Article

Innovative Renewable Technology Integration for Nearly Zero-Energy Buildings within the Re-COGNITION Project

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Abstract: With the 2010/31/EU directive, all new buildings shall be nearly zero-energy buildings (nZEB) from 2020 onward, with the aim of strongly reducing the energy consumption related to the building sector. To achieve this goal, it is not sufficient to focus on the design of the building envelope; smart and efficient energy management is necessary. Moreover, to ensure the adoption of RES systems in the built environment, innovative technologies need to be further developed in order to increase their cost-effectiveness, energy efficiency and integration capability. This paper proposes a synthesis, design and operation optimization of an integrated multi-energy system composed of traditional and innovative renewable technologies, developed within the European project Re-COGNITION. A biogas-based micro cogeneration unit, lightweight glass-free photovoltaic modules, a passive variable geometry small wind turbine optimized for an urban environment and latent heat thermal storage based on phase change materials are some of the technologies developed within the Re-COGNITION project. The optimization problem is solved to contemporarily evaluate (a) the optimal design and (b) the optimal operations of the set of technologies considering both investment and operating costs, using mixed integer non-linear programming. The optimization is applied to the four pilots that are developed during the project, in various European cities (Turin (Italy), Corby (United Kingdom), Thessaloniki (Greece), Cluj-Napoca (Romania). Simulation results show that the development and optimal exploitation of new technologies through optimization strategies provide significant benefits in terms of cost (between 11% and 42%) and emissions (between 10% and 25%), managing building import/export energy and charge/discharge storage cycles.

Keywords: multi-energy system; MINLP; mixed integer nonlinear; optimization; energy systems

1. Introduction

Most of the energy for heating and cooling in the European Union comes from fossil fuels (82%). Nevertheless, the EU is committed to develop a sustainable, competitive, secure and decarbonized energy system by 2050 [1]. The residential sector plays a significant role in achieving this objective, as it is responsible for about 40% of the primary energy consumed and it is responsible for 36% of carbon emissions in the atmosphere [2]. From this perspective, the Energy Performance of Buildings Directive (EPBD) requires all new buildings from 2021 to be nearly zero-energy buildings (nZEB), which are defined as "buildings whose energy requirement should be very low and significantly covered by renewable" [1]. Moreover, the EPBD guidelines further encourage nZEB design towards the long-term 2050 goal of reducing greenhouse gas emissions in the Union by 80–95% compared to 1990 [1].

The reduction of energy consumption and the use of energy from renewable sources are the key elements to improve the energy efficiency of European buildings and achieve a highly energy efficient and decarbonized building stock. Legislation barriers such as

limitations in the self-consumption scheme, high investment costs and sociocultural resistance to change due to lack of information or awareness are some of the challenges to face. From a more technical point of view, the intermittent availability of resources and conversion efficiency are issues still affecting renewable energy source (RES) diffusion. These problems can be partially overcome with an integrated design approach able to handle the complex interplay of energy production/consumption/storage and the interaction with the energy grid. Moreover, the inappropriateness of traditional renewable technologies for building integration limits the transition. On one hand, technologies such as photovoltaics (PV) are quite widespread and mature, on the other, solutions such as wind turbines or combined heat and power technologies are widely used on a large scale but are still not tailored to the residential building level. The latter need further development in order to guarantee more attractive investment costs, efficiency and facilitate RES integration in the built environment.

In this framework, another crucial aspect concerns the design and the operation of multi-renewable energy systems. Some researchers focused on the envelope design optimization, considering the impact of direction, shape, materials and dimensions of the building envelope on load profiles and on other parameters such as PV generation; among them are [3–6]. Other studies analyzed the possible interaction between building envelope and building energy systems, proposing multi-stage optimizations, such as [7–10]. Moreover, there are a variety of studies that focused on the optimum scheduling of a multi-generation system through effective energy management techniques, as shown in [11–14]. Typical key performance indicators refer to total costs, CO_2 emissions and primary energy consumption. Nevertheless, a different approach consists of considering a multi-criterion evaluation, taking into account that different parameters could affect the results in opposite ways: among them, several studies have investigated strategies to simultaneously reduce energy costs and environmental impacts [15–18].

Within the nZEB context, the principle of cost optimality has gained greater relevance. Ferrara et al. [19], comparing several scientific works on the cost-effective feasibility of nZEB, asserted that in most of the examined cases, energy efficiency measures related to the building envelope did not emerge as drivers of cost-optimal building design, contrary to the measures related to energy systems, which typically have a great impact in reaching cost optimality. Another important consideration that was done in [19] is that the implementation of RES has experienced a rapid decrease due to the current national policies for incentives and for energy-selling prices. This explains the selection of gas-based technologies in cost-optimal solutions in place of energy components such as electric heat pumps that can be easily supplied by renewable energy sources.

From another point of view, different optimization algorithms or energy modeling software have been used to define energy system design and optimize their operational strategies. Among the deterministic algorithms, the most common are linear programming (LP), mixed integer linear programming (MILP) and mixed integer non-linear programming (MINLP). MILP and MINLP are found to be more practical in energy management problems compared with linear and non-linear programming, e.g., binary and integer variables are used to express the selection, the number, or the on/off status of the operation of the equipment or for modeling energy system component characteristics such as limits on their operating range. Ashouri et al. [20] presented a design framework for the optimal selection and sizing of a smart building system implemented using MILP techniques. In [21] the effect of an INVELOX wind turbine on the energy management of a plus-ZEB was investigated for a year with considerations of cost and pollution priority. The problem was modeled as a MILP, the Epsilon constraint method was utilized to solve the multi-objective problem and the fuzzy satisfying approach was used to choose the best solution of the Pareto front. Although MINLP requires additional computational effort compared to the other methods, it can handle the non-linear objective function or non-linear constraints such as the nonlinearities of part-load performances. In [22], a MINLP-based scheduling control of building energy systems was compared to the corresponding non-linear problem

(NLP); the analysis highlighted that the MINLP solution is more feasible and realistic in terms of on/off frequency and minimum load ratio of the system components. Bruno et al. [23] proposed a MINLP model that incorporates rigorous performance equations for the synthesis, design and analysis of industrial plants. Moreover, Arcuri et al. [24] presented a trigeneration system for optimizing the energy management of a hospital complex, whereas Schilalu et al. [25] proposed an optimal control strategy for the power dispatch of a system composed by PV modules, grid, battery, a heat pump water heater and a diesel generator, both obtained using a mixed integer non-linear program.

If on one hand, the general background highlights an urgent need for a deep market transformation by deploying efficient and cost-effective technologies in the building sector to support the real implementation of nZEB, on the other hand the literature review shows that energy efficiency measures related to energy systems play a key role for cost-optimal nZEB design and these can be adequately evaluated only through optimization tools. From this perspective, it is clear that innovative renewable technologies suitable for building-level application need to be studied and developed. In this context, the European project Re-COGNITION [26], which aims at achieving nZEB through the smart integration of innovative building-level renewable energy technologies, fits perfectly. In order to reach this target with a significant investment cost reduction, alternative low technology readiness level (TRL) technologies for residential applications and tools for the optimal design and management of the energy systems are developed within the project.

The main goal of the present paper is to determine whether the innovative technologies developed within the European project Re-COGNITION are beneficial from both the efficiency and the cost perspective with respect to more traditional technologies. To achieve this goal, an appropriate MINLP optimization tool is proposed, which must be able to select which technologies from a given set of traditional and innovative energy components should be installed, taking into account their investment costs. More in detail, the model allows for an optimal selection and sizing of the conversion and storage systems to install in single buildings and a short-term planning of the energy system. As novel technologies are proposed in the project, existing models are not able to deal with them. The main innovations in the paper are thus (a) novel models of innovative technologies suitable for integration in system-level optimization approaches and (b) an approach for the combined optimal design and operation of systems tailored for nearly-zero energy buildings.

The paper is structured as follows:

- Section 2 introduces the Re-COGNITION project and details innovative technologies developed within the European project;
- Section 3 formulates the mathematical optimization problem used to obtain the outcomes;
- Section 4 includes a multi-energy system description and exposes the case study;
- Section 5 presents and discusses the simulation results;
- Section 6 draws conclusions obtained from the study and discusses future research work.

2. Re-COGNITION Project

The Re-COGNITION project has three main goals:

- Implement a number of different technological configurations that include renewable energy sources (such as solar, wind and bioenergy) and storage systems.
- Develop software to improve self-consumption in the building/building block.
- Develop a platform for the best design of the renewable technology configuration and the optimal management of the technologies installed during the operations.

In the following subsections the detailed descriptions of the RES for building applications that are developed within the project are reported.

2.1. Micro Combined Heat and Power Unit (mCHP)

Combined heat and power generation plays a strategic role, compensating the intermittency of RES. EnerTwin Heat&Power, developed by MTT, is a small-scale cogeneration system based on a microturbine able to operate with biogas. This is done using an innovative combustor that can deal with a wide range of methane concentrations. The main challenge is to obtain stable combustion during cold start, hot restart, full load and partial load and, at the same time, keep the level of emissions for NOx and CO compliant with legislative limitations. Appropriate materials are adopted to sustain aggressive flue gases. The technology is developed using turbocharger components of an internal combustion engine in order to minimize investment cost. The nominal electric power is 3 kWe and the electrical and the overall efficiency are, respectively, 20% and 92%, if the methane fraction in biogas is greater than 60%.

