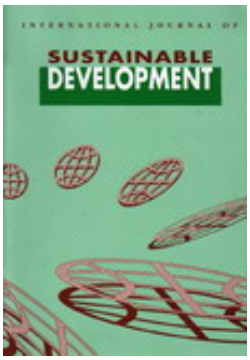

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Scoping SDG interlinkages and methods to infer them

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Scoping SDG interlinkages and methods to infer them

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Abstract: The Sustainable Development Goals (SDGs) have generated a framework of goals, targets and indicators which aim at – among others – ending poverty, improving health, reducing inequality, and spurring economic growth. In this scoping study we examine the focus, methods and approaches used to extract interlinkages between the SDGs and their targets. To that end, we perform a systematic literature review and discuss the outcomes of an expert solicitation workshop with SDG experts to generate a framework of analysis. We evidence that the interlinkages domain is still exploratory, largely neglecting the local level and being disconnected to policy making. Methods used predominantly account for

statistical and conceptual associations and correlations between SDGs, targets and indicators, and not for causal ones; hardly replicated, reproduced and verified. We therefore propose a framework of analysis, which takes into account those gaps to generate a process of integrating interlinkages into the policy and decision making process.

Keywords: Sustainable Development Goals; SDG interlinkages; UN 2030 Agenda; sustainability; sustainable development.

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1 Introduction

In 2015, the United Nations (UN) signed the 2030 Agenda and adopted the Sustainable Development Goals (SDGs) to take "[...] action to end poverty, protect the planet,

and ensure that by 2030 all people enjoy peace and prosperity." SDGs resulted as the outcome of a participatory process, requiring the consensus of country-members for accepting a stacking of goals and targets (Cling and Delecourt, 2022) and they represent a much wider set of objectives than any previous similar exercise (e.g., the Millennium Development Goals that set GDP as the core measure of economic and social progress, or the World Summits on Sustainable Development). The inherent heterogeneity of consensus building and the need to address sustainability in a holistic manner prompted the existence of conflicting or synergistic relationships between the different goals, targets and indicators. In fact, early on, the UN recognised that "the 17 SDGs are integrated" and that "action in one area will affect outcomes in others", while explicitly pinpointing that *the interlinkages of the SDGs are of crucial importance in ensuring that the purpose of the new Agenda is realised* (CF, 2015). This is reiterated in the 2019 Global Sustainable Development Report, which suggests that "policymakers will find similarities and contradictions within them [goals and targets], as well as systemic interactions and cascade effects, as action towards one Goal can alter the possibilities for meeting other goals" (Messerli et al., 2019).

The term *SDG interlinkages* itself has been interpreted in a rather broad manner in the scientific literature. We hereby adopt a compilation of these interpretations where SDG interlinkages are encompassing theoretical, evidence-based, qualitative or quantitative relations; associations; interactions; synergies; trade-offs; discords; correlations; or interconnections of positive, neutral or negative nature between any of the following: SDGs, targets, monitoring indicators, policies, new technologies and other operational interventions towards the achievement of the SDGs. These interlinkages, implicit in the SDG logic (Nilsson et al., 2016), can be realised in the form of synergistic actions (complementary or reinforcing) but also antagonistic (a positive action for a goal/target negatively affecting another goal/target). Recognising and mapping these interlinkages could support removing silos, help the adoption of integrated (indivisible) approaches to deliver upon SDGs vision (Nilsson et al., 2016; Pradhan et al., 2017; Bennich et al., 2020) and support decision/policy making with policy coherence (Horvath et al., 2022; Pradhan et al., 2017) and prioritisation of actions (Asadikia et al., 2021). The topic of synergies and trade-offs between different dimensions of sustainability was also a subject of interest for the research community before 2015 and the SDGs – see for example Luukkanen et al. (2012) and Halsnæs and Garg (2011). The fast-growing body of literature on SDG interlinkages further evidences both the rather diverse, and in many cases, contradictory nature of theirs, as well as the increasing richness of methods to infer them. Both topics, i.e., the interlinkages themselves, and the robustness and validity of ways to ascertain them, have been the subject of numerous studies and research efforts in recent years and consequently consolidating studies. The latter affirms that these form a domain yet to be unravelled, and with immense implications on policy-making and practice. It is therefore with no surprise that as we get closer to 2030, and the envisaged achievement of the SDGs, the research community is exploring several ways to contribute to the topic.

To the best of the authors' knowledge, one of the first efforts to systematically study the literature related to SDGs interlinkages was performed by the International Council for Science (ICS) in 2017 (Griggs et al., 2017). Predominantly focusing on four SDGs (2, 3, 7 and 14), Griggs et al. (2017) applied the Nilsson et al. (2016) assessment framework for identifying causal and functional relations underlying progress or achievement of the SDGs and targets, by deploying expert elicitation based

on a detailed study of the available grey and research literature (>300 articles dating from 1996 to 2016). It is important to note that as by the time of the ICS publication in 2017, research but also policy-making, and in general practice on the SDGs was at a very early stage, the reviewed literature was predominantly not-SDG related. Following a similar approach, and in the same year as the ICS work, (Moinuddin, 2017) adopted a synthesised compilation of literature and policy documents (4334 research articles) on SDGs and indicators in order to identify, and then pair SDG targets with potential relationship (108 out of 169) in a network; they subsequently used graph theory measures to infer the interlinkages in the created network. Also in 2017, Tosun and Leininger (2017) were the first to study SDG interlinkages solely based on what countries have reported by then in the UN's High Level Political Forum, studying a fraction of the 43 voluntary national reviews that were published by then, and focusing only on SDGs 2, 4, 6, 7 and 13.

Four years in the SDG era, Miola et al. (2019) reviewed 220 scientific publications focusing on identifying consensus (agreements/disagreements) on the existence of interlinkages as well as their strength. In their comprehensive review, Miola et al. (2019) also synthesised all encountered methods in five main approaches for studying interlinkages, namely in: linguistic, literature, argumentative, quantitative and modelling approaches. A year later, Bennich et al. (2020) reviewed 70 scientific publications to extract information regarding the scope of SDG interlinkages, examining among others quantitative metrics on policy challenges related to the examination of interlinkages, interaction entities, data sources and methods, without however assessing the applicability of methods used to infer interlinkages. Similar to both Miola et al. (2019) and Bennich et al. (2020), Horvath et al. (2022) performed a comprehensive and systematic review of the methods commonly used in defining interactions. They evaluated the methods found in 93 scientific publications upon 17 criteria such as the ability to detect effects and their properties (direction, scale and polarity), the knowledge generation potential, adaptiveness, and transparency; Horvath et al. (2022) concluded to six main categories of methods, which were similar but not identical to those of Miola et al. (2019), namely: argumentative, linguistic, literature, statistical, simulation and other quantitative approaches. More recently, Di Lucia et al. (2022) reviewed a set of 359 relevant publications (the highest number in the SDG interlinkages topic to date) and created a topology of the methods commonly used. They subsequently concluded in six main categories of methods used in the literature (namely: literature, statistical, modelling system dynamics, modelling coupled component, expert judgement and self-assessment) and qualitatively assessed the performance of the created categories to SDG interaction analysis, based on the views of method developers themselves, and decision-makers.

Among the first to take a sector-dive and study interlinkages having one SDG on focus, was Nerini et al. in 2018. In their work, Nerini et al. studied all published evidence by then (29 research articles) on synergies and trade-offs between any SDG target and SDG7 (on energy), and found some sort of association for 143 targets (out of the 169 in total) and SDG7; they also reported twice as many synergies compared to trade-offs (Nerini et al., 2018). In the years to follow, the approach to focus on the interlinkages of one SDG, or of one sector, versus all others became increasingly relevant, touching among others sectors like urban ecosystems (Maes et al., 2019), water (Shivakoti et al., 2015), energy (Zhao et al., 2023) and transport (Liu and Yuan, 2023).

Although the above-mentioned related studies focus on the methodological aspects of studying interlinkages, with a few exceptions (e.g., Huan et al., 2022) of limited scope, the culmination of the literature review did not yield a process that could allow for a systematic study of interlinkages and connect them to policy making (Di Lucia et al., 2022). The related work often focuses on a limited number of papers with a rather strict inclusion criteria (Horvath et al., 2022; Bennich et al., 2020), while methods assessment is either omitted (for example Miola et al., 2019) or done at high-level without specifics on the applicability of the method (for example Horvath et al., 2022); in addition, data-related aspects are not sufficiently brought to the forefront.

In this paper, we follow a bottom up approach into the generation of a framework that enables integrating SDG interlinkages into policy and decision making. We start from the review of the processes and methods to infer interlinkages and we perform consensus building activities towards the evaluation of how those different techniques bond together, into a comprehensive set of processes. To this end, we extend the current body of literature in three directions. First, we consolidate studies with broader inclusion criteria targeting the extraction of information on scope, methods and data. Second, we present bibliometric and descriptive measures that illustrate the uptake of SDG interlinkages discussion, as well as classifications and discussion of the methods used. We carry out a screening of initially more than 2,400 research articles and a further detailed analysis of more than 400 publications on methods to inferring SDG interlinkages. We then extend knowledge on the above aspects through a large-scale workshop with SDG experts. Finally, and based on the above, we present our framework of analysis for SDG interlinkages. We do that in an effort to ensure that similar to inequalities, disparities and opportunities, interlinkages are not masked, nor aggregated, but are considered at the scale they might matter the most, i.e., the local level. Given these, the purpose of the paper is not to provide definitive answers on how interlinkages should be inferred, and suggest some method(s) over other(s). Rather, it aims to lay a foundation for the systemic examination of the interlinkages, in the context of policy-making about sustainable development.

The remainder of the paper is organised as follows: Section 2 presents the methods used. Section 3 discusses the main results in the form of bibliometric and contextual analyses methods categorisation and clustering in the reviewed literature, while Section **??** presents the outcomes of a dedicated workshop on validating literature findings. Section 5 presents a SDG interlinkages framework and discusses the positioning of current research in relation to it and some potential pathways of implementation. Finally, concludes with the main takeaways of the conducted research, suggested future steps of research, and limitations of the adopted approach.

2 Methods

2.1 Literature extraction and dataset formation

To address the objectives stated above, a systematic literature review was performed to identify the variety of methods used for inferring SDGs, targets, indicators and policy interlinkages. In order to ensure conformity with previous related efforts and comparability of findings and results, we extracted the literature from the SCOPUS electronic database, following the query used by both Miola et al. (2019) and

Horvath et al. (2022). The search string we used was: TITLE-ABS-KEY (‘Sustainable Development Goal*’ AND (‘trade-off*’ OR ‘interlink*’ OR ‘interact*’ OR ‘synerg*’)). The query was run on 6 December 2022 with no constraints neither on the time nor on the language of publications, and returned a total of 2,408 publications [+31.9% compared to Horvath et al. (2022) who performed their search on December 2019]. We also attempted to repeat the search query of Lucia et al. (2021), however the resulting publication entries could not be reproduced. As such for the later (Lucia et al., 2021) we appended a selection of publications within our list of publications to be examined. In total 2,385 ones were found to be distinct and with a complete bibliographical indexation [existence of DOI, author(s) and title]. We then performed an initial screening of the publications for their overall relevance with the topic on the basis of their title and abstract. Out of the 2,385 publications, 1,974 publications were found to be irrelevant to interlinkages of either SDGs, targets, indicators or policy-actions, and were thus disregarded.

