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Design and environmental sustainability assessment of energy-independent communities: The case study of a livestock farm in the North of Italy

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ABSTRACT

This paper investigates the energy and economic performance of several energy schemes that could potentially be applied to agricultural and zootechnical communities contributing to the international objectives of sustainable development. The proposed energy schemes involve integrated energy efficiency technologies and novel system layouts aiming at reaching the zero-energy goal at a community level, by considering collective energy actions with provision of benefits for members and stakeholders. The proposed scenarios include different innovative technologies, such as anaerobic digestion, cogeneration, biogas upgrading, solar, district heating and cooling. These layouts are modelled in TRNSYS simulation environment to perform dynamic simulations and parametric analyses of the pivotal system parameters. Such analyses are conducted to find out the best scenario and the size of its system components which optimize different energy and economic objective functions. To assess the feasibility of all proposed scenarios and energy schemes, as well as to investigate the potential of the developed models, proposed scenarios are studied for an existing community. This existing agricultural community named "La Bellotta", is served through different technologies, including a gas fuelled co-generator and an anaerobic biodigester. Simulation results show that the investigated scenarios allow for achieving very high self consumption ratios of energy produced on-site (from 57 to 100%), high economic performance (measured by the profitability index up to 1.35 for the best investigated scenario) and environmental benefits. The case study provides examples of energy schemes in which citizens and communities have a major benefit to invest in projects including renewables technologies, energy efficiency, and positive energy services.

1. Introduction

The prevailing trend worldwide is to move from large scale, centralized, power plants (Bell and Gill, 2018; Verbong et al., 2013) to distributed energy generation systems (Gui and MacGill, 2018). Distributed energy production is expected to replace or complement the traditional centralized energy production paradigm, leading to self-sustaining and energy-independent communities. During the last few years, buildings are switching from being just energy consumers to both energy producers (by means of Renewable Energy Systems — RES) and consumers. This new trend leads to the idea of "prosumer" buildings (Hahnel et al., 2020) and/or Nearly and net Zero Energy Buildings (nZEB). In this scenario, the nearly-zero principles are applied to the urban context (from district to community level), in the framework of Nearly or net Zero-Energy Communities (NZEC or nZEC) (Amaral et al., 2018). To reach the nZEC goal, a crucial role is played by RES adoption and by the control and optimization of energy flows inside of the community. Recent works focused on the possibilities to assess the energy and economic potential impacts and feasibility of such energy schemes.

The importance of the transition to nZEC is highlighted by reference Mittal et al. (2019) where the authors state that the adoption of net zero energy buildings could be inadequate to meet the energy efficiency goals. The main reason is that it is possible to have just a few newly built high performances buildings in comparison to the numerous of existing ones. The proposed solution to such a problem is to extend the boundary of the analysis to building clusters and then to put the attention on net zero energy communities.

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The sustainable transition requires design process optimization, innovative system layouts, and smart-control strategies. Furthermore, the use of dynamic simulation allows for the combination of these approaches, enabling higher energy efficiency targets in communities. The concept of ZEC is first found in literature in 2009, in two studies presented in references Amaral et al. (2018) and Carlisle et al. (2009). Here, the authors propose an agent-based approach to model zero energy communities; the model is developed by means of NetLogo 6.0.4 with the target of predicting energy behaviour of a community. The authors adopt the model to study a 270 houses cluster in the City of Des Moines (Iowa, USA), achieving interesting energy savings by applying the proposed method.

The importance of nZEC is also pointed out by a recent review regarding Smart Energy Communities (SEC) and Smart Energy Municipalities (SEM), reported in reference Ceglia et al. (2020). The authors highlight the importance of SECs and SEMs by underlining their potentials for reducing the energy demand in areas with difficult energy supply, and for decreasing the global energy consumption by the adoption of distributed energy systems. Such energy consumption reduction is possible by smartly sharing energy in local districts, as also stressed in reference Galderisi et al. (2016). The authors also cited a study, conducted by the Italian Energy Strategic Committee, that underlines how SECs development is a feasible way to meet energy saving and greenhouse emission reduction equal to 50–60 Mtep and 180–220 $MtCO_2$, respectively.

Energy communities would play a crucial role toward the transition to a low carbon future, and renewables-based distributed generation systems could be the future of energy production, management, and consumption (Moroni et al., 2019).

To assess the energy and economic potentials of communities, dynamic simulations and optimization procedures and tools are widely used, as reported in several research papers (Gaiser and Stroeve, 2014; Hendron and Engebrecht, 2010; Awad and Gül, 2018). Specifically, such tools and procedures are crucial for the design of nZECs based on RES solutions, for the selection of the systems sizes and layouts, and for their optimal integration. Examples are reported in several research papers, as discussed hereinafter, mostly based on case study analyses. The optimal design of hybrid renewable energy systems assessed through dynamic simulations and optimization is discussed in reference Kim et al. (2019). The work focuses on the energy and economic analysis of the performance of a hybrid renewable energy system including a solar district heating network applied to the Jincheon eco-friendly energy town, located in Chungbuk Innovation City (South Korea). Primary energy savings up to 73% are achieved through a proper energy optimization of the proposed system conducted in TRNSYS environment. Similar results are observed in reference Hachem-Vermette et al. (2019), where dynamic simulations are used to calculate the potential energy savings obtained by implementing solar thermal collectors and seasonal borehole thermal energy storage systems at the Drake Landing Solar Community located in the Town of Okotoks (Alberta, Canada). Dynamic simulations and optimization are also used to compare the performance of different layouts including RES technologies and storage devices. The combination of renewable energy systems and active and passive solutions – allowing for reducing by 20% the energy consumptions for heating, cooling, and lighting of a nearly zero energy community located in South Korea – is investigated in reference Suh and Kim (2019). In reference Liu et al. (2019), the optimization of the energy fluxes among a multi-energy community implementing energy storage and conversion devices is conducted for an existing real multi-vector district at the University of Manchester (Liu and Mancarella, 2016).

As mentioned above, net zero energy communities are particularly crucial in case of remote areas or islands. RES adoption for remote communities is investigated through simulations in few research papers available in the literature. In reference Robertson et al. (2020), by means of a Remote Community Optimization Model (RCOM), developed in the General Algebraic Modelling System (GAMS) platform, a cost analysis for hydro, solar and wave energy systems is conducted to evaluate how the diesel-fuelled Hot Springs Cove community (British Columbia, Canada) could achieve a 100% renewable energy production. Dynamic simulations and optimization have been recently used by Barone et al. (2021) to desing and to evaluate the energy and economic feasibility of different scenarios and system layouts, including renewable energy based technologies, applied to the island of El Hierro (Canary Island), considered as a best practice example of a sustainable community.

In reference Rehman et al. (2019), the sizing of different renewable energy systems (wind turbines, photovoltaic, storage and electric vehicle) to be implemented in a remote Finnish village is studied and optimized to meet the totally renewable district goal. Through a multi-object optimization, conducted by using MOBO (Multi-objective optimization tool), wind turbines and storages showed to have a crucial role to reach the nZEC goal. In addition, the integration of electric vehicles resulted to be an effective measure to make significant the photovoltaic utilization. The use of a grid-connected photovoltaic system to reach the ZEC goal in the small rural village of Toba Tek Singh (Pakistan) is investigated in reference Rafique et al. (2018), by means of the TRETScreen clean energy simulation tool.

Other studies are focused on the energy generation of districts, searching for new optimization and management techniques. In reference Rivarolo et al. (2016) it is proposed an energy and economical approach for optimizing districts and smart polygeneration microgrids by finding out the optimal size of each technology to enhance their performance during the whole year.

In reference Calise et al. (2020), possible renewable solutions to achieve energy savings up to 58% in districts of buildings are investigated through a case study analysis, conducted by means of TRNSYS, for the weather zone of Naples (Italy). An interesting analysis on a district heating layout is also presented in reference Morvaj et al. (2016) where the research focus is on design and operating conditions of a distributed energy system linked to different district heating layouts. In reference Prato et al. (2012) a smart management system is modelled with the aim to optimize the energy coupling between cogeneration plants and district heating networks, with a focus on electric energy market and the possibility to store energy in the district. Finally, the concept of community-shared solar systems to enhance self-consumption of RES production is studied in reference Awad and Gül (2018). Specifically, the paper demonstrates the energy and economic effectiveness of the community shared solar paradigm – with respect to the individual rooftop PV scheme – applied to the community city of Edmonton (Alberta, Canada).

As highlighted in the literature presented above, the reduction of energy consumption of building clusters and communities, achieved through the implementation of RES, smart control, and optimization procedures, seems to be more efficient and cost effective than considering single building applications. However, besides the growing interest in this topic, still few research works found in literature propose comprehensive analyses and optimization procedures of energy communities by using different technologies. The need of more case study analyses is necessary to enhance the knowledge on RES based communities, to be considered by energy planners and policymakers for setting-up design guidelines (Akinyele and Rayudu, 2016).

With the aim at contributing to the knowledge of the potentials and issues related to the design of energy independent communities, this paper investigates the energy and economic performance of several integrated energy schemes that could potentially be applied to agricultural and zootechnical communities. The proposed energy schemes involve integrated energy efficiency technologies and novel system layouts aiming at reaching the zero-energy goal at a community level, by considering collective energy actions with provision of benefits for members and stakeholders. The design and the optimization of these energy schemes is conducted through dynamic simulations, performed by means of simulation models suitably developed by the authors in TRNSYS environment. The software – widely recognized within the research community – was used for conducting dynamic simulations and the optimization of the proposed energy schemes and layouts through a comprehensive parametric analysis. This allowed for finding-out the best scenario and the size of its system components which optimize several selected energy and economic objective functions (energy consumption, renewable energy share, self-sustaining energy ratio, economic performance, etc.). A suitable case study analysis is focused on an existing agricultural and zootechnical community (i.e. "La Bellotta", located nearby Turin, North Italy). The investigated community is served through several technologies, including a gas fuelled co-generator and an anaerobic biodigester, whereas various technologies – such as solar based technologies, smart mobility, district heating and cooling – are modelled and simulated to enhance its overall efficiency and sustainability level and to extend the benefits of the existing and proposed system layouts to neighbouring villages. Simulation results show that promising energy, economic, and environmental results can be achieved, and that citizens and communities have potential benefits to invest in projects including renewables technologies, energy efficiency, and energy services that return profits.

2. Material and methods

This section includes the description of the methodology to investigate the energy and economic performance of several energy schemes applied to an agricultural and zootechnical community considered as case study. To this aim, a dynamic simulation model has been developed for the energy and economic analysis and optimization of the investigated ZEC energy schemes. The proposed approach consists of several steps:

(i) identify the possible energy efficient solutions to be adopted in a particular community;

(ii) assess the energy, economic, and environmental performance of the proposed solutions;

(iii) conduct an energy-economic optimization to find out the optimal component sizes and system layouts.

To conduct such analyses, a suitably dynamic simulation model has been developed and implemented in TRNSYS. By means of this tool, the energy performance of the investigated case study can be dynamically assessed by also exploring innovative control strategies. The software TRNSYS was selected for its flexibility in simulating transient building and energy systems. It includes a large library of objects (namely "Types"), including simulation models of actual system components, allowing for the modelling of many plant configurations. The main assumption of the simulation models related to the main technologies considered in the proposed energy schemes are described hereinafter.

