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National SDG-7 performance assessment to support achieving sustainable energy for all within planetary limits

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ABSTRACT

Several gaps and limitations characterise present indicators for United Nations' Sustainable Development Goal 7 (SDG-7), thus impeding effective policy-making. Here, we propose a holistic framework which enables the assessment of national SDG-7 performances through 29 indicators capturing environmental as well as socio- and techno-economic aspects specifically relevant to the sustainability of the energy sector. The framework is applied to 176 countries, benchmarking indicator scores against absolute sustainability thresholds and targets to gauge how far current energy systems are from reaching truly sustainable levels. Our results reveal different performance patterns across countries as well as trade-offs between social and environmental indicators. All countries are found to exert unsustainable performances for several indicators, albeit with large variability, where some environmental scores lie just above the threshold and others exceed by more than a factor of 1000. Climate change impact scores are examples of the latter, where only 52 countries located in Africa and Asia are found to possibly show performances below their thresholds. With this quantitative and holistic support at the country level, it becomes possible for policy-makers to identify, prioritise and target specific sustainability aspects to achieve SDG-7, and not just move towards it. Therefore, we recommend a broad uptake of our framework while continuing its development, including for other SDGs.

1. Introduction

Energy has been recognised as an essential component of sustainable development within the 17 United Nations' Sustainable Development Goals (SDGs), which define a sustainability agenda for 2030 and beyond [1]. Within the SDG framework, it is associated with a dedicated SDG, i.e. SDG number 7 (SDG-7), which aims to "ensure access to affordable, reliable, sustainable and modern energy for all". In its current form, SDG-7 is specified through five targets defined as (7.1) ensuring universal access to affordable, reliable, and modern energy services, (7.2) increasing renewable energy share, (7.3) double global rate of energy efficiency improvement, (7.a) enhancing international cooperation on clean energy research and technology, and (7.b) expanding infrastructure and developing technologies [1]. The last two targets are means of implementation to complement the other three targets (i.e. 7.1–7.3), which can be termed "outcome-oriented targets" [2–4]. For policy-makers to assess and monitor the performances towards the SDGs, including SDG-7, sets of quantifiable indicators matching the respective targets have additionally been developed [4].

Until now, a great number of indicators have been proposed in the literature to assess and monitor the progress towards SDG-7 [4–8]. However, these proposed indicators mainly focus on socio- and techno-economic aspects, where the environmental sustainability dimension is largely underplayed, thus falling short of meeting the overall goal of achieving *sustainable* energy, as expressed in SDG-7. More generally, this observation is aligned with the tendencies of SDG indicators to not sufficiently address environmental problems [9]. Although the energy transition towards renewable energy sources has gained a lot of attention in the sustainability agenda, and technologies already exist (e.g. 17% of electricity comes from hydropower [10,11]), fossil energy sources still largely dominate the global energy production. Energy systems are associated with several sustainability challenges, including climate change impacts and their subsequent key role in meeting the 1.5/2-degree targets set by the Paris Agreement [12]. They additionally cause diverse environmental impacts, ranging from damages to human health from particulate matter emissions or chemicals, through damages to ecosystems via land use or water use, to problems of fossils or metal resources availability [13]. Energy systems are also closely linked to social and economic impacts, such as poverty and

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Nomenclature

Abbreviations

Bq	Becquerel [s^{-1}]
CFC	Chlorofluorocarbon
EU	European Union
GDP	Gross Domestic Product
GNI	Gross National Income
Gt	Giga ton
Gtoe	Giga ton oil equivalent
GVA	Gross Value Added
kt	kilo ton
ISIC	International Standard Industrial Classification
MRIO	Multi-Regional Input-Output
MJ	Mega Joule
MW	Mega Watt
PM	Particulate Matter
ppm	parts per million
RE	Renewable Energy
SDGs	Sustainable Development Goals
SI	Supplementary Information
STE	Socio- and Techno-Economic
UN	United Nations
USD	United States Dollar

Variables

$A_{i,j}$	Allocation share for indicator *i* and country *j*
GDP_j	Gross Domestic Product in country *j*
GDP_{world}	World Gross Domestic Product
GVA_j	Gross Value Added in country *j*
$GVA_{j,energy\ sector}$	Gross Value Added for the energy sector in country *j*
$I_{i,j}$	Total impact of environmental indicator *i* in country *j*
$I_{i,j,energy\ sector}$	Impact of environmental indicator *i* in country *j* from the energy sector
$I_{i,World}$	Total impact of environmental indicator *i* in the world
$IS_{i,j}$	Indicator score for indicator *i* and country *j*
$IS_{i,low}$	Lower indicator score value for indicator *i*
$IS_{i,up}$	Upper indicator score value for indicator *i*
$NS_{i,j}$	Normalised indicator score for indicator *i* and country *j*
P_j	Population in country *j*
P_{world}	World population
$T_{i,j}$	Energy-specific threshold for environmental indicator *i* and country *j*
$T_{i,World}$	Global threshold for environmental indicator *i*
$\alpha_{i,j}$	Priority factor specific to indicator *i* and country *j*
β_i	Scaling factor to avoid exceeding global threshold specific to indicator *i*
ε	Scaling factor to avoid exceeding global threshold (country-independent)
γ_j	Priority factor specific to country *j*

healthcare [14,15]. SDG-7 can therefore be regarded as having many interlinkages with other SDGs that target some of the above problems, such as SDG-13 ("tackling climate change") or SDG-3 ("good health and well-being"). To date, the integration of these inter-linkages is not operationalised by the current set of indicators, hence compromising the relevance of existing SDG-7 performance assessments as consistent support for national monitoring and policy-making purposes within the energy sector. Despite the broadly encompassing scoping of sustainability challenges, the assessment of all 17 SDGs does not offer a relevant alternative due to their lack of specificity and inability to address issues specific to the energy sector (e.g. climate change performances from the energy sector). In that setting, policy-makers require a methodological framework with a comprehensive set of indicators that enable them to assess performances towards SDG-7 at global and national levels while integrating energy-system-specific interlinkages with other SDGs [16]. Such SDG-7-targeted assessment framework is currently missing.

Another limitation in the currently proposed indicators and their past assessments is that they can only indicate how much progress is made in relative terms (e.g. compared to a previous state). They merely indicate what is better or more sustainable (i.e. relative sustainability) and do not relate the performances to thresholds or targets delimiting a sustainable state in absolute terms (i.e. absolute sustainability), like embodied, for instance, by the planetary boundaries framework aiming at defining a safe operating space for humanity [17–20]. Such benchmarking is the only way to gauge whether or not any progress made, e.g. improvements over some indicators, is sufficient or not in our striving towards absolute sustainability.

In this study, we tackle these limitations with the main goal to develop and apply a novel assessment framework for gauging national SDG-7 performances, which integrates (i) interlinkages with other SDGs, and (ii) both relative and absolute sustainability perspectives. Such a framework is proposed in Fig. 1 (box "Assessment framework"). Based on a critical review of existing SDG-7 indicators in the literature, we identify and define a new comprehensive list of indicators for assessing SDG-7, covering the environmental, social and techno-economic sustainability dimensions of energy systems and going well beyond previously used indicators for SDG-7, e.g. from the UN list [4]. The application of this recommended set of indicators, which is the main entry point in our framework (Fig. 1, left side in box "Assessment framework"), enables to assess and monitor the SDG-7 performances in a relative sustainability perspective, e.g. from year to year (i.e. Output 1 in Fig. 1). We further propose an additional step in which the indicator scores are matched with pre-calculated absolute sustainability thresholds scaled at the level of countries and energy sectors. Unlike existing frameworks, this normalisation of each indicator score unlocks the possibility to assess the SDG-7 performances of a given country in an absolute perspective, indicating how far it is from becoming truly sustainable instead of just characterising if the country does better (i.e. Output 2 vs. Output 1 in Fig. 1).

2. Material and methods

In this section, Section 2.1 clarifies the overall methodological approach pertaining to the development and operationalisation of the SDG assessment framework (see Fig. 1), while the following sections (Sections 2.2-2.6) describe each of the main steps.

2.1. Methodological approach

Fig. 1 (top part) describes the different steps undertaken to support the development of the framework; further details are available in Section S1 of Supplementary Information 1 (SI-1) as open source (see Ref. [21]). A critical literature review of existing SDG-7 indicators was first carried out to retrieve an extensive list of indicators gauging SDG-7 (see Section S1 in SI-1 [21]). The review focused on outcome-oriented targets, thus leaving out those addressing means of implementation. With the help of indicator selection criteria (see Section S3 in SI-1 [21]), a condensed list of indicators was proposed covering environmental, and socio- and techno-economic indicators. Data was then collected to support the calculation of the indicators identified from the previous step. To bring an absolute sustainability perspective into the assessment, inspiration was taken from research in the field of life cycle impact