We then performed a refined screening of the publications for their in-depth relevance with the topic on the basis of the full text and analysed them in terms of bibliometrics and content. The inclusion criteria we applied for the second screening were:

a interlinkages being described, calculated or assessed between at least two related elements (goals, targets, indicators or policies/technologies/domains/interventions)

b the method(s) to infer interlinkages were presented and described.

This approach allows for one-way SDG interlinkages, i.e., interlinkages between a policy/technology/intervention and SDG goals/targets/indicators, as well as two-way SDG interactions, i.e., interlinkages between SDG goals/targets/indicators. We believe that such an approach allows for generating a more complete picture of the approaches taken to understand the synergies or trade-offs for SDGs, and also helps generate a better understanding of required future research. At the same time, only referring to SDG interlinkages (one-way or two-way) excludes all direct-inclusion of scientific work performed before the introduction of the 2030 Agenda, that might have targeted the effects of interventions in one system resulting in effects for others (e.g., gender equality actions resulting in economic growth). The final set of extracted material on interlinkages that was analysed in terms of methods included a total of 328 publications.

2.2 Analysis approach

For generating a contextual understanding of the study of interlinkages, we utilised bibliometrics and content analysis. For the former, we generated a quantitative analysis of bibliographic data, including the number and type of publications, citations and co-citations, geographical distribution of studies, and keywords, to study the patterns and trends of – identified as pertinent – scientific research. Bibliometric analysis predominantly relied on the http://bibliometrix.com R package. Content analysis is utilised to allow for an objective extraction of indicators (variables) based on a collection of sources. The main goal of our content analysis was to identify SDG-related patterns (e.g., territorial focus, SDG-focus, interaction levels, study approach), and research methods present in the study of interlinkages. After an exploratory stage, which allowed for the evaluation of the potentially interesting indicators upon which the study of

interlinkages could take place, a relevant set of indicators was defined (Table 1), based on which, the publications content was coded. The coding was performed by two sectoral experts who are co-authors of this paper, with an approximately 10% overlapping to evaluate content analysis performance.

Table 1 Content analysis variables

Variable	*Description*
Geographic scale	Geographic scale examined (categorical)
Country	For national or lower: country examined (categorical)
Interaction levels	Level of interactions examined, with lowest (e.g., indicator level) reported (categorical)
Paper type	Reported/extracted paper type (categorical)
Method (high level)	Reported/extracted methods (categorical)
Method	For each high-level methods set (categorical)
Method specifics	Description of method (summary)

2.3 Experts workshop

Aiming at generating a better understanding of the necessary actions to enable the integration of interlinkages into the SDG implementation process, the authors organised a workshop in February 2023. The workshop brought together 24 sectoral experts, including statisticians, political scientists, urbanists, economists, geographers, engineers, and physicists, all working on SDG-related research. Hosted at the Joint Research Center in Seville, the workshop had several objectives: addressing the identified issues, scrutinising the existing line of thinking, defining the necessary components for ensuring the uptake of interlinkages, and outlining a comprehensive framework for inferring SDG interlinkages. The primary focus of the workshop was placed on the local level, allowing for the examination of aspects that could generate impact in a more decentralised manner. It included the presentation of the results of the systematic literature review and a moderated interactive session for the extraction of an understanding of the context within which SDG interlinkages are inferred and integrated within policy making as well as the corresponding challenges, issues and opportunities that emerge through their study. At the start of the interactive session participants were introduced with a framework for understanding the nuances of SDG interlinkages, which aimed to provide a systematic approach to understanding and evaluating the relationships between different SDG-related entities. The framework incorporated various components such as data collection and analysis, indicator selection, identification of causal relationships, and assessment of the impact of interventions on the interconnected goals. Following the presentation of the framework, participants engaged in a hands-on exercise using Miro (https://miro.com/), a digital collaboration platform which allow simultaneous editing of mind-maps and facilitates collaborative brainstorming processes. The exercise involved adding, modifying, or reorganising components of the proposed framework based on their expertise and understanding of the local context. Participants were instructed to either extend the provided framework or add new aspects worthy of considering as post-it notes.

3 Literature review results

3.1 Bibliometric analysis

The resulting set of publications after the initial screening (N = 461) was first analysed taking a bibliometrics approach. The field of SDG interlinkages illustrates a sustained growth since its inception in 2015. An average yearly growth rate in the number of publications of 13.7% between 2015 and 2023 illustrates the substantial interest in the topic. The vast majority of the examined publications are categorised (74%) as research articles (based on publishers' characterisation), while, notably, 14% of the publications reviewed were characterised as review articles. Our in-depth analysis however revealed that the actual number of review papers is significantly smaller, as it is often the case that papers including a literature review section, but not actually performing a literature review on the topic, are characterised as review papers. Of interest is also the diversity of the journals. The examined publications (461 papers) have been published in 234 distinct journals (or conferences). The majority of the journals (171 journals) were found to have only 1 relevant publication, based on first screening, while approximately 30% of all publication considered relevant were published in the top 10 journals. A significant percentage of publications were published in sustainability related journals (e.g., *Sustainability Science*, *Sustainability* (Switzerland) or *Sustainable Development* ranked 1st, 2nd and 3rd respectively), while many were found in environment related journals (e.g., *Science of the Total Environment*, *Environmental Research Letters* or *Environmental Science and Policy* ranked 6th, 7th and 8th respectively) evident of the fact that environment is a transversal topic in the SDGs analysis. Overall, 2,490 unique authors were identified with a total of 15,722 (Scopus) citations being recorded. It is worth noting that the resulting set of publications also includes a small number that discusses interlinkages before the actual adoption of Agenda 2030 in 2015; these are predominantly publications dealing with interactions of sustainability goals, targets or indicators, yet not per se of the SDGs, their targets, and monitoring indicators.

After the first screening, publications were further analysed by thoroughly reading the full text and extracting key selected variables (see Table 1). This second (and final) screening yielded a further specification of the resulting set of publications, as some of those examined were deemed irrelevant or of low relevance to the examination of the SDG interlinkages. For the remainder of this paper, we are going to examine only those publications which went through the second screening.

Overall, the retention rate for the second screening was approximately 70%. For the resulting set of publications (N = 328), 77% of publications were categorised as research articles and 15% of the publications reviewed were characterised as review articles. This second screening significantly reduced the total number of sources (e.g., books, journals, conferences) to 163 distinct sources. The top targeted journals all but one remained the same (e.g., *Sustainability Science*, *Sustainability* (Switzerland) or *Sustainable Development* ranked 1st, 2nd and 3rd respectively), while some were encountered in environment related journals (e.g., *Science of the Total Environment*, *Current Opinion in Environmental Sustainability* or *Environmental Research Letters* ranked 6th, 7th and 8th respectively). The number of unique authors was found to be 1,371 identified, with a total of 11,487 (Scopus) citations being recorded.

When examining the keywords utilised to describe SDG interlinkages articles, it is interesting to observe that trade-offs and synergies score high in defining keywords,

while, overall, out of 328 articles, there have been 972 unique – n-gram – keywords as defined by authors (keywords that authors choose to characterise their manuscript) and 1,348 unique – n-gram – assigned by publishers in total. The examination of the keywords co-occurrences reveals some interesting findings. Figure 1 presents the keywords co-occurances network. By analysing the frequency of keywords that appear together, we can identify the themes or topics that are prevalent in the text. For example, if 'climate change', 'global warming', and 'greenhouse gases' frequently co-occur, it suggests that the text is discussing issues related to environmental sustainability. Such an analysis can reveal the intent behind them and the potential relationships between different concepts. Although several different methods exist in doing so, in this work we have chosen to use the Fruchterman-Reingold (FR) force-directed graph layout. The FR algorithm is based on the idea of treating each node in the network as a charged particle, and then simulating the behaviour of these particles as they repel each other and are attracted to their neighbours based on the strength of their connections. When applied to keyword co-occurrence networks, the FR algorithm positions the nodes (keywords) in the network such that highly connected nodes are closer together, while sparsely connected nodes are further apart. This helps to visually highlight clusters of related concepts and can aid in identifying themes or topics in the network. Figure 1 presents the resulting graph for the 300 most commonly used keywords, using optimal clustering, as defined in Aria and Cuccurullo (2017). It is evidenced that several clusters are being defined. It appears though that the focus of different cluster emerges; for instance, the blue and red cluster appear to focus on environment and economy, while the green one appears to represent primarily keywords related to the society. Additionally, the blue cluster was found to represent themes related to water and food, possibly with a focus on the city-level. Similarly, the red cluster includes themes on energy, with a possible focus on China and the developing World; finally, themes on poverty and health are encountered in the green cluster, possibly with a focus on the EU and Africa.

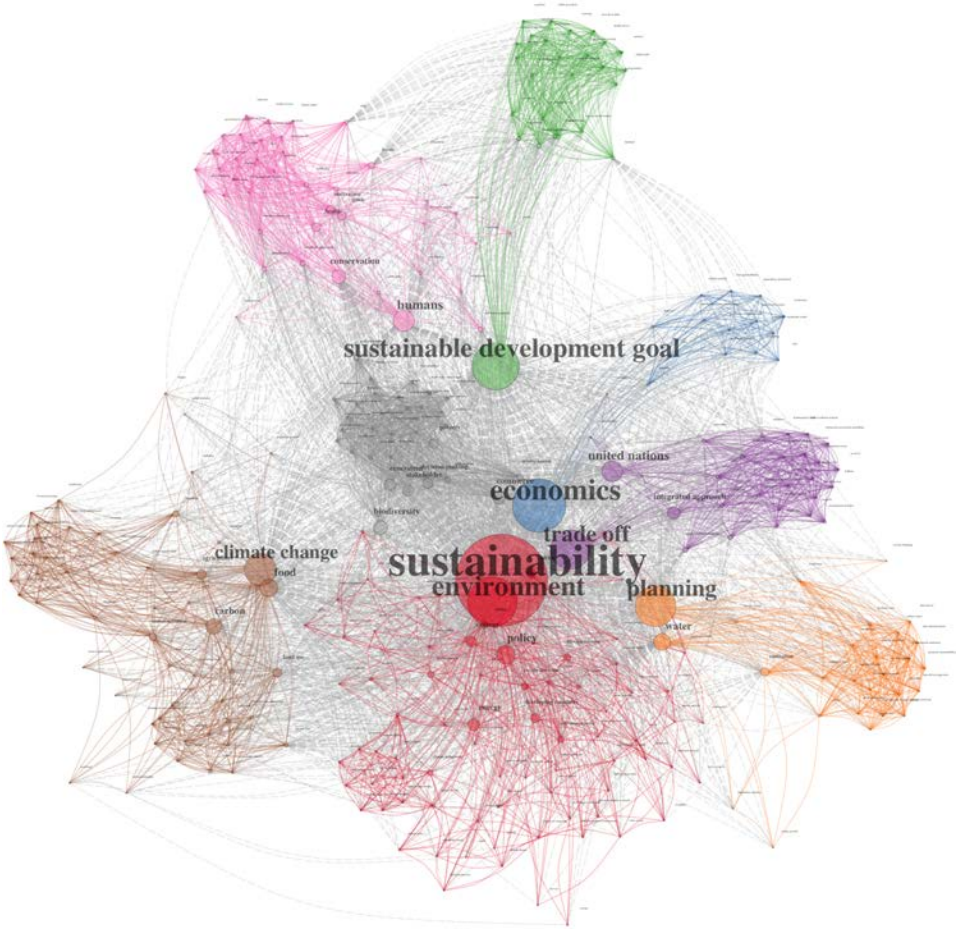
Examining the spatial properties of interlinkages studies yields interesting findings. As presented in the following collaboration network (Figure 2) the vast majority of publications is performed by a few countries (UK, China, USA and Germany) with however a relatively large network of collaborators from developing countries. The collaboration network map illustrates the global character of studying interlinkages and the involvement of large collaborating networks among developed and developing countries.