2.1. Modelling of system components

Anaerobic-Digester

One of the technologies implemented in the developed simulation tool is the anaerobic digester (AD). To overcome the lack of TRNSYS types for this technology, it has been necessary to model the behaviour of an AD by means of a suitable equation set. In particular, the anaerobic process outcomes (produced biogas amount and digestate) are connected to the solid waste mass, to the chemical enthalpy, and the biogas lower heating value (LHV), as follow (Wellinger et al., 2013):

$$\dot{m}_{waste} \cdot h_{ch} + \dot{Q}_{th} + \dot{W} = \dot{m}_{biogas} \cdot LHV_{biogas} + \dot{m}_{dig} \cdot h_{dig} \qquad (1)$$

where Q_{th} is thermal energy necessary to maintain a constant temperature during the whole process [W], W represents the mechanical need to guarantee a continuous handling [W], $\dot{m}_{waste}$ is input solid waste mass flow rate [kg/s], $\dot{m}_{biogas}$ is biogas flow rate produced during this process [kg/s], $\dot{m}_{dig}$ and h_{dig} are the mass flow rate [kg/s] and enthalpy of the liquid digestate [J/kg], and LHV is the lower heating value of the biogas [J/kg]. To evaluate the anaerobic process in an efficient way, a suitable conversion ratio (μ) can be defined:

$$\mu = \rho_{biogas} \cdot m_{waste} \cdot DM \cdot VR \qquad (2)$$

where DM is the dry matter ratio of input matter, VR is the volatility rate ratio of DM, and ρ_{biogas} represents the solid waste average density [kg/m^3].

This ratio defines the biogas production amount of 1000 kg of solid *municipal and agricultural* waste.

Cogeneration System

In the simulation model, a biogas feed cogeneration or combined heat and power (CHP) system, is also considered. This system is modelled by considering the thermal and electric power outputs [W] (P_{th} and P_{el}, respectively), linked to the biogas mass flow rate [kg/s] with the following energy balance on the component:

$$\dot{m}_{biogas} \cdot LHV_{biogas} = P_{th} + P_{el} \qquad (3)$$

Once P_{th} and P_{el} are evaluated, it is possible to estimate the cogeneration system electrical and thermal efficiencies as follow:

$$\eta_{el} = \frac{P_{el}}{P_{in}} \qquad (4)$$

$$\eta_{th} = \frac{P_{th}}{P_{in}} \qquad (5)$$

where $P_{in} = \dot{m}_{biogas} \cdot LHV_{biogas}$

Upgrading System

An upgrading system (US) has been also modelled. Such system is used to separate methane and carbon dioxide in the biogas to produce bio methane. Such separation is obtained by using the pressurized water scrubbing (PWS), requiring mechanical power. As for the AD, also for the US no TRNSYS types are available, so a suitable equations model is implemented in TRNSYS. Specifically, the US system is modelled by considering the energy balance:

$$\dot{W}_{up} + \dot{Q}_{up} + \dot{m}_{biogas} \cdot h_{biogas} = \dot{m}_{CO_2} \cdot h_{CO_2} + \dot{m}_{CH_4} \cdot LHV_{CH_4} \qquad (6)$$

where $\dot{W}_{up}$ is the mechanical power required in upgrading pumping process [W], $\dot{Q}_{up}$ is the thermal power necessary for the process [W], $\dot{m}_{CO_2}$ and h_{CO_2} are the carbon dioxide flow rate [kg/s] and its chemical enthalpy [J/kg], and $\dot{m}_{CH_4}$ is produced methane flow rate [kg/s] . Such approach could be simplified by introducing the methanogenic index (i_{CH4}) that represents the methane concentration given a certain amount of biogas:

$$i_{CH_4} = \frac{\dot{m}_{CH_4}}{\dot{m}_{biogas}} \qquad (7)$$

Note that this index is strongly linked to the biogas quality. Typically, for biogases produced by AD using solid wastes, the methanogenic index ranges between 60 and 75%.

District heating and cooling network

The district heating and cooling network is modelled by considering different technologies modelled by diverse TRNSYS Types and layouts, based on:

(i) Compound Parabolic Collectors (CPC) linked to the district heating network by means of a thermal storage tank (TK). The layout includes an heat exchanger (HE) and an auxiliary biomass heater (BH);
(ii) Flat Plate Collectors (FPC) in a configuration similar to *case (i)* (FPCs substitute CPCs);
(iii) a Biomass heater (BH), directly linked to the district heating network through the TK;
(iv) a Chiller (CH) linked to the district cooling network and powered by a PhotoVoltaic (PV) field.

All cases include a thermal storage tank (TK) necessary to eventually decouple the production of thermal and cooling energy from the district request.

To simulate these layouts, other components have been implemented in TRNSYS, modelled by means of Types in which specific assumptions are considered, as reported in Table 1 (Beckman, 1994; Mitchell and Duffie, 2012; TRNSYS, 2013).

2.2. Case study: Reference and proposed scenarios

To explore the potentials of agricultural and zootechnical communities and achieve the net-zero energy status through the implementation of several technologies, a case study based on the existing community named “La Bellotta”, located nearby Turin (North Italy), is presented. Several solutions have been already implemented within the community in the past years to improve its energy efficiency. In this regard, in 2008 “La Bellotta” realized a 180 kWp polycrystalline photovoltaic field on the roofs of buildings intended for livestock (see Fig. 1), for a total useful surface of 3000 m^2. Furthermore, PV panels are fully building-integrated into the roofs, providing an aesthetically pleasing impact and being a virtuous example of Building Integrated Photo Voltaic (BIPV). This solar field produces about 216 MWh/year. Moreover, electrical production of the plant is partly intended for corporate use and partly placed on energy market.

Starting from 2010, the investigated community is also equipped with a 1 MW co-generator plant (CHP), fed by biogas produced by an anaerobic digester (AD). Specifically, the AD converts biomass as well as the produced zoo-technical wastes (triticale and corn silage) into biogas. The produced biogas, rich in methane, is used in place of natural gas and supplied to the co-generator to produce electricity. Part of the electricity production is supplied to the AD for the whole process needs (pre-treatment of biomass, transportation, operation and controls, etc.), whereas the remaining amount is sold to the national grid (Grid). The AD also requires heat to reach the process temperature, provided by the CHP unit which also supplies heat to a district heating (DH) network belonging to “La Bellotta” community. A scheme of the existing layout (considered as reference), including the anaerobic digester/co-generator systems, is presented in Fig. 2. This system produces approximately 8.5 GWh/year of electrical energy entirely sold to the national electricity network (for a total avoided CO_2 emission equal to 4700 t/year). In addition, the anaerobic digester produces about 15.000 t/year of digestate, adopted as fertilizer, that almost completely meets the needs of farm crops (almost no fertilizer needed).

In addition to the described system, the community is also equipped with a small district heating (sDH) network used to provide thermal energy (provided by the CHP cooling jacket system) to several community buildings of “La Bellotta”.

The aim of this work is to enhance the described existing system (which is considered as the reference system — RS) by adopting the previously described developed simulation tool to investigate five innovative scenarios. Specifically, the main goals of this analysis are:

- to exploit the organic fraction of solid urban waste (currently not used), collected from the neighbouring urban area, into a new anaerobic digester (scenarios 1 and 2);
- to improve the existing DH system to serve a wider range of users (scenario 3);
- to propose the implementation of a district cooling system (scenario 4).

Each scenario is described hereinafter.

Scenario 1: Anaerobic digestor and cogeneration system

In this scenario, the chance to exploit the organic fraction of solid urban waste gathered from the neighbouring urban area is investigated. Specifically, the implementation of a new AD/CHP system, with priority given to the power production, is analysed. Note that the proposed system layout, shown in Fig. 3, is the same as the reference one (Fig. 2). The main differences are found in the AD feed and in the AD and CHP sizes (i.e. AD– 3000t biomass/month/CHP — 635 kW). At the end of the anaerobic process, produced biogas has the following features: LHV equals to 6.5kWh/Sm^3 and a density of 1.1 kg/Sm^3 (evaluated at 313 K). The selected CHP (whose efficiencies are equal to $\eta_{el} = 40.4\%$, $\eta_{th} = 43\%$) has a power request (as fuel input) of 1.57 MW supplied by 250 Sm^3/h of biogas, while thermal recovery system can extract up to 650 kW_{th}.

As for the reference scenario, the produced biogas from the AD is fed into the CHP, which is in part supplied to the AD and in part sold to the power grid. The biomass input is made up of solid waste (70%) and by rural processing waste (30%). Due to the high variability on input sources, biomass storage is needed (and is considered in the scenario).

With a community of about 200 thousand people, the garbage collection system is estimated to be able to collect about 600 m^3 of waste every week. To ensure such collection, it has been estimated that two heavy trucks (with fuel consumption of 0.25 l/km and an overall capacity of 45 m^3) and five light trucks (with fuel consumption of 0.04 l/km and an overall capacity of 11 m^3) are needed. Since the percentage of water in solid waste is more than 60%, to optimize the biogas process, a pre-treatment is required (Wellinger et al., 2013). Waste must be dried first, and then shredded to be put in an anaerobic digester. When the matrix is ready, it is stored in biomass storage. The equipment requires electrical power and, because the organic matter evaluated is the same for all cases, the energy amount necessary for the “pre-treatment need” is the same for all cases.

Scenario 2a: Anaerobic digestor and cogeneration system with upgrading

In this scenario, a plant layout similar to the one described in scenario 1 is presented as sketched in Fig. 4. As it is possible to notice from this figure, the main difference is that not all the biogas produced by the AD is supplied to the CHP. Part of the biogas is actually supplied to an upgrading system for its conversion into bio methane, which represents a very attractive alternative for the biogas utilization (compared to the use in a CHP system). Specifically, 52% of biogas is sent to the CHP system whilst the remaining 48% is sent to the upgrading system, the US. This allocation is made to generate on-site the necessary inputs, both thermal and electrical energy, for the equipment used during the anaerobic digestion process. Note that the above percentages depend on the biodigester size. The produced bio methane is then sold as fuel for methane based automotive systems. Such solution has been taken into account due to the interesting incentives

Table 1
Other components' modelling assumptions and types TRNSYS (2013).

Pipes *(Type 31)*	The thermal losses in pipes are calculated by fixing the fluid flow and pipe length and diameter. The loss coefficient is evaluated according to heat transfer relationship by approximating the pipe to an equivalent thermal network. District pressure losses are evaluated according to Colebrook and White equations (implemented in a calculator type). Mass flow rate and temperatures are calculated according to energy balances.
Pump *(Type 3b)*	This model handles a mass flow rate using a classical control system based on "on/off" control (generated by Type2b). Pump power may also be calculated by linking the power consumption to the mass flow rate.
Tank *(Type 4)*	A stratified tank is modelled by considering that the heat source flow enters the tank in the node located just below the top side of the tank and the cold source flow enters at the bottom of the tank. The boiling point of the working fluid is fixed.
Heat exchanger *(Type 657)*	A constant effectiveness/Cmin heat exchanger is modelled (implemented between the delivery and return point in the district heating network in the first two simulated layouts). The heat exchanger has the function to maintain the hot-side outlet temperature below a fixed set point guaranteeing a specified mass flow rate.
Biomass heater *(Type 6)*	A biomass heater is modelled by Type 6; produced heat is supplied to a fluid according to the set point temperature condition.
Chiller *(Type 655)*	A vapour compression air-cooled chiller is modelled through type 655. Chiller working conditions are introduced as input, as an external data file implementing the performance map obtained by manufacturers.
Compound Parabolic Collector *(Type 74)*	A Compound Parabolic Collector is a stationary concentration collector that converts both beam and part of the diffuse radiation. The CPC is characterized by a critical aperture angle called the half-acceptance angle (θ_c) and the truncation ratio.
Flat Plate Collector *(Type 73)*	A Flat Plate Collector, converting all diffuse and beam radiation, is modelled by means of the Hottel–Whillier steady-state model.
Photovoltaic panel *(Type 194)*	The array current and power produced by the photovoltaic system is calculated by fixing the load voltage, weather conditions, and module reference conditions.

