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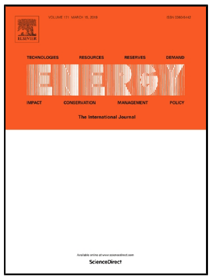

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Status and Perspectives on 100% Renewable Energy Systems

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Highlights:

- Research in design of 100% renewable energy has increased
- Energy is the leading forum for 100% RES research
- Holistic cross-sectoral analysis is becoming state-of-the-art
- There is a future need for linking the local and the global level

Abstract:

This article shows that research in the design of 100% renewable energy systems in scientific articles is fairly new but has gained increasing attention in recent years. In total, 180 articles published since 2004 have been identified and analysed. Many of these articles have a predominant focus on the electricity sector. However, an increasing number of studies apply a cross-sectoral holistic approach on the entire energy system. Most studies analyse energy systems for the final 100% renewable state, while a small, though increasing, number also investigate energy transition pathways; how to reach the target. Europe, and thereafter the US and Australia, are well researched, while other parts of the world lack behind, and there is a focus on individual country studies. Henceforward, there is a need for applying a cross-sectoral holistic approach as well as coordinating individual country studies with the global context.

Keywords: 100% renewable energy, Smart Energy Systems, Energy Scenarios, Energy Systems Analysis

Nomenclature

AR6	6th assessment report of the IPCC
BECCS	bioenergy carbon capture and storage
BECCU	bioenergy carbon capture and utilisation
CO_2	carbon dioxide
CSP	concentrating solar thermal power
DACCS	direct air carbon capture and storage
DACCU	direct air carbon capture and utilisation
ESM	energy system model
IAM	integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
NA	North Africa
PV	solar photovoltaics
R&D	research and development
RE	renewable energy
RES	renewable energy systems

SAARC South Asian Association for Regional Cooperation
SR1.5 special report on Global warming of 1.5ºC
SSA Sub-Saharan Africa
UN United Nations

Introduction

Climate action is urgent as presented by the IPCC's Special report on 1.5°C global warming stating that climate change impacts are worse than expected [1]. In 2017, human-induced warming reached approximately 1°C above pre-industrial levels, leading to severe climate change impacts. Changes are therefore required. The Paris Agreement of 2015 presents global ambitions to achieve a balance between anthropogenic emissions by sources and removals of sinks of greenhouse gases in the second half of this century. The ambition in the agreement is to maintain the increase in global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature to 1.5°C [2]. The total cumulative emissions up to that time represent a key to achieving this target and it has been estimated that stabilizing atmospheric greenhouse gas concentrations would result in continued warming [1,3].

One solution to meet these ambitions is to reduce the emissions from fossil fuels by deploying large-scale renewable energy (RE) supply in energy systems. This corresponds to UN's Sustainable Development Goal no. 7 working for affordable and clean energy for all with the aim to substantially increase the share of renewable energy in the global energy mix by 2030 [4]. Moreover, 100% renewable energy systems could also contribute to the fulfilment of Sustainable Development Goals no. 6 (clean water and sanitation), no. 9 (industry, innovation and infrastructure), no. 11 (sustainable cities and communities), no. 12 (responsible production and consumption) and no. 13 (climate action).

This paper focuses on the state of research within high-renewable energy systems to accommodate these ambitions and combat climate change.

In recent years, renewable solar photovoltaics (PV) and wind energy technologies have experienced radical cost reductions. PV account for the highest change in cost [5] due to improved efficiencies, material costs, economies of scale as well as public and private R&D [6,7]. The PV cost reduction trends are expected to continue further in the future [8] and similar trends can be found for wind power technologies and CSP [9]. Several studies conclude that wind and PV technologies are cost-competitive with traditional fossil fuel energy generation costs today [10–13].

