical details of the dependence of the trigeneration fuel energy saving function with respect to different plant parameters are discussed in [114], while [115] discusses the overall primary energy saving when considering "seasonal" trigeneration (cogeneration of electricity and heat in winter and of mostly electricity and cooling in summer). Following the rationale of the previous studies, the Trigeneration Primary Energy Saving (*TPES*) index is defined for generic trigeneration systems (not only "classical" ones with absorption chillers) and its utilization for planning and regulatory purposes is discussed in [116], including the impact of relative levels of the multi-energy loads, control strategy, and reference efficiencies. Further generalization to generic DMG and *polygeneration* systems (with focus of the discussion on the ones fuelled on natural gas) is provided in [117], while assessment models for energy-chemical systems are also discussed in [118]. Finally, electricity-oriented *incremental* indicators that discount the equivalent fuel input for electricity by the fuel that would have been used to supply the other energy outputs have been proposed for various types of DMG systems, including cogeneration [10], CHP-EHP [119] and CCHP [120], although limitations of these concepts to economic energy applications may arise, as discussed in [3].

4.3. Environmental assessment criteria

The complexity of the environmental impact of energy [121] is such that it is not possible (and it is certainly outside the scope of this work) to report comprehensively on the various criteria that have been used and are needed for a relevant MES analysis. Focusing on discussion on emissions, a basic differentiation between *global* and *local* emissions for cogeneration systems is provided in [122][123] with reference to geographical impact. More specifically, in this schematic categorization the attribute of "global" is referred to emissions that impact on a scale well beyond the emission source, such as CO_2 and in general Greenhouse Gases (GHG) for global warming, R11 for ozone depletion layer, or SO_2 for acidification. On the other hand, "local" is referred to pollution with relatively limited geographical impact such as CO, NOx, particulate matter, and so forth.

From a *GHG emissions* perspective, analysis of the potential of co- and tri-generation options to reduce climate change impact is discussed in [124], including the role of emissions other than CO_2 from fuel combustion. Generalising the discussions in [124] and providing a unified view on energy and environmental assessment criteria, a comprehensive analysis of various CHP and CCHP solutions to provide both energy saving and GHG emission reduction is discussed in [125][126], where the Cogeneration CO_2 Emission Reduction (*CO2ER*) and the Trigeneration CO_2 Emission Reduction (*TCO2ER*) indicators are introduced and exemplified with respect to conventional separate production means for electricity, heat, and cooling and with applications in different energy systems and countries. Specific applications to an integrated CHP-EHP "virtual cogeneration plants" based on these models is then reported in [88], where environmental comparison between fuel boilers, CHP, EHP, and a combination of them is also systematically carried out, while a relevant comprehensive energy and environmental comparison for different types of chillers is reported in [127]. The theoretical differences and analogies between GHG emission reduction indicators and energy saving indicators introduced in [125] (showing that under certain conditions the *PES* and the *TPES* indicators coincide with the *CO2ER* and the *TCO2ER* indicators, respectively) is then extended and discussed to a generic DMG and polygeneration system modelled as an input-output multi-energy black-box in [117]. This is done through the introduction of the Polygeneration Primary Energy Saving (*PPES*) and the Polygeneration CO_2 Emission Reduction (*PCO2ER*) indicators, which highlight the concurrent role played by system efficiencies and emission factors in both multi-generation plant and reference plant.

Other global aspects different from global warming, such as *Acidification Potential* (potential of a generic substance to build and release H^+ protons relative to SO_2 as the reference substance) and *Ozone Depletion Potential* (potential of a generic substance to deplete the stratospheric ozone relative to R11), are discussed for CHP systems and with indicators formally similar to the GHG ones in [128], while generalization to polygeneration indicators has been proposed in [129].

Concerning *local* pollutants such as NOx, CO, and so forth, where the relevant environmental impact is limited to only a geographically confined portion of the territory around the emission source, cogeneration applications are discussed in [130][122] where two *emission balance models* are proposed as proxy for the real environmental impact. More specifically, in the "global" emission balance the corresponding emission reduction indicator has the same structure as the *CO2ER* in [125], while in the "local" emission balance only the local emissions from the reference energy system for heat generation (in the specific case fuel boilers) are considered (as power plants for electricity production are assumed to be "far enough" not to have any impact). While these emission balance models are extremely useful to represent boundary impacts and in particular for regulatory purposes based on emissions rather than pollutant concentration, the actual environmental impact lies somewhere in between and would need a pollutant dispersion analysis conducted with dedicated tools that allow drawing pollutant concentration maps, as for instance illustrated in [131][132].

More general environmental impact analysis of MES includes a *cradle-to-grave LCA* that again can embed a wide range of criteria in terms of impact on humans and ecosystems. Relevant studies for optimal design of trigeneration considering both CO_2 emissions and the "Eco-indicator 99" have been performed for instance in [133][134], while thermoeconomics is used in [135] to quantify the environmental burden through the whole life-cycle for a DMG system (further discussions are provided in Section 4.4.2). Another relevant use of LCA for DMG is reported in [136] to assess the impact of bio-mass fuelled co- and tri-generation systems, while [137] points out the benefits of LCA as opposed to other approaches to assess the environmental of human activities on energy systems and territories in general. A LCA approach to biomass-based CCHP plants has also recently been proposed in [138], where it is highlighted how primary energy saving indicators such as the *PES*, envisaged by the current European regulation, might not be suitable to represent the actual wider environmental impact and benefits of such systems, differently from LCA indicators.

It is worth pointing out that various other concepts (besides for example exergy theories and relevant extensions) can be found in the literature to address environmental issues such as resource consumption and relevant environmental impact (and economics). Amongst the others, there is for instance the "*emergy*" concept, intended as a measure of the work carried out (by nature and/or humans) to realize a final product or a service and often expressed in terms of equivalent solar energy. An example of application of such concept to multi-energy systems can for instance be found in [139]. However, there are still ongoing debates in the research community regarding the role of emergy and its relationship with energy-based and exergy-based approaches to "cost" final energy products (see also Section 4.4.2) and account for resource consumption/destruction (see for instance [140][141]), so that this is certainly a topic deserving further research.

