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Is renewable energy sustainable? Potential relationships between renewable energy production and the Sustainable Development Goals

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Given the key role renewable energy plays in averting the impending climate crisis, assessments of the sustainability of renewable energy systems (RESs) are often heavily skewed towards their environmental benefits, such as reductions in carbon emissions. However, RES projects also have the potential to actively harm progress towards other aspects of sustainability, particularly when hidden within the energy generation process. Given the growing understanding of the 'dark side' of renewables, we must ask the question: Is renewable energy sustainable? To gain a better understanding of this issue, we analyzed the degree of alignment of seven aspects of the renewable energy production process with the Sustainable Development Goals (SDGs) and their targets for six renewable energy types categorizing the relationships as either enablers or inhibitors. This information makes it possible for decision- and policy- makers to move beyond carbon tunnel vision to consider the wider impacts of RESs on sustainable development.

Achieving net zero carbon emissions is the holy grail of climate change policies, with the transition to renewable energy sources often considered the hero in this quest. While the need to transition to renewables is unquestioned, the myopic pursuit of achieving net zero emissions has resulted in 'carbon tunnel vision[1]' (i.e., a focus on the ability of renewables to reduce carbon emissions at the expense of the consideration of wider impacts), as a consequence of which the broader environmental, social and economic impacts (both positive and negative) of the transition are generally ignored. This means that we are now in treacherous territory, as the switch to renewables to address the current climate crisis could unwittingly create a cascade of other problems for future generations. Consequently, there is a need to better understand the potential positive and negative impacts of renewable energy systems so that we can ensure that the transition to renewables can occur in a sustainable manner.

In order to meet this need, we present a high-level overview of the potential enabling (positive) and inhibiting (negative) relationships between renewable energy systems (RESs) and the United Nation's Sustainable Development Goals (SDGs)[2], based on a review of the literature (see Fig. 1 caption for details and definitions). We pay particular attention to how these relationships vary for different types of renewable energy systems (biomass, hydropower, solar, geothermal, wind, wave & tidal[3]) and how the various aspects of the renewable energy production process affect the environmental, social and economic elements of sustainability as characterized by the SDGs[4]. This enables us to obtain a better understanding of (i) the degree of sustainability of renewable energy systems, (ii) the impacts of adopting carbon tunnel vision, and (iii) what we need to do to broaden our vision to achieve more sustainable outcomes.

How sustainable are renewable energy systems?

While the transition from fossil fuels to renewable energy sources is strongly associated with positive impacts on climate action (SDG 13), there can also be a number of inhibiting relationships with this SDG (Fig. 1b). Such cases primarily involve the flaring (i.e., burning) of greenhouse gas, leading to emissions during certain types of renewable energy production (e.g., the generation of carbon emissions[5] and the leakage of methane during transportation and storage[6] for biomass production; the release of greenhouse gases when drilling for geothermal energy[7]; and disturbing deep underwater sediments (e.g., particles settled at the bottom of water bodies) during the operation of hydropower plants[8]). More importantly, renewable energy systems can also have potential enabling and inhibiting relationships with a number of other SDGs within the environmental category, including

