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An energy community for territorial resilience: Measurement of the risk of an energy supply blackout

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ABSTRACT

The Clean Energy Package is aimed at making the energy transition recommended by the European Union more competitive. Such an energy transition can be achieved through a variety of measures aimed at improving the security, sustainability and competitiveness of energy supply systems. These measures include the introduction of physical and regulatory infrastructures that are adequate to satisfy the energy market requirements, integrate renewable energies and ensure security of the energy supply. A risk-based approach is generally suggested for the electricity sector to prevent and manage electricity problems. A risk-based methodology is proposed in this work, and an assessment has been made of the first "oil free zone" in North-West of Italy, which is located in the Pinerolo area (near Turin). A quantitative risk analysis method was conducted considering the risk of blackouts on the national electricity grid, the probability of such occurrences, the extent of damage and the risk of exposure. The risk assessment was applied through a place-based approach, considering different types of stakeholders: private and public consumers, producers and prosumers. The risks of the analysed case study were then compared with their tolerability limits and assessed for different scenarios to reduce the risk of energy supply blackouts, including: a reduced energy consumption, an increased energy production, and an optimised energy supply and demand. The possibility of establishing an energy community was considered in the latter scenario. The results show that all the actions taken to reduce the risk of energy supply blackouts produce different results, depending on the considered user. All the stakeholders can benefit from participation in the energy community, not only from an environmental point of view, through the production of energy from renewable sources, but also from an economic one. These results are in line with what the European Community and the Italian "Integrated National Plan for Energy and Climate" currently require, in terms of energy transition, pertaining to the sustainable development of a territory.

1. Introduction

The European Commission, with the "Clean energy for all Europeans" package [1] is encouraging Europe to be more competitive in its energy transition process through three main actions: achieving energy efficiency, becoming a leader in renewables, and conceiving the consumer as an active player, especially on the electricity market. These indications were implemented in Italy in December 2019 with the publication of the Integrated National Plan for Energy and Climate (INPEC) [2]. The intervention priorities suggested to achieve these macro-objectives can be summarised as: improvements in the use of renewable energy sources, energy efficiency and energy security measures, competitiveness of energy markets, decarbonisation of the energy system, and improvements in technology, research and innovation. In this context, certain actions can be defined beforehand to guarantee that an infrastructure is adequate to make the energy market competitive, to integrate renewable energies and to ensure security of the energy supply. Moreover, in order to promote the economic development of a territory, it is important to create an internal energy market that guarantees benefits for all the stockholders and to rectify the current lack of coordination of the regulatory mechanisms in force.

Several legislative acts have been introduced to implement the "Clean energy for all Europeans" package, including EU Regulation 2019/941 [3] on risk preparedness in the electricity sector. This regulation was drafted to prevent and manage energy problems,

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Nomenclature

ARERA	Italian Energy Regulatory Authority
BAU	Business as usual
C	Consumption, [kWh]
CEC	Citizens' Energy Community
COM	Company user
CONS	Consumer
CSC	Collective Self-consumption, [kWh]
DOM	Domestic user
DSO	Distribution Service Operator
e	Exposure factor, [-]
EC	Energy Community
EE	Energy Efficiency
f	Frequency Index, [int/yr/us]
GHG	Green House Gas
GSE	Italian Energy Service Manager
HC	High Concentration
HDD	Heating Degree Days, [°C]
LC	Low Concentration
LG	Local Electric grid
LV	Low Voltage
M	Magnitude factor, [min/yr/us]
MC	Medium Concentration
MEG	Micro Energy Grid
MUN	Municipal user
MV	Medium Voltage
NG	National Electric grid
OFZ	Oil Free Zone
OP	Over-Production, [kWh]
P	Production, [kWh]
PP	Productivity
PROS	Prosumer
PV	Photovoltaic system
R	Risk Index, [min/yr^2/us^2]
REC	Renewable Energy Community
REM	Renewable energy micro grid
RES	Renewable energy sources
SC	Self-consumption
SCI	Self-Consumption Index
sOP	still Over-Production
SSI	Self-Sufficiency Index
ST	Storage
sUD	still Uncovered Demand
TC	Total Consumption
TP	Total Production
TSO	Transport Service Operator
UCD	Urban Concentration Degree
UD	Uncovered Demand

through a risk-preparedness plan, to prevent their occurrence and to mitigate their impact.

This work falls into this context, as it attempts to identify a risk-based methodology that is based on the energy demand and supply of a territory, and to evaluate various possible future scenarios, including that of energy communities.

In recent years, the number and intensity of natural disasters that have occurred due to climatic changes have increased significantly in many countries and have had destructive effects on electric power systems. Even those systems that are highly reliable, in terms of risk assessment and management, may have to deal with significant issues, such as extensive and long-lasting blackouts [4]. The main objectives of a climate-resilient community are to deter the disruption of power services and to reduce the recovery times of unavoidable outages [5]. Increasing concerns about the reliability of energy systems and green-house gas (GHG) emissions have led to an increase in the quest for self-generation and distributed energy resources [6].

Micro Energy Grids (MEG), as defined in [6], have emerged as an efficient way of managing the complexity of the grid and of adding new levels of reliability and resiliency to energy systems [7]. Moreover, renewable energy-based micro-grids (REMs) appear to be a promising solution, due to the fact that power is generated locally near the end users, which reduces the burden on the national grid [8], and thus limits the exposure to the risk of blackouts. Hybrid energy systems, with higher shares of renewable energy sources (RES), may be an affordable, sustainable and reliable solution, as they use diverse technology mixes of local natural resources [9]. Diversity is considered a key feature to improve resilience, as it may help to dilute the risks of redundancy and, from a socio-ecological point of view, it can also contribute to the reorganisation processes after the disruption of a system [10].

A risk-place-based assessment is therefore proposed in this work which uses georeferenced data at a territorial scale. The aim is to analyse how to group together energy consumers and producers, in order to guarantee a sufficient availability of renewable energy sources. The results will provide a form of aggregation that would allow economic benefits and a sustainable development of the territory to be attained.

Section 2 presents the research background. Some important definitions of energy resilience, energy communities and energy risks are given in Section 3; the risk-based methodology is then explained with reference to the risk of an interruption of the energy supply from the national grid. In Section 4, the risk-based methodology is applied to a case study of the first Oil Free Zone in Italy, which is also one of the first Energy Communities in the country; Section 5 presents the results of the proposed methodology and compares several intervention scenarios. This methodology uses typical risk analysis evaluation tools and techniques and combines them with place-based analyses to evaluate the energy supply and demand, which are of fundamental importance to guarantee energy security. The economic implications of the various scenarios are evaluated, considering the economic incentives as laid out in the national legislation in force. A cost-optimal analysis is assessed for each intervention that has been assumed to be implemented, considering that the choices that are made will also have to promote an economic development of the territory, with economic benefits for all the stakeholders.

2. Research background

The choice of the main scientific contributions was made by considering the definitions of resilience and addressing several aspects related to energy systems. Risk assessment and management starts with the identification of all the vulnerabilities of a system and with a comparison of different forecast scenarios. The indicators used to measure the reliability of systems have to consider the uncertainties resulting from disruptions caused by accidental events.

Soren and Shastri [11], with the aim of designing a resilient biomass supply chain, defined resilience as a function of four dimension: robustness, redundancy, resourcefulness and rapidity, and they measured it by referring to time and costs. They defined

Time-to-survive as the time required by a supply chain to regain the predefined service level, and they used a risk exposure index to identify the weak parts of a supply chain. Through this approach, it is possible to quantify the expected disruption cost or the expected overall restoration cost in economic indicator terms.

Mousavizadeh et al., assessed the concept of resiliency in a smart distribution network of micro-grids and distributed energy resource systems [4]. They found that a two-stage framework, based on stochastic programming, allows the optimal formation of dynamic microgrids, distributed generation and energy storage units to be evaluated, as well as the impact of an increasing penetration level of renewable energy sources (RES) and their related uncertainties.

According to Koratz and Gabbar [6], the complexity of a micro-grid system makes it necessary to consider safety right from the first phases of the design. The reliability of the safe performance of such a system, in the case of an electric blackout, is related to the ability of the system to reduce its dependence on the national grid and the margin between energy supply and demand. They hypothesised independent protection layers, starting from a hazard matrix, a fault tree analysis and a layer of protection analysis, as a multilevel hierarchical control system that may be used to prevent and mitigate the impact of hazards on micro-grids.

Fonseca et al. [10] and Kishita et al. [12] presented a broad concept of resilience, which they considered capable of including sustainability. Fonseca et al. investigated the role spatial heterogeneity plays in the resilience and environmental performances of future urban areas, and mapped energy and transportation system indicators (Shannon's entropy formula, GHG emissions, primary energy and noise pollution). They evaluated the capacity of a system to absorb, adapt and be restored after a disturbance through the use of the *minimum reserve margin*, which represents the available power capacity of a system, and the *minimum potential resource margin,* which is the percentage of the electricity demand at peak times. Kishita et al. [12] incorporated resilience in visions of desirable future energy, assuming a back-casting approach to define unwanted future scenarios upon which to create resilient futures. They used a fault tree analysis to define backward thinking by identifying long-term goals and underlining the importance of participatory back-casting: different stakeholders should be engaged in enriching the contents of a scenario through the co-production of knowledge and the support of policy design. Both contributions have the aim of defining methods that could be integrated, at a preliminary planning stage, to help define the most efficient and sustainable strategy from among various possibilities. In the same way as in the next two studies that are mentioned, a hybrid renewable power system was considered as a sustainable power solution to diversify the supply system, which, in that case, was intended as a crucial strategy to achieve low-carbon emissions and a climate resilient community.

Bagheri et al. [5] defined an optimised energy plan for an urban system, considering different energy sources and using actual real-time hourly electric loads of different types of end users. They evaluated the most techno-economic configuration, using the total net cost as an objective function and the electric demand load as a constraint. They then assessed the capacity shortage (e.g., the percentage of the demand load that was not met by the considered power system) and atmospheric emissions.

Bertheau and Blechinger [9] used a similar methodology to evaluate the investments and operational costs of a system, and to individuate the most efficient transition strategy for the small-island energy system of the Philippines in an attempt to achieve the United Nation Sustainable Development Goals. They found that, despite an increasing electricity demand, resilience could be ensured by decentralising the power supply and optimising the use of local resources, thereby reducing the dependency on central generation.

Luthander et al. [13], who assessed the potential of a PV-battery system, described the importance of daily and seasonal matching between the on-site energy supply and demand. They used two indicators to express the load matching potential: self-sufficiency and self-consumption indexes, thereby providing a novel graphic approach to visualising both the size and time of the matching.

Table 1 shows the main and most recent scientific contributions in this field. The variety of research questions aimed at studying the reliability of the different aspects that make up the energy system is evident. Consequently, different methodologies have been defined and applied to case studies at different scales.

A research gap has been identified concerning the lack of a place-based methodology which, starting from the identification of the specificities that exist on a territory, would be able to take into account, in a combined manner, the energy demand (with the characteristics of the different users and their potential level of energy efficiency) and the supply (with the characteristics of the available energy sources in a built environment), and to evaluate their contribution to the reliability of the entire energy system at a territorial scale.

3. Materials and methods

In this work, a place-based methodology, which makes use of Geographical Information Systems, that is, GIS tools, to map the resources and stakeholders in a territory, has been used to calculate and manage data of different a nature and origin in an integrated manner. As suggested in EU regulation 2019/941 [3], a risk-based method allows the territorial production, distribution and consumption of electricity to be optimised by identifying the elements that have the most impact on the reduction of the territorial energy risk. The same type of assessment can also be used for a thermal energy system.

The aim of this study has been to investigate a combination of different energy profiles of several end users (e.g. industries, residential buildings, municipalities) and their consequent impact on a renewable hybrid electrical system.

The optimal time interval, which depends on the availability of the data, and on the types of environmental and required energy balances, was also investigated. An hourly time interval was considered for this analysis; it was found that it would be difficult and too time-consuming to obtain a shorter time interval for such feasibility analyses at a territorial scale because of the huge amount of data that would be necessary. However, a shorter time interval may also be used for more accurate economic analyses.

The aim of this study has been to define a reliable methodology that can be used to support a decision-making process, to provide a complete overview and to overcome the current lack of coordination that exists between the various regulations concerning the energy market. A multiplicity and fragmentation of the regulations can at present be witnessed, concerning both the remuneration of energy (for example system charges and distribution quotas), and incentive forms. The incentives have often been drawn up for the benefit of individual categories of users. Incentives are formulated without considering any differences in the distribution of the available energy resources. At the same time, they contribute to fragmenting the possible scenarios for the different stakeholders, as can be seen, for example, by considering the variety and stringent regulations regarding aggregation models of the energy users: associations, cooperatives, consortia, simple productions and consumption systems (SSPC), or enabled mixed virtual units (UVAM) that can operate directly on market dispatching. However, the reference regulatory framework is constantly evolving, and some

Table 1
Scientific contributions considered in the research background.

Ref.	Year	Title	Keywords	Research objectives	Materials and Method	Case study
[14]	2019	Mapping Urban Resilience for Spatial Planning—A First Attempt to Measure the Vulnerability of a System	Urban Resilience, Spatial Planning, Vulnerability, Measuring, Mapping, Decision-Making	To introduce a pioneering and propaedeutic approach to the spatial measurement of urban resilience	Set of indicators and a GIS project to map the vulnerabilities of a system and to understand the spatial distribution of these vulnerabilities in a system	City-scale (Moncalieri, near Turin, Italy)
[11]	2019	Resilient design of a biomass-to-energy system considering uncertainties in the biomass supply	Biofuel, Supply chain, Disruption, Resiliency, Optimization, Uncertainty	Supply chain optimisation model of an energy system considering disruptions in the availability of biomass at the design stage	Objective function for the minimisation of the probability-weighted sum of ideal and disrupted scenario costs.	Regional scale
[5]	2019	City-integrated renewable energy design for low-carbon and climate resilient communities	Urban electrification, Hybrid renewable power system, Load patterns	To assess the impacts of different electric load patterns on the economic and emission performance of hybrid electric systems	HOMER (Hybrid Optimisation of Multiple Energy Resources), COE (Cost of Energy), Sensitivity Analysis	Neighbourhood scales, The City of Victoria, Canada
[9]	2018	Resilient solar energy island supply to support SDG7 in the Philippines: techno-economic optimised electrification strategy for small islands	Small islands, electrification, urbanisation	To analyse whether and how the provision of affordable, reliable, sustainable and modern energy from resilient systems can be achieved on small, isolated island grids in the Philippines.	Energy simulation tool (HOMER), COE (Cost of Energy), WACC (Weighted Average Cost of Capital), Sensitivity Analysis	A small island system for the Philippines
[4]	2018	A linear two-stage method for the analysis of resiliency in distribution systems considering renewable energy and demand response resources	Resiliency, Distribution network, Microgrids, Linear programming, Distributed energy resource	To analyse the resiliency of distribution networks in the face of disasters.	Fragility curve, mixed-integer linear programming, multiple simulations	–
[12]	2017	Designing back-casting scenarios to forecast resilient energy futures	Scenario design, Back-casting, Resilient future, Fault tree analysis, Energy system	To design back-casting scenarios in a way that leads to a systematic process of envisioning resilient futures.	Back-casting scenarios, Fault tree analysis	City-scale (Suita city, Osaka, Japan)
[6]	2017	Risk analysis and self-healing approach to obtain resilient, interconnected micro energy grids	MEG (electricity, heating, cooling, transport)	To create a resilient MEG that is able to mitigate major hazards.	Hazard matrix, Fault tree analysis, Independent Protection Layer, Layer of Protection Analysis (LOPA), Failure rate, Simulink®	Local scale (small-medium)
[8]	2017	Electrical machines-based DC/AC energy conversion schemes for the improvement of power quality and resiliency in renewable energy microgrids	Microgrids, Renewable energy sources, Power quality, Resiliency, Virtual inertia, Self-healing grids	To generate power quality through Renewable Energy microgrids (REMs) and to provide effective control during periods of uncertainty	MATLAB, Simulink®	–
[7]	2017	Controlling and optimising resilient distributed energy resources and microgrids with a demand-side operation platform	Distributed energy, smart grid,	To suggests some best practices for an optimal financial and operational control of a smart grid and distributed energy resources.	Presentation of a Demand Side Operation platform	–
[10]	2016	Spatial heterogeneity pertaining to the environmental performance and resilient behaviour of energy and transportation systems	Urban resilience, Environmental performance, Critical infrastructures, Decision-making, Sound environment, Spatial heterogeneity	To evaluate the effects of spatial heterogeneity pertaining to the future environmental performance and resilience of the case study area	Spatial heterogeneity indicators (Shannon entropy formula), the environmental performance of energy and transport systems (GHG emissions, primary energy, noise pollution, resilience)	Urban area in Switzerland

innovations have been formulated, at a European and at a national level, regarding incentives aimed at recognising the economic value of coordinated actions of a plurality of end users.

In this context, the concept of *collective self-consumption* has been introduced into the current legislation in Italy, as well as in the other Member States [15]. This concept offers different categories of end users the possibility of exchanging locally produced energy; moreover, specific bonus incentives are envisaged on the share of energy produced from the local RES and exchanged between stakeholders [16]. By starting from a complete, broad and risk-based vision of the energy system of a territory, it is possible to define regulations that could be of benefit for all the stakeholders, that is, without privileging certain categories of users, and which could contribute to the economic development of a territory.

In order to better understand this work, it is necessary to start from the definitions of territorial resilience and Energy Community (EC). These are energy aggregation models that are promoted by the European Union to carry out the key actions of an energy transition in a combined way.

