Trade-off between photovoltaic systems installation and agricultural practices on arable lands: an environmental and socio-economic impact analysis for Italy

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Abstract

The paper introduces and discusses an open-source spatial-based model (called *r.green.solar*) able to quantify the energy production from solar photovoltaic (PV) ground-mounted panels. Socio-economic and environmental impacts can be evaluated by the model. The model starts from the theoretical quantity of solar PV potential energy and estimates a reduction of total amount of energy based on legal, technical, recommended and economic constraints. Model outputs were used for a trade-off analysis between energy production and traditional crops for food/feed cultivation on not irrigated arable land. The model was tested at regional level for a Mediterranean context (Italy). The results confirm that the economic profitability of PV systems follows a north-south gradient, but the main impacts are related to local peculiarities - such as the disposal of not irrigated arable land and the presence of constraints, in particular the landscape maintenance, the morphological variables and the specialization index - and crop yields.

Keywords: solar energy; spatial analysis; open-source model; sustainability constraint; crop production; trade-off evaluation.

1. Introduction

In order to cope with negative effects of climate change, several political measures and actions have been applied worldwide in recent years. Normative rules have been particularly focused on the reduction of carbon dioxide emissions and substitution of fossil fuels with renewable energy (RE) sources. In this sense, the European Commission released the Directive 2009/28/EC on the promotion of the use of energy from renewable sources. This Directive – also known as 20-20-20 strategy – reports on mandatory national targets and measures for the use of energy from renewable sources, highlighting at the same time the need of national RE action plans. Despite to date several environmental and socio-economic benefits have been recognized to RE, in the recent scientific literature a growing interest is given to the evaluation of potential negative impacts as well as integrated analysis (see e.g., Valodka and Valodkienė, 2015; Bilgili et al., 2016). Taking into account the Directive 2009/28/EC, sustainability criteria for RE production are strictly defined only for biofuels and bioliquids. However, also the other RE sources (i.e. geothermal, hydropower, wind and solar power) can affect a specific production and/or consumption areas in ecological, social and economic terms. Particularly, these RE sources can have significant impacts on certain Ecosystem Services (ESs). To cope with risk of negative impacts, a number of studies and models have been carried out, paying particular attention to biomass/biofuels production (see e.g. Verkerk et al., 2011; Dominik and Rainer, 2014; Upham and Smith, 2014), wind power (Kouloumpis et al., 2013; Yuan et al., 2015), hydropower (Daini, 2000; Chen et al., 2015) and solar energy (Kaygusuz, 2009; Wanderer and Herle, 2015).

One of the first ~~study~~studies focused on assessment of the potential impacts of solar energy was developed by Neff (1981). In that work, the author pointed out some important relationships between the implementation of photovoltaic (PV) technology and the consequences on public occupational safety and health. A particular emphasis was given to the indirect effects on labor market as well as to environmental consequences. In this sense, land use, thermal and climatic effects and emissions were identified as relevant issues to be evaluated. A balance in positive and negative impacts of solar PV energy was defined in Swapnil Dubey et al. (2013), by a categorization of consequences in different classes: i) land use and landscape, ii) infrastructure, iii) political, iv) energy market, v) industry, R&D, education and vi) public & marketing. More insights about large-scale PV plants were given in Phillips (2013). The author depicted how the PV systems can be conducive to achieving a high level of sustainability, compared to traditional energy sources for both construction and operation phases. Detrimental effect could be revealed for few wildlife species (i.e. for flight hazards). Neutral impacts were defined for other features such as visual aesthetics, land occupation or habitat fragmentation. In addition, unknown effects were highlighted by the author, in particular related to soil and water impact as well as to local climatic variation (change in surface albedo and other surface energy flows). Life Cycle Assessment (LCA) approach – including disposal, and/or recycling phase of panels – is another applied methodology for PV impact appraisal (see e.g. Fthenakis and Chul Kim, 2009; Turconi et al., 2013; Dubey et al., 2013). A recent approach deals with the analysis of PV impact on ESs following the classification proposed by the Millennium Ecosystem Assessment (Hastik et al., 2015).

A literature review about territorial and landscape impacts for solar power plants was implemented by Chiabrando et al. (2009)~~-~~, with a real application for ground-mounted PV. Among different potential negative effects the authors introduced an in-depth~~-~~ assessment of glare risk due to panels. Zanon and Verones (2013) stressed the risk of PV conflicts on the use of fertile areas or the impact of technical equipment on the landscape. Public perception of PV systems was investigated by Tsantopoulos et al. (2014) in Greece with resulting environmentally-friendly, sustainable and socially acceptable opinions for this RE from citizens. Heras-Saizarbitoria et al. (2011) investigated the public acceptance of PV solar energy in Spain through the role played by the media. However, as shown in Brudermann et al. (2013), although some decision makers – such as farmers – usually have rather strong eco-attitudes and ethical considerations about PV systems implementation, these factors do not seem to be good predictors with respect to the adoption of PV technology.

An awkward problem concerning ground-mounted PV plants is often depicted in land use competition with crop production. Some ~~studies shown~~studies showed the importance of site characteristics for trade-off analysis: for example, soil fertility or type of agricultural land (arable land, marginal land etc.) were considered with different degrees of suitability for PV energy production/crop cultivation (Nonhebel, 2005; Sliz-Szkliniarz, 2013; Calvert and Mabee, 2015). A PV energy ~~Vs~~vs. food trade-off was analysed in Nonhebel (2005) stressing the yield importance of different locations. The evaluation of ground-based PV applications related to land quality were carried out in a GIS-based model of Sliz-Szkliniarz (2013). In a study by Calvert and Mabee (2015) market parameters - energy density as well as potential electricity production - were chosen as key elements to establish a trade-off analysis between solar energy and energy crops cultivation on marginal land in Ontario (Canada). Optimization techniques such as the agrivoltaic system, implemented by means of Land Equivalent Ratios, were applied to combine in a same area PV