4.4. Economic assessment criteria

4.4.1. General aspects

Economic assessment is one of the most critical points in the analysis of every energy system and in particular of MES, and as in the case of the environmental impact only an attempt will be made here to address the complexity of the main approaches that have been undertaken. In general, economic assessment can refer to *operational* aspects (for instance, to devise optimal operational strategies for each component on the basis of the relevant energy prices) or to *planning* aspects (for instance, to identify the best technologies, sizes, and topologies of the system to minimize the overall cost or maximize profits). Relevant indicators are thus needed to typically quantify the performance of different operational strategies under different conditions (given a certain energy system) or to identify the best solution and rank various alternatives at the design stage. The assessment criteria can then be of a *deterministic* nature (when the relevant variables are assumed to be known with certainty or when for example average values from a given distribution are given) or of a *probabilistic* nature (when at least one of the variables is given through a stochastic model which can be for instance based on a continuous or discrete probability distribution function, and then the relevant outcomes may also be given with probabilistic description from which synthetic metrics such as mean values can be extracted).

4.4.2. Deterministic models

<u>Energy-based operational assessment</u>

Classical *deterministic* models for assessing the economic performance of MES on the *operational* side are typically based on the analysis of costs and revenues arising from system operation. The time resolution considered in the study is normally associated to the level of detail the multi-energy load is known with and to the relevant market price resolution; this resolution can for instance be down to five minutes (as in some electricity balancing markets) or half-hourly/hourly (particularly depending on real time electricity pricing). Operational analysis intervals are typically in the order of a day, a week, or one to several months, depending on the purposes of the study (for instance, resource scheduling based on day-ahead market prices), the presence of short-term (intra-daily) or long-term (seasonal) storage, and the need for capturing specific seasonality effects. Simulations may then run up to a year, particularly if the operational analysis is to inform the planning one, as discussed further below. An application example to hourly-fine daily optimization problems in trigeneration systems is for instance given in [71], where the assessment indicator (objective function to minimize) is the *operational costs* (fuel and electricity input costs *net of profit* from electricity sold back to the grid) subject to given multi-energy demand constraints. Similar studies on a trigeneration plant are performed in [142], where again the assessment criterion for minimization is the operational costs (net of profits from electricity sold), with the option of adding a cost to wasted heat too. That paper also gives further insights on the system operational assessment by explicitly calculating the *marginal costs* relevant to each operational constraint as the dual prices of the proposed linear program. Such dual prices indicate the value change in the objective function as a consequence of unitary change in one of the constraints and are given by the Lagrangian multipliers in the Karush-Kuhn-Tucker first-order optimality conditions. A comprehensive model for optimizing MES costs-revenues balance and operational optimization also taking into account multi-energy network constraint is provided in [9], which represents the best approach available to model MES although with limitations related to the problem tractability, as mentioned above. Other relevant economic indicators for operational analysis and optimisation of MES are the "classical" *spark-spread* ratio (between the market price of electricity and the variable cost of electricity production based on the market price of fuel) [143][144][145] and its extensions proposed in [146] to take into account the contribution from heat recovery for direct supply of the heat load or for supply of cooling load through an absorption chiller. Such spark-spread models can effectively be used for profit-oriented operational decision making in a real-time market framework through heuristic approaches that do not require formulation and solution of a full optimization problem. As mentioned earlier, similar assessment criteria for market-oriented operational analysis but based on "*incremental heat rate*" indicators (which discount the quota of fuel input used to produce electricity to take into account the simultaneous production of other energy vectors) are provided in [10] for cogeneration, in [119] for CHP-EHP, and in [120] for generic trigeneration systems. Pros and cons of such indicators are also discussed in [3], as mentioned above.

Energy-based planning assessment

Deterministic assessment criteria for *operational planning* (where long-term planning aspects are supported by more or less detailed system operation analysis) in MES are borrowed from engineering economics and for planning purposes typically make use of the *discounted cash flow* theory and the *Net Present Value* (*NPV*) indicator. In this light, for an outlook on general economic assessment techniques on decentralised energy excellent readings are for instance [147][148]. In terms of cogeneration, Horlock [10] is a classical reference for comprehensive economic assessment techniques of CHP and DH, while a more recent survey on investment assessment techniques for CHP plants is reported in [149]. Amongst the various application papers recently appeared in the literature, the *NPV* is used as the indicator to maximise in the trigeneration planning study in [150], and it is also used in [151] for planning assessment of a CHP-DH system where daily profits (difference between revenues and costs) are maximised through optimal operational control strategies. Daily profit maximization for a CHP plant with hourly resolution and by exploiting the thermal storage available in the network is also carried out in [152], where again *NPV* and the *Internal Rate of Return* (*IRR*) are used for the evaluation. As an alternative assessment criterion for a trigeneration plant in a hospital complex, reference [153] proposes the *Gross Operational Margin* (to be maximised) as the difference between revenues and costs but also considering an annual tax rate within a multi-year planning problem in which the operational optimisation is embedded. Particularly when referring to DMG systems for which the alternative base solution is separate production, the *Pay-Back Time* indicator (in case discounted to take into account the time value of money)

relative to the reference case can be used, above all for preliminary screening of solutions. In this respect, a comprehensive example with pay-back time applied to various DMG options and control strategies is provided in [154], which also includes a multi-parametric analysis to take into account the sensitivity of the results to energy prices. Finally, another approach to economic assessment of MES could be based on the comparison of the *specific energy cost* (in monetary units per kWh) of the different solutions considered in the study. A MES application example to integrated electricity-and-heat network planning is for instance reported in [55], where the assessment criteria is the equivalent distribution cost per kWh of overall delivered energy (electricity and heat) for different options.
In general terms, from the analysis of various references on energy-based planning it appears that *NPV*-based approaches are the most suitable to assess MES with certain complexity. This is particularly true when some type of system evolution over the lifetime of the project is considered, so that cash flows and in case investment may change significantly throughout the years. Limitations of *NPV* methods in the presence of uncertain evolution are discussed in the next Section. The *IRR* is another suitable indicator stemming out of *NPV* analysis too, although it may present some limitations when dealing with more complex assessment techniques in the presence of uncertainties, as mentioned further below. On the other hand, while (discounted or not) pay-back time approaches could in case capture the system evolution dynamics, this is typically not done and "typical years" only are considered in the assessment, which might be not sufficient to have a clear picture of the project value unless just for option screening.

Exergy-based operational and planning assessment

Consideration of *exergetic aspects* into the economic analysis of MES for planning purposes has also been discussed in several publications through the *thermoeconomic theory*. Such an approach is capable to take into account at the same time the thermodynamic quality of the energy streams involved in the system and the associated costs, so it somehow takes into account environmental aspects (in the sense of optimal utilization of resources) too within the economic assessment. A recent systematic comparison of different technologies for community cogeneration based on energy, exergy and exergonomic approaches is illustrated in [155], where it is pointed out how natural gas or biomass integrated gasification gas turbines are the most efficient technologies in terms of exergy cost of electricity and heat. Relevant applications to trigeneration systems can be found in [156][142][157], where the exergy streams are used for cost assessment and system cost internal allocation so as to optimize the design of each component and the system as a whole while accounting for the cost of each individual piece of equipment. Thermoeconomic assessment has also been discussed for operational planning applications [158], where load variability and corresponding efficiency changes and operational decisions are taken into account in the evaluation. However, in general while thermoeconomics is widely used in "thermal engineering" research, its application to "real world" engineering and power systems is much more limited and the classical "energy-based" *NPV* and *IRR* techniques are used, probably due to their simplicity. Also, the role of thermoeconomics in future energy systems dominated by RES needs to be clarified, which certainly paves the way to new research on the topic.