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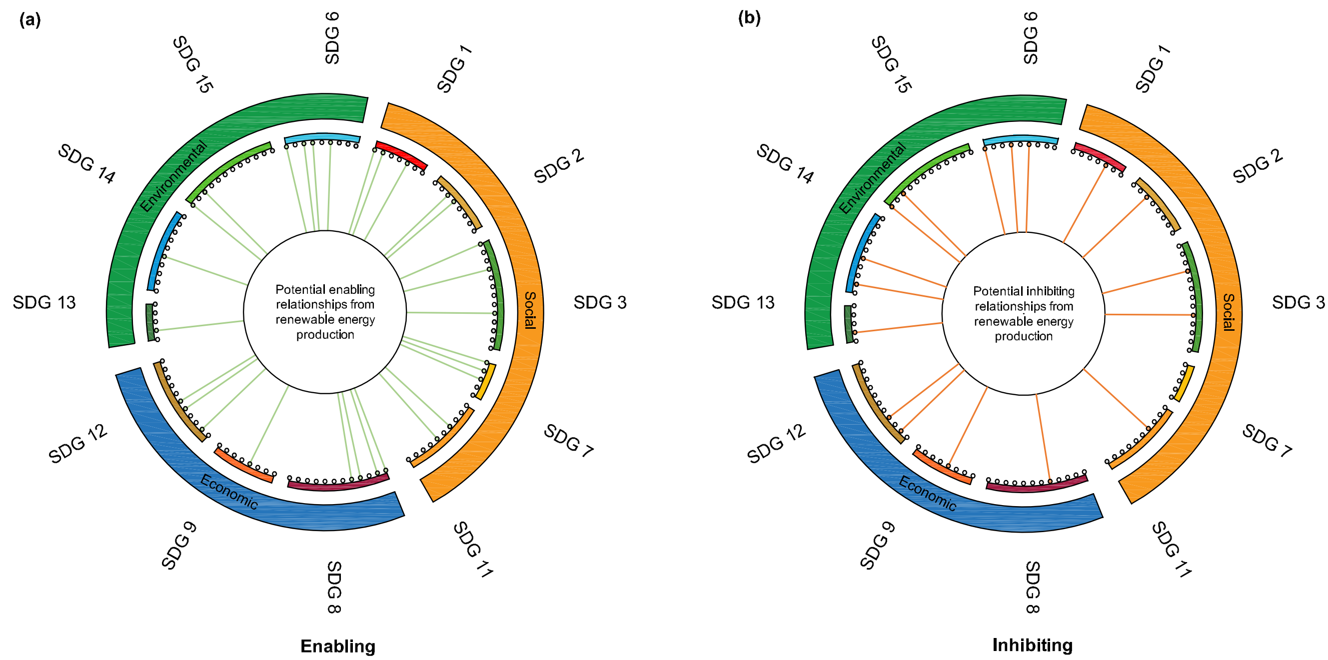

Fig. 1 | Potential enabling and inhibiting relationships between renewable energy production and the SDGs. SDGs are grouped according to the categories of social, environmental and economic factors based on the Wedding Cake Model[52]. Specific targets recognized in the 2030 Agenda for Sustainable Development[2] (excluding government implementation targets) are grouped under each associated SDG and ordered clockwise. As was done in previous papers[53], connections shown in green in (**a**) indicate a renewable energy project can potentially enable achieving a SDG target (this is equivalent to the concepts of reinforcing[54] providing synergies[55] and accomplishing[53] SDG targets). Connections shown in orange in (**b**) indicate a renewable energy project can potentially inhibit progress towards a SDG target (this is equivalent to the concepts of undermining[54], providing trade-offs[55] and inhibiting[53] progress). Full results of the assessment for each target can be found in the Supplementary Information. Note that SDGs 4, 5, and 10 are excluded from this study since no direct relationships with quantitative indicators could be identified in literature. Given that SDG 16 and SDG 17 are at the heart of the SDG synergies, serving as fundamental interconnections to all other goals[56], they are also excluded from our study. This is an original figure that was produced by the authors using AutoCAD.

life below water (SDG 14), life on land (SDG 15) and clean water and sanitation (SDG 6).

Impacts related to life below water (SDG 14) are primarily associated with the production of wave and tidal power, with potential enabling relationships including enhancing the protection of coastal areas, as the installation of barriers and turbines can contribute to nutrient accumulation for coral protection[1,9], and potential inhibiting relationships including threats to marine life, such as the harming of bird populations by offshore wind farms[10,11]. For life on land (SDG 15), potential enabling relationships include the repurposing of natural land, such as establishing wind and solar farms on degraded land[12], whereas potential inhibiting relationships include the degradation of land quality when biomass contributes to soil erosion and degradation through the use of energy crops and the collection of crop residuals[13]. Regarding clean water and sanitation (SDG 6), potential enabling relationships include improved water-use efficiency[14,15] and potential inhibiting relationships relate to the reduced availability of drinking water, such as the contamination of underground aquifers from geothermal exploration, the tainting of potable surface water as a result of the leakage of biomass feedstock, and the allocation of significant water resources for hydropower infrastucture[16,17].

