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Promoting an integrated planning for a sustainable upscale of renewable energy. A regional GIS-based comparison between ecosystem services tradeoff and policy constraints

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ABSTRACT

The upscale of renewable energy production on a regional scale implies possible negative impacts on the environment, economies and societies. To ensure the sustainability of renewable energy production on a regional scale, the lens of ecosystem services can support sustainable energy assessments. This paper proposes a GIS-based methodology to spatially analyze the integration of renewable energy with other ecosystem services in order to identify trade-offs. The work focuses on solar farms and agricultural biomass from leftovers and considers five other ecosystem services that are fundamental to agricultural landscapes. The proposed assessment methodology relates land cover types to land suitability for renewable energy production, building on the literature on ecosystem service tradeoffs. The methodology was tested on a case study. The case study is the Veneto Region, whose renewable energy policy constraints are also analyzed. The assessment methodology shows that the land cover of fruit crops has a high level of tradeoff. The results of the case study highlight the discrepancy between the two separate analyses: the policy constraints analysis favours solar agriculture, while the tradeoff analysis favours energy production from agricultural biomass. Finally, the study paves the way for further investigation in the field of ES-RES and provides policy recommendations.

1. Introduction

The transition to renewable energy sources (RES) is recognized globally as a climate change mitigation action that does not compromise access to energy [1,2]. RES production is experiencing a *momentum* in the European Union (EU) context, which offers several opportunities and favourable conditions, such as on-going energy strategies (e.g., the clean energy transition pillar of the New Green Deal) and funds dedicated to sustainable and decarbonised energy production. In addition, current international oil and gas market arrangements, such as the massive reduction of gas exports from Russia to the EU, make RES production an urgent priority for EU Member States and neighboring countries.

Energy production from RES uses ecosystem services (ES) [3,4], and can critically influence or be influenced by the provision of other ES, harming the wellbeing of communities and the sustainability of their economies [2,5]. The simultaneous supply of ES can trigger synergies as well as conflicts. In the specific case of RES production, this can trigger tradeoffs with other ES [6].

The sustainable use of RES for energy production purposes implies that RES supply chains should not trigger critical tradeoffs with other key ES [7] – e.g. food production loss due to biomass production or solar panels installation, obstruction of landscape vistas by wind plants, river ecosystem deterioration associated with hydropower [8]. Therefore, RES development can negatively impact on other ES delivering functions, and hence, it may hamper the sustainability of the transition to RES [9].

While the scale up of RES adoption is considered controversial in terms of land use competition and environmental sustainability, as it may entail tradeoffs with natural assets, the possible tradeoffs caused by RES development can also negatively affect the social acceptability of RES, and thus undermine their diffusion [10,11]. Moreover, communities opposing the installation of RES-related infrastructure and plants, e.g. striking against the disservices that these plants may activate, is the most important barrier for the development of RES production systems [12].

Therefore, if these tradeoffs remain unsolved the operativity of energy plans (e.g., regional energy plans, local climate mitigation strategies) and the sustainability of RES can be compromised.

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Abbreviations

RES	Renewable Energy Sources
ES	Ecosystem Services
GIS	Geographic Information Systems
EU	European Union
PER	Piano Energetico Regionale Regional Energy Plan

In order to achieve the long-term energy transition sustainability, the ES analytical approach, ES approach henceforth, should be integrated into spatial planning and at the service of RES design – prominent field of research yet to be further investigated. In fact, by integrating tradeoff analysis of ES into energy and spatial planning, it is possible to identify potential critical relations between RES and other ES [9]. In addition, the application of spatial-explicit analysis through Geographical Information System (GIS) can provide precious information for energy-related decision makers aiming at detecting and prioritizing areas for RES production as well as ensuring no critical tradeoffs among ES.

Scientific literature presents promising insights and set challenging perspectives addressing ES analysis in addition to traditional information adopted in the planning practice [13]. According to De Pascali et al. (2020), analyzing energy production from RES in relation to other ES is important because it allows to:

(i) keep ecosystems healthy and working,
(ii) evaluate and reduce environmental impacts deriving from RES-related pressure on ecosystems,
(iii) examine the balance between the different types of energy resources and ES,
(iv) control the energy demand and the definition of energy plans, based on a thorough knowledge of the resulting ecosystem problems.

To ensure both energy production from RES and the delivery of other ES, it becomes necessary to analyze tradeoffs, and to consider benefits, conflicts, and disadvantages. Furthermore, to ensure RES-related initiatives that effectively support decarbonization, it is required to address alternative RES and a wide range of environmental and societal repercussion from a broader perspective [8].

While Academia has progressed in the ES tradeoff analysis – including RES production – the application of an ES lens to energy planning in the real practice is still not diffused. A further development within the research arena is essential for the pursuit and upscale of the ES approach in the RES-related practices. Hence, the virtuous improvement of RES models should align and integrate with the ES' features [5,14,15].

On the base of the above-mentioned gaps set at the interfaces of Science-Policy-Action, the aim of this work is to support the investigation of the convergence of RES and other anthropogenic priorities through the lens of ES tradeoffs analysis aiming at ensuring the sustainable upscale of RES production at the regional level. In particular, the study couples GIS-based analysis of ES tradeoffs and energy planning to assess and map tradeoffs between RES and other ES. This methodological approach, which brings novelty to the ES and spatial planning fields, is applied to an illustrative case study at the regional level, i.e. Veneto Region.

Concerning the scale of research and action, landscape's changes introduced by the maximization of RES supply need to be strategically planned at the local level [5,7] aiming to enhance local communities' ownership and long-term sustainability. In addition, it is key to acknowledge the relevance of the local scale – referring to regional, provincial, metropolitan, municipal, and sub-municipal administrative levels, i.e. NUTS2 and NUTS3 when referring to EU context – to address these issues, as it is the scale where the majority of stakeholders takes decision or exerts their power. Consequently, tradeoff analysis and mapping should focus on the local scale, as it should be concrete and close to the work of the decision-makers [16]. Hence, the local dimension could enable the governance of RES integrated strategies, as well as the development of virtuous models regarding ES management. However, concerning the state of art in the EU context and with a specific focus on Italy – geographical context where this study operates – the local dimension of RES production and energy plans does neither address nor integrate ESs yetinto spatial planning frameworks [5].

Through the illustrative case study of the Veneto Region, this study detects the policy constraints (present in the Regional Energy Plan) through mapping into a GIS environment, in order to spatialize information related to suitable areas for RES production. Then, the methodology follows with the assessment and further mapping of RES-ES tradeoffs. Suitable areas for RES production – areas with no tradeoffs with other key ES – are detected.

In the last step, the previous two outputs, i.e. suitable areas for RES with and without policy constraints and suitable areas for RES with and without tradeoffs, are compared and spatially-wise analyzed.

The two types of RES taken into consideration in this study are 'solar' and 'agricultural biomass'.

The paper follows with section 2 that briefly presents the state of the art of the prominent research field of ES and spatial planning, and with section 3 that illustrates the case study and its legislative frame in terms of energy and spatial planning. Section 4 presents the methods organized into three main blocks addressing three applied research questions, respectively, and here below listed:

- which is the suitable available land for solar and biomass based on policy constraints?
- which is the suitable available land for solar and biomass based on ES tradeoffs?
- what is the difference, for solar and biomass respectively, between suitable land based on policy constraints, and suitable land based on ES tradeoff analysis?

Section 5 presents the results mirroring the three applied research questions supported by a set of explicative maps.

Discussion and conclusions (6) section builds on the empirical insights and dives into the theoretical framing aiming to fill the research gaps.

Four main aspects are discussed, which are: general synergies between RES and ES; ii) renewables' policy constraints consideration, with specific attention to the case study; iii) renewables planning and policy's challenges, with a general attention to the EU context; and iv) potential future steps in the energy policy design and research.

2. Research context: renewable energy sources, ecosystem services, and spatial planning

The concept of ES represents a powerful lens for strategic energy planning and sustainable landscape design [9,17]. However, while there is consensus on the importance to study tradeoffs among ES [18,19] and their relevance in the renewable energy production's upscale, the shift from the theory to the praxis in the local context still embeds major challenges and barriers [20,21]. From the research perspective, the assessment of spatial tradeoffs with the ES lens is still in an early stage [22]. Likewise, renewable energy planning at the local scale is also poorly investigated. In a nutshell, the present state of art highlights at least three major knowledge gaps, i.e.: i) regional/local contextualization of renewable energy planning ii) ES tradeoff assessment integrated with energy policymaking; iii) renewable energy policy constraints at the regional/local scale.

Concerning the regional contextualization of renewable energy planning, scholarship has recently started developing RES production's analysis – testing several sources, e.g., wind, solar, geothermal, and hydrogen [23–25]. In Italy, geographical frame of this research, many promising works employed the scenario modelling at the national level. Also, sustainable renewable development suitability and feasibility were investigated at the national level by [26,27]. However, the renewable energy implementation at the regional level is still very low and its potential impacts are still poorly investigated.

Tradeoffs in the RES analysis and implementation should be considered to avoid conflicts between different sectoral policy goals [28] – e.g. energy transition and climate adaptation – and the scientific community agrees to also in avoiding generalizations. In fact, tradeoffs analysis should be spatial-oriented and specifically tailored for spatial planners [29]. In the last years, scholars have started addressing tradeoffs analysis among different sets of ES, with a peculiar attention to provisioning and regulating services. However, most of these studies neither mentions or integrate policy constraints nor implies stakeholders' involvement or stakeholders-related demands. Grossman [30] study, which tailor information and insights for spatial planning and policy design, underlines the need to move beyond the over-simplification of correlations and clustering approaches.

