100% RENEWABLE ENERGY SCENARIOS

SUPPORTING AMBITIOUS POLICY TARGETS

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About the Coalition

The IRENA Coalition for Action brings together leading renewable energy players from around the world with the common goal of advancing the uptake of renewable energy. The Coalition facilitates global dialogues between public and private sectors to develop actions to increase the share of renewables in the global energy mix and accelerate the energy transition.

About this publication

This brief examines five commonly referenced energy scenarios: three focused on achieving 100% renewables and two striving for net-zero emissions. It evaluates and contrasts the similarities and differences among these scenarios, providing policy recommendations derived from the analysis to support ambitious policy objectives and achieve a fully renewable energy-powered system by mid-century.

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01 INTRODUCTION

In pursuit of the goals of the Paris Agreement, net-zero energy system scenarios incorporate a broad range of energy sources, primarily driven by renewables but also including residual fossil and nuclear energy combined with carbon removal strategies to provide pathways to limit global temperatures to 1.5°C of pre-industrial levels. Net-zero system scenarios are fundamentally based on (i) gradually phasing out fossil fuels and nuclear energy while mitigating sectoral impacts; and (ii) assuming that the use of fossil and nuclear, with carbon removal strategies, would still be needed due to perceived technical challenges to the decarbonisation and electrification of hard-to-abate sectors.

However, within the energy community there has been a growing debate on the feasibility and credibility of a fully 100% renewable energy system (defined in Box 1). 100% renewable energy scenario proponents argue that there is growing evidence that such an energy system, completely devoid of fossil and nuclear resources, is both technologically feasible and offers the lowest cost - and most environmentally sustainable - option for the decarbonisation of the global energy system.

By comparing three 100% renewable energy scenarios and two net-zero scenarios, this policy brief seeks to go beyond the feasibility and credibility debate concerning each individual scenario. Rather, this brief identifies the common challenges and opportunities for a rapid and holistic shift towards more ambitious renewable energy targets, and provides related policy recommendations. It calls for decisions to be taken and implemented today and identifies requirements to support a 100% renewable energy system by mid-century.

Box 1 **The IRENA Coalition for Action has agreed the following definition for 100% renewable energy:**

Renewable energy encompasses all renewable sources, including bioenergy, geothermal, hydropower, ocean, solar and wind energy. One hundred percent renewable energy means that all sources of energy to meet all end-use energy needs in a certain location, region or country are derived from renewable energy resources 24 hours per day, every day of the year. Renewable energy can either be produced locally to meet all local end-use energy needs (power, heating and cooling, and transport) or can be imported from outside the region using supportive technologies and installations such as electrical grids, hydrogen or heated water. Any storage facilities to help balance the energy supply must also use energy derived only from renewable sources.

BACKGROUND

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Based on the findings of the Intergovernmental Panel on Climate Change's (IPCC) 1.5°C report of 2018, and the recent 6th Assessment Report, or AR6 (2023), mitigating climate change to no more than 1.5°C above pre-industrial levels by the end of this century will require the complete elimination of all anthropogenic greenhouse gas emissions by 2050, or even earlier (IPCC, 2019, 2023). The AR6 report further calls for "rapid and deep, and in most cases, immediate greenhouse gas emissions reductions in all sectors in this decade" to limit global warming to 1.5°C. Given that the majority of anthropogenic emissions are due to energy-related activities, harnessing renewable energy technologies (solar, wind, hydro, geothermal, bioenergy, ocean, *etc.*), along with significantly increased energy efficiency measures, will be key to these emission reductions (IPCC, 2023). These measures will also provide additional societal benefits such as improved local air quality and - with adequate policies in place - will expand energy access and equity, and strengthen local economies.

Evidence from some parts of the world suggests that the energy system is already transforming into a zero-carbon, distributed system based on a diverse mix of renewable energy sources and technologies. For example, Costa Rica, Iceland and Uruguay derive more than 50% of their total energy supply from renewables - although not necessarily variable renewables such as wind and solar (IRENA, 2023a, 2023b, 2023c). In 2021, Costa Rica demonstrated that a 100% renewable electricity system is viable by meeting most of its power needs with a mix of hydro, wind and geothermal, with renewables offering the lowest-cost solution to new and upgraded power production. In addition, significant gains are being made in global clean energy access through rooftop solar systems and other distributed forms of solar electricity, increasing electric vehicle use, and sector coupling of renewable power to green hydrogen applications. However, achieving a 100% renewable energy system requires systemic changes in energy market design and infrastructure development. Long-term decisions must be implemented today, regardless of current market trends. Additionally, decisions are needed today to create an enabling environment in which the required infrastructure and capacity are readily available as we transition towards a 100% renewable energy future.