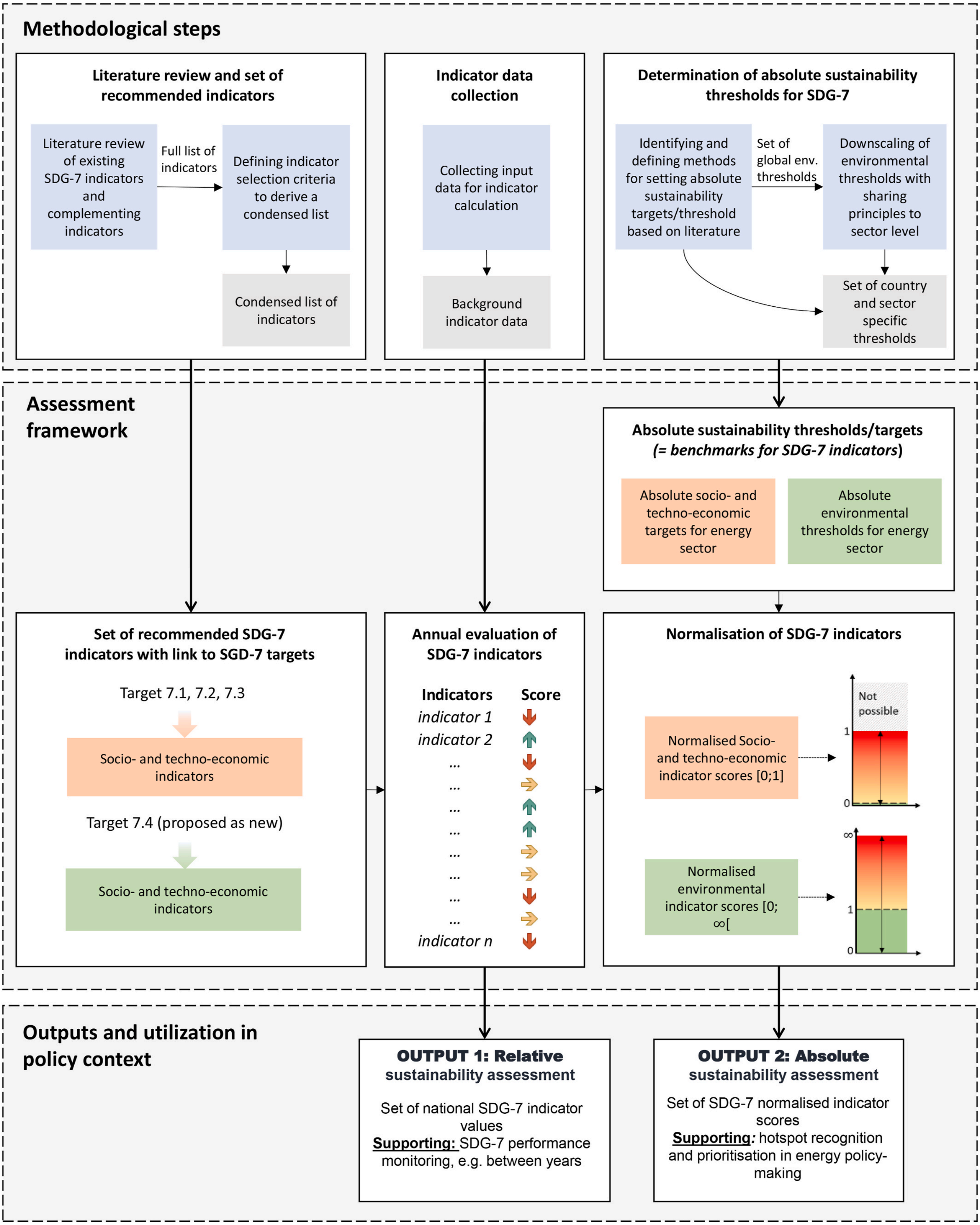


Fig. 1. Overview of the methodological steps followed in this study (top) to support the proposed SDG-7 assessment framework (middle), also describing the complementary outputs (1 and 2) resulting from its application (bottom). "STE": socio- and techno-economic; "env.":environmental.

assessment (Bjørn et al., 2015 [22]) with the inclusion of a normalisation step within the assessment framework (see Fig. 1). To operationalise this step, methods for assessing absolute sustainability targets or thresholds that matched the indicators, were identified from the literature. Environmental sustainability thresholds were handled separately due to their need to be downscaled from available or modelled global thresholds to the level of energy sector in each country. This was enabled through the definition and application of sharing principles. These aforementioned methodological steps are succinctly described in the following sections, complemented where relevant by details in Supplementary Methods in SI-1 [21].

2.2. Literature review and recommended set of SDG-7 indicators

The literature review for SDG-7 indicators was carried out in two steps. In a first step, all existing and proposed indicators for SDG-7 were identified and reviewed by conducting a literature review of (i) scientific publications retrieved from the search engines "Web of Science" (webofknowledge.com) and "Google Scholar" (scholar.google.com), and (ii) relevant publicly available reports indicating SDG-7 indicators (e.g. UN and EU affiliated reports). Only studies in English and explicitly referring to SDG-7 were considered, thus limiting the search scope to literature sources from 2015 and on. Details of the identification of the studies and their reviews are available in Section S2 of Supplementary Methods in SI-1 [21].

In a second step, additional indicators of relevance for SDG-7 were proposed based on inspiration from existing indicators addressing other SDGs and from other domains within environmental science. For the latter, this was, in particular, the field of life cycle impact assessment, which aims to frame the quantification of all known impacts on ecosystems, human health and natural resources [23]. It is important to note that most environmental indicators are impact-oriented indicators, which thus integrate the relative environmental impact potentials of different substances emitted or resources consumed. This contrasts with the often used emission-based or resource-based indicators, which bear little environmental relevance when associated with aggregation across substances emitted and resources extracted (e.g. Laurent and Hauschild [24]).

The above two steps led to the collection of 154 identified indicators, which have been reviewed and are documented, along with their sources, in Tables S1-S2 (Section S2 in Supplementary Methods, SI-1 [21]). It is important to note that, to cover all relevant sustainability aspects within SDG-7, the scope of the reviewed indicators was framed to encompass socio-techno-economic (STE) indicators as well as environmental indicators. To arrive at a recommended set of SDG-7 indicators based on the full list of 154 indicators, the following criteria were applied: (i) relevance to scope of SDG-7 (given by its outcome-oriented targets), (ii) complementarity (i.e. avoiding redundancy and overlaps between indicators, while ensuring comprehensiveness when taking them as a whole, thus aiming for mutually exclusive and collectively exhaustive indicators), and (iii) quantifiability (i.e. indicator gauged by a numerical metric); see Section S3 of Supplementary Methods in SI-1 [21]. Further classification into three tiers was then applied to describe the operability of the retained indicators, using the following criteria: A (high availability and reliability of data and supporting models for indicator computation, including its normalisation, could be defined for a minimum of 50% of the world's countries), B (limited availability and/or relative uncertainty in data and models, preventing application to all countries), and C (data availability for less than 20% of countries, and/or models did not enable evaluation and/or normalisation of the indicator). Only A- and B-flagged indicators were computed in the current assessment of national SDG-7 performances (see Section 2.5).

2.3. Determination of absolute sustainability thresholds

The term "threshold" is used in the following as a generic term, capturing the concept of "boundaries", which should not be exceeded, as well as that of "sustainability targets" (e.g. a desirable level to aim for); see Fig. 1 (top right box). To determine such thresholds, three different methods were identified and categorised from the scientific literature –see Table 1, which covers application to both STE and environmental indicators. These methods were applied to all indicators identified as operational in Section 2.2. With regard to environmental indicators, absolute environmental sustainability thresholds may be defined at sub-global levels, e.g. integrating local/regional and global definitions [18]. However, there is a general lack of regionalised thresholds covering the entire world for specific environmental issues [18]. As a result, the current study considers the global level as a starting point for scoping all thresholds pertaining to environmental indicators. This likely leads to over- or underestimation compared to the more environmentally-relevant thresholds at regional or local scales. Thresholds with such a high level of differentiation are, however, not available to the entire world. Further research is therefore required to obtain regional or local thresholds before they can be integrated as part of the proposed framework (see also Section S5 in SI-1 [21]).

2.4. Downscaling of global sustainability thresholds for environmental indicators

To enable absolute sustainability assessment at national scale, the global thresholds need to be downscaled to the country level. Thresholds relying on the zero-deprivation method (Table 1) are estimated as shares and can directly be translated from global to national levels. For other thresholds, which typically express a total maximum of impacts at the global scale, the use of sharing principles to assign a share of the maximum allowance to the energy sector in each country is required. Several sharing principles have been proposed in the literature based on different distributive justice theories, and there is currently no consensus as to which one is most appropriate [25–28]. In this setting, different sharing principles should be applied as sensitivity analysis. In the current study, all operational environmental indicators are subject to this downscaling, and we retained four commonly used sharing principles, although others could be explored (see review in Refs. [28,29]). These rely on one or a combination of the following ethical norms: egalitarian (equality among individuals), utilitarian (maximisation of utility in society), prioritarian (higher weight given to a subgroup based on a specific criterion, like level of impact or income level), and acquired rights (here: based on grandfathering, reflecting current level of impacts).

Equation (1) provides the overarching application of a given sharing principle Ai,j to a global threshold $T_{i,world}$ to reach an energy-sector-scoped threshold $T_{i,j}$ for environmental indicator i and country j:

$$T_{i,j} = A_{i,j} \cdot T_{i,World} \quad (1)$$

Equations (2)–(9) provide the mathematical expressions of each of the four applied sharing principles (i.e. term Ai,j in Eq. (1)).

Principle 1

$$A_{i,j} = \frac{P_j}{P_{World}} \cdot \frac{GVA_{j,energy\ sector}}{GVA_j} \quad (2)$$

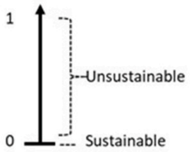
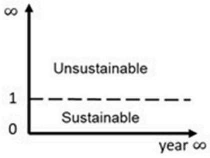
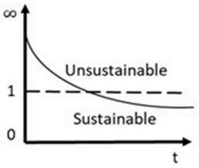
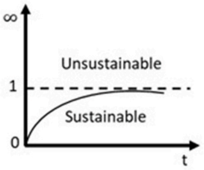
With P_j the population in country j, $GVA_{j,\ energy\ sector}$ the gross value added of the energy sector in country j and GVA_j the total GVA for country j.