plants and agriculture production in order to maximize total energy efficiency (for both solar panel and crops) (Dupraz et al., 2011).
As outlined in the literature, a consistent number of scientific works concerning potential conflict between PV plants and agricultural production was depicted. Nevertheless, the examination of the above mentioned studies denotes the presence of a few flexible and updatable Decision Support Systems (DSS) suitable for analysis at different scale, in different contexts and with diverse input dataset available to decision makers.
In this framework, the paper continues our previous works (Sacchelli et al., 2013; Garegnani et al., 2015) whose objective was to implement and test a new Geographic Information System (GIS) based model named *r.green* (http://www.recharge-green.eu/approach/). This model is carried out with ~~a modular and multistep procedure that enable~~a modular and multistep procedure that enables the quantification of energy from theoretical to economic. Reduction of energy availability can be taken into account through the evaluation of potential impacts on ESs. To date the *r.green.biomassfor* (Zambelli et al., 2012; Sacchelli et al., 2013; http://grass.osgeo.org/grass70/manuals/addons/r.green.biomassfor.html) and *r.green.hydro* (Garegnani et al., 2015; http://grass.osgeo.org/grass70/manuals/addons/r.green.hydro.html) sub-models are available as add-ons for Quantum GIS and GRASS GIS software; these DSSs are focused on forest biomass for energy production and hydropower analysis, respectively.
Specifically, the aim of this work was to develop and apply the *r.green.solar* sub-model focused on the quantification of sustainable energy from fixed ground-mounted photovoltaic (PV) panels, in order to make the DSS freely available in add-on repository of Quantum GIS and GRASS GIS softwares. The *r.green.solar* outputs were used to develop a trade-off analysis between traditional agricultural production and implemented PV plants on arable land by the integration of spatial analysis and economic indexes.

2. Methodology

Due to the fact that Mediterranean area is one of the most promising for solar energy availability in Europe, Italy was chosen as case study with a focus at a regional level (Fig. 1).

Fig. 1 Study area

The work was developed in three phases. In the first phase the *r.green.solar* model was implemented as bash scripts able to quantify electric solar energy availability classified in:

- ~~theoretical~~Theoretical;
- ~~legal~~Legal;

- ~~technical~~Technical;
- ~~recommended~~Recommended;
- ~~economic~~Economic.

In the second phase the economic profitability of agricultural food and feed production on arable lands for each region, was analyzed. Eventually, performance of PV plant as well as trade-off and potential conflict among PV plants and traditional agricultural practices were estimated according to following indicators, as better explained in section 2.2:

- Net Present Value for PV plants;
- Net Present Value for agricultural production;
- Internal Rate of Return for PV plants;
- Safety Margin of solar electric energy price;
- ~~potential~~ Potential crop losses in case of PV panels installation on arable lands.

The general framework of the work is reported in Fig. 2.

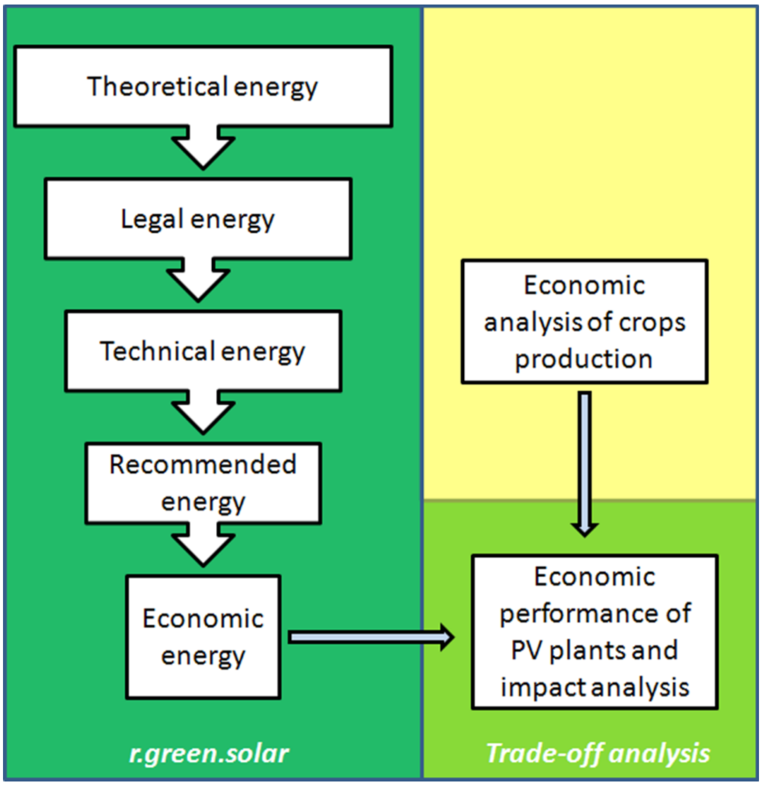

Fig. 2 General framework of the work

As a matter of fact the Directive 2009/28/EC was adopted by Italy in 2010, with a National Renewable Energy Action Plan (NREAP). According to the NREAP, the main support mechanism for electricity production from PV plants was the feed-in tariff mechanism (*Conto Energia*). This mechanism provides a sequential reduction up to 2013. Since 2013, PV incentives stopped and only tax deduction as well as facilitation for self-consumption have been maintained. However, despite the few possibilities to implement ground-mounted PV panels on arable land nowadays, a great number of PV plants have been realized. In other terms, developed impact analysis represents a spatial evaluation suitable for both implemented PV systems and potential future application.

