Renewable Energy Sources and Ecosystem Services: Measuring the Impacts of Ground-Mounted Photovoltaic Panels

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Abstract. Europe is facing complex challenges related to rising natural gas prices and the need for energy independence due to the energy crisis of 2022. To address these challenges, the European Commission presented the REPowerEU plan, which aims to accelerate the deployment of renewable energy sources (RESs), achieve greater energy autonomy, accelerate the green transition, and facilitate investments in renewable energies by 2027. Among the different RESs, the potential of ground-mounted photovoltaic (GMPV) panels in Europe is demonstrated by the spread of large-scale solar installations. Although promoting renewable energy through GMPV technology is in line with the seventh Sustainable Development Goal, it may conflict with the 15th SDG, which aims to protect terrestrial ecosystems. To identify potential impacts that may be generated by the installation of GMPVs in relation to ecosystem services (ESs), this study explores evaluation methodologies for their integration into decision support frameworks. The research reviews different methods available to quantify and/or monetize different impacts for provisioning, regulating and maintenance, cultural ESs and compares three methodological frameworks that can be used to integrate these results into decision-making: Cost-Benefit Analysis (CBA), Multi-Criteria Decision Analysis (MCDA), and COmpoSIte Modeling Assessment (COSIMA). The outcomes could be useful in supporting public and private decision-makers to structure an evaluation framework useful in defining suitable areas where to install GMPVs according to the costs, co-benefits, and negative externalities generated.

Keywords: Renewable Energy Ecosystem Services (REES) · Habitat services · Solar park

1 Introduction

The energy crisis of 2022 has led Europe to face, on the one hand, very complex challenges related to rising natural gas prices and, on the other, the need to diversify energy supplies to increase the continent's energy independence [1]. In response to the difficulties and upheavals in the global energy market, the European Commission presented the

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O. Gervasi et al. (Eds.): ICCSA 2023 Workshops, LNCS 14108, pp. 429–443, 2023.
https://doi.org/10.1007/978-3-031-37117-2_29

REPowerEU plan intending to bring forward to 2027 the targets already set for 2030 by giving a decisive boost to the deployment of renewable energies, achieving greater energy autonomy, accelerating the green transition and facilitating investments in renewable energies [2]. To implement the REPowerEU programme, Member States will not only work on the natural gas sector through joint exploration and trading, construction of storage and transport infrastructure. Indeed, the EU wants to increase the use of solar energy through the EU Solar Strategy, which recognizes the potential of rooftop photovoltaics in contributing to the climate and energy goals of the European Green Deal [3].

While the installation of rooftop photovoltaics requires the involvement of many small private investments to achieve the targets set, the installation of ground-mounted photovoltaic (GMPV) panels could lead to the promotion of larger projects that speed up the energy transition. On the one hand, this is driven by the promotion of renewable energy expansion through incentives from European governments. On the other hand, economies of scale come into play with larger projects becoming an important factor for the profitability of a project. The spread of GMPV in Europe is also demonstrated by data from the European Photovoltaic Industry Association (EPIA), which records how large-scale solar installations have grown significantly in recent years, exceeding the capacity of those installed on rooftops [4]. Indeed, in 2020, the total installed capacity of large-scale solar installations in Europe reached 23 GW, and the GMPV size is expected to continue to grow to 60% by 2025.

Although promoting renewable energy through GMPV is in line with the seventh of the Sustainable Development Goals (SDGs), which aims to ensure affordable, reliable, sustainable, and modern energy access for all, it may conflict with others [5]. In fact, the 15th SDG aims to protect, restore, and promote the sustainable use of terrestrial ecosystems, halt and reverse soil degradation, and halt biodiversity loss that are potentially threatened by the GMPV market. Moreover, the implementation of these infrastructures cannot be separated from the preservation of the landscape as heritage. This entails having to take into consideration the system of values with which the landscape is endowed, their protection and preservation [6]. The land use change (LUC) due to the development of renewable energy resources (RESs), not just photovoltaic (PV), poses both opportunities and risks to ecosystems [7]. As such, given the heightened awareness of the ecological emergency and the exponential growth of renewable energy in response to the increase in global per capita energy consumption, it is necessary to consider the potential risks of implementing RESs at the expense of natural ecosystems. On one hand, many studies show that the development of energy-efficient buildings and industrial processes, as well as electric vehicles, requires fewer energy inputs [8]. On the other hand, it is not possible to overlook the infrastructure needed to meet the remaining demand, also for new RES. Developing the scientific understanding of land consumption and related ecosystem services (ESs) for GMPVs becomes critical as solar energy covers an important role in European energy policies, dominating the entire renewable energy sector both now and in view of future forecasts.

In this study, we identify the potential impacts that can be generated by the installation of GMPVs in relation to ESs and explore evaluation methodologies for their integration into decision support frameworks. In detail, the research reviews the different methods available to quantify and/or monetize different impacts and introduces three methodological frameworks that can be used to integrate these results into decision-making: Cost-Benefit Analysis (CBA), Multi-Criteria Decision Analysis (MCDA), and a composite decision support by combining them, i.e., the COmpoSIte Modeling Assessment (COSIMA). The study could be useful in supporting public and private decision-makers to structure an evaluation framework useful in defining suitable areas where to install GMPVs according to the costs, co-benefits and negative externalities generated.