While the general concepts of ES and ES tradeoffs can be considered intuitive, the shift from the theory to the praxis still opens to major challenges [20,21]. Policymaking and practices are often clear-cut and well-defined at the beginning, but then they reveal a rather complex nature, with room for different interpretations.

The selection of a specific method to apply in a real case can depend on many factors, including the decision-making context, the ES involved, the strengths and limitations of different methods, and pragmatic reasons such as available data, time available and experts' capacity [21].

Currently, ES, including renewables, and ES tradeoffs guidelines [31,32] provides hints to support the selection of methods for decision-making. However, they refer to generic processes, without concretely enabling an effective ES assessment [33]. In fact, the renewable regional strategies still lack attention to the policy constraints implications, and this impasse hamper the sustainable implementation of RES.

3. The case study: Veneto Region (IT) and the regional planning

The Veneto Region (IT) has an area of 18.345 km^2 – the eighth largest region in Italy – where 4.849.929 inhabitants live [49]. Located in northeastern Italy and surrounded by Austria, four Italian Regions (i.e., Lombardia, Trentino, Sud Tirol, Emilia-Romagna, and Friuli Venezia-Giulia) and the Adriatic Sea, Veneto has several world-known cities: its capital city Venezia, Padova, and Verona.

From a geo-morphological perspective, Veneto is one of the two Italian Regions, the other one is Friuli Venezia-Giulia (located easter), with a heterogeneous morphology including Alpine, hilly, plain, and coastal landscapes. Plains are prevalent in the region (56.4%), but the most precious environments with highly valuable natural capitals (UNESCO labelled areas) are in the mountains, i.e., Dolomiti, and in the coast, i.e., Venezia's lagoon, and Po River delta.

In the last 70 years, Veneto has changed its plain landscape due to a low-density diffused urbanization expanded in a range area from Verona (west) to Treviso (east), conceptualized by Indovina [34,35] in the 90's as *Città diffusa* (trans. Diffused city or Sprawled city). Nowadays, the urban land has reached 2.650,84 km^2. Rural areas (8.976,19 km^2) with agricultural vocations are mostly outside the 'sprawled city', but a minority is still present within the sprawled fabric. Most of the agricultural production does not harm the ecological agricultural systems and provides several ES, e.g. landscape views, water cycle regulation, temperature comfort, among the many. However, in the last decades the intensive use of vineyards affected both the ecological systems harming both soil nutrients' cycles and human life. Finally, forest land, wetland, and water bodies have 5.580,47 km^2, 312,40 km^2, and 822,16 km^2, respectively [50].

Concerning the climatic conditions and the current climate changes, in Veneto the annual average temperature increase trend, which is roughly homogeneous over the entire region, averages +0.57 °C per decade and is statistically significant for almost all the different areas of the territory. Temporal trend of average temperature clearly shows that it is indeed supported by a continuous increase in temperature, albeit with the presence of interannual variability.

Moving from temperatures to precipitation, cumulative precipitation, averaged on a regional scale, both on an annual and seasonal basis, has not changed significantly over the last thirty years. Even extending the analysis to the second half of the last century, no significant trends can be identified. On the other hand, a marked inter-annual variability appears, which is shown in the graphs, together with the precipitation accumulation, represented by the standard deviation evaluated over the moving decade. This appears to be increasing with a trend assessed as statistically significant both annually and for the meteorological seasons winter, spring and summer, while for autumn it is decreasing but still with a statistically significant trend [51].

From the regional planning and policymaking perspectives, Veneto Region has been deeply studied under the governance, local development, and spatial planning lenses [34–38]. As part of Italy, thus framed within the Countries with the 'Mediterranean syndrome', i.e. Italy, Spain, Greece, Portugal, and France [39] – States and related Regions with similar administrative systems [39,40] and a long-standing 'Urbanism' planning tradition [41] – Veneto Region has a rigid mode of regulation with low legalistic flexibility. Furthermore, the spatial planning approach at regional and sub-regional levels is highly conformative and often implies that plans and policies are siloed in one administrative department. This highlights criticalities when addressing cross-cutting issues, e.g., ecosystem services, climate change mitigation and adaptation, smart specialization, among the many. Consequently, these plans may be hindered in their implementation and suffer of long periods of *inertia*.

From the economic and industrial perspectives, Veneto Region is one of the most important Italian areas, and local small-medium enterprises are world-known for their high-end products. These are mostly located in the plain area, which is highly energy-demanding due to both industrial and residential land uses. In this sense, current European situation concerning energy production and supply – Italy and Germany, for instance, are highly dependent on gas and oil – poses at risk regions like Veneto that are highly dependent on external energy sources and still have an underdeveloped system of RES production.

The Veneto's Energy Plan, PER [42], henceforth, which is the focus of this research, approved in 2017, is a sectoral plan approved by the Regional Council. It defines the guidelines and coordination of planning for the promotion of RES in implementation of the National laws addressing three macro-objectives, which are: burden sharing, energy efficiency-saving, and transport's emissions reduction/carbon-neutralization.

4. Methods

This study consists of a multi-step pathway on a GIS setting tested through the Regione Veneto case study. As a preliminary step, landcover of the Veneto Region was analyzed and only Level 2 (agricultural areas) of Corine Landcover was used [50]. These data consist of agricultural land use, as the massive production of energy from solar farms, and from agricultural biomass is expected to occur.

The methodological approach is organized in three main blocks: one addressing each of the three research questions listed in the introduction section. More specifically, the first block corresponds to subsection 4.1, where policy constraints defined in the PER [42] are mapped, in order to identify suitable areas for the production of energy from solar plants and agricultural biomass plants respectively (for deeper explanation see Section 3.1) based on present policy constraints.

Section 4.2 presents the core of this research work, which is the RES-ES tradeoff assessment methodology, and its test on the Veneto Region case study. Section 4.3 overlays the results from section 4.1. and 4.2. For

Table 1
Policy constraints taken from the PER (Regional Energy Plan, Veneto Region, 2017 [42]).

Policy constraints categories for non-suitability of areas	Description of the information	Data	Source of the data
Policy constraints for agricultural biomass extracted from the Regional Energy Plan (Regione Veneto, 2017)			
Siti inseriti nella Lista del Patrimonio mondiale dell'UNESCO	The sites included in the UNESCO list	c1103015322_ortobotanicopadovaunesco.shp c1103015323_sitipalafitticoliunesco.shp c1103015324_venezialagunaunesco.shp c1103015325_veronaunesco.shp c1103015326_vicenzavillepalladiounesco.shp	Geoportale del Veneto [52]
Zone all'interno di coni visuali la cui immagine è storicizzata e identifica i luoghi in termini di notorietà internazionale di attrattività turistica	Venice lagoon landscape[a]	c0401071_lagunavenezia.shp	Geoportale del Veneto [52]
Zone umide di importanza internazionale designate ai sensi della Convenzione di Ramsar	Wetlands designated under the Ramsar Convention	c1102081_zoneumide.shp	Geoportale del Veneto [52]
ReteNatura2000	The Natura 2000 Network	c1101121_natura2000.shp	Geoportale del Veneto [52]
Aree naturali protette a diversi livelli, istituite ai sensi della L. n. 349/1991 e inserite nell'elenco delle aree naturali protette	Protected areas (parks and reserves)	c1102061_riserveistituite.shp c1102051_parchiistituiti.shp	Geoportale del Veneto [52]
Geositi	Geo-sites	c0505013_geositi_2020.shp	Geoportale del Veneto [52]
Aree caratterizzate da situazioni di dissesto e/o rischio idrogeologico perimetrale nei Piani di Assetto Idrogeologico (P.A.I.) adottati dall'Autorità di Bacino	Hydrogeologic risk areas	IT_ITI017_HHP_20131222.shp (Bacino Lemene) IT_ITI026_HHP_20131222 (Bacino Fissero, Tartato, Canalbianco) IT_ITN001_HHP_20151125 (Bacino Adige) IT_ITN003_HHP_20131222 (" Brenta-Bacchiglione) IT_ITN006_HHP_20140624 (" Livenza) IT_ITN007_HHP_20140624 (" Piave) IT_ITN009_HHP_20151204 (" Tagliamento) IT_ITR051_HHP_20151204 (" interno laguna venezia - denominato Regione Veneto)	alpi orientali's database [53]
Aree di salvaguardia delle acque superficiali e sotterranee destinate a consumo umano	Protected groundwaters	c1103015030_comunifaldevincidro.shp	Geoportale del Veneto [52]
Aree ad elevata utilizzazione agricola, individuate dal PTRC adottato con D.G.R. n. 372 del 17 febbraio 2009	Agricultural area types	Shape: Aree agricoltura (layer "agricoltura ad alta utilizzazione agricola")	Geoportale del Veneto [52]
Aree agricole interessate da produzioni agroalimentari di qualità (produzioni biologiche, DOP, IGP, DOC, DOCG, produzioni tradizionali), art. 12, comma 7, D. Lgs. n. 387/2003	Agricultural areas for food production of recognized cultural/economic/gourmet value[b]		
Policy constraints for solar from ground pv extracted from the Regional Energy Plan (Regione Veneto, 2017 [42])			
Policy constraints categories for non-suitability of areas	**Description of the information**	**Data**	**Source of the data**
Siti inseriti nella Lista del Patrimonio mondiale dell'UNESCO	The sites included in the UNESCO list	c1103015322_ortobotanicopadovaunesco.shp c1103015323_sitipalafitticoliunesco.shp c1103015324_venezialagunaunesco.shp c1103015325_veronaunesco.shp c1103015326_vicenzavillepalladiounesco.shp	Geoportale del Veneto [52]
Zone di particolare interesse paesaggistico, ai sensi della Convenzione Europea del Paesaggio	Valuable landscapes, Venice lagoon landscape[a]	c0401071_lagunavenezia.shp	Geoportale del Veneto [52]
Zone umide di importanza internazionale designate ai sensi della Convenzione di Ramsar	Wetlands designated under the Ramsar Convention	c1102081_zoneumide.shp	Geoportale del Veneto [52]
ReteNatura2000	The Natura 2000 Network	c1101121_natura2000.shp	Geoportale del Veneto [52]
Aree naturali protette a diversi livelli, istituite ai sensi della L. n. 349/1991 e inserite nell'elenco delle aree naturali protette	Protected areas (parks and reserves)	c1102061_riserveistituite.shp c1102051_parchiistituiti.shp	Geoportale del Veneto [52]
Geositi	Geo-sites	c0505013_geositi_2020.shp	Geoportale del Veneto [52]
Aree ad elevata utilizzazione agricola, individuate dal PTRC adottato con D.G.R. n. 372 del 17 febbraio 2009	Agricultural area types	Shape: Aree agricoltura (layer "agricoltura ad alta utilizzazione agricola")	Geoportale del Veneto [52]
Aree agricole interessate da produzioni agroalimentari di qualità (produzioni biologiche, DOP, IGP, DOC, DOCG, produzioni tradizionali), art. 12, comma 7, D. Lgs. n. 387/2003	Agricultural areas for food production of recognized cultural/economic/gourmet value[b]		