Environmental cost internalization

Other techniques have been proposed to take into account *environmental aspects* in the economic studies by more explicit *environmental costs internalization*. A relevant approach and application to MES is for instance based on *environomics* and reported in [159][160], in which a multi-energy district energy system with a mix of centralised and decentralised CHP and EHP is assessed by augmenting the costs-revenues balance associated to the thermoeconomic energy/exergy streams with pollution costs through a specific damage cost for each (global and local) pollutant and a user-defined penalty factor. Carbon taxes and in general pollution taxes can also be applied to internalise environmental effects in economic studies, as for instance in [161] where a case study for CHP-based Microgrid is discussed. However, again, as for thermoeconomics, although environomic models are well known in research, their real world application is much more limited.

4.4.3. Probabilistic models

While deterministic techniques are widespread in the operational and planning economic assessment of MES, in recent years also *probabilistic* or *stochastic* assessment models are emerging. This is mainly in response to increasing degrees of uncertainty introduced for instance by market operation and larger volumes of intermittent RES in many countries, so that the *investment problem*, in particular, becomes more challenging. Amongst other approaches, *risk analysis* techniques can be used to deal with uncertainties for MES investment assessment in a probabilistic framework. For cogeneration systems, for instance, reference [162] adopts a risk analysis approach to the plant investment appraisal, by generating a probabilistic *IRR* (used as the economic assessment criterion) based on *Monte Carlo* simulations and starting from normally distributed price inputs. A more general and comprehensive model is proposed in [163][164], where multiple uncertainties (for profiles and evolutions of both demands and energy prices) over different temporal scales are accounted for. The CHP optimal investment problem is in that case solved through Monte Carlo simulations for short-term (daily) and medium-term (annual) uncertainties and *decision theory* techniques for long-term (plant lifetime) uncertainties and by making use of different investment criteria for which suitability to probabilistic assessment is also discussed. Amongst the other, it is highlighted how the *NPV* criterion (or equivalently the net present cost) is most suitable for system assessment under uncertainties and for decision theory applications, while there are limitations to apply the *IRR* in a decision theory framework.

The models described above solve the problem of DMG investment under uncertainty by assuming that investment is carried out at the beginning of the analysis window, with no room for instance to postpone the investment. On the other hand, in the presence of uncertainty there may be value in *waiting*, as discussed in [165] which is considered one of the reference works for the development of real option theory and where discounted cash flows and *NPV* approaches are criticised because they cannot capture investment flexibility. More specifically, *real options*, whereby financial option models are applied to engineering ("real") problems and capture the value from exercising the option – that is, investing in the plant – at a later stage, have indeed also been applied to DMG planning under uncertainty, and again particularly for CHP systems. An example is reported in [166], where the optimal investment decision and timing for a CHP plant as opposed to a classical separate production solution is made in the presence of uncertain energy and CO_2 emission prices (modelled as stochastic processes); this is carried out by adopting a classical dynamic stochastic model to calculate the option value (in a form which is equivalent to deterministic *NPV* but which extends it to take into account planning flexibility). That paper also highlights the difficulties in treating analytically multiple stochastic processes with the proposed approach. A similar CHP investment problem is in [167], where the comparison is made with respect to a conventional condensing plant and where the issue of multiple stochastic processes is dealt with by generating a stochastic "spread" between input costs and output revenues; an aggregated annual spread expressed in €/kW is used as the assessment criterion. Classical stochastic dynamic programming is also used in [168] for a CHP based Microgrid, focusing on the real option valuation of incremental investments depending in particular on the gas price volatility. A more complex MES problem is discussed in [169], where a Monte Carlo simulation based approach with expected *NPV* as the assessment criterion is adopted to evaluate the investment options in a plant with CHP, thermal storage and demand response, although the option to postpone investment is not dealt with. As a general comment, the Monte Carlo approach can be seen as an alternative view to the classical financial mathematics approaches to real options problems, and seems particularly suitable with respect to the issue (to be solved as yet) of the adequacy of using specific stochastic processes to model uncertain variables such as demand and in general different from energy prices.

Another relevant approach for probabilistic planning with expected *NPV* but based on *multi-stage stochastic programming* and weighted probabilistic scenarios is adopted in [170] to model the investment in a MES for efficient process integration. A multi-stage stochastic programming method is also proposed in [171] to plan the optimal CO_2 emission trading strategies for a multi-fuel CHP plant by using the profit-to-turnover ratio as criterion while taking into account the producer's risk attitude and the emission estimate confidence interval to help reduce the transaction costs in emissions trading. A two-stage stochastic programming model for MES is discussed in [172] too, where the optimal system design is carried out through genetic algorithms (first stage) and then Monte Carlo simulations to deal with uncertainties (second stage). As for the case of Monte Carlo approaches in real options models, multi-stage stochastic programming techniques based on scenarios appear to be more suitable to assess MES planning flexibility than numerical approaches borrowed from financial mathematics owing to the possibility of using generic stochastic processes and scenarios.

Again borrowed from the financial world, also *mean-variance portfolio analysis* has been put forward for MES investment under uncertainty, particularly to be able to model the trade-off between expected return and risk of a given option. For example, in [173] such theory is used to assess which CHP technologies should be installed to meet given policy target considering independently both the *NPV* and the expected annual portfolio return as the assessment criteria. A comprehensive study of integrated multi-energy infrastructure including generation, transmission and storage of different energy carriers through a mean-variance portfolio approach is finally performed in [59], including a case study with interaction of both conventional and renewable electricity plants, heat, and hydrogen; mean return and variance (as the risk indicator) are in that case used as criteria to build the portfolio efficient frontier.