Fig. 1. Existing PV roofs of "La Bellotta".

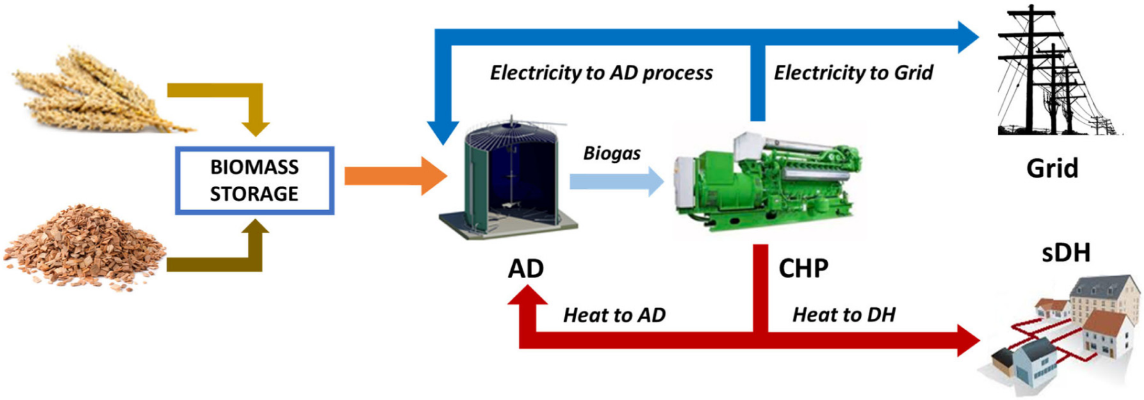

Fig. 2. Existing AD/CHP system layout (reference scenario, RS).

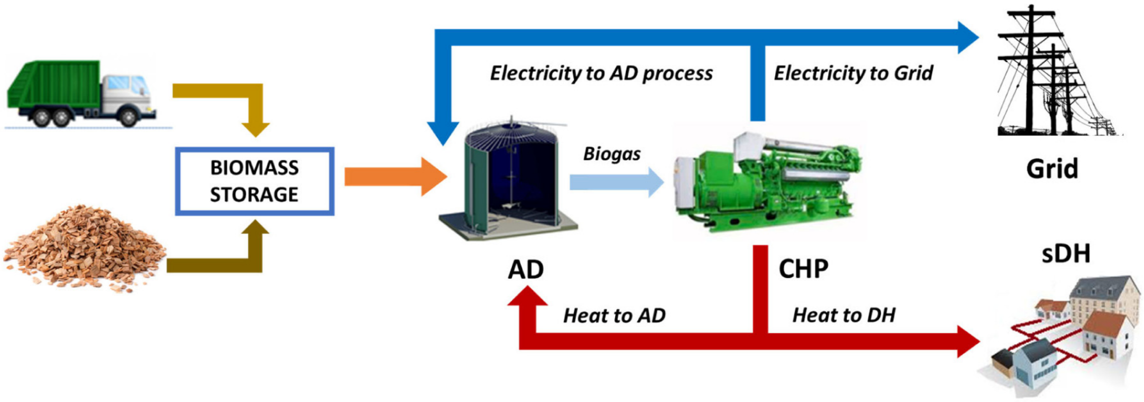

Fig. 3. Scenario 1 — system layout.

recognized for the production of bio methane for the automotive sector by the Double Counting business plan (dealt in the economic analysis). Note that, since the amount of biogas sent to the CHP is lower compared to the amount delivered in scenario 1, the CHP size needed is smaller (330 kW). The selected CHP (whose efficiencies are equal to $\eta_{el} = 38.8\%$, $\eta_{th} = 47\%$), has a power request (as fuel input) of 0.85 MW supplied by 119 Sm3/h of biogas, while the thermal recovery system is capable to extract up to 400 kWth. About the trucks fleet, the same considerations made for scenario 1 are considered (i.e. two heavy and five light trucks).

Scenario 2b: Anaerobic digestor and cogeneration system with upgrading + Supply chain ownership

This scenario represents an enhancement of the previously one. Specifically, it investigates the economic feasibility in the ownership of the entire biofuel (bio methane) supply chain (ownership of the gas stations) and the corresponding plant layout is reported in Fig. 5. Note that "La Bellotta" is located in the industrial area of Venaria Reale, so the creation of a fuelling station located close to the production site is a strategic choice. The produced biomethane, thanks to the upgrading system, is directly sent to fuelling stations through a short pipeline, while electrical power is sent through low voltage cables system. Thus, the main difference of this scenario with the previous one is that electric power and bio methane are directly sold to the final users (e.g. electric vehicles, trucks fuelled by biomethane, etc.). In addition, the possibility to adopt methane fuelled garbage trucks for the urban solid waste collection is considered. By means of such hypothesis, two goals are achieved: i) cost reduction of garbage collection service due to the adoption of an auto-produced fuel for the trucks; ii) lower CO_2 emission being the emissions of bio methane lower than those related to fossil fuels. About trucks fleet, also for this scenario two heavy and five light trucks are considered.

To estimate fuels request and consumption, it is necessary to define the trucks type. Linked to the collection process, five areas are defined considering a maximum distance of 25 km from the production site.

Scenario 3: Enhancement of the existing district heating network

As previously mentioned, a district heating network already exists in the reference scenario, as well as in the previous ones. However, this network reaches only a limited number of buildings belonging to "La Bellotta" community. This scenario investigates the possibility to enhance such district heating network by extending it to the entire "Robassomero" city (located nearby "La Bellotta" - Fig. 8). The city thermal energy demand has been estimated in 3.98 GWh_{th}/y, distributed throughout the year as reported in Fig. 6.

Table 2
FPCs main technical data.

Aperture surface area [m^2]	2.69
Conversion factor η_o	0.782
Heat transfer coefficient a_1 [W/m^2K]	3.675
Temperature depending heat transfer coefficient a_2 [W/m^2K^2]	0.007
Incidence angle modifier	0.9
Stagnation Temperature [°C]	232

Table 3
CPCs main technical data.

Wall reflectivity	0.9
Acceptance angle	45°
Truncation ratio	0.7
Higher Temperature	300 [°C]

To satisfy the thermal energy demand, three different technologies for the hot fluid preparation have been investigated:

1. Compound Parabolic Collectors (CPC — 10000 m^2, Collector Fin Efficiency Factor — 0.7, Overall loss coefficient — 0.83 W/ m^2K) with Biomass auxiliary heater (4 MW, $\eta = 0.93$);
2. Flat Plate Collectors (FPC — 10,000 m^2 , Collector Fin Efficiency Factor — 0.7, Bottom and edge loss coefficient — 0.83 W/ m^2K) with Biomass auxiliary heater (4 MW, $\eta = 0.93$);
3. (iii) Biomass auxiliary heater (8 MW, $\eta = 0.93$).

The plant layout of this scenario, including the extended district heating (eDH) is sketched in Fig. 7.

With respect to the investigated solar field, in the following Tables 2 and 3 the main technical data are presented.

To connect "La Bellotta" Community with "Robassomero" city, the resulting extended district heating network should be 6 km long, as depicted in Fig. 8.

Scenario 4: District cooling network

The last proposed scenario investigates the economic feasibility of a scenario in which a district cooling network system is implemented. This scenario is proposed to cover the cooling demand of "La Bellotta" community and of Robassomero city. Note that the district cooling network is different, in term of the adopted layout, with respect to the district heating one, being only 1 km long (e.g. small district heating, sDH). Such difference is due to chillers location, as they can be located nearby the city, whereas the hot fluid for the district heating network is produced inside "La Bellotta" community. The cooling energy requested is 127.9 MWh_c, distributed throughout the summer

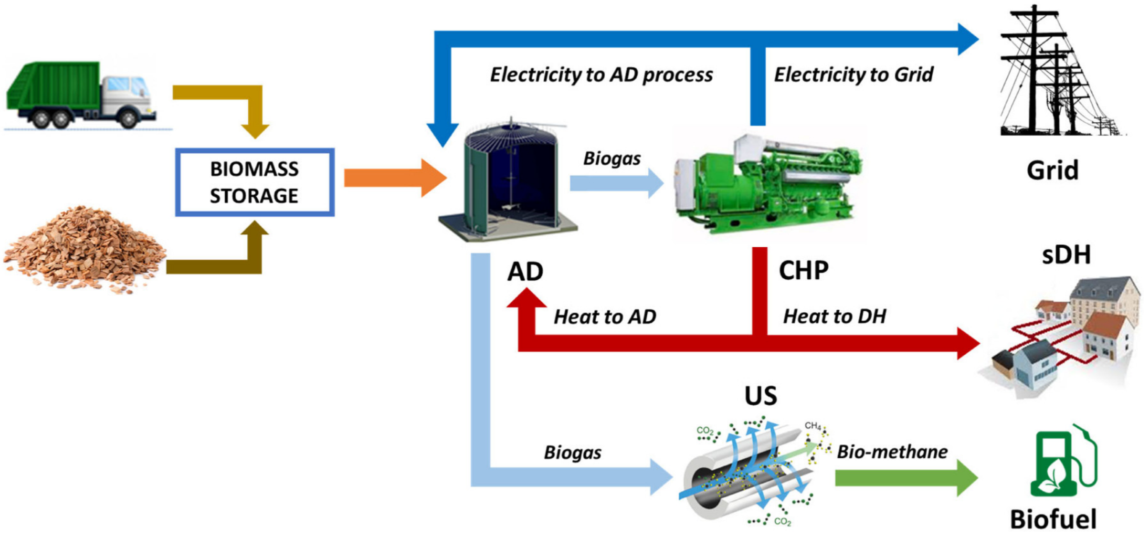

Fig. 4. Scenario 2a — system layout.

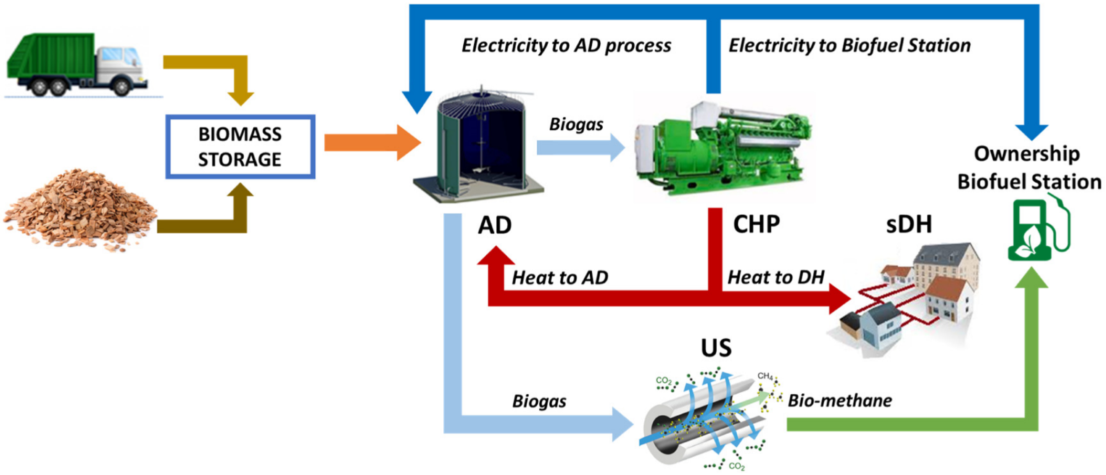

Fig. 5. Scenario 2b system layout.