Currently, the 100% RE concept is gaining momentum among a variety of stakeholders. Examples exist in Sweden where the ambition is to achieve zero net emissions of greenhouse gases by 2045 [14] and in Denmark where the target is to achieve zero net emissions by 2050 at the latest [15]. Furthermore, numerous countries aim at 100% renewable electricity by 2045 or 2050 including Bangladesh, Barbados, Cambodia, Colombia, Ethiopia, Ghana, Mongolia, Vietnam, Hawaii and California [16]. Already today, a few countries supply almost all electricity from renewable sources (mainly hydropower) such as Norway and Costa Rica [16], whereas some countries, such as Uruguay, have been the first to achieve this target in a mix of renewables [17]. Similarly, several cities have committed to 100% renewable energy by 2050 for the total energy consumption. These cities include Copenhagen in Denmark (2050), Frankfurt and Hamburg in Germany (2050), Malmö and Växjö in Sweden (2030), Oxford Country in Australia (2050), Vancouver in Canada (2050) and The Hague in The Netherlands (2040) [16]. A similar trend exists among larger companies such as IKEA, BMW and Walmart and technology companies such as Google, Apple, Sony, eBay and Facebook among many others, and even the first company from the inner core of the fossil energy business, Wärtsilä, that has committed to 100% renewable electricity [18].

In this perspective, the article first scrutinizes the status of current 100% RE systems (RES) research in terms of research focus, methods and typical regions considered. Second, gaps in 100% RES research are identified, while the third section establishes priorities for future 100% RES research. Finally, some reflections are presented.

The current status of 100% RES research

No uniform definition of 100% RE systems exists which is witnessed across the published literature. In many cases, studies focusing solely on the electricity sector label the transition as 100% RE, while other researchers focus on the entire energy system (also including heating/cooling, transport, and industry). These definitions influence the overall methods and findings. In this perspective paper, both types of studies are considered to obtain a comprehensive overview of the current research. A minimum threshold value of 95% RE is applied to the studies and only peer-reviewed journal articles are included. A total of 181 studies have been reviewed to form the insights of this perspective [19–199].

The 100% RE topic is a rather recent research field as illustrated in Figure 1, which lists all 181 publications according to their publication year. The trend indicates growing interest in the topic with very few studies published before 2009 contrasting the recent years with more than 15 studies published annually since 2014. The publications peak in 2017 and 2018 with more than 40 studies each.. It should be noticed that the first quantitative 100% RE analysis found by the authors is published in 1975 by Sorensen [200] [ref], and it took about 30 years to take up again this very early 100% RE system research with nowadays methodology.

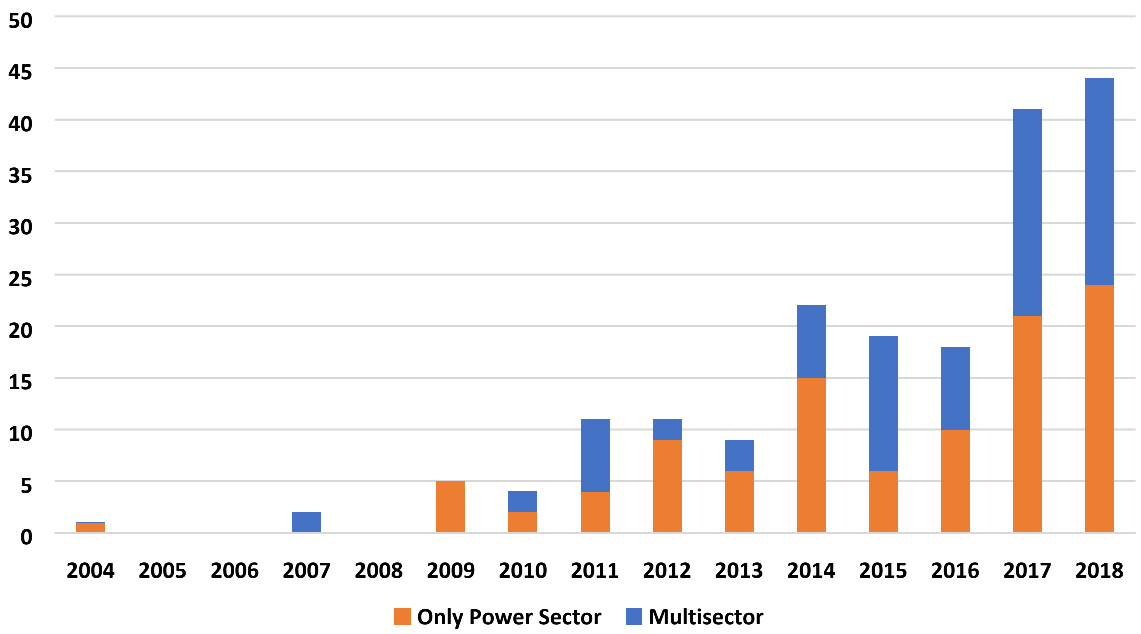

Figure 1: Number of 100% RE studies for countries, regions and globally according to their publication year