In addition to their impact on the production of affordable and clean energy (SDG 7), renewable energy systems can also affect a range of other SDGs in the social category, including no poverty (SDG 1), zero hunger (SDG 2), good health and well-being (SDG 3), and sustainable cities and communities (SDG 11). However, in contrast to SDG 7, where renewable energy systems solely act as enablers, for these other SDGs, they can act as both inhibitors and enablers. For example, in relation to no poverty (SDG 1), potential inhibiting relationships stem from the intermittency of wind and solar energy sources[18], while enablers could relate to the improvement of living standards through the provision of usable energy[19]. As far as zero hunger (SDG 2) is concerned, potential inhibiting relationships include the reduction of land availability for food production due to renewable energy installations[13], with potential enabling relationships pertaining to the integration of RESs into agricultural farms (e.g., shading crops with solar panels)[20], which has the potential to enhance resilience and productivity within the agriculture sector. Regarding good health and well-being (SDG 3), inhibiting relationships could include illnesses caused by harmful chemicals inadvertently released into the air and water, such as hazardous wastewater from geothermal energy production[21], while potential enabling relationships include the prevention of respiratory infections and disease related to carbon pollution[22]. Finally, in relation to sustainable cities and communities (SDG 11), inhibiting relationships could arise from the environmental impact of RESs on modern cities, such as foul odours from biomass conversion, alterations in the microclimate caused by wind turbines and hydropower dams[23] and light pollution from solar panels[24]. In contrast, potential enabling relationships might relate to reduced damage to heritage land compared with that caused by the exploitation of conventional energy sources[12,25].

RESs also have potential enabling and inhibiting relationships with various economic SDGs, including decent work and economic growth (SDG 8), industry, innovation and infrastructure (SDG 9) and responsible consumption and production (SDG 12). In relation to decent work (SDG 8), potential enabling relationships include the provision of decent work opportunities within emerging RES projects[26], while inhibiting relationships relate to the likely reduction in job availability in the fossil fuel industry[27,28]. As far as industry, innovation and infrastructure (SDG 9) is concerned, potential enabling relationships include decreased carbon intensity through soil carbon sequestration and CO_2 recycling, while inhibiting relationships could relate to bioenergy and hydropower, for which energy sources require transportation, potentially increasing carbon intensity[29]. With regard to responsible consumption and production (SDG 12), enabling relationships could include improved management of natural resources, where waste and

