

Simulation of Polygeneration Systems

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Abstract: This Special Issue aims at collecting the recent studies dealing with polygeneration systems, with a special focus on the possible integration of different technologies into a single system, able to convert one or multiple energy sources into energy services (electricity, heat and cooling) and other useful products (e.g., desalinized water, hydrogen, glycerin, ammonia, etc.). Renewable sources (solar, wind, hydro, biomass and geothermal), as well as fossil fuels, feeding advanced energy systems such as fuel cells and cogeneration systems, are considered. Special attention is paid to control strategies and to the management of the systems in general. Studies including thermoeconomic analyses and system optimizations are presented.

Keywords: renewable energy; polygeneration; distributed generation; dynamic simulations

1. Introduction

During the last decades, the worldwide energy consumption has increased significantly, mainly due to the economic development of emerging countries. The energy demand is mainly matched by fossil or non-renewable fuels, such as gas, oil, carbon, nuclear, whose availability and environmental impact are becoming a severe issue. Simultaneously, the consumption of fresh water is dramatically increasing, so that, according to several scientists, such resources will become even more crucial than energy [1]. In order to achieve a sustainable development, some significant actions must be taken, aimed at increasing energy efficiency levels, use of renewable and alternative sources and at reducing the environmental impact of energy-related technologies [2].

In this framework, one of the most attractive novel concepts is represented by the polygeneration, which is the simultaneous production of multiple energy vectors (electricity, heat, cooling) and other products (water, hydrogen, glycerin, etc.). In particular, polygeneration systems are very attractive when fed by renewable energy sources, since in this configuration energy efficiency and environmental compatibility are especially high. Despite their high potential, polygeneration systems are still scarcely used. In fact, on average, polygeneration only accounts for 10% of the global power generation. However, in some countries, such as Denmark, Finland and The Netherlands, this ratio may also increase up to 30%–50%. Currently, several countries are promoting the development of efficient and sustainable polygeneration systems: the European Union (EU) considers polygeneration as a strategic technology, in order to meet its target regarding the reduction of greenhouse gas emission. Similarly, USA is promoting polygeneration to cut down energy production costs in the industrial sector. Supporting mechanisms are also available in other countries worldwide [3].

As a consequence, academic institutions and industries are currently performing a significant research effort in order to develop efficient and economically viable polygeneration systems based on the utilization of both fossil and renewable energy sources. As for fossil fuels, researchers are performing several analyses aiming at optimizing cogeneration and trigeneration power plants. Conversely, researchers involved in renewable energy are developing different hybrid layouts where conventional technologies (internal combustion engines (ICEs), Stirling, Rankine, gas turbines, etc.)

are hybridized with renewable energy sources (especially solar and biomass) in a single efficient polygeneration system. In many cases, such polygeneration systems also provide other products, such as desalinated water, hydrogen, etc. [4]. Thus, polygeneration systems typically include a plurality of different technologies, integrated into a single system, so that the development of optimized control strategies becomes a crucial issue [5,6]. A special design effort must be also made to determine the optimal size of each sub-component [7]; with this aim in mind, advanced analysis methods were also used, such as exergy [8,9], exergoeconomic and thermoeconomic analysis [10,11].

Polygeneration also has a strategic role in the development of the distribute generation (DG). This is included in the more general concept of distributed energy systems (DES), which implies the integration of several small-scale DG technologies, instead of a limited number of big, remote power plants (centralized production). In DES systems, the electric energy is produced locally, avoiding transmission losses, promoting the concept of self-sufficiency and reducing the dependence on external energy supply. In DES systems, polygeneration powered by renewable energy is commonly considered the best candidate among the possible DG technologies. Such systems usually integrate district heating and cooling (DHC) networks, and off-grid generation islands which are connected by a private network [3].