As shown in Figure 2, until now research has been published in a variety of academic journals, which proves the mainstreaming of the topic and the introduction into various research disciplines. The most common journal for 100% RE studies is Energy (45 publications), followed by Energy Policy (17 publications), Applied Energy (17 publications), Renewable Energy (15 publications) and Energy Procedia (15 publications). 80 additional articles on the topic have been published in more than 40 other journals combined. One observation is that Energy Policy historically published many articles on the topic of 100% RE, but this has decreased significantly in recent years (2 in 2009, 1 in 2010, 2 in 2011, 4 in 2012, 6 in 2013, 0 in 2014, 0 in 2015, 1 in 2016, 1 in 2017 and 0 in 2018).

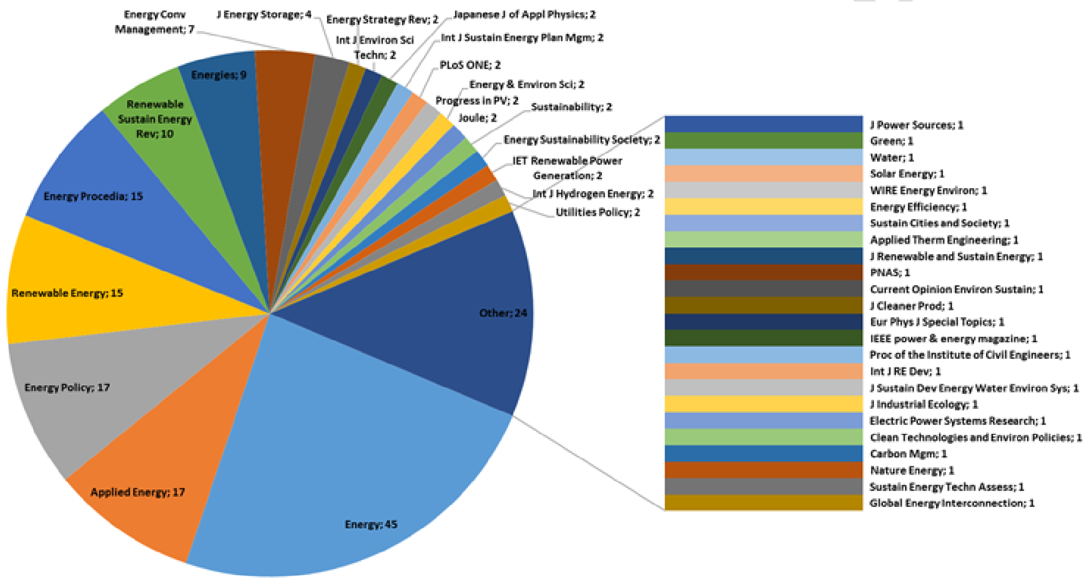

Figure 2: Number of 100% RE studies for countries, regions and globally according to the publishing journal.

Recently, 100% RE was mentioned for the first time in the IPCC SR1.5 report on 1.5°C global warming stating that the current studies “could, provided their assumptions prove plausible, expand the range of 1.5°C pathways” [1], page 112. This is a major milestone to realize that the Integrated Assessment Models (IAMs) can be complemented by sector-specific analysis about, e.g., 100% RE scenarios.

Research has focused on selected regions of the world as indicated in Acknowledgement illustrating the spread across regions. The region with largest attention is Europe, where research covers more than the electricity sector, but still not all sectors. In addition, Australia and the US are well researched, but mainly in terms of the electricity sector. Overall, national studies are most common with less focus on global levels or areas smaller than a national scale. Some islands are in focus in terms of 100% RE, in particular in Europe. Europe is also the only world region for which trans-national studies have been carried out on a broader and regular base, in some research also including North Africa, which has been triggered by the DESERTEC vision [201]. This is also based on the dissertation of Gregor Czisch [202], which represents the first peer-reviewed research on a multi-national 100% RE system.

