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Article

The Implications for Renewable Energy Innovation of Doubling the Share of Renewables in the Global Energy Mix between 2010 and 2030

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Abstract: Benefits of increasing the renewable energy (RE) share in the total energy mix include better energy security, carbon dioxide emission reductions and improved human health. This paper identifies the potential of RE technologies and role of innovation to double the global RE share from 18% to 36% between 2010 and 2030. As a first step, a Reference Case is developed based on national energy plans of 26 countries which increases the RE share to 21% by 2030. Next, the realizable potential of RE technologies is estimated beyond the Reference Case at country and sector levels. By aggregating country potentials, this paper reveals that the global RE share can double to 36% by 2030. Despite differences in starting points and resource potentials, there is a role for each country in achieving a doubling. For many countries their Reference Cases result in low RE shares and many countries are just beginning to explore ways to increase RE use. The paper identifies action areas where innovation can increase technology development and improve cost-effectiveness, thereby accelerating global RE deployment. More research is required to specify these action areas for individual countries and specific technologies, as well as to identify policy needs to address them.

Keywords: renewable energy technology; country analysis; innovation; end-use sector; power sector

1. Introduction

In 2011, total final energy consumption (TFEC) reached approximately 340 exajoules globally (EJ). TFEC includes energy use in end-use sectors from all energy carriers as fuel (for the transport sector) and to generate heat (for industry and building sectors). It also includes consumed electricity and district heat (DH). It excludes non-energy use, which is the use of energy carriers as feedstock to produce chemicals and polymers. In this paper, TFEC includes the energy use of all end-use sectors with the exception of agriculture, forestry, fishing and non-specific which all together account for about 4% of the TFEC worldwide [1]. In the period between 2001 and 2011, TFEC of developing countries grew more than 4% per year while during the same period it remained stable in high-income countries. The main drivers behind the growth in energy use are increasing population and economic growth, which are expected to grow further in developing countries. According to projections of different energy scenarios, global energy demand will grow by another 10%–40% by 2030 compared to today's level (e.g., [1–4]).

There are a number of concerns in view of the continuing energy demand growth. The current energy system relies on fossil fuels (in 2011, 80% came from fossil fuels and 2% from nuclear [1]). With increasing demand, a fossil fuel-based energy system will result in fundamental problems because of rising import dependency and resulting trade imbalances in many countries. Importing countries face supply security and trade balance effects that hamper economic growth. Combustion of fossil fuels results in carbon dioxide (CO_2) emissions. At the beginning of 2014, average concentration of CO_2 in the atmosphere reached 398 parts per million (ppm) and if global energy demand continues to grow according to the baseline, atmospheric concentrations will rise beyond 450 ppm, the widely accepted threshold to keep global temperature change to two degrees Celsius above pre-industrial levels by 2100 [5]. Additionally, fossil fuel combustion is a source of local air pollution.

A renewables-based energy system could relieve many of these concerns. However, only 18% of global TFEC comes from renewable energy (RE) sources. Half is categorized as modern renewable (modern biomass, hydro, solar, wind, geothermal) and the other half is traditional use of biomass for cooking and heating [1]. Today, modern RE use is mainly limited to biomass and hydropower. Traditional use of biomass can be defined in different ways. In this paper, it refers to the total demand for biomass in the residential sector of the non-member countries of the Organization for Economic Co-operation and Development (OECD) and it consists of the use of wood, charcoal, agricultural residues and animal dung for cooking and heating. It is converted to heat with very low conversion efficiency (10% to 20%) and typically relies on unsustainable biomass supply [6]. Traditional use of biomass also often results in deforestation and land soil degradation. In addition, around four million people die each year due to indoor air pollution from traditional use of biomass [7]. Additionally, worldwide, nearly 1.3 billion people lack electricity access today, and 2.6 billion lack access to clean cooking facilities [8,9].

The United Nations General Assembly declared in 2012 the 2014–2024 decade as the "Decade of Sustainable Energy for All". This was accompanied by the launch of the Sustainable Energy for All (SE4All) initiative. SE4ALL brings together governments and the private and public sectors to reach the initiative's three objectives: (i) provide universal energy access; (ii) double the rate of global energy efficiency improvement between 2010 and 2030 compared to the 1990–2010 rate; and (iii) double the RE share in the global energy mix by 2030 compared to 2010 level [10]. The energy efficiency objective translates to 2.6% per year energy intensity improvements between 2010 and 2030, compared to what has been achieved between 2010 and 2030 of 1.3% per year [11]. The renewable energy objective implies a growth in RE share to 30%–36% by 2030 compared to 2010 level of 18% when including traditional use of biomass, or 9% excluding traditional use of biomass [12].

The International Renewable Energy Agency (IRENA) joined the SE4All initiative as the renewable energy hub and, in June 2014, published its renewable energy roadmap—REmap 2030 [12]. REmap is based on a bottom-up analysis of the national energy plans of 26 countries, and explores additional options for RE deployment through the identification of technology pathways for a doubling. The report also discusses how countries can work together to achieve a doubling the global RE share. The 26 countries account for three-quarters of global energy demand and include: Australia, Brazil, Canada, China, Denmark, Ecuador, France, Germany, India, Indonesia, Italy, Japan, Malaysia, Mexico, Morocco, Nigeria, Russia, Saudi Arabia, South Africa, South Korea, Tonga, Turkey, Ukraine, the United Arab Emirates (UAE), the United Kingdom (UK), and the United States (US). With the exception of Brazil, Canada, Indonesia, Morocco, Ukraine, and Russia, all countries are members of IRENA (as of May 2014). The presentation of the results of Tonga is excluded from the rest of this study because of its small share of the global TFEC (<0.01%).

The potential and costs of RE to substitute conventional forms of energy vary by country, sector and technology. While RE is increasingly becoming cost-competitive, some technologies are still more expensive compared to their conventional counterparts, and may still be in 2030. In view of the global landscape described above, the general aim of this paper is the identification of areas in which innovation can assist in achieving a doubling of the global RE share by 2030. Innovation is key to diminish the cost of RE technologies, as well as to enable high levels of deployment. Bringing down the costs of expensive RE technologies and raising the efficiency or performance of others is essential to achieve a global energy system that will rely significantly less on conventional fuels.

The assessment of the RE potential at technology, region and sector level has already been the focus of many studies. Typically, the potential of renewable power generation is dealt with in detail. Various methodology and models are applied for the assessment of RE potential in power generation, for example to fulfill a policy objective at a global, country or region level (e.g., [13–15]). Studies, which assess end-use sectors, focus usually on the transport sector, and less on heating (e.g., [16–19]). Available studies, which analyze all sectors, are either limited to a global perspective (e.g., [20,21]) or the results are aggregated to regions without a specific country scope (e.g., [22–24]). Alternatively analyses can look at the deployment of a specific technology within a country or a region (e.g., [25–27]). Studies that encompass all sector, technology and cost aspects of RE based on a country level are limited.

In comparison to existing analyses, REmap covers all energy supply and end-use sectors. It also uses the national energy plans of individual countries as its starting point. In REmap, RE technology options for power generation, heating and transport are assessed in terms of potential and costs. Incorporating both potential and costs allow these options to be plotted on cost-supply curves by country, sector, technology or for the global situation. This approach provides a robust and transparent methodology for the assessment of strategies for doubling the global RE share. Based on the analysis of 26 REmap countries, REmap shows that doubling by 2030 is technically feasible and cost-effective when externalities are accounted for. Another key finding is that additional RE options exist in all countries, and that innovation will play a key role in deployment. However, innovation needs will be different for each technology, sector and country. Often missing is the link between RE technology potentials and costs and the types of policy intervention that governments can provide to guide innovation.

The general objective of this paper is to identify how innovation can catalyze RE technologies to reach a doubling of the global RE share by 2030 based on REmap's unique country methodology. It does this by attaining three specific objectives, namely by (i) quantifying growth rates for each RE technology by country, resource and sector between 2010 and 2030 within Reference Cases and, according to the results, analyzing the requirements for a doubling; (ii) discussing global TFEC growth if a doubling is reached and the implications in terms of costs, and; (iii) identifying innovation action areas to accelerate renewable energy uptake and improve cost-competitiveness in reaching a doubling, based on findings from the two previous objectives.

In the next section, this paper explains the methodology and provide the data sources. In Section 3, the paper presents the detailed results of the REmap 2030 analysis. In Section 4, the validity of the findings in view of the limitations in the methodology and data choice is discussed. Finally this paper summarizes conclusions and provides recommendations for policy makers, the public and private sectors that show the crucial role of innovation in accelerating renewables uptake in the global energy mix.

2. Methodology and Data Sources

REmap is an analytical approach based on the bottom-up assessment of the national RE plans (referred to as "Reference Case" in the rest of this paper) of 26 countries and additional renewable technology options in 2030 ("REmap Options"). For each country analysis, IRENA worked with REmap experts nominated by the respective country. We describe each step of the REmap country analysis methodology (see also Figure 1), which was applied to prepare this roadmap below:

(i) As a starting point, we developed a Reference Case for each country, which represents policies in place or under consideration. The Reference Case also includes any expected developments in energy efficiency improvement. The analysis starts with a base year of 2010 and we collected the most up-to-date national plans of each country with a time horizon of 2030. These plans include a breakdown by energy carriers for the transformation (power and DH) and end-use sectors. However, the availability of country data varies, hence we filled data gaps. If no energy plan was available, IRENA worked with the REmap experts in developing a Reference Case (see Annex for an overview). We also completed any missing datasets, for instance for end-use sector demand, with information from literature and commercial databases. In collecting data from 26 countries, we harmonized the data in terms of the energy units expressed (final energy in petajoules (PJ) per year) and the system boundary of the end-use sectors.

(ii) In a subsequent step, we investigated the REmap Options in each country together with the national experts. REmap Options are technology opportunities to replace conventional energy technologies (fossil fuel, nuclear and traditional biomass) present in 2030 with RE technologies (biomass, solar, wind, hydro, geothermal and ocean). The choice for the options approach is different than a scenario analysis since REmap is an exploratory study, and not a target-setting exercise. Each REmap Option is expressed in PJ final renewable energy per year and includes an associated substitution cost (in real 2010 US Dollars (USD) per gigajoule (GJ) final renewable energy). We collected our own data and combined this with the insights national experts provided about the technical, economic and political feasibility of different pathways to 2030. Once the REmap Options were estimated, a conventional technology that needs to be substituted is selected with additional input from national experts. This is based on the policy choices of the countries.

(iii) After the data collection step was completed, we included the REmap Options in the Reference Case, which resulted in a "REmap 2030 Case" for each country. We shared results with the countries for final review and subsequently updated them if necessary. Once the REmap 2030 results were agreed on with the countries, we aggregated and extrapolated the 26 country findings to arrive at the global potential.

We developed a spreadsheet tool to support the REmap methodology with a relatively simple accounting framework. Our aim is not to apply complex models or sophisticated tools to assess the potential, but to facilitate an open framework with countries to aggregate the national renewable energy plans, Reference Case and REmap Options. The tool allows national experts and other users to develop their own REmap 2030 analysis and it is consistent with each step of the REmap methodology. However, inter-temporal dynamics and inertia that determine deployment, system constraints, path dependencies, competition for resources, *etc.*, are not explicitly taken into account.

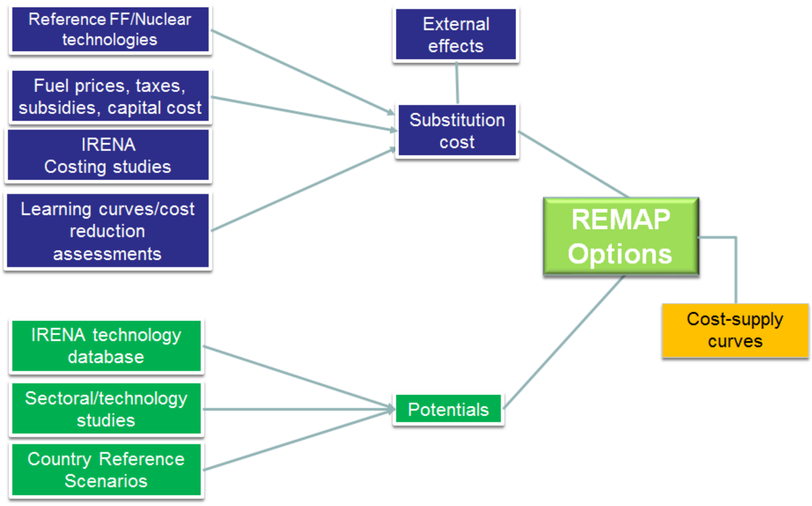

Figure 1. Steps in REmap country analysis and preparation of the roadmap. Source: [12].