4.4.4. General comments on economic assessment techniques

From the literature analysis on deterministic models it emerges how thermoeconomics is most suitable for MES plant design and could be used for operational optimization as well, although energy-based economic models and classical discounted cash flow techniques (*NPV* assessment, in particular) are much more used for investment appraisal due to their simplicity. Another point in favour of the latter is that eventually market transactions refer to energy and not exergy, hence it is easier to deal with energy-related approaches. Environomics brings the further component of environmental assessment, which in principle could be incorporated into both exergy- and energy-based economic analyses (in the latter case this basically corresponds to emission trading schemes, carbon taxes, and so forth). While internalization of environmental costs needs to be boosted by regulation and markets, certainly its perspective (possibly in the form of environomic studies) is needed from an energy policy standpoint in order to push for the best solutions from a multi-criteria perspective. However, there is clearly a challenge in moving from energy-based to other economic indicators, which may be related to clarifying the role of advanced economic techniques in MES engineering applications and particularly in the presence of increasing volumes of RES.

On the other hand, regarding probabilistic assessment techniques, while plenty of work is already available in the literature, it appears that a systematic understanding and comparison of different techniques still needs to be carried out, particularly when dealing with the applications of originally financial models (real options and portfolio analysis) to MES. On the other hand, such understanding will be more and more critical to address the economic feasibility of future "smart" MES systems where the presence of uncertainties is likely to become more dominant. Amongst others, the author is currently working on exploring these aspects.

5. Concluding remarks

In this paper, a general introduction to and critical discussion of the main characteristics, modelling methodologies and tools, and assessment approaches and criteria for MES has been provided, backed by relevant literature review of major publications appeared in recent years. The main driver for this work was that, although it is now well recognized that MES can perform better than "classical" separate energy systems from energy, environmental, and techno-economic perspectives, most works focus on specific points, and there is lack of a comprehensive view on MES. Hence, this paper has aimed at bridging the gaps among the different individual viewpoints and providing a holistic overview of MES (and DMG in particular as the most studied case). More specifically, various outlooks of MES have been explored, ranging from the geographical breadth of analysis to the end-services and sectors involved, the variety of energy networks that could be adopted, and so forth. Relevant methodological approaches that have recently been proposed for MES analysis have also been discussed, including innovative aggregation concepts such as Energy Hubs, Microgrids, and Virtual Power Plants, and a number of analysis tools that are available have also been briefly presented. Finally, a large section of the paper has been devoted to introducing and critically analysing evaluation methodologies and performance metrics that have been proposed to capture costs and benefits (from an energy, environmental, and techno-economic perspective) for different types of MES, also highlighting, when relevant, the need for future research or for bringing research into real world applications.

Future work to complement this overview aims to systematically discuss the vast literature on different optimization techniques that have been put forward for MES operation and planning, including the use of multi-criteria and multi-objective optimization approaches that bring together the performance metrics that have been presented here.

6. Acknowledgments

The author would like to thank the Journal editors for the invitation to write this paper and therefore for the opportunity to contribute with his thoughts to this important research topic.

7. References

[1] Mancarella P. Smart multi-energy grid: concepts, benefits and challenges. IEEE PES General Meeting, San Diego, US, July 2012.

[2] Chicco G, Mancarella P. Distributed multi-generation: a comprehensive view. Renewable and Sustainable Energy Reviews 2009; 13 (3): 535–551.

[3] Mancarella P, Chicco G. Distributed Multi-Generation: energy models and analyses. Nova Publisher, New York; 2009.

[4] Yang C. Hydrogen and electricity: parallels, interactions, and convergence. International Journal of Hydrogen Energy 2008; 33 (8): 1977-1994.

[5] Strbac G, *et al*. Benefits of Advanced Smart Metering for Demand Response based Control of Distribution Networks. Report for the Energy Networks Association (ENA); 2010. Available: http://www.energynetworks.org/ena_energyfutures/Smart_Metering_Benerfits_Summary_ENASEDGImperial_100409.pdf.

[6] Papadaskalopoulos D, *et al*. Decentralized participation of flexible demand in electricity markets. Part II: Application with electric vehicles and heat pump systems. IEEE Transactions on Power Systems 2013; in press.

[7] Mancarella P. Multi-energy systems: the smart grid beyond electricity. Environmental Energy Technology Division Seminar. Lawrence Berkeley National Lab, Berkeley, US; August 2012. Available: http://eetd-seminars.lbl.gov/sites/eetd-seminars.lbl.gov/files/EETD-Sem-08-03-12.pdf.

[8] Fabrizio E, Corrado V, Filippi M. A model to design and optimize multi-energy systems in buildings at the design concept stage. Renewable Energy 2010; 35: 644–655.

[9] Geidl M, Andersson G. Optimal power flow of multiple energy carriers. IEEE Transactions on Power Systems 2007; 22 (1): 145-155.

[10] Horlock JH. Cogeneration-Combined Heat and Power (CHP). Malabar, FL: Krieger, 1997.

[11] Bruckner T, Groscurth HM, Kummel R. Competition and synergy between energy technologies in municipal energy systems. Energy 1997; 22 (10): 1005-1014.

[12] Weber C, Shah N. Optimisation based design of a district energy system for an eco-town in the United Kingdom. Energy 2011; 6: 1292-1308.

[13] Keirstead J, Samsatli N, Shah N, Weber C. The impact of CHP (combined heat and power) planning restrictions on the efficiency of urban energy systems. Energy 2012; 41: 93-103.

[14] Bracco S, Dentici G, Siri S. Economic and environmental optimization model for the design and the operation of a combined heat and power distributed generation system in an urban area. Energy 2013; 55: 1014-1024.

[15] Aki H, Oyama T, Tsuji K. Analysis of energy service systems in urban areas and their CO_2 mitigations and economic impacts. Applied Energy 2006; 83 (10): 1076-1088.

[16] Pirouti M, *et al*. Energy consumption and economic analyses of a district heating network. Energy 2013; 57: 149-159.

[17] Niemi R, Mikkola J, Lund PD. Urban energy systems with smart multi-carrier energy networks and renewable energy generation. Renewable Energy 2012; 48: 524-536.

[18] Keirstead J, Jennings M, Sivakumar A. A review of urban energy system models: Approaches, challenges and opportunities. Renewable and Sustainable Energy Reviews 2012; 16: 3847– 3866,

[19] Keirstead J, Shah N (eds). Urban energy systems: An integrated approach. Taylor and Francis; 2013.

[20] Cormio C, Dicorato M, Minoia A, Trovato M. A regional energy planning methodology including renewable energy sources and environmental constraint. Renewable and Sustainable Energy Reviews 2003; 7 (2): 99-130.

[21] Karlsson M, Gebremedhin A, Klugman S, Henning D, Moshfegh B. Regional energy system optimization - Potential for a regional heat market. Applied Energy 2009; 86 (4): 441-451.

[22] Daianova L, Dotzauer E, Thorin E, Yan J. Evaluation of a regional bioenergy system with local production of biofuel for transportation, integrated with a CHP plant. Applied Energy 2012; 92: 739–749.