As mentioned before, the number of possible polygeneration layouts is virtually infinite since it is possible to combine all the available fossil and renewable conversion technologies. Obviously, the most common layout is based on cogeneration and trigeneration systems. Piacentino et al. [12] developed a study in order to evaluate the eligibility criteria to be used to consider highly efficient combined heat and power (CHP) systems. These criteria play a strategic role in the development of polygeneration systems, especially for building application, where economic viability is more difficult. In this study, three different buildings with different users are identified. For all the cases, the optimal layout and control strategy of the polygeneration system is determined, also evaluating the effects of the eligibility criteria on the economic performance of the system [12].

Dozens of papers investigate polygeneration systems integrating biomass-based conversion technologies. Calise et al. [13] investigated a hybrid system including a solar heating and cooling subsystem, where a reciprocating engine fed by vegetable oil was included. The engine waste heat is used as a backup for space heating or to drive an absorption chiller for space cooling purposes. The system was dynamically simulated in transient system simulation tool (TRNSYS) from both energy and economic points of view. The results showed that the system may be profitable, especially in case of public financial support [13]. Other studies used polygeneration systems in order to produce a specific product. For example, Lythcke-Jørgensen et al. [14] integrated biofuel production in a polygeneration system in order to reduce the operating costs and increase the energy efficiency. In particular, they integrated a Rankine steam cycle within an ethanol facility using steam extracted from the turbine to supply the heat required for ethanol production. Then, detailed simulations and optimizations were carried out. A similar study was also recently presented by the same authors integrating wood chip gasification and methanol production [15]. Methanol production and power generation by solar and biomass sources were also investigated by Bai et al. [16]. Here, the heat produced by concentrating solar thermal collectors drives biomass gasification. Syngas is used to produce methanol. Then, exhaust gases supply a combined cycle producing electricity. This is considered to be an efficient approach to simultaneously use biomass and solar sources [16]. In many cases, biomass-based polygeneration systems use cheap biomass as fuels. In fact, the possibility to fuel such polygeneration systems by agricultural wastes is extremely promising. An example of this configuration is presented by Jana and De [17,18]. They used rice straw, sugarcane bagasse and coconut fiber dust. The polygeneration system was modelled in Aspen and the results showed that the proposed system is very interesting, specifically for rural communities [17,18].

Several papers also investigated the integration of polygeneration systems with solar collectors. For example, in reference [19], an existing trigeneration system was hybridized with a solar field equipped with concentrating photovoltaic thermal (CPVT) collectors. The system includes a gas

turbine, CPVT collectors, absorption chillers, tanks and balance of the plant (BOP) devices. The system supplies electricity, heat and cooling to a lot of hospital buildings. The system was dynamically simulated and economical parameters were also evaluated. The system profitability was found to be acceptable (pay-back period equal to 12 years), even in the absence of public funding [19]. Dynamic simulations were also used by Soutullo et al. [20], who analyzed the performance of centralized polygeneration technologies using district networks. The analysis was performed for three representative Spanish buildings, located in different cities. The system, modelled in TRNSYS, includes: biomass boilers, polymer electrolyte membrane fuel cells (PEMFCs), photovoltaic (PV) collectors, solar thermal collectors and wind turbines. Such technologies were analyzed in different configurations. The results of the simulations showed that the optimal configuration is obtained by adequately combining the renewable technologies used [20]. The work by Soutullo et al. is not the only one considering the integration of fuel cells into polygeneration systems. In fact, fuel cells are known as the most efficient small-scale power plant. As a consequence, its integration into efficient polygeneration systems is extremely attractive. Therefore, a number of possible configurations are investigated in literatures, such as solid oxide fuel cells (SOFC) [21] or PEMFCs [22] integrated with solar heating and cooling systems, as well as PEM integrated with CPVT and an electrolyzer [23].