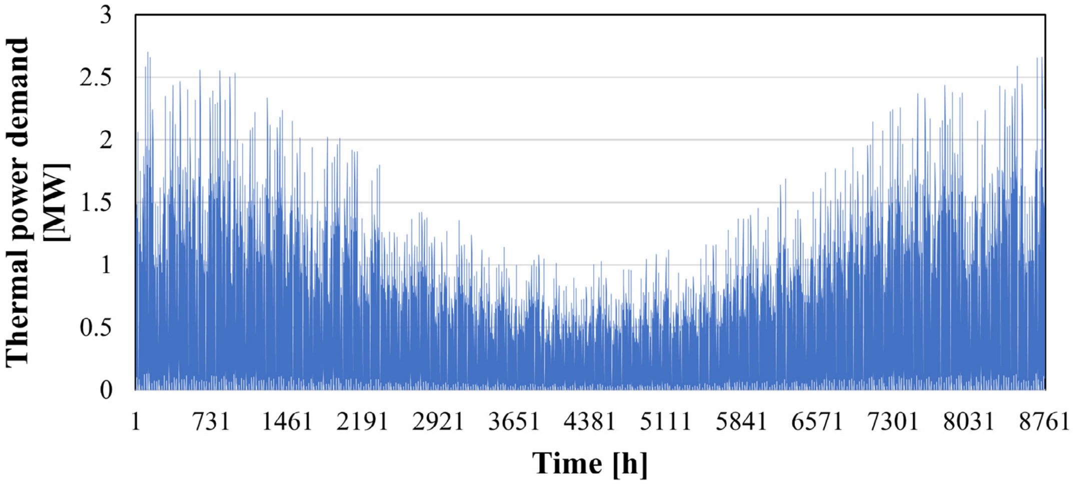

Fig. 6. District heating network users thermal power demand time histories.

period as reported in Fig. 9. The cold fluid production is ensured by adopting an air-cooled electric chiller (352 kW — with a rated COP equal to 5) coupled to a polycrystalline photovoltaic field (45 kW) that delivers the electrical surplus to the grid. The size and the layout of the PV field have been optimized and the data are

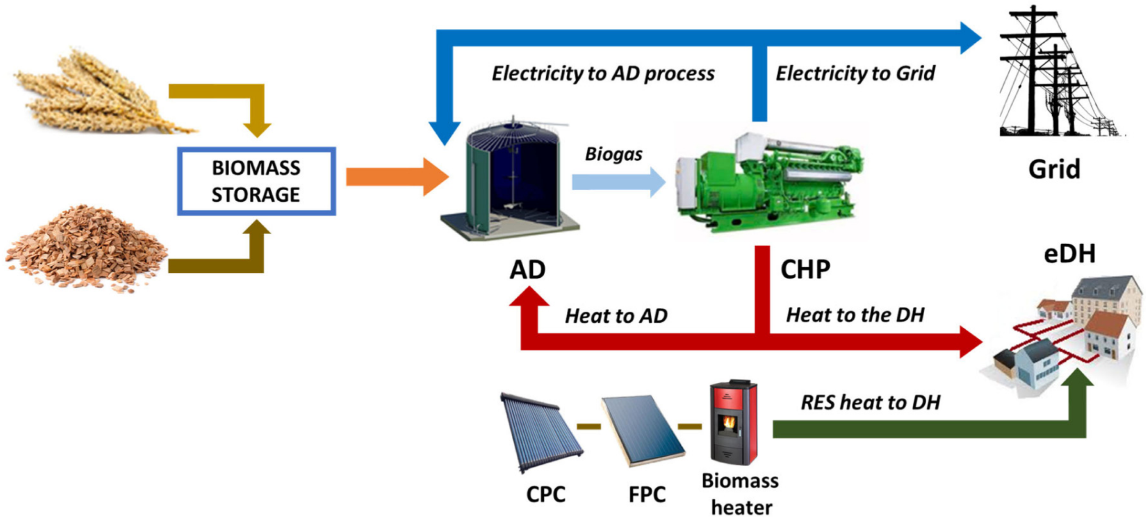

Fig. 7. Scenario 3 — system layout.

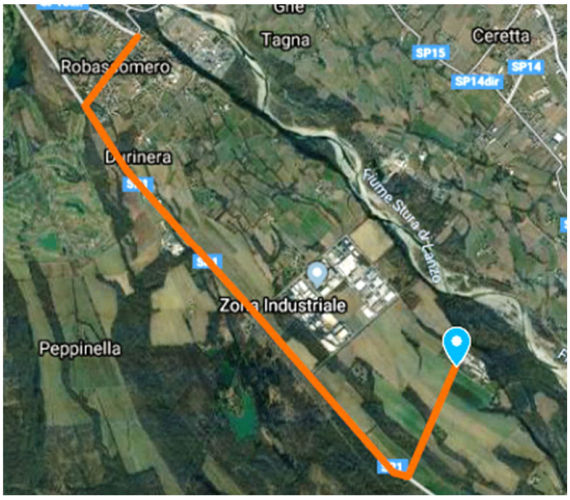

Fig. 8. Extended district heating (eDH) network layout.

reported and discussed in the results section. The layout of this scenario is sketched in Fig. 10.

2.3. Energy and economic performance indicators

The energy and economic feasibility of each scenario is defined according to performance indicators. According to the calculated indexes, the optimal combination of the main technologies included in each layout is determined.

The main economic indicators are:

- *SPB*: simple payback period [y], calculated as a function of the considered system capital cost CAPEX [k€] and the related economic profit ΔC [k€] as follows:

$$SPB = \frac{CAPEX}{(PROFIT - OPEX)} = \frac{CAPEX}{\Delta C} \tag{8}$$

- *NPV*: Net Present Value [k€], calculated as a difference between the present value of cash inflows and the present value of cash outflows over lifetime.
- *PI*: Profitability Index, calculated as the ratio between the present value of future expected cash flows at year 20, $NPV_{20th,year}$, and the initial amount invested in the project, *CAPEX*.

$$PI = \frac{NPV_{20th,year}}{CAPEX} \tag{9}$$

Two parameters considered for energy performance evaluation are:

- *Self-sustaining services ratio,* calculated as the percentage of self-consumed energy to provide the main services for heating and cooling. Where, $E_{\mathrm{INTEGRATED}}$ describes energy integration to match thermal and cooling loads of the community.

$$SSR = 1 - \frac{E_{INTEGRATED}}{E_{TOT}} \tag{10}$$

- *Self-consumption ratio,* related to energy production on site. This indicator describes the quota of self-consumed energy over the whole energy production.

$$SCR = \frac{E_{SELFCONSUMPTION}}{E_{PRODUCTION}} \tag{11}$$

Finally, the indicator of the environmental performance is:

- ΔCO_2 [tCO_2/y], represents the avoided equivalent carbon dioxide emissions calculated as:

$$\Delta CO_2 = F_f \cdot (En_{LOAD}) \tag{12}$$

where F_f is the CO_2 equivalent emission factor for the considered fuel [tCO_2/kWh], and En_{LOAD} (kWh/y) is the amount of energy delivered to users.

3. Results and discussion

In this section, the energy, economic, and environmental results related to the carried-out analyses are presented. Note that the scenarios 1, 2a, and 2b are described together, whereas the scenarios 3 and 4 are separately described.

3.1. Scenarios 1, 2a and 2b

In the following, the scenarios 1, 2a, and 2b are described by the energy, environmental, and economic points of view. Note that the energy and the environmental results for scenario 2a

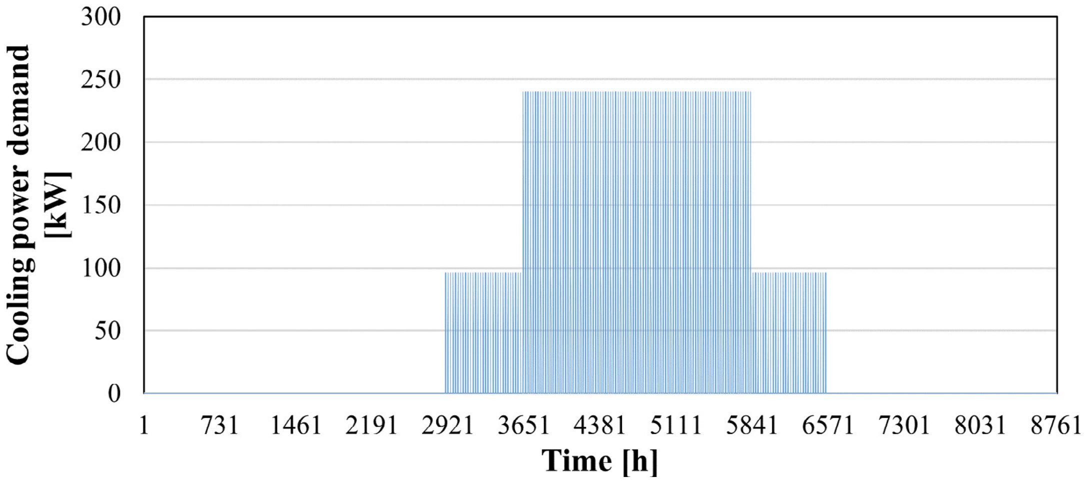

Fig. 9. District heating cooling network users thermal power demand time history.

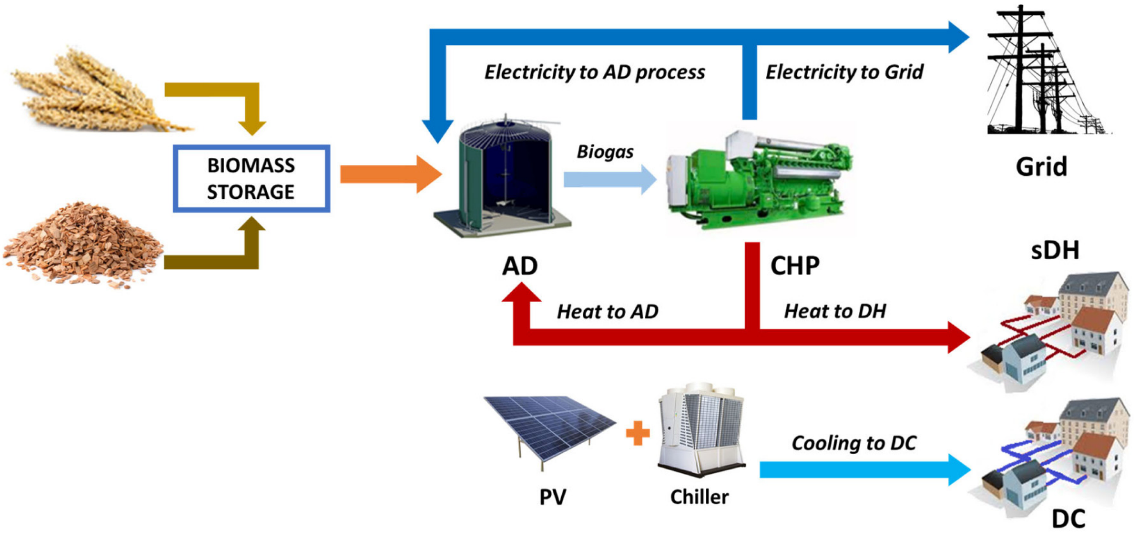

Fig. 10. Scenario 4 — system layout.

and 2b are the same, as these scenarios differ only for economic assumptions.

