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Abstract

The installation of PV systems in the Italian residential sector represents the main component within the overall PV market. Nevertheless, a strong contraction of PV investment can be observed in Italy during the last period due to the closure of the feed-in-tariff mechanism. For this reason, new opportunities have been introduced by the Italian Government to support investment in the residential sector: net-metering, tax deduction and a novel regulatory scheme where PV production can be exchanged between an end-user and an energy-provider free of network charges.

In this context, an economic assessment for PV installations in residential households is presented in this paper considering the benefits derived by the combination of these supporting schemes presently available in Italy. Increasing electricity consumptions of residential end-user are considered to explore the feasibility of PV installation in different configurations. Geographical information system is used here as a supporting tool to take into account the variation of solar radiation resource across the country, since economic results are influenced by the match between energy consumption and PV production. The results highlight how the perspective of PV invest-

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ment is still positive even if a feed-in-tariff for PV production is no longer available.

Keywords: Photovoltaic; GIS; Energy and economic analysis; PV potential.

Nomenclature and units

C_{EI}	economic value of the electricity produced and injected into the grid (€/year)
c_p	price of electricity bought from the grid excluding grid costs (€/kWh)
C_p	price of electricity bought from the grid including grid costs (€/kWh)
C_s	price of electricity sold to the grid (€/kWh)
C_{sc}	price of electricity produced by PV and sold to the end-user (€/kWh)
$CAPEX_{pv}$	investment cost for PV plant (€/kW_p)
CU_{Sf}	weighted average value of the general system costs and access costs for the end-user (€/kWh)
d	productivity loss of PV module (%)
$DPBT$	discounted pay-back time of the investment (years)
η_{pv}	efficiency of the PV modules (%)
E_{ex}	yearly electricity exchanged with the grid (kWh)

E_L	yearly end-user energy consumption (kWh)
E_p	yearly energy bought from the grid (kWh)
$E_{n,pv}$	yearly energy produced by PV (kWh)
E_s	yearly energy sold to the grid (kWh)
$G_{y,opt}$	yearly sum of global solar irradiance at optimum tilt and south facing $\left(\mathrm{kWh/m^2}\right)$
IRR	internal rate of return (%)
$LCOE$	levelized cost of energy (€/kWh)
N	technical lifetime of PV modules (years)
NMC	net-metering contribution (€/year)
NPV	net present value (€/$\mathrm{kW_p}$)
O_E	economic value of the electricity bought from the grid (€/year)
$OPEX_{pv}$	operational costs for PV plant (€/year)
P_{pv}	peak power of the PV plant (kW)
PCR	percentage of the energy cost reduction for the end-user (%)
PR	performance ratio of the PV plant
r	discount rate
S	additional net-metering income for PV energy surplus (€/year)
SC	self-consumption
SS	self-sufficiency
TD	tax deduction of PV installation

YC	yearly cost for the end-user (€/year)
YCC	yearly energy supply cost for the end-user(€/year)
YCF	yearly cash flow (€/year)
YR	yearly revenues (€/year)

1. Introduction

A significant diffusion of photovoltaic (PV) systems, as distributed generation facility, has been observed during the last decade in some of the main European countries [1]. This trend has been strongly supported by the EU commission that required member States to reach a 20% share of renewable energy in gross energy consumption by 2020 [2]. More recently, the new directive on renewable energy [3] increased this target binding the share of renewable energy for EU countries to at least 32% in 2030. The achievement of these objectives passes also through the implementation of innovative solutions like, for instance, building integrated PV (BIPV) systems making, in some cases, the buildings nearly to net-zero energy building (nZEB)[4, 5]. In particular, some novel technologies in BIPV can enhance higher efficiency and flexibility to ensure higher exploitation of the solar resource [6, 7].

In this context, a particular attention shall be given to the Italian market, where the positive effect of the national incentive scheme (i.e. feed-in-tariff) promoted a strong diffusion of PV technology characterized by an high installation cost [8, 9]. As a result, Italy became the second European country worldwide in terms of installed cumulative capacity of PV [10].

However, the progressive reduction of PV capital cost has forced governments and the national energy authority to reduce the contribution of incentive schemes, to avoid market doping and to reduce the economic impact of RES subsidies in the electricity bills [11]. This change in the Italian energy policy has highly influenced the trend of the PV market in the following years [12]. In particular, the contraction of Italian PV market has been relevant in the last three years for all sectors (domestic, industry, tertiary and agriculture) due to the closure of the feed-in-tariff scheme in 2013 [13]. In fact, starting from 2014, the growth rate of PV diffusion reduced from 30 %/year down to approximatively 2%/year [12].

Mitigation of this market reduction could be potentially obtained through a better exploitation of the energy policies introduced in Italy in alternative to the feed-in tariff [14]. Firstly, a recent change in the regulatory framework introduced a new possible configuration called "Sistemi Efficienti di Utenza" (SEU - efficient user systems), where an energy provider can install PV, other RES-based plants or high efficiency cogeneration systems and directly sell the produced electricity to an end-user free of transmission/distribution grid tariffs under specific conditions and constraints [15, 16]. Secondly, the net-metering option can be selected by PV system with an installed capacity up to 500 kW_p for partially recovering the access/grid cost of the electricity bought from the grid and economically valorize the electricity sold to the grid [17].

In addition, the Italian PV market can benefit of other opportunities especially for residential small size installations. In fact, natural person (i.e. residential end-user) can recover 50% of the capital cost for installing a residential PV system, as tax deduction in a time span of ten years [18]. Moreover, plants based on renewable energy sources (RES) with size lower than 20 kW_p benefit also of an excise discount on the generated electricity [19].

In this context, a residential end-user could positively evaluate the opportunity to directly invest in the installation of a PV system for supplying its internal appliances and to obtain energy costs saving. However, depending on PV size, end-users might not have enough economic availability to sustain the investment. For this reason, the option of SEU configuration could represent a compelling alternative to promote PV installation. Energy-providers, bearing the whole investment costs, could propose the installation of PV systems to domestic end-users: the electricity produced by PV could be sold to the end-user at discounted price to cover part of its yearly demand. This condition improves the cost-effectiveness for both subjects, since energy-provider could sell electricity at a higher price than the market one, while end-user could purchase it at a lower price than the wholesale one.

However, in both alternatives, the economic benefits of the PV investment strictly depend on the location of the domestic end-user and its behavior as customer [20]. In fact, the yearly PV production is function of the annual sum of global solar radiation that varies across Italy, while the yearly electricity demand is influenced by end-user behavior.

Analysis of PV investment for residential customers in the Italian context have been already explored in literature. For example, the economic sustainability of the integration of PV with battery systems for households is discussed in [21], by considering only three representative location in the Northern, Central and Southern part of Italy, respectively. A feasibility study of PV installation in residential sector is instead proposed by [22], where three representative average values of yearly solar irradiance for North, Central and South of Italy are used to calculate the solar yield of PV modules in the whole country. However, the approximations introduced in these cases limit the representativeness of the results for all Italy and SEU configuration is not discussed as possible option to foster PV diffusion.

According to similar studies, where spatial data are integrated within the economic analysis to evaluate RES sustainability [23, 24, 25, 26], this paper presents and discusses an economic analysis of PV investments for residential end-users in Italy by means of geographical information systems (GIS) tool, taking into account the opportunity offered by the present regulatory framework and the variability of the solar resource across the country. The analysis is performed by evaluating economic indicators considering different PV sizes and end-user yearly electricity consumption across Italy by the integration of a GIS tool and Matlab. Results are finally presented and discussed at national and regional level considering two alternative scenarios for the PV investment: with and without SEU configuration.

The paper is organized as follows: the current composition of the electricity price for Italian residential end-user, that influences the profitability of PV installation, is presented in Section 2; the energy model for calculating the electricity production by PV across Italy is introduced in Section 3, while the assumptions for identifying the economic indicators, which are the basis for investigating business opportunities, are presented in Section 4; in Section 5 the self-consumption and self-sufficiency are identified for an average Italian residential end-user with PV; finally, results at national and regional level are presented and discussed in Section 6.

2. The electricity price for Italian households

The economic analysis for PV installation in the Italian context is strongly influenced by the current electricity price for residential end-users. In fact, self-consumption of PV generation, reducing the net electricity demand of the household, leads to an yearly cost-saving capable to support the sustainability of the PV investment.

The baseline price, defined within the wholesale electricity market, is typically increased to reach the final retail price offered to the end-users by the Energy Providers. The additional components responsible for the increased electricity price, also known as value added, can be grouped in four main parts:

- costs of sales services (i.e. costs of the electricity at market price including costs of grid losses and the profit margin of the Energy Provider);
- costs for transmission and distribution of electricity (i.e. grid access costs);
- general system costs (i.e. subsides for RES, research costs, etc.);
- excise and taxes (including VAT).

For a typical Italian residential end-user, the costs of sales services account for around 50% of its electricity bill, while access costs, general system costs and taxes contribute for 18%, 20% and 12%, respectively, as reported by the Italian energy authority (ARERA) in [27]. More in detail, this final retail price is composed by a fixed and a variable (or marginal) part. The former (i.e. the fixed ones) is related to the contractual installed capacity (i.e. the maximum load power) of the domestic end-user, while the variable one is related to the electricity demand. The average final per unit cost C_p of the electricity bought from the grid, obtained summing up all the aforementioned parts, is not constant, but it changes according to the yearly electricity consumption of the domestic end-user. Figure 1 shows the variation of C_p for a domestic end-user with a maximum installed capacity of 3 kW, as reported by ARERA [28].

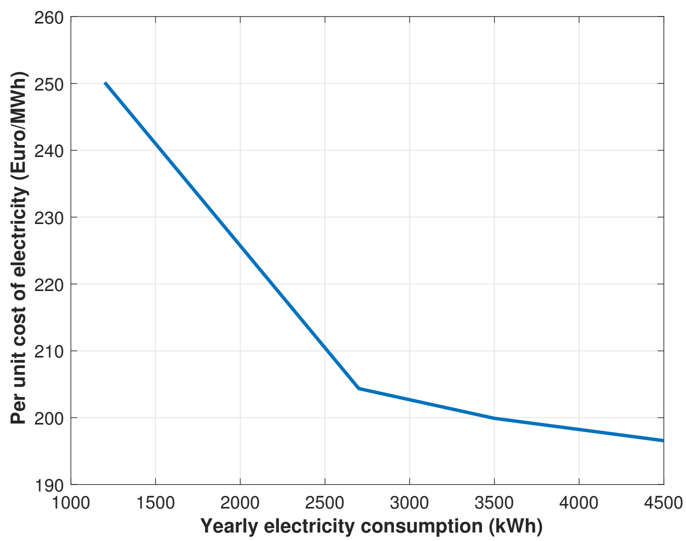


Figure 1: Average per unit cost of the electricity bought from the grid for a domestic end-user.

It can be noticed that the higher the yearly energy consumption, the lower the per unit cost and vice versa. This trend is due to the recent revision of the fixed and variable part of the retail price in the Italian billing system [29, 30]. In this work, the household installed capacity (i.e. 3 kW) is assumed constant for a typical residential customer, so the fixed part of the average electricity price C_p can be considered constant as well. Instead, the variable part changes with a trend similar to one observed in Figure 1.

When a PV system is installed, the electricity bought from the grid is reduced due to the effect of self-consumption of PV generation. Thus, the average per unit cost C_p considered in the economic analysis will change accordingly to the corresponding variation of the net electricity demand of the household.

3. Energy model

The evaluation of the economic parameters to identify the profitability of PV installation in the residential sector is based on the estimation of the following main energy parameters:

- the yearly electricity production of the PV;
- the yearly electricity sold to the grid;
- the yearly electricity purchased from the grid.

The identification of these values is essential to perform the economic assessment, since consequently an economic value can be calculated for the electricity sold to the grid, bought from the grid and self-consumed. In particular, the PV production depends on the solar radiation captured and converted in electricity by the PV modules. More specifically, since the yearly solar radiation is dimensionally expressed as an energy per unit of surface, all the energy and, consequently, the economic parameters were calculated per unit of surface of the PV module, since this formulation does not affect neither the energy nor the economic results.

3.1. Yearly PV production

An increased availability of solar radiation data can be observed in the last years, thanks to the diffusion of several websites and applications [31, 32, 33] capable to share these information that can be opportunely imported and elaborated by GIS tools and software [34, 35]. When the solar radiation data is available, the yearly electricity production of a PV system can be opportunely calculated, by taking into account:

- the yearly sum of the global solar radiation;
- an average estimated performance ratio (PR) for the PV plant, to take into account DC/AC conversion losses, cable losses, external temperature and weather effects on the yearly productivity of PV modules;
- an average efficiency η_{pv} of PV modules.

In this paper, the solar radiation data with a raster resolution of 2.5x2.5 km from the European Joint Research Center database [36] were used for Italy. In particular, the data refer to PV modules installed with optimal tilt angle (i.e. the tilt angle maximizing the PV production) and South facing (i.e. the azimuth angle is South oriented).

The dataset shown in Figure 2, that considers both weather condition and shading effect due to the horizon, was imported in MATLAB environment to perform energy and economic evaluation, since the raster of solar radiation data can be considered in a matrix form.

Subsequently, the resulting yearly electricity production was calculated in each cell of the raster, as follows:

$$E_{pv,m^2} = G_{y,opt} \cdot \eta_{pv} \cdot PR \cdot [1 - (n \cdot d_n)] \tag{1}$$

where $G_{y,opt}$ is the yearly sum of the global solar radiation at optimal tilt angle and d_n is the coefficient to consider the productivity loss due to the degradation of the PV modules at n-th year.

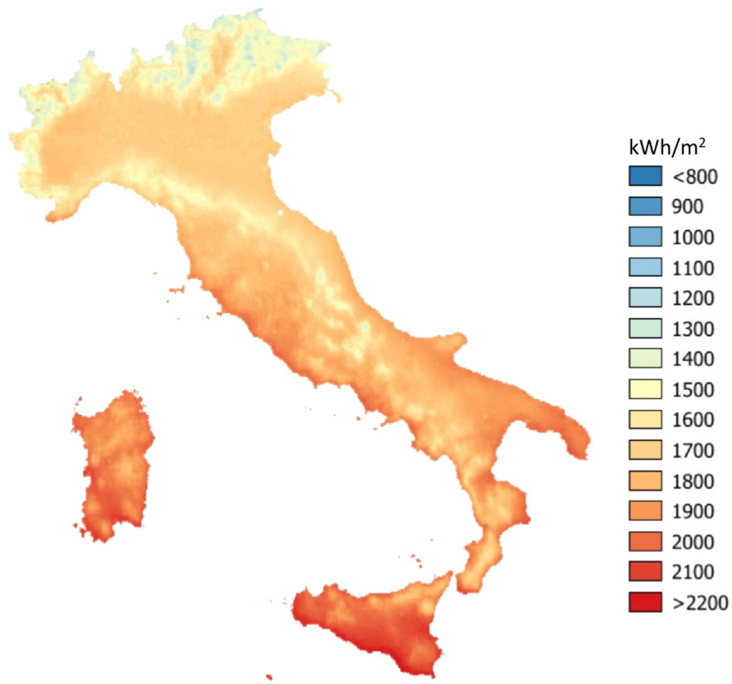


Figure 2: Yearly sum of global irradiation with optimal tilt angle of PV modules and south facing [36].

However, the altitude of the PV installation can affect the solar radiation captured, and consequently the energy production, because of the possible snow coverage of the PV modules [37]. This condition was taken into account by modifying the average performance ratio (PR) of the PV modules as function of the altitude of PV installation. For this reason, the digital elevation model (DEM) of the terrain was also imported in the GIS environment, to reduce and adapt the value of PR of all those raster cells placed on altitude higher than an identified threshold.

3.2. Electricity exchanged with the grid

Generally, the yearly electricity production of the PV modules could be only partially self-consumed to cover the yearly demand of the end-user. This depends on the match between the PV generation profile and the end-user demand profile. As a consequence, the possible PV overproduction should be sold to the grid and the net demand purchased from the grid. Thus, this yearly electricity exchanged with the grid (i.e. the energy sold to the grid and one purchased from the grid) has to be estimated for evaluating the supply costs and the revenues for the PV installation.

However, the PV generation is calculated here as yearly value and the comparison between the generation and the load profiles could not be directly performed. For this reason, the energy exchanged with the grid was identified by considering the yearly electricity balance calculated, from the end-user point of view, as follows:

$$\left(E_{pv,m^2} \cdot A_{tot}\right) + E_p = E_L + E_s \tag{2}$$

where A_{tot} is the overall surface of the PV modules. In Eq. (2) the sum of the PV production E_{pv} and the electricity bought from the grid E_p must equate the sum of the yearly demand E_L and the electricity sold to the grid E_s.