Finally, it is also worth noting that polygeneration systems are becoming more and more attractive due to their capability to produce desalinated water along with electricity, heating and cooling. This is a very interesting configuration, especially for isolated communities where a single optimized system can be used to provide, simultaneously, all the energy vectors and potable water [1]. In fact, in such cases, the availability of fossil fuels (and the related power plants) or fresh water is extremely scarce, whereas they are often rich in renewable sources (solar, wind, biomass and in some cases geothermal) and in many cases are close to the sea [24]. Several simulation models are available in literature regarding polygeneration systems integrated with seawater desalination. In reference [1], an innovative solar heating and cooling system based on CPVT collectors was hybridized with a multi effect distillation (MED) desalination unit which was powered by solar excess heat and by a biomass fired boiler [25]. A similar system was investigated for the island of Pantelleria, where the biomass heater was replaced by a geothermal well [24]. In both cases, the performance predicted through dynamic simulations, supported by appropriate economic models, was excellent. A similar layout was also investigated by Mohan et al. for United Arab Emirates locations, showing results similar to those cited before [26]. Alternative configurations were also studied where CPVT collectors are replaced by conventional parabolic solar collectors, coupled with geothermal wells. In this case, geothermal and solar energy are supplied to an organic Rankine cycle, producing electricity. The exhaust brine is subsequently used for both space heating and cooling purposes and to supply heat to a MED unit [27]. This idea was also investigated in a preliminary study by Maraver et al. [28].

2. Contents of the Special Issue

In polygeneration systems, a major issue is represented by the power quality impact of renewable energy based DG systems. This problem was investigated in several papers, in which many different optimization techniques were implemented, such as particle swarm optimization (PSO), honey bee mating, honey-bees mating optimization (HBMO) and others. However, only a few of these papers considered the stochastic nature of RES-based DG systems. Such improvement is presented in this Special Issue by Peng et al. [29], who present a novel approach to solve the problem of the optimal allocation of DG systems. The authors modelled wind turbines and PV panels using Weibull and Beta distributions, respectively. The load was modelled using a normal distribution. The optimal DG allocation (ODGA) was investigated using a multi-objective approach integrating pollutant emissions, total DG costs and system power losses as objective functions. Obviously, the system is subject to both deterministic and chance constraints. This problem was investigated by embedding the crisscross optimization algorithm with Monte Carlo simulation. The crisscross optimization is used to search the best solution among a set of feasible solutions, whereas the Monte Carlo method is used to deal

with system uncertainties and to solve the power flow problem. This novel approach was tested on two benchmark cases widely used in ODGA problems, namely IEEE 33-bus and IEEE 69-bus systems. The novel algorithm is shown to be about 25% faster than PSO. The novel approach also ensured a better stability of the voltage with respect to the case of the PSO technique. In summary, the development of such optimization techniques is very useful to design polygeneration systems including many different power plants, especially when powered by renewable energy sources.

As many researchers pointed out, the most common arrangement of polygeneration systems is based on trigeneration plants integrated into DHC networks. In this case, the system layout may be simple when compared with complex polygeneration systems including a plurality of different devices. Nevertheless, the management of such systems is not trivial, since power, thermal and cooling demands may significantly vary during the day. This problem was addressed by Conte et al. [30], who investigated the optimal management of absorption chillers integrated into trigeneration systems. Their study starts from the analysis of the state of the art, showing that, in many cases, modularity and flexibility of modern and efficient trigeneration systems are not sufficient to properly work in DHC when the partial load ratio is very low. Trigeneration systems are typically equipped with different chiller technologies (vapor compression, single and double effect absorption chillers): the time-dependent cooling demand should be redistributed among these types of chiller in order to achieve the maximum efficiency and the lowest operating cost. In conventional systems, such chillers are managed using a sequential approach where all the chillers operate at the same part load ratio. This strategy is typically implemented to operate at a constant chiller flow rate and to achieve the same chilled water outlet temperature among the chillers. However, this simple control strategy may be significantly improved using optimized sharing load approaches, as shown by several studies available in literature. The novelty of the work presented by Conte et al. [30] lies in the utilization of real data taken from an existing trigeneration plant located near Barcelona (Spain). Thermal and cooling capacities are 1.40 MW and 8.75 MW, respectively. It is based on three reciprocating engines with an electric capacity of 3.35 MW each. The engine exhaust gases drive double-effect chillers, whereas the jacket water is used to drive a single-effect chiller. The system operates about 5000 h per year. As mentioned before, the system was monitored measuring temperatures, flow rates and heat flows. The trigeneration system was modelled using a general algebraic modelling system (GAMS) in order to optimize system operation using a mixed integer linear programming (MILP) approach. The authors investigated the load sharing strategy for a typical day, varying cooling load distribution as a function of the different chillers part-load performance. The analysis showed that the single-effect absorption chiller exhibits the lowest efficiency, but its operation is beneficial in order to maximize engine heat recovery and reduce the cost of engine cooling energy rejection. The coefficient of performance (COP) of the single and double-effect chiller were 0.65 and 1.0, respectively. Such results are acceptable, considering that they typically operate at 40% of their nominal capacity. The optimization performed using economic objective functions showed that the operation of the double-effect chiller should be preferred to that of the single-effect device. In future works, the authors aim to analyze the simultaneous use of such chillers in different part-load combinations.