3.2 Contextual analysis

Aiming at understanding the context of analysis for interlinkages we have extracted a set of relevant variable and performed descriptive analysis. Examining the territorial context for the analysis performed allows for understanding the placed focus, and consequently, the gaps for evaluating interlinkages and the potential of utilising existing research work. The latter are directed towards the generation of targeted policies and interventions that can help to accelerate progress towards the SDGs, while also ensuring that no one is left behind. Regarding the distribution of the territorial focus examined in the extracted publications, the vast majority of the publications examined the SDG interlinkages on an international level (232 out of 328). Then, 49 publications examined the SDG interlinkages on a national level, and another 49 were examining interlinkages on sub-national (local) level (regional or urban). In addition, Figure 3 presents the

continental analysis of the selected publications versus the territorial analysis of them. The majority of the examined publications include an international level of analysis and a combination of continents. It is also observed that there are publications which examined the SDG interlinkages in Africa, Asia, Europe and South America on all types of territorial levels (international, national, regional and urban level). In addition, publications related to North America examined the SDG interlinkages only on international and regional level. Finally, there are a few publications which do not refer to any continent and to any level of the territorial analysis. Through Figure 3 we conclude that the SDG interlinkages are examined both on different territorial levels (urban, regional, national, and international) as well as in different continents where different social, economic, and environmental aspects were taken into account. As already mentioned, the territorial analysis reveals crucial information about possible solutions that can be applied to different regions, countries or even continents in the light of accelerating the progress towards achieving SDGs.

Figure 1 Keywords co-occurances, using FR and optimal clustering (see online version for colours)



Another interesting finding from this analysis is the exploration of the focus of the SDG methods to infer interlinkages. As presented in Figure 4, while a large number of publications focus on the actual SDG interactions (e.g., Yang et al., 2022a; Sanyé-Mengual and Sala, 2022), a significant body of the literature focuses on examining the interactions between technologies, policies and a specific domain with SDGs. In other words, they deal with how domains, policies or technologies generate SDG interactions (e.g., Peng et al., 2021; Nerini et al., 2018; Yillia, 2016), in many cases implicitly providing evidences of the potential to extract SDG interlinkages, while in others targeting the study of technologies, policies and a specific domain considering explicitly SDG interlinkages. Finally, there is a small body of literature that focuses on SDG implementation while considering SDG interlinkages, and an even smaller one that targets regional SDG interlinkages, with the focus placed on the regions rather than the interlinkages themselves (Allen et al., 2021; Ruiz-Puente and Jato-Espino, 2020).

Figure 2 Countries' collaboration network (see online version for colours)

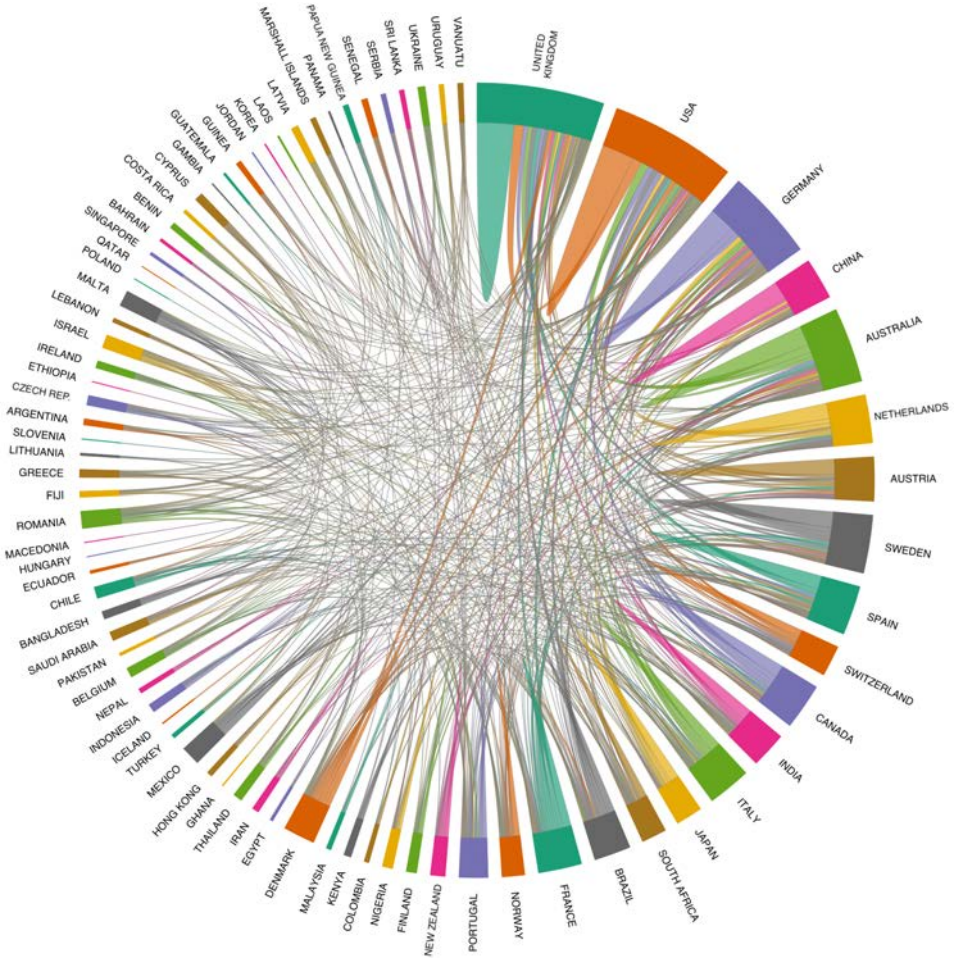


Figure 3 Continental and territorial analysis (see online version for colours)

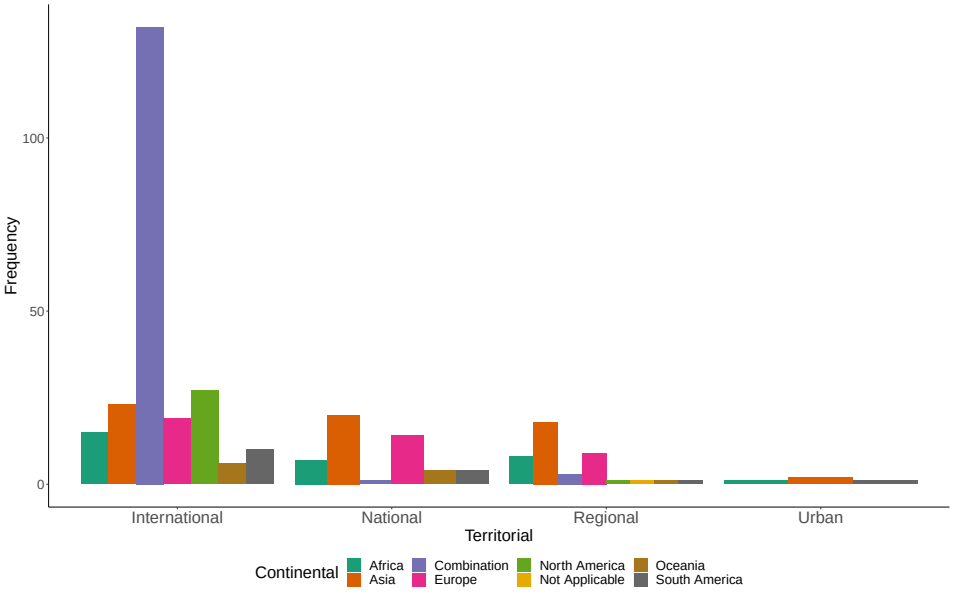
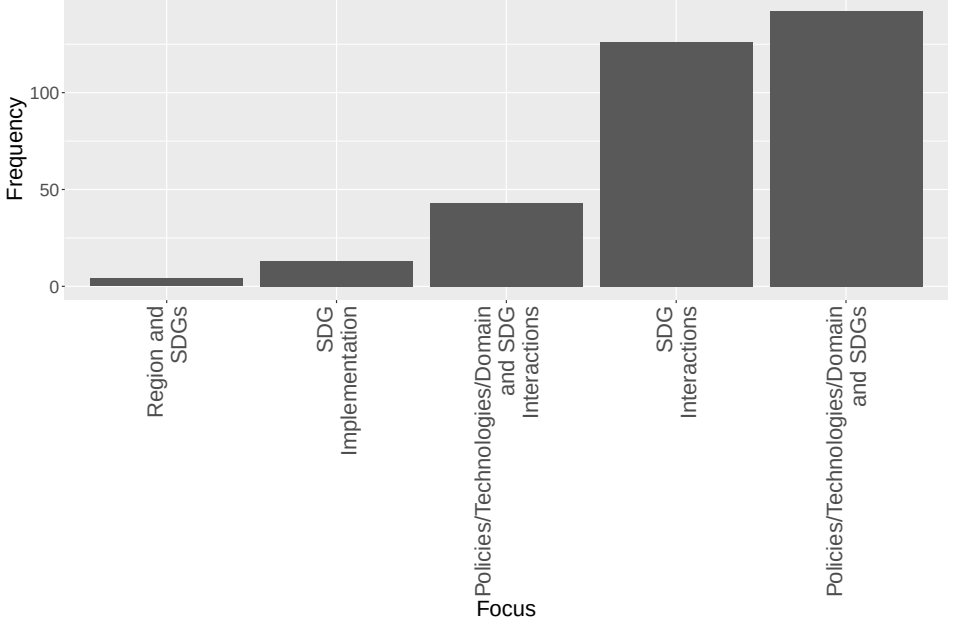


Figure 4 Publications focus



3.3 Methods to infer interlinkages

The interdisciplinary nature of SDGs prompts the study of SDGs interlinkages from different perspectives and utilising different methods. For example, while for some

domains the use of quantitative or qualitative analysis is used in specific contexts, it becomes apparent that in the SDGs interlinkages literature there is an abundance of both, almost on equal numbers. It is also the case that the study of interlinkages constitutes a new research stream, prompting the exploration of different methods and the potential these have in contributing to the advancement of the field. However, different methods are based on different assumptions and serve different goals, which is prompting the exploration of their applicability and critical appraisal. As discussed in introduction (Section 1), the categorisation often used for the different methods can also be different based on the different disciplines it involves. In this section, we investigate the methods that were used in the examined papers. Following up on the ambiguity of the categorisation discussed, we construct an in-depth hierarchical categorisation structure which on its highest level distinguishes methods among their primary methodological approach (quantitative, qualitative and literature review), which is further specified across a second hierarchical level (e.g., statistical or modelling for quantitative methods), before reaching the lower level (actual methods used). We believe that this approach will benefit future researchers on having a clearer overview of the methodological approaches in examining interlinkages, cater for the use of different methods, and create awareness in relation to what assumptions these methods are based upon, their aims and goals as well as their applicability and transferability for interlinkages analysis. The overview of the examined methods is presented in the following dendrogram (Figure 5).