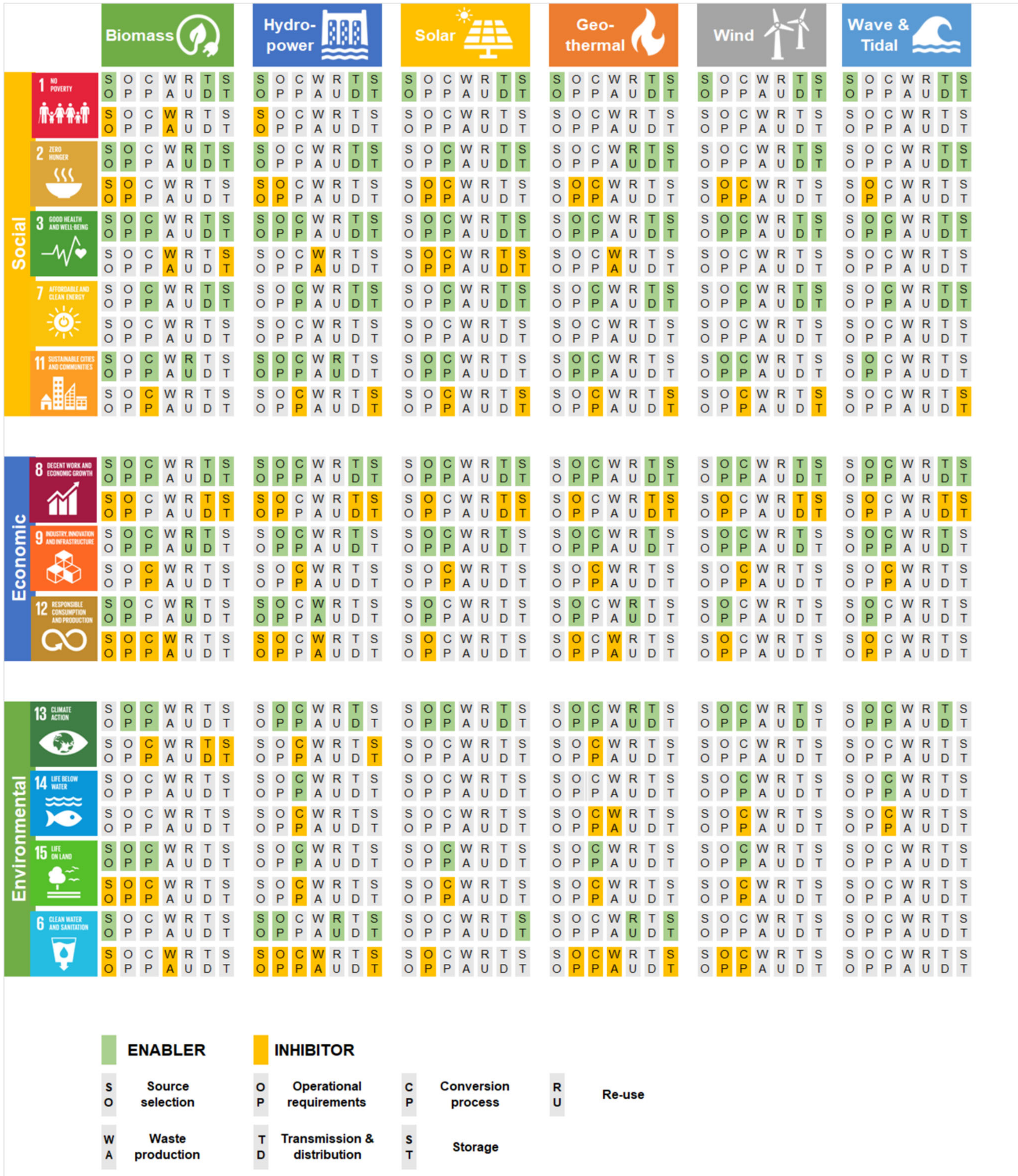

Fig. 2 | Potential enabling and inhibiting relationships between renewable energy production and SDGs grouped by renewable energy type and aspect of the renewable energy production process. SDG targets are presented by a single value and are divided into three principal spheres—social, economic, and environmental—which are depicted on the vertical axis. The horizontal axis categorizes the six renewable energy types. Within each type, the seven aspects of the energy production process (see Fig. 3) are presented in two rows, where connections are shown between a SDG, renewable energy type and aspect of the renewable energy production process. A green index color represents 'enablers,' while the orange index color signifies 'inhibitors'. A lack of highlighting indicates the absence of identified evidence from literature, although it is important to note that this does not necessarily imply the absence of a relationship per se, just that this was outside of the boundary of consideration used here (more details are provided in the Supplementary Information). This is an original figure that was produced by the authors using the Microsoft Excel Spreadsheet Software.