A crucial approach in guiding how a 100% renewable energy system can be achieved is to examine various energy transformation scenarios. Over the years, a variety of energy models have been developed and applied to analyse different transformation pathways and calculate the impacts of different policy and technology options, often with the purpose of identifying the least-cost approach for achieving an energy transformation goal or target. Whereas climate models analyse the consequences of different emission pathways of both energy- and non-energy-related greenhouse gas (GHG) emissions on the global climate, energy scenarios use various energy-related models and assumptions, such as cost or deployment optimisation techniques to identify various pathways for achieving the end goal.

03 OVERVIEW OF SCENARIOS ANALYSED

Modelling scenarios that target 100% renewable energy have gained prominence in the past decade, as described in a landmark publication by Khalili and Breyer (2022). In their publication, many 100% renewable energy scenario studies conducted at national, regional and global levels were evaluated and shown to have increasing reliability and credibility as methods and data improve.

Three energy transformation scenarios dedicated to achieving 100% renewable energy by 2050 are considered here: The Lappeenranta-Lahti University of Technology (LUT) Global 100% RE Scenario (Bogdanov *et al.*, 2021); The University of Technology Sydney (UTS) 1.5°C Scenario included in their "Achieving the Paris Climate Goals" Report (Teske, 2019); and Stanford University's 100% Wind-Water-Solar (WWS) Scenario that specifically covers 145 countries (Jacobson *et al.*, 2022). These scenarios were chosen because they adhere to the principles of 100% renewable energy, are global in scope and extend their analysis to 2050.

In addition, two scenarios that aim for net zero by 2050 by reducing greenhouse gas (GHG) emissions in order to limit global warming to 1.5°C are also considered: the International Renewable Energy Agency (IRENA) 1.5°C Scenario (IRENA, 2021) and the International Energy Agency (IEA) Net-Zero Emissions (NZE) Scenario (IEA, 2021). These two scenarios include nuclear and fossil-fuel powered generation as well as carbon removal strategies as part of a future energy mix. They also include carbon capture and utilisation (CCU), and carbon capture and storage (CCS) technologies for removing residual emissions, as well as a combination of the two: carbon capture, utilisation and storage (CCUS). CCUS is expanded in the scenarios to include bioenergy with carbon capture, and storage (BECCS, incorporated by IRENA and IEA), and direct air capture with carbon capture and storage (DACCS, incorporated by IEA). In addition, CCU can be part of a 100% renewable energy Scenario with a non-fossil CO_2 source, which is expanded on in the LUT Global 100% RE Scenario, the distinction being that CCS cannot be part of a 100% renewable energy scenario (Bogdanov *et al*., 2021).

All five scenarios share the same modelling horizon to 2050 with intermediate milestones (*e.g.*, 2030) and they all involve a rapid and large-scale deployment of renewable energy solutions, especially solar and wind technologies.

The authors of this policy brief recognise that many of these studies have been updated since their original publication. Nevertheless, the key findings from each scenario remain largely unchanged in the updated studies. Furthermore, to reiterate, the main objective of this policy brief is to identify overarching policy recommendations that can be derived from undertaking net zero and 100% renewable energy scenario analyses. According to the scenarios' authors, 100% renewable energy - or very high shares of renewables - is what policy and decision-makers should strive for. The 100% renewable energy studies found this to be, for the most part, the lower cost option for a stable and reliable energy supply in line with the objective of limiting global warming to 1.5°C, which will be further elaborated in Section 5.

Moreover, the authors of this policy brief acknowledge there are some limitations to such analyses. For example, recent events unforeseen by the authors, including COVID-19 and the related energy crisis, are not reflected in these Scenarios. Moreover, the direct comparison of some input assumptions and outputs is difficult since the models use different sets of indicators. To this end, Table 1 provides a generic overview, representing commonalities across all scenarios organised in terms of targets, inputs, methodologies used and key outcomes. Figure 1 details the envisioned total energy mixes for each scenario by 2050. While the authors of 100% renewable energy scenarios might use slightly different terminology, for consistency the definitions for the terms used for this policy brief are specified in Box 2.

Box 2 **Definitions**

Final energy consumption (FEC) refers to all fuel and energy delivered to users for their energy use. FEC includes secondary energy, *i.e.* after conversion processes and related losses, and the form in which energy is made available for final consumption (*e.g.* electricity, heat, biofuels, gasoline and diesel; but also coal, natural gas and biomass if they are used for heating or other direct uses). FEC does not include non-energy uses of fossil and biomass resources such as the feedstock to the chemical industry for plastics and bioplastics production, which would be considered total final energy consumption (TFEC).

Total energy supply (TES) consists of primary energy production and primary and secondary energy imports subtracting energy exports, international bunkers and stock changes.

Total primary energy demand (TPED) refers to primary energy, *i.e.*, the form of energy that first appears in the energy balance, before conversion processes and related losses (*e.g.*, crude oil, coal, natural gas, biomass).