2.2. Lightweight Photovoltaic (LW-PV)

Lightweight PV allows us to overcome the problem that in some particular contexts, such as in older buildings, the deployment of solar PV can be limited by the load-bearing capacity of the different building parts (i.e., roof, facade, etc.). Lightweight PV is built through composite materials and polymer films replacing standard glass/glass configuration for the back sheet and the front sheet, respectively. Indeed, within the H2020 Re-COGNITION project, the École Polytechnique Fédérale de Lausanne (EPFL) is manufacturing lightweight glass-free solar PV modules designed for integration in the built environment, particularly targeting the retrofitting of existing buildings.

Conventional modules manufactured in a glass/foil structure or in a glass/glass structure may weigh, respectively, 10–12 kg/m^2 and 15–25 kg/m^2, depending on the glass thickness and the eventual presence of an aluminum frame. According to this approach, the front glass cover is replaced by a transparent polymer film and a composite back sheet (made of a honeycomb structure reinforced with two skins of glass fibers) is used to provide thermo-mechanical stability to the modules. This allows the PV module to weigh 5–6 kg/m^2 [27–30]. A careful selection of the materials and the process parameters is required to make the modules robust and resistant to external weathering factors (e.g., hail impacts, mechanical loads, thermal cycles, ultraviolet rays, moisture, etc.).

Within the H2020 Re-COGNITION project, the aim is to upscale the size of LW-PV modules and pre-qualify them according to the relevant industry standards. CSEM [31] will work on changing the visual appearance of the LW modules by applying colored coatings or using alternative approaches. By reflecting or absorbing visible light, colored PV modules have a lower performance than conventional modules. On the other hand, the ability to change (or even to mask) the visual appearances of the modules makes them potentially more appealing for various stakeholders, including architects or building owners. In this research, standard LW-PV are examined in simulations. Rooftop installation is considered with an inclination angle of 30° and an azimuth angle equal to 0°.

2.3. Vertical Axis Wind Turbine (VAWT)

The proposed wind turbine, designed by WindCity srl [32,33], is a passive variable geometry vertical axis wind turbine (VAWT) with small-scale rating, according to IEC 61400-2 [34]. The turbine is designed for rooftop and/or ground installations; the overall dimensions are 1.5 m × 1.5 m, according to the idea of enhancing building scale integration (Figure 1a). The innovative geometry allows the performance in the turbulent urban wind to be increased (by high torque, high acceleration and quick start, also with low wind speed from all the directions) since any blade is able to self-adapt to different wind conditions. The passive variable geometry relates the variation of the pitch angle passively controlled during rotation (maximum value at startup and zero at full speed), to the variation of the radius r and/or the rotation angle. This effect is necessary because the conventional Darrieus machines, once started and in full operating conditions, provide their maximum output when the pitch angle is zero. Figure 1b schematically shows the three degrees of

freedom, in addition to Z, which is the rotation axis. The scope of the design is to make a wind turbine suitable for urban boundary layer flows, characterized by high turbulence and variable wind speeds in space and time, where conventional wind turbines perform poorly [33]. The designed modules may vary from 1000 to 2000 W power and can be installed as a building-integrated rooftop system. The embedded power converter can be directly interfaced with a similarly rated solar inverter for grid-tied applications. In the present work, the output power of the proposed turbine is 2000 W (reached with a wind speed of 16 m/s) and rooftop installation is considered.
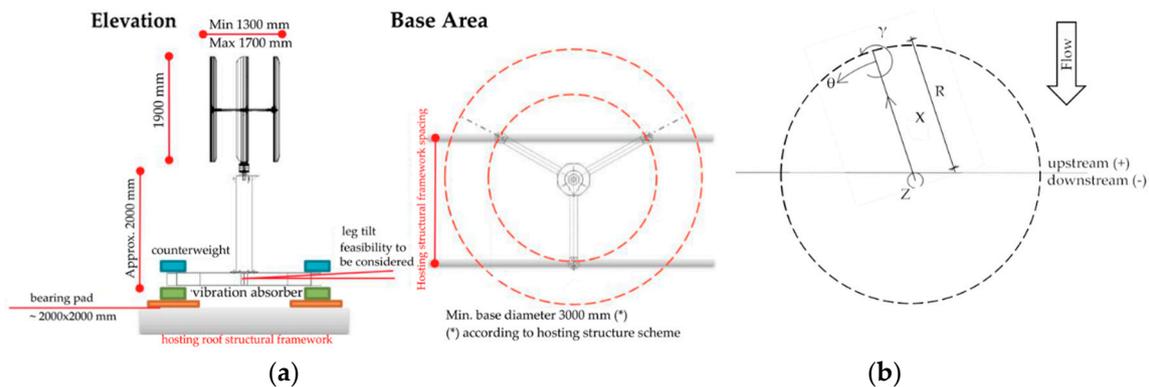

Figure 1. (**a**) Overall dimensions of the vertical axis wind turbine (VAWT) for rooftop installation;(**b**) schematic geometry of the passive variable geometry VAWT.

2.4. Latent Heat Thermal Storage (LHTS)

In latent heat storage, energy is stored and released through the phase change of a storage medium. This allows a higher storage density to be achieved in respect to the conventional water storage since a large amount of heat is absorbed at a constant temperature during the melting phase. This leads to a smaller storage volume (2–3 times smaller than water storage). This aspect is important in buildings where the space available for technology installation is limited. The main problem with latent heat storages is due to the low thermal conductivity within the phase change material. For this reason, the heat exchanged is usually enhanced through various techniques. The most widespread method is the adoption of finned pipes. In the Re-COGNITION project, a LHTS is developed with an optimized fin design that allows the thermal power exchanged during the discharging process to be maximized.

3. Methodology

The multi-energy system considered in this study has the primary objective of supplying the electricity–heating–cooling demands of a residential building through the optimal allocation of energy production by different power generation systems.

The developed algorithm for the optimization has a twofold objective:

1. Select the set of technologies that ensures minimal operational costs and simultaneously keeps the investment cost as low as possible.
2. Find the optimal scheduling for the selected technologies.

Therefore, the algorithm defines not only the optimal energy flows exchanged between the various subsystems, but also which technologies are more useful to install on the basis of their initial cost and their effective use during the day.

3.1. Formulation of the Optimization Problem

The optimal scheduling problem is mathematically formulated as a mixed integer non-linear problem (MINLP), since

- Binary and integer variables are introduced to obtain the technologies selection and size of the installed units related to their capital cost.
- The efficiencies of the production and conversion technologies depend on the operating conditions. Consequently, the correlation between the source and energy carrier produced is nonlinear.

Juniper [35], an open-source (under the MIT license) MINLP solver implemented in Julia, is used as optimization algorithm in this study. Ipopt and Cbc are the NLP (non-linear programming) subsolver and the MIP (mixed-integer programming) subsolver, respectively. The decision variables can be divided in two categories: the operation decision variables x_{op} and the design decision variables x_{des}.

More in detail, the decision variables are:

1. The input power of the conversion technologies—$x_{op,c}$;
2. The stored energy of the storage technologies—$x_{op,st}$;
3. The imported and exported electrical power from/to the grid—$x_{op,grid}$;
4. The size of some conversion technologies—$x_{des,size}$;
5. The number of some system components—$x_{des,num}$;
6. The on/off status of storage technologies—$x_{des,st}$.

Variables 1, 2 and 3 are operation variables, so they are determined at each timestep of the simulation, whereas variables 4, 5 and 6 are design variables.

Considering $f(x_{op}, x_{des})$ as the objective function to be minimized, the MINLP problem can be written in general form as:

$$\min f(x_{op}, x_{des}) = \sum_{t=1}^{Nts} c(t)\, x_{op}(t) + d\, x_{des} \tag{1}$$

subject to

$$\begin{aligned} 0 &\leq x_{op,c} \leq x_{op,c,max} \\ x_{op,st,min} &\leq x_{op,st} \leq x_{op,st,max} \\ 0 &\leq x_{op,\,grid} \leq \infty \end{aligned} \tag{2}$$

and

$$\begin{aligned} 0 &\leq x_{des,size} \leq x_{des,size,max} \\ x_{des,num} &\in [0,\,1,\,2,\,3\ldots] \\ x_{des,st} &\in [0,1] \end{aligned} \tag{3}$$

and finally

$$\begin{aligned} h(x_{op}) &= 0 \\ g(x_{op},\,x_{des}) &\leq 0 \\ A_{st}\, x_{op,st} &\leq b_{st} \end{aligned} \tag{4}$$

where t is the time interval, considered equal to 15 min; c is the unit cost vector (i.e., biogas, natural gas and electricity prices); and d is the specific investment cost. The variables included in x_{op} are continuous variables and they are optimized within their searching ranges and subject to some equality constraints (energy balances) expressed by function $h(x_{op})$. A_{st} is the matrix used to model the storages (as detailed in Section 3.2), b_{st} is the storage know-term and x_{des} are the variables related to design optimization. x_{des} includes binary variables (on/off storages variables), integer variables (number of components to install) and continuous variables (technology size). Operation variables and design variables are related by some inequality constraints expressed by the function $g(x_{op}, x_{des})$.