3.1. Definition of territorial resilience

The concept of resilience has been developed over 40 years within different disciplines linked to the sustainability science to plan the ecological transition of cities [17]. At the end of the last century, cities around the world started to develop resilience policies to provide an answer to climate change and socio-economic uncertainties. According to the co-evolutive approach [18], resilience is not only the opposite of vulnerability, but also a "broad concept", whose final scope is to encourage sustainability and inclusiveness [19]. In other words, resilience is a dynamic process that reinforces the capacity of cities to preserve and adapt their material and immaterial components to face local and global stresses (including extreme meteorological events, natural disasters, human accidents, terrorism, social unrest and economic instability). In this paper, resilience refers to "territorial resilience", here intended as an emerging concept that is capable of identifying the vulnerabilities of a system and improving the transformation of socio-geographical areas during a decision-making process [20]. In this definition, the adjective "territorial" emphasises that the characteristics and intrinsic nature of places is a fundamental starting point for the development of resilience. In line with this approach, territorial resilience is not considered the result of a conventional top-down process, but is instead a place-based and proactive vision of territorial systems used to implement collective and individual actions in order to manage unforeseen events and improve environmental and social quality [21]. Brunetta et al. [20] underlined how the relationship between the intention of a community and co-evolution is a key aspect in improving territorial resilience. These two aspects are fundamental to consider resilience as a driver that increases the chances of achieving a sustainable future from an unpredictable evolutionary perspective that needs the organisation of local communities, potential bottom-up processes and the mobilisation of creative skills through social learning practices [22]. In this perspective, the concept of territorial resilience is closely related to both the creativity of local communities and to the openness of institutions that allow individuals to respond to unexpected conditions through innovative actions, as suggested by their particular knowledge of the circumstances of time and place. Local communities and institutions can start to participate in a direct relationship in which both parties learn from each other and innovate. In a nutshell, social and institutional learning capacity is an essential factor to achieve territorial resilience [23]. Finally, it has been shown that decision making about the measures that can enhance territorial resilience can effectively be supported through a multi-risk assessment, as discussed in [24] and dealt with in more depth in [25,26].

3.2. Definition of energy community (EC)

The Council of European Energy Regulators defines a "local energy community" as a cooperative/partnership/non-profit organisation of final customers, which can involve different stakeholders, such as municipalities, local societies, and public and private companies. The decision to set up such a community is aimed at achieving energy independence, self-sufficiency and self-consumption, in order to guarantee energy security, a low environment impact and affordable energy costs. In particular, the objectives of energy communities are to achieve sustainable development, energy efficiency and low emissions through: the exploitation of renewable sources, and the implementation of energy networks and grids in order to obtain smarter, more flexible and resilient configurations, that is, a user mix which optimises the variability of energy consumptions and peak loads in the networks, diversifies the energy supply sources and improves energy cost-effectiveness, thanks to technological innovations [27]. Because of the flexibility of this definition, these energy aggregation models can be adapted to different contexts. The Clean Energy Package contains two energy community definitions: Citizen Energy Community (CEC), which is contained in Electricity Directive 2019/944 [28], and Renewable Energy Community (REC), which is contained in Renewable Directive 2018/2001 [29]. Both directives define the Clean Energy Package as a collective cooperation of energy related activities around specific ownership, governance and non-commercial purposes. RECs may be intended as a subset of CECs, but differ from them because they offer the possibility of small-medium enterprises effectively controlling a REC. This stricter approach can be confirmed by considering the obligation of Member States to promote and facilitate the development of RECs, by facilitating access to finance and information, while ensuring access to vulnerable and low-income households, and removing unjustified regulatory and administrative barriers. It is also necessary to take RECs into account when designing national renewable energy support schemes.

In transposing European Directive RED II [29], the Italian law (DL 162/2019 Art. 42bis) [15] launched the experimentation of a legislative framework aimed at recognising REC configurations: it allows a plurality of end users to act as a collective energy user, in order to share locally produced energy from newly installed small-scale RES plants (each with an installed power < 200 kW). It is envisaged that any extra energy produced locally produced energy will be fed to the national grid (*Over Production*), at the same energy market prices.

Furthermore, an economic incentive of 118,22 €/MWh is granted to shared energy, defined as the minimum between the energy fed into the national grid by all the RES plants and the energy withdrawn from the national grid by all the members of the REC (in each hourly period), of which 110 €/MWh is granted as the premium tariff on exchanged energy and 8,22 €/MWh as a refund for the transportation and distribution of energy losses. As established by the Italian Ministry of Economic Development, in agreement with the National Energy Regulatory Authority (ARERA), and as described in a technical regulatory document provided by the National Energy Service Manager (GSE), *shared energy* (also *exchanged energy*) is here defined as *Collective Self-Consumption (CSC)*; the incentive is offered for a period of 20 years in an attempt to make investments profitable [16,30].

The recognition of a "prosumer", who is both a producer and consumer of energy at the same time, is of fundamental importance at the start of the establishment of an EC. As consumers, prosumers are connected to the national grid, from which they take the amount of energy necessary to satisfy their needs, while, as producers, preferably from RES, they can feed part of the energy they produce to the grid, thus obtaining a sales profit. The energy that is produced and instantly consumed is called *Self-Consumption* (SC), and it has no cost. Depending on the technological system, the hourly production and consumption profiles may not be coincident. Placing energy on the national grid or installing a storage system are two ways of profiting from *Over-Production* (OP). A third possibility is that of setting up an EC as an aggregation model of different categories of end users (companies, municipalities and private citizens), who are considered as producers, consumers or prosumers, according to their consumption and production profiles over time. The over-production of single users is optimised within such a local network. As a result of an instantaneous energy exchange between members, which is known as *Collective Self*-Consumption (CSC), the members thus provide each other with a supply of energy. An EC can thus be assimilated to a "collective" prosumer connected to the national network who draws out and feeds in energy. This concept is represented in Fig. 1: the energy produced or purchased from foreign suppliers is delivered through the national grid (black line), which is managed by a Transport System Operator (TSO) and distributed to all the end users by a Distribution System Operator (DSO). An EC is a local network that exchanges locally produced energy (dotted arrow) between prosumers and consumers. As a single prosumer entity, it draws energy from the national grid (black black arrow) and feeds energy to it (dashed arrow). The same symbolism is used in the subsequent representation.

3.3. Definition of energy risk

A risk-based decision-making approach has been adopted in this paper to compare the effectiveness of alternative intervention measures in enhancing the energy security of a territory, that is, an

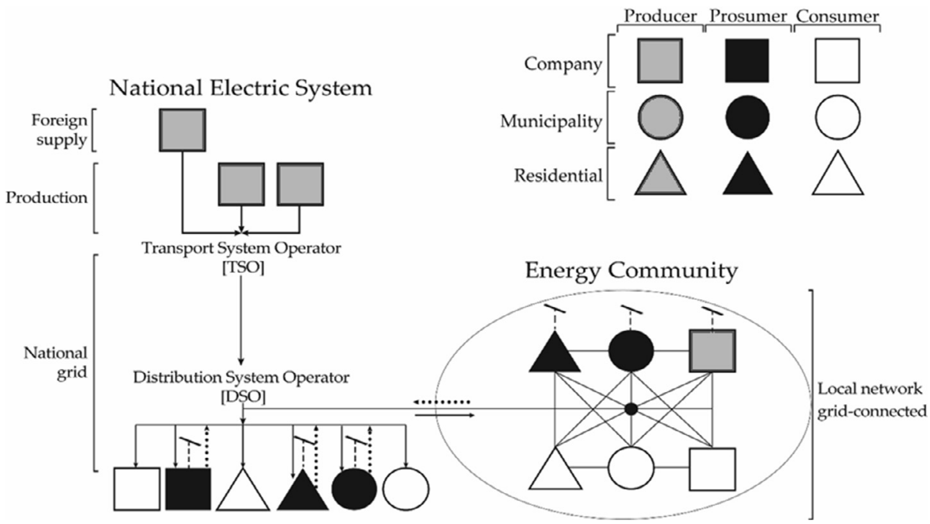


Fig. 1. Local grid-connected network of an EC in relation to the current organisation of the national electricity system. The end users are classified according to their category (company, municipality, residential user) and type (producer, prosumer, consumer).

effective management of the energy supply with reliable energy infrastructures to meet the current and future energy demands at a territorial scale [31].

Risk-based decision making is a general approach that is widely used in the process industry, as in [32–34], in which the methodologies and advancements were discussed, and in [35]. Recent examples of specific risk-based decision-making applications in the energy domain can be found, among others, in [36], where a risk assessment was applied to the whole Shanghai electric power system, in [37] for the planning of energy resources, in [38] for maintenance planning, in [39] for the optimisation of energy management in smart residential buildings and in [40] for decision-making strategies in peer-to-peer energy communities.

In this work, the risk of electric interruptions of the national grid has been investigated considering the definition of "blackout" given by the National Regulatory Authority for Energy (in Italian, ARERA) [41]: an interruption in which the voltage at a user's withdrawal or input point is < 5% of the voltage declared for all the power supply phases (CEI EN 50160). This Authority collects data on any outages that have occurred, pertaining to the different areas of influence on the Italian national territory, starting from the information transmitted by the main operators of the electricity system. This information is classified on the basis of various criteria that take into account the level of the system at which the interruption originates (production, transport, distribution), the main causes (electric system, *force majeure*, external or other) and the duration of the outage (long, brief or transient). Other criteria consider the relationship with the end users, the characteristics of the distribution network, and the type of interruptions with or without any pre-warning. The first two criteria can be described through two parameters: the voltage of the electricity withdrawn (high, medium or low) and the Urban Concentration Degree (UCD), which depends on the number of inhabitants in the territory. Table 2 summarises the considered criteria. The criteria that are used to characterise the interruptions considered in this work are in bold.

In this work, reference has been made to long-term interruptions, without pre-warning, that occurred at the distribution system level, operating at medium and low voltage in all the UCD areas. This assumption was made regarding the national electricity system described briefly in Fig. 1: the TSO operates on high voltage networks, while the DSO operates on low and medium voltage ones. Most energy users, and all the types of end users considered in this study, are connected to the latter type of system.

The energy sector shows emerging risks, including technical disruptions and extreme weather events, as well as citizen and consumer awareness and concerns about the localisation and use of an energy infrastructure. Distributed generation, such as PV integration, can cause overvoltage problems on LV networks [42]. In this regard, the Italian law on Renewable Energy Community (REC) configurations [15] offers the possibility of installing small power plants, the maximum threshold of which corresponds to 200 kW of installed power, and the requirement for each REC member to be connected to the same LV/MV transformer substation. Therefore, the envisaged configurations appear to refer to restricted territories and small-scale plant solutions.

In this work, only critical risks, such as landslides and floods caused by hydrogeological instabilities, heat waves and prolonged periods of drought, intense windstorms, snowfalls and the falling of trees on overhead lines, all of which can cause the blackout of an energy system, were considered.

The risk is here defined through the following formula:

$$R = f \cdot M \cdot e \tag{1}$$

where f is the frequency of occurrence of the considered outcome, M is the consequent severity of the outcome and e is the exposure

Table 2
Classification of the possible energy interruptions [41].

Origin (level)	Cause	Pre-warning	Duration [time]		Voltage	Urban Concentration Degree	
Producer	Electric system	With (PW)	Long	t > 3 min	High Voltage (HV)	High concentration (HC)	inh. > 50.000
Transport System Operator (TSO)	*Force majure*	Without (noPW)	Brief	1 s < t < 3 min	Medium Voltage (MV)	Medium concentration (MC)	5.000 < inh. < 50.000
Distribution System Operator (DSO)	Externalcauses		Transient	t < 1 s	Low Voltage (LV)	Low concentration (LC)	inh. < 5.000
	Other causes						

factor. Each indicator is treated separately and refers to a blackout energy risk. The national electricity network data were extracted from a report on the electricity distribution and supply service elaborated by ARERA [41].

Either a semi-quantitative approach or a fully quantitative one can be adopted, depending on the availability and accuracy of the data used to make a risk-based decision. In the semi-quantitative approach, the input variables are discretised in intervals, and a risk matrix is drawn up to support the decision and identify tolerable risks or risks that require the implementation of preventive or mitigation actions; this approach will be adopted and described in more detail in future works. In the present paper, as the data that characterise the users and the thresholds are available, a first attempt has been made to define a risk threshold through a data-driven approach and this approach has been used to compare the risks pertaining to different scenarios.

3.3.1. Indicator of frequency (f)

The frequency index (f) is expressed in terms of the average number of interruptions per end user per year [n/yr/us]. Table 3 shows the thresholds of the factors that were used to establish the tolerability limits and points out the Urban Concentration Degree (UCD) referring to Medium Voltage (MV) and Low Voltage (LV).

3.3.2. Magnitude factor (M)

The Magnitude indicator (M) is expressed as the cumulated duration of interruptions per end user per year [min/yr/us]. Table 4 shows the tolerability limits, with reference r to the Urban Concentration Degree (UCD), and to Medium Voltage (MV) and Low Voltage (LV).

The tolerability limits of magnitude for the MV users for all the Urban Concentration Degrees were estimated by doubling the tolerability limits of the LV users. This ratio has been taken from the aforementioned Arera report [41] on the recovery time; the recovery time of LV users is in fact double that of the MV users (see Table 5). Hence, the Distribution System Operator (DSO) has to guarantee the recovery of the energy supply service for any MV user in half of the time of that of any LV user. MV users are mainly industrial companies, whose production processes require that continuity of the electricity supply is guaranteed. Therefore, their energy supply takes priority over, for example, municipal (MUN) and domestic (DOM) users.

Table 3
Tolerability limits of frequency f [41].

Long interruptions - without pre-warning - other causes (from Table 2)					
HC		MC		LC	
LV	MV	LV	MV	LV	MV
[n/yr/us]	[n/yr/us]	[n/yr/us]	[n/yr/us]	[n/yr/us]	[n/yr/us]
1	6	2	9	4	10

Table 4
Tolerability limits of magnitude M [41].

Long interruptions - without pre-warning - other causes (from Table 2)					
HC		MC		LC	
LV	MV	LV	MV	LV	MV
[min/yr/us]	[min/yr/us]	[min/yr/us]	[min/yr/us]	[min/yr/us]	[min/yr/us]
25	50	40	80	60	120

Table 5
Maximum recovery time for long energy interruptions without pre-warning [41].

	Year 2016–2017		Year 2018–2019		Year 2020–2023	
	LV	MV	LV	MV	LV	MV
	[hours/int/us]	[hours/int/us]	[hours/int/us]	[hours/int/us]	[hours/int/us]	[hours/int/us]
HC	8	4	8	4	8	4
MC	12	6	8	4	8	4
LC	12	6	12	6	8	4

3.3.3. Exposure factor (e)

The energy exposure indicator (e) is expressed as the dependence of a user on the national electric grid for energy, and it corresponds to the ratio between the Uncovered Demand (UD) for energy and the Total Consumption (TC) of energy (Eq. (2)):

$$e = \frac{UD\left[\frac{kWh}{h}\right]}{TC\left[\frac{kWh}{h}\right]} \tag{2}$$

TC is the total energy consumed by a user to meet his/her needs; UD is the amount of energy taken from the national grid. UD and TC are both calculated for each hour, considering the hourly energy profile of each user for the typical days of each season, as shown in Table 6. Starting from these data, it was possible to define the consumption and the energy exposure of a typical week for each season, as presented in [6]; subsequently, using the holiday calendar, it was also possible to evaluate the yearly energy consumption and the yearly energy exposure.

The following variables were calculated to evaluate the exposure factor for each energy user, over an hourly period of time for each typical day:

- total consumption (TC) and the total production (TP) (only RES production is considered in this work),
- self-consumption (SC), that is, the share of energy produced by RES and instantly and autonomously self-consumed, is calculated with Eqs. (4) and (6),
- Uncovered Demand (UD), that is, the share of consumption that is withdrawn from the national grid as the RES production is not enough to cover the energy demand:

$$\begin{cases} \text{if TC} \geq \text{ TP and OP} = 0 \\ UD\ [kWh] = \ Total\ Consumption - Total\ Production \\ SC\ [kWh] = \ Total\ Consumption - Uncovered\ Demand \end{cases} \tag{3}$$

- Over Production (OP), that is, the energy produced by RES by the end user that is not self-consumed and is therefore transferred to the national grid:

$$\begin{cases} \text{if TP} \geq \text{TC and UD} = 0 \\ OP\ [kWh] = Total\ Production - Total\ Consumption \\ SC\ [kWh] = Total\ Production - Over\ Production \end{cases} \tag{4}$$

Table 6
Typical days.

	Weekday	Holiday
Winter season	W_W	W_H
Summer season	S_W	S_H
Mid-season	I_W	I_H

In the case of Energy Community configurations, it is also necessary to calculate other variables in order to evaluate the exposure factor for each member of the EC, considering an hourly period for each typical day. All the variables that refer to the EC as a single collective entity are calculated by summarising the results of all the EC members:

- Collective Over Production (COP) of the EC entity is the sum of all the over-productions (OP), as calculated in Eq. (5), of all the members of the Energy Community, and it corresponds to Eq. (7):

$$COP[kWh] = \sum_{m=1}^{n} OP \tag{7}$$

where n is the number of energy users (m) that are members of the EC.

As each member has already achieved individual instantaneous self-consumption (SC), he/she can withdraw the energy they still need (UD), from the share of locally produced energy (COP), on the basis of its hourly availability, instead of withdrawing it from the national grid;

- the Collective Self-Consumption (CSC) of the EC entity is the sum of all the shares of energy withdrawn instantly from the COP by each member (cSC), as expressed in Eq. (8):

$$CSC[kWh] = \sum_{m=1}^{n} cSC \tag{8}$$

where n is the number of EC members (m). An order of priority is assumed among the different categories of energy users for this withdrawal. This priority is identified on the basis of the extent of damage that would be caused by a blackout (see Section 3.3.2). The CSC can also be defined as the minimum value between the energy fed to the national grid by all the new RES plants of the EC (COP) and the energy withdrawn from the national grid by all the members of the EC (UD), in each hourly period [16];

- the Still Over-Production (SOP) of the EC entity is the sum of the still Over-Production (sOP) of each EC member, that is, the share of energy production still available after the withdrawal of energy by all the other EC members (CSC), and it can be sold to the national grid. It corresponds to the total production (TP) net of the individual self-consumption (SC) and the over-production quota (cOP), made available to the EC, that was withdrawn by the other members, as indicated in Eq. (9):

$$SOP[kWh] = \sum_{m=1}^{n} sOP = TP - (SC + OP) \tag{9}$$

where n is the number of energy users (m) that are considered as members of the EC;

- the Still Uncovered Demand (SUD) of the EC entity is the sum of the still Uncovered Demand (sUD) of each EC member, that is, the share of energy consumption that has not be autonomously satisfied by the Self-Consumption (SC), or by the collective Self-Consumption withdrawal (cSC) and, from necessity, has to be withdrawn from the national grid. It corresponds to the total consumption (TC) net of the individual self-consumption (SC) and of the share of energy withdrawn (cSC) from the overproduction made available by other EC members, as expressed in Eq. (10):

$$SUD[kWh] = \sum_{m=1}^{n} sUD = TC - (SC + cSC) \tag{10}$$

where n is the number of energy users (m) that are considered as members of the EC.