As a next step, we developed indicators that reflect the governmental intervention needed to guide innovation policy based on the readiness of each technology, infrastructure requirements to install additional RE capacity and how to address the uncertainty inherently bounded to an energy system in transition. This information indicates different aspects where innovation can play a role for RE deployment at country, sector and technology level and all indicators are based on REmap findings. These indicators are the following:

(i) Growth in RE use in TFEC (PJ/year) and technology capacity (indicator 1): We estimate the total consumption of each resource (e.g., liquid biofuels, geothermal heat) or the total installed capacity (e.g., gigawatt (GW) wind power plant, or million square meters (m^2) of solar thermal) for the years 2000, 2010, and 2030, and compare this to 2010 level. This indicator represents the scale of the deployment challenge for renewables, including potential barriers in scale-up of production, supply chains, and capacity for installation and maintenance. This indicator provides information about the policy required to overcome technological challenges, according to readiness of each technology, if the full deployment of the 2030 potential is targeted.

(ii) RE share (in %) (indicator 2): We estimate the RE share separately for end-use (buildings, transport and industry) and generation sectors (in addition to the power sector, we also estimated the RE share for the DH sector. However, given the size of the sector relative to others, it is not discussed in further detail in the rest of this paper). For the end-use sectors, we add up the total RE use by all energy carriers and the share of electricity and DH consumption originating from RE to estimate each sector's total RE use. We divide this total by that sector's TFEC to arrive at the sector RE share. We also estimate this indicator by excluding all DH and electricity use, both from RE use and the TFEC (both RE share indicators, with and without electricity and DH, could also be estimated for the TFEC of the entire country by adding up the three end-use sectors). For the power sector, we compare the total power generation from renewables and divide this by the total power generation from all energy carriers in the sector in that country. We estimate all RE share indicators for 2010 and separately for Reference Case in 2030 and REmap 2030. This indicator represents the penetration level of renewables, and as such the level of change required in the energy system. Higher penetration levels will require different system adjustments to support renewables-based energy systems. This information indicates the innovation requirement and adjustments needed in current infrastructure and energy system (manufacturers, component suppliers, installers, and support services). These requirements have to accompany the increase in the RE share [28] estimated between 2010 and 2030.

(iii) Substitution cost (in USD/GJ) (indicator 3): This is the key indicator to estimate the cost-effectiveness of renewable energy technologies. It represents the difference between the annualized costs of the REmap Options and a conventional technology used to generate the same amount of useful energy output (e.g., cooking heat, electricity, mechanical work) divided by the total renewable energy use in final energy terms. Negative substitution costs suggest that there are opportunities to save money, whilst positive substitution costs suggest that additional efforts will be needed to attract the investments required to achieve the targeted deployment levels. This indicator represents the challenges associated with the need to attract innovation investments. A thorough consultation with experts complements the estimates of substitution costs and reduces the uncertainty in the estimates. By doing so, substitution costs can guide both investors and policy-makers on innovation investment opportunities arising in certain technology and sectors, as well as the efforts required to expand the funding portfolio within certain other innovative technological fields.

Estimation of the substitution costs starts with the analysis of the generation cost of useful energy output ($COE_{i,x}$, in USD/GJ) for renewable energy technology i in country x in year 2030 according to Equation (1):

$$COE_{i,x} = \frac{\left(\propto * I_{i,x} + O\&M_{i,x} + F_x\right)}{E_x} \tag{1}$$

where α is the annuity factor in years^{-1} (estimated as $r_x/(1-(1+r_x)^{-L}$; r_x is the discount rate (in %) and L is the economic lifetime of technology i (in years)); $I_{i,t}$ is the overnight capital cost of renewable energy technology i in country x in 2030 for a reference capacity (in million USD); $O\&M_{i,x}$ is the annual operation and maintenance (O&M) costs of renewable energy technology i in country x (in USD/year) and F_x is the annual energy cost of renewable energy technology (fuel and electricity consumption) (in USD/year) to generate E_x useful energy output (in GJ/year).

All capital and O&M costs refer to the 2030 level, thereby taking into account learning effects. We estimate substitution costs based on a discount rate of 10% with international energy prices that exclude subsidy and taxes (see Annex). This approach is similar to how governments would calculate the costs without the effects of policy choices regarding taxation or subsidy, and it allows comparable results across countries. The 10% discount rate is chosen as an average of what is seen between developing countries and economies in transition (15%–25%) and industrialized economies (3%–15%). Growth of fossil fuel prices between 2010 and 2030 are estimated based on the International Energy Agency (IEA) [29] whereas the biomass supply costs are estimates based on IRENA's country analysis of biomass supply and its costs [30].

The difference between the generation cost of renewable energy technology i in country x relative to the generation cost of the substituted conventional technology yields the cost of renewable energy technology to deliver the same amount of useful energy. In a subsequent step, we expressed this cost in final renewable energy terms by taking into account the conversion efficiency of each renewable energy technology i in country x in the year 2030 to estimate their substitution costs ($SC_{i,x}$ in USD/GJ). The product of the substitution cost and the potential of the REmap Option in country x ($P_{i,x}$ in PJ/year) yields the total incremental cost of that renewable energy technology (in million USD/year). According to Equation (2), when the total cost of n renewable energy technologies deployed in country x are aggregated, total incremental system costs in 2030 of that country (TSC_x) are estimated:

$$TSC_x = \sum_{i=1}^{n} \left(SC_{i.x} \times P_{i,x}\right) \quad (2)$$

Total incremental system costs of countries can also be expressed at sector level by aggregating the total costs of technologies deployed in that sector. As a final step, we aggregate the total incremental system costs of all countries to estimate the cost implications of doubling the RE share in the global energy mix by 2030. Incremental system costs, however, do not include the costs of complementary infrastructure, such as grid integration (e.g., [31,32]).

3. Results

In this section, we present REmap 2030 results by country (Section 3.1) and technology (Section 3.2) and continue with presenting the results at sector level (Section 3.3). In Section 3.4, we focus on the costs by sector and technology. In Section 3.5, we identify action areas for innovation, which can enable cost reductions and accelerate the global deployment of RE technologies.

3.1. Findings at Country-Level

Figure 2 shows RE share in the TFEC of countries in 2010 (black boxes) and in 2030, for the Reference Case (grey filled circles) and REmap 2030 (white filled diamonds) (refers to indicator 2). The vertical lines indicate the RE share worldwide. The RE share worldwide increases from 18% in

2010 to 21% in 2030 according to the Reference Case (including traditional use of biomass). Implementing all REmap Options result in 30% RE share by 2030.

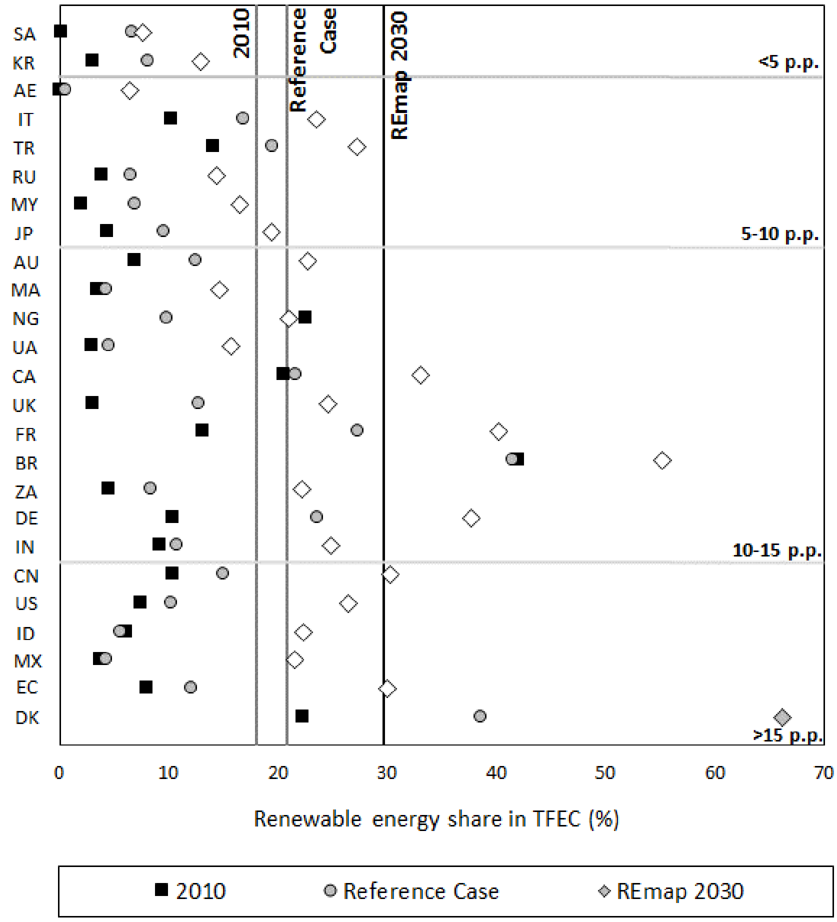

Figure 2. RE share of REmap countries in 2010, and for the Reference Case and for REmap Options in 2030. Vertical lines indicate the global RE share in 2010 and in 2030 Reference Case (grey lines) and REmap 2030 (black line). Areas between the horizontal lines represent the categories of growth in RE share between 2030 Reference Case and REmap 2030 (in percentage points, p.p.). Countries are abbreviated as follows: Australia (AU), Brazil (BR), Canada (CA), China (CN), Denmark (DK), Ecuador (EC), France (FR), Germany (DE), India (IN), Indonesia (ID), Italy (IT), Japan (JP), Malaysia (MY), Mexico (MX), Morocco (MA), Nigeria (NG), Russia (RU), Saudi Arabia (SA), South Africa (ZA), South Korea (KR), Turkey (TR), Ukraine (UA), United Arab Emirates (AE), United Kingdom (UK), and United States (US).

In Figure 2, we rank the countries by the increase in their RE shares between the Reference Case and REmap 2030 (in percentage points). We discuss the main findings below:

- Four countries of the European Union (EU) with high RE shares in 2010, namely Denmark, France, Germany and the UK, increase their shares the most by at least 10 percentage points between 2010 and the Reference Case. In 2030, these countries reach between 13% (UK) and 39% (Denmark) RE share. France and Germany more than double their shares, and the UK triples it (we assessed the RE shares for the Reference Case for France and the UK based on their 2020 RE commitments according to their national renewable energy action plans (NREAP) [33]. We included no further deployment of RE between 2020 and 2030; however, any improvements in energy efficiency were taken into account. Denmark and Germany have targets for 2030 which take their renewable energy share in the 2030 Reference Case higher than the 2020 targets according to their NREAPs).

- In 2010, 16 other countries have RE shares ranging from 0% to 10%. Given the very low starting points of some of them, the growth in Reference Case takes the RE shares to between 1% (UAE) and 13% (Australia) only. This is much lower than the global average of 18% today and efforts in national plans of these countries to 2030 are lower compared to EU countries. This is mainly an outcome of the differences in the existing policies and target setting approach between the EU countries and the rest of the world. In addition, the TFEC growth in the EU is low which helps achieving higher RE shares.
- We estimate a decrease in the RE shares between 2010 and Reference Case for Brazil (42%), Indonesia (6%), and Nigeria (23%). Brazil and Indonesia start at high RE share levels due to large amount of biomass use. The decrease in RE share is a result of the substitution of the traditional use of biomass with modern forms of renewables in the Reference Case. Traditional uses of biomass are characterized by inefficient combustion, therefore, more energy input is required than with a modern form of RE.
- Compared to the Reference Case, most countries have a potential to more than double their RE shares in REmap 2030. For example China, Ecuador, India, Indonesia, Mexico and the US increase their RE shares by at least 15 percentage points between the Reference Case and REmap 2030 (see the bottom category in Figure 2). In other countries, we estimate potential to increase the RE shares by between 10 and 27 percentage points. The large increase in RE share beyond Reference Case indicates that the potential of renewables may not be fully considered by countries. The increase in RE shares in the UAE, Malaysia, Russia, South Korea or Saudi Arabia is among the lowest, but this is also explained by their very low starting points today.

We find that opportunities to increase the RE share beyond the Reference Case exist in all countries. However, as the comparison shows most countries are just starting with their transition to renewable energy. Most Reference Cases would result in a slow adoption to higher RE shares despite considerable additional potential shown in REmap. However the national plans of a few countries could already result in high RE shares. One example is Denmark, where the entire energy system of the country is being transformed. Despite the differences in deployment and potential across countries, each region will have a role to play in raising the global RE share.

Table 1 shows the RE use between 2010 and 2030 by country (refers to indicator 1). China, the US, Brazil, India, and Indonesia account for half of the global RE use in REmap 2030. France or Denmark, despite having high RE shares (>40%), contribute less than 2% to the global RE use due to their relatively small energy consumption.