The objective function of the optimization problem is the total daily cost of the system given by the sum of the operational and investment cost. The operating cost is calculated as shown in Equation (5):

$$C_{op} = \sum_{t=1}^{Nts} P_{e,\,grid-export}(t) - \sum_{t=1}^{Nts} P_{e,\,grid-import}(t) - \sum_{t=1}^{Nts} P_{fuel-import}(t) \tag{5}$$

where Nts is the number of timesteps of the simulation, $P_{e,\,grid\text{-}export}$ and $P_{e,\,grid\text{-}import}$ are, respectively, the exported and the imported electricity and $P_{fuel\text{-}import}$ refers to the imported fuel in the energy system.

The total capital cost is the sum of the initial cost of each system component, which is calculated by multiplying the unit price of the component by its rated power and number (Equation (6)).

$$C_{tot} \,=\, C_{op} \,+\, C_{inv} \tag{6}$$

The constraints of the optimization problem can be divided into two categories: performance of the conversion and storage technologies, detailed next, and energy balances (electric, heating and cooling), which can be written in a general form as

$$P_{LOAD}(t) \,=\, P_{energy\ generators}(t) \,-\, P_{energy\ consumers}(t) \,\pm\, P_{storage}(t) \tag{7}$$

The last three equations are applied each timestep. Equation (7) states that the difference between multi-energy system generation and power load demand is handed by the difference between the import/export grid energy (if present) and the storage charging/discharging energy depending on the combination decided by the MINLP model.

3.2. Mathematical Models of Energy System Components

The energy subsystem models used by the optimal control strategy are simplified models, described as follows.

1. Micro combined heat and power unit (mCHP): The relations between input and output powers are described as nonlinear equations. The nominal coefficients of performance are listed in Table 1.
2. Lightweight photovoltaic modules (LW-PV): The generated electrical power is calculated using Equation (8), which expresses the PV output power as a function of irradiance and temperature. The normal operating condition temperature (NOCT) of the PV module was used to determine the cell temperature of PV module (T_{cel}), with the relation by Ross expressed in Equation (9) [36].

$$P_{e,\,LW-PV} = G\,A_{LW-PV}\,\eta_{LW-PV}(1 + K(T_{cel} \,-\, T_{ref})) \tag{8}$$

where

$$T_{cel} \,=\, T_{amb} + G\left(\frac{NOCT - 20}{800}\right) \tag{9}$$

and G is the plain of array (POA) global solar radiation [kW/m^2] at a 30° tilted angle, $A_{LW\text{-}PV}$ is the installed PV area [m^2], $\eta_{LW\text{-}PV}$ is the overall efficiency of the PV panels under standard test conditions, K is the temperature coefficient [1/K] of the maximum generation power of PV modules, T_{cell} is the cell temperature [°C] and T_{ref} is the cell temperature [°C] at reference conditions.

In this study, $\eta_{LW\text{-}PV}$ was set at 0.18, K at -0.4% 1/K, T_{ref} at 25 °C and NOCT at 48 °C.

3. Vertical axis wind turbine (VAWT): The power generated by the VAWT was obtained by means of the wind turbine's power curve, presented in Figure 2a, which relates its power production to the wind speed at the hub height.

4. Thermal solar (TS): The output power of the system is presented in Equation (10), which is the basic equation for the steady-state model according to the ISO 9806 standard [37].

$$P_{th,\,TS} = A_{ST}\left(\eta_0\,G_{tot} \,-\, a_1(T_m - T_{amb}) \,-\, a_2(T_m - T_{amb})^2\right) \tag{10}$$

$$T_m \,=\, \frac{T_{fluid,in} \,+\, T_{fluid,out}}{2} \tag{11}$$

where A_{ST} (m^2) is the collector area and T_m (°C) is the mean collector temperature, which is approximated to the mean fluid temperature. η_0 is the zero-loss efficiency for global radiation at normal incidence and a_1 (W/m^2 K) and a_2 (W/m^2 K) describe the temperature-dependent heat losses. The performance data of the solar flat plate collector are reported in Table 1.
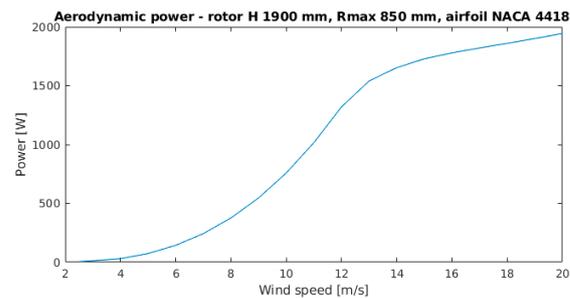
Table 1. Basic technical data.

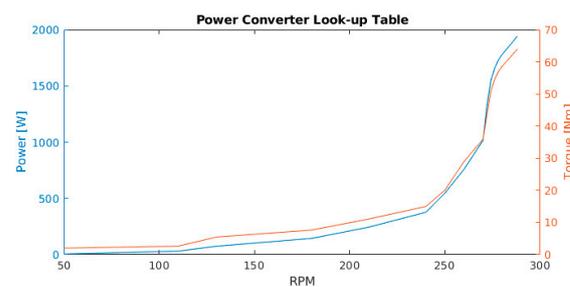| Technology	Parameter	Value
mCHP	Nominal electric power	3.2 kW
	Nominal thermal power	15.6 kW
	Net grid output efficiency (electrical)	0.16
	Total efficiency	0.94
	Reference temperature	15 °C
	Reference pressure	1.01325 bar
	Overall dimensions (h × w × d)	940 × 600 × 1040 mm
	Weight	205 kg
HOB	Maximum output power	200 kW
	Thermal efficiency	0.932
EHP	Maximum output power	180 kW
	Coefficient of performance (heating)	4.11
	Coefficient of performance (cooling)	4.43
EC	Maximum output power	200 kW
	Coefficient of performance	3.58
AC	Maximum output power	25 kW
	Coefficient of performance	0.69
LW-PV	PV module efficiency (STC)	0.18
	Temperature coefficient of power	-4×10^{-3} 1/K
	Reference temperature	25 °C
	NOCT	48 °C
VAWT	Nominal output power	2 kW
	Cut-in velocity	1 m/s
	Height of the installed wind turbine	25 m
TS	η_0—zero-loss efficiency	0.18
	First order heat loss coefficient	3.93 W/m^2 K
	Second order heat loss coefficient	0.0148 W/m^2 K
	Input fluid temperature	17 °C
	Output fluid temperature	60 °C
LHTS	Maximum capacity	50 kWh
BESS	Maximum capacity	26 kWh
	Maximum power charge	5.2 kW
	Maximum power discharge	13 kW

5. Energy storage systems: Matrix A_{st} in Equation (4) includes in the model two linear inequity constraints for each timestep for both storage systems:

- The stored energy is limited by the capacity of each storage system;
- The available output power is limited by previously stored energy.

  • Thermal storage: The model of the charging and discharging phase of a LHTS is dynamic and non-linear [38]. The thermal power absorbed or released is strongly dependent on the state of charge of the unit. The thermal power at a specific timestep depends on the state of charge. This is estimated through the interpolation of a thermo-fluid dynamic simulation of the storage. The equation is listed below.

$$P_{LHTS} = \sum \left(c_1\, e^{(c_2 t)} \right)_i \tag{12}$$

- Electric storage: Concerning batteries, the constraints for the charging and discharging rates are imposed. The maximum hourly power charging rate is set as 20% of the battery capacity, whereas the maximum hourly power discharging rate is 50% of the battery capacity.

6. Traditional technologies: The components are modeled using proper efficiency values. Performance coefficients are listed in Table 1.

(a)

(b)

Figure 2. (**a**) Aerodynamic power for the VAWT rotor 1900 mm height, 850 mm maximum radius and turbine blades of NACA airfoil 4418 and (**b**) companion power converter look-up table to the VAWT rotor.

4. System Description

The multi-energy system is a series of technologies for the production, conversion and storage of energy in different forms, as electricity, heating and cooling careers.

Various building locations were considered, as many as the number of pilot sites developed during the Re-COGNITION project. The analysis of the same system in various sites allows the technologies that are more convenient to be installed in each Re-Cognition site to be selected.