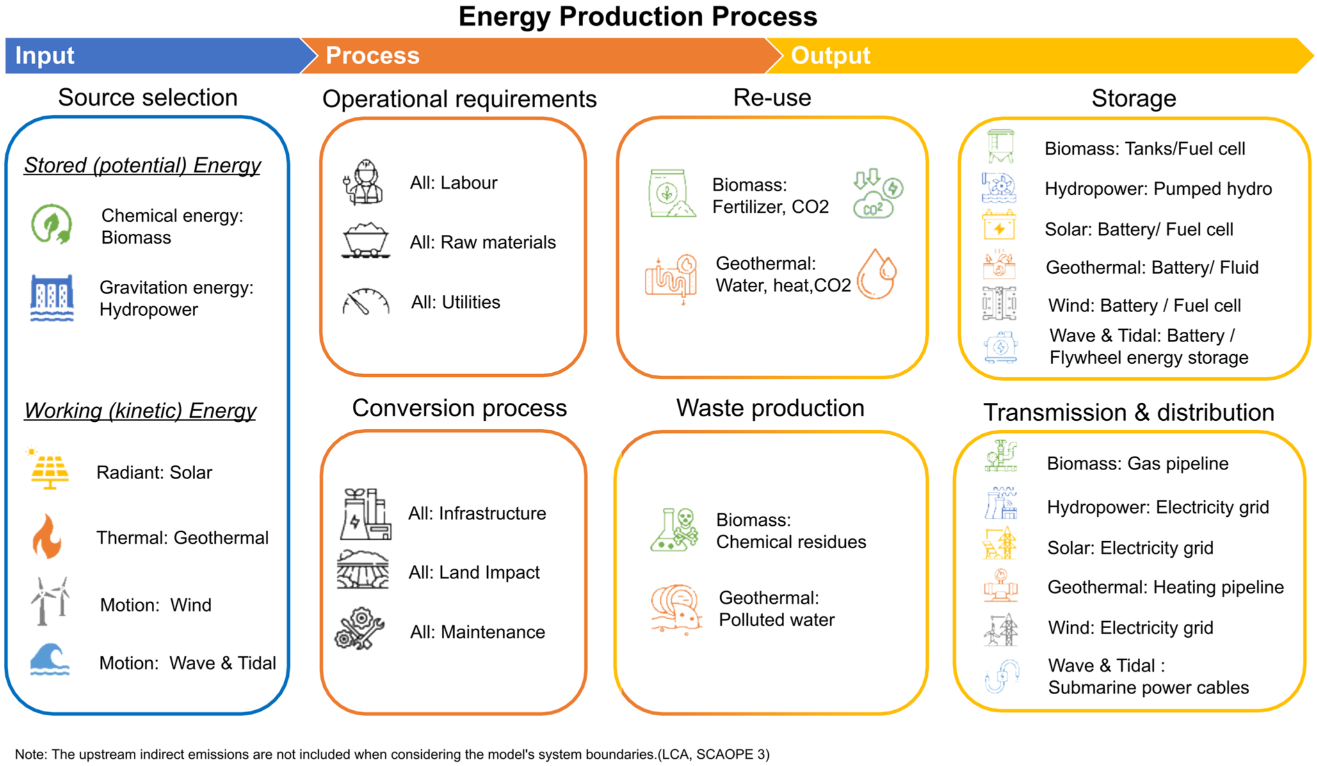

Fig. 3 | Details of the seven aspects of the renewable energy production process considered in relation to their effects on the SDGs. These aspects are presented within the context of the operational input-process-output concept. Source selection is considered as the first aspect, noting that the storing of potential energy is where impacts emerge—there are no direct impacts from renewable energy types with kinetic energy sources. The process of converting the source into energy can influence SDGs, both through the conversion process itself (i.e., plant location) and the associated operational requirements. After the completion of the renewable energy production process step and before the generation of the output, by-products can either be re-used elsewhere or go to waste. The production outputs can be divided into two parts: storage for local use and operational support, and transmission and distribution for grid connection or delivery. This is an original figure that was produced by the authors using Microsoft PowerPoint.

recyclable materials as waste can be utilized as a bioenergy source[30], whereas potential inhibiting relationships include encroachment on natural resources and the generation of hazardous waste[15,21].

What is the impact of carbon tunnel vision?

In order to obtain a more holistic and comprehensive understanding of the impact carbon tunnel vision has on broader aspects of sustainability, the relationships in Fig. 1 are decomposed by renewable energy type and aspect of the energy production process (Fig. 2). The different types of renewables considered include biomass, hydropower, solar, geothermal, wind, and wave & tidal, as these are the most commonly used sources, given current technologies. The aspects of the renewable energy production process considered include source selection, conversion and associated operational requirements, re-use, waste production, storage and transmission & distribution (Fig. 3), as these can differ for different types of RESs and include lesser-known elements of the renewable energy supply chain that often receive diminished attention. In the absence of this more nuanced understanding, it is easy to underestimate both the negative and positive sustainability impacts of renewable energy production on SDGs, making it more difficult to escape the currently adopted carbon tunnel vision, as detailed in subsequent sections.