[a] No dedicated layer was identified for this type of information (visual cones of the historical landscape). However, not to exclude this layer of information, the "Venice lagoon" areas was adopted as proxy, as globally known as historical landscape.
[b] This layer exists, but the scale is too big to be applied at the regional scale, where any area of the region belongs to the same value.

comparative purpose aiming at detecting alignments and conflicts between present policy constraints and RES-ES tradeoffs analysis.

4.1. Suitable areas for RES production according to local energy plan's constraints

The aim of this subsection is to map suitable land for energy production – from agricultural biomass and solar farms respectively – based on existing policy constraints in the Veneto Region [42]. In the PER, Veneto Region defined 'suitability of land for energy production' through a set of constraints for each RES type, which are illustrated in Table 1. In the case of "biomass", the PER [42] does not specify whether constraints refer to the production of agricultural biomass or to the installation of plants for energy production from biomass. Also, the PER [42] does not clarify the source of biomass, whether it is coming from dedicated crops or from leftovers.

Due to several reasons, i.e. high-end quality of crops for edible purposes produced in Veneto, only agricultural biomass from leftovers is considered. The table also presents the datasets used for the GIS analysis.

All categories mentioned in the PER as 'not suitable for either energy production from solar farms or agricultural biomass', were mapped – specific geo-data were used and then overlapped on the sub-categories from the agricultural land use layer. Geo-dataset is made of several vector files -.shp files – taken from official online sources – i.e. Veneto Region's Geoportale, and Alpiorientali's database – and they regards proxies (see Table 1) for all cultural and environmental protection areas, e.g. protected areas, natural reserves, safety aspects, e.g. risks of floods and landslide, mentioned by the PER 2017 as policy constraints. The 'suitable land' layer of information was obtained by extracting the sum of all 'non suitable lands from Corine land cover's Level 2, for solar farms and agricultural biomass respectively.

4.2. RES-ES assessment methodology and related suitable areas for RES production

Geographical identification of tradeoffs, where landcover is adopted as a proxy of specific ES supply [8], and a weighting system was applied to each tradeoff [8,43].

This subsection first presents the RES-ES assessment methodology, and then its application to the case study. The RES-ES methodology focuses, as the rest of the work does, on two types of RES: agricultural biomass from leftovers and solar energy.

The concept behind the proposed RES-ES assessment methodology and the calculations to determine the non-suitability of areas for RES production based on ES tradeoff analysis can by summarized by multiplying together the *level of tradeoff between RES and ES and the level of potential ES provisioning. By multiplying these two factors, we obtain the level of non-suitability for RES production.*

First, the identification and quantification of level of tradeoff between each of the two RES and other ES was determined. In order to identify both RES' tradeoffs with other ES, the framework by Hastik et al. [8] was adopted. Hastik et al. [8] highlighted the tradeoffs between different types of RES and other six ES, and scored tradeoffs from 0 to 2, where:

- 0 meant the absence of tradeoffs, and
- 2 meant the existence of critical tradeoffs.

From the framework of Hastik et al. [8], one out of six ES considered was excluded (natural hazard protection), as for our two types of RES there is no tradeoff between RES and such ES provisioning. Then, only the tradeoff between agricultural biomass as RES and provision of agricultural products was edited, as we only considered agricultural biomass from leftovers (no dedicated crops): hence, no tradeoff with provision of agricultural tradeoff is triggered. The identification of tradeoffs was based on a matrix which combines RES production and five ES (Fig. 1).

Secondly, the level of potential of ES provisioning of different landcover categories was defined. To assign a score of ES production to different types of landcover, another matrix, which builds on the work of Burkhard et al. [43], was adopted. Burkhard et al. [43] assigned a score of ES potential provisioning to each landcover type, based on Corine landcover. The scores lied on a range between 0 and 5, where:

- 0 correspond to no ES provided, and
- 5 correspond to the highest ES supply potential for that specifying landcover type

Only the five ES selected in the first step and presented in Fig. 1 were selected from the original matrix of Burkhard et al. [43]. In order to harmonize the two different ranges of scoring for facilitating the coming steps of the methods, the Burkhard et al. [43]'s was normalized (see Fig. 2) in the range 0–2, where:

- 0 corresponds to the non-provisioning of ES, and
- 2 correspond to a high provisioning of the ES.

Third, to finalize the RES-ES assessment method, identification and quantification of tradeoffs (obtained from adopting the findings from Hastik et al. [8] and presented in Fig. 1) with ES supply scores based on

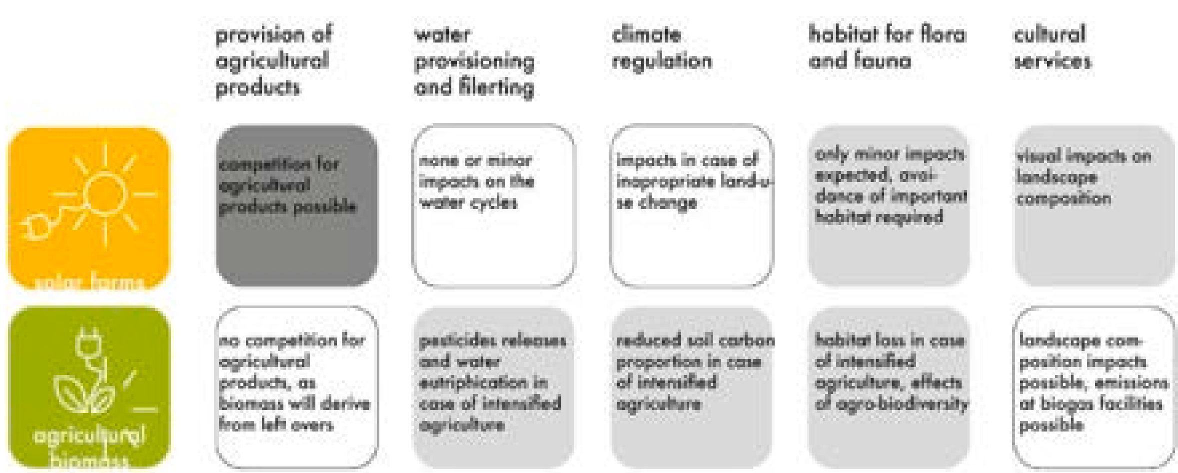

Fig. 1. Tradeoffs between RES production and other ES, adapted from Hastik et al. [8]
Legend: dark grey corresponds to level 2 of tradeoff, might grey correspond to level 1 of tradeoff, white corresponds to no tradeoff.

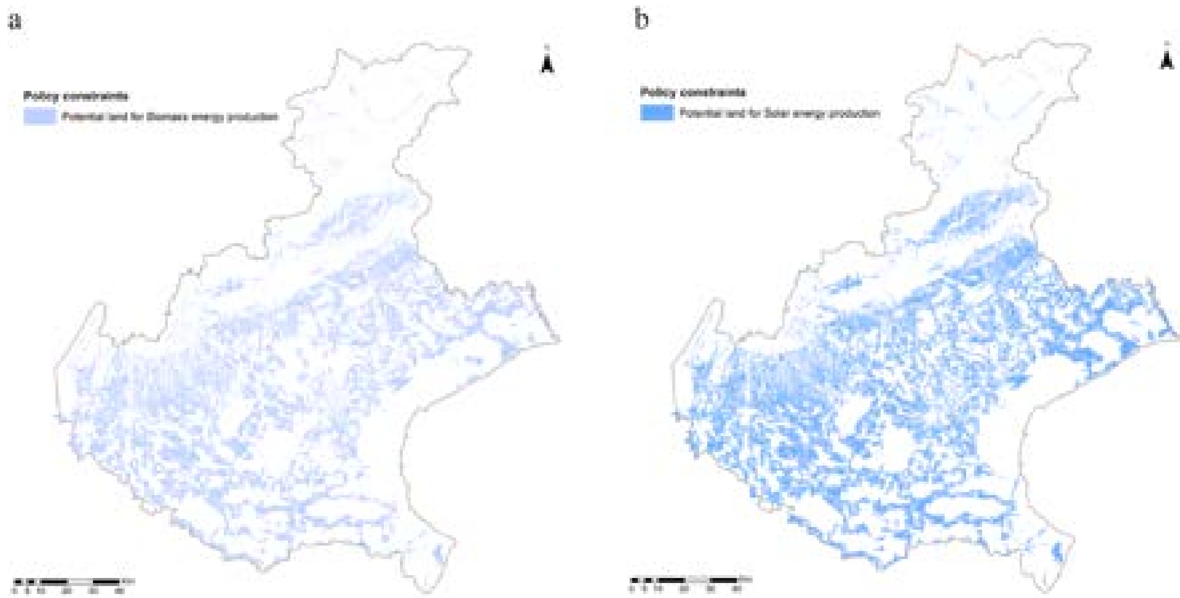

Fig. 2. Fig. 2a (on the left) shows suitable land for agricultural biomass, and Fig. 2b (on the right) shows suitable land for solar farms based on policy constraints analysis.