Table 7 shows the exposure factor tolerability limits for every end user (consumers, prosumers and producers). The maximum threshold values are defined in the Regional Law of the Piedmont Region (R.L. 12/2018) [43] in order to guarantee the non-profit organisation condition of the EC. This implies that the EC self-consumes at least 70% of the annual self-production energy, at least half of which must be produced by RES [44]. In this way, it is possible for the EC, as a non-profit entity, to sell only 30% of its overproduction to the electricity market. The minimum self-consumption requirement of 70% refers to the resolution drawn up by ARERA pertaining to Enabled Mixed Virtual Units (UVAM) [45].

3.3.4. The risk index (R)

The index that represents the energy risk level (R) is estimated according to Eq. (1). The combination of the tolerability limits for the different factors (see Tables 3, 4 and 7) allows a tolerability limit to be defined for the risk, which can be used to help support decision making, in terms of the actions that need to be implemented to reduce the level of risk pertaining to a supply interruption or blackout event. Table 8 shows the tolerability limits diversified according to the urban concentration degree, voltage and type of end user. Such a place-based methodology can reveal the different degrees of tolerability for each of the identified cases. The tolerability limits have been applied to the case study to demonstrate the effectiveness of the suggested measures.

3.4. Actions to reduce energy risks

For the purpose of this study, the frequency index, f, and the magnitude factor, M, have been considered to constitute specific features of the national electric grid, and they are therefore constant data. In order to reduce the risk of energy supply blackouts, actions can therefore only be taken to reduce exposure factor e through measures that: reduce energy consumption, allow the production of more energy, or optimise the combination of energy demand and supply of a group of stakeholders. These interventions include: energy efficiency measures in all the electricity use sectors (buildings and services), the installation of storage systems, the installation of new production plants (starting from the exploitation of the renewable resources available locally) and the creation of a local energy community, as an EC or REC configuration. In this work, the energy community allows effective energy flows to take place between the community members. In short, the over-

Table 7
Tolerability limits of exposure *e*.

	Min	Max
Consumer	0	0.5
Prosumer	−0.3	0.3
Producer	0	0

Table 8
Risk Index tolerability limits.

User	R [min/yr²/us²]					
	HC		MC		LC	
	LV	MV	LV	MV	LV	MV
Consumer	12.5	150	40	360	120	600
Prosumer	7.5	90	24	216	72	360
Producer	0.25	3	0.8	7.2	2.4	12

production of one member is directed towards another user who has an uncovered demand, according to an order of priority that is identified on the basis of the amount of damage that would be caused by a blackout. This exchange of energy within the community reduces the risk of energy blackouts and energy operating costs.

3.4.1. The self-sufficiency index (SSI) and the self-consumption index (SCI)

In the case of interconnected networks, reducing the energy dependence on the national grid to limit the risk of blackouts can also be intended as increasing energy self-sufficiency. This can be assessed by referring to the Self-Sufficiency Index (SSI) and the Self-Consumption Index (SCI) [13], whereby it is easy to compare the contribution of each hypothesised action to reducing the risk. The Self-Sufficiency Index (SSI) is defined as the share of locally self-consumed energy of the total energy consumption, and it is calculated with Eq. (11). The Self-Consumption Index (SCI) corresponds to the share of locally self-consumed energy of the total energy produced by RES, and it is calculated with Eq. (12). Both indices are calculated for each hypothesised scenario, by summarising the Self-Consumption (SC), the collective Self-Consumption (CSC), the Total Consumption (TC) and the Total Production (TP) of all the involved stakeholders:

$$SSI[\%] = \frac{(SC + CSC)}{TC} \tag{11}$$

$$SCI[\%] = \frac{(SC + CSC)}{TP} \tag{12}$$

As mentioned above, the Regional Law of the Piedmont Region (R.L. 12/2018) [38] requires a minimum threshold of the annual self-consumption index (SCI) for Energy Community configurations, which corresponds to 70%. In order to reach acceptable thresholds for both the SCI and SSI indices, the interventions that contribute the most have to be implemented, but such an evaluation implies a cost-benefit analysis.

3.4.2. Cost-benefit analysis

The aim of the present cost-benefit analysis is to highlight the economic benefits for each stakeholder, in each hypothesised scenario, in an attempt to identify the one that ensures economic benefits for all. A cost-optimal analysis allows the economic implications of the different types of interventions to be compared and the optimal level of performance to be defined as a function of the costs. In this work, the energy performance concerns the contribution to a reduction in the risk (or self-sufficiency improvement) and the economic performance concerns ensuring an economic gain for each energy user. In order to conduct a cost-optimal analysis, the Global Cost approach (i.e. energy cost plus investment costs) was applied to each scenario [46]. As long as the actions that reduce the energy risk have a low global cost, the economic operation is convenient; if the global cost increases, the economic operation is no longer convenient. The Global Cost approach consists in calculating the present value of the Energy Costs, referring to the initial year, and including the initial Investment Cost, as expressed in Eq. (13):

$$C_G(\tau)\ [€] = C_I + \sum_{i=1}^{\tau} (C_{E,i} \cdot R_d(i)) \tag{13}$$

where C_G is the Global Cost, referring to the initial year τ_0 ; C_I is the initial Investment Cost; $C_{E,i}$ is the annual Energy Cost at year i; R_d is the discount factor at year i , calculated for all the τ years. The discount factor R_d can also be expressed as in Eq. (14):

$$R_d = \frac{1}{(1 + R_r)^p} \tag{14}$$

where R_r is the real discount rate and p is the reference period of time; in this work, the reference period is annual, and the number of years considered is equal to 20 years, as is the duration of the economic incentive provided by the national law [16]; the annual discount factor R_d corresponds to 0.03%.

The Investment Cost for each scenario refers to the expenses incurred to implement the actions aimed at reducing risks. The Investment Cost of a scenario is the sum of all the expenses sustained by each stakeholder. Table 9 shows the marginal costs for each type of intervention and the scenarios in which they have been applied. Different costs were identified for the storage (ST) and photovoltaic (PV) system installations, considering the size of the plant; the investment cost for the establishment of the Energy Community institution refers to the annual contribution envisaged by the Regional Law of the Piedmont Region (R.L. 12/2018) to help technical and legal expenses [43].

The annual Energy Costs are calculated with Eq. (15). They consider the aggregation of all the expenses for the withdrawal of energy by each user, and the aggregation of all the revenues generated from the sales of the energy fed to the grid; these revenues also include the savings resulting from individual Self-Consumption (SC), as it corresponds to a lack of expenditure and, when EC corresponds to the REC configuration, to the profit from the Collective Self-Consumption incentive (REC_{inc}), as envisaged by the Italian law [16]:

$$Annual\,Energy\,Cost\ C_E \left[\frac{€}{yr}\right] = (\Sigma Expenses - \Sigma Revenues) \tag{15}$$

Each energy flow is associated with a different energy price, depending on the direction of the flow (to or from the grid), the electricity grid (national or local), and the category of end user (company, municipality or residential), as synthesised in Table 10. The REC incentive (REC_{inc}), which refers to the REC configuration as a single entity, is an exception as it is applied to the total energy exchanges between members (*Collective Self-Consumption*), without any distinction between the categories of end users. The energy prices on the national grid (NG) refer to the real energy market prices in the case study area. The prices of energy on the local grid (LG) are assumed to be defined in agreement with the EC members, according to the real discount possibilities for the case study, while the REC incentive is defined by law [16] and its value is fixed for the duration of the incentive.

Different evaluations were made for the *non-EC scenarios* (BAU, ST, PP, EE, PP + ST, EE + ST) and for the *EC scenarios* (EC, EC + PP, EC + EE, EC + ST) when calculating the energy expenses and

Table 9
Investment costs for each type of intervention.

Intervention		Marginal cost	References	Application scenarios
ST	Storage system installation	€/kWh	[47]	ST, EE + ST, PP + ST
	St < 500 kWh	600		
	St > 500 kWh	400		
PV	Roof integrated PV system installation	€/kWp	[47]	PP, PP + ST, EC + PP
	PV < 6 kWp	2000		
	6kWp < PV > 20 kWp	1600		
	PV > 20 kWp	1000		
EE	LED lamp replacement for Public Lighting	€/lamp 335	[56]	EE, EE + ST, EC + EE
EC	EC constitution (legal fees)	€/EC 5000	[43]	EC, EC + PP, EC + EE, EC + ST

Table 10
Energy prices for Energy Cost assessments.

End Users	Energy withdrawal		Energy sales		Collective Self-Consumption
	National grid	Local grid	National grid	Local grid	REC configuration
Company	$E_{NG,com}$	$E_{LG,com}$	$R_{NG,com}$	$R_{LG,com}$	REC_{inc}
Municipality	$E_{NG,mun}$	$E_{LG,mun}$	$R_{NG,mun}$	$R_{LG,mun}$	
Residential	$E_{NG,res}$	$E_{LG,res}$	$R_{NG,res}$	$R_{LG,res}$	

revenues. A further distinction was made for the latter group between a *simple EC configuration* and an *REC configuration*, in order to comply with the requirements established by the national law [14] concerning access to the REC incentive. The annual Expenses and Revenues were calculated according to Eqs. (16) and (17), respectively, for each energy user in the *non– EC scenarios*:

$$Expenses\left[\frac{€}{yr}\right] = UD \cdot E_{NG} \tag{16}$$

$$Revenues\left[\frac{€}{yr}\right] = (OP \cdot R_{NG}) + (SC \cdot E_{NG}) \tag{17}$$

where UD is the share of TC drawn from the national grid, OP is the share of TP sold to the national grid, and the instantaneous self-consumption, SC, of each prosumer is considered a saving due to non-withdrawal from the national grid. Eqs. (18) and (19) are valid for *simple EC configurations*:

$$Expenses\left[\frac{€}{yr}\right] = (sUD \cdot E_{NG}) + (cSC \cdot E_{LG}) \tag{18}$$

$$Revenues\left[\frac{€}{yr}\right] = (sOP \cdot R_{NG}) + (cOP \cdot R_{LG}) + (SC \cdot E_{NG}) \tag{19}$$

where sUD is the share of TC withdrawn from the national grid, cSC is the share of the TC withdrawn from the local grid, sOP is the share of TP sold to the national grid and cOP is the share of TP sold to the local grid.

Eqs. (20) and (21) are valid in the case of the *REC configuration*:

$$Expenses\left[\frac{€}{yr}\right] = (sUD + cSC) * E_{NG} \tag{20}$$

$$Revenues\left[\frac{€}{yr}\right] = (OP \cdot R_{NG}) + \left[(CSC \cdot REC_{inc}) * \left(\frac{cSC}{CSC}\right)\right] + (SC \cdot E_{NG}) \tag{21}$$

where OP is the share of TP net of the SC, that has the energy market sale price R_{NG};cSC is the share of energy exchanged by one single user of the total Collective Self-Consumption (CSC) realized by all the REC members to which the incentive REC_{inc} applies.

4. Case study

The case study refers to a part of the Pinerolo territory, in the Piedmont Region in the North-West of Italy (Fig. 2). The area extends for 1.348 km^2 and the Consorzio Pinerolo Energia (CPE), which is also the promoter of the initiative, is made up of 47 municipalities, 150,000 inhabitants and > 70 companies. The leading CPE company is ACEA Pinerolese Industriale S.p.A. (API), a private multi-utility company owned by the 47 municipalities in the area. These municipalities, together with businesses and citizens are the users of the different services. These services include water cycle management, integrated with waste management, anaerobic treatment of organic fractions and two hydroelectric plants. The waste–to-energy plant produces electricity and heat, and is also connected to a local district heating network. Moreover, ACEA Pinerolese Energia S.r.L (APE) deals with the supply of energy sale services to different types of public and private users.

Various clusters of territorial entities, which are involved in several projects concerning the energy theme in different ways, exist throughout the area (Fig. 2):

- The largest cluster is Metropolitan Area V (the MAV area), which is made up of the 47 municipalities and beneficiaries of the ACEA services.
- A total of 31 of the aforementioned 47 municipalities are signatories of the memorandum of understanding (signed in Turin on April 16th 2019) pertaining to the institution of the Pinerolese "Sustainable Territory" Oil Free Zone (OFZ), where pilot projects are allowed according to Italian Law (L. 221/2015) [48].
- Among the OFZ municipalities, the core group of the Energy Community project in the Pinerolo territory is made up of 6 municipalities (EC6 Area). These municipalities participated in the call for a proposal drafted by the Regulation Act of the Piedmont Region (D.D. 547/2019) [49], as required by Regional Law (R.L. 12/2018) [43] and by the Regional Council Resolution (D.G.R. 18–8520/2019) [44].

A place-based methodology foresees a preliminary territorial analysis phase. The territory is considered according to its climatic-environmental characteristics and to the socio-economic characteristics of the population, instead of those related to the built environment, in order to highlight the characteristics that have the most influence on energy production and consumption. This information was managed using Geographic Information System (GIS) software and was obtained from the available Piedmont Region online database (*Geoportale Piemonte-* technical regional map *BDTRE*, updated in 2019) [50], from Digital Terrain and Surface Models (DTM and DSM) and from a data census (ISTAT 2011) [51].

The vast area of the territory, with its heterogeneous morphology, includes different types of environmental contexts: mountains, hills and plain areas, whose specific climate conditions can influence the energy consumption and production profiles. By indicating the heating degree days (HDD), it was possible to assign a climatic zone, which is affected by the extent and duration of the heating season, to each municipality. As shown in Fig. 3, all the municipalities in the Pinerolo territory are in climatic zones E (HDD_E < 3000 °C), where there are plain and hilly areas on the Eastern side, and climatic zone F ($HDD_F \geq 3000$ °C), where there are mountain areas on the Western side. The local economy is driven by a strong industrial sector in the plain area and a tourist-accommodation vocation in the alpine valleys. The orography of the territory influences the type of urban settlements and the spatial distribution of the Urban Concentration Degree (UCD) of the municipalities, as can be observed in Fig. 3. Most of the 47 municipalities are in Low Concentration (LC) urban settlements, and only seven of them, which are in Medium Concentration (MC) settlements, are located in hilly and plain areas.

4.1. Stakeholders involved in the project

The BAU Scenario, which is here only analysed with reference to electric energy, is the core group of the Pinerolo Energy Community (EC6 Area). The members were selected on the basis of their willingness to participate in the project and considering the minimum self-consumption energy requirement established by the Regional Law [43]. This core group, "EC6 area", has a plurality of end users (companies, municipalities and residential users) and a variety of RES energy production technologies (i.e. photovoltaic modules or biogas and hydroelectric plants).

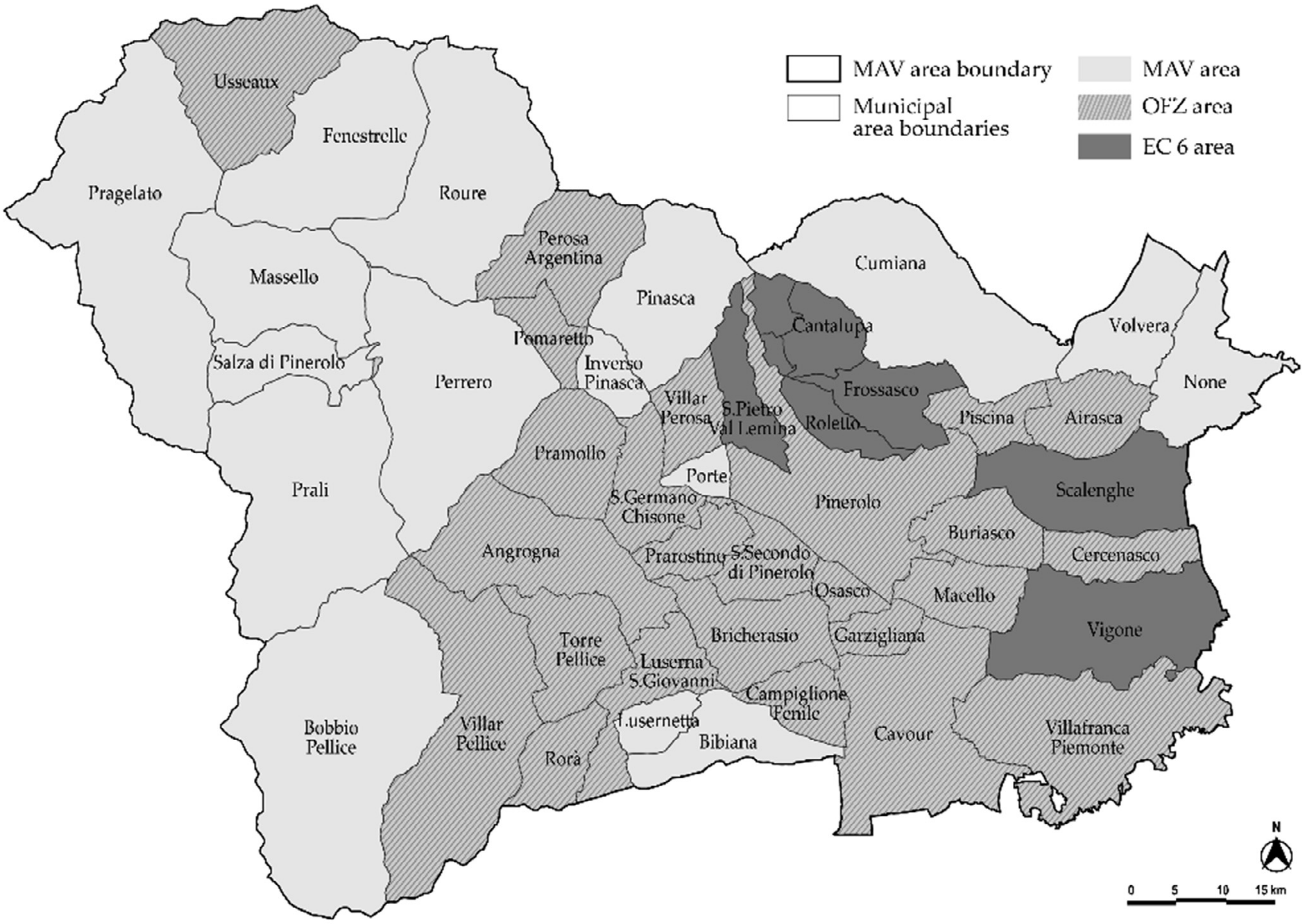


Fig. 2. Localisation of the Pinerolo Energy Community case study area (MAV area, in black) compared with the provinces that make up the Piedmont Region, north-west of Italy. The following territorial entities were involved in the project: the 47 municipalities of Metropolitan Area V (MAV area, in light grey), the 31 municipalities of the Oil Free Zone (OFZ area, in dashed grey) and the 6 municipalities of the core group of the Pinerolo Energy Community (EC 6 Area, in dark grey).