Table 1. RE use by country in 2010, for the Reference Case and REmap in 2030, and their corresponding contributions to the global RE use and shares in 2030.

Country	2010	Reference Case	REmap 2030	Contribution to global RE use 2030	RE share in REmap 2030
	(PJ/year)	(PJ/year)	(PJ/year)	(%)	(%)
China	12.2	14.0	26.7	20.2	30.2
US	4.9	6.9	17.6	13.3	26.4
Brazil	4.1	7.2	9.4	7.2	55.1
India	7.6	3.3	7.3	5.6	24.8
Indonesia	1.6	0.9	3.6	2.7	22.3
Canada	1.8	2.2	3.4	2.5	33.0
Russia	0.8	1.3	2.9	2.2	14.4
Germany	1.0	1.5	2.4	1.8	37.7
Japan	0.6	1.1	2.2	1.7	19.4
France	0.8	1.4	2.0	1.5	40.2
Mexico	0.5	0.3	1.7	1.3	21.5
Turkey	0.4	1.2	1.7	1.3	27.2
Nigeria	3.8	0.7	1.4	1.0	21.0
United Kingdom	0.2	0.7	1.2	0.9	24.5
Italy	0.5	0.8	1.2	0.9	23.5
Australia	0.3	0.6	1.0	0.8	22.7
South Korea	0.2	0.6	0.9	0.7	12.9
South Africa	0.3	0.3	0.8	0.6	22.2
Ukraine	0.1	0.2	0.6	0.5	15.7
Malaysia	0.1	0.2	0.4	0.3	16.5
Denmark	0.1	0.2	0.4	0.3	66.1
Saudi Arabia	0.0	0.3	0.4	0.3	7.7
UAE	0.0	0.0	0.3	0.2	6.4
Morocco	0.1	0.0	0.2	0.1	14.6
Ecuador	0.1	0.1	0.1	0.1	29.9
Other	21.0	46.8	41.9	32.1	30.0
World	62.9	93.0	131.5	100	29.9

3.2. Findings for Technologies

Table 2 shows the estimated growth in RE technologies between 2010 and 2030, including REmap Options (refers to indicator 1). Traditional use of biomass for cooking and heating in the residential sector of developing countries accounted for half of the global RE use in 2010 (32 EJ, 9.1% of TFEC), followed by biomass heating in buildings and industry (15 EJ, 4.3%). Hydroelectricity has a total share of 2.7% in TFEC. The share of renewable technologies in TFEC between 2010 and REmap 2030 increases by a factor of between two to eight times. One exception is hydroelectricity, which is the largest non-biomass RE technology today and already growing in large volume in the Reference Case. We estimate that by far the largest growth will be seen in power generation technologies, namely concentrated solar power (CSP), solar photovoltaic (PV) and wind. The share of solar PV grows by nearly 40 times and that of wind by about 10 times.

As a result of the significant growth in power generation technologies, the share of RE use in TFEC from power consumption increases from 3.4% in 2010 to 10.8% in REmap 2030 (from 11.5 EJ/year to 53 EJ/year RE power use). In comparison, the growth in the share of RE use in TFEC from end-use increases only slightly from 15.4% to 17.8% in REmap 2030 (from 51.5 EJ/year to 78.5 EJ/year). The rather slow growth in end-use sectors is due to substitution of traditional use of biomass with modern renewables, which are at minimum twice as much efficient, therefore requiring less biomass fuel. Biomass technologies for heating, cooking and transport would account for 15% of the global TFEC in 2030, which is similar to 2010 level. The share of biogas for heating, and the share of solid biofuels for industry show the largest increase. The share of liquid biofuels in TFEC would grow from 0.7% in 2010 to 3.5% in 2030. The share of solar thermal heating increases from 0.4% in 2010 to 2.5% in 2030.

Table 2. Global RE use of technologies and their contribution to the TFEC in 2010, and for the Reference Case and REmap Options in 2030.

	2010	Reference Case 2030	REmap 2030	RE share in TFEC		
				2010	Reference Case 2030	REmap 2030
	(PJ/year)	(PJ/year)	(PJ/year)	(%)	(%)	(%)
End-use sectors:	51.5	63.2	78.5	14.7	13.4	17.8
Modern biomass replacing traditional biomass			12.2			3.0
Traditional biomass	31.9	28.8	0	9.1	6.5	0.0
Biomass heat industry	7.3	12.1	20.7	2.1	2.7	4.7
Biomass heat/DH buildings	7.6	8.4	13.5	2.2	1.9	3.1
Biogas industry/buildings	0.4	1.9	2.1	0.1	0.4	0.5
Geothermal heat	0.2	0.9	1.3	0.1	0.2	0.3
Solar thermal heat	1.4	4.7	11.2	0.4	1.1	2.5
Biofuels transport	2.6	6.5	16.2	0.7	1.5	3.5
Electromobility (using renewable electricity)			1.3			0.3
Power sector:	11.5	29.8	53	3.3	6.7	12.0
Biogas power	0.1	0.5	1.0	0	0.1	0.2
Biomass power	0.9	3.7	7.1	0.3	0.8	1.6
Hydroelectricity	9.3	16.7	18.2	2.7	3.8	4.1
Wind	0.9	5.6	17.0	0.3	1.3	3.9
Solar PV	0.1	1.9	5.8	0	0.4	1.3
CSP	0	0.5	0.9	0	0.1	0.2
Geothermal power	0.1	0.9	1.7	0	0.2	0.4
Other			1.3			0.3
Total	62.9	93.0	131.5	18.0	21.0	29.9

3.3. Findings at Sector-Level

We present in Table 3 the RE shares in generation sectors and in TFEC of end-use sectors (industry, buildings and transport) for the world as a whole (refers to indicator 2). Table 3 shows two rows of data for each end-use sector, one including the shares of electricity and DH consumption originating from RE sources, and one excluding these quantities, thereby including only RE heat/fuel consumption for end-uses.

Table 3. RE generation and RE use in end-use sectors, in 2010 and for the Reference Case and REmap in 2030 (in absolute values and shares).

Sector		2010	Reference Case 2030	REmap 2030	RE use in REmap 2030			
					Modern biomass		Other renewables	Total (modern)
					Replacing traditional biomass	Other		
		(%)	(%)	(%)	(EJ/year)	(EJ/year)	(EJ/year)	(EJ/year)
Industry	Heat	8	9	19	N/A	21	3	24
	Heat, electricity and DH	11	15	26		26	25	51
Buildings	Heat	12	16	35	12	14	9	35
	Heat, electricity and DH	14	20	38		18	35	65
Transport	Fuels	3	5	15	N/A	16	0	16
	Fuels and electricity	3	6	17		16	0	16
Electricity generation		18	26	44	N/A	10	52	62
DH generation		4	14	27	N/A	2	0.2	2.2
Total		18	21	30	12	60	60	132

According to Figure 3, we estimate in REmap 2030 that renewable power consumption accounts for 36% of the total global RE use whereas end-use sectors account for 64% (including traditional use of biomass). When modern renewables are considered only, the share of power and the end-use sectors in total global RE are 40% and 60%, respectively.

The building, industry and power sectors start at similar levels (11% to 18%) (end-use sectors including renewable electricity and DH consumption). We estimate nearly a tripling of the modern RE share of the global building sector from 14% in 2010 to 38% in REmap 2030 whereas the RE share grows to 20% only in Reference Case. The magnitude of increase is similar in the industry and power sectors in REmap 2030, from 11% to 26% and from 18% to 44%, respectively. Compared to all other sectors, the transport sector reaches only 17% in REmap 2030 (including renewable electricity consumption), but starting from a low RE share of 3% in 2010, thereby representing some of the largest growth among the five sectors.

We find a major difference in the RE share of the industry sector when renewable electricity and DH uses are included, estimated at 26% in REmap 2030—or seven percentage points higher compared to the case where they are excluded (19%). This highlights the importance of electrification and thereby the need for innovation for the development of electricity-based process heat technologies coupled with renewable power generation (we estimate an electricity use share of 42%, 28%, and 4% in the TFEC of building, industry and transport sector sectors, respectively. DH accounts for about 5% and 3% of the industry and building sector TFEC, respectively). In contrast, we estimate only two to three percentage points of increase in the share of renewables in transport and building sectors when renewable electricity and DH uses are included. This is explained by the small share of electricity use in TFEC of 4% in the transport sector as well as the high efficiency of electric vehicles (EVs) compared to internal combustion engines (ICEs). In the building sector, the RE share is already high and close to that of the power sector, hence the effect is small.

According to Table 3, 80% of the total RE use in end-use sectors is from modern biomass. While biomass makes up all renewables in the transport sector, we estimate that 30% and 13% of the total renewables use is from other sources (solar thermal and geothermal) in the building and industry sectors, respectively.

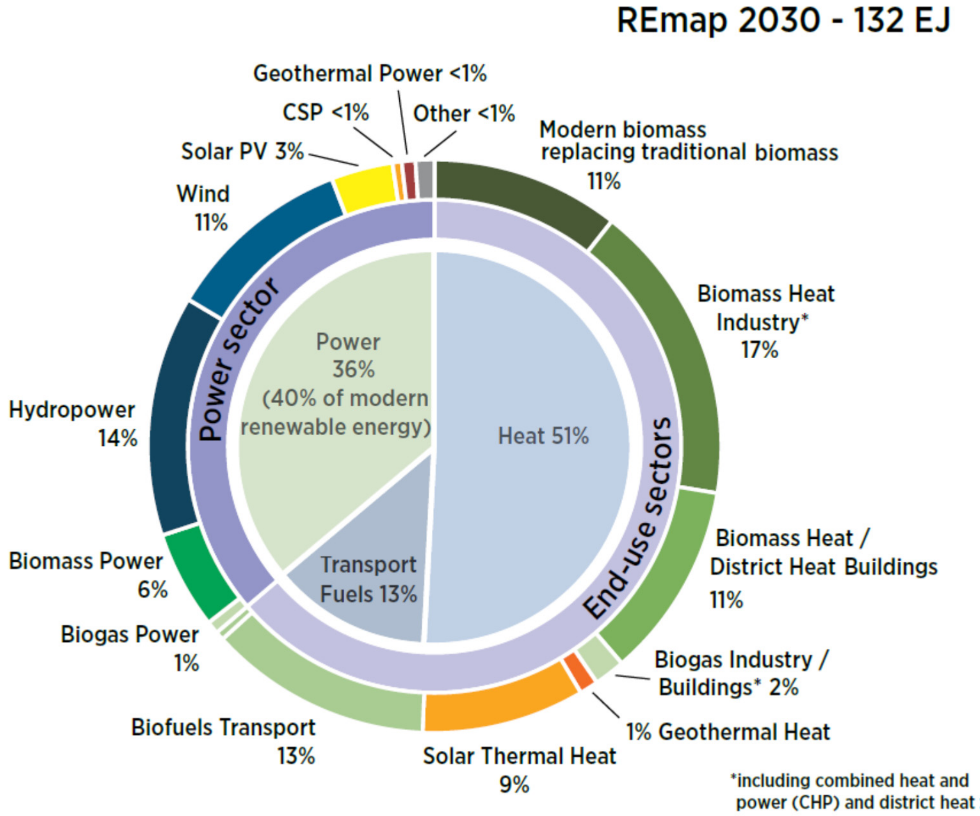

Figure 3. Breakdown of global renewable energy use in 2030 for REmap. Source: [12].

3.4. REmap 2030 Costs

We show in Figure 4 the global cost-supply curve of REmap Options in 2030. The horizontal bar to the far left shows the growth of modern renewables in the Reference Case, which rises from around 9% in 2010 to around 14% in 2030 (we did not estimate the substitution costs for the Reference Case assuming that the growth is assumed to take place). The green areas in the Reference Case indicate biomass, which accounts for about half of the uptake. The other half consists of power sector options: hydro and wind, followed by solar as well as solar thermal heating in buildings [12].

Based on the analysis of 26 REmap countries, the REmap Options raise the share of modern RE in global TFEC from around 14% to around 27% (upper x-axis). REmap Options have substitution costs ranging from negative (savings) to more costly options (refers to indicator 3). The area between the curve and x-axis is a measure of the net annualized cost in 2030. Net annualized costs divided by total final RE use yields an average cost of substitution for the total of REmap Options of approximately USD 2.5 per GJ. Therefore, showing that cost savings offset much of the cost increases.

The figure also shows the contribution of modern energy access (blue arrow on the far right). When we also account for the substitution of traditional uses of biomass outside the 26 REmap countries (largely in Africa), the global RE share increases from 27% to 30%. Finally, higher rates of energy intensity improvements raises the RE share further to over 34%. This is because the same amount of RE covers a larger share of demand (represented in the lower x-axis in the figure). Reaching a doubling of the RE share in the global energy mix requires a combined approach to develop different technologies for renewables, energy efficiency and modern energy access. The outcome also suggests that the share of renewables can be doubled with only limited additional costs [12].