Nomenclature

η_{Theo}	conversion efficiency related to the Carnot efficiency limit (%)	p	market price of PV energy (€/MWh)
S_{EN}	total solar energy (kWh/m^2 year^{-1} per each kWp of installed power)	inc	additional optional incentives for PV energy (€/MWh)
TH_{EN}	theoretical energy (MWh/pixel year^{-1})	RPV	revenues present value for PV plants (€/pixel)
$nsres$	north-south resolution of raster map (m)	CPV	costs present value for PV plants (€/pixel)
$ewres$	east-west resolution of raster map (m)	NPV_{PV}	net present value for PV plants (€/pixel)
LE_{EN}	legal energy (MWh/pixel year^{-1})	r	discount rate (%)
AL	pixel classified as not irrigated arable lands (code 2111 of IVth level Corine Land Cover)	d	yearly decay of performance of photovoltaic modules (%)
LC	pixel classified as areas with landscape constraint	lc	life cycle for PV plants (years)
NA	pixel included in protected areas	P	installed PV power (MW/pixel)
TE_{EN}	technical energy (MWh/pixel year^{-1})	u	unit cost for fixed ground-mounted PV panels installation (€/MW)
k	actual net available surface for PV plants installation (%)	i_C	purchase and installation cost for PV plants (€/pixel)
η	PV plant efficiency (%)	g_C	cost for PV plants connection to electric grid (€/pixel)
sl	slope (%)	R_{AL}	cost for rent of not irrigated arable land (€/ha year^{-1})
alt	altitude (m asl)	r_C	surface rent cost (€/pixel year^{-1})
m	municipality	m_C	maintenance cost for PV plants (€/pixel year^{-1})
r	region	c_C	cleaning cost for PV plants (€/pixel year^{-1})
$NIAL_m$	municipal surface of not irrigated arable land (ha)	a_C	administrative and consultancies costs for PV plants (€/pixel year^{-1})
$NIAL_r$	regional surface of not irrigated arable land (ha)	s_C	insurance cost for PV plants (€/pixel year^{-1})
AAS_m	municipal surface of total available agricultural surface (ha)	d_C	decommissioning cost for PV plants (€/pixel)
AAS_r	regional surface of total available agricultural surface (ha)	x	specific crop
RE_{EN}	recommended energy (MWh/pixel year^{-1})	NR	net revenues for crop (€/ha year^{-1})
FR	pixel classified as high flood risk	GAP	gross agricultural production (€/ha year^{-1})
LR	pixel classified as high landslide risk	C	cost for crop production (€/ha year^{-1})
ER	pixel classified as high earthquake risk	NPV_X	net present value for crops (€/ha year^{-1})
REV	revenues from PV energy selling (€/pixel year^{-1})	rot	rotation period for crop (years)

2.1 Implementation of r.green.solar model

The GIS-based tool computes a multistep procedure to quantify solar PV energy, taking into account -the legal, technical, recommended and economic constraints. The first step was dataset integration. The model automatically imports the variables (Tab. 1) and transforms them into a raster map (in case of shapefile format) with a specified pixel resolution. Numerical values related to spatial-~~indipendent~~independent coefficients applied in the case study, were reported in Appendix.

Table 1
Input dataset.

Variable	Variable typology
Solar radiation	Raster
Digital Terrain Model (DTM)	Raster
Corine Land Cover map	Raster
Landscape constraints	Shapefile
Natural protected areas	Shapefile
Flood risk	Shapefile
Seismic risk	Shapefile
Landslide risk	Shapefile
Arable land specialisation index	Shapefile
Roads	Shapefile
Regions boundary	Shapefile

Theoretical energy derives from Photovoltaic Geographical Information System (PVGIS, www. re.jrc.ec.europa.eu/pvgis), a spatial-based assessment of solar electric energy resource from PV systems in Europe, Africa, and South-West Asia (Šúri et al., 2007; Huld et al., 2012). Those data are obtained from the application of *r.sun* module of GRASS GIS tool (see e.g. Nguyen and Pearce, 2010) and represent long-term yearly averages, based on satellite data retrieval for global irradiation on an optimally-inclined surface (period 1998-2011). Theoretical energy was computed by transformation of original data from PVGIS into equivalent energy per *i-th* pixel (expressed in MWh/year) taking into account the physical laws. In our case, resolution was set to 100x100m for a pixel surface of 1 ha, in order to balance output detail and computational time of the model.
Most solar cells on the market are based on silicon wafers and the upper theoretical was studied by Shockley and Queisser (1961). An optimal cell with a band gap of 1.3 eV is limited by transmission losses of photons to 31% (310 $W_p m^{-2}$).
If we do not consider the current technology, according to thermodynamic laws, the conversion efficiency is related to the Carnot efficiency limit, which is nearly 95% (Green, 2002). Notice that the Carnot limit is only a theoretical limit and cannot be built in practice with technology currently available. This limit is then the uppermost value that it can be theoretically reached (Eq. 1).

$$TH_{EN_i} = \eta_{Theo} \cdot S_{EN_i} \cdot nsres \cdot ewres / 1000 \qquad [1]$$

Legal energy was depicted as the amount of theoretical energy available on exploitable surfaces from a normative point of view. According to these premises, suitable areas for PV plants implementation (in our case not irrigated arable land) were highlighted from Corine Land Cover Map (European Environment Agency, 2010); a limit of 10% of total available surface was applied based on Italian Legislative Decree 28/2011. Spatial constraints were then defined to depict inappropriate areas. A visual aesthetic limit was applied by the introduction of the national landscape constraints map (SITAP, 2015) as well as avoiding the insertion of PV panels in natural protected areas including national, regional and provincial parks, national and provincial reserves, natural protected areas of local interest as well as Natura 2000 network sites (National Cartographic Portal, 2015). It is worth mentioning how additional constraints could be defined in regional laws and regulations (e.g. constraints for PV systems implementation are depicted for Protected Designations of Origin and Protected Geographical Indications territories). However, due to the lack of uniform data at regional level for Italy and to implement a precautionary evaluation of PV energy impact due to crop substitution, regional and sub-regional legal constraints were not introduced. Legal energy was defined as in equation 2.

$$LE_{EN_i} = TH_{EN_i} \text{¿} \forall i \in (AL \wedge \neg LC \wedge \neg NA) \text{¿} \quad [2]$$

Technical energy takes into account actual PV plants available surface, morphological characteristics and solar cell efficiency. In particular, shadow effect and space for maneuver were considered by depiction of a suitable percentage on total surface (Calvert and Mabee, 2015; Karaveli et al., 2015). Upper limits for terrain slope and altitude were defined to avoid improper areas for PV plant implementation (Bedin et al., 2011). Technical manuals and research outputs were finally evaluated to stress plants efficiency (see e.g Bedin et al., 2011; Miller and Lumby, 2012) (Eq. 3).

$$TE_{EN_i} = LE_{EN_i} \cdot k \cdot \eta \text{¿} \forall i \in (sl \leq 20 \wedge alt \leq 800) \text{¿} \quad [3]$$