4.1. Technologies

The analyzed system is composed of the following technologies:

- Biogas-fueled micro-combined heat and power unit (mCHP)
- Gas heat only boiler (HOB)
- Electric heat pump (EHP)
- Electric chiller (EC)
- Absorption chiller (AC)
- Building integrated photovoltaic (LW-PV)
- Vertical axis wind turbine (VAWT)
- Thermal solar collector (TS)
- Possibility to buy/sell from/to the utility grid

- Energy storage systems
- Latent heat thermal energy storage (LHTS)
- Battery energy storage system (BESS)

In order to constantly supply the building demand, the system is composed of variable renewable energy sources but also of dispatchable energy sources such as microcogeneration units. Besides the mentioned innovative technologies, there are some more traditional energy conversion solutions such as heat only boilers or electric heat pumps. A diagram with a typical connection of the aforementioned components and the described power flows is shown in Figure 3.
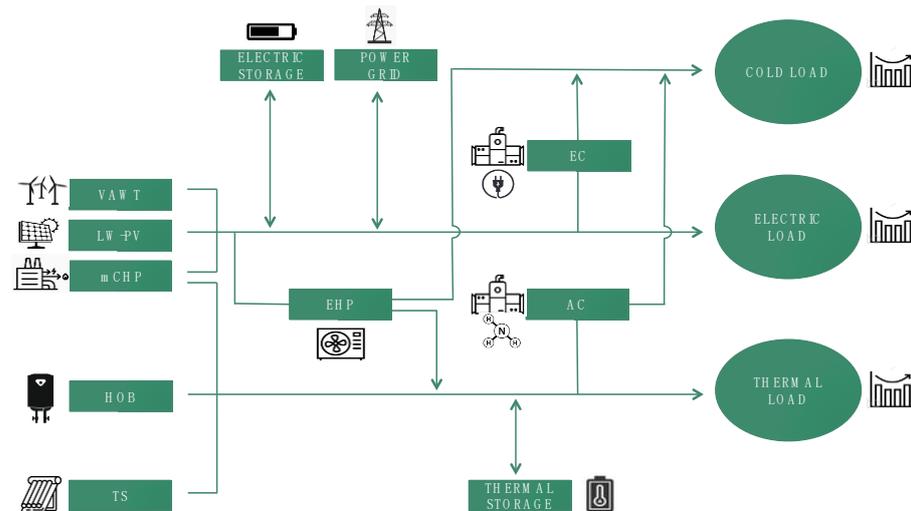

Figure 3. Schematic of the overall technology field.

The system operations follow the logics below:

— VAWT, LW-PV and mCHP directly support the attached AC loads, charge the electric energy storage, feed the electric heat pump and the electric chiller, or sell electricity to the utility grid;
— Micro-CHP, HOB, EHP and TS are activated when heat production is required or to charge the thermal storage; *-
— The cooling need is covered by electrically driven technologies (electric chiller or electric heat pump) and thermally driven technologies (absorption chiller). In the following paragraph, the main characteristics of each technology are presented, highlighting the innovative aspects compared to traditional solutions. Some basic technical data are listed in Table 1.

As previously mentioned, alongside alternative technologies, more traditional components are present in the energy system in order to evaluate, with the optimization tool, the best set of components to be installed, taking into account operating and investment costs.

Heating systems:

— Heat only boiler (HOB): A traditional condensing gas HOB is considered for space heating. The maximum thermal power is 200 kW.
— Electric heat pump (EHP) in heating mode: The EHP is a traditional air heat pump with a maximum thermal power of 180 kW. In this study, the proposed heat pump can work in a cooling or heating state simultaneously (four-pipe system heat pump).
— Thermal solar (TS): Solar collectors convert solar radiation into thermal energy. In this study, a commercial flat plate collector was analyzed. It had an area of 2.30 m^2 and it was fitted with a collection system with highly selective aluminum sheeting laser welded to a copper heat exchanger with a harp. An available area of 60 m^2 was considered for the installation.

Cooling systems:

— Electric chiller (EC): The electric chiller is a standard compression machine with a nominal power of 25 kW. Its nominal coefficient of performance is 3.58.
— Absorption chiller (AC): The absorption chiller can be driven by the heat recovered from mCHP, HOB and EHP, or by the heat from solar collectors. It is a single-stage absorption machine and its rated cooling capacity is 35 kW.
— Electric heat pump (EHP) in cooling mode.

Power systems:

— Battery energy storage system (BESS): Lithium-ion battery storage is mainly used for short-term electricity compensation due to its energy losses and high investment cost. Although it is not always cost-optimal for the system, co-siting renewables and storage turn out to be useful for fulfilling load profiles.

4.2. Case Study

The described system was adopted to supply a typical multi-family residential building constituted of 15 dwellings. The building model was defined by the U.S. Department of Energy (DOE) and it is fully described in [39].

In the Re-COGNITION project, the technologies developed will be tested and validated in power sites, realized indifferent partner locations. For this reason, in the present work the pilot sites of the Re-COGNITION project are analyzed as possible locations for the reference building. They are the following:

1. Politecnico di Torino in Turin, Italy (Lat/Lon: 45.081, 7.671).
2. Electric Corby in Corby, United Kingdom (Lat/Lon: 52.496, 0.689)
3. CERTH in Thessaloniki, Greece (Lat/Lon: 40.640, 22.939)
4. Technical University of Cluj-Napoca in Cluj-Napoca, Romania (Lat/Lon: 46.770, 23.591)

Figure 4 shows the selected Re-COGNITION pilot cases. The pilots are located in different areas of Europe (e.g., Continental, Mediterranean, Northern). Because of that, different weather conditions (and therefore, different loads) and different energy prices characterized each pilot site.

Figure 4. Recognition pilot cases selected for simulations.

Data Input

Weather conditions, electricity and gas prices, energy demand profiles and the available technologies with the corresponding performances and capital cost coefficients were inputs for the optimization problem. The input data were available every 15 min and they were referred to a typical apartment building with 15 housing units.

More in detail, the input data consisted of:

- Meteorological data: Hourly wind, temperature and solar radiation profiles for the considered locations were obtained from PVGIS weather database [40] for a 24-h timespan. Typical days in January and July were chosen as heating and cooling design days, respectively.
- Gas and electricity prices were assumed to be constant in time [41,42] and, since these values can vary widely by location, country-specific costs were considered in the simulations.
- Typical residential thermal and power load profiles were obtained from the HOMER software. The cooling demand was derived from the electric consumption: The difference between power consumption in January and July was mostly attributable to summer air conditioning, since the machines delegated to this function were generally powered by electricity.
- Investments costs for each technology are shown in Table 2 along with the references for the values assumed. The costs for the innovative technologies were given by the manufacturers or by considering cost of similar technologies currently marketed.

Table 2. Specific investment costs of energy system components.

Technology	Lifetime [Years]	Cost
mCHP	10 [43]	EUR 1950/kW [43]
HOB	12 [44]	EUR 180/kW [44]
EHP	15 [44]	EUR 720/kW [44]
EC	20 [45]	EUR 310/kW [46]
AC	23 [45]	EUR 360/kW [47]
LW-PV	20 [44,48]	EUR 2280/kW [44]
VAWT	20 [49]	EUR 3600/kW
TS	20 [48,50]	EUR 280/kW [51]
LHTS	30 [52]	EUR 50/kWh [52]
BESS	10 [53]	EUR 546/kWh [53]

5. Simulation Results

In this section, system configurations selected by the optimization tool as well as the optimized operation of the multi-energy system are presented for each examined location.

5.1. Pilot 1: Turin (Italy)

Concerning the design, the optimizer provided the best set of technologies to be installed. For the Turin site, all the technologies were selected for the installation except for vertical axis wind turbine, electric chiller and batteries. Figures 5 and 6 show the operations selected by the optimizer for the design days (winter and summer days). Figure 5 on the left includes the thermal production (above) and consumption (below). Production was achieved by the operated technologies, the energy purchase from the grid and the discharging of storages. Consumption was due to the load of the building, the energy sold to the grid, the charging of storages and the consumption of the other technologies (e.g., heat consumption included the fraction used by the absorption chiller).
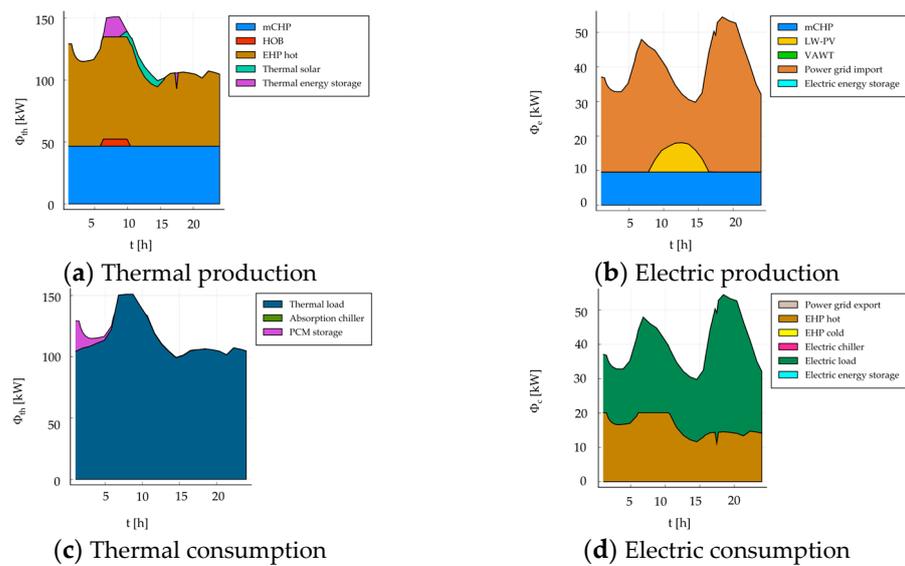
(**a**) Thermal production　　　　　　　　　　　　(**b**) Electric production

(**c**) Thermal consumption　　　　　　　　　　　(**d**) Electric consumption

Figure 5. Turin: energy scheduling January.