The stakeholders involved in the project are both private and public entities, and are mainly located in the municipalities that are members of the Oil Free Zone:

- 6 municipalities in the EC6 area (MUN)
- 8 companies (COM), members of the CPE
- 148 private citizens or domestic users (DOM)

The number of private citizens participating in the project was assumed to be 2% of the overall population of each municipality; half of them were considered to only be consumers (DOM_CONS), while the other half were considered to be prosumers (DOM_PROS). Table 11 shows the stakeholders classified into the three considered categories of users. The following are indicated for each of them: their name, the UCD of the municipality where they are located, the withdrawal voltage, the number of considered users (i.e. buildings and households), and the total amount of energy consumed (TC) and produced (TP) per year, where the technological RES system and the installed power are specified for the latter. In the name of each stakeholder, the capital letter after the underscore refers to the municipality in which the user is located, which, except for a few companies, coincides with one of the six municipalities participating in the project.

It is possible to observe, in Table 11, that only some buildings in the municipalities were considered and that the energy consumption is mainly due to the public lighting system. Companies are the only users connected to the medium voltage grid, and they are mainly prosumers with photovoltaic, biomass and hydroelectric plant energy productions. The domestic users are characterised by an annual electric consumption of 2637 kWh/yr, while the prosumers have a PV production of 3 kW. The stakeholders are allocated in low density municipalities (LC).

The symbolism and nomenclature used in Table 11 are the same as those used in Fig. 4. A spatial distribution of all the stakeholders, who are mainly grouped together in the plain-hilly areas on the east side of the Oil Free Zone, is shown in Fig. 4 (see also Fig. 3).

4.2. Energy data source

The energy data refer to the year 2017 and were collected, in collaboration with the Energy Managers of the companies and the technical offices of the municipalities, through a questionnaire prepared specifically for the different users [52]. The year 2017 was a normal weather year, with 2358 HDD at 20 °C in Pinerolo. The average value for the 2014–2019 period is 2355 HDD.

It was possible, through the database that had been elaborated, to evaluate the characteristics of the technological systems, their operating modes, their level of energy efficiency (an important parameter to hypothesise future scenarios) and to draw up the energy consumption and production balance. The average monthly and hourly energy consumptions of typical residential users were provided by Acea Pinerolese Energia (APE) S.r.L., considering a

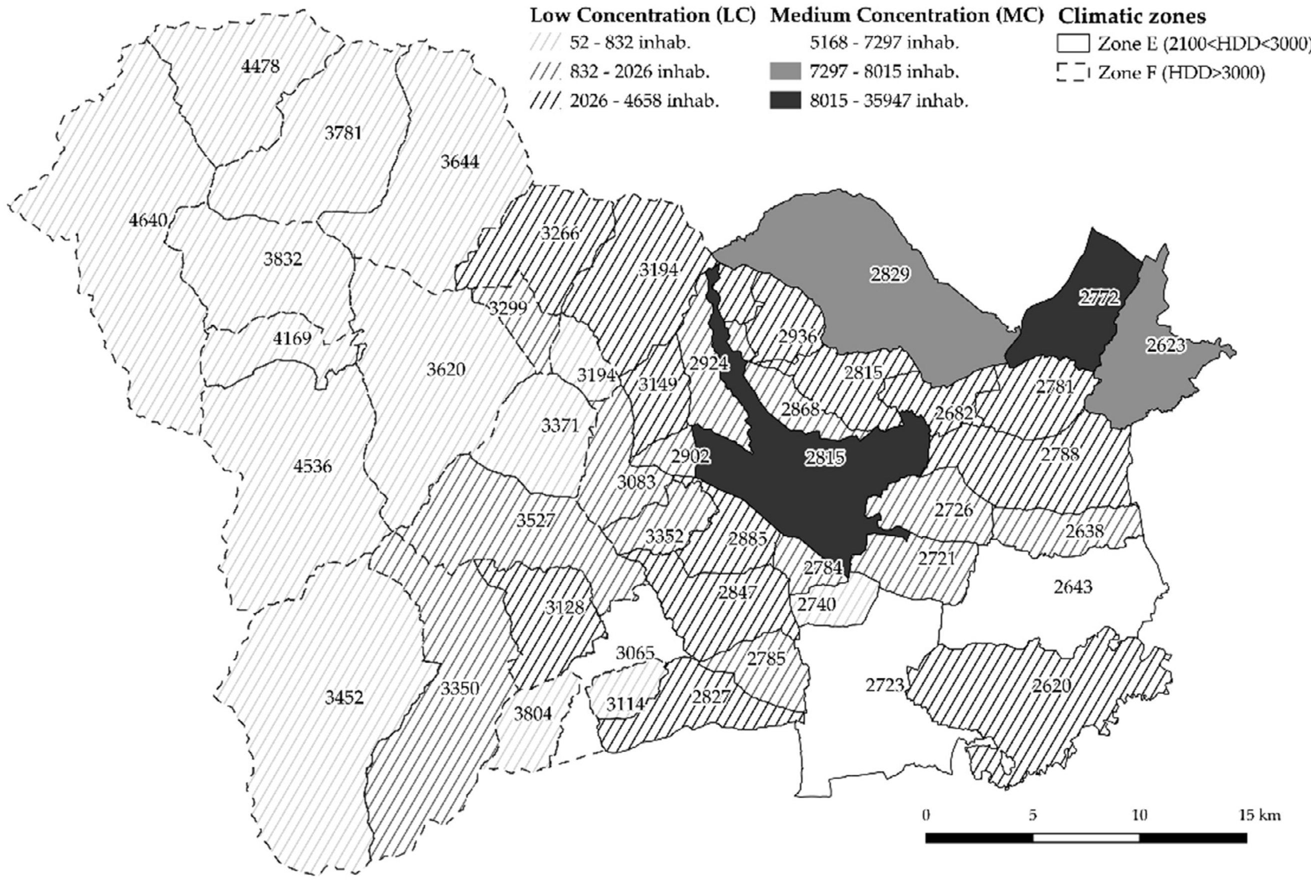


Fig. 3. Municipalities in the case study area with a Low Concentration urban degree (in dashed grey) or a Medium Concentration urban degree (in grey), and in climatic zone E (with continuous boundaries) or F (with dashed boundaries), according to the number of Heating Degree Days at 20 °C (HDD) of each municipality, the value of which is specified in the map.

sample of 380–470 domestic users located in the case study area, with 2.15 inhabitants per family. According to the Italian census database (ISTAT 2011), the typical residential user corresponds to a family of 2.15 people, in a 93.78 m^2 dwelling, located at an altitude of 581 m a.s.L. and in climatic zone E, with 2829 HDD.

4.3. Annual and monthly energy consumptions

Information on the monthly consumption of the companies and municipalities was taken from data recorded by National Energy Service Manager (in Italian, GSE) monitoring tools. The average monthly consumption of a typical residential user was multiplied by the number of users considered in each municipality. The monthly production of companies and municipalities refers to data measured by the GSE. The same was done for the monthly production of domestic prosumers, and when data were missing, they were estimated using PVGIS software tools [53] and considering a photovoltaic system with an installed power of 3 kW for each user; this hypothesis was made considering an average domestic user installed power of 2.79–2.94 kW in the different municipalities, which was obtained from the ''Atlaimpianti" online database provided by GSE [54].

The annual and monthly electric balance of the total energy consumption (TC) and total energy production (TP) are shown in Fig. 5 with reference to the EC6 Area; only local RES production is considered, with reference to the minimum requirements established by the Regional Law [44]. The yearly production is able to meet the electricity demand; the monthly trend shows the months of the year in which there is an over-production: a lower demand in spring corresponds to an excess production; this gap is reduced in summer when the electricity demand for cooling increases, while the RES production in winter is not enough to satisfy the energy needs.

4.4. Hourly energy profile

The hourly consumption profiles of the companies refer to the data recorded by means of the GSE monitoring tools, while the hourly profiles were provided, albeit only for the residential users, by APE; a procedure like that used for the monthly data was used. The municipal users' profiles were estimated from monthly data. The average daily monthly consumption was based on the annual holiday calendar and the opening times of municipal buildings. The hourly productions of the biogas and hydroelectric power plants were obtained from data provided by the Acea Pinerolese Industriale (API) S.p.A. company, and had been processed in previous studies [55]. The hourly PV production was estimated taking into account the installed power (which was known for the existing plants of companies and municipal buildings and hypothesised for domestic users), the average monthly daily production and the hourly solar irradiation profile, which was supplied by the local weather stations or obtained using PVGIS software. Hourly electric energy consumption and production profiles of representative stakeholders are shown in Figs. 6, 7 and 8 for each end-user category, considering the typical day presented in Table 6 and distinguishing between the used RES technologies.

In the same way as for the typical domestic user, the hourly consumption profile highlights two daily peaks for all three of

Table 11
Detailed description of the stakeholders considered in the case study.

End user	Name	UCD	Voltage	Number of Users		Total Consumption (TC)	Total production (TP)		
		(MC-LC)	(MV-LV)	Households	Buildings	[MWh/yr]	System	[kW]	[MWh/yr]
Municipality (MUN)	MUN_C	LC	LV	–	8	683.4	PV	33 + 35	60.8
	MUN_F	LC	LV	–	16	713.8	PV	8 + 14 + 19 + 58	95.5
	MUN_R	LC	LV	–	9	468.1	PV	59	68.3
	MUN_SPVL	LC	LV	–	9	338.2	PV	8 + 16 + 17 + 19	78.9
	MUN_S	LC	LV	–	5	782.4	–	–	–
	MUN_V	MC	LV	–	7	1168.6	–	–	–
Company (COM)	COM_A1_P	MC	MV	–	–	9561.5	BIOGAS	1642	13710.9
				–	–		PV	113	122.4
	COM_A4_I	LC	MV	–	–	–	HYDRO	450	2703.8
	COM_I_P	MC	LV	–	1	70.7	PV	40	42.9
	COM_L_C	LC	LV	–	1	101.2	–	–	–
	COM_M_C	LC	LV	–	1	51.2	PV	62	55.5
	COM_N_F	LC	MV	–	1	266.4	–	–	–
	COM_P_B	MC	MV	–	1	234.8	–	–	–
	COM_Q_P	MC	MV	–	1	2056.5	–	–	–
Residential (DOM)	DOM_CONS_C	LC	LV	11	–	29.0	–	–	–
	DOM_CONS_F	LC	LV	12	–	31.6	–	–	–
	DOM_CONS_R	LC	LV	8	–	21.1	–	–	–
	DOM_CONS_SPVL	LC	LV	7	–	18.5	–	–	–
	DOM_CONS_S	LC	LV	14	–	36.9	–	–	–
	DOM_CONS_V	MC	LV	22	–	58.0	–	–	–
	DOM_PROS_C	LC	LV	11	–	29.0	PV	33	39.5
	DOM_PROS_F	LC	LV	12	–	31.6	PV	36	43.0
	DOM_PROS _R	LC	LV	8	–	21.1	PV	24	29.3
	DOM_PROS_SPVL	LC	LV	7	–	18.5	PV	21	26.2
	DOM_PROS_S	LC	LV	14	–	36.9	PV	42	52.9
	DOM_PROS_V	MC	LV	22	–	58.0	PV	66	83.0

the considered seasons (Fig. 6a, 7a, 8a): the evening peak is present for all the typical days, while the morning-hour peak for the weekdays is postponed to the central hours on holidays. The electric consumption of the domestic users is higher in wintertime and during holidays. The hourly production profile peak for the photovoltaic technology is in the central hours of the day, but does not coincide with the peak demand, except during the holidays. In quantitative terms, the average daily production is always higher than the energy demand, thereby generating an over-production that can take advantage of storage systems or be sold to the national grid.

As can be seen from Figs. 6b, 7b and 8b, the typical municipal user profile is quite steady, for weekdays and holidays, and for the seasons. This is mainly due to the large contribution of electricity consumption for the public lighting service. The profile of a typical company highlights the need to guarantee the supply of a large amount of energy during the operating hours, in order to ensure continuity of production.

The stakeholders with systems that were able to satisfy the hourly energy demand of the most energy-consuming users (companies and municipalities) were chosen to form the energy community. As it is possible to observe, in Fig. 6b, 7b and 8b, the biogas plant guarantees a constant production for each day of the different seasons, as it is a programmable and modular system that complies with the necessary efficiency and technological performance criteria. Moreover, the hydroelectric power production is constant, as it is produced using aqueduct pipelines. The amount of electric energy produced by PV panels shows a seasonal trend that depends on climatic factors and on the weather conditions, which therefore make it not completely programmable (Fig. 6b, 7b and 8b).

4.5. Energy prices in the case study area

The energy prices used to calculate the annual energy cost, as indicated in Table 10 (see Section 3.4.2.), refer to the case study area and are shown in Table 12. The withdrawal and sale prices on the national electric grid (E_{NG} and R_{NG}) refer to the current prices on the electricity market pertaining to the Pinerolo area. The energy prices of the EC scenarios (E_{LG} and R_{LG}) pertaining to the local grid were hypothesised assuming a reduction in the energy cost and a remuneration variation of about 10% of the energy market prices. This hypothesis considers a possible variation due to reduced energy distribution losses, as recognised for REC configurations by the national energy authorities [16,30]. Such a hypothesis can be intended as a compromise between supply and demand for the EC members, as it can be an advantage for both buyers and sellers. The energy costs in Table 12 were discussed with the members of the EC and proposed in a call to tender (D. D. 547/2019 [49]) that was financed by the Piedmont Region.

5. Results and discussion

All the presented energy balances were calculated considering hourly profiles of the energy consumption (TC), the energy production (TP), the self-consumption (SC, cSC), the uncovered demand (UD, sUD) and the over-production (OP, cOP, sOP) separately for each of the involved end users. A business as usual (BAU) scenario was first considered, and new scenarios were then assumed to reduce energy exposure and therefore the risk of energy blackouts on the national electric grid. The actions that were chosen to reduce energy risks are those identified in Section 3.4, that is, reducing energy consumption, producing more energy, and reducing exposure to risks through an optimal aggregation of consumers and producers. One of the identified actions was the grouping of stakeholders together to create an energy community. The risk index is compared in this section with the threshold limit that indicates its tolerability.

The frequency index (f) and magnitude factor (M) risk indicators were extracted from the historical ARERA database, which is available online for all the scenarios [41]. The historical values of these two indicators are shown in Fig. 9 with reference to long

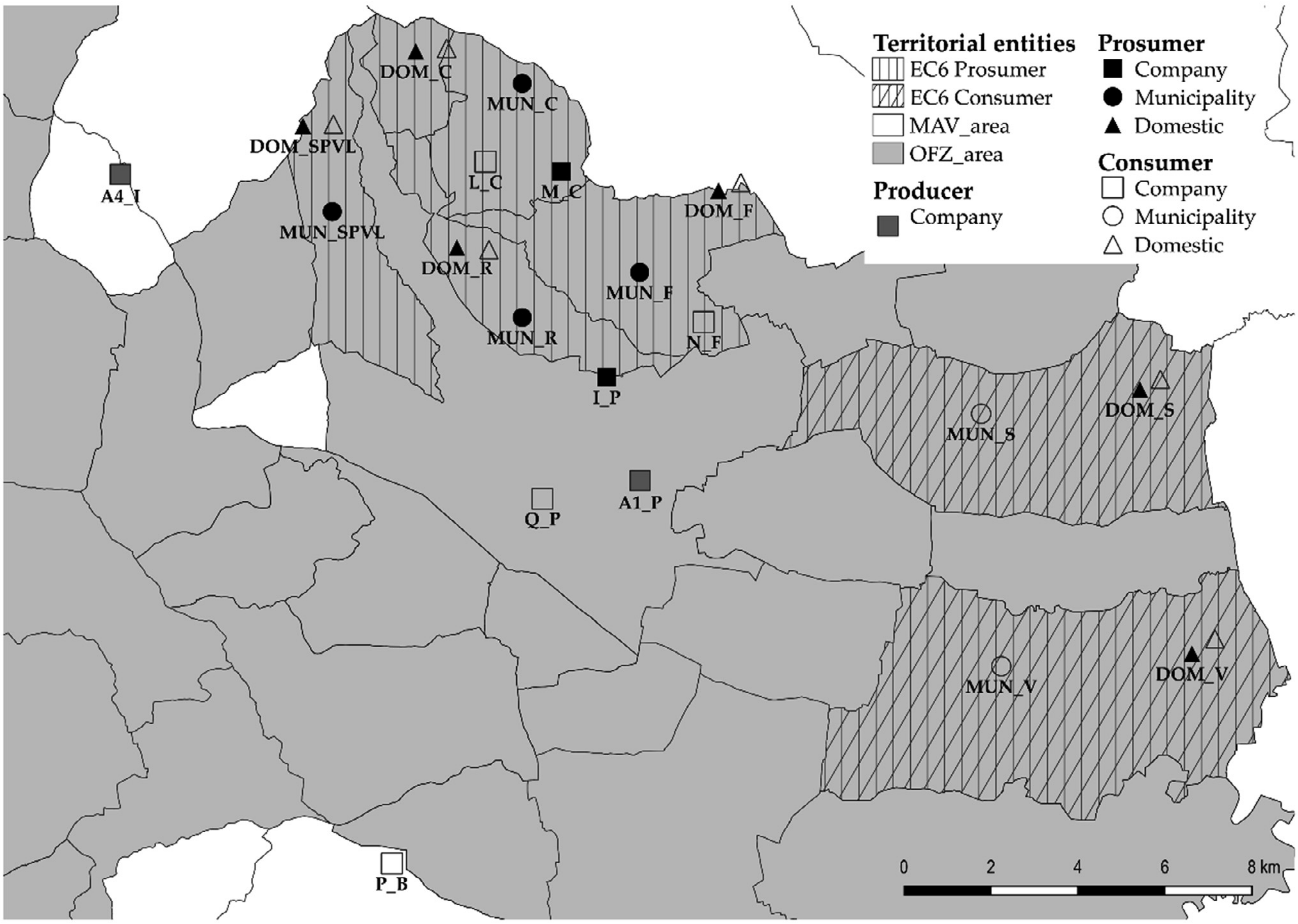


Fig. 4. Stakeholders involved in the case study classified by typology: producer (in grey), prosumer (in black) and consumer (in white) and the end user category: company (COM, square symbol), municipality (MUN, round symbol) and domestic (DOM, triangle symbol).