A large number of studies using Energy System Models (ESMs) prove the viability of performing hourly energy modelling as a core methodology in the light of large-scale integration of variable renewable resources such as supplied by wind and PV generation. This enables an optimized use of technologies reflecting their resource complementarity and storage options hour-by-hour in current energy systems and in scenarios of future energy system trajectories. The hourly resolution permits modelling of energy system flexibility in a sufficient level of detail, mainly involving storage (same location but different times), grids (same time but different locations), dispatchable renewables (hydro reservoirs and bioenergy), demand response and sector coupling. This level of detail is typically not possible when temporal resolutions are limited to time slices and annual energy balancing [203]. Overcoming this limitation enables 100% RE studies to show the economic validity in terms of a relevant cost potential, but also the technical feasibility since all hours of a year are considered [204]. Some models have the aim to identify optimal solutions, but from a more theoretical point of view. In a broader planning and policy support perspective, it has also been discussed if the concept of optimal solutions makes sense [205], including how to handle the significant uncertainties aligned with future fuel end electricity market price predictions [206].

Until now, the research has also displayed analyses of a comparably broad technological portfolio, which is significant considering the long time horizon towards 2050 in most studies. Hence, technologies uncommon to the existing energy systems can be modelled and their roles in 100% RE systems can be determined.

The majority of the reviewed studies find that 100% RE is possible from a technical perspective, while only few publications argue against this [76,78,207,208]. The studies conclude that 100% RE is possible within the electricity sector, while other studies find that it is technically achievable for all sectors in a long-term perspective [44,77,80,92,97,120,134,137,138,175]. A large variety of technologies and measures are proposed for this transition. There is a growing base of open science activities among 100% RE researchers [209], mainly driven by researchers in Europe.

With a growing tendency in recent years, an increasing number of researchers underline the importance of applying a holistic cross-sectoral approach to the design of 100% renewable energy systems - also known as a smart energy systems approach. As shown in [210], the number of papers aligned to this concept has increased significantly in recent years. The assumption is that the best solutions can be found only if one focuses on the synergies between the sectors. On one hand, the transport and industry as well as the heating and cooling sectors need input from the electricity sector. On the other hand, these sectors can provide more affordable energy storage solutions to the integration of wind and solar power production [211] and also more operational flexibility [125], which reveals the value added by sector coupling.

The value of cross-border integration is increasingly investigated with multi-node models to show that the cooperation between neighbouring countries is a further means to achieving flexibility across a larger geographic entity, which allows a more efficient utilization of infrastructure and capacities of energy conversion and storage technologies [36,51,125]. A very limited number of studies are available which could reveal the separated value of cross-sectoral integration versus cross-border integration and a final cross-sectoral-border integration [212].

Which gaps can be identified

Certain gaps have been identified in the current research on 100% RE as described in this section.

The most researched energy sector in the 100% RE literature is the electricity sector, which is part of almost all studies and is the sole energy sector analysed in numerous cases (See figure 4). Conversely, less focus is placed on other energy sectors, even though these might be responsible for similar energy demands and emissions. For example, few studies investigate the transport sector and, in even rarer cases, all transport modes are considered (road, rail, marine, aviation). Many studies that include only transport incorporate the road mode, which is motivated by a final energy share of the road mode of about 80% in the current transport sector structure. However, this may change in the future due to challenges to directly electrify marine and aviation modes [213]. Moreover, the heating and cooling sectors gain little attention despite the fact that these sectors in some cases exceed the final energy demands of the electricity sector. 50% of the total final energy demand in Europe is either heating or cooling [214], which translates to about 30% primary energy demand for the heat sector [215]. This is also a consequence of the low efficiencies of thermal power plants leading to a high primary energy share of the present electricity sector. Additionally, a few studies thoroughly analyse the industrial sectors (in particular feedstock for steel, chemicals, cement, etc.) and the potential for direct carbon removal. The carbon dioxide removal technologies are, however, mostly in their infancy [1], but a broad literature base has been created [216–218], which should enable a fast integration into existing models.

The reasons for the predisposed focus can only be speculated but might be due to more straightforward solutions in the electricity sector (integration of mature renewable resources) compared to, e.g., the transport sector, as well as competences within the research field or the distribution of research grants. The reasons for sub-sector analyses in general may also be historical, since these sectors, to a wide extent, have been operated separately from one another in the current system based on fossil fuels. However, in a future 100% renewable energy system, they need to be much more coordinated and integrated. For the same reason, this should have a high priority in the research of 100% renewable energy solutions.