As it is becoming apparent, there is a diversified landscape regarding all methods' categories. Most papers are deemed quantitative (135 publications), followed by qualitative (107 publications) and literature review (71 publications). A high number of review publications aims at utilising findings from previous (in many cases irrelevant to SDGs) studies, evaluating interlinkages evidences (e.g., policies/technologies/interventions and the SDGs). In the following subsections, the specific methods per category are discussed, within their lower-hierarchy categorisation.

3.3.1 Quantitative methods

Quantitative analysis can allow the identification of key drivers and pathways that contribute to the achievement of the SDGs. They can be deployed in a variety of contexts and serve different purposes, such as exploratory or confirmatory analysis, modelling, scenario testing and projections. Quantitative analysis operates with, and is consequently bounded by data, as well as assumptions and applicability of the methods themselves. For example, a study may find that policies aimed at reducing greenhouse gas emissions have positive impacts on both climate action and clean energy (for which data is available), but may have negative impacts on economic growth and industry, innovation and infrastructure (for which data might not be available or a method might not be able to capture them). In the examined literature, quantitative methods have been extensively utilised (a summary of the those is presented in Figure 6). The categorisation of methods broadly corresponds to the two main categories of quantitative analysis (modelling and statistical analysis) while, for methods which are not clearly part of any of the two, we introduce the other category.

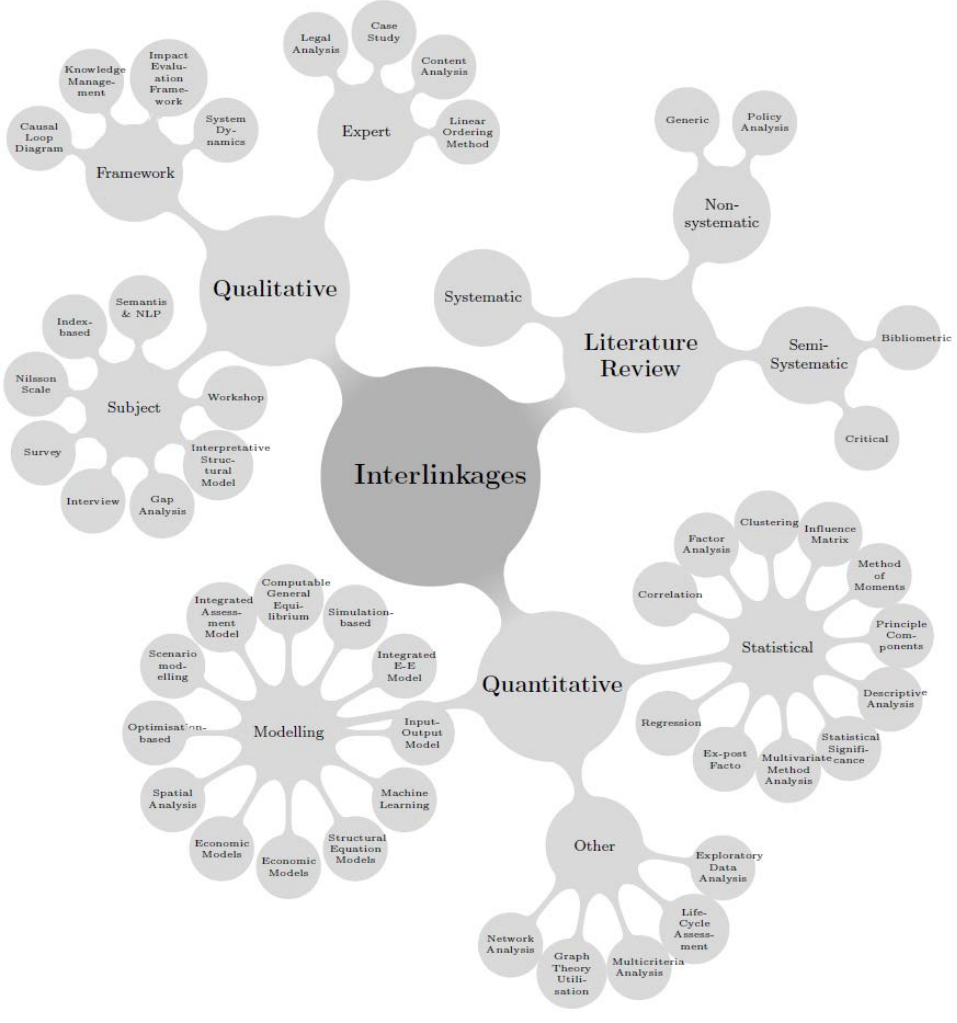
Correlation, regression, network analysis, are some of the most frequently encountered methods in the literature. These methods are applied to a wide range of data sources, including household surveys, administrative records, and satellite

imagery. Statistical methods are being used for the exploration of existence of interlinkages. Correlation analysis is by far the most commonly used method, aiming at exploring pair-wise co-evolution of primarily indicators, while in some cases this is also raised to targets or goals. The breadth of ways that quantitative methods are utilised is worth noting. The available studies seem to take different approaches on utilising methods, target different spatio-temporal contexts, use different datasets and delve into the investigation of the SDG framework as a whole or targeting specific goals/targets/indicators. To name but a few, Pradhan et al. (2017) presented a comprehensive approach on consolidating interlinkages across different goals on a global level. This was later further expanded to include the investigation of different data sources and variations in terms of population, regional and income disaggregation (respectively Warchold et al., 2020, 2022). Anderson et al. (2021) used correlation analysis to analyse the interactions between the SDG targets and identify the key drivers of progress towards the SDGs. They focused on the interactions between SDG targets across different goals, and on the role of governance and institutional factors in shaping progress towards the SDGs. In a similar fashion for local conditions, Momblanch et al. (2021) used correlation analysis to investigate the trade-offs between achieving the SDGs related to Indus River Dolphin conservation and human water security in the regulated Beas River in India. Correlation analysis was one of the first methods used in the empirical exploration of interlinkages. Moving further with empirical analyses, Awad (2022) used regression models to explore the existence of relationship between information and communication technologies (ICTs) and ecological systems in Africa, and whether there is a trade-off between the two, using data from 44 African countries, over the 2000–2015 period. Ament et al. (2020) used a regression analysis method approach to examine the relationships between the 17 SDGs and identify potential synergies and tradeoffs. The results of this regression analysis showed that SDGs related to poverty reduction, health, education, and gender equality are highly interconnected and reinforce each other, while SDGs related to climate action, sustainable consumption and production, and biodiversity conservation may have tradeoffs with other goals, such as economic growth and poverty reduction. Barbier and Burgess (2019) and Campagnolo and Davide (2019) used scenario modelling analysis to investigate interlinkages among the SDGs in general, and potential international impact of climate mitigation efforts on poverty and inequality respectively. On the other hand, Engström et al. (2019) generated and utilised a simulation-framework to examine the impacts of local climate and energy policies on water and land use, while Zhang et al. (2019) examined the impact of urbanisation on greenhouse gas (GHG) emissions from water infrastructure in China, and how this impact affects progress towards achieving the SDGs. Network analysis is also well established in the study of interlinkages. Ospina-Forero et al. (2022) utilised network analysis to evaluate pairwise conditional dependence for SDGs on a global level, Dawes et al. (2022) on a country level, while Lusseau and Mancini (2019) used network analysis for the SDG interaction networks in low-income, middle-income and high-income countries. An overview of the methods used for the identified as relevant papers is presented in Table 3.

Data availability and quality are particularly important when using quantitative data (Warchold et al., 2022). Although several studies are not clearly reporting the sources of their data, our analysis suggests that a significant proportion of studies utilises open data from international or national organisations (e.g., the UN or EU SDG databases, World Bank data, the SDG Index, Regional SDG data,

and local socio-demographics/economics). Open data availability provides a basis for standardisation for SDG interlinkages analysis, but at the same time it limits the potential of exploring or further validating them. In some instances, researchers combine different datasets, which allows for the expansion of analysis scope, but needs to take into account concepts of data granularity, conflicts, representativeness and degree of data matching.

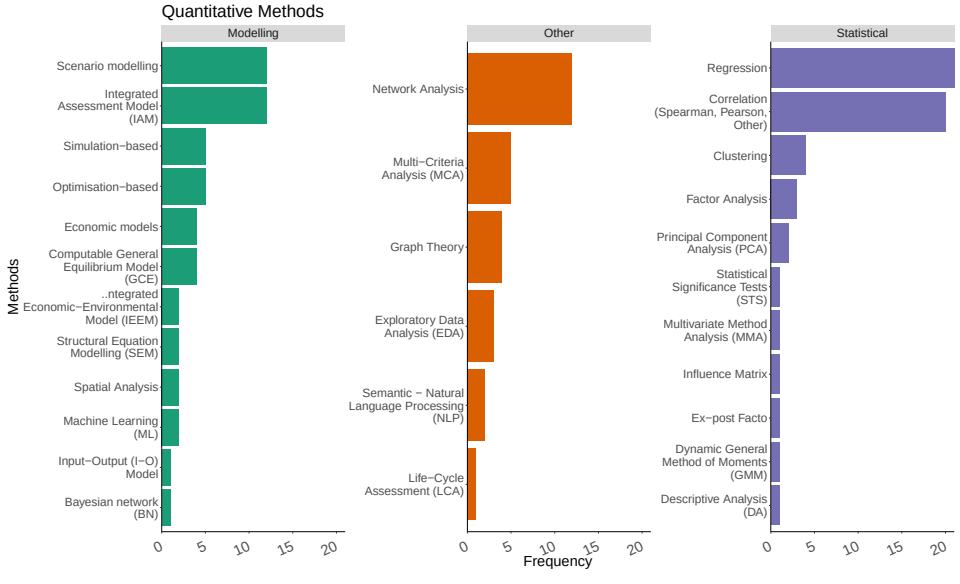
Figure 5 Methods overview



Overall, our review of the pertinent literature suggests, that while quantitative methods are of great usefulness for coming up with evidences on interlinkages, they have limitations when it comes to understanding the complex interlinkages between the SDGs. They may not capture the qualitative aspects of SDGs or take into account the unique social, economic, and political context of a particular area. Quantitative methods and the applicability are also driven by and constrained upon data availability,

applicability and quality. At the same time, given the strongly interconnected nature of SDG indicators, not all methods are able to capture causal effects (some methods are not even designed to do so). At the same time, given the long decision-making cycles, it might be complex to control for potential confounding effects. Therefore, it is important to use quantitative analysis in conjunction with other research methods, such as qualitative data analysis and case studies, to gain a more comprehensive understanding of SDG interlinkages, while validation, transferability and reproducibility of findings become concepts of utmost importance.