Underestimation of negative sustainability impacts

As can be seen from Fig. 2, one of the major impacts of adopting carbon tunnel vision is that, by solely focusing on climate action (SDG 13) and the production of affordable and clean energy (SDG 7), the vast majority of inhibiting relationships between renewable energy production and the SDGs (i.e., the orange cells in Fig. 2) are ignored, which is likely to result in a distorted view of the sustainability of RESs. However, it should be noted that the focus on net zero emissions might not be the only reason for the lack of consideration of the potentially negative impacts of renewables on sustainability. This is because inhibiting relationships are primarily associated with the less well-known and understood aspects of the renewable energy production process (such as conversion and associated operational requirements, re-use and the generation of waste), rather than the more well-known and better understood processes (such as those associated with source selection, storage and transmission & distribution).

These potentially negative impacts affect a range of SDGs (Fig. 2). For example, operational requirements of renewable energy projects can have a negative impact on SDG 2 (zero hunger) because the development of RESs competes with the agricultural sector for natural resources such as water and minerals, along with land use[15]. This is particularly the case for bioenergy, as energy farming may occupy agriculturally viable land[13,16]. The conversion process and storage of energy can have a negative impact on SDG 11 (sustainable cities and communities), as renewable energy plants and storage facilities can unintentionally encroach on cultural and heritage lands, especially sacred lands of First Nations people (i.e., for indigenous peoples who are the earliest known inhabitants of an area), posing a potential infringement on indigenous rights[25,31]. Similarly, the conversion process can have a negative impact on SDG 15 (life on land), as renewable energy facilities are likely to cause damage to the biodiversity of surrounding areas (i.e. natural wildlife)[32,33].

In most cases, the inhibiting relationships between the aspects of the renewable energy production process and the SDGs are specific to a particular renewable energy type. For example, the storage component of the source selection step (Fig. 3) can negatively impact SDG 12 (responsible consumption and production) in the case of biomass and hydropower. For the former, this is because the feedstock required for bioenergy production necessitates the use of storage facilities, like warehouses or hubs for biomass storage and pre-processing[34], thereby increasing material resource use and land occupation. For the latter, this is because the storage of water required for hydropower production necessitates the use of dams or reservoirs for storage and collection, potentially altering and using surrounding natural resources[21,35]. In contrast, this is not the case for solar, wind and wave & tidal energy (Fig. 3).

Similarly, the conversion process (Fig. 3) can result in an inhibitive relationship with SDG 14 (life below water) for hydropower, wind and wave & tidal. For hydropower, this is due to the potential to artificially alter aquatic ecosystems and redirect the flow of rivers[21,35]. For wind power, this is because of the potential contribution of offshore wind farms to biofouling and the generation of underwater noise[36], whereas for wave & tidal power, tidal barriers can modify the flow of water and wave patterns[1,9]. However, the same does not apply to biomass, solar, or geothermal. This demonstrates that particular care must be taken to understand the inhibiting factors for different renewable energy types in order to obtain a comprehensive understanding of their impact on sustainability.

Underestimation of positive sustainability impacts

Figure 2 also highlights that another significant impact of adopting carbon tunnel vision by only considering SDG 13 (climate action) is the lack of consideration of a large number of the other positive SDG impacts of renewable energy production, which is also likely to result in a distorted assessment of the sustainability of RESs. As can be seen in Fig. 2, all types of RESs exhibit potentially enabling relationships with all of the social (i.e., SDGs 1 - 3, 7, 11) and economic (i.e., SDGs 8, 9, 12) aspects of sustainability. In addition, the components of the renewable energy production process where these occur are generally the same. For example, for SDG 1 (Target 1.5: build resilience to environmental, economic and social disasters), there is a potentially enabling relationship with source selection, transmission & distribution, and storage. This is because renewable energy can directly assist individuals in impoverished conditions by providing them access to electricity, thereby reducing their risk of suffering from local disasters[37]. For SDG 2 (zero hunger), there is a potentially enabling relationship with transmission and storage, attributable to the efficiency and advanced integrated farming techniques that can be enhanced when food production is paired with RESs[38]. Similarly, for SDG 3 (good health and well-being), there is a potential enabling relationship from using renewable energy (conversion, transmission & distribution and storage), as this can reduce the risk of cardiovascular diseases caused by air pollution (PM2.5, PM10)[22], as well as chronic respiratory disease resulting from the burning of traditional energy sources like coal and fuel[39]. For SDG 15 (life on land), there is a potentially enabling relationship with the conversion process, as renewable energy plants do not require further deforestation for installation and can repurpose degraded land, such as deserts or areas suffering from soil erosion[12].