landcover (obtained from step 2 adopting the findings from Burkhard et al. [43], and presented Fig. 2) are combined. Specific objective this step is to assign a level of RES production non-suitability to Corine Land Cover Classes, based on the present of critical tradeoffs with other ES potential production by such Corine Land Cover Classes. For getting these non-suitability scores, for each RES and for each ES by multiplying the tradeoff's score by a specific ES supply's score, the level of negative impact of specific RES provisioning on a specific ES provisioning for a specific Land Cover Class is obtained, which determines a non-suitability of the Land Cover Class for RES production. All results were normalized in a scale from 0 to 4, where 0 corresponds to no impact of the RES on other ES provisioning, (hence suitability of the area for RES production), and 4 corresponds to the highest negative impact of the RES on other ES provisioning, (hence non-suitability of the area for RES production) (see Table 3 in the results section). In particular, values under the column "average" represent average values for non-suitability, calculating first the average values given from the 5 ES values for each Res from non-normalized values, and then normalizing results to get values from 0 to 4.

For applying the RES-ES assessment methodology to the Veneto Region case study, results from the combination of Fig. 1 and Table 2 (which is presents under the results section as Table 3) is used to produce GIS maps that assign the level of non-suitability (or "risk") to each land cover type, for agricultural biomass and solar farms respectively. Disaggregated maps, one per ES for each RES, presenting non-suitability of areas (where the score 0 indicates suitable areas for RES production, and score 4 indicates the highest level of non-suitability for RES production) were elaborated. In this way, a set of 5 maps (one per ES) was obtained for each of the two RES. Then, two synthetic maps (one per RES) were also produced considering the average ES-tradeoff scores, as well as one final map overlaying average non-suitability map for agricultural biomass, with average non-suitability map for solar farms. To produce credible results, the layer of "protected areas" was added, in order to also exclude them from the list of "suitable areas for RES production" emerging from the GIS ES tradeoffs analysis.

4.3. Comparing results: constraints VS trad-offs

On a GIS setting, results from section 4.1 and 4.2 were overlapped and compared and the final two maps (one per RES) highlight where it is possible to produce energy:

i) based on policy constraints analysis, but it is not possible based on tradeoffs analysis

Table 2
Level of potential ES provisioning, based on Corine Land Cover (level 2).

Corine Land Cover_liv III	Description	Provision of agricultural products (crops)	Water provision and filtering	Climate regulation (global)	Habitat for flora and fauna	Cultural services (recreational and aesthetic value)
211	Non-irrigated arable land	2	0	0	1	0
212	Permanently irrigated land	2	0	0	1	0
213	Rice fields	2	0	0	1	0
221	Vineyards	2	0	0	1	1
222	Fruit trees and berry plantations	2	1	1	1	1
223	Olive groves	2	0	0	1	1
224	Other permanent crops	2	1	1	1	1
231	Pastures	0	0	0	1	1
232	Other pastures	0	0	0	1	1
241	Annual crops associated with permanent crops	2	0	0	1	0
242	Complex cultivation patterns	2	0	0	1	0

Legend: 0 corresponds to the non-provisioning of ES, and 2 correspond to a high provisioning of the ES, by landcover type (adapted from Burkhard et al. [43]).

Table 3
Scores for non-suitability per land cover type, indicating the level of non-suitability of the areas for RES production, based on trade-off with ES. Scores for non-suitability production from agricultural biomass in order to minimize tradeoffs with other ES (above), and for energy production from solar farms in order to minimize tradeoffs with other ES (below).

Non-suitability scores for (agricultural) BIOMASS							
CLC_liv III	description	Provision of agricultural products	Water provision and filtering	Climate regulation	Habitat for flora and fauna	Cultural services	Average
211	Non-irrigated arable land	0	0	0	1	0	0
212	Permanently irrigated land	0	0	0	1	0	0
213	Rice fields	0	0	0	1	0	0
221	Vineyards	0	0	0	1	0	1
222	Fruit trees and berry plantations	0	1	1	1	0	3
223	Olive groves	0	0	0	1	0	1
224		0	1	1	1	0	3
231	Pastures	0	0	0	1	0	0
232		0	0	0	1	0	0
241	Annual crops associated with permanent crops	0	0	0	1	0	0
242	Complex cultivation patterns	0	0	0	1	0	0
Non-suitability scores for SOLAR							
CLC_liv III		Provision of agricultural products	Water provision and filtering	Climate regulation	Habitat for flora and fauna	Cultural services	Average
211	Non-irrigated arable land	4	0	0	1	0	1
212	Permanently irrigated land	4	0	0	1	0	1
213	Rice fields	4	0	0	1	0	1
221	Vineyards	4	0	0	1	1	2
222	Fruit trees and berry plantations	4	0	0	1	1	4
223	Olive groves	4	0	0	1	1	2
224	Other permanent crops	4	0	0	1	1	4
231	Pastures	0	0	0	1	1	0
232	Other pastures	0	0	0	1	1	0
241	Annual crops associated with permanent crops	4	0	0	1	0	1
242	Complex cultivation patterns	4	0	0	1	0	1

Legend: 0 indicates areas that are suitable for RES production (0 level of non-suitability), while 4 indicates the highest level of non-suitability.

ii) based on tradeoffs analysis, but it is not possible based on policy constraints analysis
iii) for both analysis

5. Results

5.1. Suitable areas for energy production based on policy constraints

Fig. 2 presents results from the policy constraints analysis for energy production from agricultural biomass (Fig. 2a) and solar farms (Fig. 2b) respectively. Overall, suitable land for agricultural biomass and for solar farms (based on policy constraints analyzed and mapped into section 4.1) is 414.437 ha and 449.841 ha respectively: Overall, policy constraints lead to a slight preferability towards energy production from solar farms (8% approx. In addition to suitable land for both energy sources).

Fig. 3 presents the comparison of the two maps presented in Fig. 2a and b. In particular, from Fig. 3b, it is possible to see that suitable land for both RES corresponds to almost half of the total analyzed area (47%), while the other half (49%) is not suitable for neither of the two RES. The remaining areas, which amounts for the 4% are suitable for solar farms but are not suitable for agricultural biomass. The reason of such difference can be identified going back to the list of policy constraints for the two RES (Table 1). Thus, the Regional Energy Plan presents the same set of constraints for the two RES, with the exception of “hydrogeologic risks areas” and “protected groundwaters” categories, which presents constraints for agricultural biomass, while they are not to be taken into account for solar plants, according to the Regional Energy Plan. This implies that the impacts by agricultural biomass and solar farms are expected to be almost the same by the Regional Energy Plan, with a minor preference for the use of solar farms.

5.2. RES-ES assessment methodology and related suitable areas for RES production

Table 3 presents the results from the RES-ES assessment methodology and can be used to analyze and map tradeoffs between the two RES and other ES (based on the Corine Land Cover data) in any context.

The table shows level of non-suitability (0 indicates areas that are suitable for RES production (0 level of non-suitability), while 4 indicates the highest level of non-suitability) for the two RES, for each land-cover type. A main aspect that emerges, is that, on the contrary of results based on policy constraints (section 5.1), agricultural biomass production presents much lower scores compared to solar farms, which means that agricultural biomass production triggers less tradeoffs with other ES production, compared to energy production through solar farms. Another aspect that emerges from Table 3, and that can provide useful inputs for policy makers is the interlinkage created between land cover categories and level of non-suitability. Thus, with regard to the Corine landcover, Table 3 provides a direct correlation between high risk of tradeoff between RES and ES for specific land cover categories. In particular, fruit-based cropping landcover (such as vineyards, fruit trees and berry plantations, olive groves, other permanent crops) presents a higher level of tradeoffs, and this poses them at risk.

The application of the RES-ES assessment methodology to the Veneto Region case study, provided a set of maps. In the figures, 0 corresponds to the lowest level of non-suitability – no tradeoff is triggered, and the land is suitable for RES provisioning – and 4 presents the highest level of non-suitability.

Fig. 4a and b report results from the ES tradeoff analysis for agricultural biomass only. Fig. 4a presents results disaggregated by ES, where it is visible that the highest level of non-suitability, which is still low and correspond to level, is given by tradeoffs between the provisioning of habitat services and the provisioning of agricultural biomass.