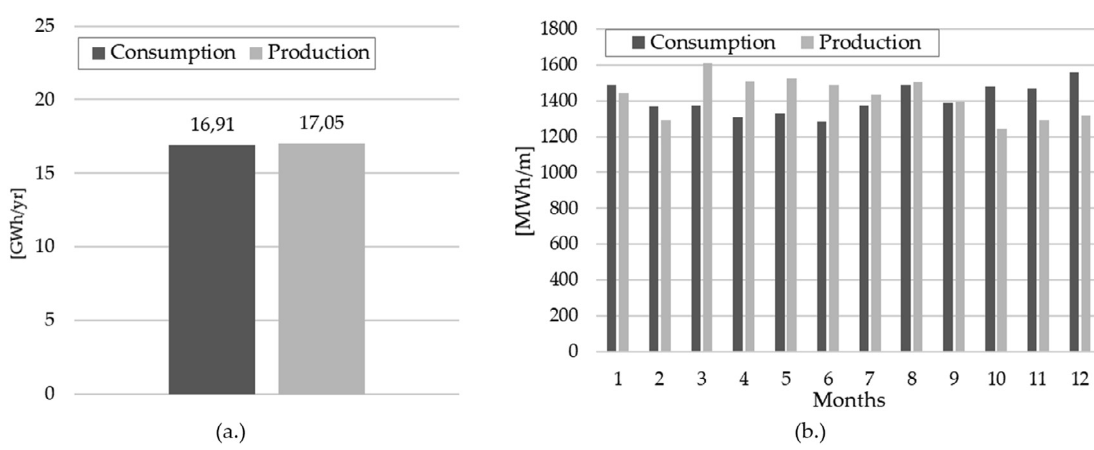
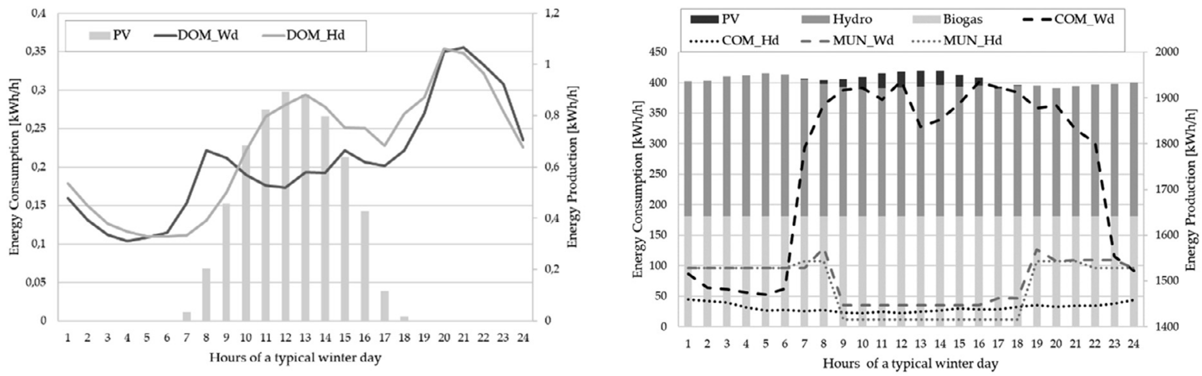


Fig. 5. Annual (a) and monthly (b) energy balance of the electric consumption and production of all the end users considered in the case study.

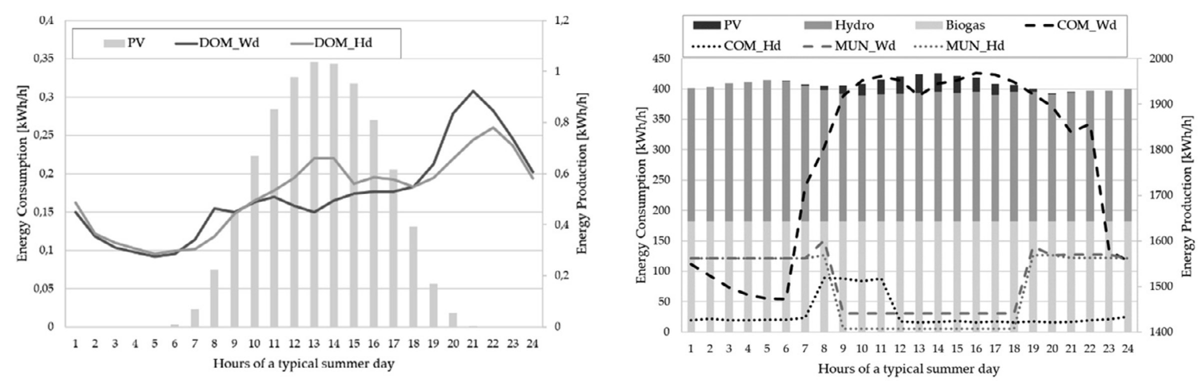
interruptions, without pre-warning, for LV users in the Metropolitan Area of Turin, that is, the area where the case study is set. It is possible to note that the values have remained constant in recent years, except for the year 2016, and for this reason the data that were used, and which are shown in Table 13, refer to the average values calculated from the data of the last four years. It can be observed that the probability of occurrence and the overall duration of long outages, without pre-warning, are lower for territories with medium and low urban concentrations, unlike those in high concentration areas, which are characterised by a greater demand and greater risks of overloading the network. The same can be observed for medium voltage users, who, having requested more energy, encountered blackouts of the supply service more easily.

The Risk Index for the BAU scenario and four different other intervention scenarios are presented separately in the next sections. Different combinations of single-intervention scenarios are presented.



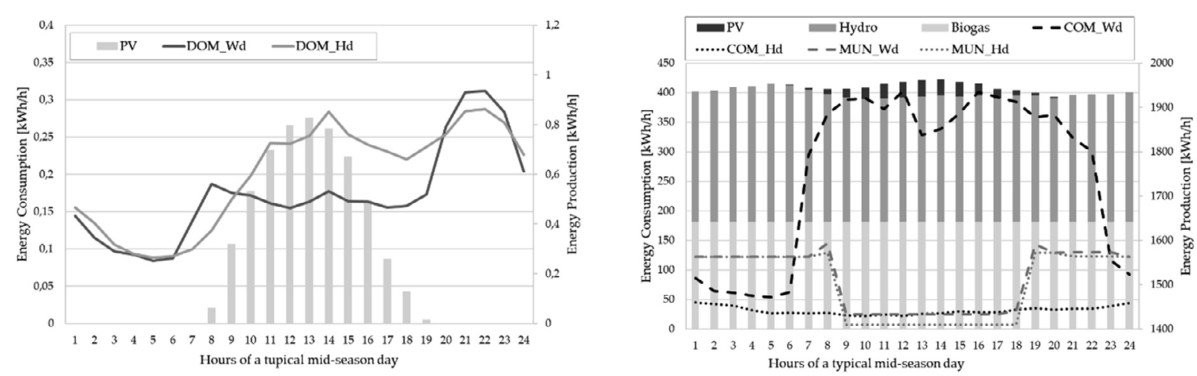
(a.) (b.)

Fig. 6. Hourly energy profiles of energy consumption (lines) and production (columns) for the winter season, distinguishing between the different types of RES technology (Biogas, Hydro, PV) and comparing a typical weekday (Wd) with a typical holiday (Hd) for a domestic end user (DOM) **(a.),** a company (COM) and a municipality (MUN) considered representative of the stakeholders involved in the case study (b).



(a.) (b.)

Fig. 7. Hourly energy profiles of energy consumption (lines) and production (columns) for the summer season, distinguishing between the different types of RES technology (Biogas, Hydro, PV) and comparing a typical weekday (Wd) and a typical holiday (Hd) for a domestic end user (DOM) (a.), a company (COM) and a municipality (MUN) considered representative of the stakeholders involved in the case study (b).



(a.) (b.)

Fig. 8. Hourly energy profiles of energy consumption (lines) and production (columns) for the mid-season, distinguishing between the different types of RES technology (Biogas, Hydro, PV) and comparing a typical weekday (Wd) and a typical holiday (Hd) for a domestic end user (DOM) (a.), a company (COM) and a municipality (MUN) considered representative of the stakeholders involved in the case study (b).

5.1. Risk index for the BAU scenario

It was possible to calculate the energy exposure to blackout risk for each component of the EC 6 area as the hourly energy demand and consumption for the year 2017 were known.

It is possible to notice, from the data shown in Table 14, the different exposures to risk of the categories of end users. Consumers show the highest exposure to risk values (i.e. 1.0 in Table 14), since they depend totally on the national grid supply service for their energy supply. The producers, instead, are not exposed to the risk of blackout since they do not require any energy consumption and depend on the national grid to buy and sell energy. Domestic and company prosumers, with values of 0.52 and 0.46–0.55 (see Table 14), respectively, are less exposed to the risk of blackouts

Table 12
Energy prices [€/kWh].

End Users	Energy Withdrawal		Energy Sales		Collective Self-Consumption
	National grid E_{NG}	Local grid E_{LG}	National grid R_{NG}	Local grid R_{LG}	REC configuration REC_{inc}
Company	0,15	0,135	0,06	0,066	0,11822
Municipality	0,18	0,162	0,10	0,110	
Residential	0,22	0,198	0,10	0,110	

Table 13
Average yearly Frequency (f) and Magnitude (M) indicators for the Metropolitan area of Turin.

	Long interruption - Without pre-warning - other causes (from Table 2)					
	HC		MC		LC	
	LV	MV	LV	MV	LV	MV
f [n/yr/us]	2.4	6.25	1.4	3.5	2.1	5.25
M [min/yr/us]	82.9	165.8	35.4	70.8	82.3	164.6

Table 14
Average yearly exposure to risk indicators (e) considering long interruptions without pre-warning, due to other causes.

Type of user	Stakeholder	MC		LC	
		LV	MV	LV	MV
Consumer	MUN_S	–	–	1.00	–
	MUN_V	1.00	–	–	–
	COM_L_C	–	–	1.00	–
	COM_N_F	–	–	–	1.00
	COM_P2_B	–	–	–	1.00
	COM_Q_P	–	1.00	–	–
	DOM_CONS_C, F, R, SPVL, S	–	–	1.00	–
	DOM_CONS_V	1.00	–	–	–
Prosumer	MUN_C	–	–	0.96	–
	MUN_F	–	–	0.88	–
	MUN_R	–	–	0.95	–
	MUN_SPVL	–	–	0.94	–
	COM_M_C	–	–	0.46	–
	COM_I_P	–	–	0.55	–
	DOM_PROS_C, F, R, SPVL, S	–	–	0.52	–
	DOM_PROS_V	0.52	–	–	–
Producer	COM_A1	–	0.00	–	–
	COM_A4	–	–	–	0.00

than municipal prosumers (0.96), whose dependence on the network is, however, still predominant (0.96).

Fig. 10 shows the results pertaining to risk index R for each end user considered in the BAU scenario, where consumers, prosumers and producers are distinguished from each other and each one is compared with its specific tolerability limit. The risk index is higher than the tolerability limit for all the users, except for the producers, due to their lack of dependence on the national grid. This dependence is greater for consumers than for prosumers, who partially satisfy their demand by resorting to other sources, and is null for producers who have no electricity consumption.

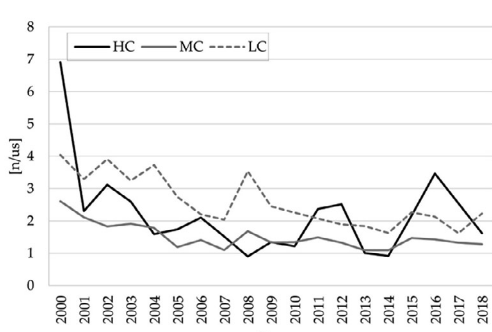
5.2. Risk index for the storage scenario (ST)

In this scenario, storage systems were added to the production plant of the prosumers in the BAU scenario, and their capacity was calibrated on the maximum daily over-production by comparing the different types of typical days in Table 6. In this work, it has been assumed that, for environmental impact and cost reasons, the capacity of the storage system is only of a day and therefore depends on the maximum daily over-production. This storage capacity is generally dimensioned during the summer period, when the production of energy from photovoltaic devices is higher and self-consumption is lower.

These storage systems can increase the daily self-consumption of the energy produced by prosumers, and therefore reduce the daily amount of uncovered demand and consequently exposure factor e. Fig. 11 shows that the risk index for prosumers decreases; domestic prosumers in fact show a negative risk index that represents the over-production that they can sell to the national grid. The daily capacity of the storage system of each prosumer is also reported. The daily storage capacity of each domestic prosumer is 6.15 kWh.

5.3. Risk index for the energy efficiency scenario (EE)

Energy efficiency measures can be implemented in all the energy use sectors concerning both the building and the territorial scale. This study has considered an energy efficiency intervention on public lighting in all the considered municipalities. This intervention consists of the installation of lighting controllers to ensure an efficient management of the operating hours and a dimming strategy in which mercury and high-pressure sodium lamps are replaced by LED luminaires. In this way, a reduction in the total energy consumption of 45% can be reached [56]. By reducing the total consumption (TC) of energy, it will be possible to reduce the uncovered demand and consequently the exposure factor e, albeit only for prosumers. Fig. 12 shows the reduction in the risk index that could be achieved for all the municipalities that are already prosumers, although it is not enough to satisfy the tolerability limits. In fact, as can be seen in Fig. 6b, 7b and 8b, the



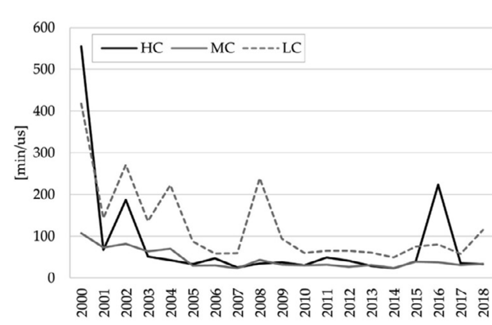


Fig. 9. Historical data of the Frequency (a.) and Magnitude (b.) for long interruptions without pre-warning for LV users in the Metropolitan Area of Turin, for the different Urban Concentration areas: High (HC), Medium (MC) and Low (LC).

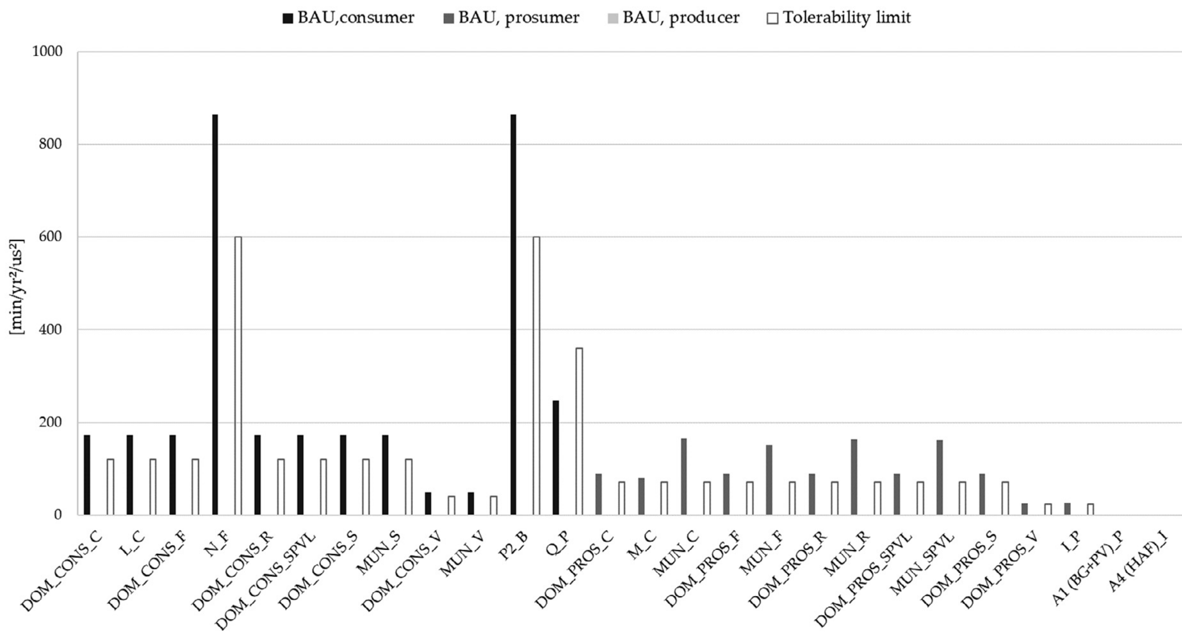


Fig. 10. Risk index of the BAU scenario, distinguishing between consumers (in red), prosumers (in black), producers (in dark grey) and the tolerability limits (in light grey).

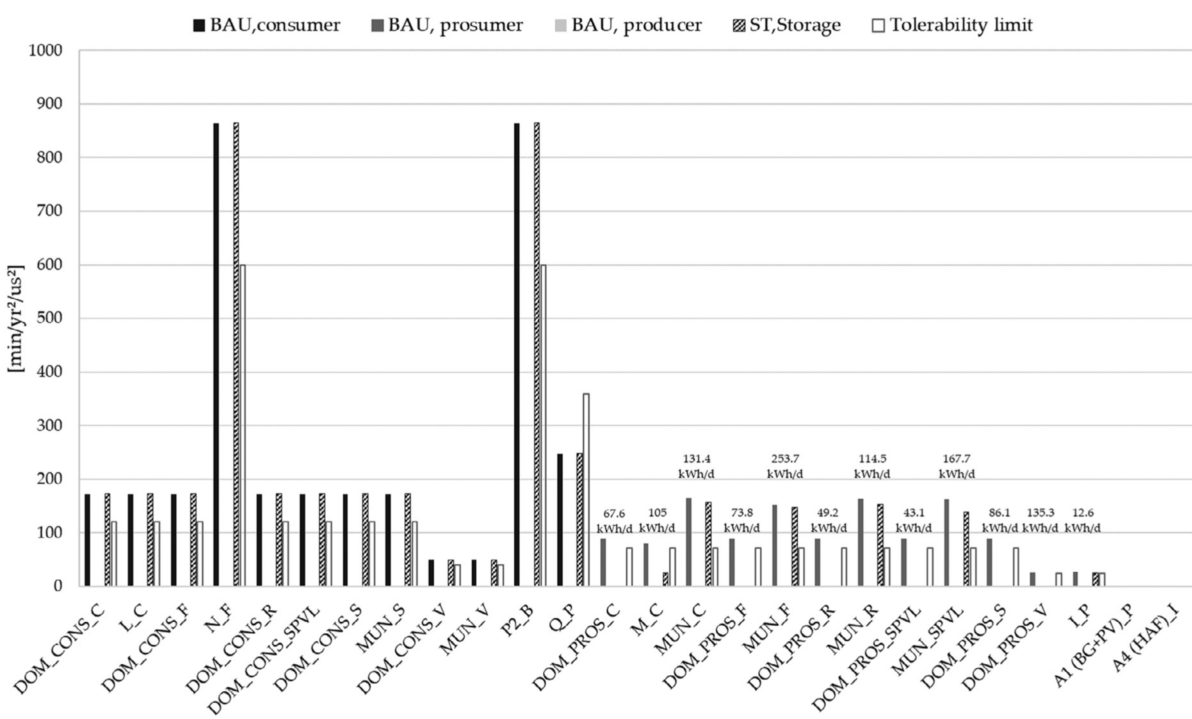


Fig. 11. Risk index of the Storage scenario (ST, grey pattern) compared with that of the BAU scenario, distinguishing between consumers (in black), prosumers (in dark grey), producers (in light grey) and the tolerability limits (grey line). The daily capacity of the storage system is specified for each prosumer.

consumption of the municipal users is mainly nocturnal for public lighting, while the production of energy is achieved through the use of photovoltaic panels, which only produce energy during the day. Even though the consumption is reduced, there is no contemporaneity between production and consumption, and the risk is therefore only reduced slightly.