[23] Wu DW, Wang RZ. Combined cooling, heating and power: A review. Progress in Energy and Combustion Science 2006; 32 (5-6): 459-495.

[24] Angrisani G, Roselli C, Sasso M. Distributed microtrigeneration systems. Progress in Energy and Combustion Science 2012; 38: 502-521.

[25] Serra LM, Lozano MA, Ramos J, Ensinas AV, Nebra SA, Polygeneration and efficient use of natural resources. Energy 2009; 34: 575–586.

[26] Uche J, Serra L, Sanz A. Integration of desalination with cold-heat-power production in the agro-food industry. Desalination 2004; 166: 379–391.

[27] Cardona E, Piacentino A. Optimal design of cogeneration plants for seawater desalination. Desalination 2004; 166: 411-426.

[28] Zhou W, Yang H, Rissanen M, Nygren B, Yan J. Decrease of energy demand for bioethanol-based polygeneration system through case study. Applied Energy 2012; 95: 305–311.

[29] Beckera WL, Brauna RJ, Penev M, Melaina M. Design and technoeconomic performance analysis of a 1 MW solid oxide fuel cell polygeneration system for combined production of heat, hydrogen, and power. Journal of Power Sources 2012; 200: 34– 44.

[30] Ahmadi P, Dincer I, Rosen MA. Development and assessment of an integrated biomass-based multi-generation energy system. Energy 2013; 56: 155-166.

[31] Mathiesen BV, Lund H, Nørgaard P. Integrated transport and renewable energy systems. Utilities Policy 2008; 16: 107-116.

[32] Pecas Lopes JA, Soares FJ, Rocha Almeida PM. Integration of Electric Vehicles in the Electric Power System. Proceedings of the IEEE 2011; 99 (1): 168-183.

[33] Münster M, Meibom P. Optimization of use of waste in the future energy system. Energy 2011; 36: 1612-1622.

[34] Tabasová A, Kropác J, Kermes V, Nemet A, Stehlík P. Waste-to-energy technologies: impact on environment. Energy 2012; 43: 146-155.

[35] Van Dyken S, Bakken BH, Skjelbred HI. Linear mixed-integer models for biomass supply chains with transport, storage and processing. Energy 2010; 35: 1338–1350.

[36] Raja NT, Iniyan S, Goic R. A review of renewable energy based cogeneration technologies. Renewable and Sustainable Energy Reviews 2011; 15: 3640–3648.

[37] Lund H, Moller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010; 35: 1381–1390.

[38] Mancarella P. Urban energy supply technologies: multigeneration and district energy systems. In “Urban energy systems: An integrated approach”, J.Keirstead and N.Shah (eds.). Taylor and Francis, 2013.

[39] Kusch W, Schmidla T, Stadler I. Consequences for district heating and natural gas grids when aiming towards 100% electricity supply with renewable. Energy 2012; 48: 153-159

[40] Rubio-Maya C, Uche-Marcuello J, Martínez-Gracia A, Bayod-Rújula AA. Design optimization of a polygeneration plant fuelled by natural gas and renewable energy sources. Applied Energy 2011; 88: 449–457.

[41] Nosrat AH, Swan LG, Pearce JM. Improved performance of hybrid photovoltaic-trigeneration systems over photovoltaic-cogen systems including effects of battery storage. Energy 2013; in press.

[42] Buoro D, *et al*. Multicriteria optimization of a distributed energy supply system for an industrial area. Energy 2013; 58: 128-137.

[43] Denholm P, Hand M. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy 2011; 39: 1817–1830.

[44] Meibom P, Kiviluoma J, Barth R, Brand H, Weber C, Larsen HV. Value of Electric Heat Boilers and Heat Pumps for Wind Power Integration. Wind Energy 2007; 10: 321–337.

[45] Papaefthymiou G, Hasche B, Nabe C. Potential of Heat Pumps for Demand Side Management and Wind Power Integration in the German Electricity Market. IEEE Transactions On Sustainable Energy 2012; 3(4): 636-642.

[46] Traube J, *et al.* Mitigation of Solar Irradiance Intermittency in Photovoltaic Power Systems With Integrated Electric-Vehicle Charging Functionality. IEEE Transactions on Power Electronics 2013; 28(6): 3058-3067.

[47] Saber AY, Venayagamoorthy GK. Efficient Utilization of Renewable Energy Sources by Gridable Vehicles in Cyber-Physical Energy Systems. IEEE Systems Journal 2010; 4 (3): 285-294.

[48] Kempton W, Tomic J. Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. Journal of Power Sources 2005; 144: 280–294.

[49] Lund H, Munster E. Integrated energy systems and local energy markets. Energy Policy 2006; 34 (10):1152-1160.

[50] Houwing M; Negenborn RR; De Schutter B. Demand response with Micro-CHP systems. Proceedings of the IEEE 2011; 99 (1): 200-213.

[51] Bliek FW, *et al*. The role of natural gas in smart grids. Journal of Natural Gas Science and Engineering 2011; 3: 608-616.

[52] Lobato E, *et al*. Barriers in the implementation of response options aimed at mitigating unpredictability and variability of wind energy. European Wind Energy Conference 2009; Marseille, France, March 2009.

[53] Girardin L, *et al*. EnerGis: A geographical information based system for the evaluation of integrated energy conversion systems in urban areas. Energy 2010; 35: 830–840.

[54] Brkic D, Tanaskovic T. Systematic approach to natural gas usage for domestic heating in urban areas, Energy 2008; 33: 1738–1753.