Energy results

Starting from scenario 1, as previously mentioned, all the biogas produced by the AD is supplied to the CHP for electricity production. Note that the matter fed into the AD (DM = 40% of input matter; VR = 50% of DM) produces a biogas with the following features: LHV = 6.5 kWh/Sm^3, and ρ_{biogas} = 300 Sm$^3_{\text{(biogas)}}$ /t; conversion ratio is: $\mu = 60$ Sm^3/ton. According to the carried-out simulations, the hourly AD biogas production is equal to 250 Sm^3/h, leading to a total yearly production of 2’025’000 Sm^3/y (the AD — CHP system operates for 8’100 h/y). In this framework, the CHP power output is equal to 635 kW, for total electricity production on yearly basis of 5.14 GWh/y. Note that, as also mentioned in the previous paragraph, the thermal output from the CHP is partially used for the AD needs. The produced electricity is exploited for different purposes (see Fig. 11 and Table 4). Specifically, 810 MWh/y (16%) are used to satisfy the AD needs; 486 MWh/y (9%) are used for pre-treatment processes and the remaining 3.84 GWh/y (75%) is sold to the grid. From the environmental point of view, considering an emission factor equal to 0,35 kgCO$_2$/kWhel, a total CO$_2$ saving equal to 1800 tCO$_2$/y is also estimated.

Table 4
Scenario 1 destinations of produced energy.

Service	Energy [MWh/y]
Power production	5143
AD- handling system	810
Pre-treatment need	486
Placed on the market	3847

Concerning the scenarios 2a and 2b, they are examined together since their only difference is the economic assumption relative to the supply chain ownership. In these two cases, the AD comes out to be in the same size of scenario 1 (3000t biomass/month), with the same assumed features, whilst the CHP required is smaller (330 kW). The smaller CHP size depends on the necessity to supply part of the produced biogas (still equal to 250 Sm^3/h as for scenario 1) to the upgrading system (US). Specifically, only 119 Sm^2/h of biogas feed the CHP whilst the remaining part is sent to the US. The results, on yearly basis, are presented in Fig. 12. From Table 5 it is possible to see that the total electricity production (2673 MWh/y) is lower in these scenarios with respect to scenario 1 (5143 MWh/y) due to the smaller size of the CHP.

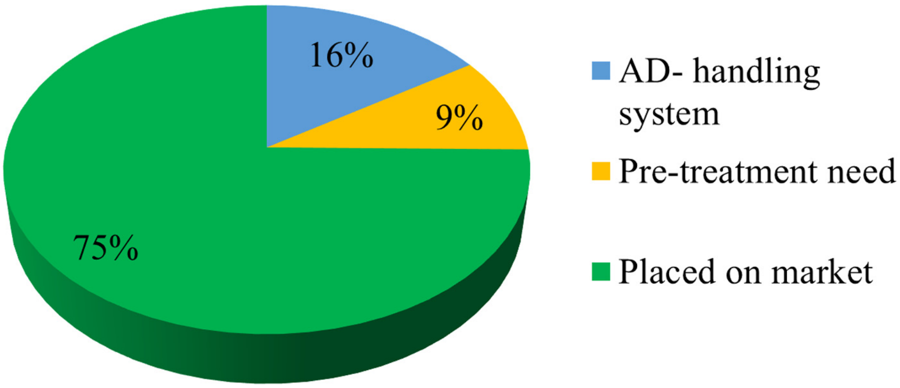

Fig. 11. Scenario 1 electricity distribution.

Table 5
Scenario 2 destination of produced energy.

Service	Energy
Power production [MWh/y]	2673
AD-handling system [MWh/y]	810
Pre-treatment need [MWh/y]	486
W_{up} [MWh/y]	243
Placed on the market	1134
V_{CH4} [Sm^3/y]	648000

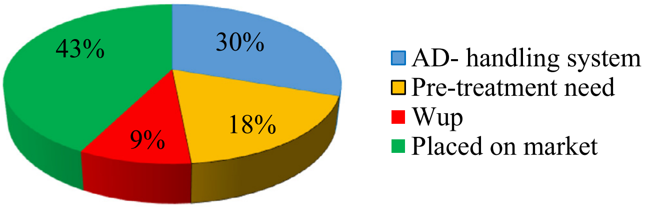

Fig. 12. Scenario 2 electricity distribution.

Table 6
Scenario 1 net profits.

	Profits [k€/year]
Power surplus	208.7
Waste collection	2380
Fertilizer	30
Total	2618.7

Table 7
Scenario 1 CAPEX analysis.

CAPEX	[k€]
AD system	3000
Trucks Fleet	3000
CS-600kW	550

Table 8
Scenario 1 OPEX analysis.

OPEX	[k€/year]
CS-maintenance	5.5
AD-maintenance	30
Maintenance fees	900
Fuel required	10

The produced electricity is then utilized, similarly to scenario 1, for different purposes. Specifically: 810 MW/y (30%) are used for the AD operations, 468 MWh/y (18%) are used for pre-treatment processes, and 243 MWh/y (9%) are used by the upgrading system to operate (Wup). The total amount of electricity sold to the grid is then equal to 1377 MWh/y (43%) (lower than case 1 — 3847 MWh/y). However, differently to scenario 1, in these scenarios also a consistent amount of CH_4 (V_{CH4}) is produced (648000 Sm^3/y) and sold the electricity market. From the environmental point of view, considering an emission factor equal to 0.35 kgCO$_2$/kWh $_{el}$ a total CO_2 saving from electrical production equal to 935 tCO$_2$/y is also estimated, whereas biogas production carries to 1296 tCO$_2$/y with an emission factor of 0.002 tCO$_2$/Sm^3, obtaining CO_2 saving about 2331 tCO$_2$/y.

Economic results

In this section, the economic results related to scenarios 1, 2a, and 2b are separately described. Note that, the following analysis is carried out by considering typical values, for the Italian energy market, of purchase and selling prices. Starting from scenario 1, with respect to the electricity sold to the national grid (resulting to be equal to 3.87 GWh/y) the revenue amounts to 208.7 k€/year thanks to the achieved daily profits (shown in Fig. 13).

In addition to the profits obtained by selling the energy surplus to the grid, other profits should be considered: the waste collection fee and the fertilizer sold on the market. As said, the AD is fed by the urban solid waste collected by "La Bellotta". Usually, for the waste collection a fee is recognized (in this case the fee has been considered equal to 70 €/t) for a total profit of 2380 k€/y. In addition, the waste from the AD operation can be sold on the marked as fertilizer (at a tariff of 1€/l) for total revenue of 30k€/y, as analysed in Table 6. The fertilizer is in terms of digestate/slurry and, due to the AD continuous process, a post-treatment is not needed. So, it can be used directly for fertilization processes.

Once the revenues due to the several services have been evaluated, to estimate the economic convenience of the proposed scenario, a CAPEX and OPEX analysis has also been carried out, where CAPEX stands for investment costs, while OPEX refers to operating costs. The CAPEX and OPEX analyses are presented in Table 7 and Table 8, respectively. Here, the investment costs [k€] for AD and CHP systems and trucks fleet are presented along with the CS and AD maintenance costs (that are evaluated as 10% of overall maintenance costs). Note that these values are obtained from diverse handbooks regarding these technologies (Wellinger et al., 2013). The operating cost includes the maintenance one, estimated as 10% of CAPEX spread on a cut-off period of 10 years (1% CAPEX per year). Specifically, the maintenance fees refer to fuel purchasing, employee salaries and other incidental expenses. Note that, in the OPEX analysis, the required fuel for the solid waste collection trucks is also presented. Specifically, for the analysis it has been assumed an average covered distance of 50 km/day for heavy trucks and 100 km/day for light trucks, returning a yearly fuel consumption about 15600 l/year.

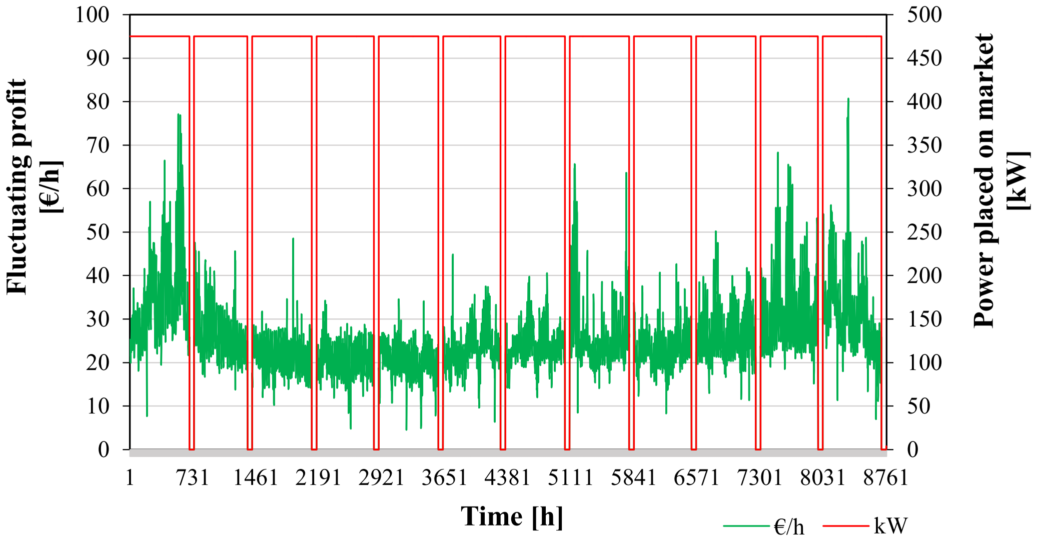

Fig. 13. Scenario 1 daily profit related to fluctuating national price.

Table 9
Scenario 2a Net profits.

	Profits [k€/y]
Power surplus	75
Biomethane selling	142
CIC	395
Waste collection	2380
Fertilizer	30
Total	3022

Table 10
Scenario 2a CAPEX analysis.

CAPEX	[k€]
AD system	3000
Trucks Fleet	3000
CS-330kW	550
UP system	1015

Table 11
Scenario 2a/2b OPEX analysis.

OPEX	[k€/year]
CS-maintenance	5.5
AD-maintenance	30
UP-maintenance	10.15
Management fees*	900
US operating	190

Table 12
Scenario 2b net profits.

	Profits [k€/year]
Power surplus	275
Biomethane selling	667
CIC	395
Waste collection	2380
Fertilizer	30
Total	3747

From these results, a Discounted PayBack (DPB) equal to 4.46 years is calculated, considering a discounting rate of 5%. In addition, the Net Present Value, after 10 years lifespan with a discount rate of 5%, is equal to 6.36 M€, with a Profitability Index (PI) equal to 0.97.

Differently from the energy point of view, scenarios 2a and 2b must be separately investigated due to the different criteria adopted in the CH_4 and electricity dispatching. Consequently, it is possible to notice that, differently from case 1, also the revenue due to the biogas sale (142 k€/y — calculated by considering a selling price of 0.22 €/Sm^3) is presented.

The electricity sold to the national grid (resulting to be equal to 1.13 GWh/y) carries to a revenue amount of 75 k€/year. The daily profits are shown in Fig. 14.

In the following Table 9 bio methane selling is evaluated by considering Double Counting business plan. Specifically, this incentive recognizes, for new companies operating in the sector of high efficiency and eco-sustainable production, a double assignment of bonus certificates (CIC) if the production concerns biofuels. It supports biofuel production and clarifies the difference between biomethane and advanced biomethane, identifying the latter based on the type of organic matrix used, for the previous cases, with a use of 70% of solid waste and 30% of rural processing waste. Then, the biofuel produced is recognized as advanced biomethane with the identification of 1 CIC for 615 Sm^3. The average economic value of 1 CIC is estimated to be equal to 375€. With an overall annual production of 648’000 Sm^3 of bio methane, 1053 CIC should be considered.