One of the most promising peculiarities of the polygeneration system lies in the possibility of hybridizing existing technologies, based on fossil fuels, with renewable energy sources. Several works are available in literature, presenting the integration of renewable technologies (solar, geothermal, wind, etc.) into different conventional systems (trigeneration, DHC, etc.). In this framework, an interesting work is here presented by Arsalis et al. [31], showing a thermoeconomic analysis of a PV-assisted 1 MW combined cooling, heating and power system. In the work, a combined cooling heating and power (CCHP) plant driven by liquefied natural gas (LNG) is combined with a PV solar field. The system includes a gas turbine cycle, absorption chillers, heat exchangers, LNG storage, PV solar field and BOP components (pumps, valves, etc.). The system is modelled and simulated in an engineering equation solver (EES). The models are based on conventional thermodynamic analyses and/or on manufacturers' data. The system is assumed to be completely autonomous. Therefore,

no electricity or thermal energy must be exchanged with external systems. A cost model is included, in order to calculate both capital and operating costs. The model validation is based on performance data available in literature. The system was simulated both at part-load and full-load, aiming at evaluating energy and economic performance parameters. The results show that the primary energy ratio is almost constant at all load condition. The simulations performed on an annual basis showed that the CCHP can completely fulfill the load profile of 436 households. In addition, without PV integration, the system must generate an additional 1959 MWh/year of electricity by LNG conversion. Finally, a parametric analysis was also performed, showing that, for larger PV solar fields, a lower amount of heat and cooling is generated by the CCHP system, as a consequence of the lower electrical production by the gas turbine. In this case, a lower average efficiency of the gas turbine is achieved due to its part-load operation. However, this drawback is balanced by the PV electrical production, showing that the primary energy ratio increases in case of larger PV areas. The economic analysis shows a minimum of the life cycle cost (LCC) around a PV capacity of 300 kW. The non-monotonic trend of LCC is justified by the fact that for large PV capacity a significant amount of electricity must be dissipated, since the system is not grid connected.

Polygeneration systems can be designed at different capacity levels. The works cited before analyze medium-large size systems. Nevertheless, small polygeneration systems can also be designed for small buildings or single family houses. In these cases, polygeneration systems are usually obtained by the hybridization of trigeneration systems with solar systems, as also investigated by Marrasso et al. [32]. The development of small-scale efficient systems is crucial to achieve the targets in terms of reduction of fossil fuels and emissions. In fact, in Europe, the residential sector consumes about 40% of the total final energy use demand. In the last few years, the residential sector consumption also surpassed the industrial one and it contributed to about 46% of the EU global greenhouse gases emissions. The authors pointed out that this increase is mainly due to the growing demand of cooling energy. In this framework, solar heating and cooling is a very promising technology. However, for such systems, large roof areas are typically required in order to match the cooling demand. This circumstance makes solar heating and cooling poorly feasible in historical buildings, where the roof area available is typically small. Therefore, the authors of this work proposed a novel arrangement, where the solar thermal collectors are coupled with a micro CHP system based on a reciprocating engine and an absorption chiller. The system was used to supply energy to a three-storey office building located in Naples, Southern Italy. Specific profiles were used in order to determine daily electrical demand and occupancy schedule. Based on these and other data, the building was dynamically simulated in TRNSYS. The system primarily uses solar energy: the cogenerator is activated only when the tank top temperature falls below a certain set point. An electrical backup heater is also considered during peak heat demands. During the winter, heat is supplied to the zones providing space heating. Conversely, in summer heat is used by the absorption chiller to provide space cooling. The results show that during the heating season, the solar fraction increases as a function of the tilt angle. Conversely, in summer, the opposite trend is detected. The tilt angle, along with other design parameters, were determined through a thermoeconomic optimization. Then, in the optimal configuration, the average efficiency of the solar collectors was 49%. The electrical efficiency of the cogenerator was approximately 26%; the thermal efficiency was higher than 60%. The electrical balance shows that the electricity drawn from the grid is higher than that provided by the CHP, both in winter and summer. Finally, the authors performed a parametric analysis varying the storage tank volume. Such analysis showed that solar fraction increases as a function of the storage capacity.