The cost curve does not imply that options should be implemented starting from left to right based on the order of costs. There are interactions among options, and all options need to be implemented together to achieve a doubling at the estimated level of substitution costs [12]. Options on the right side of the curve have higher substitution costs. Implementing these technologies, however, does not mean that the potential of REmap Options with lower costs are all utilized, or that only the potential of REmap Options with high substitution costs remain for implementation. This outcome points to the fact that some countries with very high resource potential either have few policies in place to utilize that potential at low cost, or leave deployment to the market only and other countries that already have a high RE share appear content with it and see less need to proceed further [12].

Figure 4 gives a global perspective of the REmap Options for the purpose of demonstration. In reality deployment will be done at a country level and at that level, there is a high viability of the substitution cost of the REmap Options. As explained in Reference [12], for individual countries, the shape of the cost curves and technology rankings differ depending on resource availability, capacity factors and the conventional technologies substituted. Substitution costs also change whether tax and subsidies are included and when external effects are internalized in fossil fuel prices. Furthermore when countries are ranked on cost-supply curves position of countries would change for each technology [12].

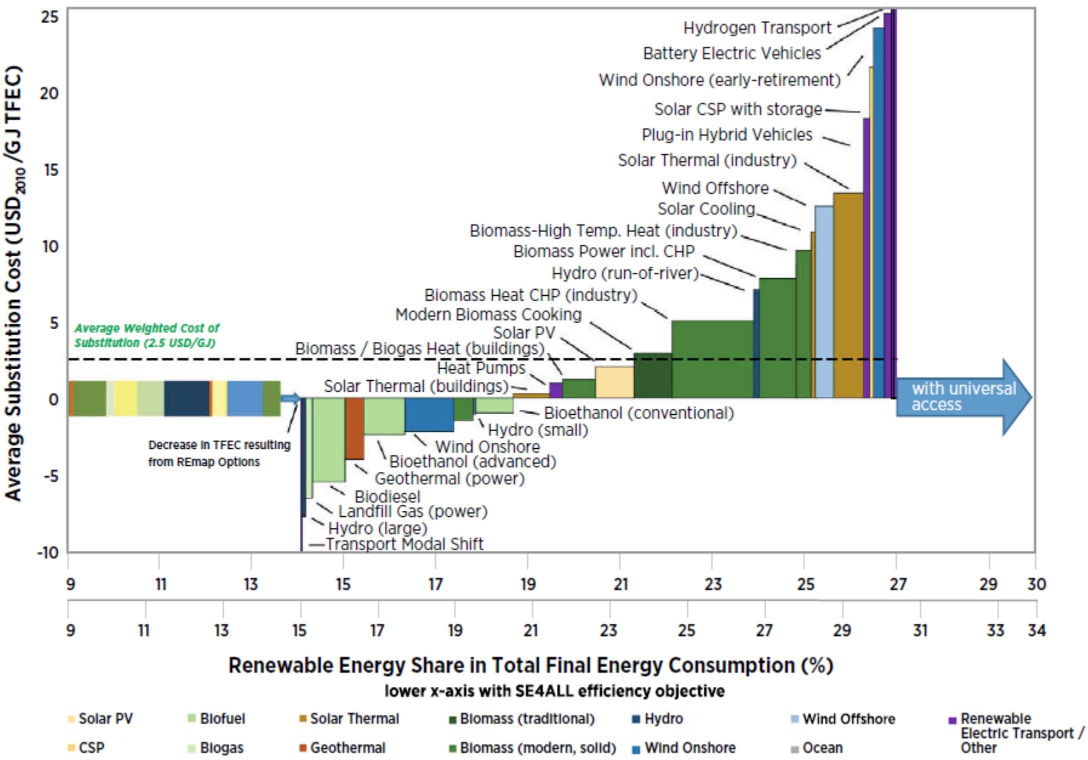

Figure 4. Global cost-supply curve of REmap Options in year 2030. Source: [12].

Based on country data, we find that the costs of individual technologies range +/− USD 10 per GJ around the average value (see Figure 5). Figure 5 indicates that although the weighted average substitution costs of some technologies are positive worldwide, attractive market options exist in certain countries where substitution cost turns negative. This is an important finding suggesting that national plans should also include the potential of these REmap Options [12].

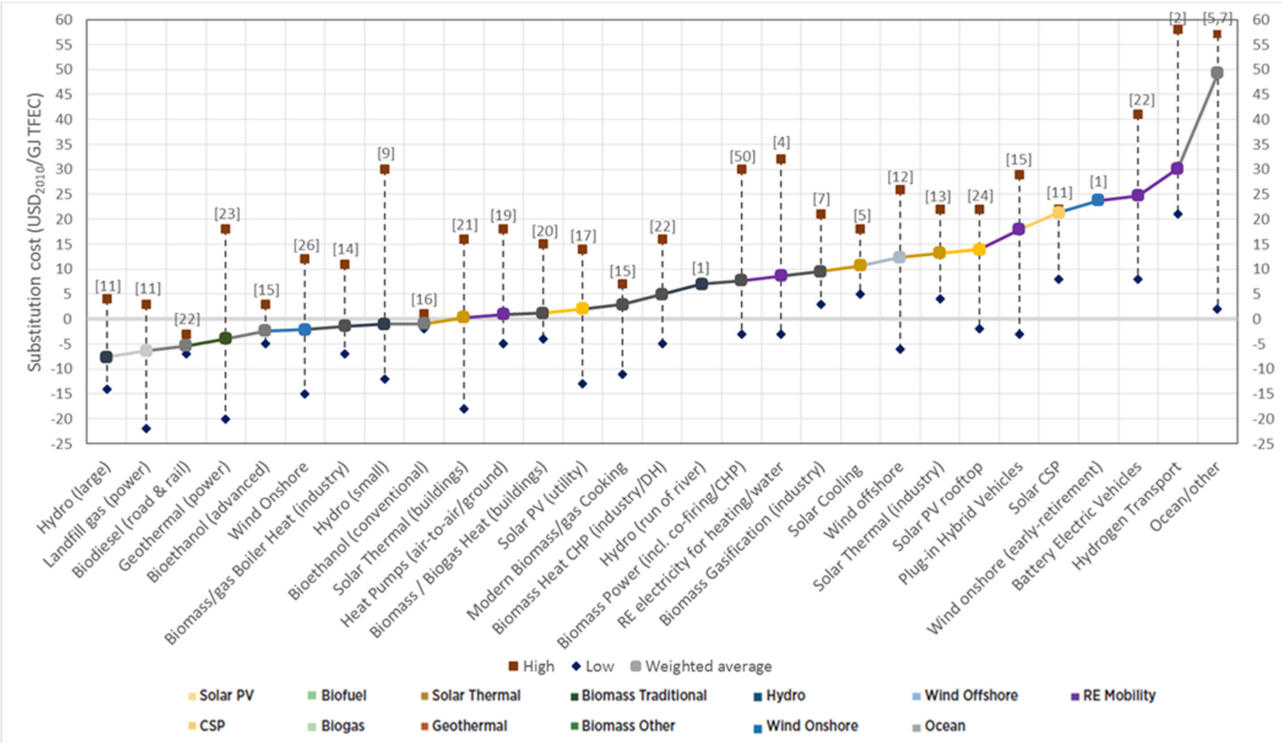

Figure 5. Global average ranges on substitution costs based on the costs differences of REmap countries in 2030. Source: [12]. Dots indicate the weighted average of all countries where different technologies are assumed to be implemented (all indicated with a separate color). The substitution costs of technologies are consistent with the bars shown in Figure 4. Values in brackets show the number of countries that implement that REmap Option. Since some technologies are grouped together (e.g., biomass power from co-firing, CHP, *etc.*), the value provided in brackets is higher than the number of 26 countries analyzed.

We estimate the average cost of the portfolio of REmap Options in the industry and building sectors as USD 5 and USD 1.6 per GJ, respectively (see Table 4). The average cost of substituting fossil fuel use in the transport sector comes at savings of USD—4.1 per GJ. In the electricity and DH sectors, the substitution costs are estimated to be between USD 5 and USD 6 per GJ. From a cost perspective, REmap Options in the transport and building sectors offer the highest economic viability, but the magnitude of their REmap Options are lower there compared to others, 12 EJ and 10 EJ, respectively. By contrast, more RE could be deployed beyond the Reference Case in the industry (13 EJ) and power (16 EJ) sectors, but this would come at a higher cost of substitution.

Table 4 also shows the total energy system costs to double the share of renewables. Worldwide, we estimate total system costs of USD 133 billion per year in 2030. More than half of this is related to power generation (USD 88 billion per year), whereas the transport sector results in savings of nearly USD 50 billion per year. Total system costs are modest compared to total global investment activity of USD 15.5 trillion per year [34] or to 2012 total global investments in RE of USD 244 billion per year [35]. These costs would, however, be much higher if costs related to infrastructure such as grids, transmission lines, biofuel plants and recharging stations are also included. In comparison, Table 4 also shows that the REmap Options can result in substantial savings if externalities related to human health and CO_2 emissions from the use of fossil fuels and traditional biomass are accounted for. Total system costs can be reduced from USD 133 to a range of between USD −123 and USD −738 billion per year in 2030. Externalities related to human health represent about 30%–40% of this total (USD 102–271 billion per year). The remainder 60%–70% (USD 154–600 billion per year) is externalities related to CO_2 emissions. Doubling the share of renewables in the global energy mix by 2030 would be economically feasible when these externalities are taken into account.

Table 4. Global average substitution costs of REmap Options in 2030 with a breakdown by sector.

Sector	Substitution costs (USD/GJ)	REmap Options (EJ/year)	Total system costs (USD billion/year)
Industry	5	12.7	63.7
Buildings	1.6	10.2	16.3
Transport	−4.1	12.0	−49.2
Power generation	5.7	15.5	88.4
DH	5.3	2.5	13.2
Total [1]	2.5	53.0	133.0
Total after accounting for externalities [1]	−13.8–−2.3		−123.0–−738.0
With human health only [2]	−2.6–0.6		31.2–−137.8
With CO_2 emissions only [3]	−8.7–−0.4		−21.2–−467.1

[1] We estimate the total by adding the total savings from externalities related to human health and CO_2 emissions. [2] The estimate includes externalities related to outdoor and indoor air pollution from sulfur dioxide (SO_2), mono-nitrogen oxide (NO_x) and particulate matter ($PM_{2.5}$) emissions from fossil fuel-based power plant operation, outdoor emissions of NO_x and $PM_{2.5}$ from road vehicles and indoor emissions $PM_{2.5}$ from biomass and coal combustion in the residential sector. The ranges for unit external costs are large and depend on the type of conventional fuel and region [12].) [3] USD 20–80 per ton CO_2 [12].

3.5. REmap 2030 Action Areas

In Table 5, we present the results of indicators 1 to 3 at a global level (deployment needs and penetration rates between 2012 and REmap 2030 and substitution costs in 2030, based on Figure 4) for each technology analyzed. Each indicator reflects different innovation policy needs to: (i) face challenges for further RE deployment according to readiness of the technologies; (ii) support the necessary changes in the infrastructure and the industrial system; and (iii) attract funding and capital investment into technologies with highest substitutions costs. For each indicator, we suggest a number of actions to accelerate deployment of each technology, represented by the compound annual growth rates (indicator 1), which is directly related to the support needed for a system transition towards renewables (indicator 2), and to improve cost-competitiveness (indicator 3). In this table, the technologies are grouped by sector, power, heating/cooling and transport.

In the power sector (first group of technologies in Table 5, in GW installed capacity), we estimate a total of 50–60 GW per year growth for solar PV and wind onshore capacity combined (respectively, 9%–15% annual growth in the 2012–2030 period) (we choose to present the capacity data for the year

2012 instead of the base year 2010 to capture the most recent developments in technology deployment). Total growth in wind offshore and CSP is lower, estimated at 13–17 GW/year. In terms of compound annual growth, growth in wind offshore and CSP equates more than 20% per year between 2012 and 2030. This is explained by today's low installed capacity for wind offshore and CSP. We estimate a much higher growth for hydropower capacity of more than 30 GW/year.

In terms of the share in total installed power generation capacity, solar PV and wind onshore/offshore would account for 12.6% and 16.1%, respectively, by 2030. This is in total 28.7% and by a factor four higher than the 2012 level of 7%. The share of hydropower would decrease by about one percentage point only.

Compared to the capacity deployment according to the Reference Case, there is an additional potential of 10%–40% for hydropower, wind onshore and CSP if all REmap Options are implemented worldwide. We find that in REmap 2030 wind offshore, solar PV, geothermal and ocean thermal energy conversion (OTEC) technologies have a potential to reach three times more than the capacity seen in the Reference Case. This highlights that utilizing the realizable potential of these technologies beyond the Reference Case will require further efforts.