After the Introduction, the chapter is structured as follows; Sect. 2 describes the different ESs generated by RESs with a focus on GMPVs; Sect. 3 explores the assessment and valuation methods of related ESs; decision-making frameworks and their potentials are presented in Sect. 4; Sect. 5 summarizes conclusions and future perspectives.

2 Ecosystem Services Related to RES

2.1 An Overview of Ecosystem Service Impacts in RES

RES offers a variety of benefits on both the environment quality and human life, spanning the reduction of greenhouse gas emissions from fossil and some types of air pollution, the diversification of energy supply reducing dependence on imported fuels and the creation of economic development and jobs in manufacturing and installation [9].

However, the spread of RES currently involves trade-offs with the environment and biodiversity protection. In order to consider both environmental and social issues in RES development, a comprehensive analysis of the benefits and impacts produced by RES is required from an ecosystem service perspective. The research discussion regarding the ES offered or impacted by RES is still ongoing [10]. From the CICES classification, “renewable abiotic energy” and “renewable biofuels” have been included as services: respectively, for the first group, they consider wind, hydro, solar, tidal, and thermal, while, for the second, plant and animal-based resources [11]. Recently, Schetke et al. (2018) [12] refer to them as Renewable Energy Ecosystem Services (REES).

However, these two interpretations (i.e., by the CICES group and Schetke et al. 2018 [12]) do not imply that the different types of RES (i.e., biomass, geothermal energy, hydropower, photovoltaic systems and wind power) produce various benefits and impacts with respect to the other ecosystem services. RES is also viewed as problematic both in terms of provisioning services, regulating and maintaining, and cultural ones [10, 13, 14].

One of the most critical impacts on provisioning services generated by the development of all RES is land use competition. Additionally, for biomass production, the removal of branches or leaves in wood management may impact soil fertility by removing nutrient-rich residues [10].

Several impacts can be observed on the habitat and, therefore, on regulating and maintenance services: for example, wind power may have destructive and disturbance effects on the air routes of specific birds and bats species [15]; deep and near-surface geothermal systems can modify habitats due to soil temperature changes [8]; hydropower can affect various physical and hydrological alternations resulting in habitat and biotope losses, decrease in ecological integrity and connectivity [16].

Concerning cultural services, RES can have a visual impact on the traditional and pristine landscape due to the construction of technical and artificial elements, particularly for both wind power and GMPV systems [10]. Additionally, hydropower can even destroy the existing natural and cultural landscape [17].

2.2 Ground-Mounted PV and ES

Photovoltaic energy is generally considered to have benign environmental impacts, as it does not generate noise or chemical pollutants during use. It is one of the most viable renewable energy technologies for use in urban and non-urban settings, such as scenic areas and national parks, where the ability to avoid pylons and cables is a great advantage [18]. However, it is also necessary to consider the negative aspects that these infrastructures, especially large ones installed on the ground, can generate [10]. Picking up on what was said in the previous section, here we explore in detail the positive and negative impacts generated by GMPVs in relation to ESs.

Provisioning Services. The resources that natural and semi-natural ecosystems generate, such as the production of food, drinking water, timber and fuel refer to the category of provisioning services. Agriculture, which serves as the foundation to produce the tangible goods required for human nutrition, is included in this typology. When installed in previously farmed areas, medium and large GMPV plants consume land and take up less space that could have been used for cultivation [19]. Therefore, energy production is likely to be considered competitive with food production, as in the case of crops dedicated to the production of renewable energy sources, such as agricultural and forestry biomass [20]. Agrovoltaic (AV) systems are one strategy that is emerging to address this problem and enable the coexistence of GMPV and agricultural production [21]. When preserving productive farmland, ensuring energy security, and environmental protection are equally important, this solution could become significant. In this sense, AVs can entail combining the development of GMPV solar energy with one or more of the agricultural activities listed below, such as crop cultivation (also known as "AV-cropping"), animal husbandry (also known as "AV-animal"), or habitat improvement to enhance ESs ("AV-habitat") [22, 23]. AVs can increase the effectiveness of the use of land, the use of water, and the production of energy while also demonstrating the viability of these dual land uses to mutually benefit different ecosystem goods and services. The cultivation of agricultural species that require semi-shaded environments, on-site habitat improvement measures like the establishment and maintenance of native grasses and forages, and the associated potential ecosystem services of these strategies for agricultural production are all examples of benefits that can be multiple in this sense [24].