The energies exchanged with the grid E_p and E_s can be calculated introducing two additional parameters: the self-consumption SC and the self-sufficiency SS [38]. The former identify the self-consumed PV production with respect to the yearly PV production, while the latter identify the self-consumed PV production with respect to the yearly end-user demand, as follows:

$$SC = \frac{E_{pv,sc}}{E_{pv}} = \frac{E_{pv,sc}}{E_{pv,m^2} \cdot A_{tot}} \tag{3}$$

$$SS = \frac{E_{pv,sc}}{E_L} \tag{4}$$

Then, the substitution of the definitions of SC and SS in Eq. (2) allows to calculate the yearly electricity sold and purchased by a residential end-user, as follows:

$$E_s = (1 - SC) \cdot E_{pv,m^2} \cdot A_{tot} \tag{5}$$

$$E_p = \left(\frac{1}{SS} - 1\right) \cdot SC \cdot E_{pv,m^2} \cdot A_{tot} \tag{6}$$

In Eq. (5) and (6), the electricity exchanged with the grid E_p and E_s still depends on the size of the installation or equivalently on its overall surface A_{tot}. Consequently, dividing Eq. (5) and (6) by A_{tot}, the electricity sold to the grid and bought from the grid can be expressed in per unit of PV surface area as E_{s,m^2} and E_{p,m^2}, respectively.

Since the analysis performed in this study are based on yearly energy value, average SC and SS need to be calculated and estimated for Italy. In the next sections, the comparison of the estimated hourly PV generation profile and the end-user's load profile will be used to estimate the value of self-consumption and the self-sufficiency levels in three different reference locations of Italy. Then, this results will be considered to extrapolate an average yearly value of SC and SS representative of the whole country.

4. Economic assumptions

The economic assumptions defined in this section are used to evaluate the yearly cash flows, the economic indicators and also to measure the economic opportunity of the PV investment. Cash flows and economic indicators depend on the energy modeling and parameters described in Section 3. Thus, all the economic parameters described in the next sections can be measured per unit of PV surface as well.

Two different possible scenarios for the PV installation in the residential context are analyzed in this paper:

- *Scenario 1*: The installation of the PV system is commissioned by the end-user to partially satisfy its own electricity needs;
- *Scenario 2*: The installation of the PV system is proposed to the end-user by an energy-provider (e.g. an energy service company) within the SEU configuration.

In both scenarios, the installation costs of a PV system (i.e. $CAPEX_{pv}$) and its yearly operational costs (i.e. $OPEX_{pv}$) are typically defined as per unit cost of PV peak power. So, $CAPEX_{pv}$ and $OPEX_{pv}$ were opportunely converted in per unit cost of PV surface, as follows:

$$CAPEX_{pv,m^2} = CAPEX_{pv} \cdot P_{pv,m^2} \tag{7}$$

$$OPEX_{pv,m^2} = OPEX_{pv} \cdot P_{pv,m^2} \tag{8}$$

where P_{pv,m^2} is defined as the ratio between the peak power of the PV system P_{pv} and the overall area A_{tot} of the PV modules.

The sustainability of the PV investment costs represented by Eq. (7) and (8) is strictly related to the remunerations gained by the PV production. In this light, the net-metering and the tax deduction, currently available in Italy, were taken into account in addition to the cost-saving due to the PV self-consumption.

In particular, the net-metering option [17, 39] was considered in both scenarios. This option has been introduced in Italy to remunerate the surplus PV production and to refund part of the access/system costs charged to the electricity bought from the grid. Basically, under net-metering, the grid is assumed as an equivalent energy storage system, where the net electricity exchanged with the grid determines the refunded access/system costs. The economic contribution NMC gained by this scheme can be calculated, as follows:

$$NMC_{m^2} = min\left(O_{E,m^2}, C_{EI,m^2}\right) + E_{ex,m^2}CUsf + S \tag{9}$$

In Eq (9), O_{E,m^2} and C_{EI,m^2} represent the economic value of the electricity bought from the grid and sold to the grid respectively, E_{ex,m^2} is the exchanged energy to the grid and $CUsf$ is the weighted average value of the general system costs and the access costs for the residential end-user. Finally, S is an additional income assigned if the economic value C_{EI,m^2} is higher than the economic value O_{E,m^2} to avoid penalization of the PV overproduction from the economic point of view.

More in detail, the economic values O_{E,m^2} and C_{EI,m^2} were calculated, as follows:

$$O_{E,m^2} = E_{p,m^2} \cdot PUN \tag{10}$$

$$C_{EI,m^2} = E_{s,m^2} \cdot C_s \tag{11}$$

where PUN and C_s represent the national average electricity market price and the zonal electricity market price, respectively. Instead, the energy exchanged with the grid E_{ex,m^2} and the additional income S in Eq. (9) are defined, as follows:

$$E_{ex,m^2} = min\left(E_{p,m^2}, E_{s,m^2}\right) \tag{12}$$

$$S = max\left(0, C_{EI,m^2} - O_{E,m^2}\right) \tag{13}$$

In addition, the Italian government has also introduced an incentive scheme to promote the diffusion of RES production in the residential sector [40]. Under this scheme, available for natural person like the homeowners, 50% of the capital costs [41] for the installation of PV system can be recovered over ten years as tax deduction.

4.1. Costs and revenues of Scenario 1

In this scenario, the end-user commissions the installation of a PV system to supply its appliances and to sell the possible PV surplus to the grid. The costs for the installation, operation and maintenance of the PV system are thus entirely covered by the end-user, who also pays for the electricity bought from the grid when PV generation is not available. The per unit costs for purchasing electricity and the yearly maintenance cost were taken into account to calculate the yearly operational costs YC_{m^2} of this scenario, as follows:

$$
\begin{aligned}
YC_{m^2} =& E_{p,m^2} \cdot C_p + OPEX_{pv,m^2} = \\
&= \left(\frac{1}{SS} - 1\right) \cdot SC \cdot E_{pv,m^2} \cdot C_p + OPEX_{pv,m^2}
\end{aligned}
\tag{14}
$$

The yearly revenues for the end-user YR_{m^2} were calculated considering the costs savings due to the self-consumption of the PV production, the net-metering contribution NMC and the tax deduction TD, as follows:

$$
YR_{m^2} = SC \cdot E_{pv,m^2} \cdot C_p + NMC + TD \tag{15}
$$

In this Scenario, the installation and the maintenance costs $CAPEX_{pv,m^2}$ and $OPEX_{pv,m^2}$ are charged to the end-user as well as the revenues. So, the yearly cash flow YCF_{m^2} obtained by the installation of a PV system can be calculated, as follows:

$$
YCF_{m^2} = E_L \cdot C_p^0 + YR_{m^2} - YC_{m^2} \tag{16}
$$

where the first term of Eq. 16 represents the reference cost for purchasing electricity from the grid E_L at average price C_p^0 when PV is not installed.

4.2. Costs and revenues of Scenario 2

In this case, the installation of the PV system is proposed by an energy-provider, which is also the owner of the plant, to the end-user by an agreement regulated under the SEU scheme [15, 16]. According to the rules of ARERA, residential costumers can buy electricity from PV system installed by a third-party in the same land parcel of the household (e.g. installed on its roof) through a private connection. The energy produced by PV and exchanged with the end-user can be traded at a price agreed between the two parties, but free of the variable part of the access/grid costs.

The possible surplus of the PV production is sold to the grid, but the net metering contribution NMC is gained by the energy-provider, that also covers all the costs for the installation, operation and maintenance of the PV system.

For its part, the end-user pays an unitary price C_p for the electricity bought from the grid and an agreed fixed unitary price C_{sc} for the energy purchased from the PV generation of the energy-provider. Consequently, the yearly costs YC_{m^2} for the end-user were calculated in this Scenario, as follows:

$$\begin{aligned} YC_{m^2} = & E_{p,m^2} \cdot C_p + E_{sc,m^2} \cdot C_{sc} = \\ & = \left[\left(\frac{1}{SS} - 1 \right) \cdot SC \cdot E_{pv,m^2} \cdot C_p \right] + SC \cdot E_{pv,m^2} \cdot C_{sc} \end{aligned} \tag{17}$$

where C_{sc} is the price charged to the electricity produced by the PV and sold to the end-user E_{sc,m^2}.

The yearly revenues gained by the energy-provider can be then calculated similarly to the one formulated in Eq. 15, by using the energy price C_{sc} and the self-consumption SC, as follows:

$$YR_{m^2} = SC \cdot E_{pv,m^2} \cdot C_{sc} + NMC - OPEX_{pv,m^2} + TD \tag{18}$$

In this case, the yearly cash flow YCF_{m^2} coincides with the yearly revenues YR_{m^2} gained by the energy-provider, since it bears the investment costs for installing and maintaining the PV system. Moreover, the tax deduction TD and net-metering contribution NMC for PV installation are supposed to be completely transferred to the energy-provider by the end-user.

4.3. Economic indicators

The profitability for the PV investment in household was evaluated through the definition of different economic indicators: net present value (NPV), internal rate of return (IRR), discounted pay back time ($DPBT$) and levelized cost of energy ($LCOE$). In particular, the NPV is calculated as follows:

$$NPV_{m^2} = -CAPEX_{pv,m^2} + \sum_{n=1}^{N} \frac{YCF_{n,m^2}}{(1+r)^n} \tag{19}$$

where N is the technical lifetime of the PV plant and r is the discount rate to actualize cash flows at any given n-th year.

From Eq. 19 $DPBP$ and IRR for a new investment in PV installation can be calculated. The former represents the period required to refund the initial capital expenditure $CAPEX_{pv,m^2}$, while the latter evaluates the opportunity of the PV investment for the energy-provider, since it typically represents a target rate of an investment. Finally, $LCOE$ is also considered to evaluate investment opportunity, since it defines the costs for RES electricity generation [42], as follows:

$$LCOE = \frac{CAPEX_{pv,m^2} + \sum_{n=1}^{N} \left(OPEX_{n,pv,m^2} - TD_n\right)(1+r)^{-n}}{\sum_{n=0}^{N} E_{n,pv,m^2}\,(1+r)^{-n}} \tag{20}$$

The introduction of tax deduction TD in Eq. 20 decreases the $LCOE$. Typically, the $LCOE$ is compared either to the cost of the electricity purchased from the grid or to the cost for generating electricity by other alternative sources. This is true both in Scenario 1 and 2, but in the latter (i.e. under SEU configuration) this parameter represents also a reference value for the electricity price C_{sc} of the PV generation. In fact, if the whole PV generation was sold to the end-user, the C_{sc} should be greater than $LCOE$ in order to have a $DPBT$ lower than PV lifetime.

Finally, an indicator of the cost saving for the end-user is defined as follows:

$$PCR = \left(1 - \frac{YC}{YC^0}\right)100 \tag{21}$$

This indicator compares the overall costs YC for the end-user to buy electricity when PV is installed, with ones YC^0 when all the electricity demand of end-user was bougth from the grid (i.e. without PV).

5. Self-consumption and self-sufficiency for Italian household

The energy model presented in 3 identifies the energy exchanged with the grid and, consequently, the economic indicators by means of an average yearly value of SC and SS. Nevertheless, as already observed, the self-consumption and the self-sufficiency levels depend on the match between the PV generation profile and the end-user's load profile. For this reason, both hourly profiles were estimated to analyze how SC and SS change according to the PV sizes and, later, annual average values have been extrapolated as representative for the whole Italy.

5.1. Domestic load profile

The yearly electricity load profile for an Italian domestic end-user was evaluated considering an average yearly electricity demand E_L for households and a normalized load profile derived by [43] and [44]. The normalized load profile shown in Figure 3 was rescaled by means of an opportune scaling factor SF to ensure that the yearly demand of the domestic end-user is kept, as follows [16]:

$$SF = \frac{E_L}{\sum_{i=1}^{12} \left(NDM_i \sum_{j=1}^{24} HLF(j) \right)} \tag{22}$$

where NDM_i represents the number of days in a given i-th month, while $HLF(j)$ is the hourly load factor from the normalized load profile. Once the yearly energy consumption E_L is fixed, the resulting yearly load profile is thus representative of an average Italian residential end-user across the whole Italy.

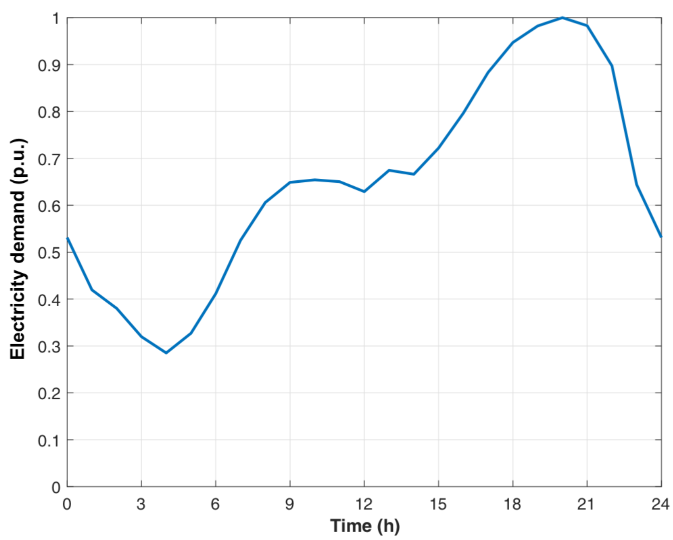


Figure 3: Normalized load profile for an Italian household

5.2. PV generation profile

The yearly PV production profile was instead calculated as a function of PV size and other factors (i.e. plant location, weather condition, etc.) by means of PVGIS data [45] and through the methodology presented in [46] to evaluate the hourly irradiance profile $G(t_i)$. Following this approach, the PV production profile can be calculated, as follows [16]:

$$P_{prod}(t_i) = \frac{G(t_i)}{1000} \cdot P_{pv} \cdot PR \tag{23}$$

where PR is the performance ratio of PV system for taking into account DC/AC conversion losses, cable losses and external temperature effects on the yearly productivity of PV modules.

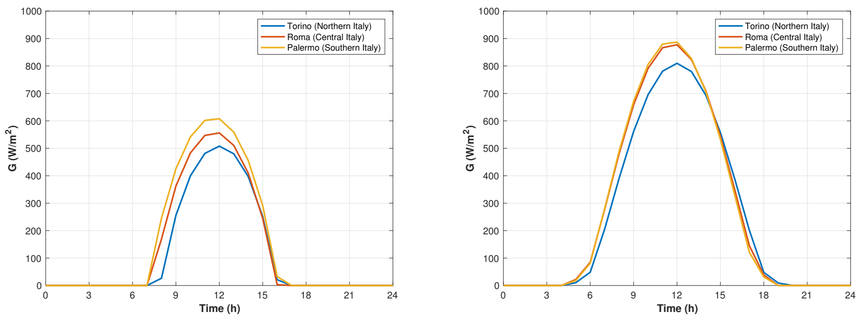
5.3. Calculation of average SC and SS

The analysis and the comparison of these two electricity profiles allows to identify the portion of the PV production effectively self-consumed by the end-user to cover in whole or in part its yearly demand E_L. Consequently, SC and SS parameters can be identified.

However, since this paper analyzes the PV investment opportunity for domestic end-user over whole Italy, the variation of irradiance profiles according to the PV location has to be taken into account, since different PV production and SC and SS levels can be expected for each location, as well.

A preliminary evaluation of SS and SC was performed in three different location (i.e. Torino, Roma and Palermo) placed in the northern, central and southern part of Italy. Figure 4 shows an example of the variation of hourly solar radiation for the three Italian cities in different seasons considering optimal tilt angle and south facing of the PV modules.

Moreover, three different levels of yearly electricity demand E_L were also considered to take into account both different end-user behavior: 2700, 3500, 4000 kWh. The first value is the representative consumption for an Italian family as reported by ARERA in [28], while the second and third ones



(a)

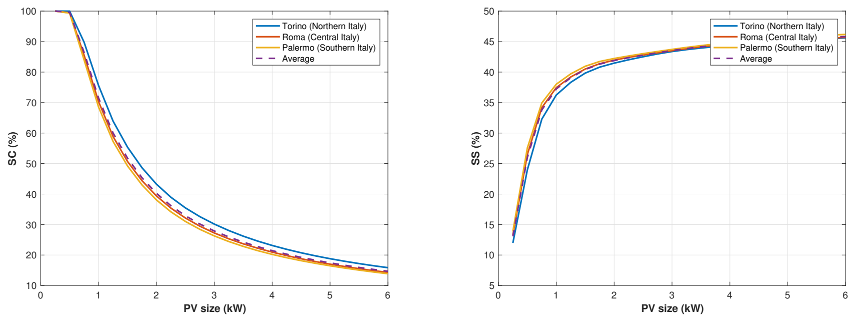
(b)

Figure 4: Solar irradiance $G(t_i)$ calculated from PVGIS for different Italian location in a) winter and b) summer.

represent household with an increased demand of 30% and 50% compared to the average one, respectively.