Aiming at evaluating the economic convenience of scenario 2, a CAPEX and OPEX analysis has also carried out. In addition to the previous case, also the upgrading system initial cost is taken into account (considering a system of 100Sm^3/h size). The results of the CAPEX and OPEX analysis are respectively reported in Tables 10 and 11. Here, the investment costs [k€] for AD, CHP an UP systems and trucks fleet are presented along with the CS and AD maintenance costs (that are evaluated as 10% of overall maintenance costs). Note that these values are obtained from diverse handbooks regarding this technology (Wellinger et al., 2013).

By these results, For Scenario 2a, the calculated Discounted PayBack is 4.58, with a discount rate of 5% over a 10-year lifespan. In addition, the Net Present Value is equal to 7 M€, with a Profitability Index of 0.93.

Regarding to Scenario 2.b, profits are reported in Table 12. Here it is possible to notice different net profit values of power surplus and biogas selling with respect to Scenario 2a (even if the biogas production and the energy surplus are the same — see Table 5).

Such discrepancies are due, as already mentioned above, to the different prices for selling electricity and biogas due to the ownership of the supply chain. Specifically, for scenario 2.b the

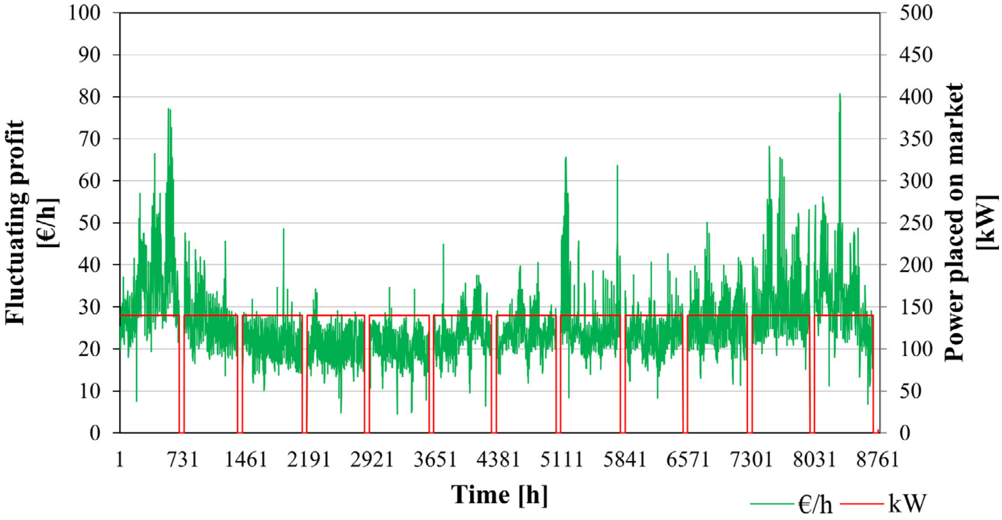

Fig. 14. Scenario 2 daily profit related to fluctuating national price.

Table 13
Scenario 2b CAPEX analysis.

CAPEX	[k€]
AD system	3000
Trucks Fleet	3000
CS-330kW	550
UP system	1015
Fuelling Station	1000

average electricity price is equal to 0.2 €/kWh (PUN for scenario 2.a) whilst the average biogas allocating price is evaluated with a retailing price of 0.95 €/kg and biomethane density of 1.1 kg/Sm^3 (0.22 €/Sm^3 for scenario 2.a).

Aiming at evaluating the economic profitability of Scenario 2.b, the OPEX analysis is the same of the previous case (Scenario 2.a), while the CAPEX analysis is reported in Table 13.

By these results, a Discounted Pay Back of 3.67 years is evaluated. In addition, the Net Present Value after 10 years lifespan is equal to 11.6 M€and a Profitability Index of 1.35.

To compare scenarios investigated so far, a Cash Flow comparison is performed in Fig. 15. From this figure, scenario 2b clearly results the most profitable from the economic point of view; it almost doubles the economic performance of scenarios 1 and 2a at the year 10.

3.2. Scenario 3

In this section the energy, environmental and economic results of scenario 3 are shown.

Energy analysis

As previously mentioned, this scenario refers to the investigation of the convenience in extending the existing district heating network to the city of Robassomero, nearby "La Bellotta". Three different system layouts are investigated with regards to the hot fluid production:

(i) Compound Parabolic Collectors (CPC) with Biomass auxiliary heater (4 MW);
(ii) Flat Plate Collectors (FPC) with Biomass auxiliary heater (4 MW);
(iii) Biomass auxiliary heater only (8 MW).

In the following, these three solutions are investigated to find out the best one for the considered scenario. In Figs. 16 and 17 the temperature time histories of the CPC and FPC proposed solutions are respectively reported along with the primary energy cumulative curve, which represents the primary energy requested by the auxiliary heater in order to satisfy the load demand. Specifically, the water temperature from the collector (T_{coll}), the water temperature from the storage tank (T_{tank}), and the water temperature from the load (T_{load}) are reported. Starting by analysing Fig. 16, it is possible to notice that, during the summer period, the working fluid (water) reaches its boiling temperature and, so, the thermal storage is limited. The mismatch between the thermal production and demand limits solar technologies implementation. This affects the primary energy required by the auxiliary heater, 3.8 GWh$_p$/y (total energy required by the district heating network, 5.29 GWh$_p$/y), so the CPC collectors can satisfy only a quarter of the global thermal demand.

Concerning the second investigated solar collector technology, the FPC, Fig. 17 shows the main system temperatures and primary energy. Note that the primary energy required by the auxiliary heater is about 4 GWh$_p$/y.

The higher primary energy demand (about $\frac{3}{4}$ of the global one) of these solutions makes them unfavourable. The economic profitability of these solutions is also affected by higher investment costs and complexity, for this reason only the third case is investigated. It should be considered that the good heating value of biomasses and the availability of one hundred acres of coppice wood by "La Bellotta" Community, makes the "Biomass Auxiliary heater" solution quite convenient. Such solution ensures less complexity and higher system control. Moreover, to maximize the profitability of the selected technology, an optimization procedure has been carried out. Specifically, two main parameters have been investigated: i) the storage tank volume (V_{tank}) whose value will be chosen between 45–100 m^3 to solve the mismatching between load and production linked to sources availability; (ii) the temperature difference between the delivery and return of the district heating network (ΔT), ranging between 5 °C and 45 °C.

The optimization of the tank volume (V_{tank}) showed that the higher the tank volume, the higher is the amount of energy to provide to the tank, due to its capacity and heat losses. The optimal tank volume value, selected to carry out the analysis, is equal to 45 m^3. By considering the optimization of the temperature difference between the inlet and outlet of the hot fluid, the results are reported in Fig. 18 which shows the thermal energy to be supplied by the boiler as a function of the temperature difference. As shown in this figure, the increasing of ΔT value helps to reduce

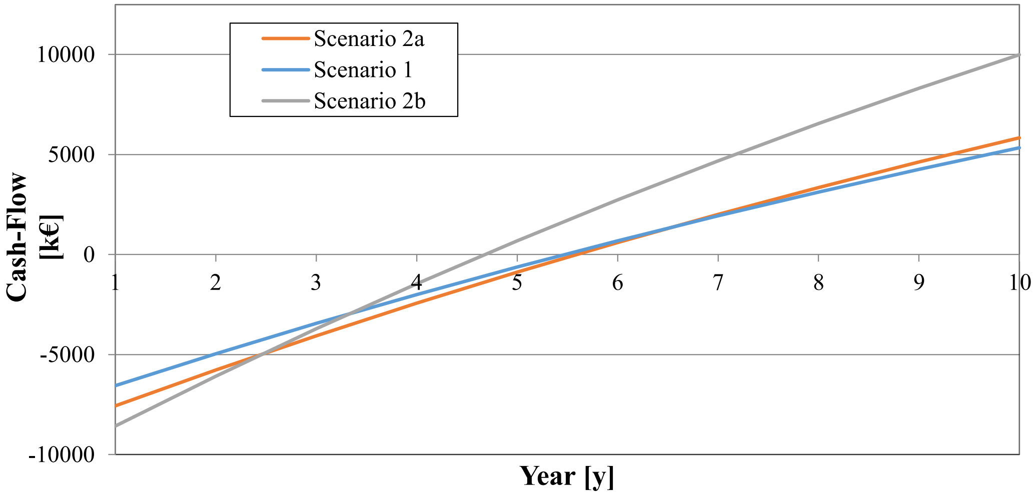

Fig. 15. Cash-Flow analysis in a 10 year cut-off period.

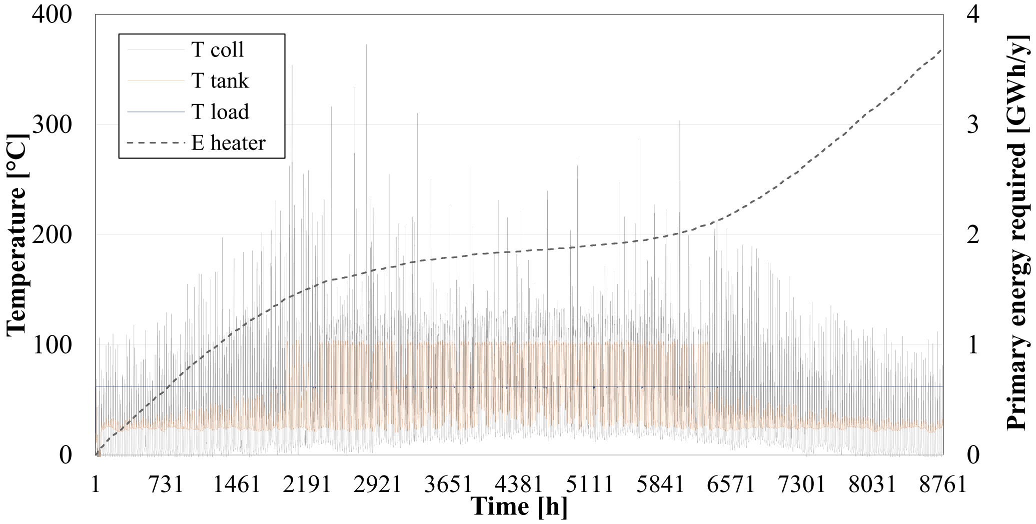

Fig. 16. Main system temperatures and primary energy required in case of CPC adoption.

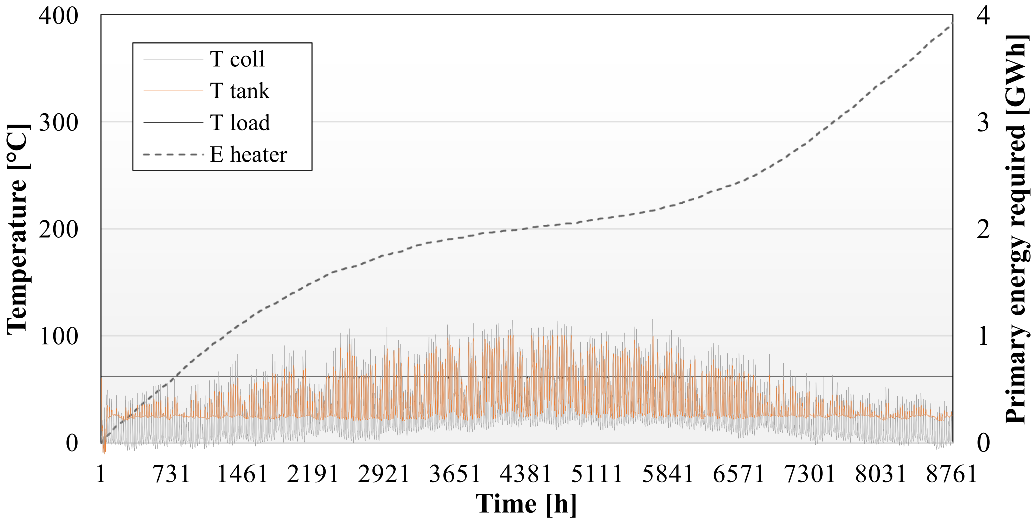

Fig. 17. Main system temperatures and primary energy required in case of FPC adoption.

m_{out}, outlet flow rate, and the primary energy provided to the heater. Even if the ΔT optimal value is near 40 °C, a ΔT equal to 30 °C has been chosen to guarantee an efficient heat exchange between working fluid and the user's one.