In addition to the legal and technical limits, other constraints could be introduced, to reduce potential environmental and socio-economic impacts due to PV plants installation. In fact, the model has the possibility to insert limits that can be included as optional maps, suggested by decision makers. Due to national characteristics, we introduced a hazard constraint on arable lands potentially subject to flood, landslide as well as earthquakes. These areas were considered unsuitable territories because of possible reduction of technical energy and damage of PV systems (National Cartographic Portal, 2015). Moreover, a Specialization Index (SI) related to arable lands was defined as an indicator of the weight that this land cover reaches at municipality level, with respect to a general context (Andini et al., 2013). In other words, SI is a particular value that is useful for detecting important local districts for a particular production in the agricultural, industrial or services sector, as well as for territorial characteristics. If the SI has a value greater than or equal to 2 it means that in the examined area there is a high specialization for the considered parameter (Fagarazzi et al., 2009). In our case study the SI≥2 indicated ~~an~~a high importance of municipal not irrigated arable lands with respect to regional context and, as consequence, agricultural lands that should not be used for PV energy production (Eq. 4).

$$SI_i = \frac{NIAL_m / AAS_m}{NIAL_r / AAS_r} \text{¿} \forall i \in (m \wedge r) \text{¿} \quad [4]$$

NIAL and AAS data derived from VIth ISTAT Agricultural National Census (http://dati-censimentoagricoltura.istat.it/).
Thus, recommended energy taken into account all the above mentioned constraints (Eq. 5):

$$RE_{EN_i} = TE_{EN_i} \text{¿} \forall i \in (\neg FR \wedge \neg LR \wedge \neg ER \wedge \neg SI \geq 2) \text{¿} \quad [5]$$

The final sub-model of *r.green.solar* computes the economic disposal of energy. In the first step, revenues from energy selling can be quantified as (Eq. 6):

$$REV_i = RE_{EN_i} \cdot (p + inc) \quad [6]$$

Actualised value of revenues can be computed as (Eq. 7):

$$RPV_i = REV_i \cdot \frac{(1 + r + d)^{lc} - 1}{(r + d) \cdot (1 + r + d)^{lc}} \quad [7]$$

Implementation as well as operating and maintenance costs (O&M) of PV plants include (Bedin et al., 2011; National Authority for Electric System, 2014): i) purchase and installation, ii) connection to electric grid, iii) surface renting, iv) maintenance, v) cleaning, vi) administrative and consultancies, vii) insurance, viii) decommissioning costs.
Purchase and installation costs are based on the installed power:

$$i_{C_i} = P_i \cdot u \quad [8]$$

Costs for the connection to the grid are differentiated according to the distance. In the absence of a national dataset on geographic distribution of grid, a first approximation considered the distance from *i-th* pixel to roads (National Cartographic Portal, 2015). That costs vary according to table 2.

Table 2
Costs for connection to the electric grid.

Distance (m)	Cost (€)
D ≤ 200	186
200 < D ≤ 700	279
700 < D ≤ 1,200	836
D > 1,200	1950

Surface rent costs for each land use are based on data from National Institute of Agricultural Economics (INEA, 2014). The other annual costs – point from iv) to vii) – were computed as a percentage of the installation costs (Tab. 3) (Bedin et al., 2011):

Table 3
Quantification of surface rent, maintenance, cleaning, administrative, consultancies and insurance costs.

Type of annual cost	Cost (€)
Surface rent	$r_{C_i} = R_{AL} \cdot nsres \cdot ewres \; \forall \, i \in AL$ [9]
Maintenance	$m_C = i_{C_i} \cdot 0.01$ [10]
Cleaning	$c_{C_i} = if\,(i_{C_i} \cdot 0.001 < 1000)\; then\; 1000\; else\; (i_{C_i} \cdot 0.001)$ [11]
Administrative and consultancies	$a_{C_i} = if\,(i_{C_i} \cdot 0.001 < 3000)\; then\; 3000\; else\; (i_{C_i} \cdot 0.001)$ [12]
Insurance	$s_{C_i} = if\,(i_{C_i} \cdot 0.0015 < 2000)\; then\; 2000\; else\; (i_{C_i} \cdot 0.0015)$ [13]

At the end of its life cycle, the plant must be dismantled, and the decommissioning costs must be taken into account (Eq. 14).

$$d_{C_i} = i_{C_i} \cdot 115 \quad [14]$$

Actualised costs can be expressed as (Eq. 15):

$$CPV_i = i_{C_i} + g_{C_i} + \left(r_{C_i} + m_{C_i} + c_{C_i} + a_{C_i} + s_{C_i} \right) \cdot \frac{(1+r)^{lc} - 1}{r \cdot (1+r)^{lc}} + \frac{d_{C_i}}{(1+r)^{lc}} \quad [15]$$

Eventually, the Net Present Value can be computed (Eq. 16):

$$NPV_{PV_i} = RPV_i - CPV_i \quad [16]$$

2.2 Trade-off analysis

The analysis of competition between PV panels and crops for food/feed was based on the selection of suitable plantations for each Italian region. The focus was on data from INEA (2013) that take into account economic analysis for the production of crops generally cultivated on non-irrigated arable lands (cereals and grain leguminous, industrial crops, forage crops[1]). For each production, the annual net revenues were computed as (Eq. 17):

$$NR_{x,r} = GAP_{x,r} - C_{x,r} \quad [17]$$

Then, the net present value for crop cultivation was calculated based on a 4 years crop rotation period, on a total investment length equal to the PV panels lifecycle. In order to develop a precautionary evaluation for PV deployment, the more convenient crop (from economic point of view) was chosen for each region (Eq. 18):

$$NPV_{X_r} = MAX\left(NR_{x,r} \right) \cdot \frac{(1+r)^{lc} - 1}{r \cdot (1+r)^{lc}} - \frac{MAX\left(NR_{x,r} \right)}{(1+r)^{y}} \quad [18]$$

where $y \in (rot \cdot n, \ldots, lc)$ with $n = (1, 2, \ldots, lc/rot)$.

Once NPV_{PV} and NPV_X were compared, two economic indexes for PV energy production were quantified: internal rate of return (IRR) and safety margin (SM). The first gives an idea of the investment's profitability. In general, the IRR corresponds to the discount rate that makes the NPV equal to 0 (Eq. 19). The latter represents the potential decrease of current energy price that maintain a convenience in renewable energy plants implementation in respect of crops cultivation (Eq. 20):

$$IRR_i = r \mid NPV_{PV_i} = 0 \quad [19]$$

$$SM_i = p \mid NPV_{PV_{i,r}} = NPV_{X,r} \quad [20]$$

1 The examined crops are: oat, chickpea, spelt, broad bean, durum wheat, wheat, buckwheat, lentil, white lupin, millet, barley, garden pea, rye, aromatic and officinal herbs, rape-seed, sunflower, lavender, alfalfa, Perennial rye-grass, French grass, Spanish esparcet, Egyptian clover, Crimson clover, White clover, Red clover, common vetch.