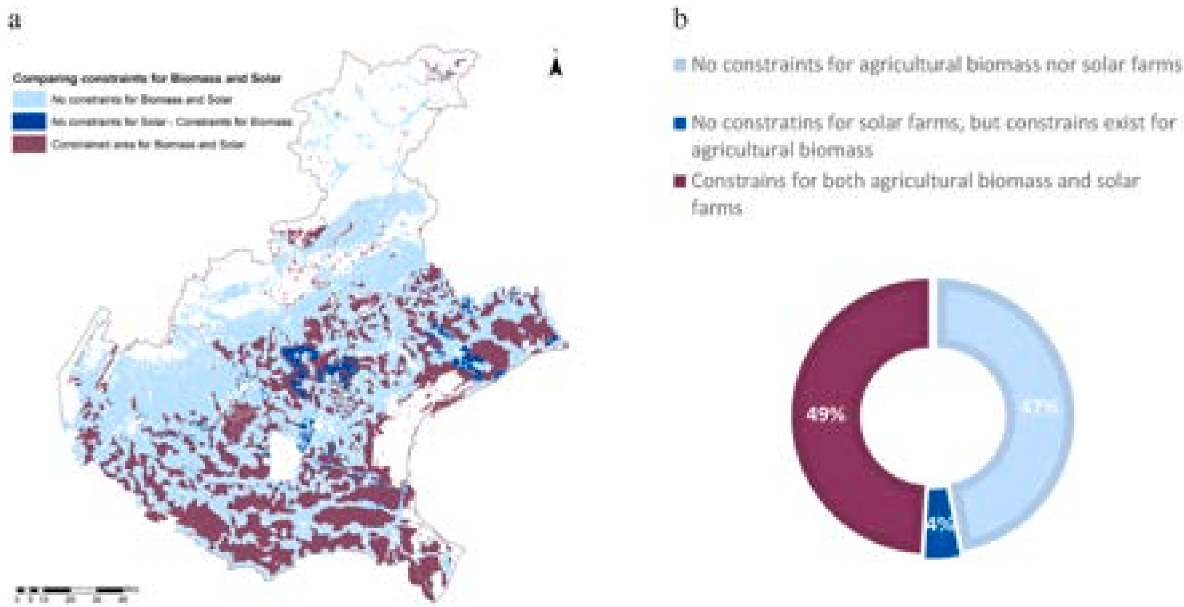

Fig. 3. Fig. 3a (on the left) shows the comparison between suitable land for agricultural biomass, and for solar farms based on policy constraints analysis on a map. Fig. 3b shows in a nutshell results from Fig. 3a.

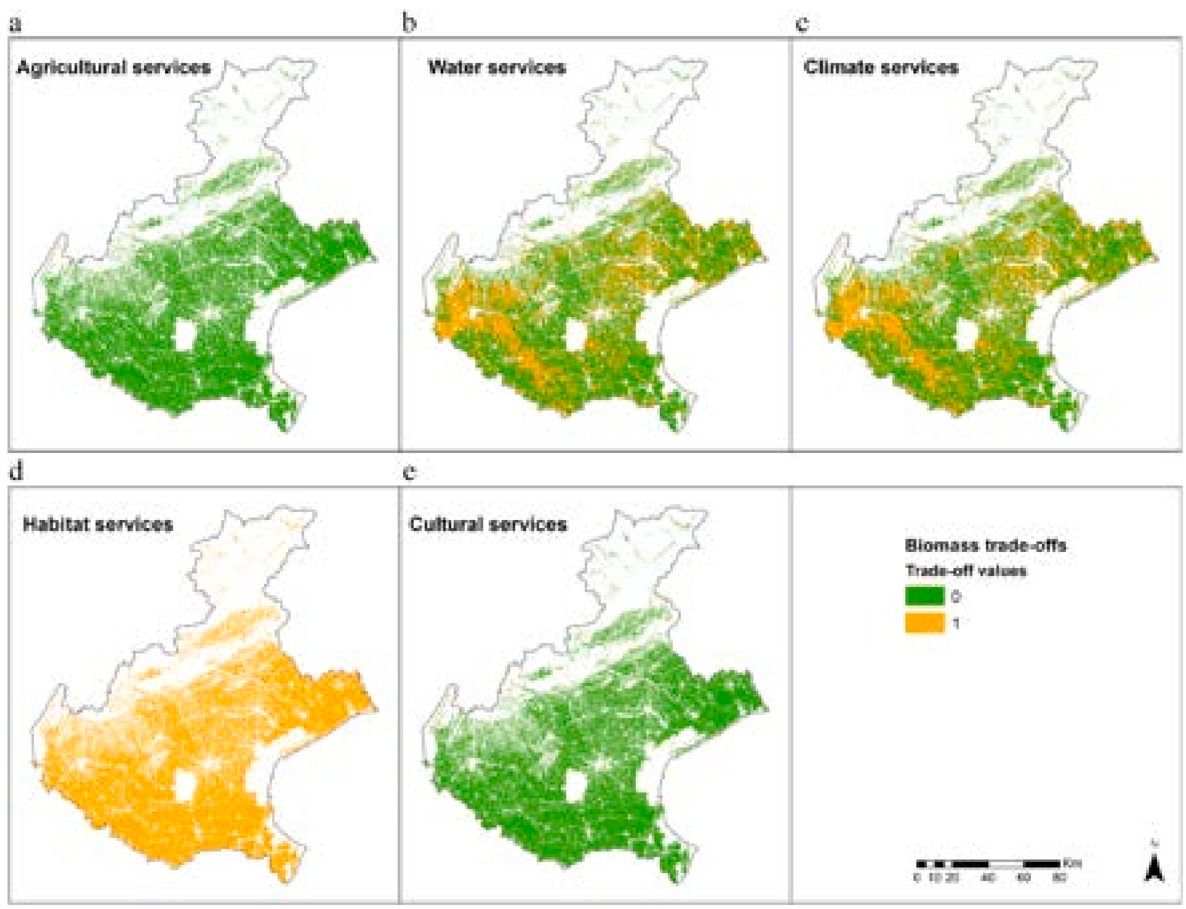

Fig. 4a. Suitable land for agricultural biomass based on ES tradeoff analysis. In particular, Fig. 4aa shows level of tradeoff between agricultural biomass and agricultural services, Fig. 4ab shows level of tradeoff between agricultural biomass and water services, Fig. 4ac shows level of tradeoff between agricultural biomass and climate services, Fig. 4ad shows level of tradeoff between agricultural biomass and habitat services, Fig. 4ae shows level of tradeoff between agricultural biomass and cultural services. Legend: level 0 of tradeoff means suitability of land for RES production, level 1 of tradeoff means suitability of land for RES production if precaution are taken.

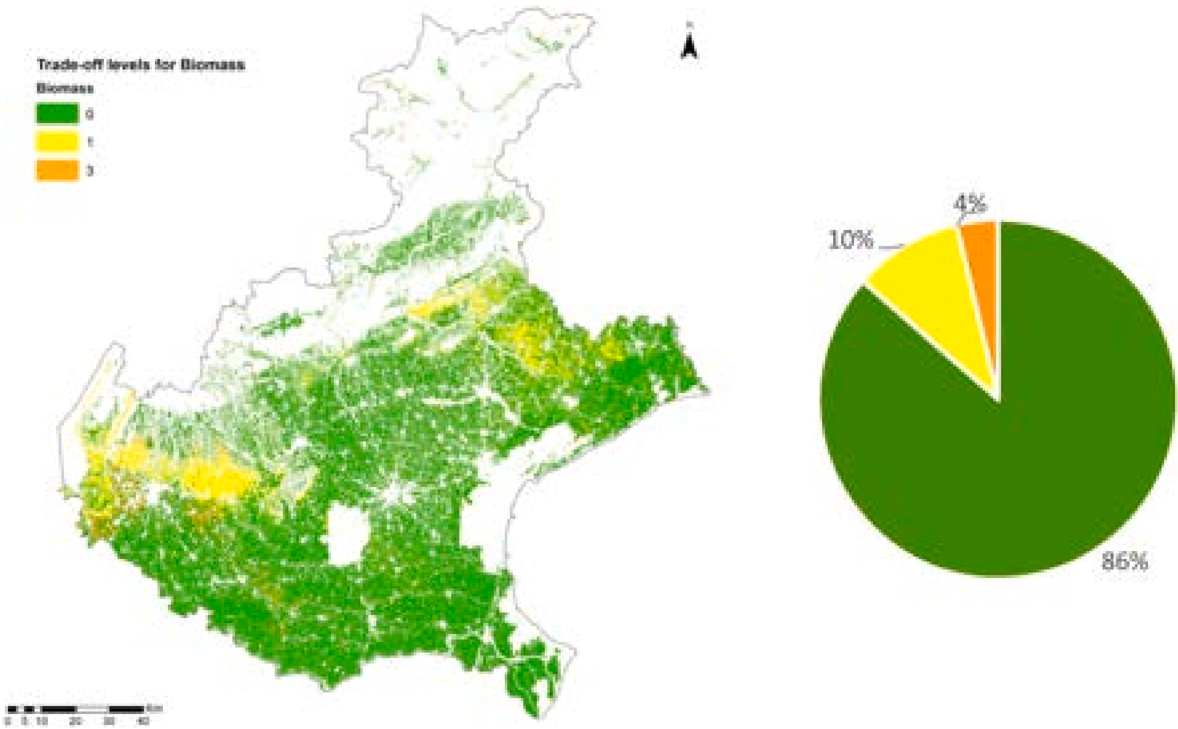

Fig. 4b. Average values indicating suitable land for agricultural biomass based on ES tradeoff analysis. Legend: level 0 of tradeoff means suitability of land for RES production, level 1 of tradeoff means suitability of land for RES production if precaution are taken, level 3 of tradeoff means non suitability of land for RES production.

Intermediate situations can be seen for water services and climate services, while no tradeoffs (hence, 0 level of non-suitability) can be seen for agricultural services and cultural services. Fig. 4b presents average values combining all 5 ES. Considering **average values**, 86% (763.298,15 ha) of the total agricultural land (CORINE level 2), excluding protected areas, is suitable (level 0 of non-suitability) for agricultural biomass production from leftovers. Then, 10% of the surface (86.638,27 ha) presents level 1 of non-suitability, no land presents level 2, approx. 4% (33.292,69 ha) presents level 3, which corresponds to, and no land presents level 4.