Figure 6 Quantitative methods (see online version for colours)

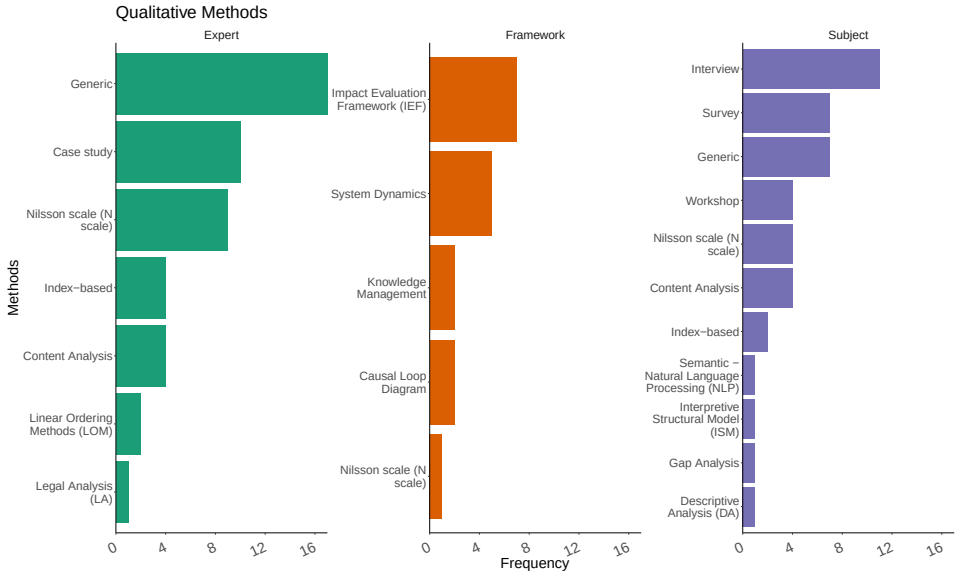


3.3.2 Qualitative methods

The second largest category of methods relates to the use of qualitative methods for the extraction of SDG interlinkages. Qualitative methods include, among others, the extraction of knowledge through interviews, case studies, content analysis, system dynamics, and workshops. The use of qualitative methods have been discussed as one way of by-passing the influence that data and assumptions inherited with the use of quantitative methods. As SDGs interlinkages often requires a deep understanding of both sub-national, national and international contexts as well as the complex social dynamics, qualitative methods can provide the necessary flexibility and capture particularities. This is commonly done with the inclusion of experts, the use of qualitative research frameworks and the deployment of subject elicitation methods. As presented in Figure 7, variations exist in their deployment. The categorisation of methods broadly corresponds to the three main categories of qualitative analysis (experts-based, framework-based, and subject-based). The largest category has been the generic reliance on experts (e.g., the authors or a pool of experts) to evaluate interlinkages. It is crucial to refer to the fact that we have defined a generic sub-category method for both expert and subject categories

of qualitative methods. The rationale for doing that was the difficulty in identifying the exact sub-category of each qualitative paper.

Figure 7 Qualitative methods (see online version for colours)



To name but a few interesting examples, the exploration of the synergies and trade-offs between the SDGs in marginal mountainous areas of India, was assessed by Orchard et al. (2019), through the use of a participatory approach, utilising interviews to engage with local communities and understand their perspectives on the interlinkages between the SDGs, while Hazarika and Jandl (2019) also run interviews to examine how the Austrian forestry sector could support the achievement of other SDGs, on a national level. Yang et al. (2020) used surveys to evaluate the perceived importance and associations between SDGs and ecosystem services, to examine the prioritisation of the SDGs, their interlinkages to ecosystem services, and the benefits that people are able to obtain from these ecosystems, on a global level. Nerini et al. (2018) presented a mapping exercise to identify which SDG indicators would require energy-systems' related interventions to enable their achievement. The execution of the mapping exercise was conducted with surveys and content analysis.

There are also several papers which have utilised index-based methods with experts, such as the Nilsson scale. Lyytimäki et al. (2020) used the Nilsson scale to examine the synergies and trade-offs among sustainability targets in the Northern European context, and specifically in Finland, Sweden and Estonia, analysing the interactions among the SDGs, while Pham-Truffert et al. (2020) examined the interactions among the SDGs and their associated targets, through relevant indicators. Other publications have utilised methods with the use of research framework (collection of methods, structured into a process). For example, Hall et al. (2020) utilised an impact evaluation framework (IEF) in order to examine the interlinkages between water and health in remote indigenous communities in Australia in the context of the SDGs, while Barquet et al. (2021) used a system dynamics framework, including stakeholder interviews, and

expert workshops to assess the effectiveness of SDG synergies in promoting systemic thinking and identifying interlinkages between SDGs. Although we report on the main method used in each paper, publications that utilise more that one scientific methods are not uncommon. Stefanovic (2022) made use of qualitative methods that fall into all three categories. Specifically, they utilised an actor system dynamic method, an experts' opinion survey, a questionnaire, and some case studies, in order to examine and evaluate the role of sustainable public procurement in supporting the SDGs in local organic food systems. An overview of the methods used for the identified as relevant papers is presented in Table 3.

Table 2 Quantitative studies overview

Category	*References*
(M) Bayesian network	Requejo-Castro et al. (2020)
(M) Equilibrium models	Philippidis et al. (2020), Campagnolo et al. (2017), Delzeit et al. (2016) and Matsumoto et al. (2018)
(M) Economic models	Bello et al. (2022), Lin et al. (2022), Adebayo et al. (2022) and Liu (2021)
(M) Input-output models	Scherer et al. (2018)
(M) Integrated assessment models	Marcinko et al. (2021), Wieser et al. (2019), Moyer and Bohl (2019), Neumann et al. (2018), Hutton et al. (2018), Collste et al. (2017), van Vuuren et al. (2015), Taghvaee et al. (2022), Rasul (2016), Wyllie et al. (2022), Lucas et al. (2019) and Dagnachew and Hof (2022)
(M) Machine learning	Asadikia et al. (2021) and Ge et al. (2022)
(M) Optimisation-based	Zhang et al. (2022d), Raimbault and Pumain (2022), Heck et al. (2018), von Stechow et al. (2016) and Siderius et al. (2022)
(M) Scenario modelling	Doelman et al. (2022), Fujimori et al. (2020), Hinz et al. (2020), Barbier and Burgess (2019), Campagnolo and Davide (2019), Moallemi et al. (2022), Ioannou et al. (2023), Bastida et al. (2020), Barbier and Burgess (2017), Amjath-Babu et al. (2019), Obura (2020)) and Rosenthal et al. (2018)
(M) Simulation-based	Zhang et al. (2019), Kurian et al. (2019), Salvo et al. (2021), Engström et al. (2019) and Vishwanathan and Garg (2020)
(M) Spatial analysis	Osman et al. (2022) and Giupponi and Gain (2016)
(M) Structural equation models	Naomi and Akbar (2021) and Xiao et al. (2022)
(M) Integrated Ec.-Env. models	Banerjee et al. (2019) and Schlör and Schubert (2022)
(O) Exploratory data anal.	Cook and Davísdóttir (2021), Kettner et al. (2019) and Zhang et al. (2022c)
(O) Graph theory	Dawes et al. (2022), Swain and Ranganathan (2021), Bellantuono et al. (2022) and Priyadarshini and Abhilash (2019)
(O) Life-cycle assessment	Sanyé-Mengual and Sala (2022)
(O) Multi-criteria analysis	Humpenöder et al. (2018), Allen et al. (2016, 2018), Toth et al. (2021) and Pauliukevičienė and Stankevičienė (2021)

Table 2 Quantitative studies overview (continued)

Category	*References*
(O) Network analysis	Dawes et al. (2022), Ospina-Forero et al. (2022), Dawes (2019), Lusseau and Mancini (2019), Mainali et al. (2018), Coenen et al. (2021), Laumann et al. (2022), Helldén et al. (2022), Wu et al. (2022), Huan and Zhu (2022), Libala et al. (2022) and Blanc (2015)
(O) Semantic-NLP	van Soest et al. (2019) and García et al. (2021)
(S) Clustering	Linnerud et al. (2021), Medina-Molina et al. (2022), Jabbari et al. (2019) and Cheng et al. (2023)
(S) Correlation	Zhou et al. (2022), Anderson et al. (2021), Momblanch et al. (2021), Xu et al. (2021), Hao et al. (2022), Warchold et al. (2022), Kostetckaia and Hametner (2022), Warchold et al. (2020), de Miguel Ramos and Laurenti (2020), Ronzon and Sanjuán (2020), Fonseca et al. (2020), Kroll et al. (2019), Pradhan et al. (2017), Rodríguez-Antón et al. (2021), Pakkan et al. (2023), Liu (2020), Bakker et al. (2021), Tian et al. (2022), Adegoke et al. (2022) and Rodriguez-Anton et al. (2019)
(S) Descriptive analysis	Elder et al. (2016)
(S) Method of moments	Molefe and Inglesi-Lotz (2022)
(S) Ex-post facto	Aderemi et al. (2022)
(S) Factor analysis	Zhang et al. (2022b), Cling and Delecourt (2022) and López et al. (2021)
(S) Influence matrix	Scharlemann et al. (2020)
(S) Multivariate analysis	Donaires et al. (2019)
(S) Principal components	Cling et al. (2020) and Feng et al. (2019)
(S) Regression	Yang et al. (2022b), Zhang et al. (2022a), Awad (2022), Sinha et al. (2022), Zhu et al. (2022), Neve and Sachs (2020), Ament et al. (2020), Koçak et al. (2019), Selvakkumaran and Silveira (2018), Topothai et al. (2022), Adedoyin et al. (2022), Breu et al. (2020), Guang-Wen et al. (2022), Gutierrez et al. (2022), Pérez-Martínez et al. (2023), Liu and Yuan (2023), Hassani et al. (2021), Mariappanadar and Hochwarter (2022), Asongu et al. (2019), Aust et al. (2020) and Baloch et al. (2020)
(S) Statistical tests	Yesuf and Aassouli (2020)

Overall, although the use of qualitative methods overcome some of the problems identified for quantitative methods (assumptions, applicability and data), these methods can also introduce limitations. One of the primary challenges relates to its inherent subjectivity. As researchers engage in interpretation and analysis, the potential for bias arises. When taking into account that SDG interlinkages could be perceived as a topic of sub-national, national or international importance, unconscious biases (such as desirability to showcase achieving SDG goals and positivity regarding performance) could arise for the researchers and participants. At the same time, and given the nature of the SDGs, sub-national or national competition might consciously affect the responses from subjects and lay participants. Qualitative studies, often involve a small sample size

or number of involved experts, and might be of limited generalisability, while, at the same time, they can be resource intensive when considering the need for tailored data collection, yet not standardised, making them difficult to compare and replicate and transfer elsewhere.