The final evaluations considered: i) an analysis based on a percentage of economic surface that can be hypothetically used for PV energy production. For that areas, it was computed the amount of potential decline of crops due to PV plants implementation; ii) a sensitivity analysis based on discount rate variation for computation of PV plants' economic efficiency.

3. Results

Table 4 shows potential available surfaces for PV implementation and energy from legal, technical, recommended and economic viewpoint. As matter of fact these variables assume a relevant importance for territorial planning; theoretical energy is synthetically reported in Fig. 4. A high potential for PV energy production is related to Sicily, Emilia Romagna, Lombardy, Veneto, Apulia and Sardinia. This denotes the disposal of a large amount of not irrigated arable lands (see legal energy).

Table 4
Energy potential (GWh/year·10^{-3}) and available surface (ha) per region.

Region	Legal		Technical		Recommended		Economic	
	Energy	Surface	Energy	Surface	Energy	Surface	Energy	Surface
Piedmont	716.5	41,081	107.32	41,022	106.23	40,604	106.23	40,604
Aosta Valley	0.0	0	0.00	0	0.00	0	0.00	0
Lombardy	1,382.1	80,724	206.70	80,455	206.69	80,451	206.69	80,451
Trentino-South Tyrol	5.2	358	0.08	36	0.02	10	0.02	10
Veneto	1,227.6	71,915	183.98	71,850	183.14	71,525	183.14	71,525
Friuli-Venezia Giulia	308.0	18,647	46.15	18,624	44.11	17,757	44.11	17,757
Liguria	8.9	536	1.15	459	0.27	111	0.27	111
Emilia Romagna	1,480.9	86,463	221.14	86,066	220.89	85,967	220.89	85,967
Tuscany	897.3	49,778	133.09	49,212	123.52	45,736	123.52	45,736
Umbria	404.7	22,570	58.27	21,636	53.66	19,938	53.66	19,938
Marche	647.8	37,674	91.07	35,279	85.53	33,140	85.53	33,140
Lazio	847.9	44,839	123.97	43,620	119.39	41,952	119.39	41,952
Abruzzo	146.0	8,216	19.94	7,471	10.94	4,078	10.94	4,078
Molise	211.4	11,735	28.44	10,508	24.16	8,850	24.16	8,850
Campania	377.5	20,509	53.72	19,412	30.14	10,611	30.14	10,611
Apulia	1,203.7	63,685	179.31	63,228	155.66	54,739	155.66	54,739
Basilicata	555.8	30,057	75.06	26,954	63.76	22,701	63.76	22,701
Calabria	352.2	18,299	45.41	15,584	20.96	7,158	20.96	7,158
Sicily	1,588.5	77,542	219.19	71,133	210.31	68,232	210.31	68,232
Sardinia	1,023.7	51,418	150.55	50,382	100.79	34,079	100.79	34,079
Total	13,385.6	*736,047*	*1,945*	*712,929*	*1,760*	*647,637*	*1,760*	*647,637*

A reduction of both energy and surface disposal is evident in case of introduction of technical constraints. The inclusion of technical and recommended constraints considerably reduced the energy potential of some regions in northern Italy. Specially, Trentino-South Tyrol and Liguria highlight a reduction of recommended energy up to 97.2% and 79.3% in comparison with legal energy, respectively. Higher decrease of recommended energy in southern regions is found for the following regions (Fig. 3): Calabria (60.9%), Abruzzo (50.4%), Campania (48.3%), Sardinia (33.7%), Molise (24.6%) and Basilicata (24.5%). In these regions the major limits are related to recommended constraints, in particular the earthquake risk and the SI (Fig. 4). Some of the central and northern regions - such as Emilia Romagna, Veneto, Lombardy and Piedmont - seem to be favorite by the low amount of surface with morphological (technical) constraints, i.e. slope and altitude (see Fig. 3 and Fig. 4). In these cases the reduction of energy availability from legal to recommended ranges from 0.3% to 1.2%. In those regions it depends on the low weight of recommended constraints in respect to the legal and technical ones (in particular, as expressed by Fig. 4, a consistent overlap between the few area with recommended constraints and legal/technical limits is highlighted). Recommended and economic energies show the same results. This is due to the fact that neither current discount rate does not exceed IRR nor price of energy is lower than safety margin. Therefore, the economic profitability of PV plants is always guaranteed.

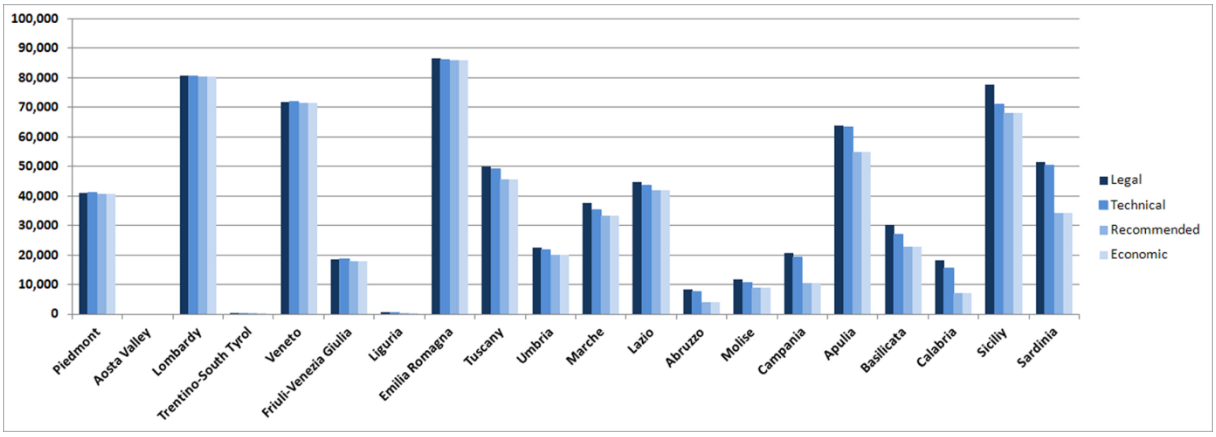

Fig. 3 Reduction of PV surface from legal to economic parameters for each Italian region (ha)