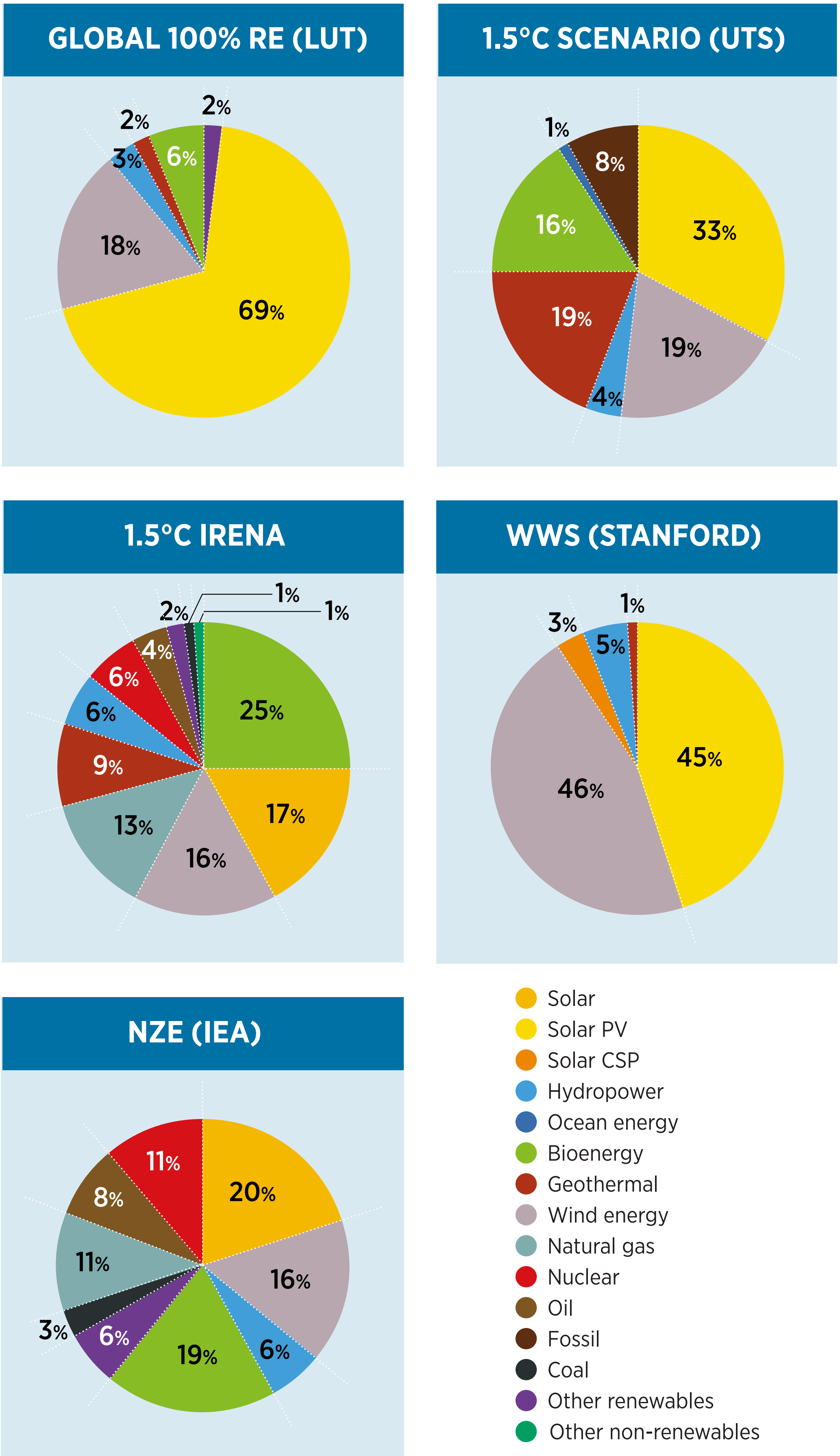
Source: *UN International recommendations for energy statistics (IRES, 2018), (IRENA, 2013).*