[55] Mancarella P, Gan CK, Strbac G. Fractal models for electro-thermal network studies. 17^{th} Power Systems Computation Conference (PSCC) 2011. Stockolm, Sweden, August 2011.
[56] Mancarella P, Gan CK, Strbac G. Evaluation of the impact of electric heat pumps and distributed CHP on LV networks, IEEE PES Power Tech Conference 2011, Trondheim, Norway, June 2011.
[57] Weber C, Favrat D. Conventional and advanced CO_2 based district energy systems. Energy 2010; 35: 5070-5081.
[58] Favre-Perrod P. Hybrid Energy Transmission for Multi-Energy Networks. PhD dissertation, ETH Zurich, 2008.
[59] Favre-Perrod P, Kienzle F, Andersson G, Modeling and design of future multi-energy generation and transmission systems. European Transactions on Electrical Power 2010; 20 (8): 994–1008.
[60] Braun M, Strauss P. A review of aggregation concepts of controllable distributed energy units in electrical power systems. International Journal of Distributed Energy Resources 2008; 4 (4): 297-319.
[61] Lasseter RH. Smart distribution: coupled microgrids. Proceedings of the IEEE 2011; 99: 1074-1082.
[62] Pudjianto D, Ramsay C, Strbac G. Microgrids and virtual power plants: concepts to support the integration of distributed energy resources. Proceedings of the Institution of Mechanical Engineers Part A-Journal of Power and Energy 2008; 222: pages:731-741.
[63] Asmus P**.** Microgrids, Virtual Power Plants and Our Distributed Energy Future. The Electricity Journal 2010; 23 (10): 72-82.
[64] Geidl M, *et al*. Energy hubs for the future. IEEE Power and energy Magazine 2007; 5 (1): 24–30.
[65] Leontief W. Input-output economics. Oxford, UK, Oxford University Press, 1986.
[66] Geidl M, Koeppel G, Favre-Perrod P, Klöckl B, Andersson G, Fröhlich K. Energy Hubs for the Future. IEEE Power and Energy Magazine 2007; 5 (1): 25-30.
[67] Krause T, Andersson G, Fröhlich K, Vaccaro A. Multiple-Energy Carriers: Modeling of Production, Delivery, and Consumption. Proceedings of the IEEE 2011; 99 (1): 15–27.
[68] Hemmes K, Zachariah-Wolff JL, Geidl M, Andersson G. Towards multi-source multi-product energy systems. International Journal of Hydrogen Energy 2007; 32 (10-11): 1332-1338.
[69] Hajimiragha A, *et al*. Optimal Energy Flow of Integrated Energy Systems with Hydrogen Economy Considerations. VII IREP Symposium- Bulk Power System Dynamics and Control, Charleston, SC, August 2007.
[70] Galus MD, Koch S, Andersson G. Provision of Load Frequency Control by PHEVs, Controllable Loads, and a Cogeneration Unit. IEEE Transactions On Industrial Electronics 2011; 58 (10) 4568-4582.
[71] Chicco G, Mancarella P. Matrix modelling of small-scale trigeneration systems and application to operational optimization. Energy 2009; 34 (3): 261-273.
[72] Yokoyama R, Hasegawa Y, Ito K. A MILP decomposition approach to large scale optimization in structural design of energy supply buildings. Energy Conversion and Management 2002; 43: 771–790.
[73] Voll P, *et al.* Automated superstructure-based synthesis and optimization of distributed energy supply systems, Energy 2013, in press, http://dx.doi.org/10.1016/j.energy.2012.10.045.
[74] Hatziargyriou N, Asano H, Iravani R, Marnay C. Microgrids. IEEE Power and Energy Magazine 2007; 5 (4): 78-94.
[75] Stadler M, *et al*. Optimal planning and operation of smart grids with electric vehicle interconnection. Journal of Energy Engineering, American Society of Civil Engineers 2012; 138 (2): 95-108.
[76] Schwaegerl C, *et al*. A multi-objective optimization approach for assessment of technical, commercial and environmental performance of Microgrids. European Transactions on Electrical Power 2011; 21 (2): 1269–1288.
[77] Pudjianto D, *et al*. Closed loop price signal based market operation within microgrids, European Transactions on Electrical Power 2011; 21 (2): 1310–1326.
[78] Menon RP, Paolone M, Maréchal F. Study of optimal design of polygeneration systems in optimal control strategies. Energy 2013; 55: 134-141.
[79] Marnay C, *et al*. Optimal technology selection and operation of commercial-building microgrids. IEEE Transactions on Power Systems 2008; 23 (3): 975–982.
[80] Delfino F, *et al*. The University of Genoa smart polygeneration microgrid test-bed facility: The overall system, the technologies and the research challenges. Renewable and Sustainable Energy Reviews 2013; 18: 442–459.
[81] Kyriakarakos G, *et al*. Intelligent demand side energy management system for autonomous polygeneration microgrids. Applied Energy 2013; 103: 39–51.
[82] Kyriakarakos G, *et al*. Polygeneration microgrids: A viable solution in remote areas for supplying power, potable water and hydrogen as transportation fuel. Applied Energy 2011; 88: 4517–4526.
[83] Kyriakarakos G, *et al.* A fuzzy logic energy management system for polygeneration microgrids. Renewable Energy 2012; 41: 315-327.

[84] Kyriakarakos G, *et al*. A fuzzy cognitive maps–petri nets energy management system for autonomous polygeneration microgrids. Applied Soft Computing 2012; 12: 3785–3797.
[85] Piacentino A, *et al*. A comprehensive tool for efficient design and operation of polygeneration-based energy lgrids serving a cluster of buildings.Part I: Description of the method. Applied Energy 2013; 111: 1204–1221.
[86] Piacentino A, Barbaro C. A comprehensive tool for efficient design and operation of polygeneration-based energy lgrids serving a cluster of buildings. Part II: Analysis of the applicative potential. Applied Energy 2013; 111: 1222–1238.
[87] FENIX Project. http://www.fenix-project.org/.
[88] Mancarella P. Cogeneration systems with electric heat pumps: energy-shifting properties and equivalent plant modelling. Energy Conversion and Management 2009; 50 (8): 1991-1999.
[89] Wille-Haussmann B, Erge T, Wittwer C. Decentralised optimisation of cogeneration in virtual power plants. Solar Energy 2010; 84: 604–611.
[90] Kusch W, Schmidla T, Stadler I. Consequences for district heating and natural gas grids when aiming towards 100% electricity supply with renewable. Energy 2012; 48: 153-159.
[91] Wanga D, *et al*. Hierarchical market integration of responsive loads as spinning reserve. Applied Energy 2013; 104: 229–238.
[92] Mancarella P, Chicco G. Real-time demand response from energy shifting in Distributed Multi-Generation. IEEE Transactions on Smart Grid 2013, in press.
[93] Mancarella P, Chicco G. Integrated energy and ancillary services provision in multi-energy systems. Proceedings of the IX Bulk Power System Dynamics and Control Symposium (IREP 2013). Rethymnon, Crete, Greece, 25-30 August 2013.
[94] Pade LL, Schröder ST. Fuel cell based micro-combined heat and power under different policy frameworks – An economic analysis. Energy Conversion and Management 2013; 66: 295–303.
[95] Almassalkhi M, Hiskens IA. Optimization framework for the analysis of large-scale networks of energy hubs, Proceedings of the 17th Power Systems Computation Conference, Stockholm, Sweden, August 2011.
[96] Connolly D, *et al*. A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy 2010; 87: 1059–1082.
[97] Mendesa G, Ioakimidisa C, Ferraoa P. On the planning and analysis of Integrated Community Energy Systems: A review and survey of available tools. Renewable and Sustainable Energy Reviews 2011; 15: 4836– 4854.
[98] National Resources Canada. RETScreen International. http://www.retscreen.net/.
[99] Leng GJ, *et al*. RETScreen International: results and impacts 1996–2012. Minister of Natural Resources Canada, 2004. http://www.retscreen.net/ang/impact.php.
[100] Lund H. EnergyPLAN software. Available at http://energy.plan.aau.dk/.
[101] Lund H, Munster E. Modelling of energy systems with a high percentage of CHP and wind power. Renewable Energy 2003; 28: 2179–2193.
[102] Gota DI, Lund H, Miclea L. A Romanian energy system model and a nuclear reduction strategy. Energy 2011; 36: 6413-6419.
[103] Østergaard PA. Wind power integration in Aalborg Municipality using compression heat pumps and geothermal absorption heat pumps. Energy 2013; 49: 502-508.
[104] Stadler M, *et al*. Control of greenhouse gas emissions by optimal DER technology investment and energy management in zero-net-energy buildings. European Transactions on Electrical Power 2011; 21 (2): 1291-1309.
[105] Bakken BH, Skjelbred HI, Wolfgang O. eTransport: Investment planning in energy supply systems with multiple energy carriers. Energy 2007; 32: 1676–1689.
[106] Danny Harvey LD. A handbook on low-energy buildings and district energy systems: fundamentals, techniques, and examples. James & James; UK, 2006.
[107] Cardona E, Piacentino A. Cogeneration: a regulatory framework toward growth. Energy Policy 2005; 33 (16): 2100-2111.
[108] Frangopoulos CA. A method to determine the power to heat ratio, the cogenerated electricity and the primary energy savings of cogeneration systems after the European Directive. Energy 2012; 45 (1): 52-61.
[109] Martens A. The energetic feasibility of CHP compared to the separate production of heat and power. Applied Thermal Engineering 1998; 18 (11): 935-946.
[110] Dincer I, Rosen MA. Exergy: energy, environment and sustainable development. Elsevier Science. 2012.
[111] Nesheim SJ, Ertesvåg IS. Efficiencies and indicators defined to promote combined heat and power. Energy Conversion and Management 2007; 48 (3): 1004–1015.