However, some of these enabling relationships only apply to specific combinations of renewable energy type and aspects of the energy production process. For example, biomass and hydropower can have a positive impact on SDG 6 (clean water and sanitation) and SDG 11 (sustainable cities and communities) because they are able to use municipal wastewater as one of their energy sources[30,40], thereby purifying water and reusing it as a product or by-product[41]. Additionally, bioenergy, geothermal energy and hydropower can have a positive impact on SDG 12 (responsible consumption and production), as bioenergy production can result in the generation of fertilizer as a by-product, thereby reducing material usage and promoting recycling[42,43], hydropower can supply clean water to downstream areas[44], and geothermal energy can provide heating/irrigation water for direct applications such as greenhouse farming[45].

How do we broaden our vision?

As highlighted in the previous sections, while renewable energy sources are a strong enabler of climate action, as well as a number of other SDGs, they can also have a range of negative social, environmental and economic impacts. Consequently, there are several significant conclusions to draw that affect how we should think about climate policy:

- Ignoring the potential negative impacts of RESs in the singular pursuit of net zero carbon emissions has the potential to result in disastrous consequences and the perverse outcome that solutions intended to increase the sustainability of humankind actually have the opposite effect. We need to heed the lessons of history to avoid another “hole in the ozone layer” by trying to “fix” a specific issue without considering all potential consequences in an integrated fashion. For policy makers, this can be combated by more cross-agency participation in the management of renewable energy zones and planning, so that trade-offs of a proposed solution can be more apparent.
- RESs have enabling relationships with a much broader range of SDGs, not just climate action (SDG 13) and affordable and clean energy (SDG 7), which, if ignored, can significantly underestimate their positive impact on sustainability. This includes the potential to improve the living conditions of communities through the creation of employment opportunities, improved access to resources or reduced health risks, as well as through supporting the biodiversity of the surrounding environment. While there is mounting political pressure to deliver on decarbonization targets, these synergies are at risk of not being capitalized on, and the multiple benefits of implementing renewable energy projects need to be framed in a more holistic way.

By identifying the potential inhibiting and enabling relationships between RESs and the SDGs, this paper provides a blueprint for sustainability assessments that will enable us to broaden our vision beyond considering the impacts of renewables on net-zero emissions to considering the full range of sustainability impacts, allowing for more structured conversations to occur within project management and policy development. This includes an awareness of all potential negative and positive impacts of different types of renewables on different elements of sustainability, as well as for which aspect(s) of the renewable energy production process they occur. Such awareness is especially important for the aspects for which management decisions determine whether sustainability impacts are enabling or inhibiting. For example, the conversion process can have both positive and negative impacts on SDG 11 (sustainable cities and communities), depending on how the government and local society manage their strategy for the preservation, protection, and conservation of all cultural and natural heritage. Similarly, operation and transmission & distribution can have both positive and negative impacts on SDG 8 (decent work and economic growth), depending on the degree to which renewable energy sources are able to promote GDP growth[46] and create more job opportunities with fair pay[47]. To further the ability for renewable energy projects to be more sustainable, future work on this topic should focus on ways to quantity the impact renewable energy projects can have on the SDGs identified, to allow for more direct comparisons for decision makers[48,49], and policy makers alike[50,51].

The enabling and inhibiting relationships between renewable energy sources and the SDGs identified in this paper provide a step toward the information needed to develop climate policy and associated action plans that ensure that we can achieve net zero emissions by implementing RESs in a sustainable manner. This will enable us to address the climate crisis in a manner that avoids mistakes of the past and creates a positive future for our planet.

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Competing interests

The authors declare no competing interests.

Additional information

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