Table 1 **Overview of scenarios analysed**

ENERGY SYSTEM MODEL	GLOBAL 100% RE	1.5°C SCENARIO	100% WIND-WATER-SOLAR (WWS)	1.5°C SCENARIO	NET-ZERO EMISSIONS (NZE)
Institution	LUT (2021)	UTS (2019)	Stanford (2022)	IRENA (2021)	IEA (2021)
Target(s)	100% renewable energy system by 2050	Achieving 1.5˚C by 2050 with primary energy supply based on 100% renewable energy	80% WWS by 2030; 100% WWS by 2050 for 145 countries	Energy transition pathway aligned with the 1.5°C target (net zero by 2050)	Net zero by 2050
Renewable energy share in total energy supply (TES) by 2050	100%	100% (<92%, including non-energy consumption, which will still include fossil fuels. Primary energy supply in 2050 will be based on 100% renewable energy)	100%	74% in total energy supply (90% in electricity generation)	67% in total energy supply (88% in electricity generation)
Energy sources included in 2050	Solar photovoltaic (PV), concentrated solar power (CSP), wind, hydropower, geothermal and bioenergy	TPED: solar, wind, hydro, geothermal, biomass, ocean energy (tidal and wave), natural gas, oil, coal (latter due to non-energy consumption)	Generation: wind, solar PV, CSP, geothermal, hydro and ocean energy. Heat: solar thermal, geothermal heat	TES: solar, wind, biogas, biomass, hydropower, geothermal, solar, ocean energy, natural gas, oil, coal and nuclear	TES: solar, bioenergy, wind, hydropower, geothermal, other renewables, nuclear, natural gas, oil and coal.
2050 share of electricity (electrification level)	89% (total primary energy demand)	92.3% (total final energy demand)	Efficiency measures result in total energy demand decreasing by 56.4%, so that remaining energy is nearly all (~99.1%) electricity: 85% higher than 2018 actual levels (total installed capacity)	51% of direct electricity in total final energy consumption and 14% from hydrogen	49% of electricity in total final energy consumption
Cumulative investment needed to 2050	USD 72 trillion, noting net energetic yield per invested unit of capital in renewable electricity solutions far exceeds the one in upstream fossil fuels	USD 51 trillion across the power sector (an average investment of USD 1 420 billion per year, 2015-2050) USD 12.4 trillion for the heating sector (an average investment of USD 344 billion per year, 2015-2050)	Around USD 61.5 trillion Upfront costs are recovered through energy sales, covering WWS electricity; heat and green hydrogen generation; storage for electricity, heating, cooling and green hydrogen; district heating heat pumps; all-distance transmission; and distribution	USD 131 trillion (annual funding requirement averaging USD 4.4 trillion), adapted from planned government cumulative energy and energy related infrastructure investment strategies amounting to USD 98 trillion by 2050	Annual average capital invested is indicated for 2030-2040-2050: - 40-50 trillion USD, annual investments of 4-5 trillion per year by 2030 - Almost USD 5 trillion annually by 2040 - USD 4.5 trillion annually by 2050
Job creation	134 million by 2050 in the global energy sector*	47.8 million energy-sector jobs by 2050 (up to 89% would be renewable energy jobs by 2030)	28.4 million (net increase) by 2050	122 million jobs in the global energy sector: - 43 million directly in renewable energy - 25 million in power grids and flexibility - 25 million in energy efficiency - 2.24 million in hydrogen	30 million more people under NZE working in clean energy, efficiency and low-emissions technologies.

*(Ram, *et al.*, 2022).

Figure 1 **Compared energy Scenarios and their total energy supply in 2050**



04 KEY FINDINGS

All scenarios covered in Section 3 are in line with a 1.5°C target by mid-century. This is the preferred target set by the Paris Climate Accord of 2015 (UN, 2015). Details of what these emission reduction pathways could look like over time were published in the 2018 IPCC Special Report, *Global Warming of 1.5°C* (IPCC, 2019). All the scenarios examined call for:

1. energy related GHG emissions to fall to zero (or Net Zero) by 2050, if not earlier;

2. a rapid reduction of emissions to about half of the current levels by the year 2030, consistent with the IPCC AR6 report (IPCC, 2023); and

3. energy efficiency measures to be significantly increased, so that per capita energy intensity and total final energy consumption (TFEC) are lower by 2050 than currently, even as the global population grows.

Various steps to achieve these end-use energy reductions are suggested, such as greatly improved efficiencies in building design and retrofits, expanded use of heat pump technologies, and demand-side management strategies.

The IEA's NZE and IRENA's 1.5°C Scenario include carbon removal strategies, thus, allowing for continued infrastructure for, and exploitation of, fossil resources to a limited extent. The 100% renewable energy scenarios differ in the milestones and exact technology and resources mix, but they do not allow for other than renewable energy sources by 2050 or soon after. Additionally, the three 100% renewable energy scenarios start from the assumption that from a certain year onwards only renewable sources should be used. In sum, the 100% renewable energy scenarios require higher system flexibility on the demand and supply side and therefore various storage and flexibility options.

This section focuses on the key findings from the 100% renewable energy scenarios; similarities and relevant differences compared with the net-zero studies will also be highlighted (further detailing the differences provided in Table 1 and Figure 1). The succeeding section will provide a summary with recommendations for policymakers.

4.1. Electrification

Perhaps the most important common finding among all scenarios is that electricity in TFEC will grow substantially over the next 30 years, in part due to the electrification of the industrial, transport and building sectors as well as due to a general increase in electric goods worldwide and an overall increase in sector coupling applications. Depending on the scenario, electrification will provide anywhere from 50% to more than 90% of TFEC by 2050, compared to around 20% in 2022 (IEA, n.d.). Consequently, there is a need to build a significant amount of new electricity capacity and enabling infrastructure to cover the needs of these sectors.