Fig. 5a and b report results from the RES-ES assessment methodology applied to the Veneto case study for solar farms. Fig. 5a presents results disaggregated by ES, where it is visible that the highest level of non-suitability (level 4) is given by tradeoffs between agricultural production and the provisioning of energy through solar farms. Intermediate situations can be seen for habitat services and cultural services, while no tradeoffs (hence, 0 level of non-suitability) can be seen for water services and climate services. Fig. 5b presents average values combining all 5 ES. Considering average values, 73% (653.765,13 ha) of the total agricultural land (CORINE level 2), excluding protected areas, presents a level 1 of non-suitability. Compared to average values for agricultural biomass, where the 86% of the land presented level 0 of non-suitability, the difference is relevant. For solar farms, 13% only (109.533,02 ha) of the surface present level 0 of non-suitability, and 10% presents level 2 of non-suitability, which corresponds to 86.638,27 ha. No surface presents a level 3, while 4% present a level 4 of non-suitability (33.292,69 ha).

Still, it is key to remember that even where average values present level 0 of non-suitability, it does not mean the absolute absence of tradeoffs (for example, tradeoff with agricultural production is always present), as well as the presence of tradeoffs of level 1 or 2 do not imply non feasibility of RES production. Still, average value from level 3 above call for a particular attention by decision makers.

Fig. 6 combines in one map results from Figs. 4 and 5 and assigns score equal to 0 to land where both agricultural biomass and solar farms presents no tradeoffs (level 0 of non-suitability in Figs. 4 and 5). Such type of areas corresponds to the 13% (113.227,24 ha*)* of the total. From the map, we can state that 13% of total land is suitable for both types of RES, 74% of land suitable for agricultural biomass and solar farms can be considered if measures to minimize impacts on agricultural production and cultural services are taken. The 10% of land is suitable for agricultural biomass if measures to minimize impacts on habitat, water and climate services are taken, while it is not suitable for solar farms. The remaining 4% of land is not suitable for either of the two RES production.

In general, the application of the RES-ES tradeoff assessment methodology provides a completely different picture, compared to the spatialization of current policy constraints. First of all, ES-tradeoff analysis identifies - based on average values - solar farms as more impacting compared to agricultural biomass, which is the contrary of what policy constraints demonstrate. The disaggregated results of the two RES show that i) agricultural biomass mainly triggers tradeoffs with habitat, followed by water services and cultural services, ii) solar farms mainly trigger tradeoffs with agricultural services, followed by habitat services and cultural services.

5.3. Comparing results from policy constraints analysis with results from RES-ES tradeoff assessment application

By comparing results from section 5.1 and 5.2, it emerges that overall, suitable area for RES production based on policy constraints analysis (meaning where no constraints are in place for the land cover level 2), and based on the tradeoff analysis (meaning where non-suitability scores are below level 2 both RES), it emerges that based on policy constraints less territory is suitable for RES production. In figures, we can say that around the 50% of territory that is suitable for RES production based on RES-ES assessment methodology, is also suitable based on the policy constraints. In both cases (5.1 and 5.2), the highest amount of land fits both RES production. Another difference, as mentioned, is that policy constraints tend to promote solar farms as if they were less impacting compared to agricultural biomass, while based

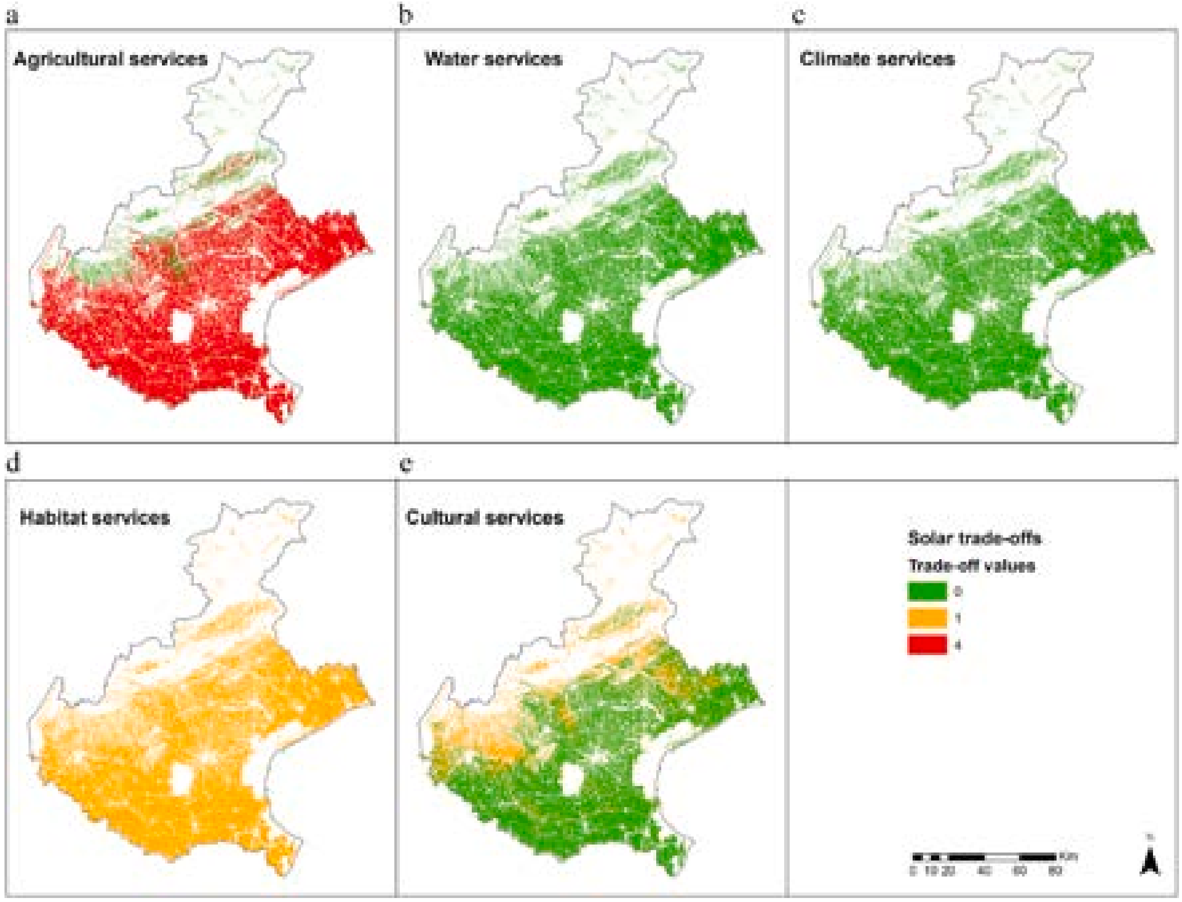

Fig. 5a. Suitable land for solar farms based on ES tradeoff analysis. In particular, Fig. 5aa shows level of tradeoff between solar farms and agricultural services, Fig. 5ab shows level of tradeoff between solar farms and water services, Fig. 5ac shows level of tradeoff between solar farms and climate services, Fig. 5ad shows level of tradeoff between solar farms and habitat services, Fig. 5ae shows level of tradeoff between solar farms and cultural services.
Legend: level 0 of tradeoff means suitability of land for RES production, level 4 of tradeoff means no suitability of land for REs production.

on ES-tradeoff analysis, agricultural biomass in presented to be less impacting (on average values) than solar farms.

Figs. 7 and 8 compare results from section 5.1 (land suitability for RES production based on policy constraints), and from section 5.2 (land suitability for RES production based on ES tradeoff analysis) for agricultural biomass (Fig. 7) and solar farms (Fig. 8) respectively.

Fig. 7 shows that the 51% of land (453.610,69 ha) is suitable for agricultural biomass based on ES tradeoffs analysis, but not based on policy constraints: a missed opportunity (in yellow). 45% of land (396.325,73 ha) is suitable for both approaches. Policy constraints and RES-ES tradeoff assessment also coincide in the 2% of areas colored in blue, where for both categories no RES production shall be allowed. However, the numbers that shall alert decision makers' attentions are the 2% or areas in red, which present tradeoffs but are not constrainted by policies.

Fig. 8 presents slightly different numbers, but the same relations among them. Thus, Fig. 8 shows that the 44% of land (390.483,22 ha) is suitable for agricultural biomass based on ES tradeoffs analysis, but not based on policy constraints: a missed opportunity (in yellow). 42% of land (372.814,93 ha) is suitable for both approaches. Policy constraints and RES-ES tradeoff assessment also coincide in the 5% of areas colored in blue, where for both categories no RES production shall be allowed. However, the numbers that shall alert decision makers' attentions are the 9% or areas in red, which present tradeoffs but are not constrainted by policies.

This latter category (the areas in red, which represent the 2% for agricultural biomass, and the 9% for solar farms) is critical because in these areas RES production that triggers tradeoffs with other ES provisioning, is not limited by any policy constraint. In this case, further reasoning by policy designers is needed.

6. Discussion and conclusions

This study aimed at supporting the design of sustainable energy-related policies and plans, by investigating the convergence of RES and ES. Thus, applying an ES lens to RES identifies possible negative impacts of RES development, and provides insights that can ensures RES-related decisions and their upscaling towards sustainable development. The present work couples GIS evaluation and energy planning, which represents a novelty in the energy planning field aiming at providing a tailored set of information to policymakers aiming at the RES development.

Four critical aspects emerged from the work: i) general synergies between RES and ES emerged from the work; ii) renewable policy constraints implications, with specific attention to the case study; iii) spatial planning and energy policy challenges; and iv) potential future steps in the energy policy design and research.

The core-product provided by this work is the methodology. The methodology developed and tested in this study is a GIS-based tool that demonstrated to be easily applicable to any regional context to detect suitable areas for either agricultural biomass or solar farms. The methodology can be applied to other regional context in Europe, at is needs Corine Land Cover data. Also, the methodology produced data and empirical evidence able to provide key insights in terms of synergies and tradeoff between RES and ES.