5.4. Risk index for the productivity scenario (PP)

In this scenario, productivity corresponds to the potential energy production that results from the exploitation of the renewable resources available locally. This study has dealt with the energy productivity of roof integrated solar photovoltaic panels,

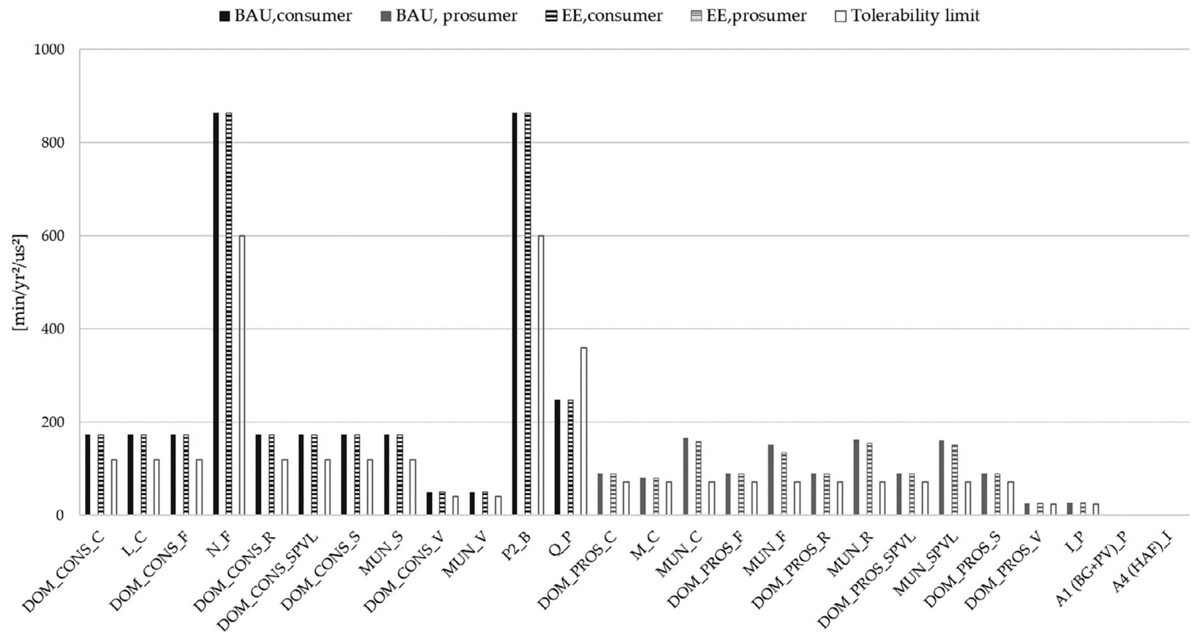


Fig. 12. Risk index of the Energy Efficiency scenario (EE), distinguishing between consumers (black pattern) and prosumers (grey pattern), and comparing it with the tolerability limits (grey line) and the risk index of the consumers (in black) and prosumers (in grey) in the BAU scenario.

considering the available surfaces of the roofs of the existing buildings that have not yet been used. The available surface, or installed power, and the annual amount of energy that can be produced are reported in Table 15 for each considered user. The energy productivity for residential users was calculated assuming PV polycrystalline panels with an installed power of 3 kW.

The amount of produced energy was estimated using the ArcGis "Area Solar Radiation" tool, considering climatic and environmental conditions and the orography of the territory. The solar irradiation characteristics, with direct, diffuse and albedo components, and the transmissivity of the atmosphere [57,58] were evaluated on a monthly basis with the PVGIS [53] and the Enea Solar Atlas [59].

In this scenario, consumers become prosumers, while prosumers increase their energy production: both groups are capable of self-consumption, and of reducing their uncovered demand (UD)

Table 15
Detailed description of the energy productivity.

End User	Name	Productivity			
		System	[kW]	[m²]	[MWh/yr]
Municipality	MUN_C	PV	–	1261	255.0
	MUN_F	PV	–	811	164.0
	MUN_R	PV	–	468	94.7
	MUN_SPVL	PV	–	266	53.7
	MUN_S	PV	–	532	107.6
	MUN_V	PV	–	579	117.1
Company	A1_P	–	–	–	–
		–	–	–	–
	A4_I	–	–	–	–
	I_P	–	–	–	–
	L_C	PV	–	170	34.4
	M_C	–	–	–	–
	N_F	PV	–	537	108.6
	P_B	PV	–	200	40.4
	Q_P	PV	–	438	88.6
Residential	DOM_CONS_C	PV	33	–	39.5
	DOM_CONS_F	PV	36	–	43.0
	DOM_CONS_R	PV	24	–	29.3
	DOM_CONS_SPVL	PV	21	–	26.2
	DOM_CONS_S	PV	42	–	52.9
	DOM_CONS_V	PV	66	–	83.0
	DOM_PROS_C	–	–	–	–
	DOM_PROS_F	–	–	–	–
	DOM_PROS _R	–	–	–	–
	DOM_PROS_SPVL	–	–	–	–
	DOM_PROS_S	–	–	–	–
	DOM_PROS_V	–	–	–	–

and the relative exposure factor, e, to the risk of blackouts on the national electric grid. Fig. 13 shows that all the users benefit from this intervention and reduce their risk index, but the reduction is more interesting for the companies and domestic consumers than for municipalities, whose consumption is mainly related to over-night public lighting. The risk reduction is associated with a lower risk exposure, due to the reduction of the uncovered demand (UD); UD decreases when the hourly consumption profile has the same trend as the hourly solar production that maximises self-consumption.

5.5. Risk index for the energy community scenario (EC)

An Energy Community can be defined as a single prosumer in which all the EC members (producers, prosumers and consumers) contribute by first satisfying their hourly energy demand and then selling their over-production to the national electric grid; each user that has an uncovered demand can withdraw electricity from the national grid.

The Over Production (OP) of all the prosumers and producers was aggregated hourly for the risk index assessment; this quota of energy (COP) was redistributed to make up for the uncovered demand of all the members of the EC. The following order of priority was defined for the EC members in relation to the economic damage caused by national grid blackouts: companies, municipalities and then domestic users.

All the EC users, after satisfying their own self-consumption (SC), contribute, according to their possibility (cOP), to the electricity supply of the community (COP); this maximises the energy self-sufficiency of the energy community and the collective self-consumption (CSC), while it reduces the withdrawals from the national grid (UD). This is possible thanks to the good combination of the different hourly consumption and production profiles distributed over time for each category of users. This form of aggregation allows the energy risk to be reduced for all the users, according to the order of priority chosen for the energy supply. Fig. 14 shows that all the members of the EC can reduce their risk index to well below the tolerability limits. Compared to previous scenarios, in which some users benefited while others did not, the risk in this scenario is reduced for all the categories. The users that still have a high uncovered demand (sUD) and, consequently, a high exposure to risks, are the ones at the bottom of the priority list, that is, municipality prosumers, and domestic consumers and prosumers.

5.6. Combined scenarios

The different, previously presented scenarios are combined in this section. Therefore, the interventions consist of the actions that were described individually in the previous sections. The risk index was calculated for each user in each combined scenario with reference to the respective tolerability limits.

5.6.1. Risk index for the energy efficiency + storage scenario (EE + ST)

This scenario consists of a combination of the energy efficiency of the public lighting system and the installation of storage systems. As shown in Fig. 15, compared to scenario "ST" in Fig. 11, in which all the prosumers benefit from a reduction of the energy risk, in this scenario, all the municipalities in which the energy efficiency measure is carried out obtain a further benefit. When the energy consumption for public lighting is reduced, both the uncovered demand and the total consumption decrease. The storage systems with a daily capacity allow municipalities to postpone the self-consumption of their RES production, thereby enhancing their daily self-consumption and reducing the daily uncovered energy demand. The amount of RES produced daily is not enough to cover the energy needs, and for this reason, the municipalities still

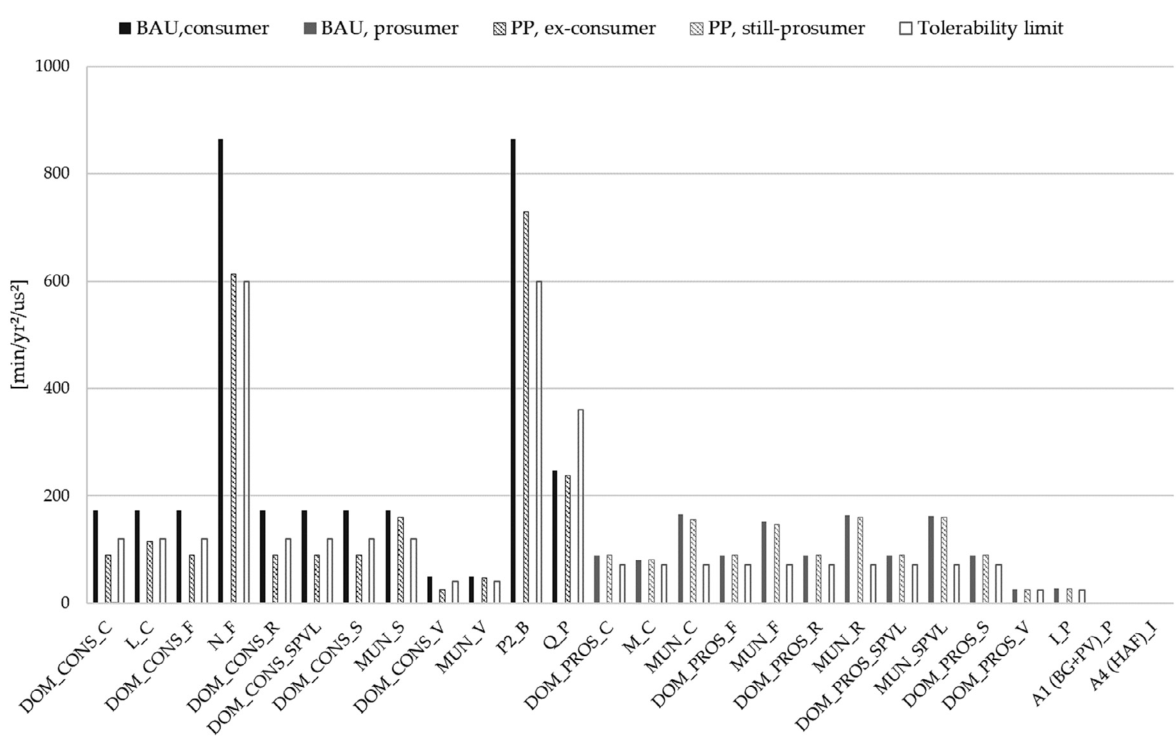


Fig. 13. Comparison of the Risk index of the Productivity scenario (PP), the BAU scenario and the tolerability limits (grey line). The risk index of the BAU consumers (in black) and BAU prosumers (in grey) is compared with the risk index of the PP ex-consumers (in black pattern) and the PP still-prosumers (grey pattern).

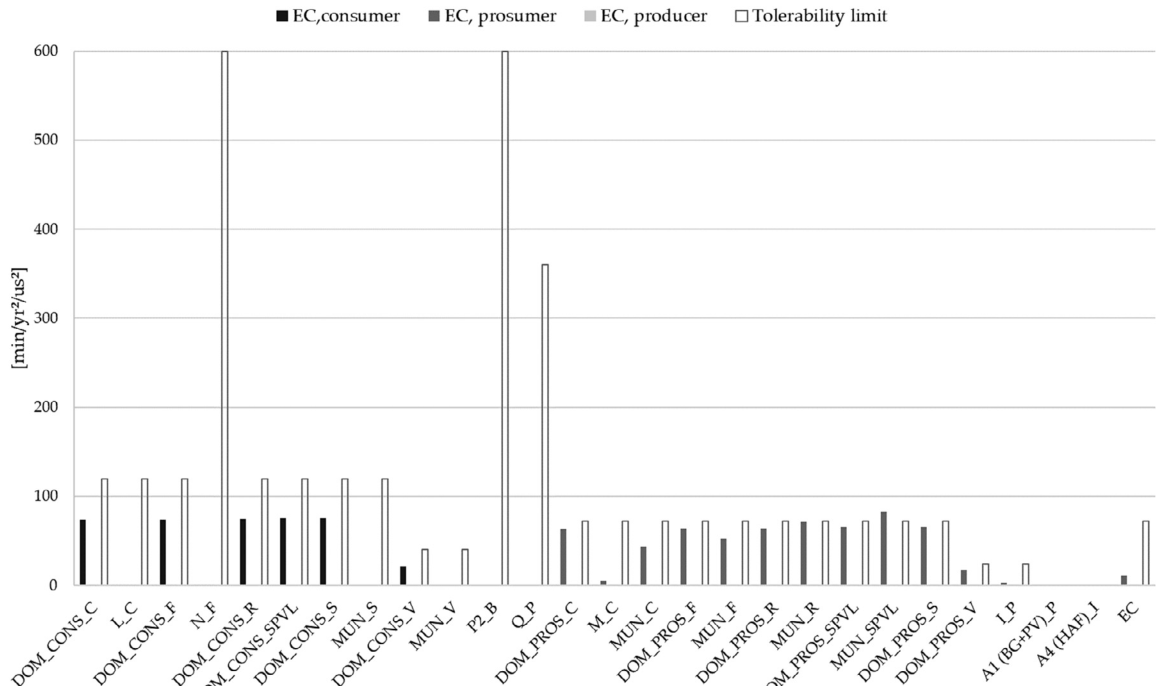


Fig. 14. Risk index of the EC scenario compared to the tolerability limits (grey line), distinguishing between consumers (in red), prosumers (in black), producers (in dark grey) and the collective EC users (in light grey).

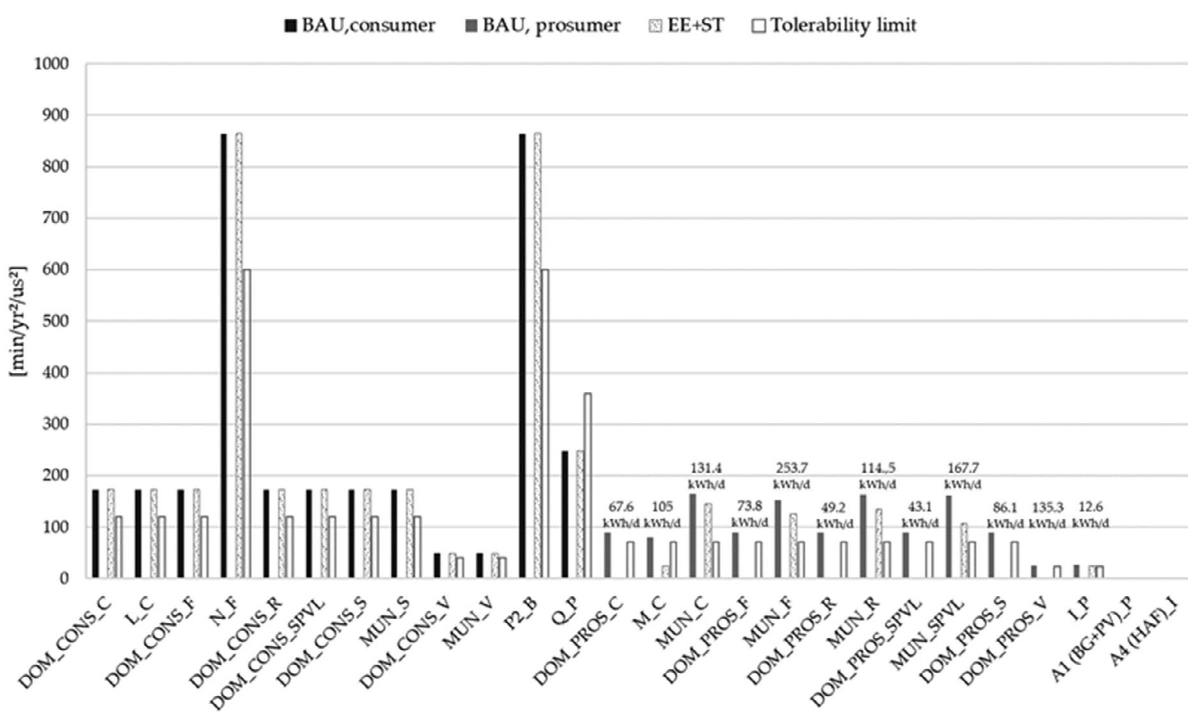


Fig. 15. Risk index of the EE + ST scenario (grey pattern) compared with the tolerability limits (grey line) and the BAU scenario, distinguishing between consumers (in black) and prosumers (in grey).

depend on the national network and still have an energy risk that is higher than the tolerability limits.