Principle 2

$$A_{i,j} = \frac{P_j}{P_{World}} \cdot \frac{GVA_{j,energy\ sector}}{GVA_j} \cdot \alpha_{i,j} \cdot \beta_i \quad (3)$$

With $\alpha_{i,j}$ being a priority factor (see Eq. (4); specific to country j and environmental indicator i) and β_i being a scaling factor to avoid exceedance of the global share assigned to the energy sector for environmental indicator i (see Eq. (5)).

Table 1
Methods supporting the determination of absolute sustainability thresholds for different indicators.

Method	Absolute sustainability threshold definition	
Zero-deprivation	• Threshold defined at the best obtainable score possible within a fixed range (e.g. percentage-based) • Best score/value of zero defining the level of 'zero deprivation' and corresponding to being absolutely sustainable, while values above 0 describe a degree of 'deprivation' (adapted from Raworth [22]).	
Steady-state	• Threshold defined at a level of pressure/impact (e.g. kg of emissions or number of deaths) ensuring that a sustainable state can be maintained (e.g. Earth's life support systems) • Applicable to indicators that are not defined by a fixed range • Threshold values are is time-independent	
Budgeting	• Threshold defined by a maximum allowance or a cap amount of accumulated impacts (i.e. budget) to achieve or avoid exceeding a sustainable state at a certain point in time • Applicable to indicators that are not defined by a fixed range. • Threshold values are time-dependent	Current level as unsustainable (aim to mitigate and reach sustainable state)  Current level as sustainable (aim to remain within sustainable state) 

$$\alpha_{i,j} = \frac{I_{i,World}}{P_{World}} \cdot \left(\frac{I_{i,j}}{P_j}\right)^{-1} \tag{4}$$

$$\beta_i = \frac{P_{World}}{I_{i,World}} \cdot \left[\frac{\sum_j \left(P_j \cdot \frac{GVA_{j,energy\ sector}}{GVA_j}\right)}{\sum_j \left(\frac{P_j^2}{I_{i,j}} \cdot \frac{GVA_{j,energy\ sector}}{GVA_j}\right)}\right] \tag{5}$$

with $I_{i,world}$ being the total impact of consideration in the world (e.g. global climate change footprint) and $I_{i,j}$ is the total impact of consideration in country *j* (e.g. national climate change footprint).

Principle 3

$$A_{i,j} = \frac{P_j}{P_{World}} \cdot \frac{I_{i,j,energy\ sector}}{I_{i,j}} \tag{6}$$

With $I_{i,j,energy\ sector}$ being the impact for environmental indicator *i* (e.g. climate change footprint) stemming from the energy sector within country *j*.

Principle 4

$$A_{i,j} = \frac{P_j}{P_{world}} \cdot \gamma_j \cdot \varepsilon \cdot \frac{I_{i,j,energy\ sector}}{I_{i,j}} \tag{7}$$

With γ_j being a priority factor (specific to country *j*) as defined in Eq. (8), where GDP_{world} and GDP_j are the gross domestic products for the world and country *j*, respectively. The term ε (dimensionless) is a country-independent scaling factor ($\varepsilon = 0.23$ in year 2018) to avoid exceedance of the global threshold when aggregating the shares assigned to each country (see Eq. (9)).

$$\gamma_j = \frac{GDP_{world}}{P_{world}} \cdot \left(\frac{GDP_j}{P_j}\right)^{-1} \tag{8}$$

$$\varepsilon = \frac{P^2_{world}}{GDP_{world}} \left(\sum_j \frac{P_j^2}{GDP_j}\right)^{-1} \tag{9}$$

Sharing Principle 1 (egalitarian + utilitarian) is the only one independent of the type of environmental indicator considered. It has been the most widely applied until now in setting absolute thresholds assessment of industrial sectors (here: energy sector), with the choice of GVA consistent with previous practice when assessing absolute sustainability [20,28,29]. The use of GVA is intended to approximate the added utility to society, although it brings some uncertainty in the current context. The GVA for the energy sector (retrieved from the Eora26 model [30]; see next sub-section) was indeed found to account for ca. 11.27% of total GVA globally. This relatively small share reflects the role of energy systems in supporting all other economic sectors, which bring larger added values from a strictly economic perspective. Alternative metrics to better capture the societal utility of energy systems may lead to a larger share, and should be researched as part of improving the use of sharing principles [28].

Principle 2 supplements Principle 1 with an additional prioritarian dimension by considering a priority factor α to favour low-impacting countries based on their current per-capita impact level (i.e. higher shares given to low-impacting countries, relative to global mean; see Eq. (4)). The total national impacts are considered in the term α – and not just the impacts from the energy sector – with the view that each country manages its assigned share of the global thresholds and that, if a given sector in a country performs poorly (i.e. exceeds its assigned sector-specific threshold), other sectors should compensate. To ensure that the total share of the energy sector is not exceeded globally, an indicator-specific scaling factor (β) needs to be considered (Eq. (5)). The values for both priority and scaling factors are provided for each indicator in Tables S39 and S40 in Supplementary Information 2 (SI-2) available as open source in Ref. [21].

Principle 3 (egalitarian + acquired rights) downscales the thresholds to the country level based on the equal-per-capita method before considering the status quo level of impacts (also often called grandfathering) to estimate the share for the energy sector.

Principle 4 (egalitarian + prioritarian + acquired rights) allocates the threshold to each country based on the equal-per-capita principle, which is corrected to factor in the different income levels across countries, assumed here to reflect an ‘ability to pay’ (considered in γ). The GDP per capita is taken as a proxy to reflect the income level in the countries. Hereafter, the shares are distributed to the energy sector based on the current impacts level of the sector as in Principle 3 (i.e. acquired rights).

While sharing principles based on equal-per-capita or economic values are relatively straightforward to translate into quantified shares for each country, other principles can be more challenging owing to their underdevelopment in the scientific literature, e.g. sufficientarism (i.e. distributing based on what is sufficient enough for everyone) or historical responsibility (i.e. being responsible for historical emissions) [28,31]. In the current study, the choice of the four sharing principles is intended to cover diverse ways of distribution based on the most common principles described in the literature. Conceptually, other sharing principles may be considered more appropriate to capture sustainability, like defining an absolute sustainable space for the energy sector based on overall human needs (along with food, etc.) to better relate to the definition of sustainability by the Brundlandt Commission [32]. However, the definition and operationalisation of such approaches remain a field in need of further research. In the context of the current study, it is therefore important to interpret the results of the environmental indicators with respect to their related sharing principles and use the multiple approaches considered herein as sensitivity analyses.

2.5. *Data collection and determination of indicators*

The proposed framework is operationalised by fully applying it to a number of countries worldwide. For that purpose, data sources for each of the recommended indicators have been explored and selected according to their ability to provide the data needed for the indicator computation, also considering their country coverage and up-to-date nature. The data sources and their potential limitations are fully documented for each individual indicator in Tables S4-S32 (also covering the eight C-flagged indicators; Section S4 in SI-1 [21]). For the retained environmental indicators, no directly implementable data exist and the use of modelling was required, in particular, that of environmentally-extended multi-regional input-output (MRIO) models [30,33,34]. MRIO models enable to capture the trade mechanisms between sectors and countries across the world and, as such, are the primary method for performing consumption-based environmental footprints of nations [35–37], such as carbon footprint [38], water footprint, or material footprint [39]. The consumption-based approach allows to capture the impacts triggered by a country’s consumption activities, including those that may take place outside the country’s territorial boundaries (thus including impacts, e.g. from outsourced activities). In such MRIO models, monetary flows are linked to country- and sector-specific resource use and emission intensities to derive environmental indicators.

The Eora26 model was selected in this study because of its harmonised structure, its broad coverage of 188 countries (only 185 could be assessed due to limited data for defining thresholds for three island countries) and its possibility of segregating the energy sectors [33, 40]. Eora26 consists of 26 industries that follow the sector correspondence of the United Nations International Standard Industrial Classification of All Economic Activities (ISIC) revision 3 [40], for which we selected the two industries’ electricity, gas and water’ and ‘transport’ as the primary energy-related industries. The water-related processes were disregarded by additional steps (see Supplementary Methods in SI-1 [21]). Furthermore, the environmental flows in Eora26 allowed for identifying energy-specific emissions and resource use in other sectors (e.g. energy-related CO_2 emissions from food sector activities), which we added to our assessment of the full consumption-based impacts related to the energy sector. Using the Python programming language, the two energy-related industries as well as all other energy-related emissions were retained and aggregated in the computation of the consumption-based environmental indicators (see details in Section S6 of Supplementary Methods in SI-1 [21]).

Due to the top-down nature of MRIO models, calculating footprints for a specific sector bears some limitations and uncertainties associated with the delimitation of the sector boundaries and the general inconsistencies between national accounting of environmental pressures [34,36]. With the increased robustness expected from ongoing and foreseen research on MRIO modelling, e.g. better sector, country and environmental flow coverage [34], some of these issues can be mitigated, also offering opportunities to perform sensitivity analyses using several MRIO models. In the current study, given the current state of knowledge, we limited the study to the use of Eora26, which has unrivalled country and sector resolutions.

As reflected in Fig. 1, the framework could be applied for multiple years to enable monitoring of the national SDG-7 performances from one year to the next. However, due to the study scope focusing on indicator development and the integration of an absolute sustainability perspective via the normalisation step, the framework was only applied to assess the national performances in a single year. Thus, the results show the status quo performances without dynamic progress over time. The inclusion of such dynamic perspective should be explored in future research. The assessment year used in this study was 2018, which is the most recent year for which data and modelling could enable to quantify them consistently across both STE and environmental indicator groups. Hence, it is noteworthy that more up-to-date data exist for several individual indicators (e.g. Eora26 currently provides data up to 2021; [33, 40]).