The table also shows the compound annual growth rates between 2000 and 2012. Hydropower had the lowest growth among all renewable power technologies at 3%/year. It is estimated that the global installed capacity will continue to grow at similar rates between 2010 and 2030. In the case of solar PV and wind onshore, the growth between 2010 and REmap 2030 (9%–15%/year) is lower than historical developments (23%–26%/year). However, the absolute growth in the capacity is still substantial with solar PV increasing by 10 times in 2030 compared to today's levels and wind onshore by five times. Solar CSP and geothermal power technologies would need to triple their annual rate of capacity growth in 2012–2030 compared to 2000–2012. In the next two decades, solar CSP and wind offshore would need to repeat, what solar PV and wind onshore had experienced in 2000–2012 in terms of annual capacity growth.

The second part of the table shows the growth in various biomass technologies for heating and as liquid biofuel (in EJ/year consumption). We estimate that total demand for biomass more than doubles from 51 EJ/year in 2012 to 108 EJ/year in 2030 in primary energy terms for different applications (including 12 EJ of non-substituted traditional use of biomass). This implies a doubling in biomass use in the total primary energy supply, from 10% in 2012 to 20% in 2030. This translates to a total RE consumption of 78 EJ in power and heat generation or as fuel for the transport sector. Total biomass use would account for nearly 60% of the total global RE use in REmap 2030 (132 EJ) or approximately 18% of the TFEC in REmap 2030 (445 EJ) (108 EJ is the total demand for biomass as raw material before the first conversion to any commercial biomass product, e.g., power, wood pellets, and liquid biofuels). In comparison, 78 EJ is the total final consumption of biomass products.

Table 5. Global installed capacity, deployment expressed as compound annual growth rate and penetration level between 2012 and REmap 2030, substitution costs of RE technologies in year 2030 and identified action areas for deployment, system change and cost-competitiveness.

Technology	Units	2012	REmap 2030	CAGR (Indicator 1)		Penetration level (Indicator 2)		Action areas for deployment and system change (for Indicators 1 and 2)	2030 substitution costs (Indicator 3)	Action areas for cost-competitiveness (for Indicator 3)
				2000–2012 (%/year)	2012-REmap 2030 (%/year)	2012 (%)	REmap 2030 (%)		(USD/GJ)	
Power generation technologies [1]:										
Hydropower (excl. pumped storage)	[GW]	1004	1,601	3	3	18.2	17.1	Retrofitting dams with turbines Focus on micro/small hydropower	−7.6	- -
Pumped hydro	[GW]	150	325	N/A	4	2.7	3.5	Recognize its role as energy storage technology	N/A	-
Wind onshore	[GW]	283	1266	26	9	5.1	13.5	Improved wind forecasting; grid integration	−2.6	Higher turbine efficiency
Wind offshore	[GW]	6	240	N/A	23	0.1	2.6	Balance between high potential wind resource area and generation costs; shortages of skilled labor force and more learning experiences	12.3	Balance between high potential wind resource area and generation costs; minimize material requirements (e.g., copper, steel); increase component recycling
Solar PV	[GW]	100	1,180	23	15	1.8	12.6	-	2 (utility), 13.9 (rooftop)	Higher efficiency with focus on solar cell and material technologies
CSP	[GW]	3	83	8	22	0.1	0.9	High temperature steam for advanced turbines; combination with desalination; energy storage	21.3	Development of alternative heat transfer fluids; new receivers, reflector and material designs

Table 5. *Cont.*

Technology	Units	2012	REmap 2030	CAGR (Indicator 1)		Penetration level (Indicator 2)		Action areas for deployment and system change (for Indicators 1 and 2)	2030 substitution costs (Indicator 3)	Action areas for cost-competitiveness (for Indicator 3)
				2000–2012	2012-REmap 2030	2012	REmap 2030			
				(%/year)	(%/year)	(%)	(%)		(USD/GJ)	
Power generation technologies [1]:										
Biomass power	[GW]	83	383	7	9	1.5	4.1	Utilize CHP potential; convert coal power plants to biomass plants in countries where coal plants are being retired, as well as those with large and/or young coal power plant capacity	7.7	-
Geothermal	[GW]	11	64	3	10	0.2	0.7	Reach higher maturity level by modularizing/off-site assembly of plant components for high altitudes; novel drilling for high-temperature well operation	−3.9	Exhausted steam condensation; explore feasible applications of condensation heat
Ocean	[GW]	1	9	-	17	0.0	0.1	Resolve construction issues; assessment of environmental impacts	13	Consider combined generation with air-conditioning/fresh water production; hybrid options

Table 5. *Cont.*

Technology	Units	2012	REmap 2030	CAGR (Indicator 1)		Penetration level (Indicator 2)		Action areas for deployment and system change (for Indicators 1 and 2)	2030 Substitution costs (Indicator 3)	Action areas for cost-competitiveness (for Indicator 3)
				2000–2012	2012-REmap 2030	2012	REmap 2030			
				(%/year)	(%/year)	(%)	(%)		(USD/GJ)	
Biomass:										
Traditional	[EJ/year]	27	12	0	-5	8.0	2.7	Creating a market for affordable and reliable modern cooking equipment; efficient technologies utilizing a range of fuels	N/A	Develop and deploy advanced biofuel technologies; improving quality and energy density of solid biomass products; higher efficiency conversion technologies to final products
Advanced cooking	[EJ/year]	1	4	10	8	0.3	0.9		3	
Industrial/DH CHP	[EJ/year]	3	14	10	13	0.9	3.1	Consider biomass-fired process heat technologies in new plants; prioritize plants which has better access to biomass	5–10	
Industry boilers	[EJ/year]	4	7	0	0	1.2	1.6			
Wood pellets	[EJ/year]	1	3	49	6	0.3	0.7	-	1–2	
Chips, logs	[EJ/year]	5	6	6	1	1.5	1.3			
Liquid biofuels (incl. biogas)	[bln ltrs/year]	105	650	16	11	0.7	3.4	Phase out the use of conventional feedstocks	−5 (conventional)–−1 (advanced)	
Total demand [2]	[EJ/year]	51	108	1	4	10.6	17.1	Feedstock collection; sustainability issues; international trade; infrastructure; resource efficiency	N/A	
Non-biomass renewable heat:										
Total solar thermal	[mln m^2]	383	4,029	9	14	0.4	2.5	High temperature process heat in industry; modifying existing processes for retrofitting	N/A	Consider when new capacity is being built
Share in buildings [3]	[%]	99	67	-	11	1.2	6.2		0.3	
Share in industry [3]	[%]	1	33	-	43	0.0	1.6		13.2	
Geothermal heat	[EJ/year]	1	1	10	4	0.4	2.5	Long term delivery for low/high heat	2	Optimization of heat extraction

Table 5. *Cont.*

Technology	**Units**	**2012**	**REmap 2030**	**CAGR (Indicator 1)**		**Penetration level (Indicator 2)**		**Action areas for deployment and system change (for Indicators 1 and 2)**	**2030 Substitution costs (Indicator 3)**	**Action areas for cost-competitiveness (for Indicator 3)**
				2000–2012	**2012-REmap 2030**	**2012**	**REmap 2030**			
				(%/year)	**(%/year)**	**(%)**	**(USD/GJ)**		**(USD/GJ)**	
Electrification:										
Heat Pump	[GW]	50	474	N/A	13	-	-	Utilize high temperature options in industry where technology exists; better information on its benefits	1	Improve coefficient of performance
Battery storage [4]	[GW]	2	150	N/A	27	0.5	5.6	Identify key areas it can play a role next to interconnectors, DSM, dispatchable, e.g., islands and off-grid, residential PV, high variable RE shares	N/A	-
BEV, PHEV [5]	[mln]	0	160	N/A	46	0	10	Overcome maximum range and speed limitations; develop enabling infrastructure; fast chargers and higher capacity batteries	20–25	-

Penetration levels are estimated relative to: [1] total power generation capacity, [2] total primary energy supply, [3] sector TFEC, [4] total variable renewable energy share (wind onshore/offshore and solar PV), [5] total vehicle stock. CAGR: compound annual growth rate. Sources: [12,36].

The growth in biomass demand differs per application. We estimate that total demand for heating and cooking increases from 41 EJ in 2012 to 46 EJ in 2030. This is 43% of the total biomass demand and lower than the 2012 share of 80%. This rather modest growth is explained by modern biomass, which is two to three times more efficient than its traditional uses. In REmap 2030, total biomass use for power generation and as transport fuel gains a larger market share of 57% in 2030 compared to the 2012 levels of 20%.

Compared to a historical biomass use growth rate of 1.4%/year, in REmap growth worldwide would triple to 4.3%/year between 2012 and 2030. According to REmap 2030, modern biomass use for CHP in industry and DH sectors, for cooking and for the transport sector would grow by between 6% and 13%/year in 2012–2030. In comparison, total biomass use for industrial boilers and in the form of chips/logs in buildings would grow only slightly in the entire period.

Non-biomass renewable heat technologies include solar thermal and geothermal heat, and heat pumps. We estimate about 13% per year growth for solar thermal heat and heat pump capacities in the industry and building sectors. This is higher than historical growth rates in solar thermal (which until now has only been used in buildings) of 9%/year. In particular, the use of solar thermal for process heat generation in industry is a new market and between 2010 and 2030 the installed capacity could grow by more than 40%/year. This would translate to one-third of the total global solar thermal capacity installed in all sectors, compared to today's level of about 1%. Growth in geothermal heat is about 4%/year between 2012 and 2030, lower than historical developments. Its rather limited deployment is mainly explained by the fact that demand locations (urban areas, industrial plants) need to be close to the sources which is not always the case.

In Table 5, we show that capacity deployment will be a challenge for some RE power technologies in realizing the REmap 2030 estimates. This is particularly the case for solar PV, CSP, wind offshore and ocean power generation technologies (all have annual capacity growth rates above 10%/year). Total biomass demand for all sectors is estimated to double between 2010 and REmap 2030. This implies in particular a substantial growth in liquid biofuels for the transport sector and biomass use for industrial applications. Likewise realizing the solar thermal capacity for industrial process heat generation will require large growth rates.

4. Discussion of Results and Indicators

REmap 2030 shows that penetration levels of renewables remain relatively low at a global level except for the power sector and with biomass use in the end-use sectors. This means that for renewables-based power generation and biomass use, enabling infrastructure such as grid expansion, energy storage devices or biomass supply networks will be an important area for innovation.

For example, high penetration levels of variable renewables (in particular solar PV and wind power) in selected countries will require accompanying efforts to balance supply and demand and support grid stability. Grid codes and interconnections also require special attention not just due to technical matters, but also because of its impact on socio-economic and political discussions. One area where efforts have to be made is in developing an electricity grid code with a regional approach rather than based on individual national perspectives. Hence, a stable regulatory framework has to accompany the technological progress of the grid infrastructure. The main drawback of renewable resources, intermittency, also gives a central role to energy storage devices. Providing more affordable energy storage devices is one of the principal areas of research.

For biomass, enabling its supply will be important to meet increasing demand. The main challenge is to increase collection rates of affordable non-food feedstocks (e.g., residues), which do not compete with resources for food production (land and water) and build the necessary infrastructure that can facilitate sustainable supply of biomass in meeting the increasing demand. This is, however, an area of action beyond the boundaries of the energy sector, and it includes efforts from agriculture, to the trade and infrastructure sectors. In the longer term, the electrification of end-use sectors will also be an important area where innovation is required.

The challenge does not lie only in deployment and system changes, but also in costs. Technologies that are mature today (e.g., hydro) or have experienced fast deployment rates in the past decade (e.g., wind onshore, solar PV) are cost-competitive in 2030. In comparison, we estimate additional costs for emerging technologies, thereby also requiring a large deployment between today and REmap 2030 (e.g., CSP, ocean, EVs, solar thermal for industry).

Substitution costs of RE technologies are determined to a large extent by capital costs. One exception is biomass, where fuel costs and type of biomass feedstock also play a role. This presents a specific challenge for biomass technologies. For example, bioenergy products from waste and residues used to generate heat in the building sector is close to economic viability (USD 1–2 per GJ). In comparison, biomass used for process heat generation in the industry sector is much more expensive, partly explained by the more expensive feedstocks, but also typically the lower fossil fuel price in industry. Furthermore, substituted conventional fuel also determines economic viability. In the power and transport sectors coal and petroleum products were substituted to large extent, respectively. In comparison, there are variations in the type of fuels substituted in the building and industry sectors. Coal is typically substituted in the industry sector and a mix of more expensive oil and natural gas are substituted in the building sector. Hence, biomass is less competitive in the industry sector for heat generation as opposed to the building sector. In the transportation sector, liquid biofuels are cost-competitive assuming that both conventional and advanced biofuels will reach full commercialization by 2030. However, the cost-competitiveness of conventional biofuels are higher compared to advanced biofuels which is explained by the fact that advanced biofuels are just at the start of their commercialization today.