Table 3 Qualitative studies overview

Category	*References*
(E) Case study	Menton et al. (2020), Zhao et al. (2020), Eisenmenger et al. (2020), Nash et al. (2020), Nash et al. (2021), Filho et al. (2022a), Everard and Longhurst (2018), Alarcón and Cole (2019), Alawneh et al. (2019) and Macmillan et al. (2020)
(E) Content analysis	Bisaga et al. (2021), Anderson et al. (2018), Thacker et al. (2019) and Vinuesa et al. (2020)
(E) Generic	Pingali and Plavšić (2022), Frame et al. (2022), Baffoe et al. (2021), Mulligan et al. (2020), Sampantamit et al. (2020), Schweiger (2016), Griggs et al. (2014), Horan (2020b), Sebestyén et al. (2019), Agarwal (2018), Dong et al. (2018), Ntona and Morgera (2018), Pascual-Fernández et al. (2018), Goi et al. (2022), Eguiguren and Piedra (2020), Mateen (2022) and Hickel (2019)
(E) Index-based	Gjorgievski et al. (2021), Zhou and Moinuddin (2021), Pham-Truffert et al. (2020) and van Noordwijk et al. (2018)
(E) Legal analysis	Agbaitoro and Oyibo (2022)
(E) Linear ordering methods	Sompolska-Rzechuła and Kurdyś-Kujawska (2021) and Nhamo et al. (2022)
(E) Nilsson scale	Zanten and Tulder (2021), Iacobuţă et al. (2021), Lyytimäki et al. (2020), Fader et al. (2018), Wang et al. (2022), Oghenekaro and Kant (2022), Milan (2017), Nilsson et al. (2016) and Nerini et al. (2019)
(F) Causal loop diagram	Zhang et al. (2016) and Bennich et al. (2020)
(F) Impact evaluation framework	Hall et al. (2020), Saric et al. (2021), Wendling et al. (2018), Park and Savelyeva (2022), Stubbs et al. (2022) and Rajan and Sushil (2022)
(F) Knowledge management	Annan-Aggrey et al. (2021) and Borrell and Reynolds (2017)
(F) Nilsson scale	Braks et al. (2019)
(F) System dynamics	Barquet et al. (2021), Jin (2018), Marzouk et al. (2022), Benson et al. (2019) and McGowan et al. (2018)
(S) Content analysis	Nerini et al. (2018), Schleifer et al. (2022), Baker et al. (2023) and Blasi et al. (2022)
(S) Descriptive analysis	Gissi et al. (2022)
(S) Gap analysis	Sterling et al. (2020)
(S) Generic	Wei et al. (2021), Zhao et al. (2021), Dolley et al. (2020), Martín et al. (2020), Schwindenhammer and Gonglach (2021), Otsuki et al. (2022) and Singh et al. (2021)
(S) Index-based	Eppinga et al. (2022) and Bandari et al. (2022)
(S) Interpretive structural model	Kumar et al. (2017)

Table 3 Qualitative studies overview (continued)

Category	*References*
(S) Interview	Orchard et al. (2019), Cook et al. (2019), Hazarika and Jandl (2019), Almeida (2018), Bala and Kang'ethe (2022), Ruiz-Puente and Jato-Espino (2020), Coghlan et al. (2021), Sareen and Nordholm (2021), Gaur and Vazquez-Brust (2019), Brandli et al. (2019) and Hägele et al (2022)
(S) Nilsson scale	Hernández-Orozco et al. (2021), Hoeltl et al. (2020), Huong et al. (2021) and Keeling et al. (2019)
(S) Semantic – NLP	Maher et al. (2022)
(S) Survey	Venkatesh (2022), Yang et al. (2020), Horan (2020a), Stefanovic (2022), Venkatesh (2022), Pärli et al. (2021) and Arthur-Holmes et al. (2022)
(S) Workshop	Singh et al. (2018), Gouvello et al. (2017), Chen et al. (2022) and Adhikari et al. (2021)

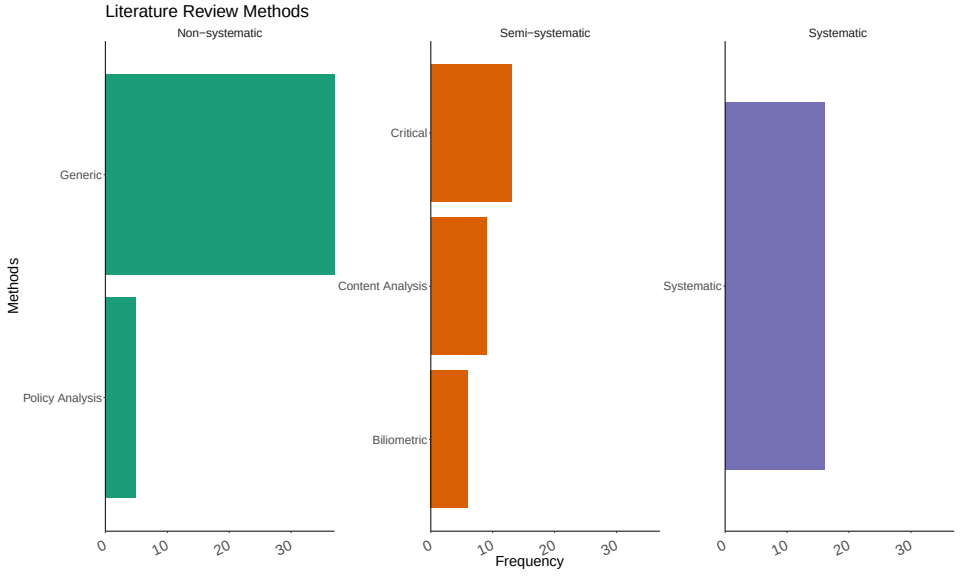
3.3.3 Literature review methods

The third largest category of methods found in the examined literature review papers refers to the consolidation of previous research for understanding SDG interlinkages, extraction of valuable information on the process and identification of possible gaps. Review studies are naturally emerging early on in the SDG era. This is because interconnections between the (commonly studied independently) systems have been long identified (e.g., nexus approaches) and researchers have been generating knowledge on these interconnections, long before the emergence of the SDG framework, as well as previous instances. The diversification of the methods used by researchers in this category is not as large as with the previous two categories, yet there are subtle differences in the way that the consolidation of pertinent findings from past research takes place. A summary of the used methods related to the literature review is presented in Figure 8. The categorisation of methods broadly corresponds to the three main categories of literature review analysis (non-systematic, semi-systematic, and systematic). Also, we had to define a *generic* sub-category within the non-systematic methods to address the difficulty in identifying the exact sub-category of some literature review papers.

As presented in Figure 8, there are several papers which have utilised non-systematic methods such as policy analysis method and a case study method. To name but a few, Yillia (2016) performed a review-based policy analysis to identify and characterise the discovered interlinkages between water, energy and food systems with SDGs. Cunha et al. (2022) explored the relationship between social innovation projects and the SDGs in Portugal. Cunha et al. (2022) used a case study method in order to examine how social innovation initiatives in Portugal are contributing to the achievement of the SDGs, and to identify the key factors that have enabled or hindered their success. Moreover, there are some papers that utilised semi-systematic methods, such as content analysis, bibliometric analysis and critical methods. Yeh et al. (2022) reviewed 4,781 research articles published between 2000 and 2018 that address sustainable development (before 2015) and the SDGs (after 2015). For the analysis of these papers, Yeh et al. (2022) used bibliometric analysis and specifically a multi-stage document clustering method which includes text mining and network analysis, to identify the most studied SDGs.

Maes et al. (2019) used content analysis for the identification of interlinkages between urban ecosystems and the SDGs, while Hirons (2020) performed critical analysis for risks associated with the implementation of the SDGs in the small-scale mining sector. Boar et al. (2021) performed a systematic literature review to identify three main approaches to addressing trade-offs and promoting synergies: integrated approaches, transformative approaches, and prioritisation approaches. Roy et al. (2021) focused on the relationship between demand-side climate change mitigation actions and the SDGs. Finally, Mantlana and Maoela (2019) identified the key themes and areas of interlinkages between SDG 9 and other SDGs, such as SDG 1 (no poverty), SDG 3 (good health and well-being), SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), SDG 11 (sustainable cities and communities), and SDG 12 (responsible consumption and production) by utilising a systematic literature review method. An overview of the methods used for the identified as relevant papers is presented in Table 3.

Figure 8 Literature review methods (see online version for colours)



The use of literature review methods is essential for comprehensively understanding the interlinkages between the SDGs and identifying those which have not been examined yet. Yet again, literature review studies are not free of drawbacks. Starting with the search process, the interdisciplinary nature of interlinkages necessitates a diverse background for involved researchers to allow for appropriate coverage. Inclusion criteria and process of selecting needs to minimise the influence of biases and allow for reproducibility and validation (e.g., more than one observers with overlap of studies and overall existence of quality assessment processes). Given the fast growing field, fast (yet reliable) review cycles are necessary to keep up and be of value.