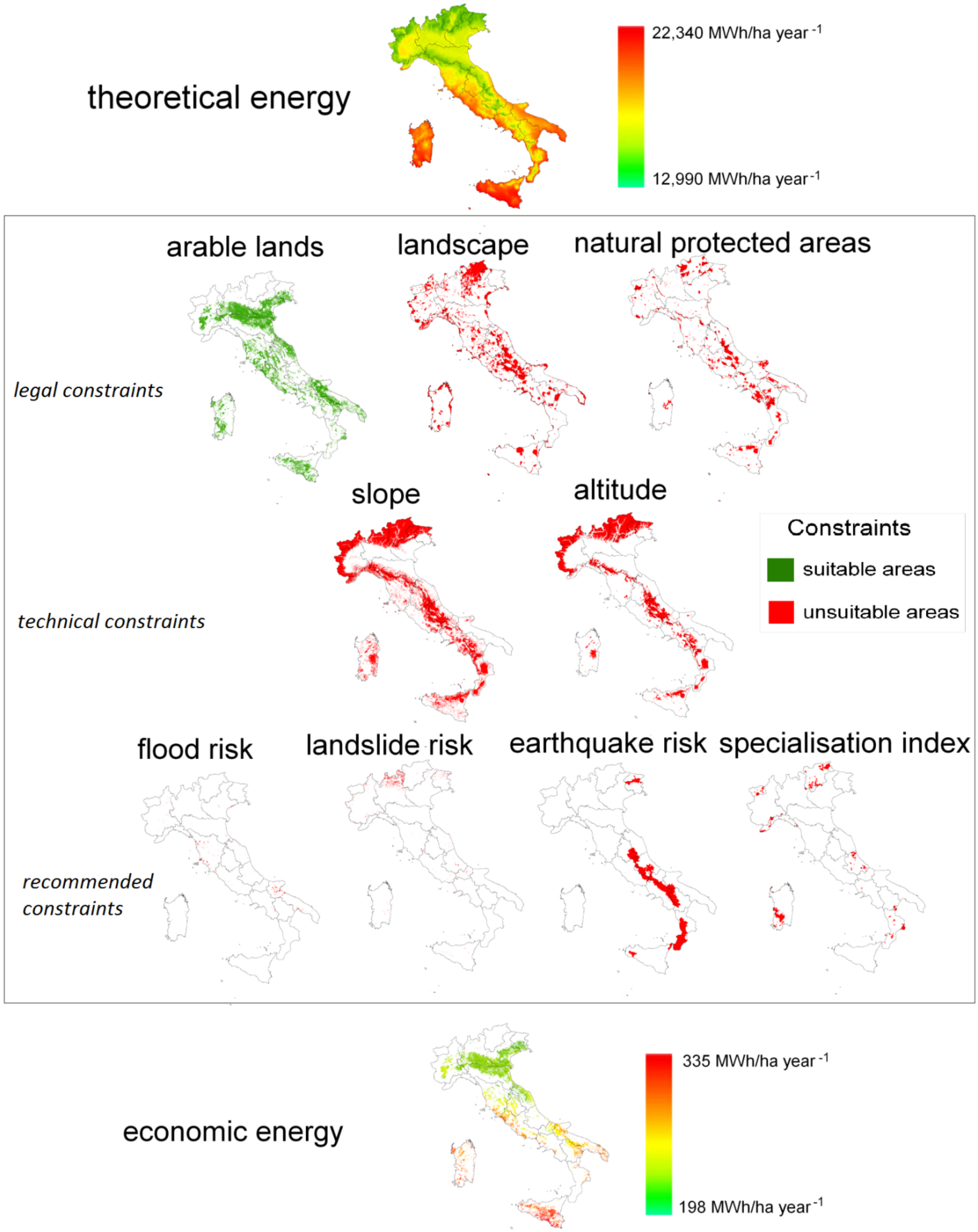

Fig. 4 Theoretical and economic energy; constraints applied for computation of legal, technical and recommended energy.

NPV_{PV} was computed as the average value of pixel with economic profitability for PV plants; the analysis was carried out by means of zonal statistic operations for each region (Fig. 5a). NPV_X derives from Eq. 18 (Fig. 5b).

Results denote a north-south gradient of convenience for PV plants. The average NPV_{PV} ranges from 169,798 €/ha of Trentino-South Tyrol to 287,282 €/ha of Sicily taking into account a 20-years PV systems life cycle and a discount rate of 3% (Fig. 5a).