Figures 5, 6 and 7 show the trends for SC and SS as result of the comparison between the end-user load profile and generation profiles with different PV sizes in different locations when yearly electricity demand corresponds to 2700, 3500 and 4000 kWh, respectively. It can be noticed that the estimated self-consumption SC for an household with PV size of 4kWp is in a range between 20% and 30% compliant to the data reported in [12] for an Italian domestic end-user with the same average PV size.

However, even if the solar radiation varies for the three locations, the difference in terms of SC and SS, at a given PV size, is generally lower than 4% as reported by the comparison of the colored lines of Figures 5, 6 and 7. Consequently, a simplification can be assumed here: the same average values of SC and SS, represented by the dashed lines, were used as reference values for Italy, instead of assuming different SC and SS in each cell of the raster.



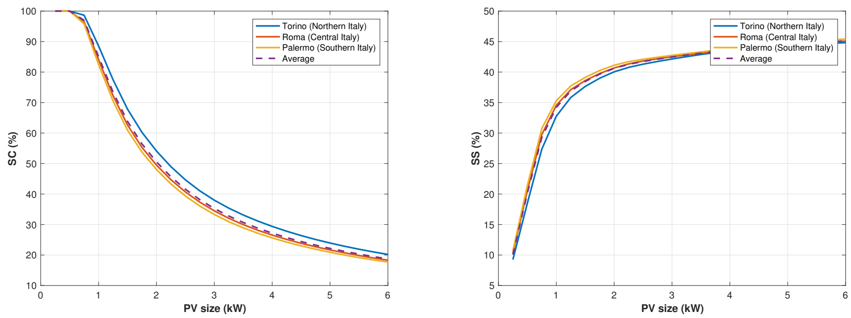
(a) (b)

Figure 5: Self-consumption (SC) and self-sufficiency (SS) values for different Italian locations with $E_L = 2700$ kWh.

Finally, to reduce the complexity of the analysis without loss of generality, only a reduced number of PV sizes was considered for the economic evaluation of the two scenarios discussed in Section 4. In particular, PV sizes within the range from 1 and 6 kWp were considered, since the average PV size for Italian domestic users does not exceed 4 kWp [12]. Consequently, only a selected number of possible average values of SC and SS was chosen from Figures 5, 6 and 7, as reported in Table 1.

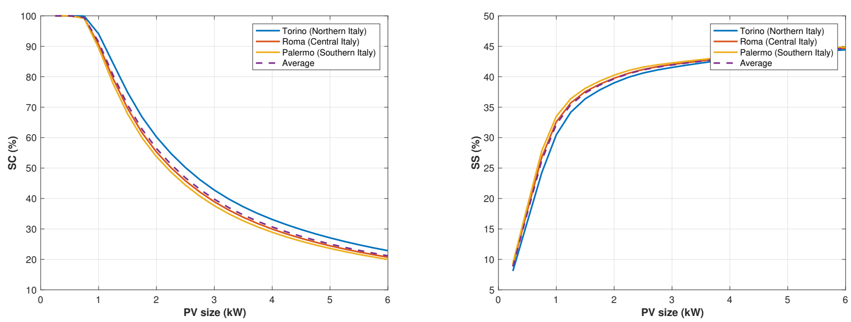
6. Results

The economic indicators for PV installations defined in Section 3 and 4 were calculated for residential end-users across Italy. These indicators highlight the possible opportunity both for end-user and for the energy-provider to invest on residential PV installation in Scenario 1 and 2, respectively. In the first case (i.e. Scenario 1), homeowner invests to install PV system and consequently to self-consume in whole or in part the PV production. In the second case (i.e. Scenario 2), an energy-provider explores a possible invest-



(a) (b)

Figure 6: Self-consumption (SC) and self-sufficiency (SS) values for different Italian locations with E_L = 3500 kWh.



(a) (b)

Figure 7: Self-consumption (SC) and self-sufficiency (SS) values for different Italian locations with E_L = 4000 kWh.

ment in PV installation for implementing a supply contract approach under the Italian SEU scheme. Scenario 2 can be thus considered as an alternative to Scenario 1 for all those homeowners without available financial resources.

Different levels of yearly electricity demand were taken into account (i.e. 2700, 3500 and 4000 kWh) to consider different residential end-user behavior in energy consumption. Also different PV plant sizes (i.e. from 1 to 6 kWp)

Table 1: Average values of SC and SS calculated for different PV sizes and electricity consumption of Italian household end-user.

E_L (kWh/y)	P_{pv} (kWp)	1	2	3	4	5	6
2700	SC (%)	71	40	28	21	17	15
	SS (%)	37	42	44	45	45	46
3500	SC (%)	85	50	35	27	22	19
	SS (%)	34	41	42	44	44	45
4000	SC (%)	91	56	40	31	25	21
	SS (%)	32	40	42	43	44	45

were considered to exploit all the possible configurations in the residential buildings.

Data from JRC dataset [36] were used to represent the distribution of solar radiation across the country. In particular, the data concerning the yearly sum of the solar radiation are available as raster, so the calculation was performed in each cell within MATLAB environment by importing the raster as a matrix. The main energy and economic parameters used to perform the energy and the economic analysis are shown in Table 2, 3 and 4, but a reduced value of 0.65 was assumed for PR [47], when the altitude of PV installation (i.e. the altitude in the DEM) is higher than 2000 m in order to limit yearly PV production owing to possible snow coverage.

Table 2: Energy and economic assumptions used for calculating indicators in each raster cell [16, 48, 49, 50].

$CAPEX_{pv}$ (€/kWp)	$OPEX_{pv}$ (€/kWp)	P_{pv,m^2} (kWp/m^2)	d (%/y)	r (%)	PUN (€/MWh)	PR	η_{pv} (%)
2000	50	0.156	0.4	5	53.14	0.75	15

Table 3: Electricity zonal prices of the different Italian market areas [50].

	North	**Northern central**	**Southern central**	**South**	**Sicily**	**Sardinia**
C_s (€/MWh)	54.41	54.07	51.61	49.80	60.76	51.47

Table 4: CU_{sf} values according to the yearly electricity bought from grid E_p [51].

	$E_p \leq 1800$ kWh/y	$E_p > 1800$ kWh/y
$CUSf$ (€/MWh)	47.51	79.08

In particular, Table 3 describes the zonal prices C_s used for calculating the revenues due to the net-metering option in Scenario 1 and 2. Thus, the price was changed in eq. (11) according to the location of the PV plant that corresponds to the geographical position of the raster cell where PV is supposed to be installed. The variation of the zonal market price was performed considering the six Italian market zones grouping different administrative regions of Figure 8, as follows:

- *North*: Valle D'Aosta, Piemonte, Liguria, Lombardia, Trentino, Veneto, Friuli Venezia Giulia, Emilia Romagna.
- *Northern-Central*: Toscana, Umbria, Marche.
- *Southern-Central*: Lazio, Abruzzo, Campania.
- *South*: Molise, Puglia, Basilicata, Calabria.
- *Sicily*: Sicilia.

- *Sardinia*: Sardegna.

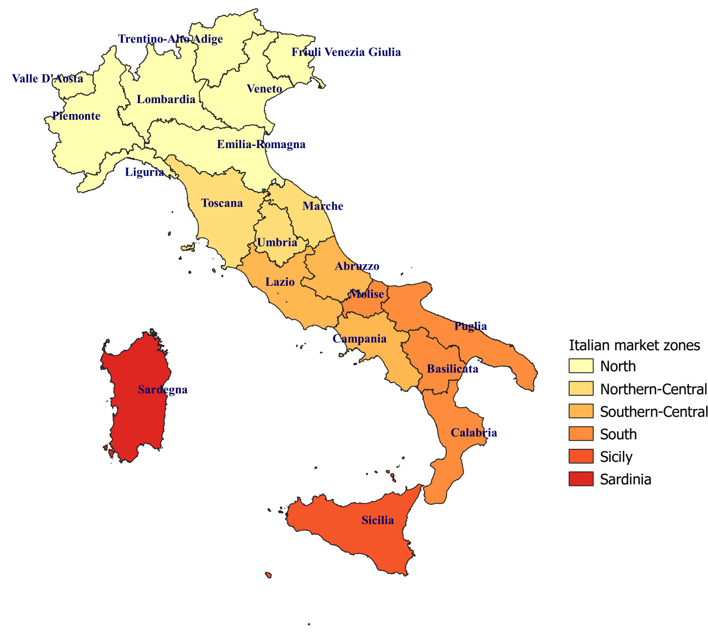


Figure 8: Geographical locations of the 20 administrative Italian regions and market zones.

Moreover, different C_{sc} prices for the electricity produced by the PV plant and sold to the end-user (see Table 5) were considered in Scenario 2 (i.e. under SEU configuration), in order to take into account different equilibrium price agreed between the energy-provider and the end-user. Three different level of C_{sc} have been considered: Case A, Case B and Case C, where C_{sc} is around 90%, 80% and 70% of the electricity cost C_p for an average end users (i.e. E_L=2700kWh), respectively. Higher C_{sc} prices typically shift the economic balance in favor of the energy-provider that benefits of an increased income for the PV production sold to the End-User. Vice versa, lower C_{sc} prices are favor the end-user paying a reduced cost to cover part of its annual demand.

Table 5: C_{sc} prices assumed in Scenario 2

	Scenario 1	**Scenario 2**		
	Case 0	Case A	Case B	Case C
C_{sc} (€/MWh)	-	185	165	145

Finally, a further simplification in the economic assumption is also considered here: the financing of the PV system is under equity, so both scenarios do not include debts for installing the PV system.

Result on the $LCOE$ calculation is presented in Figure 9, where, for the PV sizes considered, the unitary installation cost is assumed independent from the plant size itself and equal to the value reported in Table 2. In general, it can be noticed that $LCOE$ is significantly lower than the average electricity prices for residential end-user presented in Figure 1. The result suggests how PV installations could reach the grid parity in the residential sector thanks to the remarkable contribution of the tax deduction available for PV size lower than 20 kWp. This is particularly true for southern regions of Italy, where the yearly solar radiation, and thus PV production, is higher than other regions.

However, even if grid parity could be potentially reached, the profitability for PV investment depends on the cost-savings obtained by self-consuming PV production and on the revenues gained by selling overproduction. In particular, the self-consumed energy has a relevant economic value since it replaces electricity bought from the grid at a higher cost. In contrast,

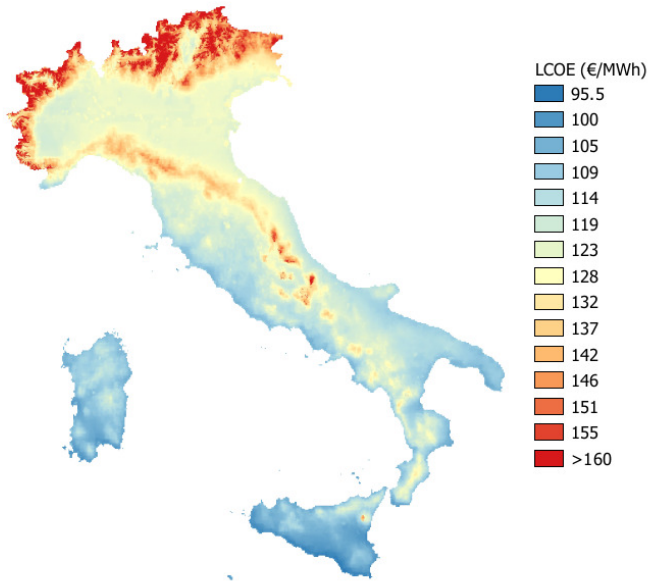


Figure 9: $LCOE$ calculated for PV installation in residential buildings.

overproduction is generally depreciated when sold to the grid, even if net-metering offers the possibility to mitigate this effect. Thus, better benefits can be expected by all those PV sizes ensuring higher self-consumption.

The overall economic results of the following subsections are presented here in different forms. Firstly, the geographical distributions of the economic indicators are shown to better identify how these indicators change across the country according to the variation of solar radiation. Secondly, average values of the same economic indicators are shown at regional level according to their geographical location in Figure 8 to supply a short and simplified overview of the results. Finally, average values of the economic indicators at national level are exposed to summaries main findings of the analysis.

6.1. Economic and energy results for E_L = 2700 kWh

The results for a typical residential end-user are considered and presented in this section. Figure A.14, A.15 and A.16 show the spatial distribution of the IRR, NPV and $DPBT$, respectively, calculated according to the different PV sizes, solar radiation and self-consumption/self-sufficiency levels. Average values of these indicators, aggregated by regions, are instead briefly presented in Figure A.17, A.18 and A.19. The southern regions benefit of higher yearly solar irradiation and consequently all the economic indicators are significantly favorable in these areas.

The economic indicators are positive in almost all the Italian regions both in Scenario 1 (i.e. Case 0) and in Scenario 2 (i.e. Case A, B and C) when PV size is the smallest (i.e. P_n = 1 kWp): the main benefit derives from the high self-consumption level (SC) potentially achievable. For example, IRR varies within a range from 1.5 to around 5.6%, NPV changes within 20 and 110 €/m^2 and $DPBT$ is between 10 and 17 years, except for Valle d'Aosta and Friuli Venezia Giulia showing a negative average value of IRR and NPV due to the high altitude of their territories and to a reduced availability of the solar resource. Moreover, a progressive reduction of the economic benefits can be observed for the energy-provider when Scenario 2 is considered and C_{sc} progressively decreases.

When the PV size increases (i.e. $P_n = 2$ kWp), the consequent reduction of self-consumption leads to a decrease of the economic benefits in both in scenarios. In this case, only central and southern regions keep profitability with positive value of IRR and NPV up to 3% and 70€/m^2, respectively. However, $DPBT$ increases with a minimum value of 12.5 years.

A further increase in PV size (i.e. $P_n \geq 3$ kWp) reveals a strong decrease in the economic benefits for all the scenarios and in all the Italian regions.

In this context, IRR and NPV are negative with a consequent increase of the $DPBT$ which does not fall below 20 years.

In Table 6, the average yearly cost saving obtained by the end-user in both scenarios is shown. It can be noticed that higher benefits are reached when PV installation is implemented by the end-user instead of the energy-provider. In fact, all the economic benefits due to the tax deduction and the net-metering option are gained directly by the end-user in the Scenario 1, improving its yearly costs saving from 26.5% up to 54.1%.

Table 6: Average yearly cost saving in the different scenarios for E_L = 2700 kWh.

	Scenario 1	**Scenario 2**		
P_{pv} (kWp)	Case 0	Case A	Case B	Case C
1	26.5%	-3.66%	-0.03%	3.60%
2	42.2%	-4.05%	0.07%	4.19%
3	45.6%	-4.14%	0.18%	4.49%
4	49.0%	-4.17%	0.25%	4.66%
5	51.4%	-4.44%	-0.02%	4.39%
6	54.1%	-4.45%	0.06%	4.57%

Differently, in Scenario 2, both tax deduction and net-metering contribution are transferred by the end-user to the energy-provider, since it bears the costs of PV installation. As a result, energy-provider improves its profitability, but the cost saving gained by the end-user is reduced, if compared to Scenario 1. Moreover, negative cost savings (i.e. increase in energy supply costs) can be observed in some configuration of Case A and B of Scenario 2. This effect is mainly due to the increase of the per unit cost C_p of the electricity purchased from the grid by the end-user when PV is installed. In fact, as already observed, the self-consumption of PV production reduces the net energy demand of the end-user and consequently the unitary price C_p is increased (see Figure 1).

As a general remark, the Case B within Scenario 2 has similar results of Case 0 in Scenario 1 in terms of economic performance. Thus, a C_{sc} price close to 165 €/MWh represents an acceptable compromise between the energy-provider and the end-user who buy in whole or in part the PV production under SEU configuration. However, the lower yearly cost saving observed in Table 6 can discourage end-user to adopt the solution offered by Case B.

In conclusion, when the yearly energy demand E_L is close to the average value for an Italian residential end-user (i.e. 2700 kWh), the most promising configurations in all the regions seem related to Scenario 1 (i.e. Case 0) with small PV size. However, if end-user has scarce financial resources, the PV installation costs could be sustained by an energy-provider, who could positively evaluate investment in small size PV plant, because IRR and NPV are still positive in almost alla regions in Scenario 2. In contrast, small or negative yearly cost savings are expected by the end-user in Scenario 2, leading to a possible dampening effect for the diffusion of SEU configuration.

6.2. Economic and energy results for E_L = 3500 kWh

The results for an Italian residential end-user with an yearly electricity consumption increased up to 30% of the typical one is considered and presented in this section. Figure B.20, B.21 and B.22 show the spatial distribution of the IRR, NPV and $DPBT$, while the average values of these indicators, aggregated by regions, are presented in Figure B.23, B.24 and

B.25. Once again, the southern regions benefit of an higher yearly solar irradiation. So, all the economic indicators are more favorable in these areas.