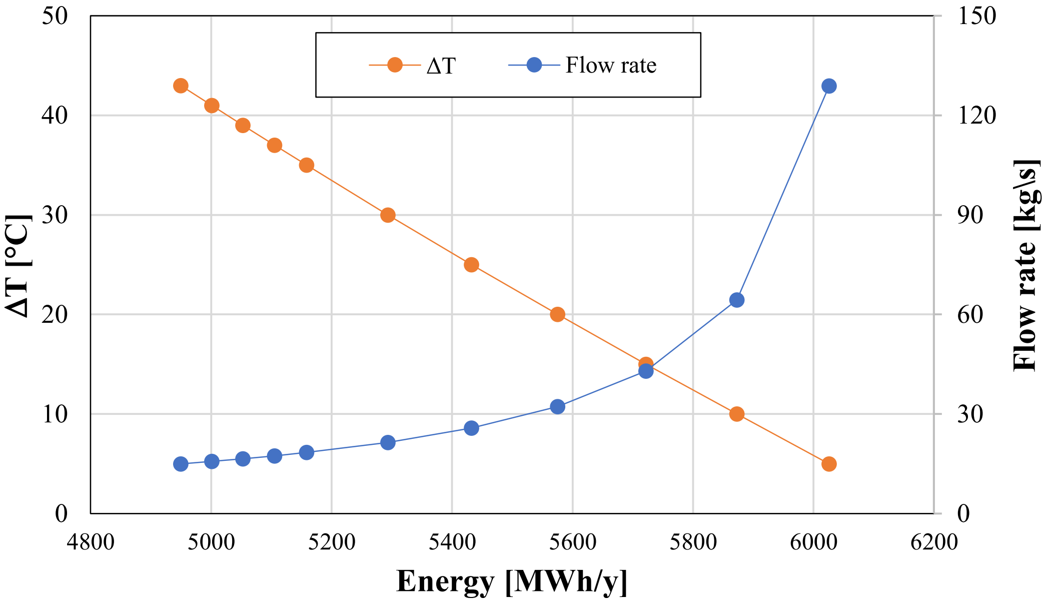

Fig. 18. Temperature difference and flow rate optimization.

Table 14
Scenario 3 CAPEX analysis.

CAPEX	[k€]
Piping	1600
Biomass Heater	100
Tank	100

Table 15
Scenario 3 OPEX and earnings analysis.

Profits or OPEX	[k€/y]
Biomass input	−130
Electrical power	−31
Thermal energy service	+398.2

Once the optimal solution has been found out ($V_{\text{tank}} = 45$ m^3; ΔT = 30), the energy, economic and environmental analyses are carried out.

From the energy point of view, the biomass heater satisfies the complete thermal demand, about 3.98 GWh$_t$. The primary energy to provide is calculated by knowing the heater efficiency and the district thermal losses, with a consequent primary energy input of 5.29 GWh/y. The biomass input is calculated, knowing the biomass heating value (4.07 kWh/kg), equal to 1300 t_{biomass}/y. The electrical energy required by the pumping system is calculated by knowing the pressure drop ($m_{\text{c.a.}}$) and the variable flow rate during the year, 141 MWh$_{\text{el}}$/y, where pump efficiency is assumed equal to 0.9, as:

$$E_{el} = \sum_{i=1}^{8760} \frac{\dot{m}_{out,i} \cdot g\Delta h}{\eta_{el,pump}} \text{ [Wh]} \tag{13}$$

From the environmental point of view, a CO$_2$ emission factor equal to 1.96 kgCO$_2$/Sm^3 and PCI = 10.6 kWh/Sm^3 is assumed. As a consequence, a total CO$_2$ saving of 740 tCO$_2$/y is also estimated.

Economic analysis

Following the energy analysis, the economic one is presented. Specifically, it has been carried out by evaluating the initial cost and the achieved profits. In this framework, the CAPEX of piping, storage tank and biomass heaters are reported in Table 14. The piping cost takes into account the costs of excavation and pipes, pumping system, control building and thermal substation. While the OPEX and the earnings are presented in Table 15. Biomass cost is 100 €/t$_{\text{biomass}}$, the electrical power is provided by the grid at 0.22 €/kWh $_{\text{el}}$ and the thermal energy is sold at 0.10 €/kWh $_{\text{th}}$.

By these results, a Discounted PayBack (a = 0.05) equal to 8.20 years is calculated, whereas the Net Present Value after 20 years lifespan resulted to be equal to 1.1 M€.

3.3. Scenario 4

In this section the energy, environmental and economic results of scenario 4 are shown.

Energy analysis

In this scenario, the option of building a district cooling network for the same community of scenario 4 is investigated. In this case, the cold fluid is produced by an air cooled electric chiller (352 kW) coupled with a PV solar field. According to the cooling energy demand (see the previous section), the electric chiller provides to the users 128 MWh$_{\text{th}}$/y for cooling purposes, requiring a total of 25.6 MWh$_{\text{el}}$/y. Aiming at maximizing the system performance, an optimization procedure has been carried out in order to determine the optimal PV field size (see Fig. 19). The analysis is carried out by varying the number of PV panels and by investigating the resulting SPB. According to the figure, the 45 kW$_{\text{p}}$ solution is selected (20 panels in series, 45 panels in parallel).

The resulting energy analysis is presented in Fig. 20 where the electric energy time histories are reported for the considered scenario. Here, the electricity is sold to or taken from the grid when > 0 and < 0, respectively. On a yearly basis, by means of the selected PV field layout, 70% of the chiller electricity demand (20 MWh/y) is covered by the PV field production. The remaining part (30% − 5.6 MWh) is taken from the electric grid. By the environmental point of view, an emission factor equals to 0.35 kgCO$_2$/kWh $_{\text{el}}$ is used, which leads to a total CO$_2$ saving of 20 tCO$_2$/y, if compared to an 100% purchase of electricity from the national grid.

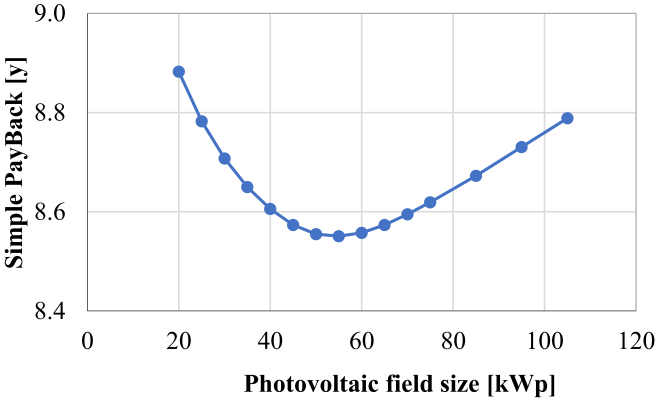

Fig. 19. Solar field optimization.

Table 16
Scenario 4 CAPEX analysis.

CAPEX	[k€]
Piping	140
Chiller	50
PV plant	36

Economic analysis

In order to analyse the proposed system from an economic point of view, a CAPEX and OPEX analysis similar to those performed for the previous case studies is here presented. Specifically, the CAPEX of piping, storage tank and biomass heaters are reported in Table 16 whereas the OPEX in Table 17. Note that the initial cost of the pipeline takes into account the costs of excavation, pipes and pumping system. By energy required for the electric chiller (and for the circulation pump) is equal to 1.2 k€/y (evaluated assuming a purchase price equal to 0,22 €/kWh $_{\text{el}}$), whereas the exceeding PV electricity production is sold to the grid at the PUN cost. Lastly, the cooling energy delivered by means of the district cooling network is sold at 0.20 €/kWh $_{\text{c}}$.

By these results, a Discounted Pay Back (a = 0.05) equal to 8.56 years is evaluated. In addition, the Net Present Value after 20 years lifespan is equal to 150 k€.

Table 17
Scenario 4 OPEX and earnings analysis.

Profits or OPEX	[k€/y]
Electrical energy from the grid	−1.2
Electrical energy to grid	+ 2
Cooling energy service	+ 25.6

3.4. Energy and economic comparative analysis

In this final section the results of each single scenario are analysed by considering energy, economic and environmental indicators, as shown in Table 18. Summarizing, these are the simulated scenarios:

- *Scenario 1*: Anaerobic digestor and cogeneration system,
- *Scenario 2a*: Anaerobic digestor and cogeneration system with upgrading,
- *Scenario 2b*: Anaerobic digestor and cogeneration system with upgrading + Supply chain ownership,
- *Scenario 3*: Enhancement of the existing district heating network,
- *Scenario 4*: District cooling network.

Obtained results underline promising energy and economic benefits for all users. Specifically, self-sufficiency in the production of thermal and cooling loads is showed by the self-sustaining services ratio (SSR) – only applied to Scenario 3 and 4 – which surpasses 80% in Scenario 4 and reaches 100% in Scenario 3 where heating and cooling are fully balanced through self-consumed energy. Concerning the self-consumption ratio (SCR), it reaches 57% in case of Scenario 1 and 2a, and 100% in case of Scenario 2b, showing that the ownership of the gas stations enables the full self-consumption of on-site energy production. This scenario is the only one that returns a profit index (*PI*) higher than 1, such as 1.35, underlying how that the gas stations ownership is the best economic solution despite the lowest discounted pay back (3.7 years). The highest emission savings are obtained for Scenarios 2 (2300 tCO_2/y), due to the production of bio methane; such saving corresponds to the average yearly emission of 500 typical passenger vehicles [(EPA, 2018)]. It is worth noticing that biofuel – depending on the scenario – is delivered to the distribution network or addressed to retailing. This highlights how different strategies influenced the self-consumed energy quota over

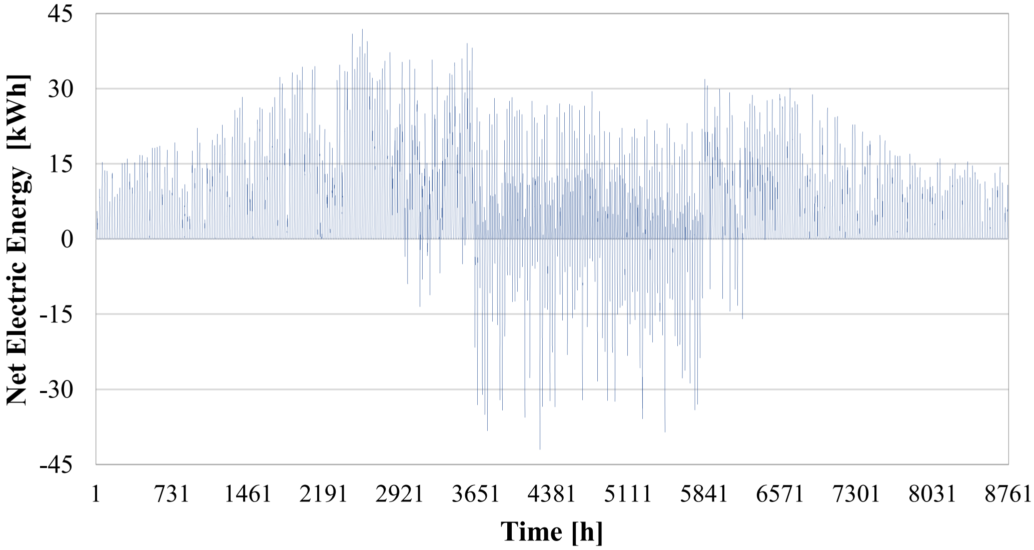

Fig. 20. Net electric energy ($E_{\text{el,PV}}$ + $E_{\text{el,chiller}}$) on a yearly basis.