The LUT Global 100% RE Scenario (Bogdanov *et al.*, 2021); UTS 1.5°C Scenario included in their *Achieving the Paris Climate Goals* report (Teske, 2019); and Stanford University's 100% WWS Scenario (Jacobson *et al.*, 2022) specify that the electrification of all energy sectors can be achieved without the need for any fossil-fuel-powered generators. The electrification of transport and heating are consistent across all three scenarios, with a focus on electrifying the transport sector by replacing internal combustion engine (ICE) vehicles with electric vehicles (EVs). The IRENA 1.5°C Scenario states that 49% of the transport sector will be electrified by 2050.

With electricity inherently being the main 'energy carrier' of the future in all scenarios, a resulting substantial increase in electricity demand by 2050 is expected. The Global 100% RE Scenario suggests that 90% of TPED will be met by electricity in 2050 (Bogdanov *et al.*, 2021). This scenario anticipates that electricity demand will increase substantially by 2050 with the greatest increase coming from end-use sectors in transport and industry. In this regard, the Global 100% RE Scenario is consistent with IEA's NZE and IRENA's 1.5°C Scenario. In comparison, the WWS Scenario (Jacobson *et al.*, 2022) assumes a near-total electrification of TFEC, with only a small portion achieved through solar thermal and geothermal heat.

In terms of energy efficiency, the WWS Scenario assumes that efficiency measures as well as a reduction in traditional fossil-related industry demands will reduce the overall demand for energy by 56.4% by 2050 (Jacobson *et al.*, 2022). The UTS 1.5°C Scenario also assumes more than 50% reduction in final energy demand worldwide due to efficiency and conservation measures (Teske, 2019). The Global 100% RE Scenario anticipates a 49% efficiency improvement in the ratio of TFEC to TPED from 2015 to 2050 (Bogdanov *et al.*, 2021). All scenarios, particularly the 100% renewable energy scenarios, assume that the total energy demand will decrease owing to energy efficiency improvements by 2050.

The overall rapid expansion of the electricity sector and the growth of variable renewable energy (VRE) sources will demand a transformation of the transmission and distribution capabilities of the grid. This will require large investments to expand and enhance the grid leading to smart and highly digitalized grids; *e.g.*, upgrades in control and monitoring of grids. Additional storage capacities and various storage technologies will also be required. The UTS 1.5°C Scenario, for example, underscores that a short-term large quantity of over 244 GW of hydro-pumped storage and 12 GW of battery storage by 2030 must be installed to support the major expansion of solar PV (Teske, 2019).

Finally, sector coupling is an important requirement to match VRE and flexible demand, particularly via hydrogen production, electric vehicles and space heating demand. Power quality, reliability and security requirement demands by consumers are increasing. Yet, as more distributed and variable sources are being tied into the grid these factors can potentially be negatively impacted. Grid flexibility, achieved through storage technologies covering time scales from hourly to daily to seasonally, demand-side management of the load, and regional power trading, will be a major driver for a stable and reliable decarbonised energy system that still meets consumer requirements.

4.2. Solar and wind

The three 100% renewable energy scenarios propose that by around 2050 electricity will come entirely from renewable power production, especially from wind and solar technologies (Teske, 2019; Bogdanov *et al.*, 2021; Jacobson *et al.*, 2022). This is achieved largely through the current competitive cost and projected future cost reductions and technological innovation improvements of these two technologies. For solar PV, dramatic growth is expected in both distributed (rooftop) residential and commercial systems as well as large utility scale systems. The three 100% studies estimate that total solar capacity by 2050 can range anywhere from 33% to 69%. On the other hand, the IRENA 1.5°C Scenario and IEA's NZE indicate solar PV capacities would comprise 17% (TFEC) and 20% (TES) by 2050 (IRENA, 2021; IEA, 2021).

For wind, significant growth in offshore and onshore wind deployments is anticipated. All the scenarios, except the WWS Scenario anticipate that wind could contribute 16-19% of total energy supply. The WWS Scenario gives wind more prominence with a 45% share of installed capacity. In all the scenarios, other renewable technologies, notably hydro, but also sustainable modern biomass use, geo- and solar- thermal systems and wave and tidal systems will be relevant, but no other generating technology will see anywhere near the growth that will be achieved through wind and solar technologies.

4.3. Biomass

With the exception of the WWS Scenario (Jacobson *et al.*, 2022), all scenarios analysed include bioenergy as an important part of a 100% renewable energy system or net zero future. The four Scenarios that include bioenergy show that biomass technologies can supply anywhere from around 6% to more than 20% of all primary energy by mid-century. The contribution of bioenergy is most prominent for residential and industrial heat sectors where it is expected to provide hot water and steam for households as well as industries such as cement, steel, paper and pulp.

The contribution of bioenergy is limited in the transport sector, where other options such as electricity and hydrogen are more prominent. Power generation from biomass is considered complementary to other sources such as solar PV, wind and hydropower.