The growth in energy consumption makes the installation of a PV system more profitable, since an increased self-consumption is expected (see Table 1). The Scenario 1 and Scenario 2 with small PV size still remain the more profitable configurations capable to ensure, in most of the Italian regions, an IRR within a range between 2% and 7%, an NPV between 40 and 195 €/m^2 and a $DPBT$ down to 8 years in the southern regions.

An increased yearly electricity demand keeps the profitability for both scenarios also if PV sizes increase up to 3 kWp. In fact, from Figure B.23, B.24 and B.25, a PV plant with an installed capacity of 2 kWp is still profitable since positive economic indicators are ensured in almost all the Italian regions: IRR and NPV can reach up to 5.5%, 120 €/m^2, respectively, while $DPBT$ can decrease down to 10 years. When PV size increases up to 3 kWp, the economic indicators are still positive only in the central and southern Italian regions. In fact, in those areas, IRR can vary between 1% and 3.3%, NPV is lower than 75 €/m^2 and $DPBT$ can not fall below 12 years. Negative values are instead already calculated for northern regions with reduced availability of solar resource.

A further increase in PV size (i.e. $P_n \geq 4$ kWp) reduces the economic benefits for all the scenarios in all the Italian regions, with the exception of Sicilia that is favored by the highest solar radiation: IRR and NPV are negative with a consequent increase of the $DPBT$ which does not fall below 17 years.

In Table 7, the average yearly cost savings obtained by the end-user in Scenario 1 and 2 are shown. As already observed for $E_L = 2700$ kWh, higher cost savings are potentially achievable when all the PV installation costs are covered by the end-user (i.e. Scenario 1) instead of the energy-provider (i.e. Scenario 2), since all the economic benefits (i.e. tax deduction and the incomes from net-metering option) are gained by the end-user, improving its yearly costs saving from 26.2% up to 62.3%.

Table 7: Cost saving obtained in the different scenarios for E_L = 3500 kWh.

	Scenario 1	**Scenario 2**		
P_{pv} (kWp)	Case 0	Case A	Case B	Case C
1	26.2%	-0.86%	2.54%	5.94%
2	46.3%	-1.44%	2.66%	6.76%
3	55.3%	-1.78%	2.42%	6.62%
4	58.2%	-1.78%	2.62%	7.02%
5	59.9%	-2.02%	2.38%	6.79%
6	62.3%	-2.02%	2.48%	6.98%

Vice versa, in Scenario 2 energy-provider improves its profitability in PV investments, but the cost savings gained by the end-user are still lower than the ones obtained in Scenario 1. This occurs in Scenario 2 since end-user only benefits of a reduction in its energy supply costs, while tax deduction and the incomes from net-metering option are gained by the Energy Provider. However, costs savings tend to increase if compared to the results obtained in Table 6 when $E_L = 2700$ kWh, thanks to the increase of self-consumption level. Negative cost savings (i.e. increase in energy supply costs) can be observed in some configurations of Case A due to the increase of the per unit cost C_p of the electricity purchased from the grid by the end-user when PV is installed.

Similarly to the results exposed in the previous section, Case B in Scenario 2 has economic indicators similar to the ones of Case 0 in Scenario 1, but cost savings in Case B are significantly lower than Case 0 even if they can reach around 2.5%. A more favorable condition for the end-user in Scenario 2 can be potentially obtained within Case C, where cost savings can increase up to 7% due to a reduced unitary cost C_{sc} of 145 €/MWh. Moreover, Case C has still positive average indicators in southern Italian regions for PV sizes up to 3 kWp (see Figures B.23 and B.24), and the $DPBT$ is still acceptable for the energy-provider as well, since it is close to 13 years.

Merging the results from the different economic indicators, a synoptic overview reveals that Case 0 is still the most promising configuration from the economic point of view when PV sizes are lower than 3 kWp. Nevertheless, Case C could represent an interesting opportunity for energy-providers investing in small PV sizes in the southern and central Italian regions, paving the way for a possible diffusion of the SEU scheme in households.

6.3. Economic and energy results for E_L = 4000 kWh

Finally, the results for an Italian residential end-user with an yearly electricity consumption increased up to around 50% of the typical one is considered and presented in this section. Figures C.26, C.27 and C.28 show the spatial distribution of the IRR, NPV and $DPBT$, while the average values of these indicators, aggregated by regions, are presented in Figures C.29, C.30 and C.31. As already observed in the previous sections, the southern regions benefit of an higher yearly solar irradiation and, consequently, all the economic indicators are more favorable in these areas.

The higher yearly electricity consumption with respect to the average one (i.e. $E_L = 2700$ kWh/y), makes more profitable the installation of PV system, since a corresponding increase of the self-consumption is expected as well (see Table 1). Small PV size still remains the more profitable configurations in both scenarios capable to ensure, in most of the Italian regions, an average IRR up to 8%, an NPV up to 210 €/m^2 and a $DPBT$ down to 8 years in the southern regions.

It can be noticed from Figure B.23, B.24 and B.25 that the PV investment for both scenarios is still profitable when PV size is lower than 4 kWp. The increase in PV size is capable to ensure profitability as a consequence of the increase in the electricity demand covered by the PV production. In fact, PV plants with an installed capacity of 3 kWp still ensure positive economic indicators in almost all the Italian regions: IRR and NPV can reach up to 4.5%, 120 €/m^2, respectively, while $DPBT$ can decrease down to 8-9 years.

When the PV size is further increased up to 4 kWp, the economic indicators are positive only in the central and southern Italian regions for Case 0 and Case A even if they significantly decrease if compared with the ones calculated for smaller PV sizes. In fact, IRR can vary between 0.5% and 2.3%, NPV is lower than 55 €/m^2 and $DPBT$ is always higher than 14 years. Negative values are instead observed in northern regions with reduced solar resource. Case B and C of Scenario 2 show instead negative values for almost all the economic indicators, when PV size is greater than 4 kWp.

A further increase in PV size (i.e. $P_n \geq 5$ kWp) reduces the economic benefits for both scenarios in all the Italian regions: IRR and NPV are negative with a consequent increase of the $DPBT$ which is always higher than 18 years.

In Table 8, the average yearly cost savings obtained by the end-user in Scenario 1 and 2 are shown. Again, higher cost savings are potentially achievable when PV installation costs are entirely covered by the end-user (i.e. Scenario 1) instead of the energy-provider (i.e. Scenario 2), since all the economic benefits (i.e. tax deduction and the incomes from net-metering option) are gained by the end-user, improving its yearly costs saving from 24.9% up to 62.8%.

Table 8: Cost saving obtained in the different Scenarios for $E_L = 4000$ kWh

	Scenario 1	**Scenario 2**		
P_{pv} (kWp)	Case 0	Case A	Case B	Case C
1	24.9%	0.41%	3.62%	6.84%
2	43.0%	-0.03%	3.99%	8.01%
3	56.3%	-0.26%	3.96%	8.18%
4	58.2%	-0.39%	3.93%	8.25%
5	60.7%	-0.47%	3.95%	8.38%
6	62.8%	-0.50%	4.03%	8.56%

On the other hand, energy-provider improves its profitability in PV investments within Scenario 2, but the cost savings gained by the end-user are always lower than the ones obtained in Scenario 1. Once again, this occurs since tax deduction and the incomes from net-metering option are gained by the energy-provider in Scenario 2. Nevertheless, costs savings tend to increase if compared to the results obtained when E_L is equal to 2700 kWh or 3500 kWh thanks to the increase of self-consumption observed in Table 1. Negative cost savings (i.e. increase in energy supply costs) can be still observed in some configurations of Case A due to the increase of the per unit cost C_p of the electricity purchased from the grid by the end-user when PV is installed.

Similarly to the results observed for $E_L = 3500$ kWh, a more favorable condition for the end-user can be potentially obtained in Scenario 2 within Case C where cost savings can increase up to 8.56% due a reduced cost $C_{sc} = 145$ €/MWh. Moreover, Case C has still positive average indicators in southern Italian regions for PV sizes up to 3kWp (see Figure C.29 and C.30), and the $DPBT$ is acceptable for the energy-provider as well, since it is close to 13 years.

A final remark reveals that Case 0 is still the most promising configuration from the economic point of view, when PV sizes are lower than 3 kWp. In fact, in this case the best combination of the economic indicators and cost savings is obtained. Nevertheless, when end-user has scarse economic resources, Case C could represent an interesting opportunity for energy-provider investing in small PV sizes in the southern and central Italian regions, paving the way for a possible diffusion of the SEU scheme also in the residential sector.

6.4. Results overview at national level

Figure 10, 11, 12 and 13 summarize a general overview of the economic results for Italy. These figures represent the national average value of IRR, NPV, $DPBT$ and PCR, respectively, by considering different installed PV sizes, yearly electricity demand and scenarios. As general remark, it can be noticed that the higher the electricity demand, the more profitable is the investment in PV system. For instance, the increase in electricity demand from 2700 to 4000 kWh/year nearly doubles the NPV and the IRR, especially for low PV size (i.e. $\leq$2kWp). In particular, low PV sizes appear the best solution for investing in the solar resource due to the high level of self-consumption potentially achievable.

However, Figure 13 highlights that PV investment is still attractive in scenario 1 with high electricity demand, when PV does not exceed 3kWp, because a fair compromise between the return of the investment (i.e. $IRR \simeq 2.5\%$, $NPV \simeq 60€/\text{m}^2$ and $DPBT \simeq 14$ years) and the energy cost reduction (i.e. $PCR \simeq 55\%$) can be obtained.

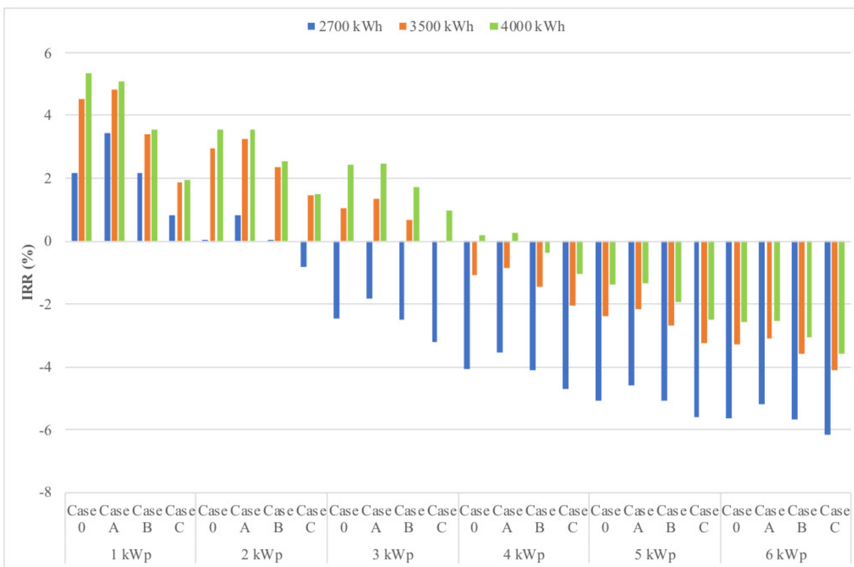


Figure 10: Average IRR for different end-user yearly energy consumption and Scenarios

A similar result can be observed for Scenario 2, but the influence of the price of the PV production sold to the end-user C_{sc} is relevant. In fact, the higher the C_{sc}, the higher the benefits in the PV investment for the energy-providers (see Figure 10, 11 and 12), but the lower the energy costs reduction for the end-users (see Figure 13). Thus, scenario 2 in Case A, B and C under SEU configuration is generally less attractive than scenario 1 for domestic end-users.

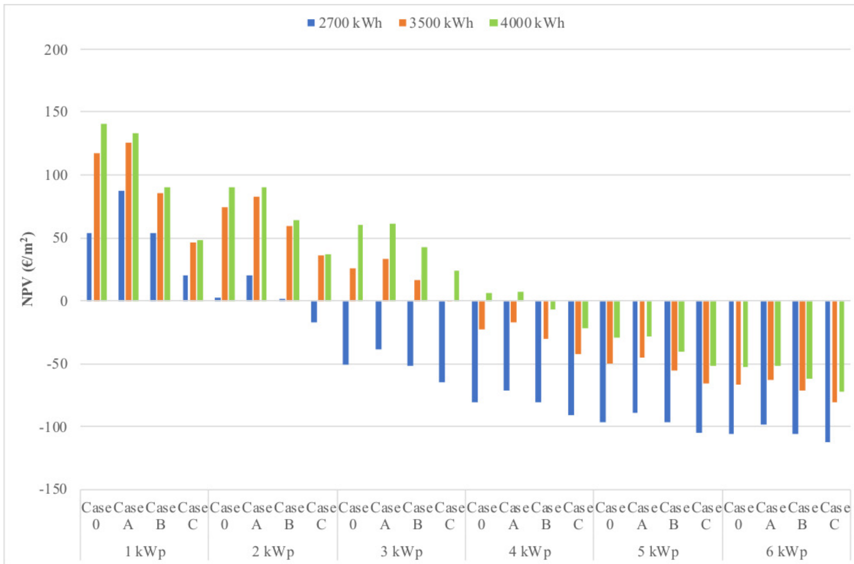


Figure 11: Average NPV for different end-user yearly energy consumption and Scenarios

In case of small PV size (i.e. $\leq$ 2kWp), the sharing of the benefits due to the net-metering contribution between the energy-provider and the end-user could be an option for contributing to make acceptable both higher C_{sc} by residential costumers and the economic drawback by the investors. Alternatively, the possibility of selling, through the distribution network, the electricity produced by PV system to third parties, located near the PV plant, could represent an interesting opportunity. In the next future, the recent development of the EU regulation introducing the concept of the energy communities [3, 52] could introduce this opportunity. This new regulatory framework would allow C_{sc} prices to be lowered potentially less than 145 €/MWh overcoming the existing limit within SEU configuration that is based on one-to-one electricity exchange. In fact, a C_{sc} price reduction could be accepted by investors in this new context (i.e. based on one-to-many electricity exchange), since the PV production could be almost entirely allocated at a higher price than the market zonal ones. Contemporarily, the end-users could benefit of a significant reduction in terms of costs for their energy provision.

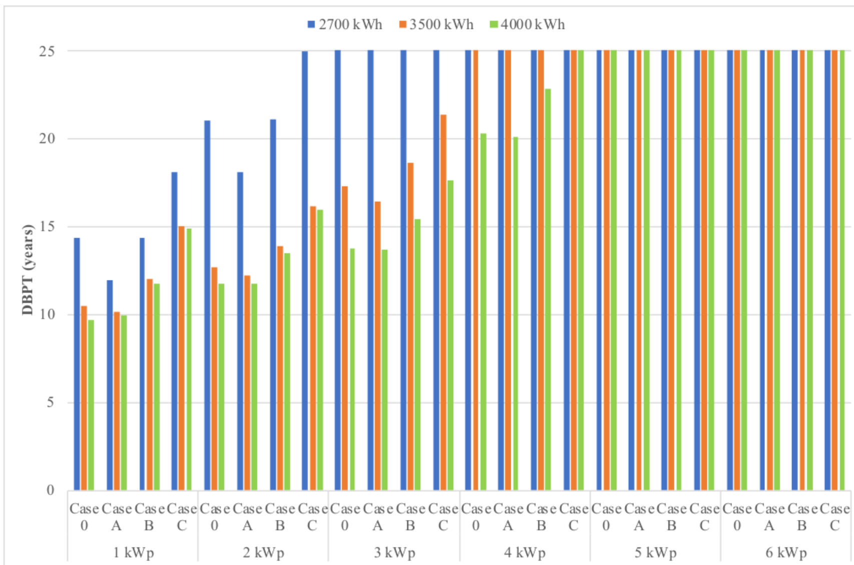


Figure 12: Average $DPBT$ for different end-user yearly energy consumption and Scenarios

As final remark, it can be noticed that the benefits due to the net-metering contribution and to the tax deduction are still decisive for the PV development in the Italian residential sector. In fact, the impact of these incentive schemes mitigates the high installation cost of small size PV plants (up to 20 kWp) making more profitable the investment in PV installation.