(**a**) Thermal production　　　　(**b**) Cooling production　　　　(**c**) Electric production

(**d**) Thermal consumption　　　(**f**) Cooling consumption　　　(**g**) Electric consumption
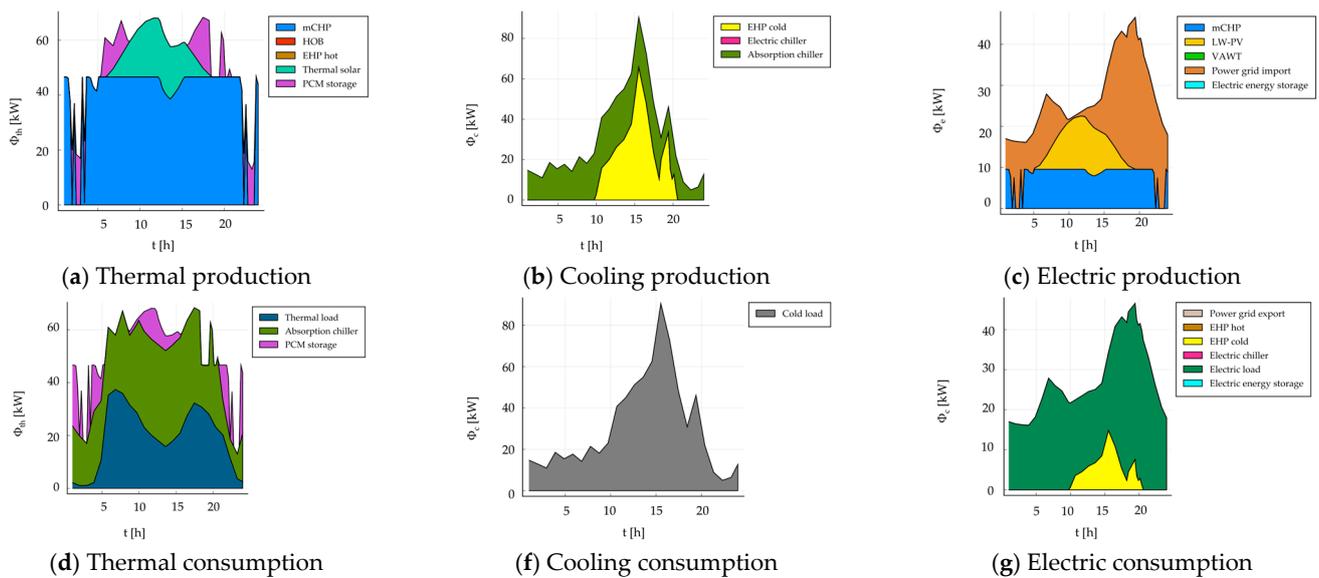
Figure 6. Turin: energy scheduling July.

Concerning winter operations, three micro-cogeneration units, an electric heat pump, a LHTS storage and thermal solar were adopted to cover the thermal load. No HOB was installed since the pilot in Turin had high gas price. The mCHP and the air heat pump were used to cover most of the thermal load. Thermal solar had a low impact on the demand supply and only around midday. The electricity demand was covered by mCHP and grid purchase. The photovoltaic system had a non-negligible impact on the demand supply between 9 a.m. and 4 p.m.

In summer operations, the absorption chiller and the electric heat pump satisfied the cooling demand. The absorption chiller was supplied with heat produced by the mCHP (operated to supply electricity) and the thermal solar system. The electricity consumption (due to the load and the electric heat pump operations) was supplied in winter by the mCHP, grid purchase and photovoltaics; the latter obviously covered a much larger share than in winter. The wasted heat of the mCHP was adopted to supply the absorption chiller (the largest fraction) and the thermal load.

Among the storages, only the thermal one was installed. The benefit of the LHTS installation was twofold. First, it allowed the winter thermal peak to be covered in the morning, avoiding installation of the heat only boiler or extra mCHP capacity. Secondly, in summer this was adopted to supply heat during peak consumption of domestic hot water (in the morning and evening).

The total cost of the operations was equal to EUR 194.11/day. This value was achieved as an average cost between the winter design day and the summer design day. This includes the investment cost for the technology purchase and the cost for the operations: fuel, maintenance and electricity/heat purchase and sale.

5.2. Pilot 2: Corby (United Kingdom)

The pilot site in Corby presented some distinctive features, especially due to the significant difference in the weather conditions with respect to Turin. In fact, in Corby the wind speed was higher than in Turin and consequently the installation of the wind turbine turned out to be useful. Another peculiarity was the lower solar irradiation compared to the other pilot sites. For this reason, the selected technologies were all the available ones except for thermal solar and batteries.

Figures 7 and 8 show the operations for the design days (respectively in January and July). Concerning the electricity production, the evolution was similar to that in Turin, except for the adoption of the wind turbine that, especially in winter, covered a non-negligible fraction of the load. The heat only boiler (125 kW) operated to satisfy the winter base thermal load along with the mCHP. Compared to the Turin case, the difference was mainly due to the lower price of natural gas in the United Kingdom. A small-scale electric heat pump was adopted and this was mainly used for cooling in summer (although this was moderately used also in winter for heating purpose). As in the Turin site, thermal storage was installed to cover the thermal peak for heating and domestic hot water, respectively, in winter and summer.
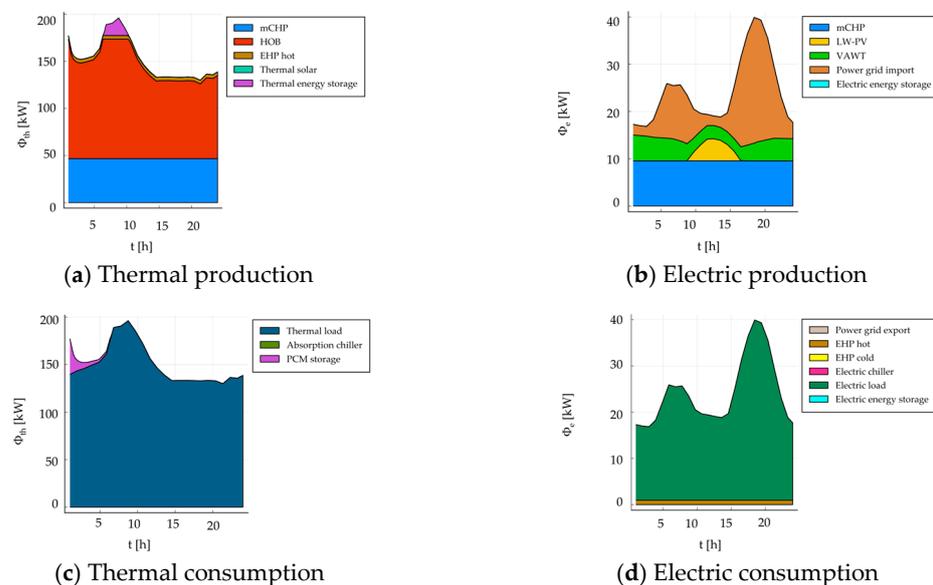

(**a**) Thermal production   (**b**) Electric production

(**c**) Thermal consumption   (**d**) Electric consumption

Figure 7. Corby: energy scheduling January.

(**a**) Thermal production

(**b**) Cooling production

(**c**) Electric production

(**d**) Thermal consumption

(**f**) Cooling consumption
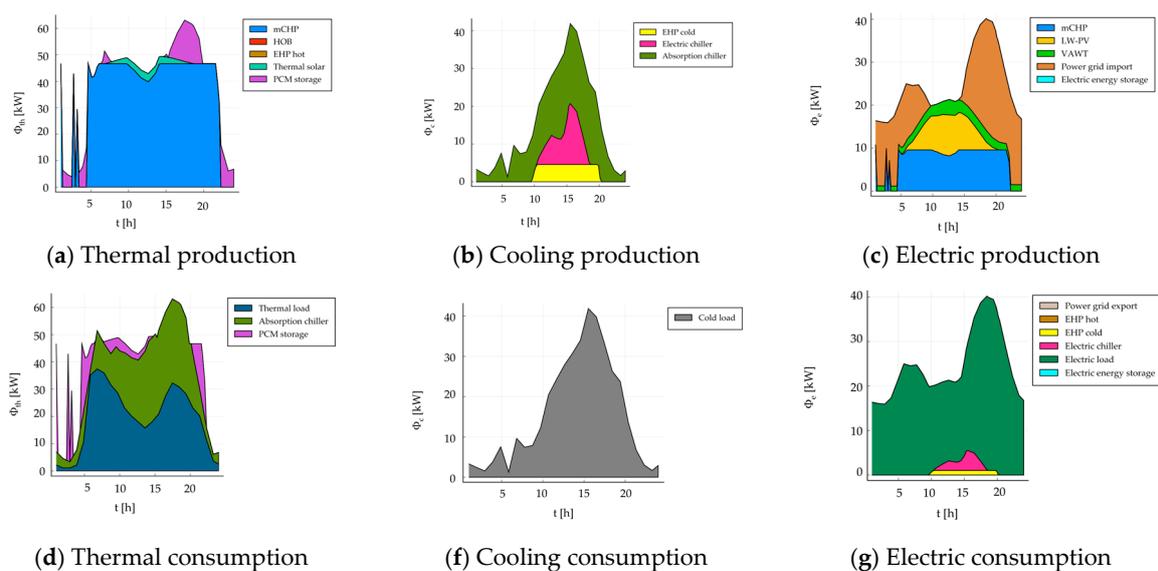
(**g**) Electric consumption

Figure 8. Corby: energy scheduling July.