In the four scenarios that include bioenergy, the share of traditional biomass use will largely be replaced by modern biomass use, factoring in air pollution and sustainability as adoption drivers, and overall, marginally contributing to the energy supply by 2050. Other key factors for considering bioenergy include dispatchability of biopower systems and the possibility to integrate alternative fuels into existing fossil fuel infrastructure (*e.g.*, biogas and bio-methane to gas grids), as well as a possible contribution to negative emissions via BECCS.

4.4. Other renewable sources

Hydropower and geothermal form part of each of the scenarios, with geothermal sometimes limited to residual heating systems or combined with heat pumps. Apart from the Global 100% RE Scenario, ocean energy (tidal and wave technologies) was identified by the scenarios as playing only a minor role in the energy transformation and could help reduce the impacts of variable offshore wind supply.

The WWS Scenario highlights the geographic limitations for ocean energy, as well as geothermal energy, with the main countries identified for geothermal deployment as a primary source of heat being the

United States, China, Sweden, Türkiye and Germany (Jacobson *et al.*, 2022). For tidal energy the main market potential is in Canada, the United States, Ireland, France and the United Kingdom; for wave energy the markets are broader, including much of the Atlantic coastline of Europe, as well as coastal regions of Canada, the United States, Australia and remote islands (Jacobson *et al*., 2022).

4.5. Green hydrogen

Hydrogen, and in particular green hydrogen, is recognised by all scenarios as a major strategic building block to decarbonise hard-to-abate sectors such as long-distance and heavy-duty transport and high-temperature industrial process heat. In IRENA's 1.5°C Scenario, hydrogen (not only from renewables) and its derivatives are listed as key solutions to achieve net zero by 2050, contributing towards the abatement of carbon emissions in industry by up to 12%, and transport by up to 26% by 2050 from 2021 (IRENA, 2021). Green hydrogen, in IRENA's original 1.5°C Scenario, accounts for 9% of the final energy output by 2050 and will play a key role in balancing supply and demand. The IEA's NZE Scenario maps out the initial rationale behind using hydrogen (across energy sources including green hydrogen) as an energy carrier, since hydrogen could use the same transmission and distribution infrastructure as fossil gases. The NZE Scenario also specifies a relevant role for non-renewable hydrogen with and without CCUS in the ramp-up phase and through 2050.

Hydrogen is also proposed as a means to assist with grid management in the IEA NZE Scenario (IEA, 2021) and the Global 100% RE Scenario (Bogdanov *et al*., 2021), where the high relevance of hydrogen-to-X conversion (kerosene, diesel, methane) is highlighted for faster replacement solutions in existing infrastructure. The IEA NZE Scenario similarly recognises green hydrogen as a solution to help balance the issue of variability and issues of grid instability (IEA, 2021). Green hydrogen will also play a strong role in the WWS Scenario (Jacobson *et al*., 2022).

The WWS Scenario envisages that fossil and nuclear energy, along with biofuels and bioenergy, will be phased out by 2035, driven by an increase in VRE, energy efficiency, and storage - which would result in the significant acceleration of the hydrogen sector (Jacobson *et al*., 2022). The Global 100% RE Scenario refers to hydrogen as being a viable alternative to fossil fuels by 2040, when liquid gases will be used for long-distance and heavy-duty transport such as aviation and marine vessels (Bogdanov *et al.*, 2021). Overall, significant investment in electrolyser technology is needed to make green hydrogen economically viable, competitive and readily available.

4.6. Transport

While the electrification of transport plays an important role in all scenarios, the way in which the decarbonisation of the transport sector is addressed varies. Electrification is the major choice, especially for passenger cars vehicles and for road freight. In some scenarios, hydrogen fuel cell vehicles are also proposed. For the shipping industry a variety of technologies is discussed, including advanced biofuels, hydrogen fuel cells, power-to-liquid synfuels and wind-assisted shipping. For the airline industry a rapid transition towards sustainable biofuels and power-to-liquid synfuels is proposed, although green hydrogen and electrification (especially for short-range commuter aircraft) are also suggested. Major research and development (R&D) commitments to these new technologies are emphasised in all the Scenarios.

As with the production of green hydrogen, the production of synthetic fuels will cause significant additional electricity demand and a corresponding expansion of renewable power-generation capacities (Teske, 2019; Bogdanov *et al*., 2021).

4.7. Heating and cooling

Heating and cooling at the household level is widely projected to be largely electrified, particularly by using heat pumps, except perhaps in certain markets where solar domestic hot water systems already play a key role. Along with passive solar designs, these non-electrified applications of solar energy will continue to play an important role in the future in terms of reducing demand on electricity. In some markets, there is also widespread adoption of geothermal heat pumps as a supplemental source of heating and cooling for residential and commercial buildings, which also serves to reduce electricity demand.

For end-use sectors, in the cases where electrification of heating and cooling using heat pumps is not technically feasible (especially for high-temperature industrial applications which can be difficult to abate), the different scenarios offer alternative technology options, with a particular emphasis on high temperature solar thermal technologies. Various other approaches include producing and using hydrogen and synthetic energy carrier technologies. As with the technologies themselves, all the 100% renewable energy scenarios emphasise the need for accelerated research and development in the heating and cooling sector, especially in these hard-to-abate sectors.