Regulating and Maintenance Services. Among the many regulating ecosystem services are those that keep ecosystems healthy and functioning properly, control water, erosion, pollination, and safeguard against hydrogeological disruption brought on by wind and rain. The stabilization of the climate is just one example of the many services in this category that benefit people both now and in the future. The preservation of biodiversity is another crucial component. In terms of GMPV, the impacts associated with ESs are highly dependent on previous land uses. Impacts could be positive if disused areas, such as brownfield areas, industrial sites or former caves, are redeveloped, or if selective agricultural extensification occurs. In this case, the development of a photovoltaic field could provide benefits in terms of regeneration of areas that cannot be dedicated to agricultural use due to location or environmental concerns [10]. Negative effects, on the other hand, are likely to occur in ecologically sensitive areas due to shading effects and microclimatic changes. Another issue is the fragmentation of ecological corridors for certain animal species because of the fencing required around the facilities [25–27]. However, it is worth mentioning that the above-mentioned strategies related to AV systems can provide a combination of solutions to limit impacts on habitats, preserve biodiversity and ensure regulatory services related to carbon sequestration and erosion control. Solar panels can be mounted on pile or screw foundations, such as stakes, rather than heavy foundations, to reduce negative effects on the natural functioning of the soil (filtering and buffering characteristics). To improve the fence, a space can be left between the base of the barrier and the ground. Passages can also be created by modifying the structure of the fence to allow animals to walk freely.

Cultural Services. Natural ecosystems contribute to the maintenance of human health by producing opportunities for spiritual enrichment, cognitive development and recreational experiences [28]. One of the drawbacks of GMPVs is related precisely to their presence in lowland and hillside landscapes often associated with agricultural nature, cultural identification, and space for recreation. Generally, GMPVs are significantly distinguishable from the natural or agricultural environment in which they are often built because of their size, regular geometry, and highly reflective surfaces [29]. In this regard, GMPV infrastructure views have been recognized as a potential source of negative aesthetic impact on national park units, wilderness areas, national historic and scenic highway corridors, residential towns, and other visually sensitive places. In regions with a high value for scenic views, it should be prioritized to examine the visual effects induced by GMPV [11]. In this regard, visual compatibility standards that maximize GMPV context integration can be found [30]. Furthermore, as seen above, it is well recognized in the literature that the installation of GMPV can lead to a change in land use. While the occupation of an agricultural field can lead to the loss of temporary ES, the occupation of public land can lead to the overturning of the recreational and spiritual benefits provided by the area. In this regard, the tangible and intangible components of the landscape must both be considered in order to understand how the PV system influences the perception of the landscape in urban, rural and natural contexts [31].

3 ES Assessment for Ground-Mounted PV

These two decades (and more) of research and applications on ESs have intensively investigated how to express their values and benefits [32]. A first major effort sought to translate these values into economic and monetary scales, since the loss or gain of ESs often involves economic costs to be compensated or avoided [33–35]. A second crucial step coincides with the increasing attention on environmental issues that require the quantification of the amount of ecological and biophysical values produced by a territory [34, 36]. The research in this field has strongly increased also thanks to the development of GIS technologies and a variety of tools able to translate land use changes into quantified physical values for each ES [37, 38], such as INVEST [39]. A third ongoing process has regarded the assessment of cultural and social values produced by a territory or an area. Some tentative works were done to consider these subjective and individually different opinions in evaluation procedures, using qualitative assessments, narrations and constructed scales, deliberative processes, locally defined metrics or guiding principles [40], but also econometric models.

According to these three families of values, this section provides a comprehensive overview of how to assess the loss or gain of ESs due to the development of GMPV. In particular, Table 1 summarizes all the possible indicators, i.e., physical, monetary and qualitative, to be used for the assessment of each benefit or impact generated according to an ES perspective. Moreover, the last two columns of Table 1 respectively suggest the most suitable appraised methods for the assessment of each ES according to the indicator used and some examples of applications in which similar work was done.

From Table 1, it is evident the ability of physical indicators to cover the entire list of benefits and impacts compared to monetary and qualitative scales. Their quantification is often easy to be performed knowing the characteristics of the project developed or using GIS data. However, the variability of units of measurement does not allow to have a comprehensive assessment of GMPV in a specific territory, without the use of specific procedures able to convert them into a unique scale. On the contrary, monetary indicators solve this conversion problem, since each impact is estimated from the beginning through a monetary scale. The use of market valuation, both based on market or cost-based prices, are quite easy to be estimated. This approach, however, is not without drawbacks. Firstly, it has to deal with the difficulty of some estimating procedures, such as revealed and stated preferences, which require the collection of a huge amount of data for high quality and representativeness of the estimation procedure. Secondly, these monetary indicators are not always able to quantify all the impacts. As for the case of GMPV, benefits such as plant community changes or biodiversity increase are hard to be assessed from this economic perspective. Finally, regarding qualitative indicators, they represent a more flexible way to evaluate some benefits and impacts, in particular when physical or monetary indicators are hard to be quantified. However, also these indicators require specific procedures to convert them into a unique scale for obtaining an overall performance of all benefits and impacts produced, as for physical indicators. At the same time, as for monetary indicators, qualitative scales are not always the most suitable way to assess some ESs.

From these considerations, it is clear that specific evaluation methods and, particularly, a combination of them is necessary to assess multiple ecosystem services.

Table 1. Ground-mounted photovoltaic panel (GMPV) impacts on ecosystem services (ESs) and related indicators and appraisal methods.