Table 18
Energy, economic and environmental indices for each investigated scenario.

	Scenario 1	Scenario 2a	Scenario 2b	Scenario 3	Scenario 4
Energy indicators					
SSR	–	–	–	100%	81%
SCR	57%	57%	100%	–	–
Economic indicators					
DPB [y]	4.47	4.59	3.67	8.20	8.57
NPV [M€] *10-year*	6.34	7.00	11.6	/	/
NPV [M€] *20-year*	/	/	/	1.11	0.150
PI [-]	0.97	0.93	1.35	0.62	0.67
Environmental indicator					
Emission saving [tCO2/y]	1800	2300	2300	740	20

the whole energy production and the economic feasibility. Finally, overall results clearly show that agricultural industries can play a crucial role in laying the foundations for the sustainable development of adjacent communities.

4. Conclusions

This paper investigates the potentials of several innovative energy efficient scenarios to support the sustainable transition of agricultural and zootechnical communities. To this aim, a case study based on the existing community of "La Bellotta", located in North Italy – to be considered as a reference case – is presented and discussed. Several scenarios integrating a gas fuelled co-generator and an anaerobic biodigester, and several other technologies (e.g. solar systems, smart mobility, district heating and cooling) are modelled and simulated in TRNSYS environment by means of dynamic simulations. Furthermore, by taking into account local weather conditions and energy market prices, a parametric analysis is conducted to find out the best scenario among those investigated. Promising energy, economic and environmental results and findings related to the optimal investigated scenarios are achieved, such as:

- The use of an anaerobic digester, fed with agricultural waste, coupled with the co-generation system (Scenario 1) leads to a significant amount of electricity production (equal to 5143 MWh/y), allowing for achieving a ratio of self-consumed electricity equal to 25%. Economic savings (due to avoided energy consumptions and remuneration due to electricity sold to the grid) make the system feasible considering the promising economic indexes ($NPV = 6.3$ *M€*, DPB $= 4.47$ *y*, $PI = 0.97$). Correspondingly, savings of 1800 tCO_2/y, corresponding to the average yearly emission of about 390 typical passenger vehicles.
- By considering an anaerobic digester – this time feed by solid urban waste – coupled with the co-generation system, and by integrating an upgrading system (Scenarios 2a and 2b) with respect to Scenario 1 an electricity surplus (from the co-generator) equal to 1134 MWh/y is obtained, as well as and additional production of bio-methane of 648000 Sm^3/y is obtained. In Scenario 2b, the ownership of the gas stations enables the full self-consumption of on-site energy production, resulting in much better economic and environmental results. Indeed, the maximum PI (equal to 1.35), the lowest DPB (equal to 3.7 *y*), the highest NPV (equal to 11.6 *M€*) are obtained for Scenario 2b, which leads to a total of avoided 2300 tCO_2/y (sum of 935 tCO_2/y due to electricity produced on-site and to 1296 tCO_2/y due to biogas), corresponding to the average yearly emission of about 500 typical passenger vehicles.
- The enhancement of the existing district heating network allows providing to the near Robassomero city about 3.98 GWh_t of thermal energy for heating needs (corresponding to 5.29 GWh/y of primary energy). The environmental benefits achieved by adopting the biomass heater-based district heating system (Scenario 4) is calculated in 740 tCO_2/y; however, due to the low energy performance, economic indexes suggest the non-profitability of the proposed scenario.
- The adoption of a solar assisted district cooling system (Scenario 5) leads to a total electricity saving equal to 20 MWh/y which is equal to 70% of the total demand (25.6 MWh_{el}/y), for a total CO_2 saving of 20 tCO_2/y. Nevertheless, this scenario is less profitable, with very low economic indexes
- General outcomes suggest that from the economic point of view, all the investigated solutions always lead to interesting DPBs ranging from 3.7 to 8.6 years in case of scenario 2b and 4, respectively; though, Scenario 2b is the most profitable layout ($PI > 1$).

In conclusion, although there are challenges that should be faced to boost the transition to energy independent communities, like practical ones and related to technical and policy issues, it can be achieved by the proper integration of energy efficient systems. This paper shows the feasibility, from the energy, economic and environmental point of view, in accomplishing an energy independent community enhancing existing infrastructures. This may represent the very first step to raise awareness, especially of policy makers, leading to the spread of near zero energy communities (nZEC). About the limits of this research, its case-sensitive results must be noted, though obtained findings could be qualitatively generalized. Therefore, as future perspective, the proposed scenarios will be applied to different agricultural and zootechnical communities, subjected to diverse economic and weather conditions, with the aim to produce a range of different case studies, which could be useful for stakeholders. This would allow to extend obtained findings both qualitatively and quantitatively to build road maps for the proper and efficient implementation of the proposed novel energy schemes in real applications. In addition, an extension of similar multi-scale analyses, applied to diverse communities and energy sources should be conducted to provide a comprehensive framework of potentials and limits of communities to support the sustainable transition of our economy. A particular attention would be focused on the proposition and assessment of collective energy actions with provision of benefits for members and stakeholders.

Nomenclature

AD	Anaerobic digester
CHP	Cogeneration or combined heat and power system
CPC	Compound parabolic collector
DM	Dry matter
FPC	Flat plate collector
h	Enthalpy
i	Methanogenic index
LHV	Lower heating value
m	Flow rate
NPV	Net present value
nZEB	Net zero energy buildings
nZEC	Net zero energy community
P	Power
PI	Profitability index
Q	Thermal power [W]
RES	Renewable energy source
SEC	Smart energy community
STC	Solar thermal collector
US	Upgrading system
V	Volume
VR	Volatility rate
W	Mechanical power

Greek symbols

η	efficiency
ρ	density
μ	conversion ratio

CRediT authorship contribution statement

Anthony Maturo: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing - review & editing, Visualization, Investigation. **Andrea Petrucci:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing - review & editing, Visualization, Investigation. **Cesare Forzano:** Methodology, Data analysis, Visualization, Investigation, Writing - review & editing. **Giovanni Francesco Giuzio:** Methodology, Data analysis, Visualization, Investigation, Writing - review & editing. **Annamaria Buonomano:** Supervision, Writing - review & editing, Conceptualization, Investigation. **Andreas Athienitis:** Supervision, Funding acquisition, Writing - review & editing, Resources, Conceptualization, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Akinyele, D., Rayudu, R.J.S.E.T., 2016. Assessments, strategy for developing energy systems for remote communities: Insights to best practices and sustainability. 16, pp. 106–127.

Amaral, A.R., et al., 2018. Review on performance aspects of nearly zero-energy districts. Sustainable Cities Soc. 43, 406–420.

Awad, H., Gül, M., 2018. Optimisation of community shared solar application in energy efficient communities. Sustainable Cities Soc. 43, 221–237.

Barone, et al., 2021. Increasing renewable energy penetration and energy independence of island communities: a novel dynamic simulation approach for energy, economic, and environmental analysis, and optimization. J. Cleaner Production 311, 127558.

Beckman, W.A, 1994. TRNSYS the most complete solar energy system modeling and simulation software. 5, (1–4), pp. 486–488.

Bell, K., Gill, S., 2018. Delivering a highly distributed electricity system: Technical, regulatory and policy challenges. Energy Policy 113, 765–777.

Calise, F., et al., 2020. Energy efficiency in small districts: Dynamic simulation and technoeconomic analysis. 220, 113022.

Carlisle, N., Van Geet, O., Pless, S., 2009. Definition of a Zero Net Energy Community (No. NREL/TP-7A2-46065). National Renewable Energy Lab.(NREL), Golden, CO.

Ceglia, F., et al., 2020. From smart energy community to smart energy municipalities: Literature review, agendas and pathways. J. Cleaner Prod. 254, 120118.

EPA, United States Environmental Protection Agency, 2018. Greenhouse gas emissions from a typical passenger vehicle. Available from: www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle.

Gaiser, K., Stroeve, P., 2014. The impact of scheduling appliances and rate structure on bill savings for net-zero energy communities: Application to west village. Appl. Energy 113, 1586–1595.

Galderisi, A., Mazzeo, G., Pinto, F., 2016. Cities dealing with energy issues and climate-related impacts: Approaches, strategies and tools for a sustainable urban development. In: Smart Energy in the Smart City. Springer, pp. 199–217.

Gui, E.M., MacGill, I., 2018. Typology of future clean energy communities: An exploratory structure, opportunities, and challenges. Energy Res. Soc. Sci. 35, 94–107.

Hachem-Vermette, C., et al., 2019. Towards achieving net-zero energy communities: Investigation of design strategies and seasonal solar collection and storage net-zero. Sol. Energy 192, 169–185.

Hahnel, U.J.J., et al., 2020. Becoming prosumer: Revealing trading preferences and decision-making strategies in peer-to-peer energy communities. Energy Policy 137, 111098.

Hendron, R., Engebrecht, C., 2010. Building America House Simulation Protocols. Office of Energy Efficiency and Renewable Energy (EERE), Washington, DC.

Kim, M.-H., et al., 2019. Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community. Energy 187, 115916.

Liu, X., Mancarella, P., 2016. Modelling, assessment and sankey diagrams of integrated electricity-heat-gas networks in multi-vector district energy systems. Appl. Energy 167, 336–352.

Liu, X., Yan, Z., Wu, J., 2019. Optimal coordinated operation of a multi-energy community considering interactions between energy storage and conversion devices. Appl. Energy 248, 256–273.

Mitchell, J.W., Duffie, J.A., 2012. TRNSYS 17 - Mathematical Reference.

Mittal, A., et al., 2019. An agent-based approach to modeling zero energy communities. Sol. Energy 191, 193–204.

Moroni, S., et al., 2019. Energy communities in the transition to a low-carbon future: A taxonomical approach and some policy dilemmas. J. Environ. Manag. 236, 45–53.

Morvaj, B., Evins, R., Carmeliet, J.J.E., 2016. Optimising urban energy systems: Simultaneous system sizing, operation and district heating network layout. 116, pp. 619–636.

Prato, A.P., et al., 2012. Integrated management of cogeneration plants and district heating networks. 97, pp. 590–600.

Rafique, M.M., Rehman, S., Alhems, L.M., 2018. Developing zero energy and sustainable villages – a case study for communities of the future. Renew. Energy 127, 565–574.

Rehman, H.u., et al., 2019. Towards positive energy communities at high latitudes. Energy Convers. Manage. 196, 175–195.

Rivarolo, M., et al., 2016. Design optimisation of smart poly-generation energy districts through a model based approach. 99, pp. 291–301.

Robertson, B., Bekker, J., Buckham, B., 2020. Renewable integration for remote communities: Comparative allowable cost analyses for hydro, solar and wave energy. Appl. Energy 264, 114677.

Suh, H.S., Kim, D.D., 2019. Energy performance assessment towards nearly zero energy community buildings in South Korea. Sustainable Cities Soc. 44, 488–498.

TRNSYS TESS Component Libraries - General Descriptions, 2013. Available from: http://www.trnsys.com/tess-libraries/TESSLibs17_General_Descriptions.pdf.

Verbong, G.P.J., Beemsterboer, S., Sengers, F., 2013. Smart grids or smart users? Involving users in developing a low carbon electricity economy. Energy Policy 52, 117–125.

Wellinger, A., Murphy, J.D., Baxter, D., 2013. The Biogas HandBook: Science, Production and Applications. Elsevier.