4.8. Socio-economic aspects of the scenarios

All the scenarios build on the capabilities of existing technologies to achieve 100% renewable energy (or net-zero emissions) by 2050. In addition, all five scenarios propose that the transformation costs, which can be seen as high, must be balanced with the benefits of addressing the externalities. This policy brief focuses on two externalities that are covered by each scenario: (i) jobs and a just transition; and (ii) health. While the overall benefit from reducing externalities is widely accepted among each scenario, what is less certain is how to address the socio-economic aspects of the transformation within the available time frame (<30 years). All the scenarios acknowledge that significant investments are required for target achievement, although the means for incentivising these investments can be quite varied and are addressed in varying detail. Additional action is required to stimulate the investments, with policy measures taking on different forms and levels of detail in different scenarios (IRENA, 2021; IEA, 2021). The following sub-sections will further detail the externalities and key results from each scenario (see Table 1).

(i) Jobs and a just transition

One of the clearest socio-economic benefits of the energy transformation stated in all scenarios is the positive impact on employment and job creation. Each of the scenarios provides estimates of net job creation, with some being clearer about the specific sectors in which these jobs will be created. In the IRENA 1.5°C Scenario, for example, there is also an acknowledgement of the work yet to be done to achieve gender equality (IRENA, 2021). According to the data of 2021, women made up 32% of the renewables workforce, which is 10% higher than that of the fossil fuel industry (IRENA, 2021).

The energy sector employed more than 65 million people with 12.7 million renewable energy jobs in 2021 (IRENA and ILO, 2021). Following IRENA's 1.5°C Scenario, a transformed energy sector will support about 122 million jobs, with 43 million of those jobs directly attributed to the renewable energy sector by 2050 (IRENA, 2021). The job projections in the Global 100% RE Scenario are a bit higher at 134 million by 2050 in the global energy sector, primarily driven by renewable and sustainable technology value chains, which are found to be more labour intensive than extractive fossil fuels (Bogdanov *et al.*, 2021; Ram *et al.*, 2022). In addition, this scenario projects a distribution of renewables across the globe that will encourage local development and in turn promote higher economic activity in various regions. However, as noted by IEA's NZE Scenario, the job benefits of the energy transformation will have disproportionate effects across different geographies and communities, with fossil fuel producer economies likely to bear the brunt of economic impacts (IEA, 2021). The WWS Scenario estimates a total of 55.6 million new long-term and full-time jobs, but also indicates that 27.2 million jobs in traditional energy sectors will be lost, resulting in a net increase of 28.4 million jobs by 2050 (Jacobson *et al.*, 2022). The WWS Scenario's lower number, compared with some of the other scenarios, is a result of the considered lower growth in the overall energy supply by 2050 due to more extensive efficiency measures (Jacobson, *et al.*, 2022).

The WWS and the UTS 1.5°C scenarios both use a just transition framework to communicate the socio-economic impacts for workers and wider societies. Although a just transition is stated, the limited data on the impact on employment is not yet clear. The UTS 1.5°C Scenario envisages 47.8 million energy-sector jobs by 2050, and projects that 89% of energy-sector jobs would be in renewable energy by 2030.

(ii) Health

As both local pollution and greenhouse gas emissions result from the combustion of fossil fuels, there is an understanding that transforming the energy system to 100% renewable energy is not only a way to address climate mitigation but also a health, equality and human rights necessity. The five scenarios highlight a major socio-economic impact of the energy transformation: the increased health benefits to society at large. One such aspect is the phase-out of traditional biomass for cooking which will also have positive health impacts to those living in communities lacking access and those in less economically developed regions. All scenarios have around the same baseline number of 5-5.5 million premature deaths caused by air pollution annually but differ in terms of premature deaths prevented. For example, the WWS Scenario estimates that 5.3 million premature deaths would be avoided annually by 2050, while IEA's NZE Scenario estimates at least 2 million premature deaths per year would be avoided by 2050 (IEA, 2021; Jacobson *et al*., 2022). Moreover, the IEA's NZE identifies that, of the 2 million premature deaths prevented, around 85% of these are from emerging market and developing economies (IEA, 2021).

05 SUMMARY AND RECOMMENDATIONS FOR POLICYMAKERS

As a necessary step, by 2050 at the very latest, the temperature rise associated with climate change must be limited to 1.5°C above pre-industrial levels. All five scenarios analysed in this policy brief provide pathways towards achieving the targets of the Paris Agreement (UN, 2015). The five scenarios analysed suggest that it is not only possible to mitigate climate change but also economically and socially beneficial to achieve the Paris Agreement goals by transitioning to renewable energy. The three 100% renewable energy scenarios go one step further by presenting that a fully 100% renewable system will most likely be more socio-economically and environmentally beneficial, efficient and cost-effective in achieving the Paris Agreement goals in comparison to the net-zero scenarios. Dedicated policies and especially those following the 100% renewable energy scenarios will significantly reduce societal costs and improve public health, and they will also provide clean and sustainable jobs for tens of millions of people.