CICES ES categories	Impacts	Physical indicator (PI)	Monetary indicator (MI)	Qualitative indicator (QI)	Appraisal methods	Sources
Provisioning services	Competition with Food/Fodder/Wood production	sqm or tons year^{-1}	€/tons year^{-1}	Degree of suitability of crop production	PI: GIS-based MI: Market valuation (market prices) QI: GIS-based/Spatial MCA	PI: [41] MI: [42] QI: [43]
	Land-mix for pastures, honey production, as well as cultivation of plants (e.g., aloe vera, lettuce, aquafarming)	sqm or kg (tons)	€/kg year^{-1} or €/ton year^{-1}		MI: Market valuation (market prices)	[44–46]
Regulating and maintaining ser-vices	Plant community changes	sqm or number of species unable to survive		Nominal		[47]
	Biodiversity increases if combined with plants for pollination	sqm				[46, 48]
	Alternation of green corridors in case of fence constructions	sqm	€/sqm		MI: Market valuation (cost-based: compensation costs)	[49]
Cultural services	Visual impact on "pristine" or "traditional" landscapes due to the construction of technical/artificial elements	• Visibility coefficient from settle-ments/panoramic view; • Distance coefficient from settle-ments/panoramic view; • Number of PV; • Number of close inhabitants (or total impact matrix)	€/ab	Level	PI: e.g., Multicriteria analysis for total impact matrix MI: Stated preferences (contingent valuation or choice experiment) QI: survey	PI: [50] MI: [51, 52]

(*continued*)

Table 1. (*continued*)

CICES ES categories	Impacts	Physical indicator (PI)	Monetary indicator (MI)	Qualitative indicator (QI)	Appraisal methods	Sources
	Occupation of public land use areas	sqm	€/sqm or €/ab (or reduction of dwelling values)		MI: Stated preferences (contingent valuation or choice experiment) or Revealed preferences (hedonic pricing)	PI: [53] MI: [28, 54–56]

4 Integrated Frameworks for the ESs Evaluation of GMPV

When dealing with large-scale energy investment decision problems and wanting to include impacts on ESs, specific evaluation tools are needed to consider not only technical and economic aspects, but also environmental and/or social impacts in the decision-making process [57, 58]. In the scientific literature, the most frequently used approaches to include economic and extra-economic aspects are Cost-Benefit Analysis (CBA) [59] and Multi-Criteria Decision Analysis (MCDA) [60]. However, new hybrid methods are emerging that integrate these two analyses, such as COmpoSIte Modeling Assessment (COSIMA) [61]. In this section, we review these three key methodological frameworks, explaining the methodological background, advantages, and disadvantages in the GMPV investments evaluations (Table 2).

4.1 Cost-Benefit Analysis

According to the European Commission [59], CBA is an analytical tool used in investment decisions to evaluate project alternatives from a social perspective. In theoretical terms, CBA introduces economic analysis into the financial analysis, typical of private investment, allowing the positive and negative externalities generated by the project to be considered in the assessment. A disadvantage of the method is the need to translate all impacts into monetary terms. While the monetization of direct costs is trivial, such as the cost of food lost due to land use change, nonmarket goods are more difficult to quantify, such as recreational or spiritual SEs. In the latter case, specific valuation approaches based on the concept of Willingness To Pay (WTP) and opportunity cost are needed [62]. The CBA method involves calculating performance indicators such as Net Present Value (NPV), Internal Rate of Return (IRR) and Benefit/Cost ratio (B/C) to assess the feasibility of projects, as well as comparing different alternatives. Due to limitations related to impacts monetization, ESs that could be examined are: estimation of food and wood production loss, land-mix use benefits, biodiversity increase trought alternation of green corridors, visual impact and occupation of public land valuation.

Table 2. Methodological frameworks available for decision-making.

	CBA	MCDA	COSIMA
Description	The project benefits and costs are expressed in monetary terms and adjusted for the time value of money	Different project alternatives are compared against predetermined criteria	Different project alternatives are compared considering CBA and MCDA outcomes
Input data	Monetary indicator	Monetary indicator Physical indicator Qualitative indicator	Monetary indicator Physical indicator Qualitative indicator
Output data	NPV, IRR, B/C	Aggregated index	TRR
Pros	Project feasibility Standardized approach Time weight	Stakeholders' engagement Multiple impacts	Project feasibility Stakeholders' engagement Economic and extra-economic impact Time weight
Cons	No stakeholders' engagement	No conventional procedure	No conventional procedure
ESs impacts evaluated	Competition with food Wood production Land-mix use Alternation of green corridors Visual impact Occupation of public land	Competition with food Wood production Land-mix use Plant community changes Biodiversity increases Alternation of green corridors Visual impact Occupation of public land	Competition with food Wood production Land-mix use Plant community changes Biodiversity increases Alternation of green corridors Visual impact Occupation of public land