As evidenced in the results section, agricultural biomass production

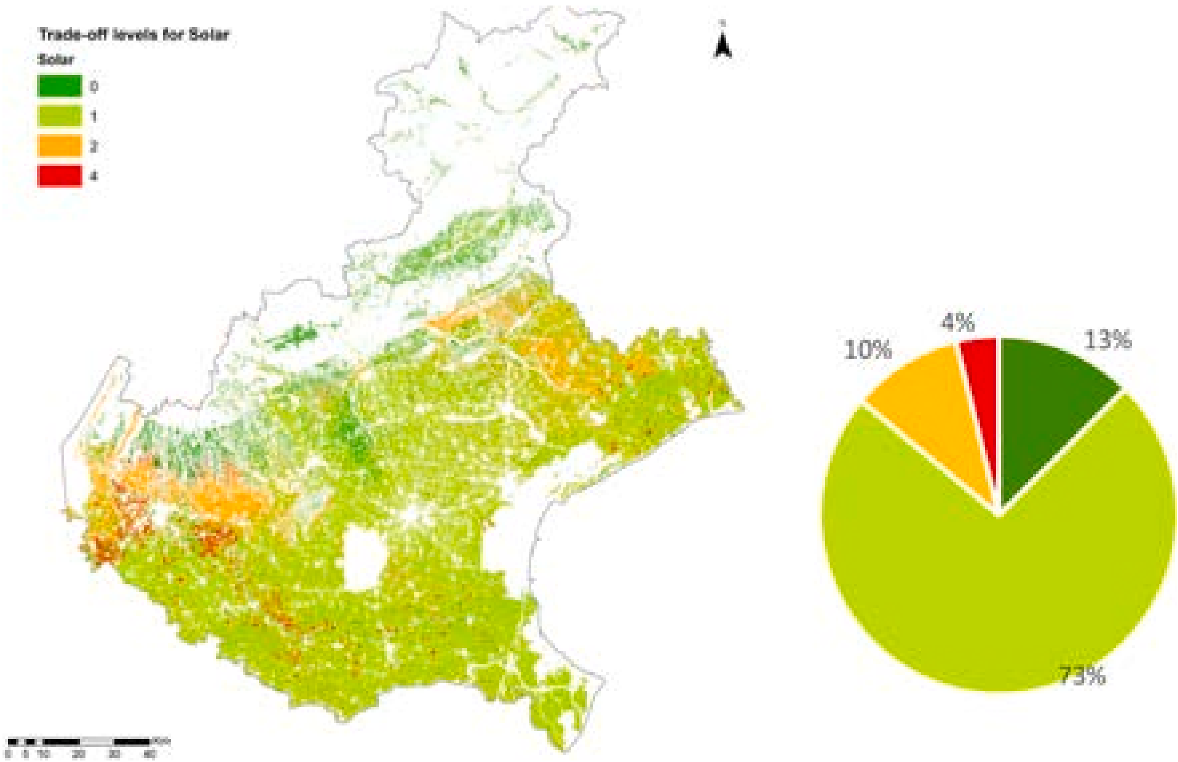

Fig. 5b. Average values indicating suitable land for solar farms based on ES tradeoff analysis, indicated through a map on the left, and through a graph on the right. Legend: level 0 of tradeoff means suitability of land for RES production, level 4 of tradeoff means no suitability of land for REs production.

presents traits of synergy with other ES, such as provision of agricultural products, water provisioning and filtering, climate regulation, and cultural services. Likewise, solar farms present traits of synergy with other ES, such as water provisioning and filtering, climate regulation, and cultural services.

In both cases of agricultural biomass and solar farms, fruit-based cropping landcover, such as vineyards, fruit trees and berry plantations, olive groves, other permanent crops, presents higher score of tradeoffs between RES and certain ES. This poses the ES at risk, and hence, a protection-oriented policy to these areas becomes necessary.

The work undertaken to build the RES-ES tradeoff assessment identifies agricultural biomass as RES that trigger less tradeoffs with other ES, compared to solar farms.

Concerning the renewable policy constraints implications, the case study shows divergent results in terms of RES preferability; thus, it emerges that solar farms are less impacting compared to agricultural biomass. In addition, the similarity of sets of constraints per RES shows that renewable policy constraints neither reveal nor take into account the different impacts of the two RES to other ES.

The third step of the methodology consisted in overlapping the policy constraints analysis' results with the tradeoff assessment's results, and this allowed to detect consistencies and mismatches. Almost half of the agricultural land, 50% (approx.), shows that policies constraints and RES-ES tradeoff assessment agree on suitability or non-suitability of areas for RES production.

On the other hand, the remaining half presents mismatches, showing a high percentage of areas that are recalled as "missed opportunities" – e.g. the RES-ES tradeoff assessment's areas are "suitable" for REs production, while policy constraints' areas are non-suitable. Within this second half, a percentage between 2 and 9% highlights hotspots of potential tradeoffs that are not regulated by policy constraints. This opens the floor for important considerations within the energy policy making arena – in Italy, Veneto Region represent a case among many others, in this sense.

Focusing on planning policies challenges, one of the issues that this study aimed to address and to solve is the inherent risk of scale mismatch between the analytical phase and the decision-making phase. Reminding that landscape transformations introduced by the maximization of RES supply need to be planned at regional or local scale [5,7], this study provided technical information and insights at the same scale of the decision-making. Moreover, it responds to the call raised by Smith et al. [16]- among others - to provide action-oriented tools which are designed based on a fit-for-purpose analysis. RES potential operativity was spatialized at regional scale by employing an integrated planning approach, aiming at the "*planning of a case*" [9]. This approach allowed to analyze possible impacts of choices and supported the future planning of a case, instead of assessing what exists. No *scenario* were developed, although the premise for building future *scenario* was set and the work provides potential impact foresights. Concerning an interpretative issue of the results, the definition of "non-suitability", when average values indicate *suitability*, does not necessarily mean that tradeoffs are not triggered at all. Instead, it says that tradeoffs are minor and should be also considered. Hence, the attention paid to disaggregated data helped in providing exhaustive and complete information.

Overall, this work builds on the knowledge at the crossroad of RES planning, ES tradeoff assessments, and GIS-based evaluations. It provides a replicable method, which is not data-hungry, aiming to support a regional authority to map and quantifying potential suitable areas for RES and potential impacts on a set of ES. In this way, this work addresses the operationalization and localization of possible actions to promote the energy transition. It also agrees with the scholarship about proposing a narrative on renewables and the identification of suitable areas to avoid negative impacts from clean energy production [14,44–48].

Furthermore, it contributes to the knowledge of RES-ES nexus in the frame of regional energy strategies and plans. The interpretation of the results leads to the assertion that if new policy constraints would be designed to be consistent with ES tradeoff analysis, the set of constraints for agricultural biomass would not coincide at all with the set for solar farms. Thus, if the two RES impact differently on ES provisioning, the set of constraints needs to reflect such differences in behaviour.

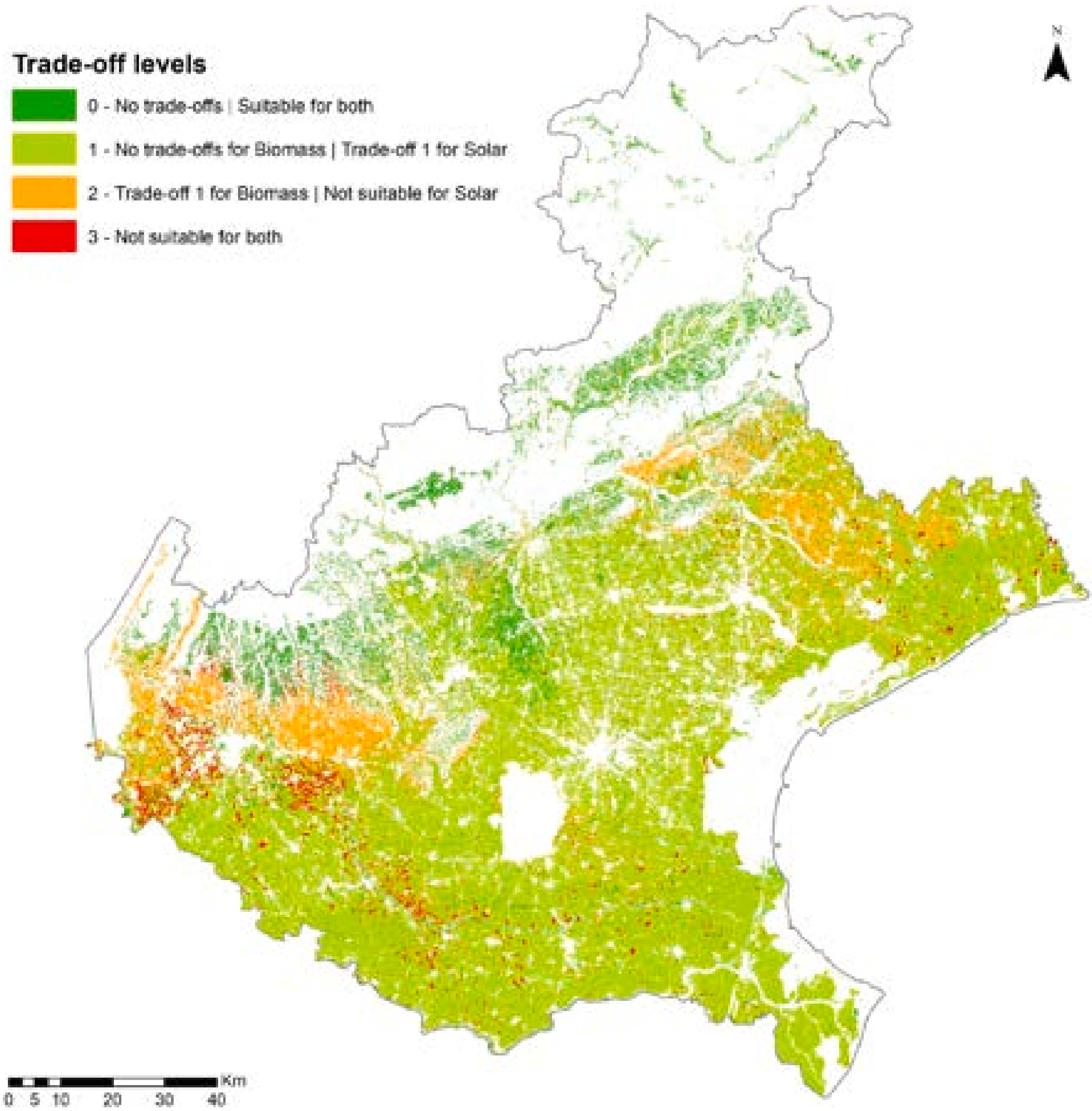

Fig. 6. Combination of tradeoff levels (non-suitability) for agricultural biomass and non-suitability for solar farms.