The total daily cost for the Corby pilot was EUR 187.00/day. The cost was lower than in Turin for the large availability of wind source and lower gas price.

5.3. Pilot 3: Thessaloniki (Greece)

In the Thessaloniki pilot, the technologies not selected by the optimizer were the electric storage and the vertical axis wind turbine. The distinguishing feature of this pilot was that solar energy (thermal and photovoltaics) reached the maximum share: the entire available areas were exploited for the installation of photovoltaics and thermal solar.

Figures 9 and 10 show the operations for the design winter and summer days in the Thessaloniki site. In winter, the thermal and electrical loads were supplied in a similar way as the Turin site. Nevertheless, a small HOB was used to supply the morning thermal peak. The cooling load was also supplied by using the same technologies adopted in the Turin site. However, in this case the mCHP operated intermittently because of the availability of the heat produced by solar collectors and phase change materials (PCM) storage. Concerning the thermal needs in summer, the mCHP intermittent operations are balanced by the thermal storage.
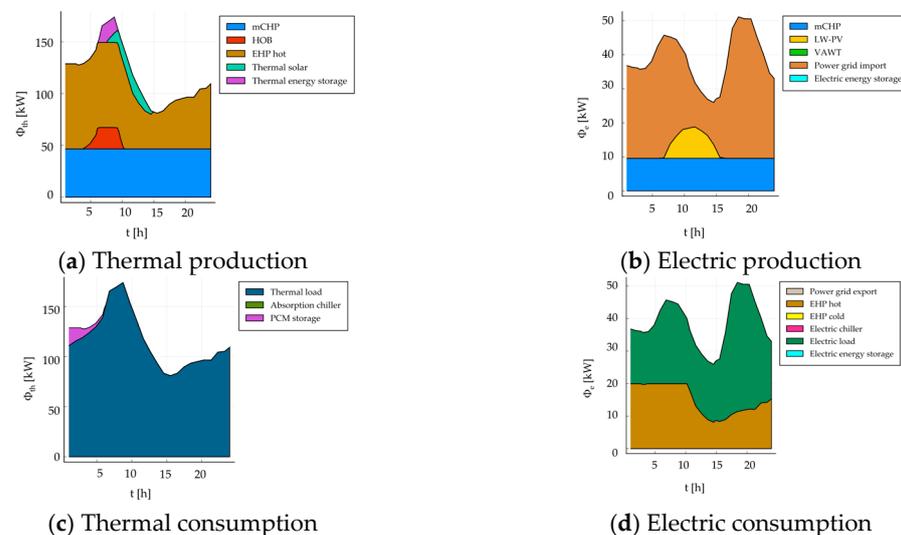

(**a**) Thermal production

(**b**) Electric production

(**c**) Thermal consumption

(**d**) Electric consumption

Figure 9. Thessaloniki: energy scheduling January.

(**a**) Thermal production (**b**) Cooling production (**c**) Electric production

(**d**) Thermal consumption (**f**) Cooling consumption (**g**) Electric consumption
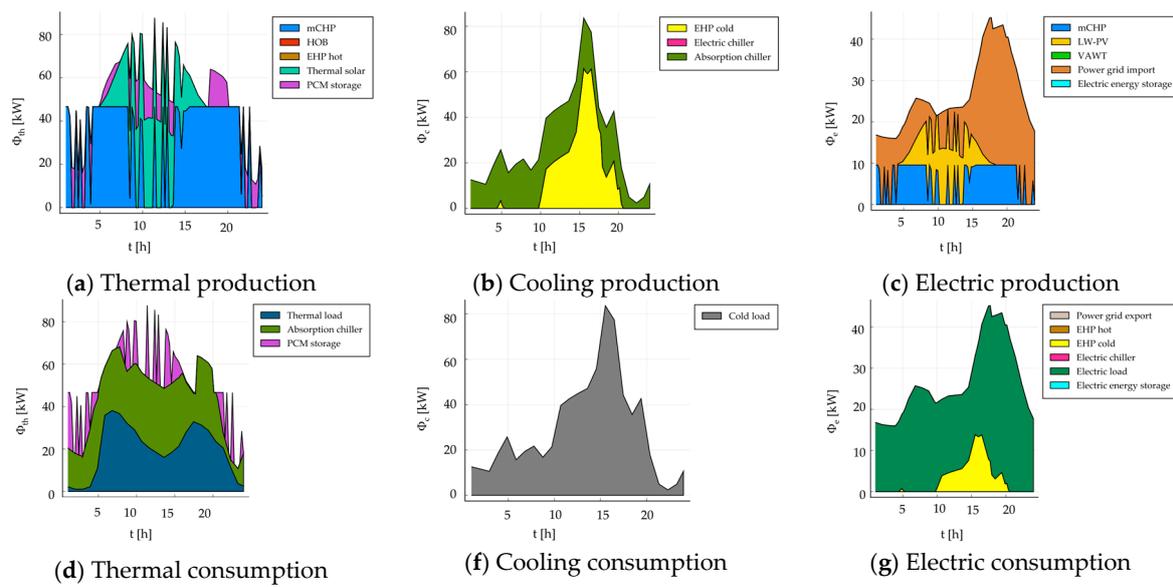
Figure 10. Thessaloniki: energy scheduling July.

In general, the pilot in Thessaloniki operated similarly to the pilot in Turin because of the similar climate zone and therefore with similar load profiles. Nevertheless, the total cost was equal to EUR 150.35/day (the lowest of the analyzed sites). This value was lower than the Italian one because of the largest exploitation of solar energy and the lower gas and electricity prices.

5.4. Pilot 4: Cluj-Napoca (Romania)

The results of the pilot in Cluj-Napoca are shown in Figures 11 and 12. This site was characterized by a high thermal demand. Peaks reached 280 kW (with respect to 180 kW in Thessaloniki). The thermal load in this case was mainly supplied using the heat-only boiler, due to the low cost of natural gas. The low cooling demand was mainly supplied with the electric heat pump. The absorption chiller was used at a lower load than the other sites, exploiting the heat produced through the mCHP. Thermal storage was used to manage the thermal peak of the summer load, which was covered by the mCHP and the solar collectors.
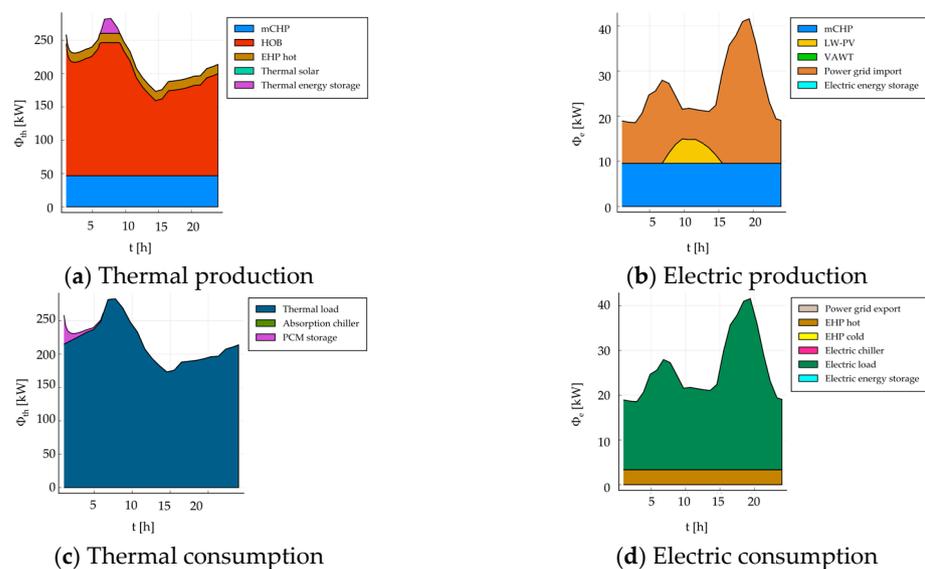

(**a**) Thermal production (**b**) Electric production

(**c**) Thermal consumption (**d**) Electric consumption

Figure 11. Cluj-Napoca: energy scheduling January.