4.2 Multi-criteria Decision Analysis

MCDA is a family of evaluation methods that allow the consideration of a multiplicity of qualitative and quantitative characteristics of the alternatives that can be considered simultaneously. The basic assumption of this family of techniques is that the object of analysis can be broken down into simple factors (criteria) and analyzed separately [63]. Some techniques result in a standardized aggregate index that allows a comparison of the performance of alternatives according to the selected set of criteria. Furthermore, the MCDA allows the different views of stakeholders to emerge, involving them in the definition of the importance of the criteria. However, it is a less well-known approach in the field of evaluation than other more conventional cost-based methods. In an MCDA framework, the opinion of decision-makers is incorporated into the decision-making

process to capture a wide range of perspectives through the criteria weighting phase. In terms of ES related to the installation of GMPVs, having the opportunity to consider multiple impacts expressed with different scales of measurement, the MCDA allows for the inclusion of a greater number of them: competition with food, timber production and the opportunity of mixed land use expressed in physical or monetary terms; the changes in plant communities expressed with quantitative or qualitative scales; the increase in biodiversity through the combination of plants with GMPV or the creation of green corridors; the assessment of visual impact and occupation of public land with specific coefficients or economic evaluation approaches.

4.3 COmpoSIte Modeling Assessment

COSIMA analysis can be briefly explained as an analysis that combines the advantages of CBA and MCDA analysis to provide a feasibility assessment and comparison between alternative projects. In fact, COSIMA measures the performance of each alternative by including both nonmonetary criteria and monetizable benefits and costs through an index that aggregates the results of both CBA and MCDA analyses, namely the Total Rate of Return (TRR) [64]. Therefore, the COSIMA framework is very useful when performance is measured on different rating scales. The COSIMA technique implicates the involvement of stakeholders, incorporating their views into the decision-making process to capture a wide range of perspectives through the criteria weighting stage. Moreover, temporal weighting of impacts, a key feature of CBA, would allow different value judgments on future effects to be taken into account by assigning different weights to short-term and long-term effects [65–67]. In terms of impacts on the ES related to the implementation of GMPV, the method allows the same number of impacts to be included as in the MCDA technique, but also offers the possibility of expressing the evaluation in monetary terms by considering the ES proper in the CBA.

5 Discussion and Conclusions

The paper provided a comprehensive discussion about the losses or gains resulting from the development of GMPVs according to an ES perspective. Specifically, the research collected potential indicators—physical, monetary, and qualitative—that may be used to evaluate each benefit or effect produced by RES. From this analysis, the work suggested different methods available to quantify and/or monetize different impacts for provisioning, regulating and maintenance, and cultural ESs. Three methodological frameworks are proposed in order to integrate all these benefits/impacts into decision-making: i.e., CBA, MCDA, and COSIMA. Although they are all decision-making techniques, there are some significant differences between these approaches that define their advantages and disadvantages. CBA is a quantitative approach to comparing costs and benefits all expressed in monetary terms. Although a well-established technique based on European Commission manuals, CBA has limitations that do not allow its wide use in the energy sector. First and foremost, the monetization of impacts requires specific analyses that transform quantitative parameters, often expressed in physical units, into monetary terms. Instead, in some cases, it is impossible to estimate the monetary value of some

impacts leading to their exclusion in the assessment (such as plant community changes or biodiversity increases if combined with plants for pollination). MCDA, on the other hand, considers multiple criteria, including economic, social and environmental factors, to evaluate the performance of a given project. One of the advantages of MCDA is that it involves creating a matrix of different criteria and weighting them according to the importance expressed by the decision-maker. This provides a truthful assessment that allows for the engagement of crucial stakeholders in the decision-making process. In addition, using different measurement scales (qualitative or quantitative) allows the inclusion of more criteria. COSIMA is a hybrid approach that combines the strengths of CBA and MCDA. Indeed, it may include quantitative (monetary and non-monetary) and qualitative data, which can be weighted according to their level of importance. The model also can be used to determine the overall net present value of an option, considering monetary criteria alone, or extend the valuation to include extra-economic criteria of an intangible nature. The flexibility of the COSIMA approach thus allows the inclusion of different valuation criteria, chosen by the decision maker, until an all-inclusive valuation is achieved making the method most suitable for investigating GMPVs projects.

The findings may assist both public and private decision-makers in the identification of appropriate locations to place GMPVs based on the associated costs, co-benefits, and negative externalities.

Future perspectives of the present research will regard the application of one of the methods to a real-world case study where a GMPV need to be developed. This application can highlight its potentialities and limits to include all benefits and impacts of a GMPV installation, as well as to support the decision-making process. Moreover, the application could highlight the possible presence of other gains or losses generated by GMPVs or more useful metrics to assess them.

References

1. Ciot, M.: The impact of the Russian-Ukrainian conflict on Green Deal implementation in central–southeastern Member States of the European Union. Reg. Sci. Policy Pract. **15**(1), 122–143 (2023). https://doi.org/10.1111/rsp3.12591
2. European Commission. REPowerEU: A Plan to Rapidly Reduce Dependence on Russian Fossil Fuels and Fast Forward the Green Transition. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0230
3. European Commission. EU Solar Energy Strategy. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0221
4. European Photovoltaic Industry Association. Connecting the Sun Competing in the Energy Sector - On the Road to Large Scale PV Grid Integration. Brussels (2012)
5. United Nations. Transforming Our World: the 2030 Agenda for Sustainable Development (2015). https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981#:~:text=View%20PDF%3A%2021252030%20Agenda%20for%20Sustainable%20Development%20web.pdf
6. Rossitti, M., Torrieri, F.: How to manage conflicting values in minor islands: a mcda methodology towards alternative energy solutions assessment. In: Gervasi, O., et al. (eds.) ICCSA 2021. LNCS, vol. 12955, pp. 582–598. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-87007-2_42