We find a strong relationship between cost-competitiveness and the need for deployment between 2010 and 2030 for RE technologies as shown in Table 5. With the exception of hydro, solar PV (utility), wind onshore and some biomass technologies, most technologies require additional costs in 2030 to reach the higher deployment available for these technologies. To overcome these challenges, we identified a number of action areas for each technology. Ensuring commercialization through research and development (R&D) will be key for emerging technologies given this process takes typically between 10 and15 years for energy technologies. It will also be important to continue to develop capacity to reduce high investment costs and reduce technology barriers and technology related risks [37]. For example, technical limitation in cellulosic feedstock processing and reducing the high capital costs of conversion plants are two areas where R&D need to play a role [38,39]. Extensive research will be required to find the optimum for cost and efficiency perspectives by choosing between accessible and low wind resource *versus* high wind resource areas. In addition to accelerating the deployment of emerging technologies with innovation and R&D, there is also a need to continue improving existing technologies such as wind turbines and solar PV and improve their efficiency and performance. This is necessary to sustain cost-competitiveness at a global level, but also to increase capacity in markets where deployment still needs to happen and where economic viability has not been fully reached. A holistic approach for technological R&D and innovation encompassing both emerging and existing technologies will be crucial to ensure the deployment of a portfolio of technologies that result in a doubling of the RE share.

The REmap technology options guide the definition of policy intervention by assessing the current stage of technology through a bottom-up, disaggregated analysis at a country and global level. An appropriate mix of policies can foster technological innovation along the whole continuum of innovation, from early research to commercial diffusion [40]. For example, a combination of technology-push and demand-pull policy instruments can encourage investments in emerging technologies and balance the allocation of available resources on solely technologies, which are close to, or attained already, a significant market penetration. From basic and applied research to commercial diffusion of breakthroughs and upgraded technology, policy intervention is needed to address issues such as technical risk of applied research, mobilization of appropriate resources for technological development or identification of niche markets [41]. Thus, on one hand, policy intervention comes hand in hand with the appropriate mix of instruments to support existing and emerging technologies along each phase of their life-cycle. On the other hand, the mix of policy instruments and governmental intervention depends on the country-contexts and hence, policy intervention has to be tailored on a case-by-case basis. The REmap Options can guide policy makers on the innovation policy requirements, integrating the specificities of technological readiness for each technology and the country context.

In addition to the deployment potential, the REmap analysis also considers the replacement of conventional technology and the implications this entails to existing infrastructure. Addressing this issue is key to support an energy system towards higher shares of RE. A transformation in the infrastructure of the energy system is taking place, although not yet in a context of deregulation [42]. Policies are particularly relevant for RE technologies because they have to be integrated into the existing infrastructure. This step is critical to support the step from RE inventions at a demonstration scale to profitable innovations at a market development scale [40]. Often, only those inventions that can be integrated in the existing infrastructure in a cost-efficient way, make the step between inventions and market products. Under normal market conditions, emerging technology is tested using past experience and established infrastructure and practices. However, the infrastructure needs to be modified to accommodate significant shares of RE technologies and their markets are not necessarily formed when these new technologies are tested. Together with uncertain returns and high capital costs, this makes policy and government intervention necessary to test the performance and embed these technologies in different operational environments and realistic user environments [28]. The REmap methodology considers the integration of RE in current infrastructure. This consideration results into realistic results, which allow for a sensible identification of policy needed in this regard.

In addition to guiding policy makers on policy intervention and RE integration in the energy system, REmap is also an expert elicitation protocol. The REmap methodology merges the best available estimates on costs and potential with accurate and proficient judgments. Complementing models and analysis of the evolution of technologies with expert judgment and trade-offs [43] reduces the uncertainty in the REmap Options. This is key to define medium and long term RE targets. At the same time, these targets are a relevant factor to be considered when defining appropriate policies for further development, demonstration and deployment of RE. With the REmap methodology, the uncertainty inherently bounded to information of development and deployment costs of emerging technology is reduced by incorporating judgments of national experts. This can increase the accuracy of the REmap results, which presents a portfolio of realistic REmap Options to expand the RE share beyond 30% by 2030.

5. Strength and Limitations of the REmap Methodology

In this section, we first discuss the strengths of the REmap methodology. Subsequently, we compare our results with the findings from other studies and finally discuss the methodological limitations.

Earlier in this paper, we presented the realistic RE potential worldwide based on the bottom-up analysis of 26 countries at technology and sector levels, as well as the costs at a global level. Moreover, we showed that this potential is sufficient for doubling the RE share in the global energy mix by 2030. We used this information to develop action areas for RE technology deployment, thereby assessing the innovation needs.

A recent review by Reference [44] categorize decarbonization scenario studies into four types of methodologies (the low-carbon technology options considered in some of these studies include carbon capture and storage and nuclear), namely (i) top-down, scenario based back-casting; (ii) top-down integrated assessment modeling; (iii) bottom-up energy system modeling; and (iv) bottom-up technical or techno-economic assessments. These methodologies typically apply cost as a cut-off criteria, otherwise the models stop with technology deployment once its desired objective (e.g., emission reduction) is reached. While both cost and country-targets are important aspects in REmap, neither of them restrict the technology portfolio in sector and countries, and REmap is not a scenario analysis, and its findings are not prescriptive. The aim is to communicate results with a diverse group of audience: from policy makers to technology developers, academia and the general public. It is the choice of countries to determine their realistic RE technology portfolio in 2030. Although REmap builds on a simple accounting framework, it relies to the extent possible on country engagement and dialogue which makes its methodology unique. Furthermore, REmap provides feedback to countries to support them in new policy making. As shown in this paper, REmap also creates the link to governmental intervention needed to guide innovation policy.

The methodology allows IRENA and countries to work together in assessing future deployment pathways, next to other practical benefits; for example, national experts can easily review assumptions and provide data/feedback. The cost and potential of each technology can be calculated back to the raw technology performance and cost data, which allow results to be re-estimated by varying the default parameter values (e.g., energy prices, discount rates). This flexibility is important because each country has its own characteristics, and countries not covered in this analysis may want to analyze their potential and compare themselves with others on a comparable metric.

In Figure 6, we compare REmap 2030 with the findings of studies looking at the development of RE use in the global energy mix for the same timeframe. The estimated RE share and the total RE use in REmap fall between the estimates of these studies. References [17,45,46] focus on the potential of RE. With total final RE use of 134 EJ and 151 EJ, References [45,46], estimate RE shares above 40%, respectively. Although the absolute RE use is similar to REmap 2030 estimates, their higher RE share is explained by the fact that REmap 2030 has a higher TFEC. The opposite is the case according to Reference [47] (2030 values estimated based on the 2025–2040 trend) and Reference [17] which show RE shares of approximately 20% based on total RE uses of approximately 120 EJ and 100 EJ respectively because of their much higher TFEC. Reference [48] estimates a lower RE share of 24% compared to REmap 2030, explained by its lower total RE use of 104 EJ/year. The RE share according to the Reference [48] was estimated by including non-energy use and the consumption of renewables from DH generation was excluded.

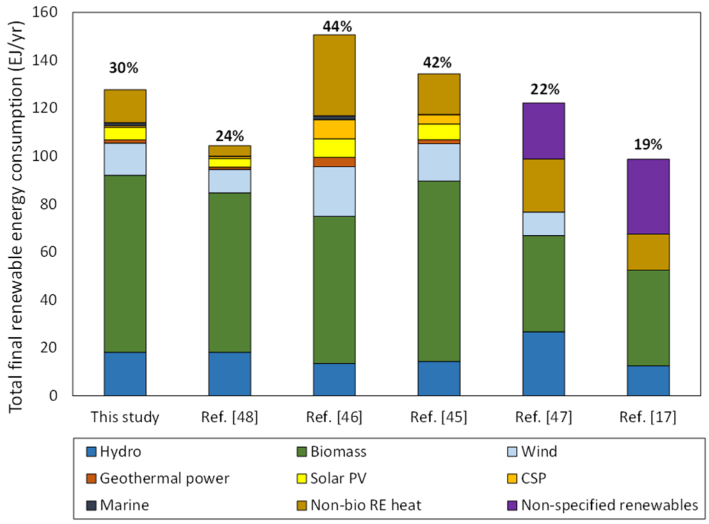

Figure 6. Comparison of REmap 2030 results with literature assessments.

Hydro use in 2030 is similar across the different studies, ranging between 14 EJ and 18 EJ with the exception of Reference [47] which estimates about 27 EJ/year. REmap biomass demand estimate is as high as the estimate of Reference [46], approximately 75 EJ/year, and it accounts for nearly 60% of the total global final RE consumption. In comparison to our estimates, Reference [46] and Reference [45] estimate much higher wind, solar PV and CSP potentials.

Although REmap estimates are comparable to the findings of other studies, the analysis could be improved in a number of ways. Reliability of our results depend on the methodology we applied as well as the quality of the underlying data. Moreover a number of issues are not entirely covered in the cost-supply curves and in general in the simplified methodology. The main limitations are discussed below:

(i) We compiled the national energy plans originating from countries to develop the Reference Case into comparable format. However, background assumptions on drivers for population growth and economic development as well as the ambition level of target setting within the plans vary across countries, thereby representing different scenario families. For countries where national plans were unavailable or availability was limited to few sectors only, we used data from other studies to fill the gaps. Similarly, this may add uncertainty due to lack of consistency across data sources. Although the aim of this study is not to develop detailed energy scenarios for countries, background assumptions in national energy plans of countries need to be harmonized further and consistency should be improved before aggregation.

(ii) For each country, the Reference Case includes current policies related to energy efficiency and RE. It is straightforward to quantify the extent RE policies contribute to 2030 TFEC at sector level since RE policies often have targets based on generation, capacity or RE share. Given energy consumption is aggregated at sector level, it is not possible to monitor energy efficiency progress in the absence of physical activity indicators (e.g., ton-km freight transported per year) and specific energy consumption data in both 2010 and 2030. To the extent possible, such data also needs to be available at country level in addition to national plans. This is essential to understand the nexus between energy efficiency and RE since as shown in this study the synergies between them should be considered to double the global RE share.

(iii) We developed the Reference Case starting with the 2010 base year of the SE4All objective and looked out to 2030. National plans are often prepared with data from a few years prior (see Annex) and therefore may not take into account the rapid developments in the RE sector. It is therefore likely that the RE share will reach the 2030 Reference Case estimates of 21% before that time. At country level, with the current progress in deployment of renewables, the US will exceed its Reference Case projections according to the Annual Energy Outlook 2014 within the next few years [49]. China is also exceeding its targets [50]. Therefore it is necessary to continuously update the Reference Case of the countries to take into account the latest developments because this determines the gap to a doubling of the global RE share.

(iv) Depending on data availability, we followed different approaches to estimate the REmap Options of each country. If countries provided an accelerated RE projection (e.g., Germany), we took this as a basis to estimate the realizable potential of technologies. Otherwise, literature data and communication with the national experts were the basis of the assessment. Although we defined a number of criteria to determine the realizable potential (e.g., costs, age of capital stock, resource availability), the estimated potentials could differ on how the criteria are prioritized across countries. The link between the realizable potentials and the criteria for each country should be identified further and compared across countries with further analysis of cost-benefits of technologies, utilization of technical resource potentials, and retrofits of existing capacity *versus* new investments.

(v) The analysis represents an assessment of a point in time and we did not estimate in detail the time period between 2010 and 2030, and any of the interactions, developments and dynamics across technologies and feedbacks in energy prices due to demand and supply changes (e.g., rebound effects). We rather assumed that all REmap Options are implemented in a single step by 2030. Furthermore, the costs of infrastructure were excluded from the analysis, which would raise the costs estimated in this analysis. Most variables in the assessment are exogenous without taking into account the potential effect in demand reduction due to the implementation of the REmap Options. While the cost-supply curve is static, the energy system in general—for instance, the process of meeting electricity or heat demand—is dynamic. For example, there are institutional barriers, or transaction costs along with technology costs. Incorporating these could change the ranking of technologies.

Based on the aggregated country findings, we provided action areas for specific technologies and sectors at a global level. In a similar way for the global situation, the assessment of action areas should be expanded further for individual countries as innovation needs differ based on the differing aspects of countries. These can include the varying starting point of RE share, resource availability, local costs and the extent national energy plans consider the deployment of RE technologies. With these regards, the indicators presented in this paper can still be used as a first estimate to identify areas for policy intervention at a country level. Therefore, further work to apply this methodology at a country level in a case-by-case basis is strongly recommended for looking into the future national innovation policy needs on a country level.