6.5. Limits of the study

The results presented in this paper intend to explore the advantages and drawbacks of the diffusion of PV systems in the Italian residential sector taking into account electricity demand, energy costs, incentive schemes and solar radiation availability. Specifically, the analysis are performed through

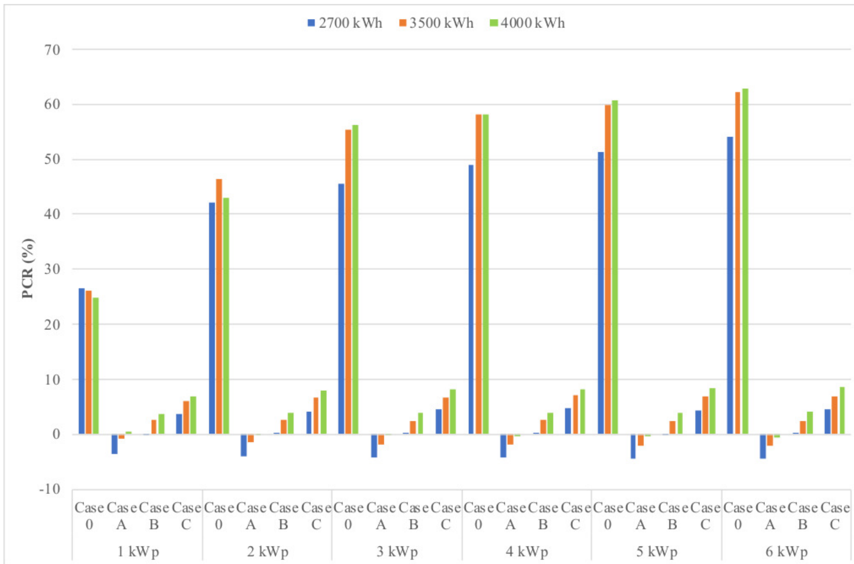


Figure 13: Average PCR for different end-user yearly energy consumption and Scenarios

an energy model based on average yearly values. As a consequence, the main findings and results reported in the previous sections are certainly influenced by this modeling approach.

Firstly, the simplification introduced in section 3 and 5 assumes that self-consumption and self-sufficiency levels are equal for all the residential end-users across the whole country. These values are estimated by considering three different locations (i.e. in the North, Centre and South of Italy, respectively) for the installation of PV system and then extrapolating national average values for Italy. However, load profile for residential end-user as well as solar radiation can vary at different location. For instance, the duration of the daylight hours during a day can change across the country, conditioning the electricity consumption for lighting in households.

Secondly, the influence of temperature variation in the PV production is included within the performance ratio (PR). This simplification assumes that PR is constant across the whole country. However, the efficiency and, consequently, the yearly production of PV modules can change according to the temperature variation at any different location.

Furthermore, due to the energy model introduced in this paper, the economic results are based on average yearly electricity prices, as exposed in section 4. Nevertheless, zonal market prices C_s as well as PUN (i.e. the national average electricity market price) are not constant, since electricity market prices have a typical hourly variation.

Finally, the energy model introduced here limits the analysis of energy storage solutions (e.g. electrochemical battery) to increase self-consumption, self-sufficiency and cost savings. In fact, the impact and sustainability of battery implementation in residential household with PV can be only explored by considering the comparison of the demand and the generation profiles.

For these reasons and limitations, a more complex and detailed modeling could be properly implemented in a future research. In particular, the introduction of an hourly profiles of the solar radiation and the outside temperature could overcome the limits individuated in this research, paving the way for a further discussion on the feasibility of storage solution in residential sector.

7. Conclusion

The paper presents and discusses an energy and an economic analysis for evaluating the possible diffusion of PV installations in Italian residential sector after the closure of the feed-In-tariff support scheme. The analysis was performed by using spatial data of solar resources across Italy and assuming different yearly electricity demands of a residential end-user, as well as different PV sizes. During the economic evaluation, the present Italian supporting scheme for PV (i.e. tax deduction and net-metering) and the new Italian regulatory framework (i.e. the SEU configuration) were also taken into account.

The profitability of PV installation has been evaluated in two different scenarios. The first one (Scenario 1) investigates the profitability of PV installation, when end-user invests its own economic resources for the PV installation and maintenance. Differently, in the second scenario (Scenario 2), the PV installation and maintenance costs are covered by a third-party, like an energy-provider, who sells part of the PV production for suppling residential end-user demand exploring the opportunity of SEU configuration. Under the SEU scheme, the energy-provider and the end-user agreed an appropriate equilibrium price for the energy produced by PV and acquired by the household. Consequently, different possible equilibrium prices were also considered in the economic analysis. Moreover, in Scenario 2, tax deduction and net-metering contribution are supposed to be totally transferred to the energy-provider who bears all the costs for the PV installation and its maintenance.

The results were presented in terms of economic indicators, considering spatial data of the solar resource, the current framework of electricity costs/prices in Italy and the investment costs for PV installation. From these results, it can be noticed that only small PV sizes under Scenario 1 are the most profitable when the yearly electricity demand coincides with the average one for an Italian residential end-user (i.e. 2700 kWh). In fact, low electricity consumption is a negative condition for implementing SEU scheme in Scenario 2, because an increase in the energy supply costs for the end-user is generally observed.

More favorable conditions can be instead observed for situations with an increased yearly electricity demand of about 30% and 50% with respect to the typical one. In this case, PV sizes up to 3 kWp can show positive economic indicators in both Scenarios. In particular, win-win solutions can be observed in Scenario 2 ensuring a positive and a non-negligible costs saving for the residential end-user. This is particularly true for central and southern Italian regions receiving an higher solar radiation that can make possible the exploitation of PV under SEU configuration in all those cases with poor end-user financial resources. In this context, higher payback period are also acceptable for energy-providers since residential sector can be assumed as less risky than industrial and commercial one, where end-user can potentially fail or transfer its activities elsewhere.

However, in both scenarios, the present incentive schemes are still crucial to sustain the diffusion of PV installation in Italian households. Even if the per unit capital cost of PV progressively decreases in EU and in Italy during the last decades, the combination of net-metering and tax deduction are in fact still necessary to compensate the relatively high installation cost for small size PV plants (i.e. $\leq$ 10 kWp). This is the case of other EU context with reduced electricity costs or solar radiation availability, where lower cost savings and economic benefits can be expected by the self-consumption of the renewable distributed generation. Nevertheless, the recent upgrade of the regulatory framework at EU level introduces the concept of energy communities. This novel regulatory subject could be potentially a boost for the diffusion of PV in Italian and EU residential sector. In fact, passing from a one-to-one to a one-to-many energy exchange rules, the application of SEU configuration could be potentially extended and became more attractive for investors reducing the electricity sold to the grid at a price lower than the market one, increasing the electricity sold to residential end-users and, consequently, promoting the local self-consumption of the distributed generation.

An increase of PV diffusion can be also potentially expected in context with higher electricity demand, for instance in all those cases where electrification of the energy consumption is widely diffused. The implementation of renewable distributed generation can potentially also contribute in decarbonizing electricity consumption. For this reason, possible future work will consider, for example, the shift of the energy demand for space heating under the electricity energy vectors (i.e. decarbonization) through the diffusion of heat pump in the Italian residential sector.

Finally, according to the energy model presented in this paper, similar analysis could be potentially performed in other contexts (i.e. countries) taking into account electricity demand, energy costs, incentive schemes, solar radiation availability and the regulatory framework. In addition, a more complex modeling will be properly implemented in a future research for taking into account the hourly profiles of the solar radiation at each raster cells paving the way for a further discussion on the feasibility of storage solution in residential sector.

Appendix A. Results for $E_L = 2700$ kWh

Appendix B. Results for $E_L = 3500$ kWh

Appendix C. Results for $E_L = 4000$ kWh

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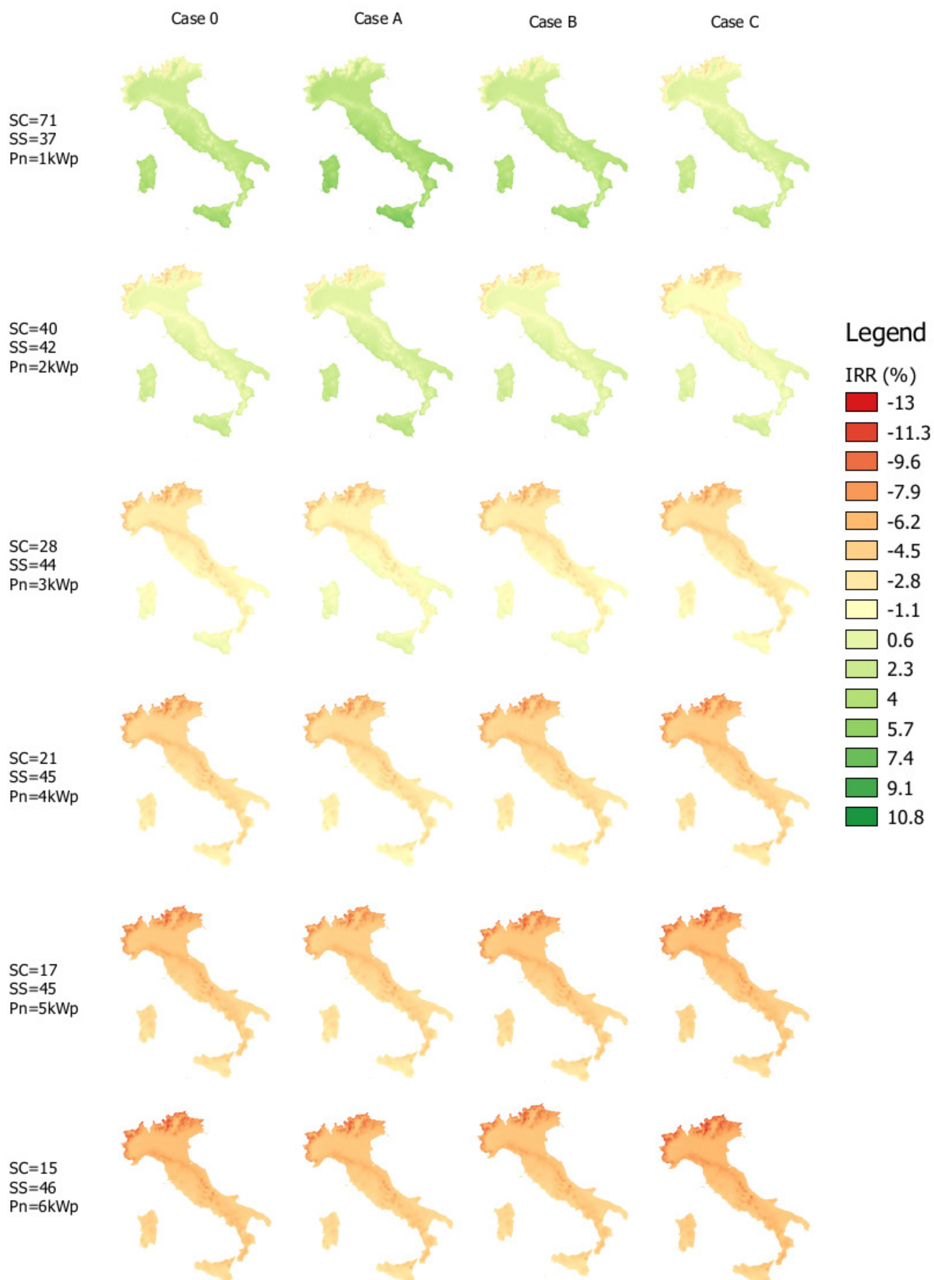

Figure A.14: Maps of IRR for $E_L = 2700$ kWh.

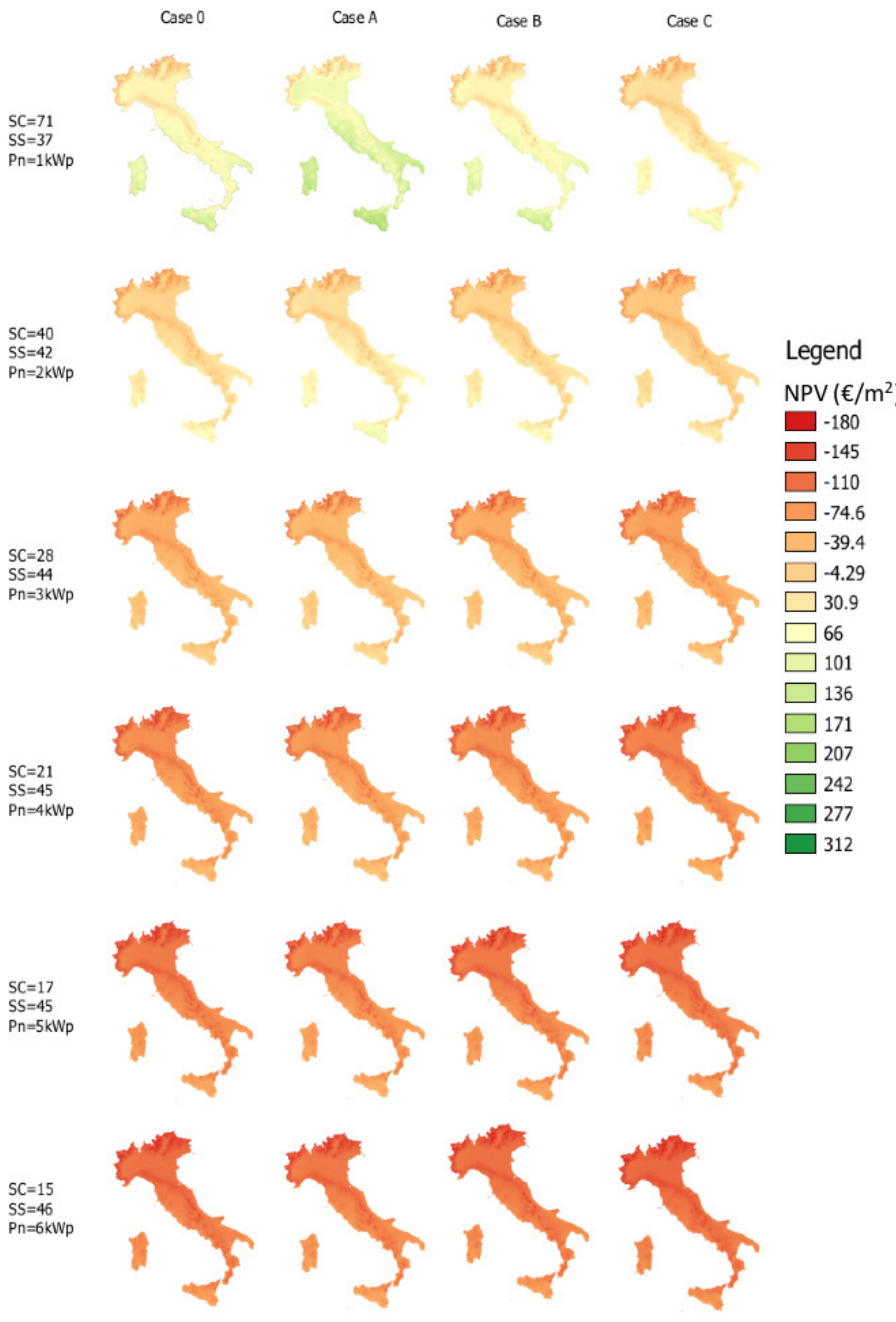

Figure A.15: Maps of NPV for $E_L = 2700$ kWh.

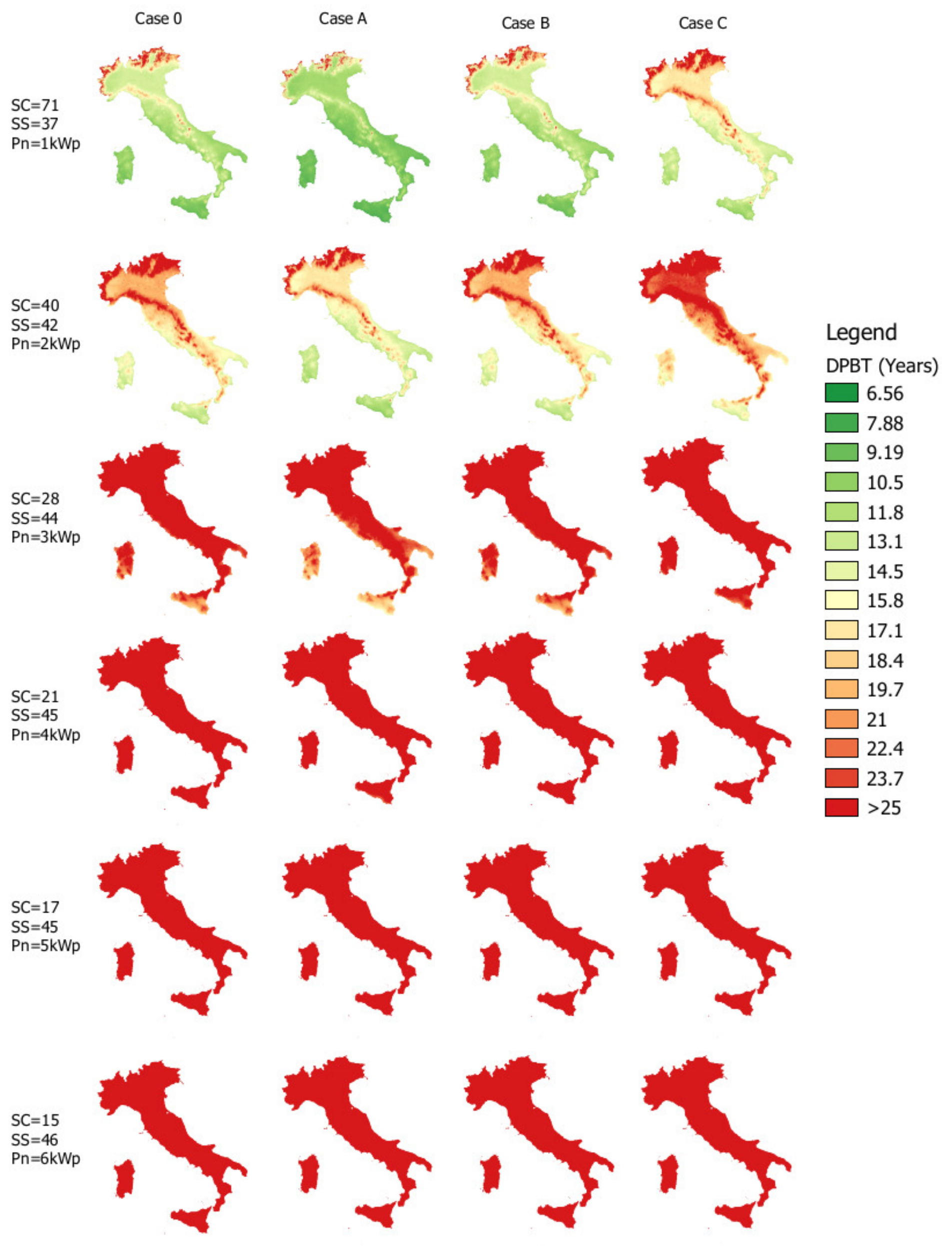

Figure A.16: Maps of $DPBT$ for $E_L = 2700$ kWh.