[112] Havelsky V. Energetic efficiency of cogeneration systems for combined heat, cold and power production. International Journal of Refrigeration 1999; 22 (6): 479-485.
[113] Heteu PMT, Bolle L. Economie d'énergie en trigenération. International Journal of Thermal Sciences 2002; 41 (12): 1151-1159.
[114] Minciuc E, Le Corre O, Athanasovici V, Tazerout M. Fuel savings and CO_2 emissions for tri-generation systems. Applied Thermal Engineering 2003; 23 (11): 1333-1346.
[115] Li H, Fu L, Geng K, Jiang Y. Energy utilization evaluation of CCHP systems. Energy and buildings 2006; 38 (3): 253-257.
[116] Chicco G, Mancarella P. Trigeneration primary energy saving evaluation for energy planning and policy development. Energy Policy 2007; 35 (12): 6132-6144.
[117] Chicco G, Mancarella P. A Unified Model for Energy and Environmental Performance Assessment of Natural Gas-Fueled Poly-Generation Systems. Energy Conversion and Management 2008; 49 (8): 2069-2077.
[118] He C, Feng X. Evaluation indicators for energy-chemical systems with multi-feed and multi-product. Energy 2012. 43: 344-354.
[119] Chicco G, Mancarella P. Incremental indicators for assessing the performance of cogeneration systems with heat pumps. WSEAS Transactions on Power Systems 2006; 1 (8): 1491-1498.
[120] Chicco G, Mancarella P. Planning evaluation and economic assessment of the electricity production from small-scale trigeneration plants, WSEAS Transactions on Power Systems 2006; 1 (2): 393-400.
[121] Dincer I. Environmental impacts of energy. Energy Policy 1999; 27 (14) :845-854.
[122] Mancarella P, Chicco G. Global and local emission impact assessment of distributed cogeneration systems with partial-load models. Applied Energy 2009; 86 (10): 2096–2106.
[123] Mancarella P, Chicco G. Distributed cogeneration: modeling of environmental benefits and impact. In "Distributed generation", D.N. Gaonkar (ed.), 2010, pp. 1–26, In-Tech, available at http://cdn.intechopen.com/pdfs/10137/InTech-Distributed_cogeneration_modelling_of_environmental_benefits_and_impact.pdf.
[124] Meunier F. Co- and tri-generation contribution to climate change control. Applied Thermal Engineering 2002; 22 (6): 703-718.
[125] Chicco G, Mancarella P. Assessment of the Greenhouse Gas Emissions from Cogeneration and Trigeneration Systems. Part I: Models and Indicators. Energy 2007; 33 (3): 410-417.
[126] Mancarella P, Chicco G. Assessment of the Greenhouse Gas Emissions from Cogeneration and Trigeneration Systems. Part II: Analysis Techniques and Application Cases. Energy 2007; 33 (3): 418-430.
[127] Mancarella P, Chicco G, Energy and CO_2 emission assessment of cooling generation alternatives: A comprehensive approach based on black-box models. WSEAS Transactions on Power Systems 2008; 3 (4): 151-161.
[128] Wang J, *et al*. Optimization design of BCHP system to maximize to save energy and reduce environmental impact. Energy 2010; 35 (8): 3388-3398.
[129] Mancarella P, Chicco G, Operational optimization of multigeneration systems. In "Electric power systems: Advanced forecasting techniques and optimal generation scheduling", J. Catalao (ed.), CRC Press, Taylor & Francis Group, 2012.
[130] Canova A, *et al*. Emission characterization and evaluation of natural gas-fueled cogeneration microturbines and internal combustion engines. Energy Conversion and Management 2008; 49 (10): 2900-2909.
[131] Torchio MF, *et al*. Merging of energy and environmental analyses for district heating systems. Energy 2009; 34 (3): 220-227.
[132] Genon G, *et al*. Energy and environmental assessment of small district heating systems: Global and local effects in two case-studies. Energy Conversion and Management 2009; 50(3): 522-529.
[133] Carvalho M, Serra LM, Lozano MA. Optimal synthesis of trigeneration systems subject to environmental constraints. Energy 2011; 36: 3779-3790.
[134] Carvalho M, Lozano MA, Serra LM. Multicriteria synthesis of trigeneration systems considering economic and environmental aspects. Applied Energy 2012; 91: 245–254.
[135] Carvalho M, *et al*. Modeling simple trigeneration systems for the distribution of environmental loads. Environmental Modelling & Software 2012; 30: 71-80.
[136] Chevalier C, Meunier F. Environmental assessment of biogas co- or tri-generation units by life cycle analysis methodology. Applied Thermal Engineering 2005; 25 (17-18): 3025-3041.
[137] Loiseau E, *et al*. Environmental assessment of a territory: An overview of existing tools and methods. Journal of Environmental Management 2012; 112: 213-225.
[138] Maraver D, *et al*. Environmental assessment of CCHP (combined cooling heating and power) systems based on biomass combustion in comparison to conventional generation. Energy 2013; 57:17-23.