5.6.2. Risk index for the productivity + storage scenario (PP + ST)

This scenario consists of a combination of the exploitation of the energy productivity of the end users and the installation of storage systems. Fig. 16 shows the combination of these two interventions, which is mainly of benefit to the domestic consumers, who obtain the same advantages as the domestic prosumers. Self-production is maximised, thanks to the possibility of storing energy and postponing self-consumption when needed. Since the total daily production is greater than the energy needs, the leftover production can be sold to the national grid, and a negative risk index is thus achieved. Municipal and company consumers also

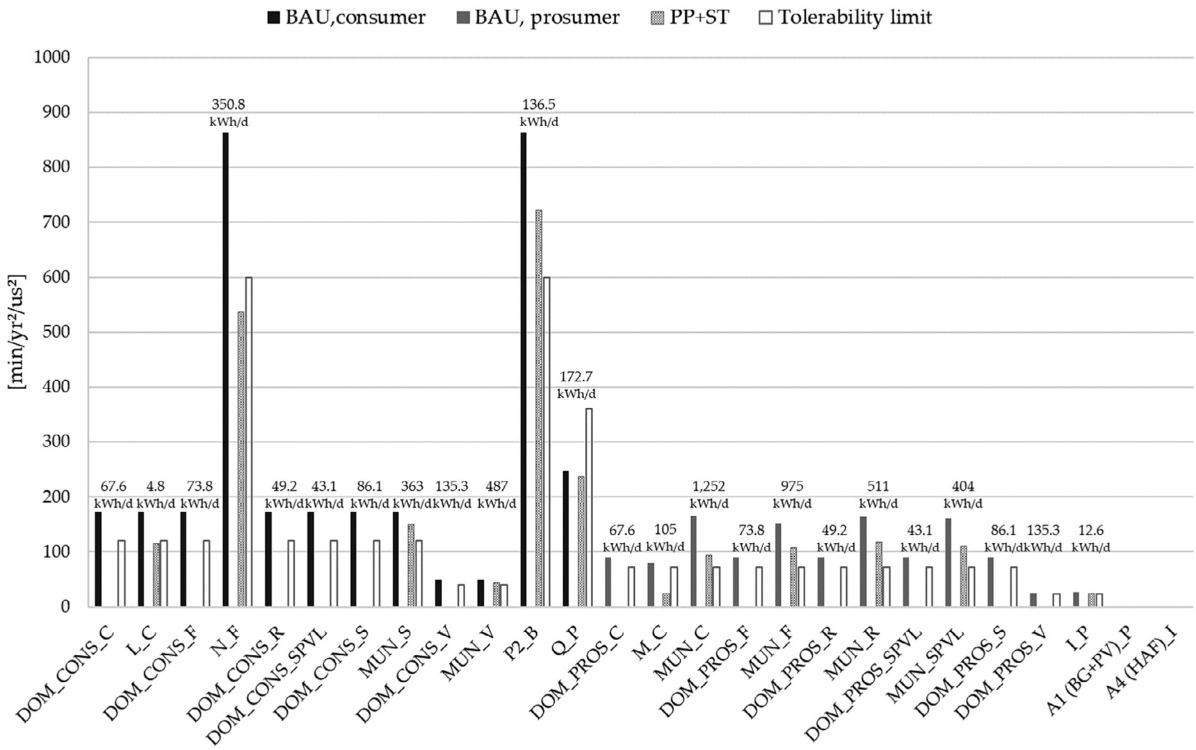


Fig. 16. Risk index of the PP + ST (grey pattern) scenario compared with the tolerability limits (grey line) and the BAU scenario, distinguishing between consumers (in black) and prosumers (in grey).

enjoy the same advantage: as their energy demand is greater than their productivity capacity, the daily energy storage is not enough to cover their needs. Although they still depend on the national grid, they now have a positive risk index, which is lower than the tolerability limits, with the exception of the Q_P user, who is particularly exposed as he/she is the only user with a medium voltage and medium urban concentration degree.

5.6.3. Risk index for the energy community + productivity scenario (EC + PP)

This scenario pertains to the constitution of the EC and the exploitation of the energy productivity of the end users. Therefore, it appears to be the only one, among all the hypothesised scenarios, that complies with the legal conditions for the configuration of the Renewable Energy Community (REC) [15] and which can access the economic incentive connected to *Collective Self-Consumption* [16]. The hourly electric balance of the total energy consumption (TC), the total energy production (TP) and the productivity (PP) of the aggregated EC members is shown in Fig. 17, considering a typical day, as presented in Table 6. The production of the hypothesised PV systems increases the total daily production of the EC, but only in the central hours of the day.

Fig. 18 shows that when the consumers of the EC become prosumers, both the prosumers and the whole EC benefit, as already seen in the "PP" scenario. In fact, the RES production that prosumers make available to the EC members increases as the collective self-consumption increases, according to the previously mentioned service supply priority list. The uncovered demand of energy decreases for all the users, as does the risk index, according to the order of priority. This scenario allows the risk to be reduced much more than the EC scenario alone does, and to below the tolerability limits for all the users. The users that still have a high uncovered energy demand, and consequently a high exposure to risks, are the ones at the bottom of the priority list, that is, the municipality prosumers, and the domestic consumers and prosumers.

5.6.4. Risk index for the energy community + energy efficiency scenario (EC + EE)

This scenario consists of a combination of the EC and the energy efficiency measures on public lighting. The energy consumption for public lighting has a significant impact on the total energy demand of the municipalities. Municipalities fall into the middle of the previously mention priority list and this means that, if the municipalities require less energy, there is consequently a greater availability of RES production to cover the energy needs of the users that come after those municipalities in the priority list. This scenario allows the energy risk to be reduced more for all the users than the "EC" scenario, according to the order of priority chosen for the energy supply. Fig. 19 shows that the risk index of all the members of the EC can be reduced way below the tolerability limits. The users that still have an uncovered energy demand, and consequently are exposed to risks, are the ones at the bottom of the priority list, that is, the municipalities and domestic prosumers.

5.6.5. Risk index for the energy community + storage scenario (EC + ST)

This scenario consists of a combination of the EC and the installation of storage systems. If a storage capacity is assumed for all the energy produced by the EC, the total daily production can be postponed and self-consumed, when necessary, by the end users. The EC RES production can cover the daily consumption of all the end users, thereby obviating the issue of matching different hourly profiles. None of the users experiences an uncovered energy demand and does not therefore need to draw energy from the national grid, thereby reducing the risk index to zero. As shown in Fig. 20, the risk index for all the members of the EC falls way below the tolerability limits, more so than for any of the other scenarios presented so far (UD = 0, therefore e = 0 and R = 0).

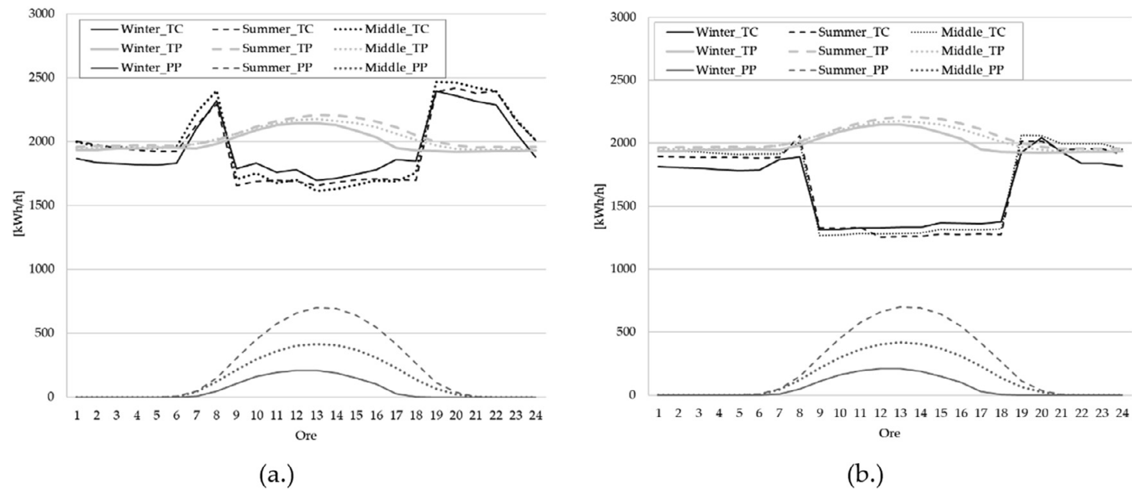


Fig. 17. Aggregation of the hourly energy consumption (TC) profile (in black), the production (TP) profile (in light grey) and the productivity (PP) profile (in dark grey) of all the EC end users, for the three different seasons, during a typical weekday (a) and a typical holiday (b).

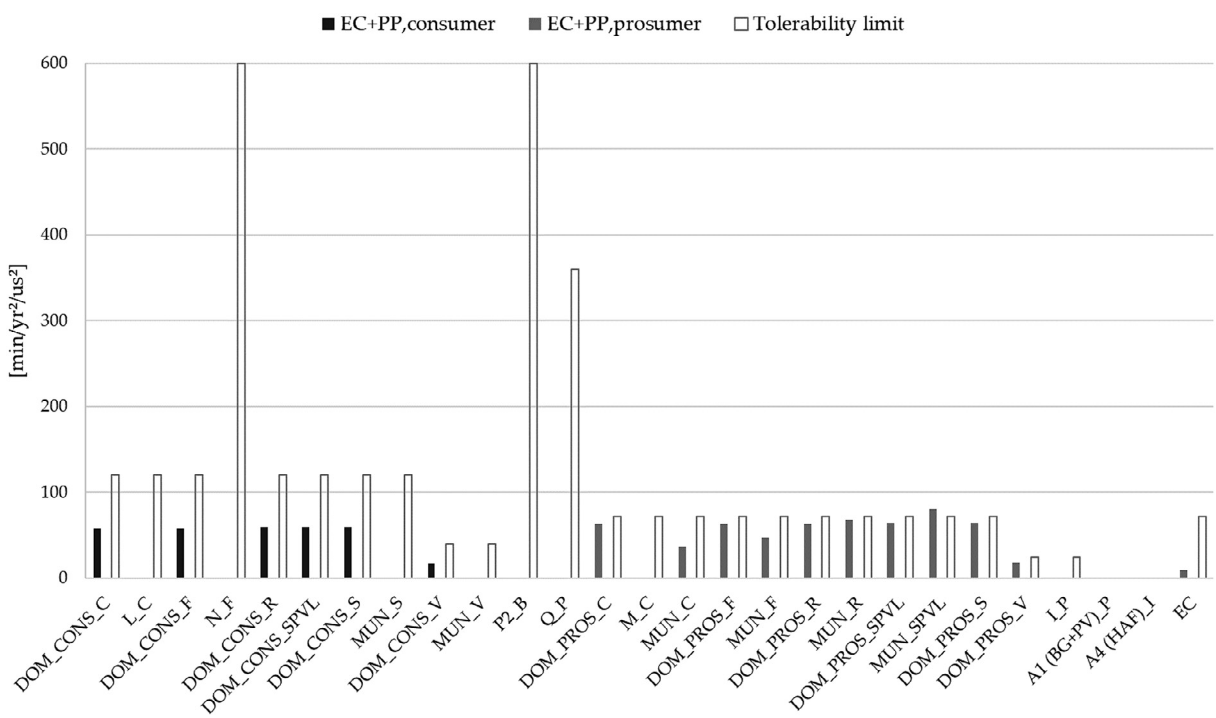


Fig. 18. Risk index of the EC + PP scenario compared with the tolerability limits (in grey), distinguishing between consumers (grey line), prosumers (in black) and the collective EC users (in grey).

Indeed, the over-production remaining at the end of each day, which is not collectively self-consumed, can be sold for a profit to the national grid.

5.7. Comparison of the risk Index, Self-Sufficiency index and Self-Consumption index

In this paragraph, all the hypothesised scenarios are compared, according to results of the Risk Index (R), as shown in Fig. 21a; the results of the Self-Sufficiency Index (SSI) and the Self-Consumption Index (SCI) are represented in Fig. 21b, as described in [13]. A distinction is made between the *non-EC scenarios* (in blue), and the *EC scenarios*, and simple EC (in orange) and REC configurations (in red) are further distinguished.

As can be seen in Fig. 21a, the BAU scenario has the highest risk index (84.95). The installation of storage systems (ST), as well as the increase in local production (PP), has little effect on the risk reduction (82.40 and 78.98, respectively). In the former case, there are only a few prosumers compared to the total number of users involved; in the latter case, the consumers, who become prosumers, require larger amounts of energy, and its production is limited by the lack of availability of their roofing surfaces on which to install the PV panels. Storage systems have a better effect (67.99) when combined with an increase in local production (PP + ST). An efficiency intervention on public lighting (EE) has a direct effect on reducing the risk (68.88), as it decreases the share of energy consumption that occurs at night and which therefore has to be withdrawn from the national grid. This reduction

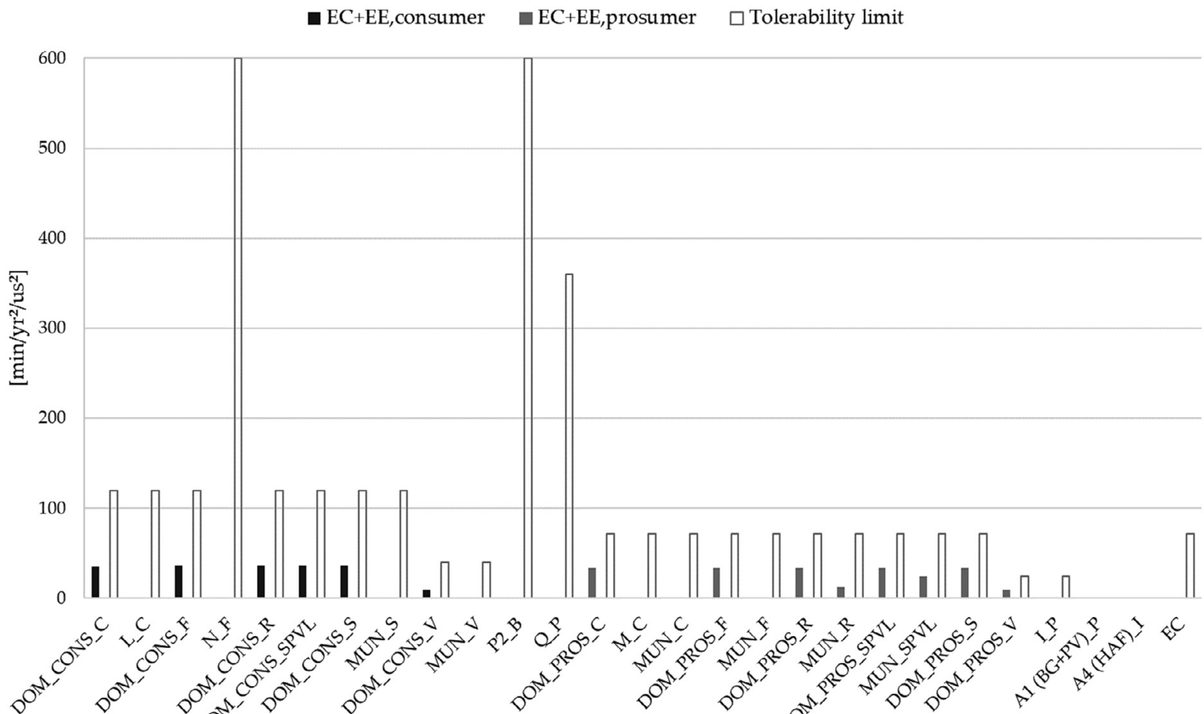


Fig. 19. Risk index of the EC + EE scenario compared with the tolerability limits (grey line), distinguishing between consumers (in black), prosumers (in grey) and the collective EC users (in dark blue).

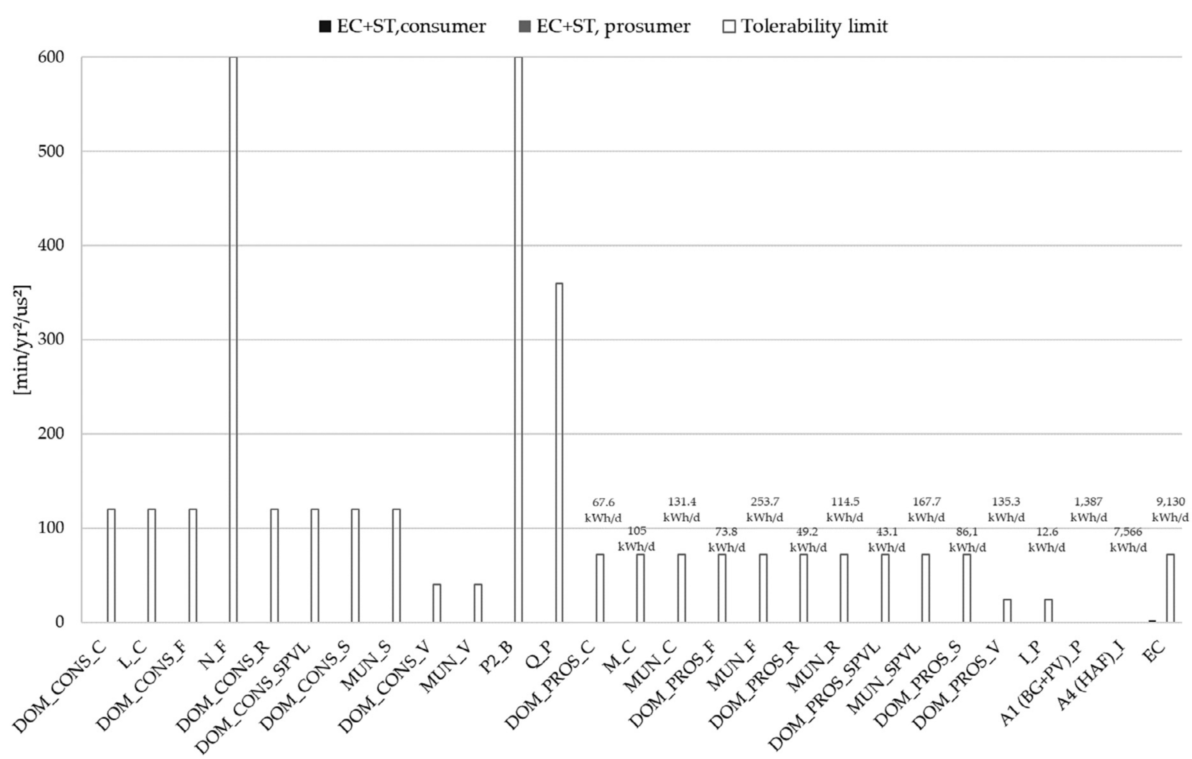


Fig. 20. Risk index of the EC + ST scenario compared with the tolerability limits (grey line), distinguishing between consumers (in black), prosumers (in grey) and the collective EC users (in dark blue).

increases (66.00) when EE is combined with the installation of storage systems (EE + ST), as the municipal prosumers, considering their same energy production, increase their share of self-consumption. The risk index is significantly reduced in all the EC scenarios, compared to the non-EC scenarios. The risk index is reduced drastically (10.76) simply by introducing the possibility

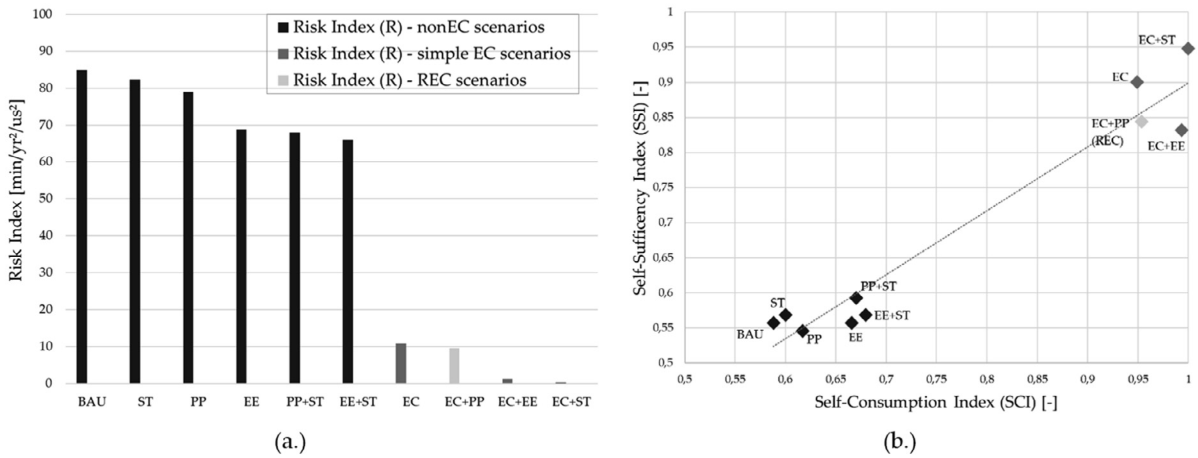


Fig. 21. Comparison of the different scenarios of the risk index (a.), the self-sufficiency index and the self-consumption index (b.), distinguishing between non-EC scenarios (in black) and EC scenarios, including the simple EC configurations (in dark grey) and the REC configuration (in light grey).

for stakeholders to mutually satisfy their energy demand, that is, by realising collective self-consumption (EC). Among the actions combined with EC, the possibility of storing and further sharing the local energy production (EC + ST) and the reduction of energy consumption (EC + EE), can lead to almost zero risk index values (0.21 and 1.26, respectively); increasing energy productivity (EC + PP) also has a positive effect on reducing the risk of EC (9.48).