The IRENA 1.5°C and IEA NZE scenarios outline a net-zero future, where fossil and nuclear energy still provide a small share (~25%) of energy supply in 2050. Net zero, for both scenarios, is achieved by including CCS, CCU and CCUS for removing fossil GHG emissions from the atmosphere. Conversely the 100% renewable energy scenarios provide pathways without any fossil or nuclear energy to achieve a carbon-free, stable, reliable, affordable, and just global energy supply for all, where the socio-economic and environmental benefits would outweigh a net-zero approach.

Each scenario provides policy makers with key information and data for planning and implementing an energy system that is compatible with the 1.5°C goal. They provide meaningful insights for accelerating the energy transformation. The findings - particularly when enriched by more granular local, national or regional data - can encourage broad public support of policies for significantly higher shares of renewables, and eventually 100% renewable energy in all sectors.

It is against the collective findings of the previous sections that this policy brief makes the following recommendations that can facilitate the shift towards a more ambitious renewable energy system:

Recommendation 1
Embrace a 100% renewable energy system and phase out fossil fuels

Renewable energy ambitions aiming at up to 100% renewable energy should be increased and combined with enabling frameworks and incentives for their deployment and expansion, including the planning and development of power networks and local supply chains. Given their maturity, rapidly decreasing costs and deployability, renewable energies provide a safe and secure energy supply without having to wait for emerging innovations or rely on risky and harmful nuclear and fossil-based technologies combined with costly and untested large-scale technologies for removing residual fossil fuel emissions, such as CCU and CCS, to remain within the 1.5°C limit.

Given the competitiveness of renewable energy technologies, the continued exploration and extraction of fossil fuels and the building of new fossil fuel infrastructure and facilities should be phased out completely. Continued activities in fossil fuel extraction and infrastructure development would result in stranded investments, socio-economic and environmental impacts and subsequent costs, and would almost certainly result in global warming exceeding the 1.5°C limit. A complete phase-out of fossil fuel use and fossil fuel subsidies in a just and equitable manner should be a priority in energy policy agendas, in order to create a level playing field where the advantages of renewable energies are no longer counteracted by subsidising unsustainable energy sources.

Recommendation 2
Energy efficiency as a priority: "The [best] energy supplies are those that are not needed"

Energy efficiency is a key requirement towards a truly sustainable energy system. Investment into energy efficiency must be prioritised and significantly increased. By doing so, it can be ensured that per capita energy intensity and total final energy consumption (TFEC) are lower by 2050 compared to current levels, even with a growing global population.

Recommendation 3
Electrification: A path to a sustainable energy transformation

Electricity will become the main 'energy carrier' of the future, growing substantially over the next 30 years across sectors. The direct electrification of end-uses - and indirect electrification particularly of hard-to-abate sectors - through sector coupling, and green gases and fuels, plays a crucial role in achieving the 1.5°C global target. In many cases, electrification also improves the efficiency of end uses (*e.g.* heat pumps and electric vehicles). This will require grid expansion and enhancement of the electricity system.

Recommendation 4
Infrastructure for a resilient, decentralised and flexible energy system

The energy system of the future will rely on very high shares of VRE like wind and solar PV as well as power networks as the backbone of a secure, reliable and decarbonised energy system. However, it is important to note that the complementarity of other renewable energy technologies, such as biomass and storage, in their role as dispatchable energy, ensuring a balanced and resilient energy grid. A more geographically and ownership-diverse (residential, commercial and governmental) energy system will require high levels of digitalisation, smart grids, sector coupling and storage availability in order to match supply with demand at all times. In addition, a more distributed, renewables-based energy system results in broader inclusion of consumers and 'prosumers' in their energy choices. Flexibility is key for a resilient energy system of the future, including for the integration of green hydrogen production, electric vehicle charging, demand response and energy storage to accommodate high shares of variable renewable energy sources. This will always ensure an efficient and resilient energy system at all times.

Recommendation 5
International co-operation: Paving the way for the transformation of the global energy system

A fully sustainable global energy system cannot be achieved by a single country or sector alone. Dialogues and actions are needed to fast-track progress towards a resilient and sustainable renewable energy system. Increased cooperation, as well as proactive implementation of the energy transformation, should focus on the feasibility of such a transformation. Scenarios should be based on existing renewable energy technologies, as discussed in this policy brief. International cooperation, including capacity building, is a key enabler for the success of energy system transformation.

Targeting a 100% renewable energy system will be the most compelling way to accelerate the deployment of renewable energy installations. A fully renewables-based energy system that has broad public support will result in benefits such as cost savings, energy security and a healthier environment. Such a system remains within the boundaries of the requirements for an inhabitable planet without costly deviations, stranded investments or prolonged carbon emissions.

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