[139] Peng T, *et al*. Should a small combined heat and power plant (CHP) open to its regional power and heat networks? Integrated economic, energy, and emergy evaluation of optimization plans for Jiufa CHP. Energy 2008; 33: 437–445.
[140] Lazzaretto A. A critical comparison between thermoeconomic and emergy analyses algebra. Energy 2009; 34: 2196–2205.
[141] Sciubba E. On the Second-Law inconsistency of Emergy Analysis. Energy 2010; 35: 3696-3706.
[142] Lozano MA, Carvalho M, Serra LM. Operational strategy and marginal costs in simple trigeneration systems. Energy 2009; 34 (11): 2001–2008.
[143] Cardona E, Piacentino A, Cardona F. Matching economical, energetic and environmental benefits: An analysis for hybrid CHCP-heat pump systems. Energy Conversion and Management 2006; 47 (20): 3530–3542.
[144] Cardona E, Piacentino A, Cardona F. Energy saving in airports by trigeneration. Part I: Assessing economic and technical potential. Applied Thermal Engineering 2006; 26 (14-15): 1427-1436.
[145] Cardona E, Sannino P, Piacentino A, Cardona F. Energy saving in airports by trigeneration. Part II: Short and long term planning for the Malpensa 2000 CHCP plant. Applied Thermal Engineering 2006; 26 (14-15): 1437-1447.
[146] Piacentino A, Cardona F. An original multi-objective criterion for the design of small-scale polygeneration systems based on realistic operating conditions. Applied Thermal Engineering 2008; 28 (17–18): 2391-2404.
[147] Borbely AM, Kreider JF (eds). Distributed Generation: the power paradigm for the new millennium. CRC Press, 2001.
[148] Willis HL, Scott WG. Distributed power generation: planning and evaluation. Marcel Dekker, New York, 2000.
[149] Biezma MV, San Cristobal JR. Investment criteria for the selection of cogeneration plants – a state of the art review. Applied Thermal Engineering 2006; 26:583–8.
[150] Piacentino A, Cardona F. EABOT – Energetic analysis as a basis for robust optimization of trigeneration systems by linear programming. Energy Conversion and Management 2008; 49 (11): 3006-3016.
[151] Aringhieri R, Malucelli F, Optimal Operations Management and Network Planning of a District Heating System with a Combined Heat and Power Plant, Annals of Operations Research 2003; 120: 173–199.
[152] Pini Prato A, *et al*. Integrated management of cogeneration plants and district heating networks. Applied Energy 2012; 97: 590-600.
[153] Arcuri P, Florio G, Fragiacomo P. A mixed integer programming model for optimal design of trigeneration in a hospital complex. Energy, 2007; 32 (8): 1430-1447.
[154] Chicco G, Mancarella P. From cogeneration to trigeneration: profitable alternatives in a competitive market. IEEE Transactions on Energy Conversion 2006; 21 (1): 265-272.
[155] Bagdanavicius A, Jenkins N, Hammond GP. Assessment of community energy supply systems using energy, exergy and exergoeconomic analysis. Energy 2012; 45: 247-255.
[156] Deng J, *et al*. Exergy cost analysis of a micro-trigeneration system based on the structural theory of thermoeconomics. Energy 2008; 33: 1417–1426.
[157] Roque Díaz P, Benito YR, Parise JAR. Thermoeconomic assessment of a multi-engine, multi-heat-pump CCHP (combined cooling, heating and power generation) system – A case study. Energy 2010; 35 (9): 3540–3550.
[158] Piacentino A, Cardona F. On thermoeconomics of energy systems at variable load conditions: Integrated optimization of plant design and operation. Energy Conversion and Management 2007; 48 (8): 2341–2355.
[159] Curti V, von Spakovsky MR, Favrat D. An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part I – Methodology. International Journal of Thermal Sciences 2002; 39 (7): 721-730.
[160] Curti V, von Spakovsky MR, Favrat D. An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part II – Application. International Journal of Thermal Sciences 2002; 39 (7): 731-741.
[161] Siddiqui AS, *et al*. Effects of carbon tax on microgrid combined heat and power adoption. Journal of Energy Engineering 2005; 131 (3): 2-25.
[162] Al-Mansour F, Kozuh M. Risk analysis for CHP decision making within the conditions of an open electricity market. Energy 2007; 32: 1905–16.
[163] Carpaneto E, *et al*. Cogeneration planning under uncertainty. Part I: Multiple time frame approach. Applied Energy 2011; 88 (4): 1059-1067.
[164] Carpaneto E, *et al*. Cogeneration planning under uncertainty. Part II: Decision theory-based assessment of planning alternatives. Applied Energy 2011; 88 (4): 1075-1083.
[165] Dixit AK, Pindyck RS. Investment Under Uncertainty. Princeton University Press, 1994; Princeton.

[166] Wickart M, Madlener R. Optimal technology choice and investment timing: a stochastic model of industrial cogeneration vs. heat-only production. Energy Economics 2007; 29: 934–52.
[167] Westner G, Madlener R. Investment in new power generation under uncertainty: Benefits of CHP vs. condensing plants in a copula-based analysis. Energy Economics 2012; 34 (1): 31-44.
[168] Siddiqui AS, Maribu K. Investment and upgrade in distributed generation under uncertainty. Energy Economics 2009; 31 (1): Pages 25-37.
[169] Kienzle F, Ahčin P, Andersson G. Valuing Investments in Multi-Energy Conversion, Storage, and Demand-Side Management Systems Under Uncertainty. IEEE Transactions on Sustainable Energy 2011; 2 (2): 194-202.
[170] Svensson E, Strömberg AB, Patriksson M. A model for optimization of process integration investments under uncertainty. Energy 2011; 36 (5): 2733-2746
[171] Rong A, Lahdelma R. CO_2 emissions trading planning in combined heat and power production via multi-period stochastic optimization. European Journal of Operational Research 2007; 176 (3): 1874-1895.
[172] Zhou Z, *et al*. A two-stage stochastic programming model for the optimal design of distributed energy systems. Applied Energy 2012, in press.
[173] Westner G, Madlener R. Development of cogeneration in Germany: A mean-variance portfolio analysis of individual technology's prospects in view of the new regulatory framework, Energy 2011; 36: 5301-5313.