Other research topics that have not been comprehensively researched regarding 100% RE are sector-coupling studies with more sectors for different world regions, Power-to-X studies (fuels, chemicals, metal refining, etc.) and requirements for future energy grids. The latter is relevant because of the large increase in variable electricity sources that will challenge the existing electricity grids. Hence, it is pertinent to analyse transmission and distribution grids in more detail in scenarios with broad electrification of large parts of the energy demand. Moreover, the impact of the energy transition and sector coupling on other energy grids, such as gas grids, district heating networks and potential hydrogen and carbon dioxide grids requires more investigation.

In addition, the literature has a predominant focus either on supply side solutions such as the integration of further renewable energy sources or on the integration of technologies to enhance the energy system efficiency. These could be storage technologies, transmission grid options [96], integration of efficient technologies such as heat pumps, electric vehicles and reverse osmosis desalination [219], or power-to-fuels and power-to-chemicals to respect sustainable biomass limits in all-sector 100% RE scenarios. Less focus is placed on demand side solutions such as reducing energy demands at the consumer side to reduce the need for energy supply. Some studies indicate that demand side reductions are vital for transitioning to 100% RE systems in all sectors while remaining within sustainable resource limits [141,220]. Studies have introduced and applied methodologies to identify optimal balances between savings and production measures [221,222].

The geographical distribution of the research is, as previously described, limited to certain world regions. Less tradition for 100% RE research exists in regions such as South America, Sub-Saharan Africa, Eurasia, Northeast Asia, Southeast Asia and India/South Asia that have been scarcely researched. This limited research creates less support for decision-makers when developing future high renewable policies. The 100% RE studies to a large degree focus on national studies, particularly in the regions of origin of the researchers. Moreover, almost no global studies are carried out with energy system analysis, using the features of high temporal and hourly resolutions. No single study exists for the world in high regional resolution for all sectors, in full hourly resolution and describing energy transition pathways. The first studies conducted can cover parts of the desired profile, as summarized in Table 1.

ESMs in global-local resolution in an all-sector approach may be able to fill the gap of the comprehensive country-based studies and the much rougher description of IAMs to enable energy system models for 100% RE to contribute more effectively to tackling climate change. More ambitious research on the pathway options is needed, as claimed by Creutzig et al. [223] and Breyer et al. [125], reflecting high renewable energy shares. This is particularly important for the next IPCC AR6, as 100% RE system results were acknowledged, but not yet considered on a broader scale in the recent IPCC SR1.5 [1].

Table 1: Global highly renewable energy system studies indicating the level of covering the desired aspects. Latest versions of articles of the respective groups are listed.

	Model	Model type	Temporal resolution	Sectors	Pathway	Regions	Electricity exchange among regions	Energy trade among regions	RE share in 2050	long-term	Remark
Jacobson et al. [168]	LOADMATCH, GATOR-GCMOM	optimisation	hourly	all	overnight	20	no	no	100%	100%	1
Teske et al. [24]	Mesap/PlaNet	simulation	annual	all	transition	10	no	no	100%	100%	2
Breyer et al. [224]	LUT model	optimisation	hourly	power	transition	145	partly	no	99.7%	100%	
Löffler et al. [173]	GENeSYS-MOD	optimisation	time slices	power, heat, transport	transition	10	no	fuels	100%	100%	
Pursiheimo et al. [225][	VTT-TIMES	optimisation	time slices	all	transition	13	no	no	84.1%	84.1%	3
Deng et al. [191]	Ecofys	simulation	annual	all	transition	1	no	no	95.0%	95%	
Sgouridis et al. [226]	NETSET	simulation	annual	all	transition	1	no	no	90.7%	98.3%	4

[1] industrial feedstock is missing
[2] non-energy use of 9620 TWh_{th} still fossil
[3] model is unable to defossiliate non-energetic industrial demand
[4] remaining non-renewable is nuclear energy

Looking at the global distribution of studies as well as at the lack of global studies fulfilling all requirements, there seems to be a need for coordinating the individual city, country and regional studies and identifying how they fit into an overall solution with neighbouring countries and ultimately the rest of the world. Only few papers have addressed the principle of this problem [50]. Most studies focus on 100% RE analyses in the overnight approach, which may lack information to policy-makers and energy system planners in terms of how and by when to transition from the current state to a 100% RE system. In contrast to the overall picture, most global studies describe transition pathways as shown in Table 1.