7. Randle-Boggis, R.J..: Realising co-benefits for natural capital and ecosystem services from solar parks: a co-developed, evidence-based approach. Renew. Sustain. Energy Rev. **125**, 109775 (2020). https://doi.org/10.1016/J.RSER.2020.109775
8. van de Ven, D.-J., et al.: The potential land requirements and related land use change emissions of solar energy. Sci. Rep. **11**(1), 2907 (2021). https://doi.org/10.1038/s41598-021-82042-5
9. United Nations (UN): Climate Action Summit. (2019). https://www.un.org/en/climatechange/2019-climate-action-summit
10. Hastik, R., et al.: Renewable energies and ecosystem service impacts. Renew. Sustain. Energy Rev. **48**, 608–623 (2015). https://doi.org/10.1016/j.rser.2015.04.004
11. Picchi, P., van Lierop, M., Geneletti, D., Stremke, S.: Advancing the relationship between renewable energy and ecosystem services for landscape planning and design: a literature review. Ecosyst. Serv. **35**, 241–259 (2019). https://doi.org/10.1016/j.ecoser.2018.12.010
12. Schetke, S., Lee, H., Graf, W., Lautenbach, S.: Application of the ecosystem service concept for climate protection in Germany. Ecosyst. Serv. **29**, 294–305 (2018). https://doi.org/10.1016/j.ecoser.2016.12.017
13. Jackson, A.L.R.: Renewable energy vs. biodiversity: Policy conflicts and the future of nature conservation. Glob. Environ. Chang. **21**(4), 1195–1208 (2011). https://doi.org/10.1016/j.gloenvcha.2011.07.001
14. van der Horst, D.: NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies. Energy Policy **35**(5), 2705–2714 (2007). https://doi.org/10.1016/j.enpol.2006.12.012
15. Directorate-General for Environment (European Commission). Wind energy developments and Natura 2000 (2013). https://op.europa.eu/en/publication-detail/-/publication/65364c77-b5b8-4ab6-919d-8f4e3c6eb5c2
16. Bratrich, C., et al.: Green hydropower: a new assessment procedure for river management. River Res. Appl. **20**(7), 865–882 (2004). https://doi.org/10.1002/rra.788
17. Renöfält, B., Jansson, R., Nilsson, C.: Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. Freshw. Biol. **55**(1), 49–67 (2010). https://doi.org/10.1111/j.1365-2427.2009.02241.x
18. Tsoutsos, T., Frantzeskaki, N., Gekas, V.: Environmental impacts from the solar energy technologies. Energy Policy **33**(3), 289–296 (2005). https://doi.org/10.1016/S0301-4215(03)00241-6
19. Chiabrando, R., Fabrizio, E., Garnero, G.: The territorial and landscape impacts of photovoltaic systems: definition of impacts and assessment of the glare risk. Renew. Sustain. Energy Rev. **13**(9), 2441–2451 (2009). https://doi.org/10.1016/j.rser.2009.06.008
20. Srinivasan, S.: The food v. fuel debate: A nuanced view of incentive structures. Renew. Energy **34** (4), 950–954 (2009). https://doi.org/10.1016/j.renene.2008.08.015
21. Semeraro, T., Scarano, A., Santino, A., Emmanuel, R., Lenucci, M.: An innovative approach to combine solar photovoltaic gardens with agricultural production and ecosystem services. Ecosyst. Serv. **56**, 101450 (2022). https://doi.org/10.1016/J.ECOSER.2022.101450
22. Huang, L., et al.: Effects of grassland restoration programs on ecosystems in arid and semiarid China. J. Environ. Manage. **117**, 268–275 (2013). https://doi.org/10.1016/J.JENVMAN.2012.12.040
23. Walston, L.J., et al.: Opportunities for agrivoltaic systems to achieve synergistic food-energy-environmental needs and address sustainability goals. Front. Sustain. Food Syst. **6**, 374 (2022). https://doi.org/10.3389/FSUFS.2022.932018/BIBTEX
24. Barron-Gafford, G.A., et al.: Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nat. Sustain. **2**(9), 848–855 (2019). https://doi.org/10.1038/S41893-019-0364-5
25. Hernandez, R.R., et al.: Environmental impacts of utility-scale solar energy. Renew. Sustain. Energy Rev. **29**, 766–779 (2014). https://doi.org/10.1016/J.RSER.2013.08.041