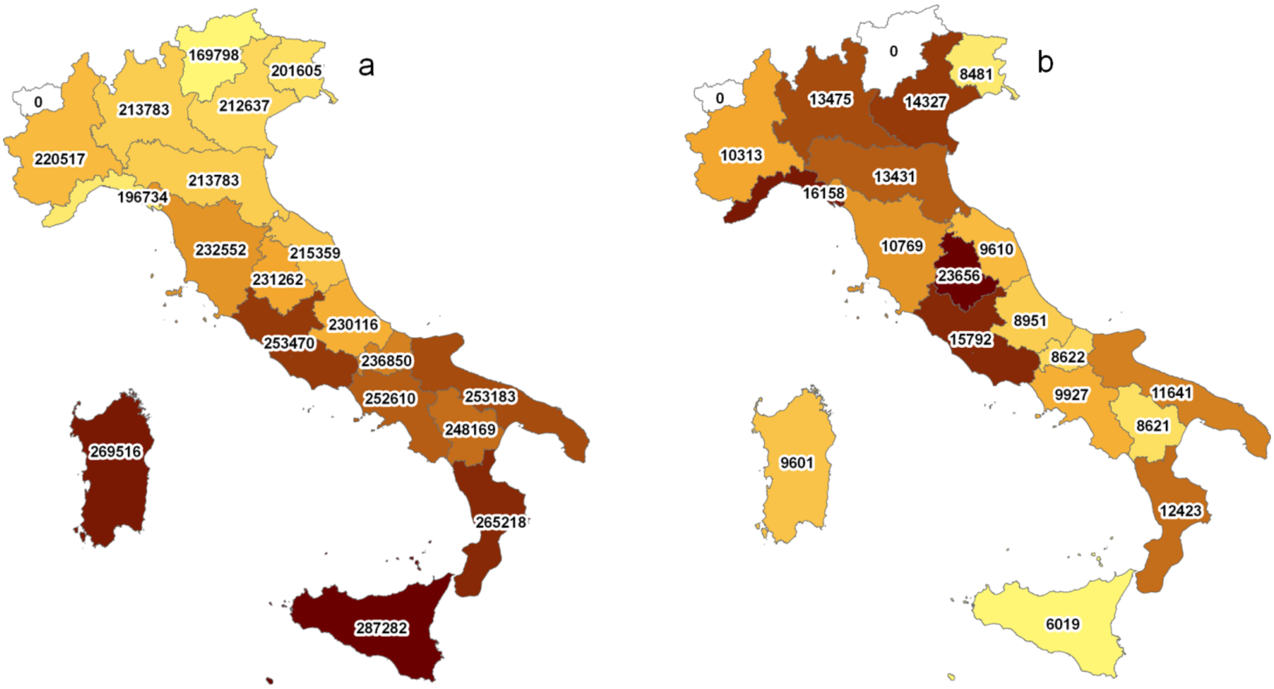

Fig. 5 a) Average Net Present Value for PV plants – NPV_{PV} (€/ha); b) Average Net Present Value for crop production – NPV_X (€/ha).

A similar trend is denoted for both average IRR and SM (Fig. 6). IRR varies from 31% (Trentino-South Tyrol) to 49% (Sicily). SM ranges from 54 €/MWh of Liguria to 69 €/MWh of Sicily. A great profitability of PV investments is denoted by both indexes.

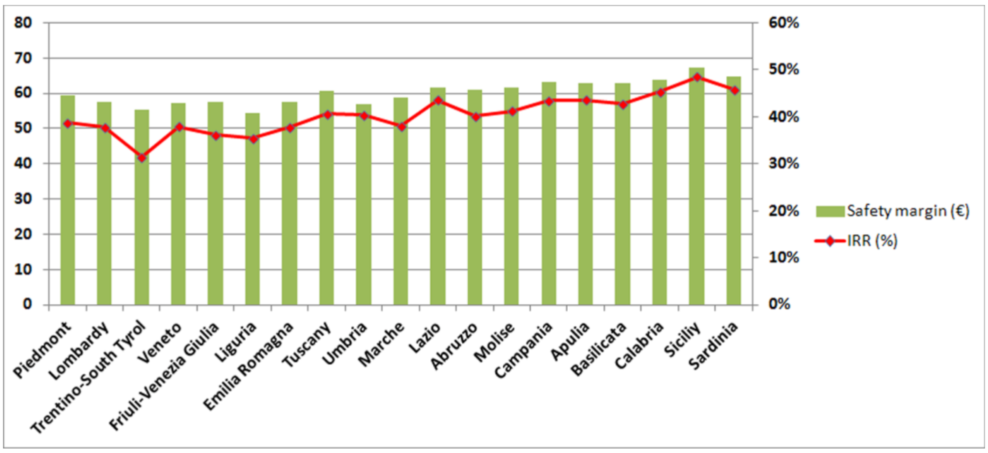

Fig. 6 Safety margin and Internal Rate of Return for PV plants.

This aspect was also confirmed by the analysis of Figg. 5a and 5b, in which the difference between NPV_{PV} and NPV_X reaches an order of magnitude (range from $NPV_{PV,Umbria}=10 \cdot NPV_{X,Umbria}$ to $NPV_{PV,Sicily}=48 \cdot NPV_{X,Sicily}$).

In this framework, it is interesting to evaluate the potential drop in crop production due to PV plants implementation. Three ~~scenario~~scenarios were carried -out assuming 5%, 10% and 15% of economic surface use and real data concerning the crop yield (INEA, 2013). Results are reported in Tab. 5.

Table 5
Example of potential crop losses in case of PV panels installation on arable lands.

Region	Surface (ha)	Crop yield (t/ha year^{-1})	Potential crop losses (t/year)		
			PV surface (5%)	PV surface (10%)	PV surface (15%)
Piedmont	40,604	5.93	12,033	24,065	36,098
Aosta Valley	0	0.00	0	0	0
Lombardy	80,451	5.60	22,524	45,047	67,571
Trentino-South Tyrol	10	0.00	0	0	0
Veneto	71,525	9.87	35,307	70,614	105,921
Friuli-Venezia Giulia	17,757	9.40	8,343	16,686	25,029
Liguria	111	9.68	54	107	161
Emilia Romagna	85,967	9.75	41,927	83,853	125,780
Tuscany	45,736	2.09	4,772	9,545	14,317
Umbria	19,938	0.86	862	1,724	2,586
Marche	33,140	4.53	7,503	15,005	22,508
Lazio	41,952	0.97	2,042	4,083	6,125
Abruzzo	4,078	4.11	838	1,675	2,513
Molise	8,850	1.94	859	1,718	2,576
Campania	10,611	11.16	5,923	11,846	17,770
Apulia	54,739	0.89	2,439	4,878	7,317
Basilicata	22,701	6.90	7,836	15,672	23,508
Calabria	7,158	3.85	1,378	2,756	4,134
Sicily	68,232	1.84	6,262	12,524	18,786
Sardinia	34,079	2.95	5,029	10,058	15,086

Basing on yield of crop that maximize NPV_X for each region, results show how potential agricultural losses do not follow PV economic convenience. As matter of fact, relevant decreasing of crop production are depicted for region with a combination of high crop yield as well as availability of not irrigated arable lands (i.e. Emilia Romagna, Veneto, Lombardy and Piedmont). A final remark regards the potential variability of technical as well as economic parameters and their impact on PV plants profitability. Available technology suggests how a strong increase in plants efficiency cannot be forecasted at short-medium term. On the other hand, is demonstrated that one of the most significant variable for economic efficiency is discount rate. Given this premise a sensitivity analysis for NPV_{PV} computation, based on modification of discount rate, was developed. Results are expresses by Tab. 6.

Table 6
Sensitivity analysis based on discount rate.