2.6. *Normalisation of indicators*

The normalisation step in the framework (see Fig. 1) can be expressed as in Equation (10) for determining the normalised indicator score ($NS_{i,j}$) for indicator i and country or region j:

$$NS_{i,j} = \frac{IS_{i,j} - IS_{i,low}}{IS_{i,up} - IS_{i,low}}\text{, with } \begin{cases} NS_{i,j} \in [0;1]\ , & \text{for STE indicators} \\ NS_{i,j} \in [0;\infty[\ , & \text{for envionmental indicators} \end{cases} \tag{10}$$

where $IS_{i,j}$ is the value of indicator i for the energy sector in country j, and $IS_{i,low}$ and $IS_{i,up}$ are respectively defined as pre-set lower and upper values for indicator i (with potential country specificity depending on the indicator considered).

The definition of Eq. (10) means that the higher the normalised indicator value is, the more deprivation (distance to the sustainability target/threshold) or the more impacts (relative to the thresholds) the energy sector embodies. The upper and lower bound values in Eq. (10) are dependent on the type of indicators considered. For percentage-based indicators (majority of STE indicators), upper or lower bounds are set to 0 or 100%, depending on whether 0% or 100% represents the sustainability target. For scale-based or value-free STE indicators, the best obtainable value (scale-based) or the sustainability target value defines the lower bound. For environmental indicators with defined absolute sustainability thresholds, the lower bound is set to zero impact, while the upper bound is set to the absolute threshold. In the latter case, it is worth noting that Equation (10) only holds for positive impact values, meaning that if a sustainability threshold is negative (e.g. achieving net negative emissions), it needs to be treated differently (see Section S7 in Supplementary Methods, SI-1 [21]).

3. Results and discussion

3.1. *New recommended set of indicators for SDG-7*

Out of the 154 identified and reviewed indicators, a resulting list of 29 indicators is proposed, including 12 STE indicators and 17 environmental indicators. Table 2 reports them, along with indication of their operability (i.e. A-B-C; see Section 2.1). In the country assessments presented as a proof-of-concept in the following sections, only the 21 indicators flagged as "A" and "B" are retained, with C-flag indicators currently prevented from wide application. The detailed descriptions and categorisation of each of the 29 retained indicators assigned to each of the SDG-7 targets, are reported in Tables S4-S32 (see Section S4 in SI-1 [21]). These descriptions also address their main uncertainties and limitations and provide recommendations for further indicator development (Section S4 in SI-1 [21]).

Recent SDG-7 Policy Briefs have raised discrepancies between the goal and its proposed indicators due to the lack of indicators that can measure affordability and reliability [41,42]. The absence of SDG-7 indicators, which can capture the linkages to other SDGs and are consistent with the targets set in the Paris Agreement, has also been reported [41,42]. This evaluation is consistent with the results from our literature review, in which we retrieved a total of 61 indicators addressing SDG-7 explicitly (see Section 2.1 and Supplementary Methods in SI-1 [21]). Through this review, gaps were observed in addressing impacts on ecosystems, resources, and human health associated with energy systems, which can be explained by the fact that these are not addressed by Targets 7.1–7.3. For example, an energy system at the country level may have an increased share of renewables, promote accessibility and increase energy efficiency while still leading to an increase in environmental impacts, e.g. due to an overall increasing energy demand nationally [13]. With the current setup of existing or proposed SDG-7 targets and indicators, such possible trends would not be captured. They might lead to biased policy support and potential burden-shifting if policies address the mitigation of a specific aspect while inadvertently increasing others.

Building on the common recognition that interlinkages between SDGs should be accounted for [15,16], and acknowledging the fact that SDG-7 has a strong technology focus, which could be directly linked to more environmentally-oriented SDGs, such as SDG-13 ("climate action"), SDG-14 ("life below water") or SDG-15 ("life on land"), we propose to integrate the tracking of environmental impacts that energy systems cause, i.e. elements of environmental sustainability, within the set of indicators for assessing SDG-7 (see Table S2 in Supplementary Methods, SI-1 [21]). In large part, we call for the use of environmental footprint indicators, which can be applied to address specific areas of concern [43–45]. Since these indicators cannot fit within the existing UN SDG-7 targets, we propose to create a new target, i.e. Target 7.4, defined to "*ensure environmentally sustainable energy systems*". This target would complement the other three outcome-oriented targets to guarantee a holistic perspective of the sustainable development of energy systems.

Some of the indicators addressing environmental sustainability for SDG-7 may be argued to be similar to those listed for other SDGs, like SDG-12 ("responsible consumption and production") or SDG-13. However, the indicator scopes for those SDGs are set at the full country level, while the proposed ones under SDG-7 are specifically catered to energy systems, hence demonstrating no redundancies. A number of SDG indicators from the current UN list already feature in several relevant SDGs. For example, the indicator 'number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population' is used to address Targets 1.5 (SDG-1), 11.5 (SDG-11), and 13.1 (SDG-13) [4]. In the authors' opinion, this precedence justifies a possible addition of the proposed environmental sustainability-related indicators and their associated umbrella Target 7.4 to help achieve the full extent of SDG-7.

3.2. *An absolute sustainability perspective to complement relative sustainability*

The application of the indicators provides measures of a country's performances, which can then be compared to performances from previous assessments to support policy-making (i.e. Output 1 in Fig. 1). For example, it can allow identifying trends, gauging the efficiency of earlier actions and policies, or unveiling possible trade-offs between increasing and decreasing trends across indicators. With the application of a normalisation step, it becomes possible to benchmark the indicator performances against absolute sustainability thresholds or targets that reflect environmental limits that should not be exceeded or desired socio-economic targets to reach (Fig. 1). In contrast to the relative assessment, such absolute sustainability assessment (i.e. Output 2 in Fig. 1) can inform policy-makers whether a country's SDG performances are within a sustainable or unsustainable state (for each individual indicator), and how far they are from the thresholds separating these states. Both relative and absolute sustainability assessments should therefore be considered complementary support to policy-making when assessing and monitoring SDGs performances.

To operationalise this approach, we determined absolute sustainability thresholds for all 21 currently applicable indicators (see Section 3.1). Values derived at the global scale are reported in Table 2, while the details on data sources, modelling and further research needed (incl. for the eight non-operational indicators) are extensively documented in Section S5 of SI-1 (see Ref. [21]). For all STE indicators, except fossil fuel subsidies (Indicator 2.3) and energy intensity (Indicator 3.1) indicators, for which specific thresholds were defined, the absolute sustainability thresholds (i.e. "targets") were set at the best obtainable score. The zero-deprivation concept (see Table 1) was applied to define the performances for all STE indicators, in which indicators are defined on a fixed scale indicating zero deprivation or full deprivation (possible value range between 0 and 100%, corresponding to best/worst case).

With respect to environmental indicators (addressing proposed Target 7.4), existing literature proposing environmental limits or ways of defining global thresholds for each environmental issue was considered [18,22,48]. Several of these sources referred to environmental control variables, which do not directly match with the metrics of the indicators (e.g. 1.5 or 2° targets to translate into kg-CO_2eq/yr). Modelling, considering the use of budgeting and/or steady-state methods (see Table 1) was thus performed. Particularly for climate change footprint, several control variables could be retrieved (i.e. the 1.5 and 2° targets under the Paris Agreement [55], and the two control variables for climate change from the planetary boundaries framework [15,16]) and several modelling methods (budgeting/steady-state) could be identified as applicable. In the absence of consensus, all relevant thresholds, combining proposed control variables and modelling methods, were modelled and computed, resulting in six global thresholds for climate change footprint to be used for sensitivity analysis (see Section S5.3.1 in Supplementary Methods, SI-1 [21]).

Overall, these estimated absolute thresholds should be considered with caution due to large uncertainties for several of them, particularly for environmental indicators, e.g. climate change footprint and its six defined thresholds based on different approaches. Further research should therefore concentrate on refining them where possible (see Supplementary Methods for detailed recommendations for each individual indicator [21]). Despite these uncertainties, the proposed values can be considered as interim operational estimates of the global thresholds. When comparing to the current indicator values at the global level, which are provided in Table 2, it can be observed that the global performances are overall unsustainable for most STE and environmental indicators.

3.3. *Absolute national SDG-7 performances*

Detailed results for the 176 countries are presented in SI-2 (see Ref. [21]), in Table S46 (indicator values, i.e. Output 1 from framework in Fig. 1) and Tables S47-S51 in SI-2 (normalised indicator values, i.e. Output 2). Following the normalisation step (see Section 2.5.), the global sustainability thresholds (Table 2) were downscaled at the level of the energy sector in each of the 176 considered countries. The resulting values for all 21 operational indicators when considering each of the four sharing principles are reported in Table S42-S45 in SI-2 (see Ref. [21]), so they can directly be utilised in future applications of the

Table 2
Recommended list of 29 indicators to assess SDG-7 performance (operational indicators are flagged as A or B).