26. McCombie, C., Jefferson, M.: Renewable and nuclear electricity: Comparison of environmental impacts. Energy Policy **96**, 758–769 (2016). https://doi.org/10.1016/J.ENPOL.2016.03.022
27. Kim, J.Y., Koide, D., Ishihama, F., Kadoya, T., Nishihiro, J.: Current site planning of medium to large solar power systems accelerates the loss of the remaining semi-natural and agricultural habitats. Sci. Total Environ. **779**, 146475 (2021). https://doi.org/10.1016/j.scitotenv.2021.146475
28. Bravi, M., Bottero, M., Dell'Anna, F.: An application of the life satisfaction approach (LSA) to value the land consumption and ecosystem services. J. Knowl. Econ. (2023). https://doi.org/10.1007/s13132-023-01150-x
29. Chiabrando, R., Fabrizio, E., Garnero, G.: On the applicability of the visual impact assessment OAI SPP tool to photovoltaic plants. Renew. Sustain. Energy Rev. **15**(1), 845–850 (2011). https://doi.org/10.1016/j.rser.2010.09.030
30. Zorzano-Alba, E., et al.: Visibility assessment of new photovoltaic power plants in areas with special landscape value. Appl. Sci. **12**(2), 703 (2022). https://doi.org/10.3390/app12020703
31. Grodsky, S.M., Hernandez, R.R.: Reduced ecosystem services of desert plants from ground-mounted solar energy development. Nat. Sustain. **3**(12), 1036–1043 (2020). https://doi.org/10.1038/s41893-020-0574-x
32. Caprioli, C., Bottero, M., Zanetta, E., Mondini, G.: Ecosystem services in land-use planning: an application for assessing transformation scenarios at the local scale. In: Bevilacqua, C., Calabrò, F., Della Spina, L. (eds.) NMP 2020. SIST, vol. 178, pp. 1332–1341. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-48279-4_124
33. European Environment Agency. Green infrastructure and territorial cohesion (2011). https://doi.org/10.2800/88266
34. TEEB (The Economics of Ecosystems & Biodiversity). Mainstreaming the economics of nature: A synsthesis of the approach, conclusions and recommendations of TEEB (2010). https://teebweb.org/publications/teeb-for/synthesis/
35. Bottero, M., Bravi, M., Giaimo, C., Barbieri, C.A.: Ecosystem services: from bio-physical to economic values. In: Mondini, G., Oppio, A., Stanghellini, S., Bottero, M., Abastante, F. (eds.) Values and Functions for Future Cities. GET, pp. 37–50. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-23786-8_3
36. Caprioli, C., Oppio, A., Baldassarre, R., Grassi, R., Dell'Ovo, M.: A multidimensional assessment of ecosystem services: from grey to green infrastructure. In: Gervasi, O., et al. (eds.) ICCSA 2021. LNCS, vol. 12955, pp. 569–581. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-87007-2_41
37. Oppio, A., Dell'Ovo, M., Caprioli, C., Bottero, M.: A proposal to assess the benefits of urban ecosystem services. In: Calabrò, F., Della Spina, L., Piñeira Mantiñán, M.J. (eds.) New Metropolitan Perspectives: Post COVID Dynamics: Green and Digital Transition, between Metropolitan and Return to Villages Perspectives, pp. 1947–1955. Springer International Publishing, Cham (2022). https://doi.org/10.1007/978-3-031-06825-6_187
38. Assumma, V., Bottero, M., Caprioli, C., Datola, G., Mondini, G.: Evaluation of ecosystem services in mining basins: an application in the piedmont region (Italy). Sustainability **14**(2), 872 (2022). https://doi.org/10.3390/su14020872
39. Sharp, R., et al.: InVEST User's Guide (2018). https://doi.org/10.13140/RG.2.2.32693.78567
40. Gómez-Baggethun, E., de Groot, R., Lomas, P.L., Montes, C.: The history of ecosystem services in economic theory and practice: from early notions to markets and payment schemes. Ecol. Econ. (2010). https://doi.org/10.1016/j.ecolecon.2009.11.007
41. Nonhebel, S.: Renewable energy and food supply: will there be enough land? Renew. Sustain. Energy Rev. **9**(2), 191–201 (2005). https://doi.org/10.1016/j.rser.2004.02.003