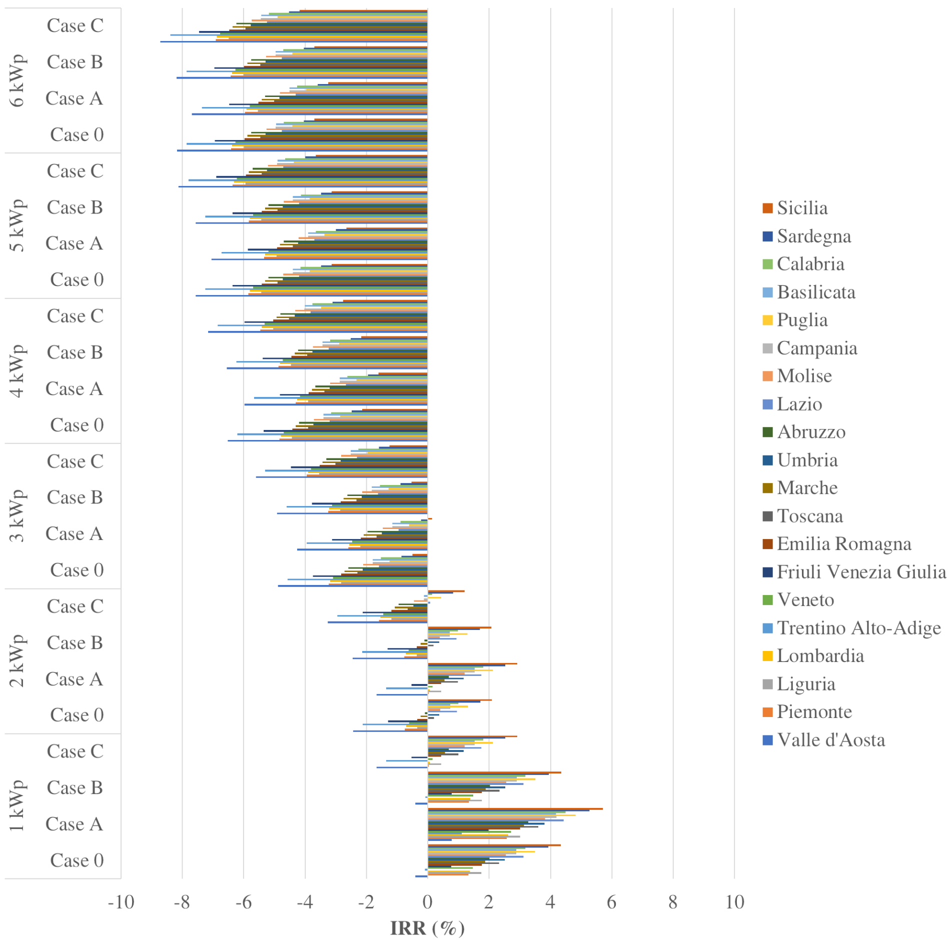

Figure A.17: Regional average of IRR for $E_L = 2700$ kWh.

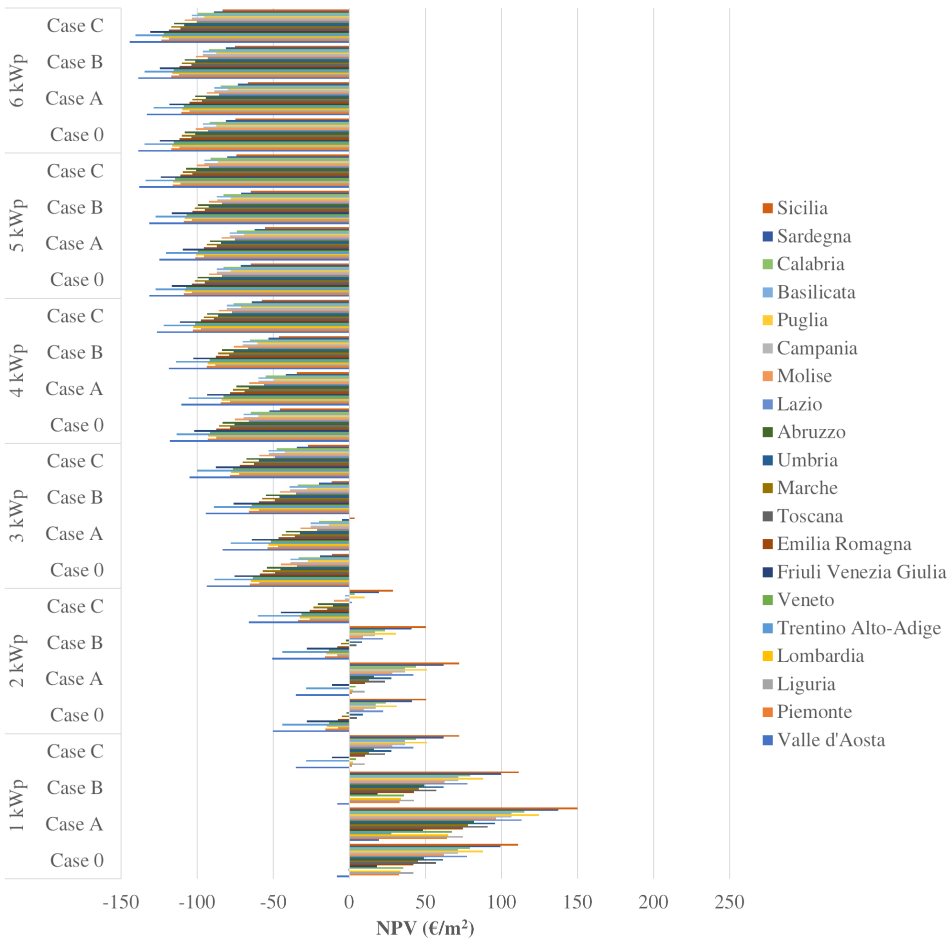

Figure A.18: Regional average of NPV for $E_L = 2700$ kWh.

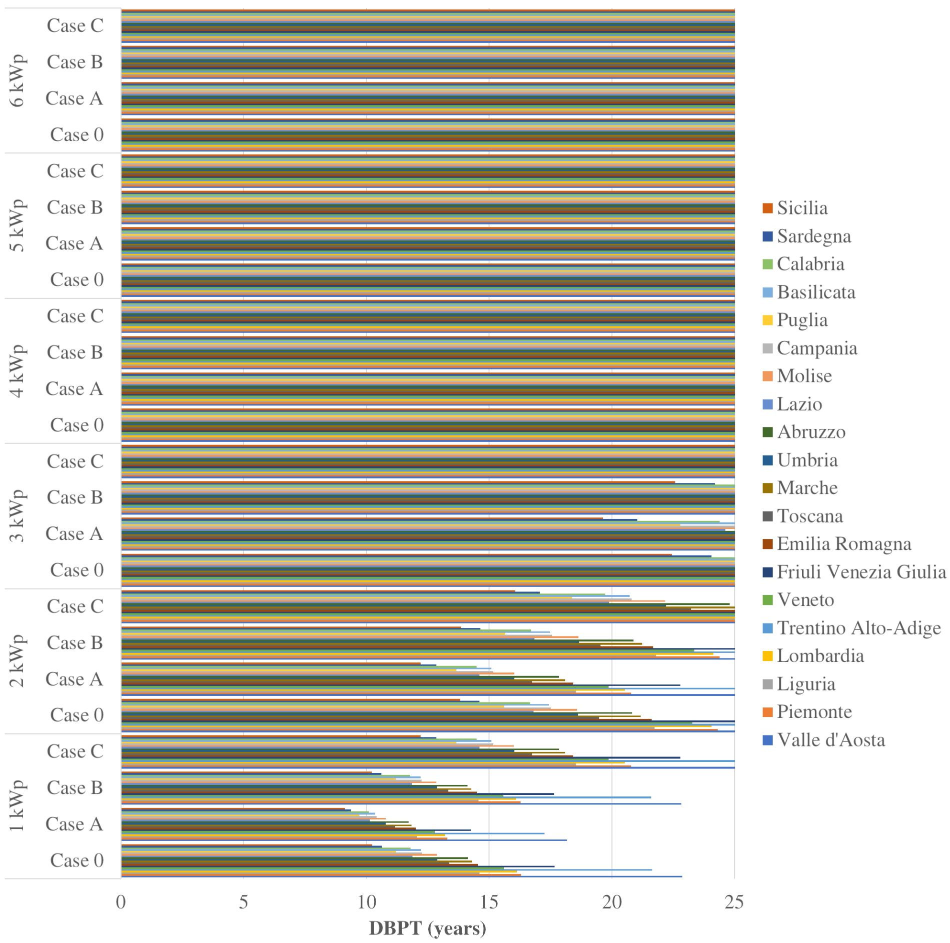

Figure A.19: Regional average of $DPBT$ for $E_L = 2700$ kWh.

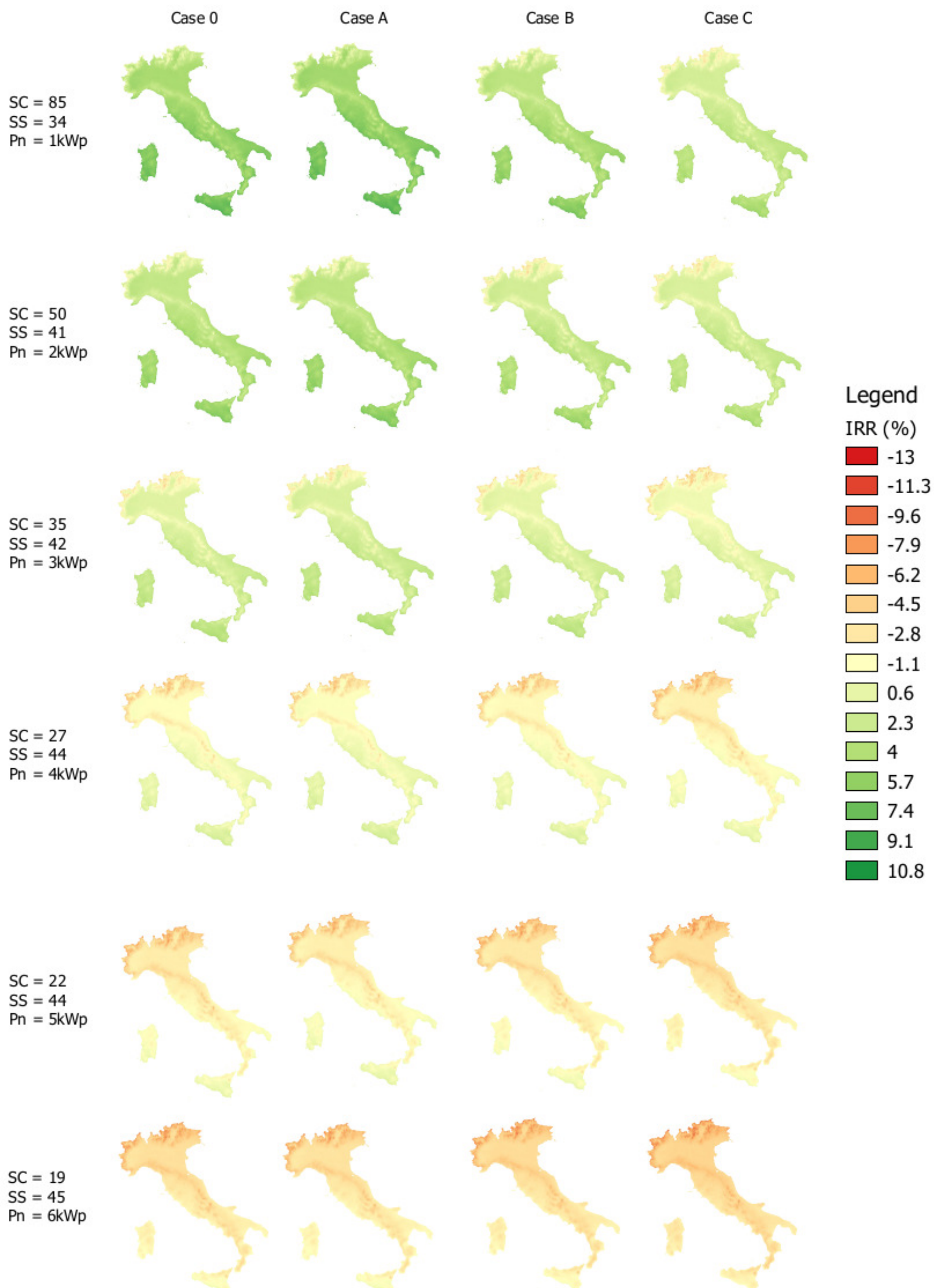

Figure B.20: Maps of IRR for $E_L = 3500$ kWh.

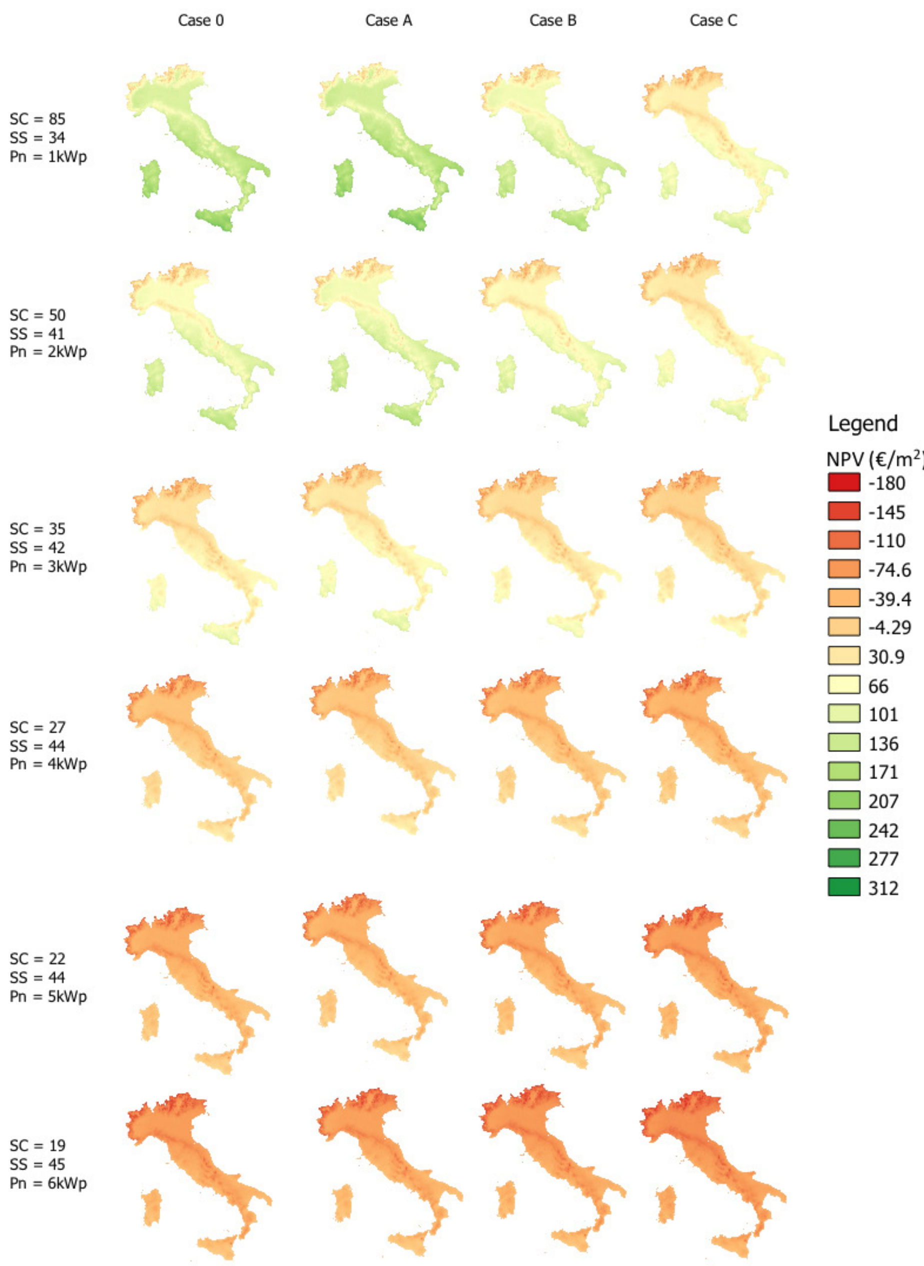

Figure B.21: Maps of NPV for $E_L = 3500$ kWh.