ID[a]	Indicator developing source	Theme/Aspect addressed	Name and brief description[b]	Tier[b]	Global threshold value[c]	Global current value[c]	Unit	Threshold method
1.1	UN (2017, 2020) [3,4]	Accessibility to electricity	*Access to electricity* Proportion of population with access to electricity.	A	100	89	% capita	Zero-deprivation
1.2	UN (2017, 2020) [3,4]	Accessibility to modern & renewable energy sources	*Reliance on clean fuels and technologies* Proportion of the population with primary reliance on clean fuels and technologies.	A	100	65	% capita	Zero-deprivation
1.3	This study	Reliability of electricity	*Reliability of electricity supply* Due to lack of observational data (occurrences of interruptions and voltage fluctuations), survey-based indicator 'Quality of electricity supply' by World Economic Forum [46] used as proxy.	B	7	4.7	1 (worst) – 7 (best)	Zero-deprivation
1.4	UNECE (2017) [7]	Reliability and affordability of energy services	*Energy corruption* Corruption index for energy. Due to lack of data, national corruption index by TI [47] used as proxy.	B	100	43	0 (worst) – 100 (best)	Zero-deprivation
1.5	This study	Energy security	*Energy import dependency* Proportion of net energy imports in total primary energy use.	B	0	−1.0	% energy	Zero-deprivation
1.6	This study	Affordability of energy services	*Energy poverty* Share of the population, for whom energy expenses exceed 10% of the household income.	C	0	NA	% capita	Zero-deprivation
1.7	This study	Safety of energy services	*Energy safety* Number of reported accidents or risk of accidents associated with energy services.	C	0	NA	NA	Zero-deprivation
2.1	UN (2017, 2020) [3,4]	Increased use of renewable energy	*Share of renewable energy (RE) sources* Share of RE in the total final energy consumption (TFEC).	A	100	17	% energy	Zero-deprivation
2.2	This study	Increased use of renewable energy	*Share of non-renewable energy sources in newly installed capacity* Captures tendencies in national energy policies to move away from fossil fuels; estimated as difference between consecutive years.	A	0	48	% $MW_{installed}$	Zero-deprivation
2.3	Schmidt-Traub et al. [8]	Increased use of renewable energy	*Fossil fuel subsidies* Captures financial actions/mechanisms directed or not to RE deployment; estimated as share of gross national income (GNI) spent on subsidies to fossil fuels.	B	0	0.8	% GNI	Zero-deprivation
3.1	UN (2017, 2020) [3,4]	Gains in energy efficiency	*Energy intensity* Captures energy required to produce economic output; estimated as total primary energy supply (TPES) per GDP.	A	3.3	5	MJ/USD_{2011}	Zero-deprivation
3.2	This study	Gains in energy efficiency	*Supply-side energy efficiency* Captures efficiency of energy conversion and transmission and distribution losses within the energy systems; estimated as ratio of TFEC to TPES.	B	100	69	% energy	Zero-deprivation
4.1	This study	Environmental sustainability	*Climate change footprint of the energy sector* Captures climate change impacts of greenhouse gas emissions from the energy sector with a consumption-based perspective.	A/B[d]	−0.7–16.6[e]	58	Gt-CO_2eq/yr	Steady-state & budgeting
4.2	This study	Environmental sustainability	*Marine acidification footprint of the energy sector* Captures marine acidification impacts of CO_2, CH_4 and CO from the energy sector with a consumption-based perspective.	A/B[d]	26.6	52.6	Gt-CO_2eq/yr	Budgeting
4.3	This study	Environmental sustainability	*Stratospheric ozone depletion footprint of the energy sector* Captures impacts of ozone-depleting substances from the energy sector with a consumption-based perspective.	A/B[d]	360	204	kt–CFC–11eq/yr	Steady-state

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Table 2 (*continued*)

ID[a]	Indicator developing source	Theme/Aspect addressed	Name and brief description[b]	Tier[b]	Global threshold value[c]	Global current value[c]	Unit	Threshold method
4.4	This Study	Environmental sustainability	*Photochemical ozone formation footprint of the energy sector* Captures photochemical ozone impacts associated with ozone precursor emissions from the energy sector with a consumption-based perspective.	A/B[d]	642	152	Mt-NO_xeq/yr	Steady-state
4.5	This Study	Environmental sustainability	*Particulate matter footprint of the energy sector* Captures human health impacts of primary and secondary particulate matter from the energy sector with a consumption-based perspective.	A/B[d]	62	94	Mt-$PM_{2.5}$eq/yr	Steady-state
4.6	This Study	Environmental sustainability	*Terrestrial acidification footprint of the energy sector* Captures impacts on terrestrial ecosystems from acidifying substances emitted in the energy sector with a consumption-based perspective	A/B[d]	202	246	Mt-SO_2eq/yr	Steady-state
4.7	This Study	Environmental sustainability	*Marine eutrophication footprint of the energy sector* Captures impacts of eutrophying substances (N-compounds) on large marine ecosystems from the energy sector with a consumption-based perspective.	A/B[d]	23	41	Mt-Neq/yr	Steady-state/ budgeting hybrid
4.8	This study	Environmental sustainability	*Freshwater eutrophication footprint of the energy sector* Captures impacts of eutrophying substances (P compounds) on freshwater ecosystems from the energy sector with a consumption-based perspective.	A/B[d]	5.8	1.5	Mt-Peq/yr	Steady-state
4.9	This Study	Environmental sustainability	*Land use footprint of the energy sector* Captures biodiversity impacts of land use from the energy sector with a consumption-based perspective.	A/B[d]	18	34	10^6 km^2-cropland-eq/ yr	Steady-state
4.10	This Study	Environmental sustainability	*Water scarcity footprint of the energy sector* Captures potential of water deprivation to humans and ecosystems from water consumption in the energy sector with a consumption-based perspective.	A/B[d]	4000	2600	$km^3_{world\text{-}eq}$/yr	Steady-state
4.11	This study	Environmental sustainability	*Fossil resource scarcity footprint of the energy sector* Captures fossil fuel energy demand from the energy sector with a consumption-based perspective.	A/B[d]	5.7	11.2	Gtoe/yr	Budgeting
4.12	This study	Environmental sustainability	*Metal and mineral resource availability footprint of the energy sector* Captures metals and minerals availability and accessibility issues associated with energy systems, accounting for resources in both lithosphere and anthroposphere.	C	NA	NA	NA	Budgeting
4.13	This study	Environmental sustainability	*Ionising radiation footprint of the energy sector* Captures health and ecosystems impacts of radionuclides released from the energy sector with a consumption-based perspective.	C	NA	NA	Bq-Co-60eq/yr	Steady-state
4.14	This Study	Environmental sustainability	*Toxicity footprint of the energy sector* Captures damages to human health and ecosystems caused by toxic chemical substances released from the energy sector with a consumption-based perspective.	C	NA	NA	NA	Steady-state
4.15	This Study	Environmental sustainability	*Thermal pollution from the power sector* Capture freshwater impacts of temperature increases from cooling water emissions in the energy sector; proposed as time-integrated water releases weighted by river temperature differences above local temperature limits.	C	0	NA	m^3.K.yr	Zero-deprivation
4.16	This study	Environmental sustainability	*Particulate matter peak exposure events* Proxy for health impacts during peak events (complementary to Ind. 4.5); proposed as time-integrated number of people exposed to a $PM_{2.5}$ concentration in excess of a limit.	C	0	NA	person.ppm.hr	Zero-deprivation

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Table 2 (*continued*)

ID[a]	Indicator developing source	Theme/Aspect addressed	Name and brief description[b]	Tier[b]	Global threshold value[c]	Global current value[c]	Unit	Threshold method
4.17	This Study	Environmental sustainability	*Ozone peak exposure events* Proxy for health impacts during peak events (complementary to Ind. 4.4); proposed as time-integrated number of people exposed to an ozone concentration in excess of a limit.	C	0	NA	person.ppm.hr	Zero-deprivation

[a] Indicators are numbered, with the first number reflecting the SDG-7 target number.

[b] Full description of the indicators (incl. tier classification, data sources, further research needs, etc.) are provided in Tables S4-S32 in Section S4 of SI-1 (see Ref. [21]).

[c] The global threshold values and current global values for the footprint-based indicators are global totals and hence are not limited to the energy sector. The determination of the global thresholds is fully documented in Section S5 of SI-1 (see Ref. [21]). Background details for deriving the current level estimates (based on the latest available data) are detailed in Tables S33 and S34 (Section S5, SI-1 [21]). NA: not available.

[d] The indicator fulfils the criteria of Tier A because of the high country coverage and temporal availability, however, the modelling carries large assumptions and uncertainties [34], hence the "A/B" Tier classification.

[e] The global threshold value for climate change footprint is indicated here as a range, capturing all six global threshold values determined in the study (see details in Table S34 and Section S5.3.1 in SI-1 [21]).

assessment framework.

An overview of the normalised indicator results is displayed in Fig. 2 (i.e. absolute sustainability assessment). Interpretation of these results should primarily be made within each country to identify indicators for which absolute sustainability thresholds are exceeded or, as for most STE indicators, where targets are far from being reached. Such prioritisation could help national energy policy-makers focus on "hotspots" and prioritise actions to strive towards sustainable energy systems in absolute terms. Taking Portugal as an example, priority (indicated by red and orange-marked cells in Fig. 2) should thus be directed to addressing climate change (Indicator 4.1), photochemical ozone formation (4.4), terrestrial acidification (4.6), fossil resource scarcity (4.11), energy import dependency (1.5) and, to a lesser extent, the share of renewable energy sources (2.1), and marine acidification and particulate matter footprints (4.2 and 4.5). Such assessment results demonstrate that the proposed framework enables to bring more scientific robustness to the SDG performance assessment and, through both relative and absolute sustainability perspectives, can provide new science-based support to national policy makers in their striving towards SDGs, thus answering earlier calls from many stakeholders [16,49].

Although the normalisation method between STE and environmental indicators differ, preventing the resulting scores from being comparable, a general pattern can be observed with marked opposition between countries in different regions. From the country-level overview provided in Fig. 2, countries in the African region, for example, exert poor performances with regard to STE indicators, with many indicators being red- or orange-flagged (i.e. normalised indicator values above 50%, where 0% is the desired sustainability state), while environmental indicators generally perform better with respect to their absolute sustainability thresholds (green or yellow flags in Fig. 2) compared to other countries. In contrast, results for European countries, and more generally for all high-income countries, call for a strong need to reduce the environmental footprints of their energy systems, while the countries perform relatively satisfactorily with respect to STE indicators (Fig. 2).