6. Conclusions

Our analysis shows that the renewable energy options in REmap can bring the global RE share to 30% by 2030. Importantly when considering benefits, the higher RE share results in cost-savings. By improving energy efficiency and ensuring access to modern energy, the RE share will rise further. This paper provided action areas for technology innovation that can help to achieve the deployment levels by developing three indicators. Each indicator points to a key finding. First technology deployment need to be sustained and in most cases grow beyond what has so far been achieved. Second, innovation is required to support a system transition towards renewables. Only in few countries is a clear transition in the power sector towards renewables underway. Importantly although potentials in end-use sectors are large, they are almost universally overlooked. Third, the cost-competitiveness of technologies needs to be improved. The combination of these three indicators provides a first assessment of innovation needs, but this study should be expanded with the assessment of action areas in individual countries and by determining the right policies to accelerate RE uptake.

Finally doubling the RE share of as much as 36% by 2030 is not an end-point. The remaining two-thirds of global TFEC will continue to come from non-RE sources. Part of this could potentially be substituted with renewables as the existing building and manufacturing plant capital stock retires. The remaining part is in markets where renewables deployment faces different challenges due to economic and technical feasibility. Innovation will play an important role to overcome these barriers and broaden the portfolio of technologies that are available to a country. Innovation is crucial for RE deployment and to reduce costs in these areas, and in that respect, its role should be understood better.

Both doubling the global RE share and going beyond a doubling will require specific strategies for innovation, and in particular for the deployment of new and emerging technologies. Technology commercialization and high levels of technology penetration require substantial time, and only certain technologies will be mature by 2030. To sustain RE growth beyond a doubling requires technology developers to start conducting R&D today, and governments to support this for continuous innovation.

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Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

AD	Anaerobic digestion
CHP	Combined heat and power
CO_2	Carbon dioxide
CSP	Concentrated solar power
DH	District heat
EU	European Union
EV	Electrical vehicle
FF	Fossil fuel
ICE	Internal combustion engines
IRENA	International Renewable Energy Agency
LPG	Liquified Petroleum Gas
NOx	Mono-nitrogen oxide
NREAP	National Renwable Energy Action Plans
OECD	Organisation for Economic Co-operation and Development
O&M	Operations and Maintenance
OTEC	Ocean thermal energy conversion
PM2.5	Particulate Matter (ø 2.5 µm)
PT	Parabolic Trough
PV	Photovoltaic
R&D	Research and development
RE	Renewable energy
REmap	Renewable Energy Roadmap
SE4All	Sustainable Energy for All
SO_2	Sulphur dioxide
TFEC	Total final energy consumption
UAE	United Arab Emirates
UK	United Kingdom
US	United States

Annex

Table A1. Bibliographic sources that complement IRENA analysis for the Reference Case of the 26 REmap countries.

Country	Main source for Reference Case	Time frame	Sectors covered in cited sources
Australia	[51]	2012–2050	TFEC
Brazil	[52,53]	2005–2030	TFEC
Canada	[54]	2010–2035	TFEC
China	[29]	2010–2035	TFEC
Denmark	[55]	2012–2025	TFEC
Ecuador	[29]	2010–2035	TFEC
France	[33,56]	2010–2030	TFEC
Germany	[33,57]	2010–2050	TFEC
India	[29]	2010–2035	TFEC
Indonesia	[58]	2010–2030	TFEC
Italy	[33,59]	2010–2050	TFEC
Japan	[29]	2010–2035	TFEC
Malaysia	[60]	2010–2035	TFEC
Mexico	[61]; IRENA analysis	2011–2025	Power sector
Morocco	[62]	2012–2030	TFEC
Nigeria	IRENA analysis	2010–2030	TFEC
Russia	[29]	2010–2035	TFEC
Saudi Arabia	[29,63]	2010–2035	TFEC; Power sector
South Africa	[64]; IRENA analysis	2010–2030	Power sector
South Korea	[65]	2010–2030	TFEC
Tonga	IRENA analysis	2010–2030	TFEC
Turkey	[66]; IRENA analysis	2012–2021	Power sector
Ukraine	[67,68]	2009–2030	TFEC
UAE	[69]	2010–2030	TFEC
UK	[70–72]	2010–2050	TFEC
US	[73]	2013–2040	TFEC

Table A2. Assumed international energy prices in year 2030.

Crude oil	(USD/GJ)	20
Coal [1]	(USD/GJ)	2–5
Natural gas (household) [1]	(USD/GJ)	15–22
Natural gas (industry) [1]	(USD/GJ)	8–11
Electricity (household) [2]	(USD/kWh)	0.02–0.38
Electricity (industry) [2]	(USD/kWh)	0.04–0.20
Petroleum products	(USD/GJ)	16.4
Diesel and Gasoline	(USD/GJ)	30
Biodiesel	(USD/GJ)	23
Conventional ethanol	(USD/GJ)	27
Advanced ethanol	(USD/GJ)	25

Table A2. *Cont.*

Crude oil	**(USD/GJ)**	**20**
Primary biomass [3]	(USD/GJ)	8–30
Biomass residues and waste [3]	(USD/GJ)	1–15
Traditional biomass	(USD/GJ)	3
Nuclear fuel	(USD/GJ)	0.2

[1] The low end of the range refers to the price in exporting countries, and the high end refers to those which are importers. [2] The range is based on the differences across the 26 REmap countries. [3] The range is based on the differences across 6 world regions, namely Africa, Asia, Europe, North America, Oceania and South America.

Table A3. Assumed international technology cost and performance data in 2030.

Renewable energy technologies						
	Capacity factor	**Lifetime**	**Reference capacity or annual mileage**	**Overnight capital cost**	**O&M costs**	**Conversion efficiency**
INDUSTRY SECTOR	(%)	(years)	(kW)	(USD/kW)	(USD/kW/year)	(%)
Solar thermal	10	25	500	655	9.8	100
Geothermal	55	42	100	1500	37.5	100
Biomass boilers	85	25	500	580	14.5	88
BUILDINGS SECTOR	(%)	(years)	(kW)	(USD/kW)	(USD/kW/year)	(%)
Space heating: Geothermal heat pumps	50	15	12	1500	37.5	350
Space heating: Air-to-Air heat pumps	50	15	12	780	19.5	350
Water heating: Biomass	30	15	20	600	15.0	80
Water heating: Solar (thermosiphon)	12	20	82	150	3.8	100
Space heating: Biogas	50	15	50	600	15.0	80
Space heating: Pellet burners	30	15	20	775	19.4	85
Space Cooling: Solar	12	20	5	1350	33.8	80
Cooking biogas (from AD)	10	25	9	39	1.0	48
Cooking biomass (solid)	10	20	5	15	0.4	30
Cooking bioethanol	10	20	5	10	0.3	50
TRANSPORT SECTOR (passenger road vehicles)	(%)	(years)	(passenger-km/ year/vehicle)	(USD/vehicle)	(USD/vehicle/year)	(MJ/passenger-km)
Conventional bioethanol	N/A	12	15,000	28,000	2,800	1.06
Conventional bioethanol	N/A	12	15,000	28,000	2,800	1.06
Biodiesel	N/A	12	15,000	30,000	3,000	0.98
Plug-in hybrid	N/A	12	15,000	30,000	3,000	0.98
Battery electric	N/A	12	15,000	32,000	2,880	0.47
POWER SECTOR	(%)	(years)	(kW)	(USD/kW)	(USD/kW/year)	(%)
Hydro (Small)	50	40	0.05	2800	56.0	100
Hydro (Large)	50	60	100	1500	30.0	100
Wind onshore	38	30	100	1500	60.0	100
Wind offshore	48	30	50	2870	157.9	100
Solar PV (Rooftop)	16	30	0.1	1400	14.0	100
Solar PV (Utility)	18	30	1	1000	10.0	100

Table A-3. *Cont.*

Renewable energy technologies						
	Capacity factor	**Lifetime**	**reference capacity or annual mileage**	**Overnight capital cost**	**O&M costs**	**Conversion efficiency**
POWER SECTOR	(%)	(years)	(kW)	(USD/kW)	(USD/kW/year)	(%)
Solar CSP PT no storage	35	35	50	3500	35.0	100
Solar CSP PT storage	50	35	50	4500	135.0	100
Biomass power	80	25	50	2750	68.8	38
Landfill gas power	80	25	0.5	1800	45.0	32
Geothermal	80	50	25	3100	124.0	10
Tide, wave, ocean	50	25	5	3350	67.0	100
Conventional fuel technologies						
	Capacity factor	**Lifetime**	**Reference capacity or annual mileage**	**Overnight capital cost**	**O&M costs**	**Conversion efficiency**
INDUSTRY SECTOR	(%)	(years)	(kW)	(USD/kW)	(USD/kW/year)	(%)
Coal	85	25	2000	300	7.5	90
Petroleum products	85	25	2000	200	5.0	85
Natural gas	85	25	2000	100	2.5	95
BUILDINGS SECTOR	(%)	(years)	(kW)	(USD/kW)	(USD/kW/year)	(%)
Space heating: coal	85	15	20	175	6.1	90
Space heating: petroleum products	85	15	20	175	6.1	85
Space heating: natural gas	85	15	20	162	5.7	95
Water heating: natural gas	80	15	20	150	5.3	95
Space & Water heating: traditional biomass	85	25	2,000	100	2.5	50
Water heating: electricity	10	10	5	150	3.8	85
Space cooling: electricity	10	10	10	150	3.8	250
Cooking LPG/kerosene	10	20	5	10	0.3	50
Cooking natural gas	10	25	9	39	1.0	48
Cooking electricity	10	10	7	24	0.6	75
Cooking traditional biomass	10	3	5	10	0.25	10
TRANSPORT SECTOR (passenger road vehicles)	(%)	(years)	(passenger-km/ year/vehicle)	(USD/vehicle)	(USD/vehicle/year)	(MJ/passenger-km)
Petroleum products	N/A	12	15,000	28,000	2,800	1.06
POWER SECTOR	(%)	(years)	(kW)	(USD/kW)	(USD/kW/year)	(%)
Coal (type 1)	80	60	650	1300	52.0	30
Natural gas	80	30	650	1000	40.0	55
Oil	30	50	400	1200	18.0	40
Nuclear (type 1)	84	60	1200	5500	137.5	33
Diesel (gen-set)	40	20	0	1500	37.5	42
Coal (type 2)	80	60	650	3000	120.0	42
Nuclear (type 2)	84	60	1200	7500	187.5	33

Note: kW: kilowatt; km: kilometer; MJ; megajoule.

References

1. IEA (International Energy Agency). *World Energy Balances*; OECD/IEA: Paris, France, 2013.
2. IPCC (Intergovernmental Panel on Climate Change). *Renewable Energy Sources and Climate Change Mitigation*; Prepared by Working Group III of the Intergovernmental Panel on Climate Change; Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., *et al.*, Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2011.
3. GEA (Global Energy Assessment). *Global Energy Assessment—Toward a Sustainable Future*; Cambridge University Press: Cambridge, UK; New York, NY, USA; International Institute for Applied Systems Analysis: Laxenburg, Austria, 2012. Available online: http://www.globalenergyassessment.org/ (accessed on 10 September 2014).
4. US EIA (United States Energy Information Administration). *International Energy Outlook 2013*; U.S. Energy Information Administration, U.S. Department of Energy: Washington, DC, USA, 2013. Available online: http://www.eia.gov/forecasts/ieo/ (accessed on 10 September 2014).
5. IPCC. *Technical Summary*; Prepared by Working Group III of the Intergovernmental Panel on Climate Change Assessment Report 5. Final Draft. IPCC: Geneva, Switzerland, 2014. Available online: http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc_wg3_ar5_final-draft_postplenary_technical-summary.pdf (accessed on 10 September 2014).
6. IEA. *Technology Roadmap: Bioenergy for Heat and Power*; OECD/IEA: Paris, France, 2012. Available online: https://www.iea.org/publications/freepublications/publication/2012_Bioenergy_Roadmap_2nd_Edition_WEB.pdf (accessed on 10 September 2014).
7. Lim, S.S.; Vos, T.; Flaxman, A.D.; Danaei, G.; Shibuya, K.; Adair-Rohani, H.; Amann, M.; Anderson, H.R.; Andrews, K.G.; Aryee, M.; *et al.* A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: A systematic analysis for the Global Burden of Disease Study 2010. *Lancet* **2013**, *380*, 2224–2260.
8. IEA. *World Energy Outlook 2013*; OECD/IEA: Paris, France, 2013. Available online: http://www.worldenergyoutlook.org/publications/weo-2013/ (accessed on 10 September 2014).
9. SE4All. *Sustainable Energy for All*; United Nations, Vienna International Centre: Vienna, Austria, 2014. Available online: www.se4all.org (accessed on 10 September 2014).
10. UN (United Nations). *United Nations General Assembly Declares 2014–2024. Decade of Sustainable Energy for All*; United Nations: New York, NY, USA; Geneva, Switzerland, 2012. Available online: http://www.un.org/News/Press/docs/2012/ga11333.doc.htm (accessed on 21 December 2012).
11. Banerjee, S.G.; Elizondo Azuela, G.; Bhatia, M.; Bushueva, I.; Inon, J.G.; Jaques Goldenberg, I.; Portale, E.; Sarkar, A. *Global Tracking Framework*; Volume 3 of Global Tracking Framework. Sustainable Energy for All. The World Bank: Washington, DC, USA, 2013. Available online: http://documents.worldbank.org/curated/en/2013/05/17765643/global-tracking-framework-vol-3-3-main-report (accessed on 10 September 2014).
12. IRENA (International Renewable Energy Agency). *REmap 2030: A Renewable Energy Roadmap*; IRENA: Abu Dhabi, UAE, 2014. Available online: http://www.irena.org/remap/REmap_Report_June_2014.pdf (accessed on 10 September 2014).