Table 4 Literature review studies overview

Category	*References*
(Non-S) Generic	Roy et al. (2022), Renaud et al. (2022), Hanafiah et al. (2021), Vera et al. (2022), Horvath et al. (2022), Nerland et al. (2022), Alcamo et al. (2020), Ulbrich et al. (2018), Heimann (2019), Schleicher et al. (2018), Bowen et al. (2017), Wolf et al. (2016), Allen et al. (2021), Bendixen et al. (2021), Harahap (2021), Carugi and Bryant (2021), Lewis et al. (2021), Peng et al. (2021), Tucho and Kumsa (2020), Hone et al. (2018), Timko et al. (2018), Chirambo (2018), Swamy et al. (2017), Bidoglio et al. (2019), Kuruvilla et al. (2017), Lima et al. (2017), Bali and Taaffe (2017), Hotez (2017), Yedla and Park (2009), Onabola et al. (2022), Lucia et al. (2021), Cunha et al. (2022), Zelinka and Daher (2022), Walston et al. (2022), Baumgartner (2019) and Lee (2019)
(Non-S) Policy analysis	Storey et al. (2017), Yillia (2016), Kirton et al. (2021), Poto (2020) and Smith et al. (2018)
(Semi-S) Bibliometric	Yeh et al. (2022), Londoño-Pineda and Cano (2022), Cheng et al. (2021), Struelens and Silvie (2020), Filho et al. (2022b) and Alvino et al. (2020)
(Semi-S) Content analysis	Santika et al. (2019), Maes et al. (2019), Mensah (2019), Dannevig et al. (2022), Zeigermann (2020), Bhaskar and Kumar (2019), Karuppiah et al. (2022), Goubran (2019) and Kanter and Brownlie (2019)
(Semi-S) Critical	Nilsson et al. (2018), Velis et al. (2017), Kim (2016), Atukunda et al. (2021), Hirons (2020), Huan and Zhu (2022), Bringezu (2018), McCollum et al. (2018), Eweje et al. (2020), Amprazis and Papadopoulou (2020), Dell'Angelo et al. (2017) and Jasovský et al. (2016)
(S) Systematic	Boar et al. (2021), Morales et al. (2021), Roy et al. (2021), Afzal et al. (2021), Mantlana and Maoela (2019), Flörke et al. (2019), Kanter et al. (2018), Gomez-Echeverri (2018), Blanchard et al. (2017), Pouramin et al. (2020), García-Parra et al. (2022), Jacob-John et al. (2021), Estoque (2023), Aftab et al. (2020), Alonso-García et al. (2019) and Omahne et al. (2021)

4 Workshop outcomes

Through the collaborative exercise, participants engaged and raised a number of critical issues in relation to the realisation of the SDG framework and the integration of SDG interlinkages within policy making in a way that the actual process of achieving the SDGs is being streamlined. Local level was particularly of interest, given the well recognised necessity to be able to support decision-making at a local level that supports reaching SDG goals or at least contributes is in line with SDGs.

4.1 SDG contextualisation

Participants raised the need for better contextualisation of the SDG framework. Contextualisation was approached from several perspectives. The most signified one was considered to be the need for systematisation of the SDGs framework

for local communities and national bodies. This was reflected upon systematic policy prioritisation, discussed by experts as a increasingly pressing need, linked to "local contexts/challenges (e.g., energy transition, food system transitions, rural-urban linkages)." Experts highlighted the need to take into account resource constraints (e.g., money, time, institutional capacity, conflicting priorities, political situation), secure necessary support (e.g., political, stakeholders, citizens) as well as address spillover effects in time and space and across administrative boundaries when addressing policy prioritisation.

Another perspective referred to the actions, processes and tools required to enhance and achieve implementation. As brought up into the interactive workshop, a first significant step would be to bringing SDGs into policy making agenda at all governance levels and even towards citizens themselves, as 'lack of knowledge' or lack of 'knowledge applied to SDGs' has been identified as broadly missing. This step does not necessarily only imply the generation of knowledge, but also knowledge transfer or knowledge management. This was considered critical given the fact that knowledge might exists (e.g., for synergies/trade-offs), but it is not managed or contextualised within the SDG framework. Corresponding complexity of the SDG framework should also be addressed and brought down, so that:

a the SDG framework becomes more accessible

b actions towards achieving SDGs becomes more straightforward ('life of policy makers should be easier').

The local perspective was also brought to the forefront. Aspects of jurisdiction, influence areas and silos in addressing SDGs were identified as potential barriers to the actual contextualisation of SDGs. Of importance was considered the potential to lead to territorial competition ("creating a target at the local level may generate a territorial competition which limits the capacity to achieve more broader goals"). Of interest was found to be the discussion on the actual territorial definition of local ("how local is local and what is local?"), the levels and specificities which might be considered important in its definition.

4.2 SDG interlinkages

Participants also highlighted the significant importance of approaching the fragmented and rather diverse field of identifying and quantifying interlinkages (both on a global and local level) and integrate them into policy making. This aspect was also approached from a number of different perspectives. Participants highlighted the need to define points of entry for interlinkages into policy making (e.g., design/generation phase, prioritisation phase, confirmation phase, etc.). With 'potentially everything being interconnected' experts agreed on the need for 'knowledge and tools to understand what to prioritise and where' in a way that 'leverage points for synergies' and addresses 'negative externalities', mentioning that there is a need for targeting the increase of the uptake of tools in a way that supports policy making ('why tools are not used?, what can be done?'). The local aspect was also brought up in relation to interlinkages. It was highlighted that the work so far targets largely the examination of interlinkages from a global point of view, with techniques and methods for localisation neglecting local and spatial dimensions.

The approaches taken to identify, estimate and utilise interlinkages were also discussed. Participants largely agreed upon the notion that methods currently employed to analyse interlinkages predominantly focused on exploratory analysis. While exploratory approaches have been useful in identifying potential connections among the SDGs, they do not necessarily imply causation, which raises the question of their validity and potentially limits the ability to draw meaningful conclusions about the nature and direction of the interlinkages. At the same time qualitative assessments (which are perceived as being able to reveal causality), are susceptible to subjective interpretations and biases. Participants also commented on reproducibility and validity of outcomes, arguing on the nature of it and mentioning that a 'model/framework that is replicable' is needed, recognising though that 'reaching a replicable model/framework' at the SDGs interlinkages level or coming up with standardised modelling approaches might be difficult 'given the specificities of urban (or even, intra-urban!) level'.

Finally, extended collaboration with stakeholders, emerged as a topic of interest, to ensure that the insights gained from the analysis of SDG interlinkages are effectively integrated into policy design, implementation, and evaluation processes. This will enable the development of evidence-based policies that strategically address the complex and interconnected challenges of sustainable development. However, these stages are not disconnected. They need to be integrated into a widely applicable cycle of analysis.

5 Integrating SDG interlinkages studies within SDG policy making: the ReMeRA framework

The scoping analysis on methods used in the research for SDG interlinkages and the workshop results both point towards the need to consolidate and synthesise the existing work and to find ways to streamline the generation of impact from them. Based on the pertinent literature review conducted herein, as well as the workshop with the experts solicitation, it became imperative to systematically approach the study of interlinkages and to position research studies and methods into a framework of analysis. As such, we introduce the ReMeRA framework (*re*veal, *me*asure, *t*eplicate and *a*ddress), which will support researchers, policymakers, and practitioners towards efficient knowledge consolidation, better support policy coherence, and improve monitoring and budgeting of progress towards sustainable development.

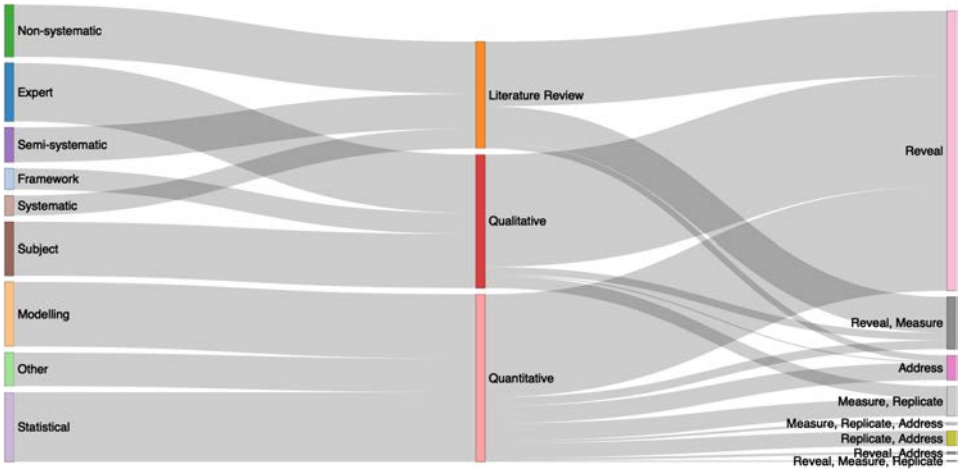
Expanding upon the findings of our study, it appears that the large majority of studies focus on exploring/revealing interlinkages. While this is a vital part of any endeavor related to revealing associations, between different entities, it does not automatically mean that it reaches decision makers and that those findings find their way into drawing support to achieving SDGs. Similarly, the fact that SDG interlinkages are identified does not imply that all are of similar significance or that all would have the same effect. As such, being able to define the degree of association and how progress towards one aspect of the SDGs influences another is of significance. However, revealing and measuring interlinkages is not enough. As pointed out by the large number of literature review papers, the Independent Group of Scientists Appointed by the Secretary-General 2019 and the views of experts expressed in the workshop, there is lack of coverage in terms of

a assessing interlinkages – in 2020 (Dolley et al., 2020) indicated that only 10% of target to target interactions have been assessed at least once – and most importantly

b reproduce the effects.

The latter is of utmost importance as – so far – research has primarily targeted understanding interlinkages on a global level, something that masks local particularities and generates a potentially false picture especially when thinking that actions (e.g., policies, projects, regulations) have to reach local communities and be implemented through consensus building on a local level.

Figure 9 ReMeRA framework studies disposition (see online version for colours)



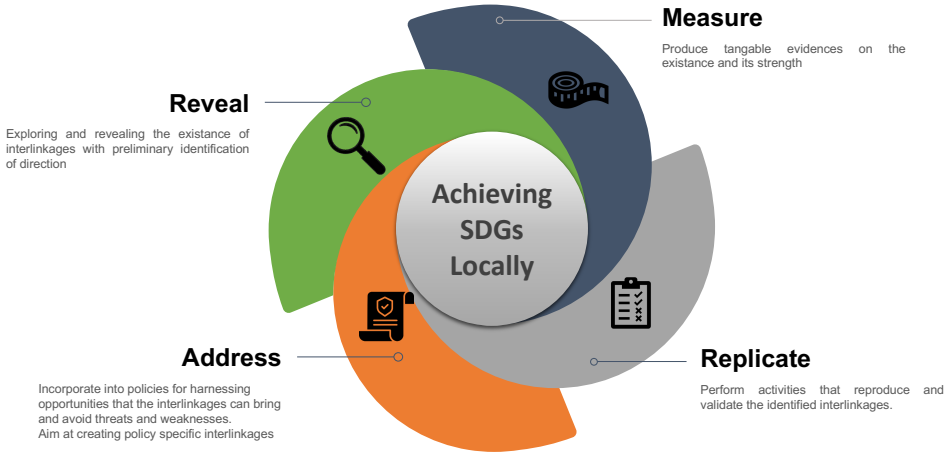
Perhaps of importance though, is instigating those findings on a policy level. While there is a small – but growing – number of studies that examine interlinkages from the lenses of specific sectors or specific policies, it still remains an open question how those interlinkages identified are addressed in and how they are related to actual actions that decision-makers take to progress towards SDGs. Approaching this in a systematic way is by itself vital, when considering that the application of similar policies in different contexts could produce different outcomes. At the same time inferring, revealing and exploring interlinkages resulting from the application of policies produces valuable insights that would be of interest to everyone involved in the application of the SDGs framework.