Such patterns are statistically visible in Fig. 3, in which marked differences across the three income levels can be observed for nearly all indicators (albeit with some variability). A case in point is Indicator 1.1 ("access to electricity"), for which all high-income countries have reached the desired level of sustainability, while low-income countries remain far from it (Fig. 3A). With the exception of Indicator 2.1 (renewables share in energy mix), an anti-correlation between STE and environmental indicators seems apparent, with high-income countries performing worse than middle- and low-income countries across all environmental indicators (regardless of the considered sharing principles; Fig. 3B and Figure S6 in SI-1 [21]) while the opposite appears for nearly all STE indicators (Fig. 3A). Broader assessments evaluating all SDGs (e.g. Sachs et al. [6]) have revealed such tendencies between SDGs addressing environmental sustainability issues (e.g. SDG 12–15) and other SDGs [50]. The increasing affluence in a country (reflected by better STE indicator scores) typically leads to a larger consumption and, as a result, to larger national environmental footprints (i.e. poor environmental indicator performances) when that increased consumption is not mitigated sufficiently by increased technology efficiency [51]. Although the present assessment does not include any temporality, such a mechanism is likely to explain the current environmentally-unsustainable levels of high-income countries and the reverse trends observed in medium- and low-income countries.

Generally, the availability and quality of the data sources varied considerably between indicators, from data with high spatial coverage and a direct match with the indicator requirements (e.g. Indicators 1.1 and 1.2), through the need to use proxy indicators to cover a specific issue (e.g. indicator 1.4), to a complete lack of data (e.g. indicator 1.7). Hence, when interpreting the indicator performances in the current recommended indicator set, one should pay attention to the uncertainties and limitations associated with each indicator, which could only be flagged qualitatively in the current study through the tier A-C approach. Future studies should investigate how quantitative uncertainty analyses can be achieved (incl. uncertainty propagation across all input parameters and potentially used models).

3.4. Variability across indicators

No STE indicator consistently shows sustainable performances in absolute terms for all countries and regions. However, out of the 10 assessed STE indicators, Indicator 2.1 (renewables share in final energy consumption) is observed to display poor sustainability performances for all considered countries (Fig. 3A). Indeed, although an increasing share of renewables can be noted in the electricity grid mix of several countries, particularly in high-income countries, the penetration of renewables in the transportation sector to substitute fossil fuels still remain a challenge [52]. Overall, no homogenised pattern across countries and regions is observed for STE indicators, thus preventing generalisation and calling for country-specific assessments to capture each country's specificities and identify its major SDG-7 hotspots.

Similar observations and conclusions can generally be made for environmental indicators, although some indicator patterns can be recognised. Although different sharing principles show different trends across indicators (Fig. 3B and Figure S6 in SI-1 [21]), indicator 4.8 (freshwater eutrophication) shows results suggesting that the energy systems for nearly all countries (approx. 56–97% of all countries across all four sharing principles) perform sustainably according to this environmental issue (Fig. 3B; Figure S6). Likewise, albeit with a

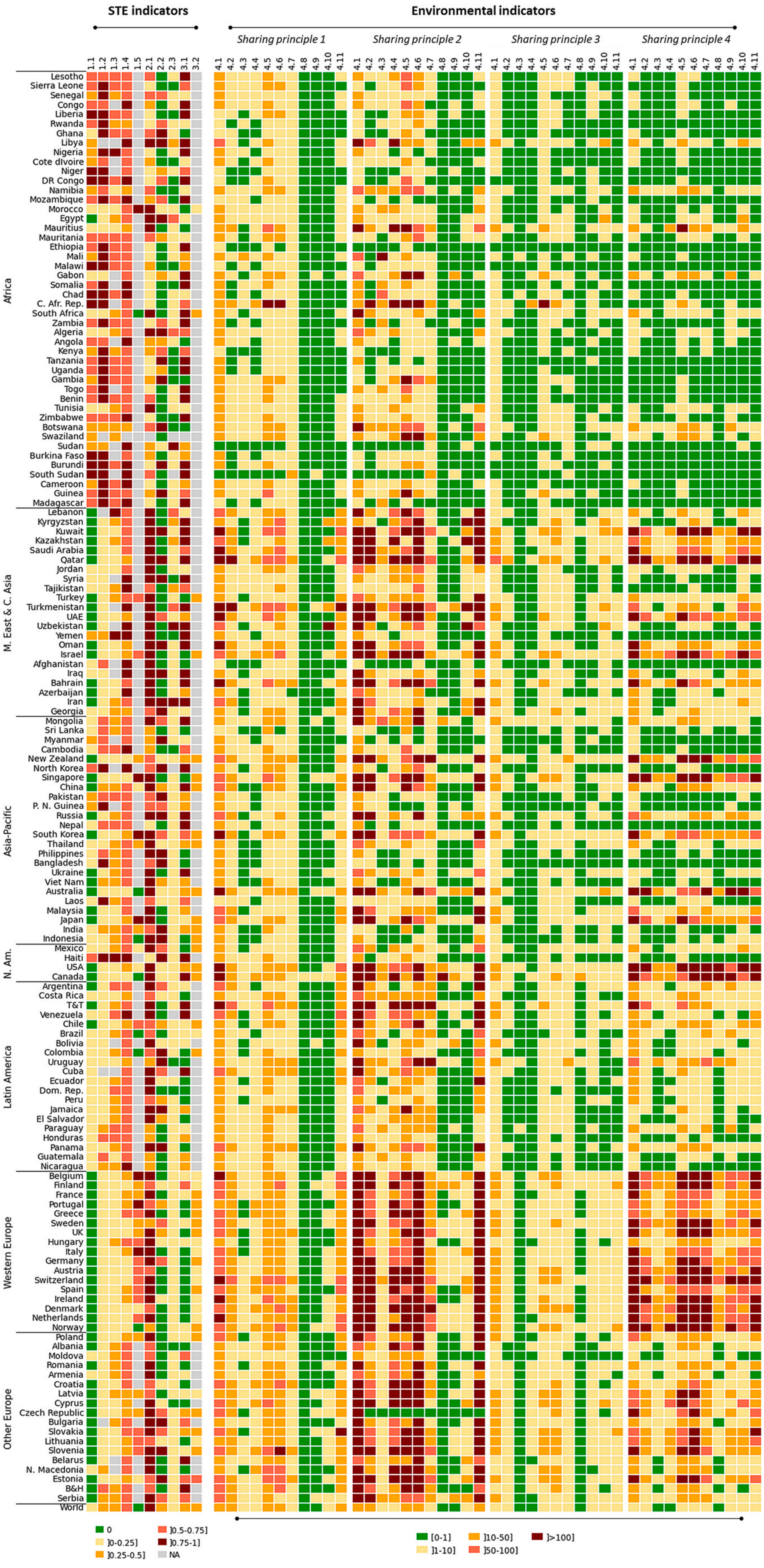

Fig. 2. Heat maps of normalised scores for the 21 operational socio- and techno-economic (STE) and environmental indicators assessing SDG-7 performances of 151 countries out of the 176 assessed with population size larger than one million (i.e. Output 2 in the framework proposed in Fig. 1). All 176 countries are listed in Table S47-S51 (SI-2) [21]. Green-coloured cells reflect sustainable performances, while warmer colours indicate poorer performances in absolute terms. Indicator names corresponding to the IDs are available in Table 2. For environmental indicators, four sets of results are provided, matching the application of four sharing principles to downscale global sustainability thresholds (see Section 2.3.); compared to Principle 1 (egalitarian and utilitarian), Principle 2 allocates a higher share to low-impacting countries (prioritarian) while Principle 3 assigns higher shares to currently high-impacting energy sectors (acquired rights), and Principle 4 allocates lower shares to high-income countries (based on their ability to pay). For climate change footprint (Ind. 4.1), the displayed results reflect the average of the six normalised indicator scores obtained when using each of its six defined global thresholds (see Section S5.3.1 of SI-1 [21]). The numerical values behind each coloured cell are provided in Tables S47-S51 (SI-2) [21]. Country grouping into regions is based on that from the Eora database [33,40].