In this paper, if a scenario has a high-risk index (Fig. 21a), it consequently shows a low value of the self-sufficiency index (Fig. 21b). In fact, a clear distinction can be made between the energy performance (SSI and SCI) of non-EC and EC scenarios (Fig. 21b): the latter have higher values for both indices, and ensure a greater SCI than 70%, as required by the Regional Law [43]. Among all the hypothesised scenarios, the EC + ST one ensures the best level of energy performance. With reference to the BAU scenario, an improvement in the SSI index can be reached by decreasing the energy withdrawal from the national grid instead of increasing local production (PP); this can be achieved by reducing the energy consumption (EE), storing the local production (ST) to shift to self-consumption over time, or by aggregating different end users (EC) to overcome the mismatch in the energy consumption and production profiles. All the combined actions have a greater effect than the application of each single action on its own, particularly when storage systems are associated with an increase in local production or when the same type of intervention is associated with an EC scenario. The increase in the self-consumption index is related to both the availability of the local RES, and to the ability of users to boost their actual self-consumption, in quantitative and qualitative terms. In the former case (PP), this intervention can be limited by considering the characteristics of the context in which the case study is applied (local energy mix and surfaces available for PV). In quantitative terms, self-consumption increases as the number of storage systems (ST) increases, but these systems only have a considerable effect if there is a large number of prosumers (PP + ST), and even more so if the energy demand decreases (EE + ST). The self-consumption qualitatively increases with the EC, due to the addition of the individual and collective self-consumptions. Reducing the energy consumption (EC + EE), rather than increasing the energy production (EC + PP), helps to increase the SCI index, which can almost reach the same level as the scenario that performs the best (EC + ST). In the latter scenario, the local production is almost totally exploited, although some remains available for local withdrawal, due to the combination of the plurality of EC members, and the capacity to maximise storage.

5.8. Cost-benefit and cost-optimal analyses

The hypothesised scenarios pertaining to the results of the cost-benefit analysis are first compared with reference to the investment and annual energy costs (Fig. 22), and the results of the cost-optimal analysis are then presented (Fig. 23). The economic analyses have been assessed for each EC scenario considering both the simple EC configuration and the REC configuration, to which specific energy prices are applied. The aim has been to evaluate the effect that an REC incentive would have if it were applied to those EC scenarios that involve actions that are different from those required by law to access the incentive (new RES production plants, EC + PP).

When considering the investment costs, the storage installation is the most expensive investment for both non-EC and EC scenarios. However, it should be considered that only the existing prosumers sustain the expenditure in the "ST" scenario, while all the stakeholders become prosumers in "PP + ST" and someone has to bear the combined expenditure of the PV panel and battery, and the cost of the battery on the local grid is added to the cost of the individual battery of each prosumer in "EC + ST" (or "REC + S T"). The investment cost of new PV systems (PP) is slightly higher than the expenditure for public lighting efficiency (EE); the establishment of the EC is the lowest initial investment of all. As far as the BAU scenario is concerned, the storage (ST) and energy efficiency (EE) scenarios contribute to decreasing the expense without increasing the revenues to any great extent, even when combined (EE + ST); although both have similar initial investments, a reduction in energy consumption (EE) requires a more effective reduction in annual expenses. A combined effect of higher revenues and lower costs can be observed, due to the greater number of prosumers, in the PP and PP + ST productivity scenarios, as a result of a higher production and greater self-consumption, which generate economic savings, and as a result of a greater overproduction, which generates sales profits. The overproduction of the EC members is used in the EC scenarios to reduce the uncovered demand, thereby realising collective self-consumption (CSC), and the community can then sell less energy to the national grid, but at a higher cost for members of the local grid. Moreover, the exchanged energy (CSC) is bought at a lower price, and the reduction in the uncovered demand entails a reduction in expenses at a higher price on the national grid. This combination of expenses and revenues allows all the members to earn something, and the overall cost of the energy in fact decreases, compared to the BAU scenario. Consider-

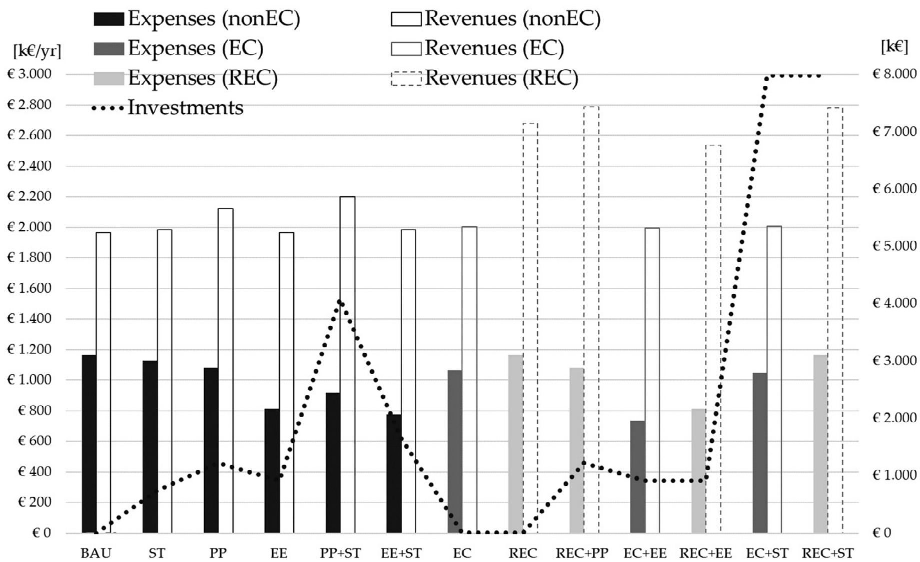


Fig. 22. Investment costs, annual energy expenses and revenues for non-EC scenarios (non-EC, in black), EC scenarios as a simple EC configuration (EC, in dark grey), and as a Renewable Energy Community configuration (REC, in light grey).

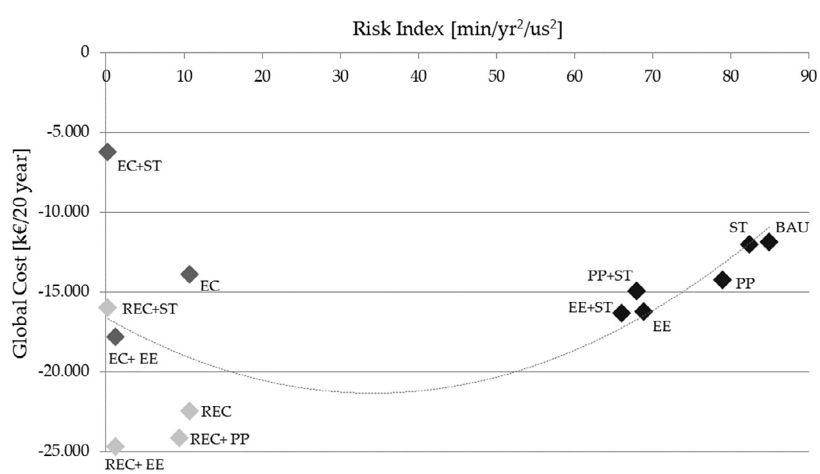


Fig. 23. Cost-optimal graph of all the interventions aimed at reducing the risk, for non-EC scenarios (in blue), and for EC scenarios, as a simple EC configuration (in dark grey) and as a Renewable Energy Community (REC) configuration (in light grey).

ing the EC scenarios in their hypothetical REC configuration, the annual revenue is considerably higher than the corresponding one in the simple EC configuration. The national incentive on collective self-consumption refers to a premium rate and, consequently, results in a net annual revenue being added to the sales profits and savings; this makes it convenient for stakeholder to join in a REC configuration. In addition, the REC incentive, which also includes a refund, due to avoided energy grid losses, is more profitable than the reduction/increase of about 10% of the energy market prices that is assumed on the local grid of the ECs (again as a refund on tariff components due to avoided energy losses).

Fig. 23 shows how all the EC scenarios can ensure the energy performances and economically advantageous interventions, compared to the *non-EC* scenarios. Among the latter, the intervention that guarantees the greatest economic benefits over time is the energy efficiency one (EE and EE + ST). Among the EC scenarios, it can be noted that the REC configuration ensures a more profitable economic return over time than the simple EC configuration. The use of storage systems allows a nearly zero energy risk index to be reached, but with higher energy costs. The best scenario is that of the establishment of the energy community and retrofitting intervention: in fact, reducing the energy consumption leads to a reduction in energy costs, the effects of which remain over the long term, and also leads to a nearly zero energy risk. This result occurs assuming access to REC incentives (REC + EE), and the energy cost with energy prices defined for single user (EC + EE).

In this work, the Pinerolese EC case study was analysed to evaluate how different scenarios (which lead to different technical solutions) can be applied to reduce the risks of blackout on the national electric grid.

The presented results show that the risks are reduced more for users who already have low risk thresholds. Prosumers have an advantage because they partly self-produce energy, and the implementation of combined interventions leads to a greater risk reduction than a single intervention. The increase of both autonomous and collective self-consumption is the main goal of an energy community. To this end, one of the further possible actions concerns the use of Information Technology systems for the provision of a Demand-Response strategy on the local grid. Monitoring, prediction of the local production and consumption, and real-time communication to all the EC members would offer the possibility of further maximising the self-consumption [60]. In this way, each user would be aware of the best moment in which to consume the local overproduction efficiently; in addition, each type of end user would be more aware of the impact of his/her energy use and could consequently decide spontaneously on when to reduce his/her energy demand. In order to do this, the EC would have to rely on Information and Communication Technologies (ICT), as well as an energy service provider. Such an investment could lead to greater engagement of the EC members in participating in local decisions.

The optimal configuration of the EC requires a balanced composition of stakeholders, in terms of energy demand amount and hourly profiles. The composition should involve a heterogeneous group: stakeholders with different and complementary energy profiles, such as categories of users (domestic, municipal and company) and producers, thereby ensuring a mix of available energy sources. Through the use of a place-based assessment, it is possible to spatially compare energy consumption and production profiles, on a monthly and an hourly time basis, and to hypothesise possible scenarios that would ensure economic and environmental advantages for all the members.

As can be seen in Fig. 22, the benefits of EC, related to the supply of energy, are not only an immediate individual benefit but rather that of a "collective purchasing" [61], in terms of lower energy prices and fewer environmental concerns (with only RES production).

The open and voluntary participation of citizens in an EC can affect the optimal configuration and the efforts to ensure benefits for all the stakeholders, and the benefits may not exclusively be economic, but also environmental (i.e. GHG reduction or RES production increase) and social (i.e. citizens' participation and responsibility). Evaluating the interactions among the stakeholders who decide to participate in the EC requires appropriate methodologies and tools. As described in [62], the game theory can be applied to EC case studies to address the interaction among different stakeholders whose decisions can influence one another's benefits. In fact, an objective function can be set to identify the optimal aggregation of EC members in order to obtain benefits for all, taking into account the propensity of each stakeholder to cooperate in the common strategy.

As is evident in the literature review section, energy is a key factor for regional development. The IPCC Fifth Assessment Report highlighted that between 60 and 80% of the final energy use is globally concentrated in urbanised areas [63]. In this global scenario, availability, accessibility, affordability and acceptability are four key aspects that should be considered when addressing energy [64] from a sustainability-related perspective. These aspects are closely connected to the importance of the spatial proximity of the energy supply and demand, which should entail an equitable distribution of the energy services (in terms of both quantity and quality) to all the members of the local community. In such a perspective, ECs are increasingly being assigned a fundamental role to respond to the need for energy security and accessibility in the frame of a clean energy economy.

The Pinerolo case study is a first step in this direction, and it has been demonstrated to what extent the considered EC scenarios can guarantee a reduction in the vulnerabilities related to the energy supply risk. As a result of their specific features, ECs can be considered as territorial resilience enablers as they produce co-benefits for all the stakeholders by simultaneously integrating a reduction in the energy risk, and the use of RES with economic advantages.

The term "energy community" is here used to denote a range of different circumstances of distributed energy generation [65]. The EC model included in [29] is defined as a legal entity which, according to the applicable national law, is based on open and voluntary participation, is autonomous and is effectively controlled by the shareholders who are located in the proximity of the renewable energy projects that are owned and developed by that legal entity (for the full definition given by the Council of European Energy Regulators, see Section 3.2). At the same time, the EU recognises that legislative barriers, rather than technical ones, currently limit the operation of energy communities: "To ensure that such initiatives can freely develop, the new market design requires the Member States to put in place appropriate legal frameworks to enable their activities" [66].

In transposing European Directive 2018/2001 [29], Italian Legislative Decree 162/2019 [15] defines modalities and conditions for the institution of collective self-consumption communities and the implementation of renewable energy sources. The possibility of end users self-consuming the energy produced by the community using existing networks is recognised, and economic incentives are provided for new plants and storage systems. Furthermore, this decree, which recognises the EC as an effective energy policy, encourages the experimentation and implementation of such communities, starting from such territories as the Italian small-island territory. This kind of territory represents a perfect occasion for ECs, because they are territorially isolated and the risk of blackout could have disastrous consequences; therefore, energy independence is even more important in such a territory than in other contexts. With the aim of implementing RES production, to cover the local energy demand, the incentive plan for RES technologies involves several authorities: the region, the municipalities, the Superintendence and other local entities. In order to facilitate such a participatory decision-making process, the national law has provided specific discussion boards to prevent limits and constraints.

An economic incentive can be a good strategy to make the initial investments profitable and therefore to promote the replication of EC initiatives by creating favourable financial conditions for citizens. Therefore, in addition to new local energy production systems, interventions related to the reduction of energy consumption in all sectors should be encouraged and supported through specific incentives. In this regard, European directives [1] encourage taking r action to reduce and optimise energy consumption before exploiting the local energy resources, even RES. These considerations should be evaluated when transposing the European directive on Citizens' Energy Community (CEC) [28], which all Member States will be called upon to put into force.

National institutions are therefore responsible for defining specific national objectives and incentives, while regional entities should identify how EC can best contribute to meeting the local energy goals (and other aims, such as social policy goals) and to establishing mechanisms that support their development, including advisory services or the provision of financial support. From a technical point of view, the EU recognises that "local energy communities can be an efficient way of managing energy at a local community level by consuming the electricity they generate either directly for power or for (district) heating and cooling, with or without a connection to distribution systems" [66]. As far as the Italian national situation is concerned, Piedmont is the first Italian Region to have introduced energy communities, according to Law 12/2018 [43], which foresaw the allocation of Euros 50,000 in the 2018–2019 period to encourage the creation of communities of people, entities and companies to produce, distribute and market the energy necessary to satisfy their needs.

6. Conclusion

The risk-place-based methodology presented in this work allows the energy risks connected to energy supply blackouts to be assessed. This methodology is used for risk-based decision making, in terms of optimising the energy demand and supply system, and of grouping energy consumers and producers together to establish Energy Communities (EC); it can also be applied to other energy risks and is very flexible and replicable for different territorial contexts.

As outlined in [67], ECs can help territorial systems to achieve their carbon emission targets by increasing the engagement of community members in energy issues, by making them more aware of their energy use, and by reducing a variety of related emissions. The establishment of an energy community can therefore be one of the actions that combines the economic development and environmental sustainability of a territory; it is currently promoted in the Italian "Integrated National Plan for Energy and Climate" [2].

The correct setting up of an EC not only involves the application of technical solutions (a technical solution is always found), but also planning and regulation support. A place-based approach makes it possible to identify the most effective solutions, from all the various points of view, for each territory and population.

The definition of a shared general strategy should be accompanied by local policies, not only in the energy field, which are able to exploit the existing opportunities and mitigate the critical issues of each territory. If the particular socio-economic features of each context are known, these policies can be used to leverage on local resources and enhance the initiatives of local stakeholders, thereby facilitating the implementation of ECs and ensuring their sustainability over time.

In spite of such a flexible definition, and recalling that there are various legal and economic models, ECs can be defined as regional developments that involve groups of citizens, social entrepreneurs, public authorities and community organisations that can participate directly in the energy transition by jointly investing in, producing, selling and distributing renewable energy [68]. From this perspective, EC can be defined as a device that can be used to achieve territorial resilience, as it is able to reduce energy risks and, at the same time, to guarantee a collective energy provision which results in a general improvement of the social and economic conditions of a community.

In short, we believe EC is a promising field of research, which, however, surely needs further exploration and innovative approaches. Further developments are necessary to obtain a better understanding of three main points pertaining to:

1. The refinement of the risk model, with a further analysis of the exposure factor and the definition of risk intervals to better guide risk-based decision-making;
2. The optimal dimension and spatial distribution of ECs throughout a territory;
3. The integration of energy policies for ECs in land use planning and territorial planning tools.

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.

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