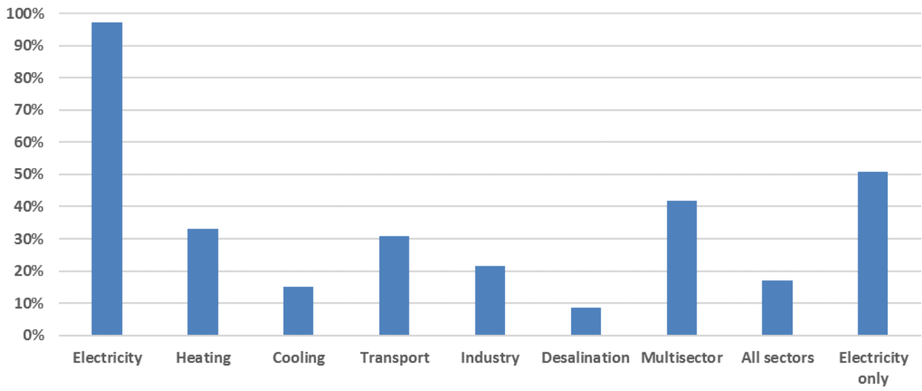

Figure 3: 100% RE studies according to their inclusion of different sectors.

Perspectives for future 100% RES research insights

Based on the current status and the identified research gaps, certain insights should be prioritized for future 100% RE research.

The research of future 100% RE mainly prioritise the mix of flexibilities for hosting high RE shares. A variety of solutions have been suggested such as developing optimal mixes of RE supply to accommodate temporality issues, demand response solutions, supply side management of dispatchable renewables, sector coupling, grid extensions and energy storage. However, these solutions have rarely been analysed in combination and therefore it is appropriate to focus on the optimal mix of these solutions in a 100% RE system. Other imminent challenges relate to the degree of centralized versus decentralized elements in 100% RE systems. This issue concerns both the decentralization of the energy supply (PV and wind power), the role of various energy grids (electricity, thermal and gas grids) and the role of the individual consumer/prosumer. Consequently, ownership structures will change, but have rarely been the focus of 100% RE studies. In addition, all-sector integrated global-local models also need to be able to describe the regional and international trade of fuels and chemicals to supplement the domestic supply, which effectively adds an international dimension to the discussion of decentralization versus centralization.

Moreover, research priority should be given to combining the design of future 100% RE systems with the available resource potentials within and across regions. For example, certain regions are affluent in hydropower, biomass, wind or solar resources, but could possibly benefit from exchanging resources with neighbouring regions. Hence, regions with limited renewable resources will also have the possibility to carry out a full RE transition. Finally, the integration of renewable resource potentials should be combined with changes to energy demands to ensure that these align.

One final priority concerns the feasibility of future 100% RE systems for various regions. Most studies find that it is technically probable to carry out a 100% RE transition (at least in certain sectors), but less consistency exists regarding the economic feasibility of this transition. In some studies, authors argue that it will be extremely costly (and technically infeasible) to perform this 100% RE transition [75,207,208], while other researchers find that it is both technically and economically feasible [143,145,150,224,227]. These studies typically differ in terms of geographical regions and analysis assumptions for future technology efficiencies and prices, and therefore more streamlined research is needed.

Biophysical limits require more consideration in 100% RE system research. This goes beyond the complex limits for bioenergy [150,228,229], since net energy analyses should be considered to a larger extent [226]. In addition, assessments should be made of the material demand for the energy transition, since the current energy system based on fossil energy fuels will be replaced by a system that is mainly based on metal resources.

A key contribution of 100% renewable ESMs could be to the development of future IPCC defossilisation pathways. ESMs with higher resolutions than IAMs could recalculate the technical feasibility of suggested pathways. Furthermore, IAMs do not account in sufficient detail for energy system flexibility effects, which is an area of expertise within ESMs. These measures might include BECCU (BioEnergy with Carbon Capture and Utilization) or DACCU (Direct Air Capture with Carbon Utilization), more described as Power-to-X. In addition, negative CO_2 emissions, based on BECCS and DACCS (storage instead of utilization) is a field to which ESMs can contribute with a deeper energy system understanding of these climate change mitigation options, which may be needed [1]. All energy system modelling, independent of ESMs or IAMs, should take care of sustainability guardrails [203].