The application of the methodology to other regional contexts, to identify common trends and peculiarities, as well as scenario modelling, and the inherent understanding of the effective mix of RES, would also represent a precious further step to support decision-makers. In addition, further ES could be included in the tradeoffs analysis aiming to incorporate the ones crucial for the economies, the society and the cultural identities.

The work also presents some limitations. With regard to the case study application and the policy constraints analysys, the study limited the list of policy constraints to the one published in the PER [25] - further related legislation was not analyzed. Policy constraints for biomass refer to plants installation, not to the direct production of biomass, even though it is not clearly stated. However, it was not indicated in the PER any information about the production of biomass, neither from dedicated crops nor agricultural leftovers. In this sense, the study built the analysis on a gap of the policy instrument, not to stop the research due to lack of information, and to highlight an aspect that deserves to be further investigated in the future updated version of the PER. In addition, by mapping only the policy constraints in the PER, the study overcame the mapping of technical constraints -such as the slope - in order to be as much consistent as possible with the targeted document, and to produce useful insights to the regional authorities. Another limit referred to the mapping was the impossibility to detecting agricultural areas providing valuable products (such as DOP, IGP, DOCG, …)[1] as the shape file available adopts a scale that is too coarse - making the analysis useless, as the whole Region looks like producing valuable food.

Concerning the research topic and its broader theoretical dimension, this study paves the way for further deeper analysis. It is encouraged to researching on synergies jointly with tradeoffs, in order to start identifying main bundles of ES tradeoffs and synergies to enhance multifunctional landscapes. In addition, research endeavours aiming at the improvement of tools and mapping approaches can help overcoming current barriers to the upscale of RES and can lead to a promising research path.

[1] Acronyms of High-end valuable agricultural products and their origin land. DOP = Denominazione di Origine Protetta; IGP = Indicazione Geografica Protetta; DOCG = Denominazione di Origine Controllata e Garantita.

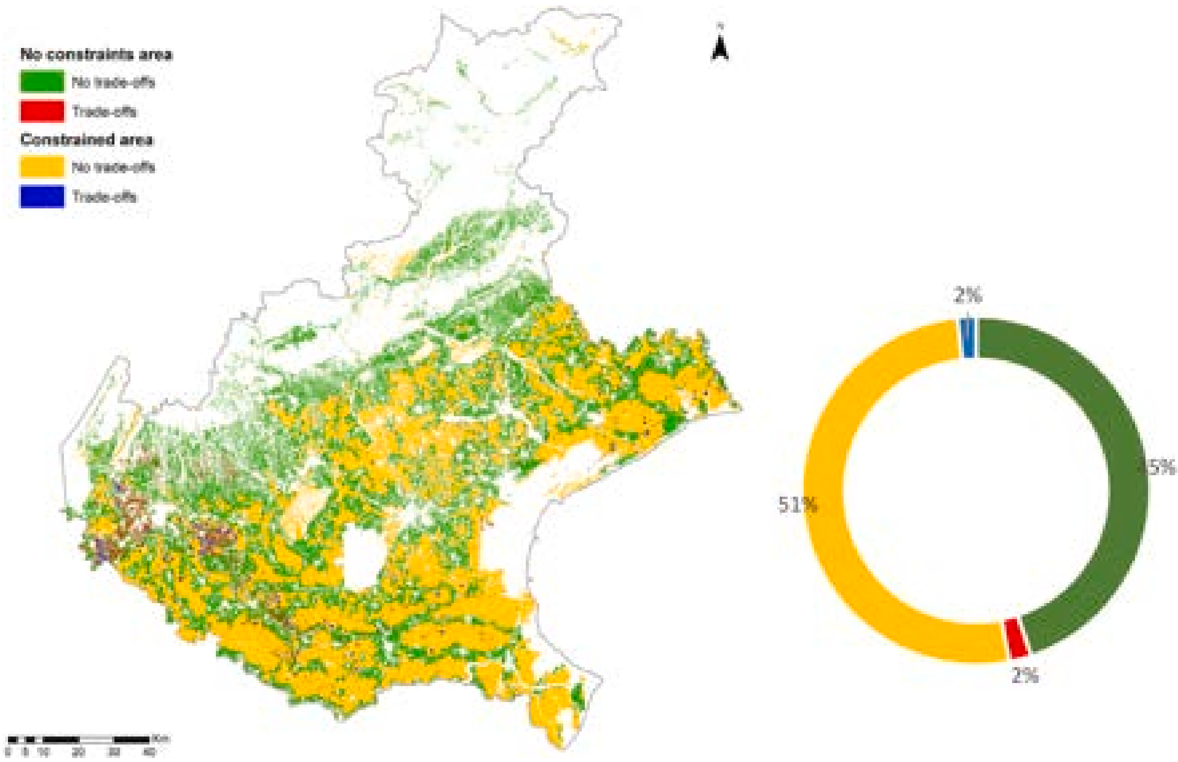

Fig. 7. Suitable land for agricultural biomass comparing policy constraints and tradeoff analysis.

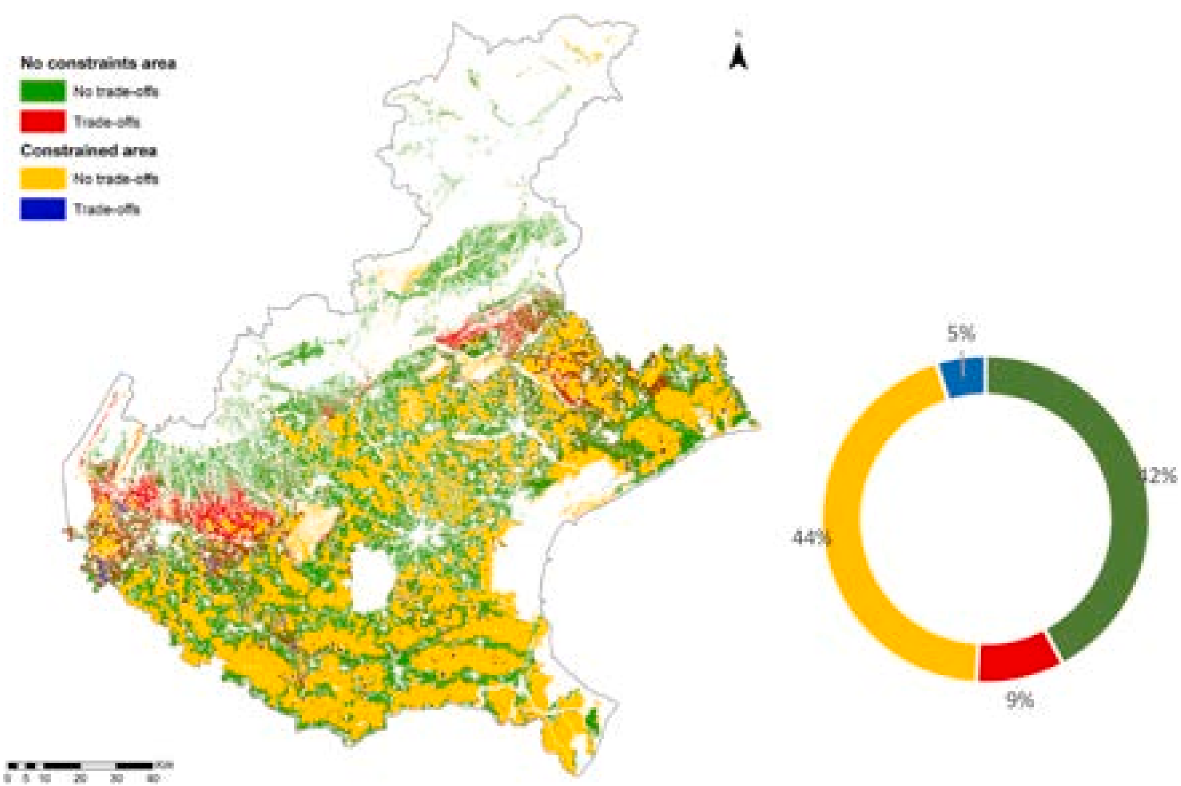

Fig. 8. Suitable land for solar farms comparing policy constraints and tradeoff analysis.

CRediT authorship contribution statement

L. Zardo: Conceptualization, Methodology, Writing – original draft. **M. Granceri Bradaschia:** Methodology, Data curation, Software, Validation, Writing – review & editing. **F. Musco:** Supervision. **D. Maragno:** Software, Supervision.

Declaration of competing interest

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

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