(**a**) Thermal production

(**b**) Cooling production

(**c**) Electric production

(**d**) Thermal consumption

(**f**) Cooling consumption
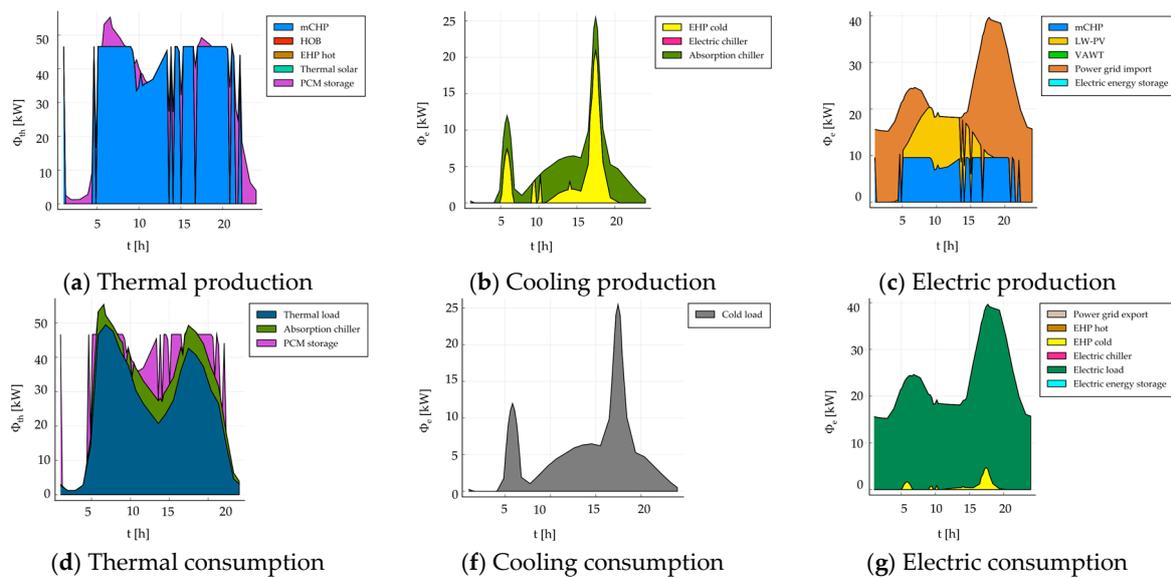

(**g**) Electric consumption

Figure 12. Cluj-Napoca: energy scheduling July.

In this case the total cost was EUR 177.35/day. This was larger than in Thessaloniki because of the lower available solar radiation but smaller than in Turin and Corby because of the lower price of gas.

5.5. Pilot Comparison

Table 3 shows, on the basis of the simulation results, the devices installed in each pilot site. The three micro-cogeneration units were selected in all the sites. This was due to the fact that the combined production of thermal and electric power always results as a convenient opportunity. Similarly, electric heat pumps were installed in all the sites, but the size was strictly related to the energy prices: in Corby and in Cluj-Napoca, smaller heat pumps were selected for the cooling load whereas heat only boilers provided the largest amount of thermal power. Concerning the cooling demand, the absorption chiller and the heat pump were preferred, followed by the electric chiller that was selected in case the electric heat pump was not convenient in heating operations.

Table 3. Installed devices.

Technology	Pilots			
	Turin	**Corby**	**Thessaloniki**	**Cluj-Napoca**
mCHP	✓	✓	✓	✓
HOB	✓	✓	✓	✓
EHP	✓	✓	✓	✓
EC	✗	✓	✗	✓
AC	✓	✓	✓	✓
LW-PV	✓	✓	✓	✓
VAWT	✗	✓	✗	✗
TS	✓	✓	✓	✗
LHTS	✓	✓	✓	✓
BESS	✗	✗	✗	✗

Concerning the electricity production, wind turbines were installed only in the Corby pilot, where the wind distribution justified the installation. Solar energy was significantly exploited in all the pilot sites, where for photovoltaics in particular the maximum module capacity was installed. Regarding thermal solar, the number of installed modules depended on the pilot location. This was not the case of the Cluj-Napoca pilot, where no thermal solar was installed. As can be noticed from Table 3, there were no pilots where the lithium-ion batteries were installed because of their high specific investment costs. Latent heat thermal storage was always selected due to the expected low investment cost and the ability to mitigate the peak load.

The results obtained in the analysis show that although there were some common features such as the installation of a micro-cogeneration system, photovoltaics and a heat pump, and the preference of thermal storage with respect to lithium-ion batteries, there were still several differences between the pilot sites. This proves that the adoption of an optimization tool is meaningful, since it is not possible to directly define the best set of technologies to be installed.

The solutions obtained for each Re-COGNITION pilot were compared to a reference case where a set of pre-defined conventional technologies was considered. The reference case was a grid-connected building with a heat only boiler for space heating and domestic hot water production and a traditional electric chiller for supplying the cooling demand. The schedules of each technology were calculated using the MINLP model to minimize the economic objective function. The results are summarized in Table 4. It can be noticed that in each pilot, a significant reduction in terms of cost was reached by using the technologies selected by the optimization tool. The total cost ranged between EUR 200/day and EUR 335/day in the reference scenario and between EUR 150/day and EUR 200/day in the Re-COGNITION scenario. The overall cost savings ranged between 11% and 42%. Higher gains occurred in Turin and Thessaloniki, where the natural gas price was higher and the use of heat only boilers was minimized.

Table 4. Comparison of typical solution vs. the Re-COGNITION proposal.

Pilots	Typical Solution [EUR/Day]	Re-Cognition Proposal [EUR/Day]	%
Turin	335.37	194.11	−42%
Corby	258.29	187.00	−28%
Thessaloniki	219.61	150.35	−32%
Cluj-Napoca	198.64	177.35	−11%

The bar chart in Figure 13 shows the pilot total costs and the partial costs for investment (in blue) and operations (in red). The conventional solutions involved lower investment costs, whereas Re-COGNITION solutions included a largest number of different technologies and, therefore, a bigger percentage of total costs was associated with the investment costs. Nevertheless, the total cost was lower in the case of the Re-COGNITION solutions because of the significantly lower operating costs.

In Figures 14 and 15 the percentages of increase and decrease, in terms of investment and operating costs of the Re-COGNITION solution in respect to the reference cases, are shown for each location.
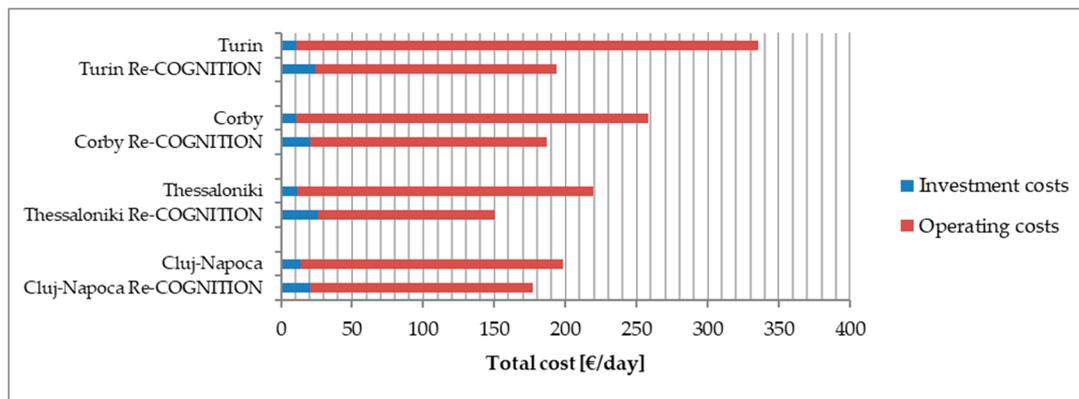
Figure 13. Investment and operating costs for the reference case and Re-COGNITION optimized technologies in the four pilots.
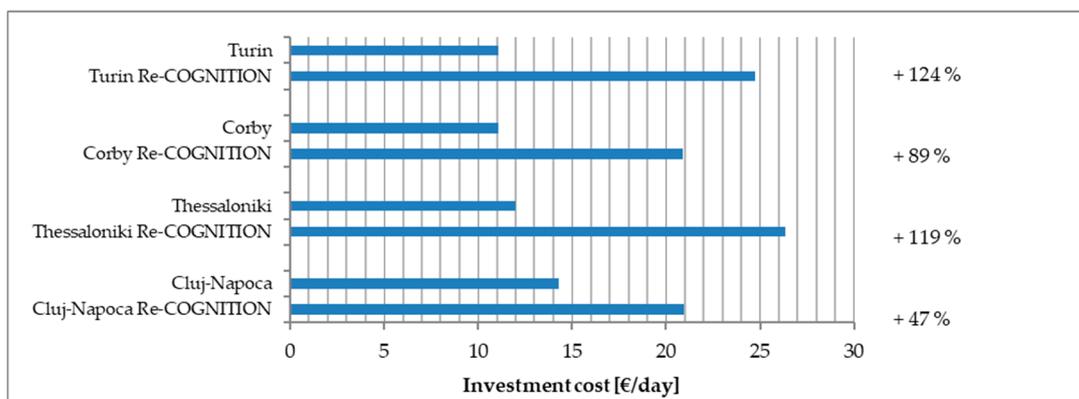