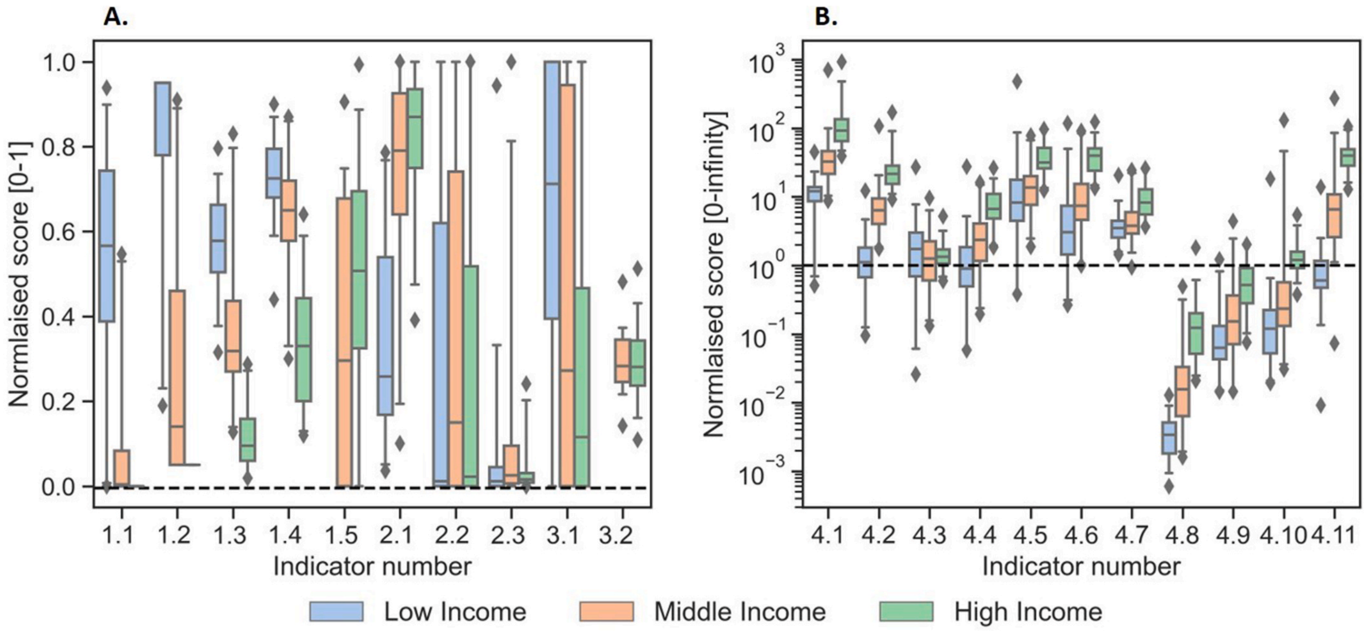

Fig. 3. Boxplots of the normalised scores for (A) the 10 operational socio- and techno-economic (STE) indicators s and (B) the 11 environmental indicators for Sharing Principle 1 (egalitarian + utilitarian). In inset A, the dotted line indicates the desired sustainability target level, over which everything indicates a degree of deprivation. In inset B, the dotted line indicates the environmental threshold level separating the sustainable level (below) and the unsustainable level (above). The box plot indicates the 25th, 50th and 75th percentiles (namely Q1, Q2 and Q3, respectively), and the whiskers indicate the minima and maxima, excluding outliers; the represented dots indicate outliers defined as values below 1.5 times Q1 and higher than 1.5 times Q3. The number of countries (N) for each group differs between indicators for the STE indicator group depending on data availability, with ranges of: N = 0–38 (low income), N = 12–73 (middle income), and N = 31–40 (high income); for the environmental indicators: N = 38 (low income), N = 73 (middle income), and N = 40 (high income); data availability visible in result datasets in Table S47-S51 (SI-2) [21]. Boxplots for the three other sharing principles are provided in Figure S6 in SI-1 [21].

larger dependency on the sharing principles, results for indicators 4.3 (stratospheric ozone depletion), 4.9 (land use), and 4.10 (water scarcity) also reveal that the energy sectors tend to respect their threshold levels for those aspects in many countries, i.e. in 13–93%, 30–85% and 34–63% of all countries, respectively (high sensitivity due to sharing principles). This is also confirmed by the normalised indicator scores at the global scale for all four tested sharing principles (last row in Fig. 2).

Phosphorus compound emissions stemming from the energy sector are negligible compared to other sectors, e.g. agricultural sector with fertiliser use [53], explaining the observed trends for freshwater eutrophying impacts, as also noted for national electricity systems in previous studies [13]. Likewise, the accomplishments realised under the Montreal Protocol have led stratospheric ozone depletion to become a less relevant environmental issue, with the remaining issues, including the unchecked N_2O emissions [54], having little sourcing to the energy sector. The same reasons apply for land and water use impacts, which are predominantly caused by agricultural activities [55,56], although the relevance of these two impact categories should not be dismissed due to the increasing role of biofuels in energy systems like transportation [57]. When accounting for the uncertainties in the calculations and the sensitivity to the sharing principles, nearly all other environmental indicators show assessment results with unsustainable performances in absolute terms for several countries (yellow-orange-red coloured cells in Fig. 2).

Climate change footprint (Indicator 4.1) appears as a major hotspot across all countries (see Fig. 2; detailed values in Tables S48-S51, SI-2 [21]). Normalised indicator scores reach values in excess of 1000, particularly for high-income countries. This is aligned with results obtained for the US electricity sector by Algunaibet et al. [20], who reported exceedance by more than a factor of 1000 for climate change when relating current environmental impacts to the planetary boundaries (using a downscaling approach equivalent to sharing principle 1). In our study, results for climate change are observed to be sensitive to the different choices of absolute sustainability thresholds and to the considered sharing principles, which assign shares of thresholds to the global energy sector ranging from 11 to 73% across the four principles (see Section 2.3.). Yet, out of the 4224 combinations resulting from the assessed 176 countries and regions, six thresholds and four sharing principles, only 238 permutations (ca. 5%) display normalised results below their absolute thresholds (Tables S48-51, SI-2 [21]). This corresponds to 52 countries (including small island states) of Africa and, to a lesser extent, Asia, which are found to show such sustainable normalised results for at least one of the considered sharing principles. Sudan, South Sudan and Ethiopia are the countries showing results below the threshold for nearly all thresholds and sharing principles considered. Regardless of the large variability in the numerical values, these findings, therefore, evidence the need for stringent and urgent actions for most countries and regions worldwide.

Other indicators also exert normalised scores above two orders of magnitude for some countries, such as Indicators 4.5 (respiratory impacts from particulate matter), 4.6 (terrestrial acidification) or 4.11 (fossil resource scarcity). It is also noteworthy that for all environmental indicators, the range of normalised scores generally spans several orders of magnitude, indicating clear segregation between countries; while remaining sensitive to the selected sharing principle, that range can reach up to 5–6 orders of magnitude for the same indicator (see Fig. 3B and Figure S6, SI-1 [21]). Altogether, the indicator results call for considering the entire spectrum of issues and indicators when prioritising and implementing actions to avoid the risk of burden shifting, i.e. addressing the reduction of a specific indicator/problem while inadvertently increasing others. It also calls for further research to refine and complement the operational set of indicators with those in need of method development (i.e. tier C; Table 1) and thus be able to cover all relevant environmental issues (e.g. addressing chemical pollution, ionising radiation, etc.). In that effort, the knowledge accumulated within the field of life cycle impact assessment, which provides a modelling framework and methods to quantify impacts on ecosystems quality, human health and natural resources, should be tapped [23,58]. Proposed steps and guidance to improve the recommended set of indicators are available in Section S4 of SI-1 [21].

3.5. Support for country specific policy making

With a focus on single countries, the assessment framework can provide a starting point to prioritise SDG-7 indicator hotspots and develop adapted strategies at a national level. Fig. 4 exemplifies the type of refined assessments that can be derived at the national level, with the two contrasting countries of Denmark and Kenya. While the overall performance on STE indicators is relatively good in Denmark (Fig. 4A and B), with one single major hotspot in the renewable energy (RE) share (i.e. 35% of renewables), most environmental indicators are found to overshoot their allocated shares regardless of the selected sharing principle (red-coloured area). A few environmental indicators, like land use, remain within a 'risk zone', i.e. ranging in the sustainable or overshoot zones depending on the sharing principle considered (yellow area reflecting this sensitivity in Fig. 4B). These findings specific to Denmark can help policy-makers prioritise and target those impacts in dire need of mitigation. When doing so, potential interdependencies between indicators should be considered. For example, a mitigation plan to increase the share of RE in Denmark should account for potential implications on the already unsustainable levels of environmental indicators. Whereas some indicators may be reduced, like climate change, other impacts might inadvertently increase, triggering burden-shifting across indicators and hence across sub-dimensions of sustainability. Tools such as life cycle assessment, coupled with energy system modelling [59,60], could help prevent such a situation from happening and allow to gain a holistic perspective of the assessment of environmental sustainability and its management with respect to energy technologies. Sub-sectors with high-impact contributions in the energy sector should thus be prioritised.

Kenya offers a contrasting view to Denmark, with different characteristics in terms of income level, size and climate. This results in very different observations, as illustrated in Fig. 4C and D. While Kenya's normalised scores are relatively poor across most STE indicators, except the share of RE, seven out of eleven environmental indicators are found to range within their absolute sustainability thresholds, regardless of the considered sharing principle. It is also noteworthy that the threshold exceedance in Kenya can be 10–1000 times lower than the exceedance in Denmark for some indicators, e.g. particulate matter formation impacting human health with scores of 4 vs 244, respectively (Fig. 4B and D). Kenya is associated with overall smaller energy consumption per person (compared with Denmark) and presents major shortfalls in energy access (e.g. shortage occurrences), which calls for policy makers to prioritise energy accessibility and cleaner fuels while reducing the four overshot environmental impacts of climate change, particulate matter, marine eutrophication and, to a lesser extent, terrestrial acidification (Fig. 4D), and preventing the other relevant impacts from increasing. It is important to note that such transition is not cost-free raising the question of how the overall financial burden of mitigating environmental impacts and improving living standards in some countries should be shared (e.g. some countries considered to bear an ecological debt [61]).

The two examples illustrate the case-specific nature of the SDG-7 performance assessment, where the energy systems of each country have their own singularities, which trigger specific STE and/or environmental problems. One of the major strengths of the framework is that it provides a holistic view of all relevant STE and environmental aspects, from which hotspots can be identified from an absolute sustainability perspective and prioritised in national policy-making processes. Furthermore, throughout the view in Fig. 2 and detailed Tables S47-S51, it is possible to identify countries that may perform well on specific indicators as well as countries that share similar needs to move towards more sustainable energy systems. Such knowledge drawn in the context of a specific country can thus serve as inspiration or as starting points for synergistic efforts in order to develop effective energy planning, i.e. meeting energy needs while mitigating environmental impacts and improving socio- and techno-economic conditions associated with the energy sector.