To understand to what extent the literature captures such a process-continuum, we have also characterised the studies we analysed, based on their disposition within those four research processes. Figure 9 presents this categorisation aiming at generating an awareness of the current scope of analysis, but most importantly identifying the areas which need further development. With the size of bars – relatively – representing the number of studies, it becomes apparent that the majority of studies target revealing interlinkages (approx. 68%) with some of the studies also targeting combinations that includes revealing interlinkages (such as reveal and measure, or reveal, measure and replicate). As rather clearly presented, there is a mismatch in terms of the four research

processes believed to be required to enable the materialisation of SDG interlinkages studies.

It is however evident that there is a need to define a holistic, iterative method-driven SDG integration process that to some extent systematises the process. To do this, scientific work needs to be properly positioned and should rigorously follow some – widely established – principles of responsible research. The process (presented in Figure 10) is inclusive, generic and systematic in nature, allowing for the streamline of the interactions between policy-making and research through a set of defined processes.

Figure 10 The ReMeRA framework (see online version for colours)



Starting from the reveal process, this includes studies which target the identification of interlinkages. Methods that could be used are qualitative, quantitative or literature-review based, however they primarily target revealing the existence of an association. Essentially, any study that identifies an association could fit into this process. It should be noted however, that approaching the topic on a granular basis (e.g., local, or collection of countries, or specific policy or specific domain) and with new evidences emerging, as the SDG framework is more widely adopted, revealing is continuous process with new evidences emerging and new knowledge being generated, within that block. In a similar notion, *measuring* aims at quantifying the influence, extracting causality and generating an understanding of how an SD goal, target, indicator can change based on another. This includes more targeted studies which could be used to predict what would happen if there is a change in one of the SDG parameters. Those studies could be either based on progress or value (e.g., progress/value towards/of one goal, target, indicator) or based on how an action to progress towards would influence other SDG parameters. While *measuring* is not widely met into the pertinent literature, it is of great importance when planning and devising prioritisation of actions, particularly when referring to revealed trade-offs. For example, if actions towards sustainable urban environment have been identified to hinder economic development, then it is important to understand how and how much a policy (e.g., limiting the usage of private cars) can influence economic development, so that policy makers can select the proper mix of policies. *Revealing and measuring* could be performed simultaneously. However,

it is important to distinguish the two, at least on a conceptual level to allow for an understanding of what researchers are targeting.

Consolidation/validation is vital within any SDG interlinkages process. It involves processes and methods that allow for replicating the effect, comparing effects identified within the same scope to those identified from studies, and generating knowledge on similarities, differences and conditions upon which effects change. It can involve literature review studies, qualitative studies or quantitative studies for consolidating studies. Examples include comprehensive or scoping reviews, articles which device meta-models, include expert elicitation on findings and in general generate knowledge and measurements based on combinations of results from different studies. Consolidation has to be based on principles of responsible research. The SDG research community should be implementing open science practices to the widest possible extent, including wide open data policies, allowing for *replicable* results, as well as further extension or re-use of models and methods. Finally *address* needs to be built upon a partnership which involves stakeholders within planning, decision making and research to enable the integration of SDG interlinkages within the SDG implementation process and generate new data and insights on how the integration is taking place, actual effect of policies and planning and potentially new interlinkages.

For the implementation of the ReMeRA framework, the community needs to generate a set of tools that streamline the conventional research generation, with the main goal being quick turnarounds of knowledge consolidation. This could involve the generation of a web-app platform which has some core functionalities:

a allow researchers to add research findings and pertinent meta-data (report functionality)

b enable community-based administration to verify the validity of the information provided (verify functionality)

c enable the findings to be compared with other similar studies (view functionality)

d enable the generation of knowledge on research gaps (e.g., which potential interlinkages have not been explored, or which policies seem to be performing better and in what contexts).

6 Discussion and conclusions

The literature on SDG interlinkages is growing year by year. This would inevitably lead to the study of additional methods and generate additional findings (reinforcing or contradicting existing interlinkages-related findings). Given the widely recognised importance of SDG interlinkages, the study of SDGs interlinkages brings opportunities far beyond the academic knowledge generation sphere. However, the urgency of enabling SDGs realisation calls for a coalition of forces and wide consolidation into probably the most interdisciplinary field ever conceived. Research generated must be able to capture particularities of examined fields and be able to inform policy making and drive efforts towards SDGs. There are though some corrective actions necessary to achieve that. SDG interlinkages field must not generate yet another research silo. We note here that sustainability issues, as those of the SDGs, are according to Rittel and Webber (1974) ‘wicked problems’, and have been so since the early 1970s; we second

that as these issues insist up to today, and affect the study of interlinkages between them, they require solutions that are inter-disciplinary, tackled with multi-method approaches, and conceived and addresses in a systemic way.

On the nature of the SDG interlinkages themselves, regardless of the items being interlinked (goals, targets, indicators or policies) and the territorial level considered, the literature suggests that in the vast majority of the cases, there are more positive ones, i.e., suggesting positive correlation and complementarity, than negative ones, i.e., suggesting trade-offs. Although findings are not definitive on this, the reported range of positive interlinkages is between 80% to 95% of the cases. This appears to be rather realistic, given that SDGs are largely driven by advancements already evidenced in many of the developed countries, but this could also suggest the existence of positive/likeness bias, a reluctance of reporting on trade-offs, or lack of methods that can reveal these interlinkages. In all cases, understanding SDG interlinkages – at all territorial levels – appears according to the literature to be a resource-intensive task. Taking into account the pragmatic limitation of resources (be it budgetary, political or other) to address and implement the SDGs, the literature is largely undecided on what to prioritise over the other, i.e., where and how to act given the inherent constraints; including SDG interlinkages in this mix of decision-making, as daunting and complex as it might appear, is a crucial aspect to take into account.

Out of the different items that form the focus of the SDG interlinkages topic, we found that of policies (or actions, measures, strategies and other operational initiatives) to be largely underrepresented. As we are moving closer to the year 2030 and the envisaged achievement of the SDGs, this is the exact area that can yield the most interesting, and necessary findings, if we – as a society – are to achieve the SDGs. Not knowing whether, and how, a certain action will influence another SDG element (goal, target or indicator) might be problematic as it can easily have adverse effects, nulling the effort to concretely achieve the objectives that are set. In this sense, we recommend a research drift away from the study of static high-level objectives (that is interlinkages between goals, targets and related indicators to measure them) to that of dynamic, systemic ones (that is the interlinkages between concrete policy and other actions to implement the goals and targets). This drift would allow the sector to develop new or apply known methods that can sufficiently infer the causality of such interlinkages, as currently used statistics and other quantitative methods hardly do. To this end, we argue that a registry of identified interlinkages with methods and case study (real-world evidence, on-field evidences) needs to be supported in an inclusive, yet standardised way which requires the collection of data and reproducibility. We found that replication (reproducing and verifying) is largely missing from the literature to confirm nature, strength and relevance of interlinkages, and hardly ever we encountered verification and validation studies in different e.g contexts, territorial or governance levels. To the contrary, there is a considerable amount of heterogeneity found in SDG interlinkages at least between the international and national level (see for example Pradhan et al., 2017) In this sense, participatory approaches need to be further developed and standardised, and the literature needs to move towards more reproducible methods which are verified with relevant findings on the implementation of policies and generally interventions.

From the large body of literature reviewed, we found that the methods deployed are overall exploratory and target primarily the exploration of interlinkages within the SDG framework. In many cases, researchers deploy statistical, largely exploratory methods based on available datasets for the identification of interlinkages. This approach poses

significant challenges related to the validity of the approach and the interpretation of results. Quantitative methods are scarcely able to capture causality. They primarily target a broader statistical association which is in the form of existence of a statistical relationship. This does not guarantee that for two positively associated goals (in a statistical manner), any policy implemented for improving one of them would result into benefit for the other. Instead, they focus on identifying interactions and not on the effect that actions/policies have on interactions. In addition, these offer little help towards the definition of a pathway for monitoring of interlinkages and towards examining how these interlinkages practically emerge and evolve. The landscape is rather similar for qualitative methods. Those largely depend on experts opinions and views, while the complexity of primary data collection for this topic makes it difficult to be able to compare results, given different settings, local particularities and a large list of relevant (subjects-specific) biases. From the examination of the literature, it is also evidenced that standardisation in the process of collecting and examining qualitative data as well as reaching conclusions is lacking. This makes the examination of interlinkages even more problematic, when compared to quantitative methods, as at least the latter do not suffer from a clear definition of the assumptions, the processes and the expected applicability. As such, it is rather easily concluded that SDG interlinkages exploration is still on an exploratory phase, with the outcomes being largely dependent upon the methods used and are indeed in many cases contradictory. The general approaches need to cater for replication of results (reproducing and verifying), something largely missing so far to confirm interlinkages. Quite often a chicken and egg problem arises (what is contributing to what). Is it economic growth that contributes to equality, or is it equality that contributes to growth?

Our review also contradicts recent findings in terms of nature of methods used to infer interlinkages. Allen et al. (2021) suggests that quantitative methods are used much less frequently than qualitative methods in VNRs. However, our review finds quantitative methods to be the prevailing ones when studying interlinkages. This could be partially explained because of the demand of resources in implementing and amount of complexity in interpreting interlinkages suggested by quantitative methods. The recent work of Lucia et al. (2021) suggests that indeed methods for inferring SDG interlinkages need to be easy to apply, transparent and flexible to contribute to decision-making. It is however certainly limited to interpret these findings with leaning only on qualitative, or other, easier to understand and apply, methods, as the risk to mask, and inability to reveal interlinkages of any nature would arise. Current scientific discourse points towards the explainability of methods rather than their applicability. Contrary to this, we argue that the scientific community would be best aiming at developing communication media to convey the results of the application of methods on the SDG interlinkages, instead of downgrading the method complexity to fit the diverse technical background of policy makers.

The local level is largely disregarded in the pertinent literature of SDG interlinkages. A large part of literature on SDGs interlinkages seems to generally approach the topic neglecting the particularities of the local level, or addressing them as secondary topic adjacent to the study of SDGs implementation. However, interlinkages are central to any local implementation. Different local conditions could dictate different outcomes when implementing policies. As such delving into the local reporting (VLR) and studying interlinkages while taking into account local particularities emerges as one of the highest priority findings of this literature review in order to account for SDG and territorial

trade-offs. It is also worth mentioning that there is no scientific literature which studies interlinkages on a local level using VLRs.

Finally, what the current state-of-art on interlinkages sets to answer, i.e., how SDG interlinkages are estimated, both in terms of the methods (analysed above) and the data suffers from the nature of reporting itself. Reporting includes the views and interests of policy-makers. This makes them prone to false (by error or even intent) entries or lack of reporting as a whole. The data that is largely utilised for interlinkages is diverse and as already asserted by some studies could lead to completely different interlinkages. As such, it is of vital importance to generate processes and standards for the reporting. As we move towards the boundaries of achieving SDG goals (closer in time or targeted value), the realisation of the targets becomes more and more difficult. As such, interlinkages need to be established on solid ground (data) to enable their synergistic realisation and avoid potentially negative effects from trade-offs.

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