Figure 14. Comparison of investment costs for the reference case and Re-COGNITION optimized technologies in the four pilots.
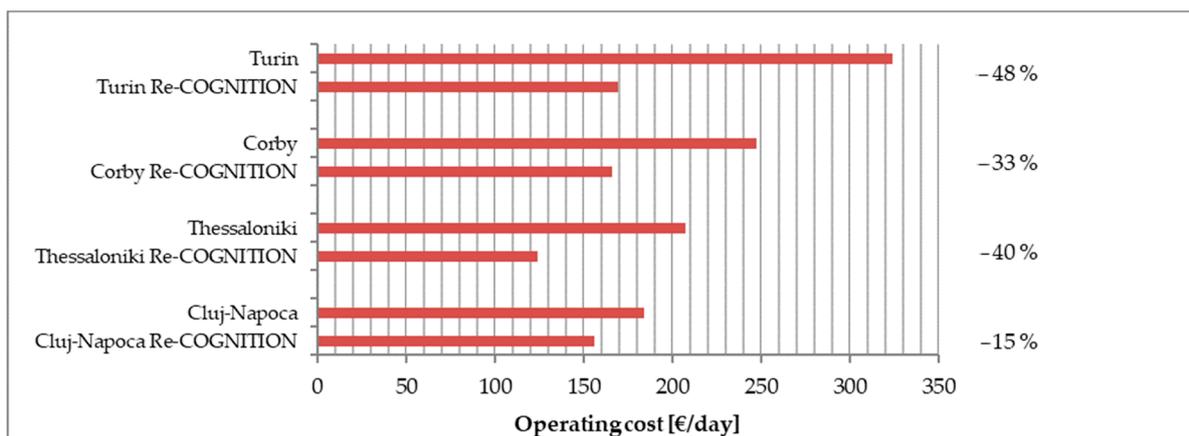

Figure 15. Comparison of operating costs for the reference case and Re-COGNITION optimized technologies in the four pilots.

Significant benefits were also obtained in terms of CO_2 emissions. Figure 16 reports the CO_2 emissions produced by the multi-energy system in the reference case and in the Re-COGNITION case. CO_2 emission reductions achieved in the various pilots ranged between 10% and 25%. This was mainly due to the exploitation of the renewable energy

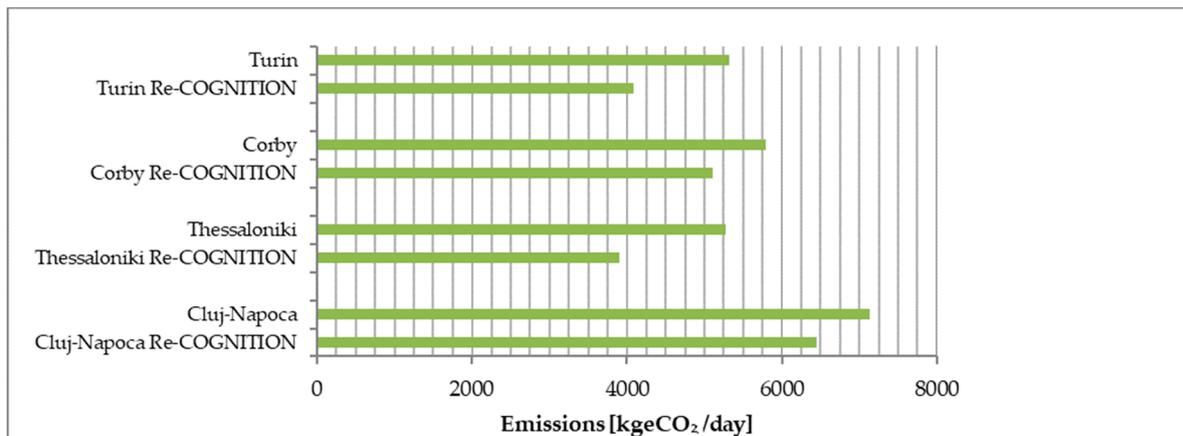sources and the adoption of mCHP for the combined production of heat and electricity in all the pilots.

Figure 16. CO_2 emissions of the pilots.

6. Conclusions

The present paper proposes a MINLP optimization tool able to define the best design and operations of a series of conventional technologies and innovative renewable energy sources for the supply of heat, cold and electricity load of a typical multi-family building. The innovative renewable energy technologies were developed within the framework of the European project Re-COGNITION, which meets the need to deploy efficient technologies in the building sector to support the real implementation of nearly zero-energy buildings. The innovative renewable energy technologies developed within this framework were a micro-cogeneration system fed by biogas, a passive variable geometry small wind turbine for rooftop installation, lightweight glass-free photovoltaic modules and latent heat thermal storage based on phase change materials. The proposed tool was used to define whether these innovative technologies were competitive with respect to traditional technologies from both efficiency and cost perspectives. For this reason, the analyzed system consisted of both traditional and alternative technologies and the optimization tool was able to select the set of components to be installed, taking into account operating and investment costs. As the energy consumption of buildings and RES production depended strongly on the climate and local weather conditions and energy prices had a great influence on the simulation results, the developed model was tested on the four pilot sites within the Re-COGNITION Project: Turin (Italy), Corby (United Kingdom), Thessaloniki (Greece) and Cluj-Napoca (Romania).

The results obtained in the analysis show that Re-COGNITION proposed technologies are competitive with respect to more traditional ones since, although the presence of innovative renewable energy technologies typically doubles investment costs, operating costs decrease, affecting the total cost. The reduction strongly depended on the pilots (and therefore meteorological data and cost of fuel and energy vectors), ranging between 11% and 42%. The combined adoption of innovative renewable technologies and operation optimization also allowed for a decrease in the CO_2 emissions of a percentage between 10% and 25%. Focusing on the alternative proposed technologies, the biogas-based mCHP units and the lightweight PV modules were installed in all the considered pilot sites at the maximum capacity. PCM thermal storage also was always installed but the size of the component was slightly different from one pilot site to another on the basis of load profiles. Moreover, it can be noted that LHTS capacity was quite small mainly due to constant energy prices considered for the study. The vertical axis wind turbine was instead selected only for the Corby site; even if the examined wind turbine were specifically designed to increase the performance in the turbulent urban wind, on the basis of our preliminary

investigation, the WT power curve along with its investment cost would not be suitable enough to guarantee their installation in all the countries.

For a more accurate analysis, it would be interesting to consider uncertainty on input data, and especially, since the proposed alternative technologies are under development, a sensitivity analysis should be carried out on their investment cost values. Moreover, since the cost-optimal analysis is not able to address the multi-dimensionality of the decision according to the new European objectives in the field of the nZEB design, a more complex analysis can be carried out, including in the study the role of multi-criteria decision analysis for guiding energy investment decisions.

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

Abbreviations

a_1	First order heat loss coefficient (W/m^2 K)
a_2	Second order heat loss coefficient (W/m^2 K)
$A_{LW\text{-}PV}$	LW-PV area (m^2)
G	Solar irradiance (W/m^2)
$P_{biogas\text{-}import}$	Imported biogas (kW)
$P_{c,\,AC}$	AC cooling power output (kW)
$P_{c,\,EC}$	EC cooling power output (kW)
$P_{c,\,EHP}$	EHP cooling power output (kW)
$P_{c,\,LOAD}$	Cooling load (kW)
$P_{e,\,EC}$	EC electric power input (kW)
$P_{e,grid\text{-}import}$	Imported electricity (kW)
$P_{e,grid\text{-}export}$	Exported electricity (kW)
$P_{e,\,LOAD}$	Electricity load (kW)
$P_{e,\,LW\text{-}PV}$	LW-PV electric power output (kW)
$P_{e,\,mCHP}$	mCHP electric power output (kW)
$P_{e,\,VAWT}$	VAWT electric power output (kW)
P_{LHTS}	Charge/discharge power LHTS
$P_{NG\text{-}import}$	Imported natural gas (kW)
$P_{th,\,AC}$	AC thermal power input (kW)
$P_{th,\,EHP}$	EHP thermal power output (kW)
$P_{th,\,HOB}$	HOB thermal power output (kW)
$P_{th,\,LOAD}$	Thermal load (kW)
$P_{th,\,mCHP}$	mCHP thermal power output (kW)
$P_{th,\,TS}$	TS thermal power output (kW)
NOCT	State of charge (-)
T_{amb}	Cell temperature at reference condition (°C)
T_{cell}	Temperature coefficient (1/K)
T_{ref}	Cell temperature (°C)
x_{op}	Operation variable
x_{des}	Design variable
η_{LW-PV}	LW-PV efficiency at STC (-)
η_0	Zero loss efficiency (-)

Abbreviations

AC	Absorption chiller
BESS	Battery energy storage system
EC	Electric chiller
EHP	Electric heat pump
HOB	Only heat boiler
LHTS	Latent heat thermal energy storage
LW-PV	Lightweight photovoltaics
mCHP	Micro-combined heat and power unit
MILP	Mixed-integer linear programming
MINLP	Mixed-integer non-linear programming
NLP	Non-linear programming
nZEB	Nearly zero energy building
RES	Renewable energy sources
TS	Thermal solar
VAWT	Vertical axis wind turbine

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