Polygeneration systems based on the coupling of CHP and solar energy systems may be used in a plurality of applications. As an example, Rey et al. [33] developed a micro CHP system to be used in recreational sailing boats used as mobile homes; these users are not considered much in literature, but they are very sensitive to solutions able to improve their self-sufficiency. They designed, built and tested, in different European Climates, a micro-CHP system devoted to recreational sailing boats. The micro-CHP system was developed on the basis of the Honda GX360 gasoline two cylinder engine

as prime mover. The engine was originally liquid-cooled, and was modified in order to recover the heat from its jacket. In addition, two three-ways valves were installed in order to recirculate coolant and exhaust gases to the storage tank coils. Such a micro-CHP system was constructed and tested in the laboratory under steady state conditions. As mentioned before, a sailing boat for recreational use was considered as a mobile home. The system was dynamically simulated in a TRNSYS environment using Meteonorm weather data. The authors present their experimental results showing electrical and thermal capacities of 0.653 kW and 5.414 kW, respectively. In order to test the suitability of the CHP, the system was simulated in three different locations (Helsinki, Breskens and Malaga). In all these cases, the CHP system was adequate in supplying energy to the end users. Then, the performance of the ICE was compared with similar systems based on a Stirling engine, and the results were similar as for electric and thermal energy production, for all the locations considered. Finally, a sensitivity analysis was performed as a function of the battery size. The related results showed that the optimal capacity of the battery was double with respect to the initial configuration, leading to a significant increase (11%) of the electrical production.

Nowadays, the integration of renewable energy technologies within buildings is of crucial importance for the reduction of energy consumption of the building sector, which is responsible for about 40% of global energy consumption. In this framework, the development and the adoption of building energy performance simulation (BEPS) tools is crucial and highly recommended for promoting the building integration of renewable energy technologies, toward the design of the next generation of buildings (e.g., NZEBs). The development and validation procedure relative to a BEPS tool, also adopted for performing innovative building-plant simulation, based on renewable technologies, is reported by Buonomano [34]. The author describes the steps of the development and validation procedure of a BEPS tool, named DETECT. After outlining the general framework relative to BEPS tools, the author discusses: (i) the main features of DETECT, with a particular focus on the innovative capabilities recently implemented for research purposes analyses; (ii) the steps and results of a validation procedure, based on the BESTEST standard [35], carried out to assess the code reliability. Specifically, the simulation model, based on a nodal description of the building obtained by assuming a one-dimensional thermal domain, allows one to carry out comprehensive and whole building energy performance and comfort analyses, by properly taking into account the passive and active effects due to the building integration of innovative building integrated technologies, such as building integrated photovoltaic/thermal (BIPVT)-building integrated solar thermal systems (BISTS), phase change materials (PCM), etc. The validation of the code is obtained through the well-known BESTEST standard, developed for testing, diagnosing and validating the capabilities of new BEPS tools. In this regard, it is worth noting that for validating novel BEPS tools, several general criteria and standard procedures have been developed and are available in literature. They consist of comprehensive and integrated suites, such as BESTEST, of building energy analysis tool tests and their adoption has been recently emphasized by the EU Energy Performance Building Directive (EPBD). In order to help readers to understand the sources of errors, as well as eventual bugs to be detected and fixed, arising during the development of a BEPS tool, the author detailed the refinement iterative process carried out for minimizing the differences between the DETECT simulation results and the reference ones, suitably provided within the reliability test suite. All the results were in good agreement with those provided by the BESTEST [34].