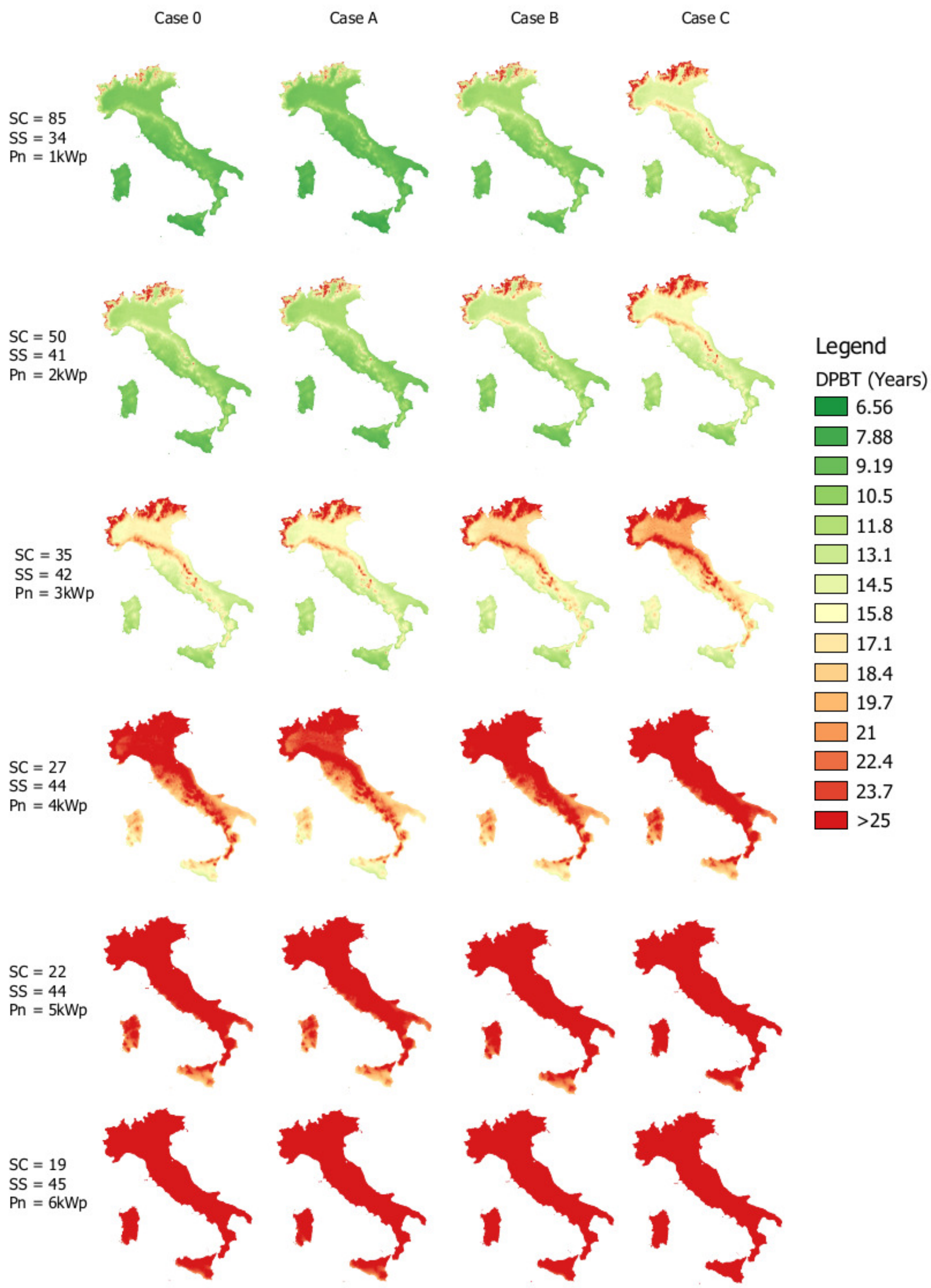

Figure B.22: Maps of $DPBT$ for $E_L = 3500$ kWh.

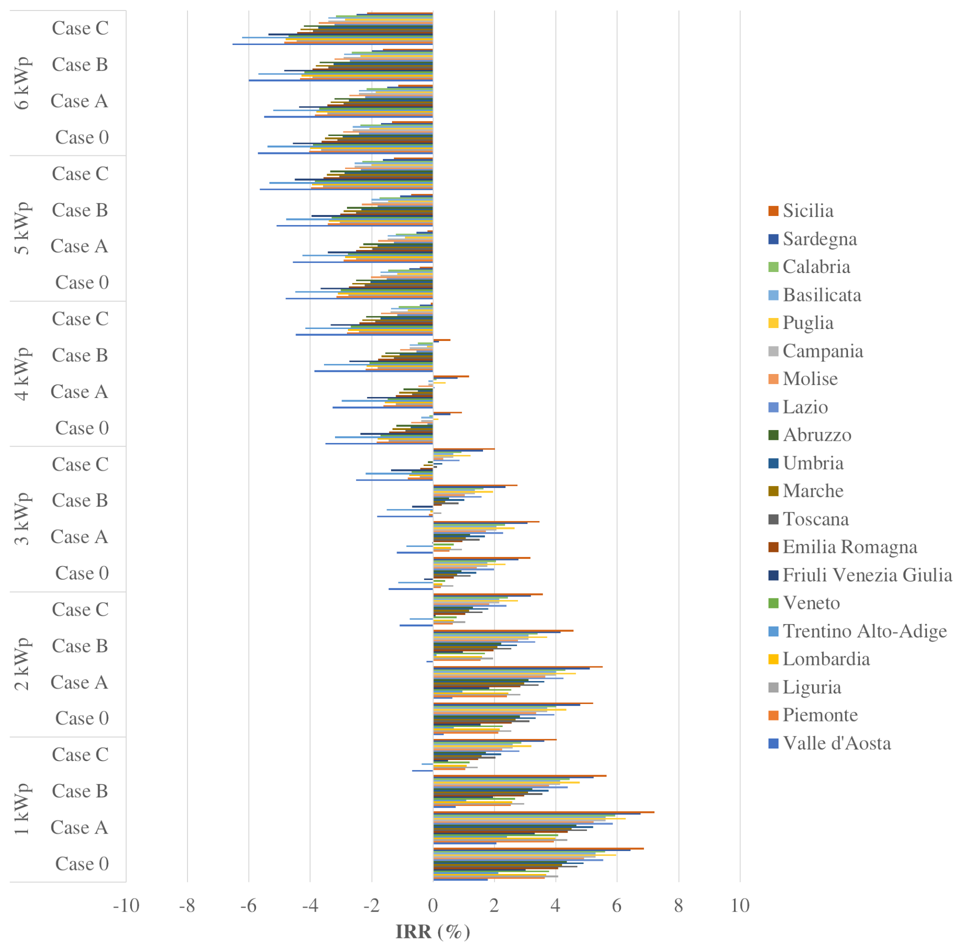

Figure B.23: Regional average of IRR for E_L = 3500 kWh.

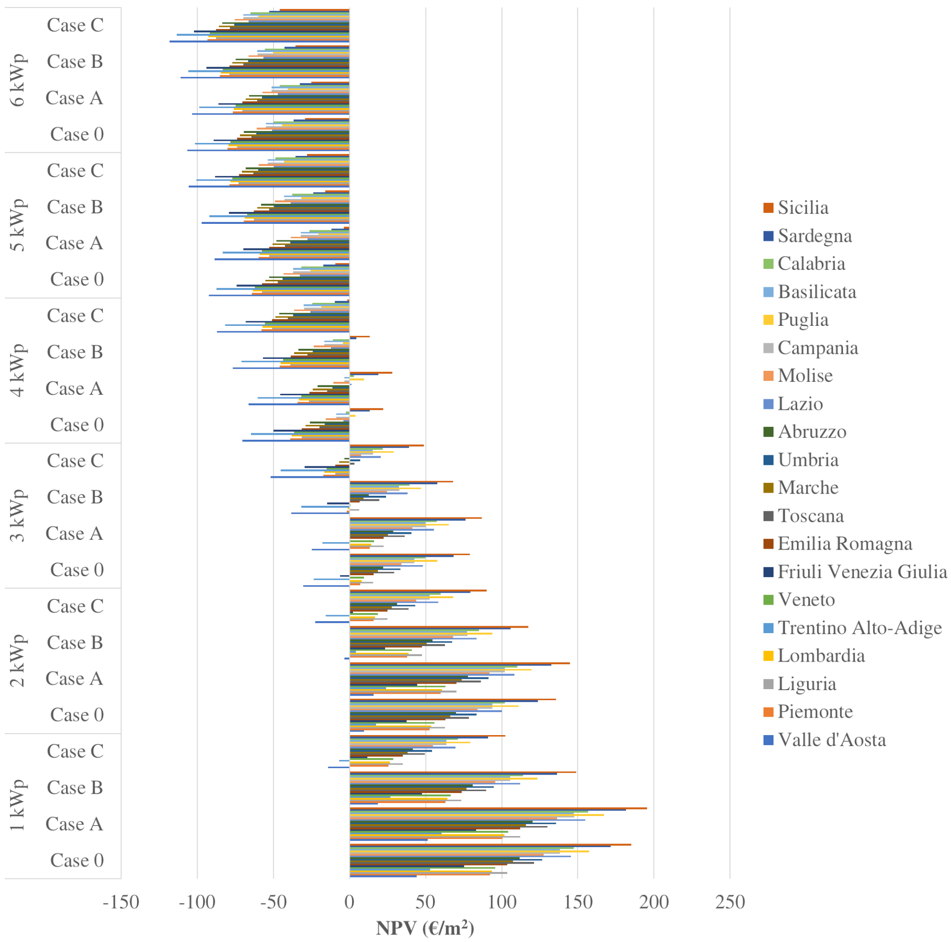

Figure B.24: Regional average of NPV for $E_L = 3500$ kWh

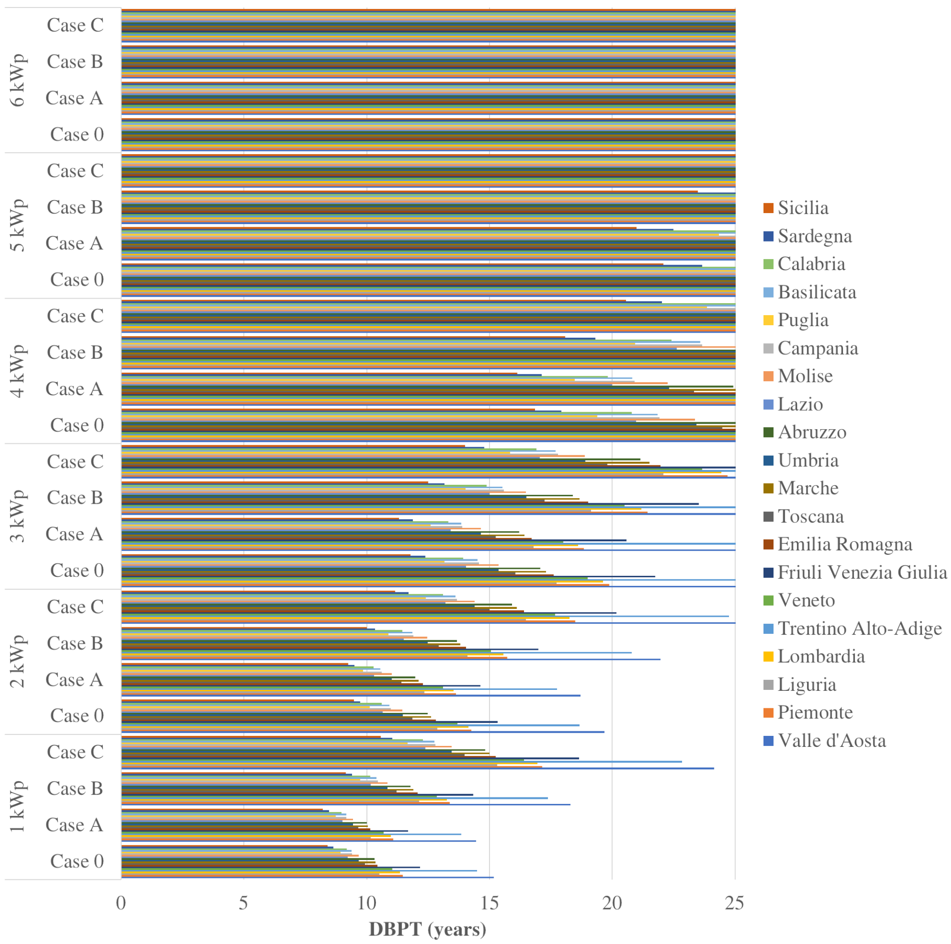

Figure B.25: Regional average of $DPBT$ for $E_L = 3500$ kWh.

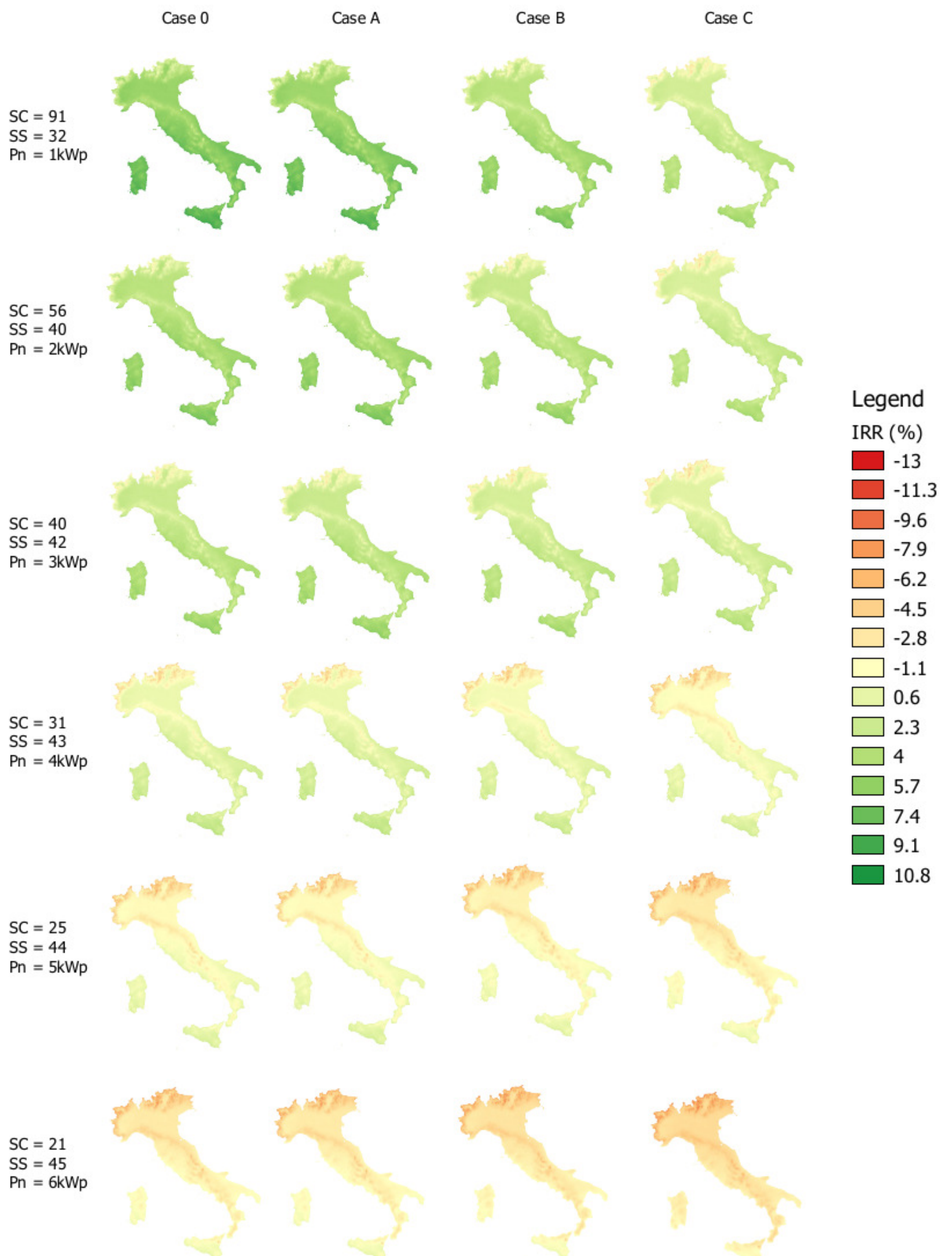

Figure C.26: Maps of IRR for $E_L = 4000$ kWh.