	NPV_{PV} (€/ha)					*reduction of NPV_{PV} (%)*				
Region	*r: 1%*	*r: 2%*	*r: 3%*	*r: 4%*	*r: 5%*	*"r" from 1% to 2%*	*"r" from 2% to 3%*	*"r" from 3% to 4%*	*"r" from 4% to 5%*	*"r" from 1% to 5%*
Piedmont	267,892	239,796	220,517	193,593	174,543	-11.7%	-8.7%	-13.9%	-10.9%	-53.5%
Lombardy	259,780	232,419	213,783	187,421	168,867	-11.8%	-8.7%	-14.1%	-11.0%	-53.8%
Trentino-South	206,751	184,177	169,798	147,024	131,693	-12.3%	-8.5%	-15.5%	-11.6%	-57.0%

Tyrol										
Veneto	258,248	231,022	212,637	186,245	167,781	-11.8%	-8.6%	-14.2%	-11.0%	-53.9%
Friuli-Venezia Giulia	245,031	218,996	201,605	176,171	158,510	-11.9%	-8.6%	-14.4%	-11.1%	-54.6%
Liguria	239,182	213,687	196,734	171,747	154,449	-11.9%	-8.6%	-14.5%	-11.2%	-54.9%
Emilia Romagna	259,753	232,387	213,783	187,381	168,823	-11.8%	-8.7%	-14.1%	-11.0%	-53.9%
Tuscany	282,383	252,968	232,552	204,603	184,666	-11.6%	-8.8%	-13.7%	-10.8%	-52.9%
Umbria	280,736	251,469	231,262	203,348	183,511	-11.6%	-8.7%	-13.7%	-10.8%	-53.0%
Marche	261,703	234,158	215,359	188,860	170,183	-11.8%	-8.7%	-14.0%	-11.0%	-53.8%
Lazio	307,320	275,641	253,470	223,569	202,108	-11.5%	-8.7%	-13.4%	-10.6%	-52.1%
Abruzzo	279,626	250,477	230,116	202,550	182,792	-11.6%	-8.8%	-13.6%	-10.8%	-53.0%
Molise	287,242	257,369	236,850	208,255	188,009	-11.6%	-8.7%	-13.7%	-10.8%	-52.8%
Campania	306,588	275,001	252,610	223,078	201,679	-11.5%	-8.9%	-13.2%	-10.6%	-52.0%
Apulia	306,989	275,346	253,183	223,332	201,895	-11.5%	-8.8%	-13.4%	-10.6%	-52.1%
Basilicata	300,845	269,746	248,169	218,623	197,552	-11.5%	-8.7%	-13.5%	-10.7%	-52.3%
Calabria	321,445	288,487	265,218	234,317	211,995	-11.4%	-8.8%	-13.2%	-10.5%	-51.6%
Sicily	348,132	312,768	287,282	254,657	230,714	-11.3%	-8.9%	-12.8%	-10.4%	-50.9%
Sardinia	326,621	293,204	269,516	238,283	215,652	-11.4%	-8.8%	-13.1%	-10.5%	-51.5%

Table 6 highlights the importance of discount rate for NPV_{PV} quantification as well as how its variation can bring to relevant instability of economic performance. Also in this case a north-south gradient is revealed stressing a higher worsening of PV plants economic performance in northern regions, in case of augmented discount rate.

4. Discussion and conclusions

The developed model permits an evaluation of PV energy availability, based on modular and multistep analysis. Starting from the total solar energy disposal and the theoretical availability, different constraints can be included to reduce the harvestable quantities from legal, technical, recommended and economic point of view. The flexible approach allows the consideration of different input dataset and the modification of the constraints, as well as of variables facilitating applications in contexts with different characteristics and normative prescriptions. The raster-based method consents a multiscale analysis through various level of pixel aggregation (e.g. at municipal, regional or national level). Potential environmental and socio-economic impacts due to PV plants implementation can be considered and reduced by the definition of related constraints.

In this work, the *r.green.solar* model was applied to define energy potential from ground-mounted PV system, hypothetically inserted on not irrigated arable land. In fact, one of the aims of the research was to depict a trade-off between PV energy and crop for food/feed production. In future analyses, an extension to other land use could be easily carried out with the modification of a few input data. A potential application of the model to other European and global regions is also facilitated by modular composition and a wide availability of input data.

Although an higher disposal of solar energy per unit of surface is shown in southern regions of Italy, total amount of PV energy is strongly influenced by two main parameters: i) the availability of not irrigated arable land and ii) the presence of constraints, related to the landscape maintenance, morphological variables (slope and altitude), the earthquake risk and the specialization index. These features, linked to crop yield, lead to a greater potential impact – in terms of crops substitution – in northern region of Italy respect to central and southern ones, unless a north-south increasing gradient is shown for economic profitability. In fact, average Net Present Value, Internal Rate of

Return and Safety Margin on electric energy price stress a strong convenience for PV plants investments in region such as Sicily, Sardinia and Calabria. With these premises, the model could represent a useful D~~ecision Support System~~SS for policy makers and local stakeholders, to quantify and communicate strengths as well as weaknesses of PV plants in a spatial-based manner. Nevertheless, the application of *r.green.solar* for a local scale planning must consider additional analysis and data. For example, further constraints should be evaluated in case of geographic peculiarities (e.g. the presence of Protected Designations of Origin and Protected Geographical Indications territories as well as areas with ~~an~~a high specialization index for crops cultivated on arable land). An in-depth analysis of regulation could be also developed in order to consider provincial and regional variability as well as temporal dynamics of rules and incentives. Additional applications could go beyond the Boolean structure of constraints by the introduction of weighted value, e.g. in the form of Multi Criteria Analysis.
Trade-off analysis can be improved taking into account the geographical suitability for each cultivation and rotation among different crops. This aspect was here simplified by the comparison of PV energy production with the more profitable regional crops, to ~~carried~~carry out a precautionary analysis.
Eventually, additional future insights could focus on the implementation of different scenarios and sub-models. The evaluation of the economic performance for different technologies (e.g. fixed Vs single/dual axis trackers ground-mounted PV systems) or the quantification of impact on ~~Ecosystem Services~~ESs (e.g. avoided CO_2 emission in respect to fossil fuel and the impact on ecological corridors) could be developed to improve the study and better highlight the existing trade-offs.

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