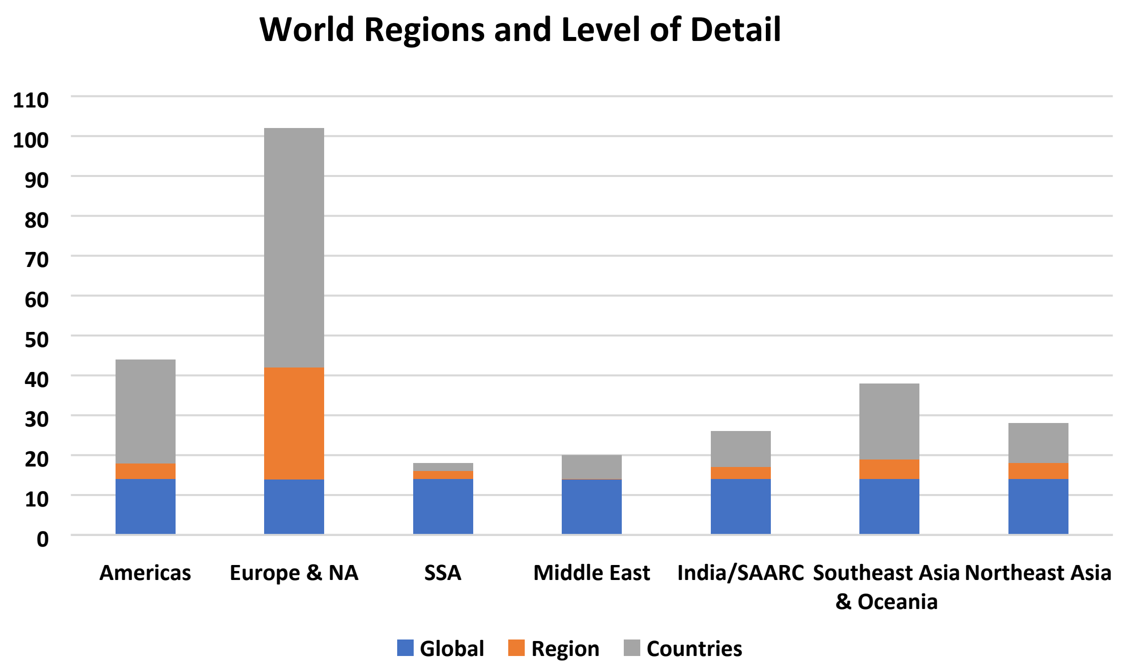

Figure 4: Number of publications according to world regions and level of detail in the 100% RE studies. NA: North Africa, SSA: Sub-Saharan Africa, SAARC: South Asian Association for Regional Cooperation.

Conclusions

The research field of 100% RE was established around the mid-2000s and has been referenced in an increasing number of articles since the early-2010s. In recent years, the 100% RE research field has provided scientific insights for policy-making, which is reflected by a fastly growing number of countries, states, cities and companies now committed to 100% RE targets. The best researched region in the world is Europe which is covered by more than half of all identified articles, followed by the US and Australia. The articles are published in various journals, led by *Energy*. The great majority of all publications highlights the technical feasibility and economic viability of 100% RE systems. State-of-the-art in 100% RE modelling applies a full hourly methodology with the aim to capture the various forms of flexibility to achieve optimized energy system solutions. This is increasingly complemented by a broad portfolio of energy technologies.

An increasing number of articles cover several energy sectors, overcoming the limited view of only the power sector. This reflects the integration of future energy systems and the increasingly important role of electricity in all energy sectors. More emphasis is required in 100% RE research on the full transport sector, industrial feedstock, power-to-X technologies, carbon dioxide removal options, and sector coupling. Major regions and countries in the world are not yet well covered by 100% RE research, such as South America, Sub-Saharan Africa, Eurasia, Northeast Asia, Southeast Asia and India/South Asia, which may be a substantial bottleneck for effective policy-making.

Several energy system models have been established for modelling global 100% RE research, but only few models have yet been developed to such extent that they can describe all required sectors and features in a sufficient level of detail and they have not been applied to the global level. Energy system models may be further progressed to be coupled with integrated assessment models for a more comprehensive and multi-disciplinary understanding of defossilisation pathways to the benefit of all involved communities and stakeholders.

Acknowledgement

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