The integration of solar technologies within buildings was also investigated by Marín-Sáez et al. [36]. In particular, the authors of this work focused on a building integrated holographic CPVT system, simulated from both optically and energy viewpoints. The utilization of concentrating PV systems is very promising, since in this case a lower amount of PV material per unit receiver area is required. As a consequence, capital costs may be potentially lower than for conventional PV systems. In addition, when CPVT configuration is considered, excess thermal energy determined by the PV overheating caused by concentration may be delivered to some thermal user. Cooling the PV also enhances its electrical performance. A further strategy to prevent PV overheating may consist of the spectral

selection of incident irradiance. Holography is the technology which concentrates sunlight and simultaneously selects the irradiance based on its spectral characteristics. Several studies are available in literature presenting different analyses of holographic optical elements (HOE). However, none of these also evaluated the dynamic performance of the system when integrated within the building. This gap is here covered by the work of Marín-Sáez et al. [36]. The authors analyzed a building integrated PVT systems which is designed to be superimposed on the blinds of a solar louvre shading system. The system is equipped with a cylindrical holographic lens. The simulations are performed calculating the direct normal irradiance spectrum by the SMARTS radiative model, which relies on the following parameters: air mass, aerosol optical depth, precipitable water, and Angstrom exponent. This model is subsequently validated versus experimental data, showing a good agreement. The optical model is based on the Kogelnik's coupled wave theory and the approximate scalar theory established by Syms [37]. Finally, energy simulations are carried out in TRNSYS; in particular, the system was evaluated under the weather conditions of Sde Boker (Israel) and Avignon (France), for specific case studies. In order to perform a comprehensive simulation, the optimal model, developed in MATLAB, was also integrated in TRNSYS environment. In addition, the developed PVT collectors were coupled with a conventional solar thermal system, obtaining a "combysolar" system able to supply the building with space heating, domestic hot water and electricity. Simulations were performed for the two above mentioned climatic conditions. The authors found that the optical efficiency in Avignon is higher than that calculated for Sde Boker. In addition, for both cases, optical efficiency dramatically decreases in the summer. The maximum monthly average optical efficiency is about 81% (Avignon, December). A similar trend is also detected for the efficiency related to space heating. However, in this case, Sde Boker exhibits higher values. Solar fractions, related to domestic hot water production, were 79.3% and 95.5%, for Sde Boker and Avignon, respectively. The solar fraction for space heating was above 15% in both locations. The solar fraction for electric energy was slightly below 10% in both cases.

3. Conclusions

Due to the recent development of small-scale energy technologies and renewable energy sources, energy systems are rapidly changing from the classical centralized model to new, de-centralized configurations, mostly focused on the use of renewable sources and therefore including energy storage devices, needed to face the unprogrammability of most renewable sources. In this framework, a very promising solution is represented by polygeneration systems, using multiple energy sources to generate multiple products (electricity, thermal energy, hydrogen, ammonia, etc.). In fact, such systems are potentially able to ensure high energy efficiency, environmental compatibility and high flexibility, with respect to conventional systems, even from an economic point of view: for example, they can be more efficient in facing fluctuations of energy prices and changes in end-product demand. In other terms, the systems for DG, that are often intended only for power production, can become much more energy-efficient and interesting when many technologies are combined to simultaneously provide heat, power and other energy products within a single, integrated process.

Due to their intrinsic complexity and to the large amount of different possible configurations, an important research effort is needed on polygeneration systems, in order to correctly address their design, optimization and control and to develop efficient decision support tools for designers, policy makers and end users. This is one of the reasons for the recent, significant growth in the number of scientific papers dealing with this type of system. This Special Issue intends to contribute to such research effort.

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

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