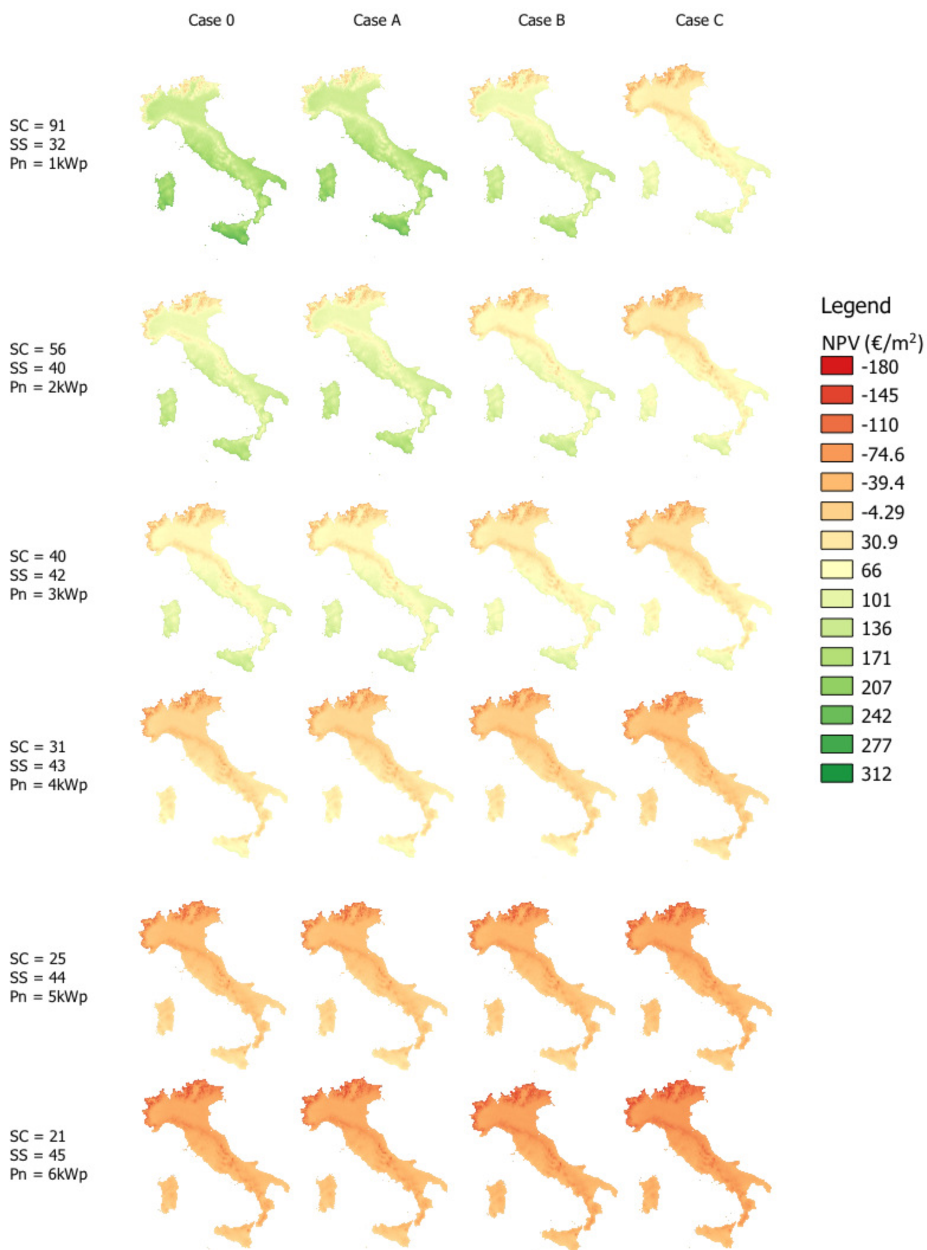

Figure C.27: Maps of NPV for $E_L = 4000$ kWh.

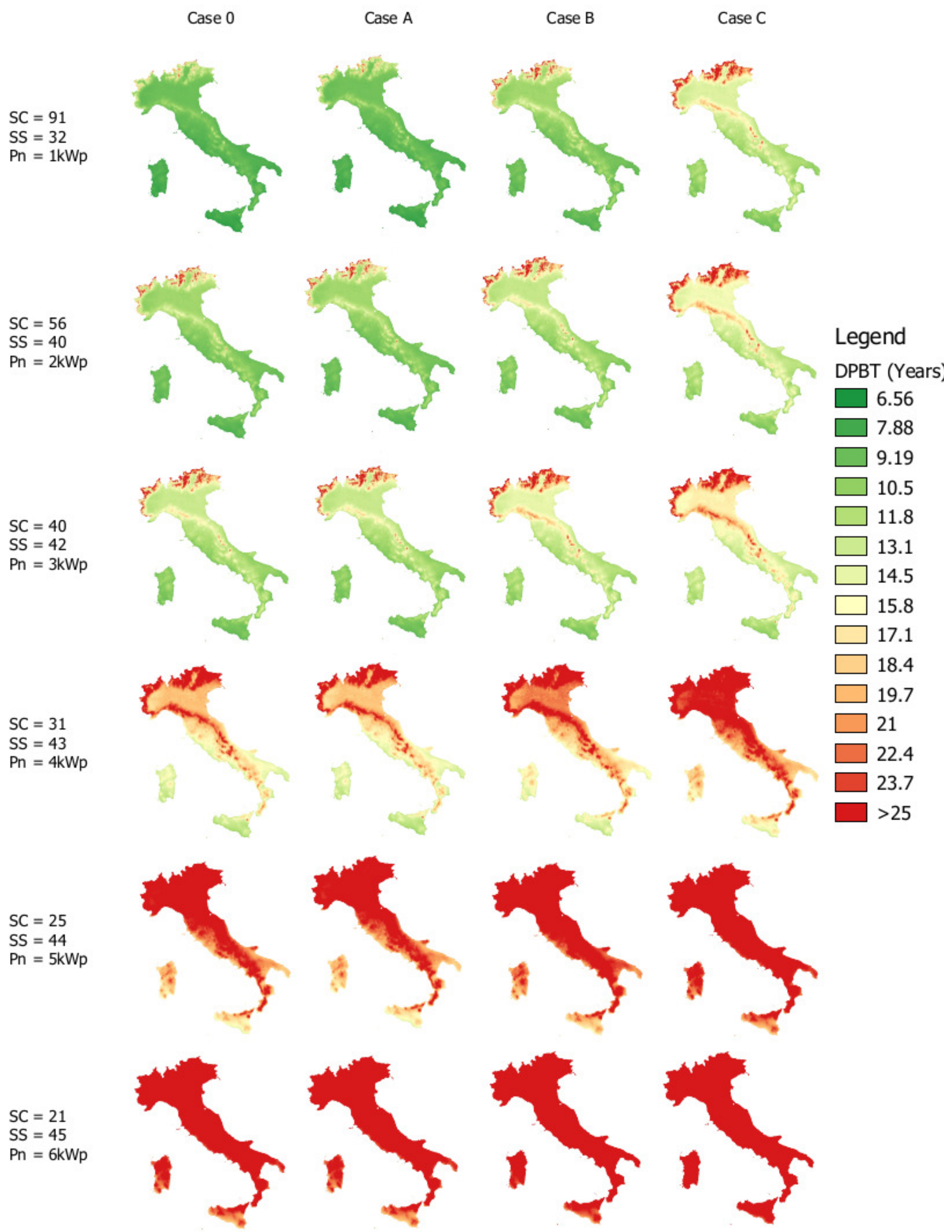

Figure C.28: Maps of $DPBT$ for $E_L = 4000$ kWh.

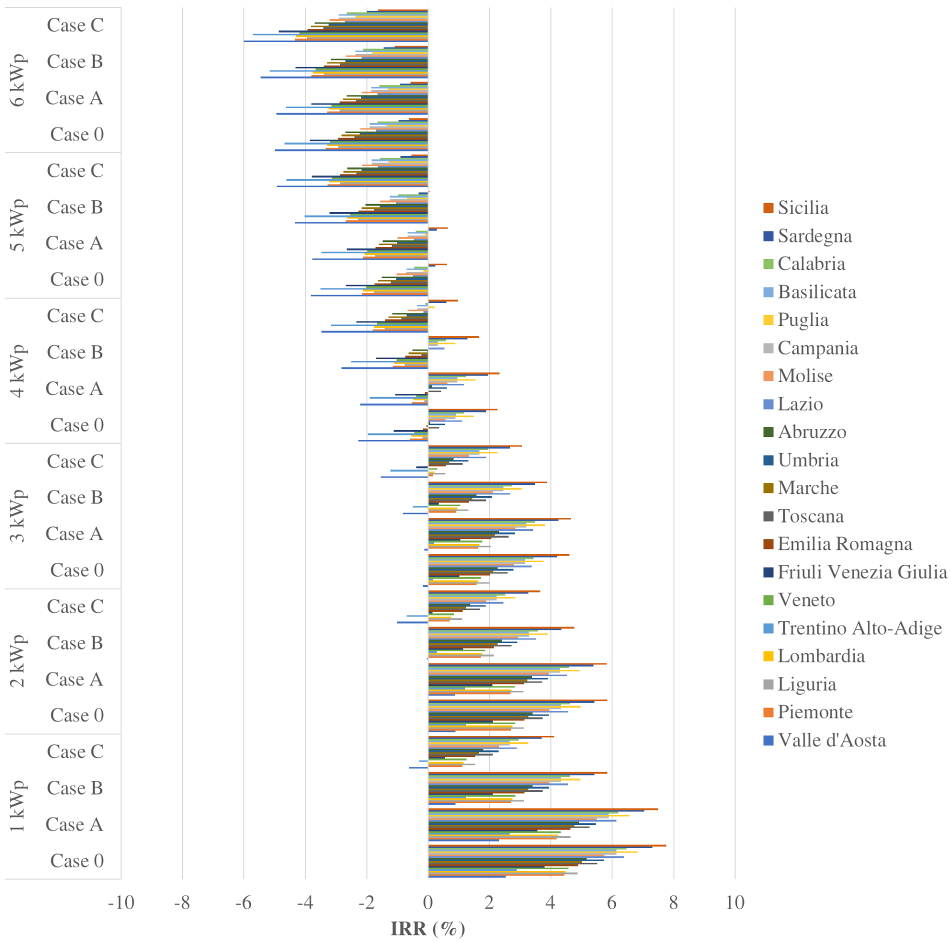

Figure C.29: Regional average of IRR for $E_L = 4000$ kWh.

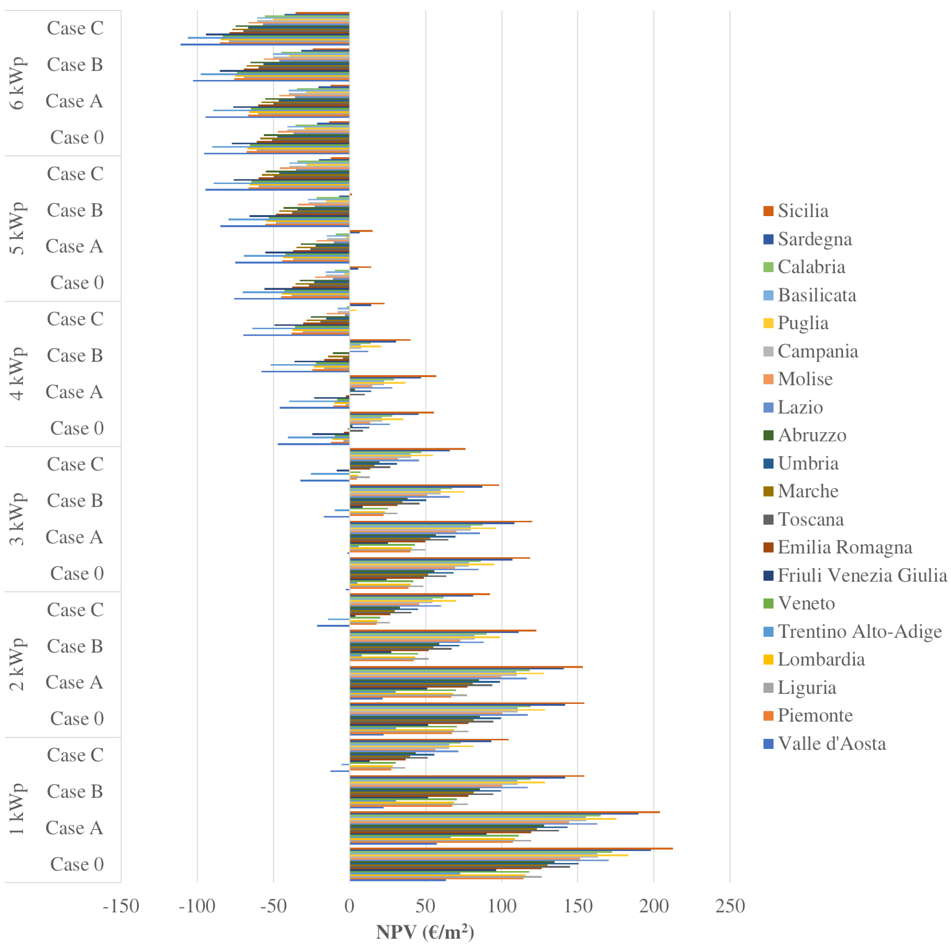

Figure C.30: Regional average of NPV for $E_L = 4000$ kWh.

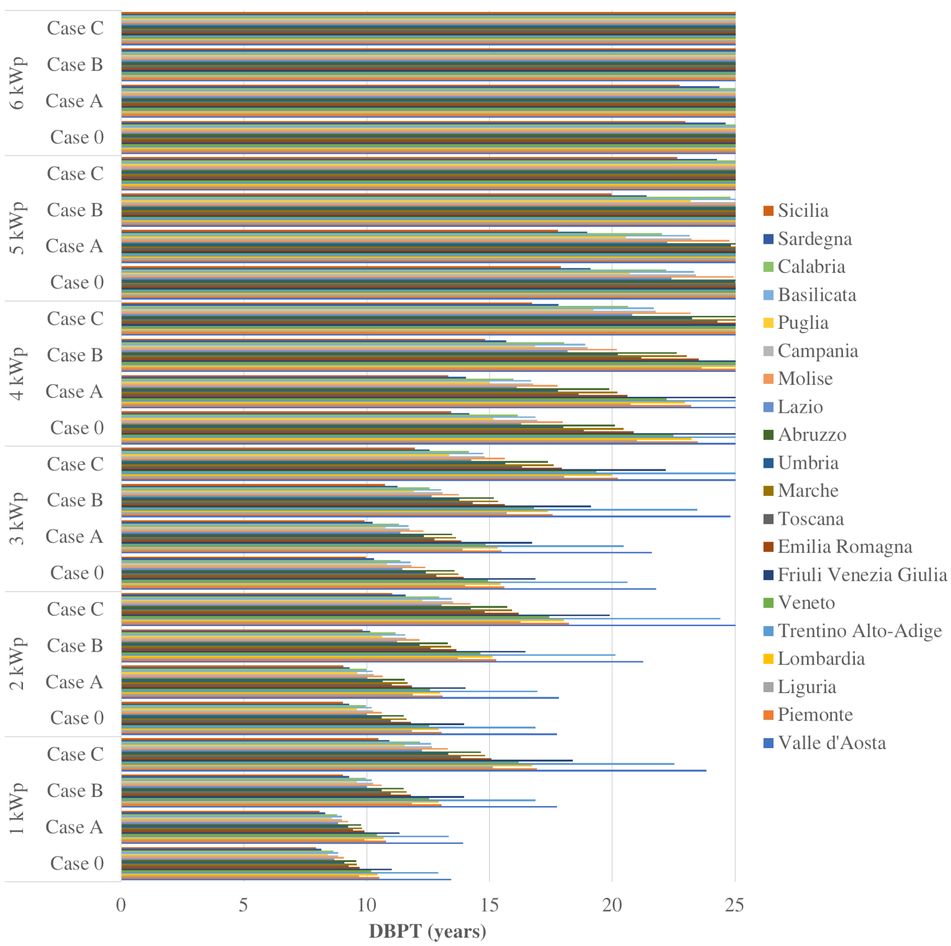

Figure C.31: Regional average of $DPBT$ for E_L = 4000 kWh.