4. Conclusion and way forward

The above application of the assessment framework to 176 countries demonstrates its operability and results evidence that no country currently performs sustainably in absolute terms with regard to SDG-7. All countries show several SDG-7 indicators that stand far from their sustainability targets (STE), e.g. renewables share in final energy consumption or vastly exceed their sustainability thresholds (environmental), e.g. climate change footprint. These hotspot indicators should be prioritised in national energy policy-making. While doing so, it is essential to consider potential implications on other indicators to prevent burden-shifting from one or more STE and/or environmental problems to others. The trends observed across countries, and in particular across income level groups, suggest that the improvements of STE indicators alone do not ensure meeting SDG-7; such improvements seem to have been realised and still bear the risk of being realised at the expense of increased environmental impacts. In future policy making, it is therefore essential to anticipate the combined effects of affluence rise, demographic evolutions and technology eco-efficiency to ensure a consistent move of all indicators towards sustainability targets or below sustainability thresholds.

Despite the advances associated with the proposed SDG 7 assessment framework, it should only be considered a stepping stone towards a more holistic assessment methodology to assess SDG performances at the country level. Several improvement needs should be addressed to increase further its scientific robustness and operability across countries in the world. These include: (i) the development of quantitative methods for the eight indicators, which could not be made operational (see Table 2) and the potential development of new indicators reflecting yet uncovered SDG interlinkages; (ii) the generation of more data and their dissemination via publicly-available databases, which could provide support for application of SDG-7 indicators to all countries, particularly lower-income countries, for which data gaps are often an issue [16,62]; (iii) the development of high-resolution data characterising the energy systems in order to unlock a sub-country level differentiation in the assessment of countries (e.g. states for USA, provinces for China, etc.); (iv) the further development of MRIO models, which are used for nations footprinting and, although enabling assessment for 188 countries today, still retain a number of uncertainties and limitations [34,36]; (v) the conduct of comprehensive uncertainty analyses on indicators categorised under tiers B and C to characterise potentially low data quality and its influence on the results; (vi) the refined determination of global and regional absolute sustainability thresholds, in particular for environmental indicators, based on the rapidly increasing knowledge in this domain [29,63–65]; and (vii) the further testing and consolidation of sharing principles to scale absolute sustainability thresholds to the energy sector at national level [28]. While these limitations and sources of uncertainties are being addressed in ongoing research, sensitivity analyses should be routinely performed along the different steps of the proposed framework, e.g. use of several sharing principles as performed in this study.

In addition to the above scientific refinements, the framework and its indicators could further gain relevance by the consideration of two major development needs. To provide more refined support to policy-makers, a differentiation of the indicators to segregate specific sub-sectors and technologies within the energy sector should be done. Although the implementation of this recommendation may be constrained by data availability, it would enable stakeholders to better

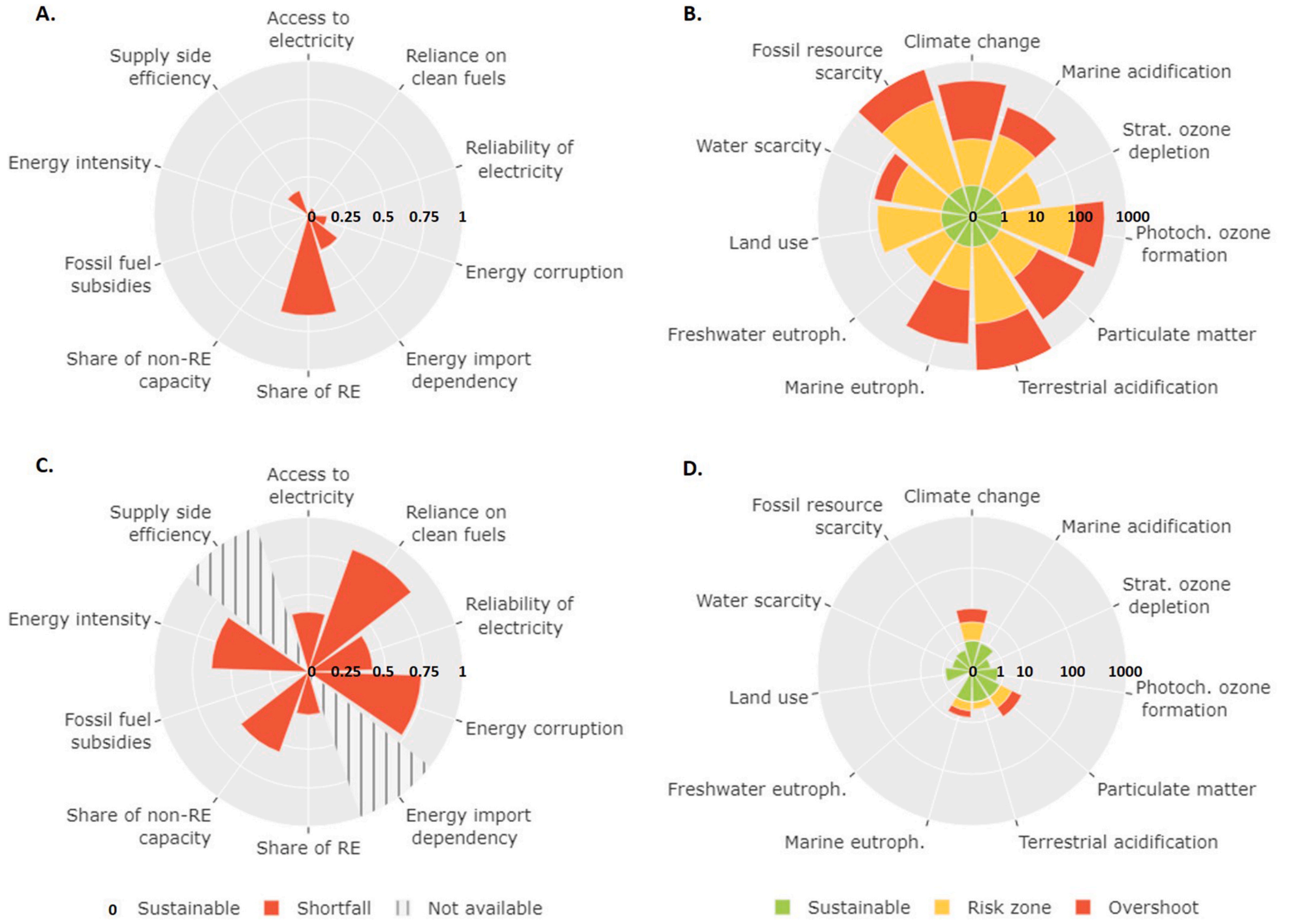

Fig. 4. Polar charts showing the normalised performances for Denmark (top row, A-B) and Kenya (bottom row, C-D) for both STE (A and C) and environmental indicators (B and D). For STE indicators, the score ranges from 0 to 1, with the red area illustrating a degree of deprivation (all non-zero values reflect an unsustainable level). For the environmental indicators, the score is defined from 0 to infinity, and the results are normalised according to the smallest country-specific threshold across the four sharing principles (see Section 2.2.). The range 0–1 (green) thus indicates an indicator score that is found sustainable for all four sharing principles. Scores within the yellow area indicate that the performance lies within the range of determined country-specific thresholds, meaning above the smallest but below the largest threshold values found when using the four sharing principles (termed here the "risk zone"). A performance lying in the red zone means that the country-specific thresholds associated with the four sharing principles are all exceeded, rendering this performance unsustainable. Note the logarithmic scale used for B and D. For climate change; the displayed results reflect the average of the six normalised indicator scores obtained when using each of its six defined global thresholds (see Section S5.3.1 of SI-1 [21]). The detailed numerical values for each selected country are provided in Tables S47-S51 (SI-2) [21].

target and prioritise actions on sub-sectors and technologies of concern. Furthermore, to facilitate decision-making processes, research should be directed to defining and operationalising a weighting scheme that could allow balancing the relative significance of the different indicators within SDG-7. In the absence of better alternatives, weighting approaches currently applied in various national and international SDG assessments (e.g. Sachs et al. [6]) have to rely on equal weighting across indicators and SDGs. While the framework proposed in the current study, in particular its normalisation step, offers an important step forward and an unprecedented opportunity for consistently identifying SDG-7 hotspots, the addition of a scientifically-sound weighting step could further increase its relevance for policy-making. It could thus allow mitigating potential trade-offs between indicators and reducing their numbers to a reduced set or a single score, which would be more manageable for all stakeholders.

With its status as a technology-oriented SDG, SDG-7 bears a direct connection to decision- and policy-makers within the energy sector. Currently, these stakeholders are constrained to rely on incomplete SDG-7 assessments, which run the risk of inadvertent burden-shifting across uncovered sustainability aspects, or on too broad SDG assessments, which, through their scope of including all 17 goals without including indicators focusing on the energy sector, are too unspecific to be relevant for energy policy making. To tackle these barriers, we recommend the adoption of our SDG-7 assessment framework as a starting point and, with it, the integration of our complementary indicators, including those framed under the newly-proposed Target 7.4. By incorporating relevant interlinkages between SDGs while keeping the focus on the energy sector, thus substantially increasing SDG-7 indicator completeness, and by integrating an absolute sustainability perspective, which enables to benchmark current performances against quantified sustainable levels, this framework allows for a more science-based, versatile, and relevant support for monitoring and policy-making within the energy sector (cf. range of possible Outputs in Fig. 1). With a wide application, it could additionally help accumulate knowledge in our striving towards meeting all 17 SDGs and stimulate the development of a holistic SDG performance assessment framework, methods and tools, thus looking beyond just SDG-7.

Credit author statement

Caroline H. Gebara: Methodology, Software, Formal analysis, Investigation, Data curation, Writing - Orignal Draft, Review & Editing, Visualisation. Alexis Laurent: Conceptualisation, Methodology, Validation, Formal analysis, Writing – review & editing, 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112934.

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