42. Sacchelli, S., et al.: Trade-off between photovoltaic systems installation and agricultural practices on arable lands: an environmental and socio-economic impact analysis for Italy. Land Use Policy **56**, 90–99 (2016). https://doi.org/10.1016/j.landusepol.2016.04.024
43. Sliz-Szkliniarz, B.: Energy Planning in Selected European Regions: Methods for Evaluating the Potential of Renewable Energy Sources. KIT Scientific Publishing (2013)
44. Lytle, W., et al.: Conceptual design and rationale for a new agrivoltaics concept: pasture-raised rabbits and solar farming. J. Clean. Prod. **282**, 124476 (2021). https://doi.org/10.1016/j.jclepro.2020.124476
45. Dinesh, H., Pearce, J.M.: The potential of agrivoltaic systems. Renew. Sustain. Energy Rev. **54**, 299–308 (2016). https://doi.org/10.1016/j.rser.2015.10.024
46. Semeraro, T., Pomes, A., Del Giudice, C., Negro, D., Aretano, R.: Planning ground based utility scale solar energy as green infrastructure to enhance ecosystem services. Energy Policy **117**, 218–227 (2018). https://doi.org/10.1016/j.enpol.2018.01.050
47. Armstrong, A., Waldron, S., Whitaker, J., Ostle, N.J.: Wind farm and solar park effects on plant-soil carbon cycling: uncertain impacts of changes in ground-level microclimate. Glob. Chang. Biol. **20**(6), 1699–1706 (2014). https://doi.org/10.1111/gcb.12437
48. Peschel, T.: Solar parks – Opportunities for Biodiversity: A report on biodiversity in and around ground-mounted photovoltaic plants, Berlin (2010)
49. Sijtsma, F.J., et al.: Ecological impact and cost-effectiveness of wildlife crossings in a highly fragmented landscape: a multi-method approach. Landscape Ecol. **35**(7), 1701–1720 (2020). https://doi.org/10.1007/s10980-020-01047-z
50. Hurtado, J.: Spanish method of visual impact evaluation in wind farms. Renew. Sustain. Energy Rev. **8**(5), 483–491 (2004). https://doi.org/10.1016/j.rser.2003.12.009
51. Botelho, A., Pinto, L., Sousa, P., Sousa, S.: Using contingent valuation to measure welfare losses to local communities due to the impacts of photovoltaic farms. In: Conference: VIth GECAMB, Leiria (2014)
52. Botelho, A., Lourenço-Gomes, L., Pinto, L., Sousa, S., Valente, M.: Using stated preference methods to assess environmental impacts of forest biomass power plants in Portugal. Environ. Dev. Sustain. **18**(5), 1323–1337 (2016). https://doi.org/10.1007/s10668-016-9795-6
53. Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., Theuray, N., Lindley, S.J.: Characterising the urban environment of UK cities and towns: a template for landscape planning. Landsc. Urban Plan. **87**(3), 210–222 (2008). https://doi.org/10.1016/j.landurbplan.2008.06.008
54. Bottero, M., Caprioli, C., Foth, M., Mitchell, P., Rittenbruch, M., Santangelo, M.: Urban parks, value uplift and green gentrification: an application of the spatial hedonic model in the city of Brisbane. Urban For. Urban Green. **74**, 127618 (2022). https://doi.org/10.1016/j.ufug.2022.127618
55. García, J.H., Cherry, T.L., Kallbekken, S., Torvanger, A.: Willingness to accept local wind energy development: does the compensation mechanism matter? Energy Policy **99**, 165–173 (2016). https://doi.org/10.1016/j.enpol.2016.09.046
56. Tyrväinen, L., Miettinen, A.: Property prices and urban forest amenities. J. Environ. Econ. Manage. **39**(2), 205–223 (2000). https://doi.org/10.1006/jeem.1999.1097
57. Bottero, M., Dell'Anna, F., Morgese, V.: Evaluating the transition towards post-carbon cities: a literature review. Sustainability **13**(2), 567 (2021). https://doi.org/10.3390/su13020567
58. Strantzali, E., Aravossis, K.: Decision making in renewable energy investments: a review. Renew. Sustain. Energy Rev. **55**, 885–898 (2016). https://doi.org/10.1016/j.rser.2015.11.021
59. European Commission. Guide to Cost-benefit Analysis of Investment Projects: Economic appraisal tool for Cohesion Policy 2014–2020 (2014) https://doi.org/10.2776/97516
60. Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., Zhao, J.-H.: Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew. Sustain. Energy Rev. **13**(9), 2263–2278 (2009). https://doi.org/10.1016/j.rser.2009.06.021

61. Barfod, M.B., Salling, K.B., Leleur, S.: Composite decision support by combining cost-benefit and multi-criteria decision analysis. Decis. Support Syst. **51**(1), 167–175 (2011). https://doi.org/10.1016/j.dss.2010.12.005
62. Dell'Anna, F., Bravi, M., Bottero, M.: Urban green infrastructures: how much did they affect property prices in Singapore? Urban For. Urban Green. **68**, 127475 (2022). https://doi.org/10.1016/j.ufug.2022.127475
63. Figueira, J., Greco, S., Ehrgott, M.: Multiple Criteria Decision Analysis: State of the Art Surveys. Springer New York, New York, NY (2005)
64. Barfod, M.B., Jensen, A.V., Leleur, S.: Examination of decision support systems for composite CBA and MCDA assessments of transport infrastructure projects. Lect. Notes Econ. Math. Syst. **648**, 167–176 (2011). https://doi.org/10.1007/978-3-642-19695-9_14
65. Dell'Anna, F., Pederiva, G., Vergerio, G., Becchio, C., Bottero, M.: Supporting sustainability projects at neighbourhood scale: Green visions for the San Salvario district in Turin guided by a combined assessment framework. J. Clean. Prod. **384**, 135460 (2023). https://doi.org/10.1016/j.jclepro.2022.135460
66. Salling, K.B., Leleur, S., Jensen, A.V.: Modelling decision support and uncertainty for large transport infrastructure projects: The CLG-DSS model of the Øresund Fixed Link. Decis. Support Syst. **43**(4), 1539–1547 (2007). https://doi.org/10.1016/j.dss.2006.06.009
67. Barfod, M.B., Salling, K.B.: A new composite decision support framework for strategic and sustainable transport appraisals. Transp. Res. Part A Policy Pract. **72**, 1–15 (2015). https://doi.org/10.1016/j.tra.2014.12.001