13. Elliston, B.; MacGill, I.; Diesendorf, M. Least cost 100% renewable electricity scenarios in the Australian National Electricity Market. *Energy Policy* **2013**, *59*, 270–282.
14. Mileva, A.; Nelson, J.H.; Johnston, J.; Kammen, D.M. SunShot solar power reduces costs and uncertainty in future low carbon electricity systems. *Environ. Sci. Technol.* **2013**, *47*, 9053–9060.
15. Taliotis, C.; Miketa, A.; Howells, M.; Hermann, S.; Welsch, M.; Broad, O.; Rogner, H.; Bazilian, M.; Gielen, D. An indicative assessment of investment opportunities in the African electricity supply sector. *J. Energy South. Afr.* **2014**, *25*, 2–12.
16. Demirbas, A. Global renewable energy projections. *Energy Sources Part B Econ. Plan. Policy* **2009**, *4*, 212–224.
17. Foyn, T.H.S.; Karlsson, K.; Balyk, O.; Grohnheit, P.E. A global renewable energy system: A modelling exercise in ETSAP/TIAM. *Appl. Energy* **2011**, *88*, 526–534.
18. Jacobson, M.Z.; Delucchi, M.A. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* **2011**, *39*, 1154–1169.
19. Krey, V.; Clarke, L. Role of renewable energy in climate mitigation: A synthesis of recent scenarios. *Clim. Policy* **2011**, *11*, 1131–1158.
20. Luderer, G.; Krey, V.; Calvin, K.; Merrick, J.; Mima, S.; Pietzcker, R.; van Vliet, J.; Wada, K. The role of renewable energy in climate stabilization: results from the EMF27 scenarios. *Clim. Change* **2014**, *123*, 427–441.
21. Deng, Y.Y.; Blok, K.; van der Leun, K. Transition to a fully sustainable global energy system. *Energy Strategy Rev.* **2012**, *1*, 109–121.
22. Teske, S.; Preffer, T.; Simon, S.; Naegler, T.; Graus, W.; Lins, C. Energy Revolution—A sustainable world energy outlook. *Energy Effic.* **2011**, *4*, 409–433.
23. Taibi, E.; Gielen, D.; Bazilian, M. The potential for renewable energy in industrial applications. *Renew. Sustain. Energy Rev.* **2012**, *16*, 735–744.
24. Saygin, D.; Gielen, D.J.; Draeck, M.; Worrell, E.; Patel, M.K. Assessment of the technical and economic potentials of biomass use for the production of steam, chemicals and polymers. *Renew. Sustain. Energy Rev.* **2014**, *40*, 1153–1167.
25. Liaquat, A.M.; Kalam, M.A.; Masjuki, H.H.; Jayed, M.H. Potential emissions reductions in road transport sector using biofuel in developing countries. *Atmos. Environ.* **2010**, *44*, 3869–3877.
26. Juul, N.; Meibom, M. Road transport and power system scenarios for Northern Europe in 2030. *Appl. Energy* **2012**, *92*, 573–582.
27. Connolly, D.; Mathiesen, B.V.; Ridjan, I. A comparsion between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system. *Energy* **2014**, *73*, 110–125.
28. Brown, J.; Hendry, C. Public demonstration projects and field trials: Accelerating commercialisation of sustainable technology in solar photovoltaics. *Energy Policy* **2009**, *37*, 2560–2573.
29. IEA. *World Energy Outlook 2012*; OECD/IEA: Paris, France, 2012. Available online: http://www.worldenergyoutlook.org/publications/weo-2012/ (accessed on 10 September 2014).
30. IRENA. *Global Bioenergy Supply and Demand Projections. A Working Paper for REmap 2030*; IRENA: Abu, Dhabi, UAE, 2014. Available online: http://www.irena.org/remap/IRENA_REmap_2030_Biomass_paper_2014.pdf (accessed on 10 September 2014).

31. Hirth, L.; Ueckerdt, F.; Edenhofer, O. Integration costs revisited—An economic framework for wind and solar variability. *Renew. Energy* **2015**, *74*, 925–939.
32. Delucchi, M.A.; Jacobson, M.Z. Providing all global energy with wind, and solar power, Part II: Reliability, system and transmission costs, and policies. *Energy Policy* **2011**, *39*, 1170–1190.
33. EC (European Commission). *National Renewable Energy Action Plans*; European Commission: Brussels, Belgium, 2010. Available online: http://ec.europa.eu/energy/renewables/action_plan_en.htm (accessed on 10 September 2014).
34. WB (The World Bank). *Gross Fixed Capital Formation*; The World Bank: Washington, DC, USA, 2014. Available online: http://data.worldbank.org/indicator/NE.GDI.FTOT.CD/countries?display=graph (accessed on 10 September 2014).
35. FSFM (Frankfurt School of Finance & Management). *Global Trends in Renewable Energy Investment 2013*; UNEP Collaborating Centre Frankfurt School of Finance & Management GmbH: Frankfurt, Germany, 2013.
36. CSIRO (Commonwealth Scientific and Industrial Research Organization). *Unlocking Australia's Energy Potential*; Commonwealth Scientific and Industrial Research Organisation: Clayton South, VIC, Australia, 2011. Available online: http://www.csiro.au/~/media/CSIROau/Divisions/CSIRO%20Energy%20Technology/Aust_energy_potential_CET_publcation%20Standard.pdf (accessed on 10 September 2014).
37. Jenkins, J.; Mansur, S. *Bridging the Clean Energy Valleys of Death*; Breakthrough Institute: Oakland, CA, USA, 2011. Available online: http://thebreakthrough.org/blog/Valleys_of_Death.pdf (accessed on 10 September 2014).
38. IRENA. *Road transport: The cost of renewables solutions*; IRENA: Abu Dhabi, UAE, 2013. Available online: http://costing.irena.org/media/2787/Road_Transport.pdf (accessed on 10 September 2014).
39. ACORE (American Council on Renewable Energy). *Input on Biofuel Pathways for U.S. Department of Energy, Bioenergy Technologies Office*; American Council on Renewable Energy: Washington, DC, USA, 2014. Available online: http://www.acore.org/images/uploads/ACOREMemberCommentsDOERFIBiofuelPathways.pdf (accessed on 10 September 2014).
40. Auerswald, P.E.; Branscomb, M.L. Valleys of Death and Darwinian Seas: Financing the Invention to Innovation Transition in the United States. *J. Technol. Transf.* **2003**, *28*, 227–239.
41. Nemet, F.G. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. *Res. Policy* **2009**, *38*, 700–709.
42. Jacobsson, S.; Johnson, A. The diffusion of renewable energy technology: An analytical framework and key issues for research. *Energy Policy* **2000**, *28*, 625–640.
43. Anadón, L.D.; Bosetti, V.; Bunn, M.; Catenacci, M.; Lee, A. Expert Judgements about RD&D and the future of nuclear energy. *Environ. Sci. Technol.* **2012**, *46*, 11497–11504.
44. Loftus, P.J.; Cohen, A.M.; Long, J.C.S.; Jenkins, J.D. A critical review of global decarbonization scenarios: What do they really tell us about feasibility? *WIREs Clim. Change* **2014**, *324*, doi:10.1002/wcc.324.
45. WWF, Ecofys, OMA. *The Energy Report: 100 Percent Renewable Energy by 2050*; World Wide Fund for Nature: Gland, Switzerland, 2011. Available online: http://assets.panda.org/downloads/the_energy_report_lowres_111110.pdf (accessed on 10 September 2014).

46. Greenpeace, EREC, GWEC. *Energy Revolution: A Sustainable World Energy Outlook 2050*; Greenpeace International, European Renewable Energy Council, Global Wind Energy Council: Amsterdam/Brussels, the Netherlands/Belgium, 2012. Available online: www.greenpeace.org/international/Global/international/publications/climate/2012/Energy%20Revolution%202012/ER2012.pdf (accessed on 10 September 2014).
47. ExxonMobil. *The Outlook for Energy: A View to 2040*; ExxonMobil: Irving, TX, USA, 2014.
48. IEA. *World Energy Outlook 2014*; OECD/IEA: Paris, France, 2014.
49. US EIA. *Annual Energy Outlook 2014*; U.S. Energy Information Administration, U.S. Department of Energy: Washington, DC, USA, 2014. Available online: http://www.eia.gov/forecasts/aeo/ (accessed on 10 September 2014).
50. IRENA. *Renewable Energy Prospects: China, REmap 2030 Analysis*; IRENA: Abu, Dhabi, UAE, 2014. Available online: http://www.irena.org/remap/IRENA_REmap_China_report_2014.pdf (accessed on 10 September 2014).
51. BREE (Bureau of Resources and Energy Economics). *Australian Energy Projections*; Bureau of Resources and Energy Economics: Canberra, Australia, 2012. Available online: http://www.bree.gov.au/sites/bree.gov.au/files/files//publications/aep/australian-energy-projections-to-2050.pdf (accessed on 10 September 2014).
52. EME (Ministerio de Minas e Energia, Brasilisa). *Plano Decenal de Expansao de Energia 2021*; Ministerio de Minas e Energia: Brasilisa, Brazil, 2007. Available online: http://www.epe.gov.br/PDEE/20130326_1.pdf (accessed on 10 September 2014).
53. EME. *Plano Nacional de Energia 2030*; Ministerio de Minas e Energia: Brasilisa, Brazil, 2012. Available online: http://www.epe.gov.br/PNE/20080512_2.pdf (accessed on 10 September 2014).
54. NEB (National Energy Board). *Canada's Energy Future: Energy Supply and Demand Projections to 2035*; National Energy Board: Calgary, AB, Canada, 2011. Available online: http://www.neb-one.gc.ca/clf-nsi/archives/rnrgynfmtn/nrgyrprt/nrgyftr/2011/nrgsppldmndprjctn2035-eng.pdf (accessed on 10 September 2014).
55. DEA (Danish Energy Agency). *Danish Energy Outlook*; Danish Energy Agency: Copenhagen, Denmark. Available online: http://www.ens.dk/sites/ens.dk/files/dokumenter/publikationer/downloads/danish_energy_outlook_2011.pdf (accessed on 10 September 2014).
56. DGEC (Direction Generale de l'energie et de Climat). *Synthese. Scenarios prospectifs Energie—Climat—Air a Horizon 2030*; Direction Generale de l'energie et de Climat: Paris, France, 2011. Available online: http://www.developpement-durable.gouv.fr/IMG/pdf/11–0362_5A_ET_note_synthese_sc_pros_v3.pdf (accessed on 10 September 2014).
57. DLR/Fraunhofer IWES/IFNE. *Langfristszenarien und Strategien fuer den Ausbau der erneuerbaren Energien in Deutschland bei Beruecksichtigung der Entwicklung in Europa und global*; DLR/Fraunhofer IWES/IFNE: Stuttgart/Kassel/Teltow, Germany, 2012. Available online: http://www.dlr.de/dlr/Portaldata/1/Resources/bilder/portal/portal_2012_1/leitstudie2011_bf.pdf (accessed on 29 March 2012).
58. MEMR (Ministry of Energy and Mineral Resources). *Indonesia Energy Outlook 2010*; Ministry of Energy and Mineral Resources Republic Indonesia: Jakarta, Indonesia, 2012. Available online: http://www.esdm.go.id/publikasi/indonesia-energy-outlook/ringkasan-eksekutif/doc_download/1255-ringkasan-eksekutif-indonesia-energy-outlook-2010.html (accessed on 10 September 2014).

59. MSE (Ministry of Economic Development). *Strategia Energetica Nazionale: per un'energia pie Competitive e Sostenibile*; Ministry of Economic Development: Rome, Italy, 2013. Available online: http://www.sviluppoeconomico.gov.it/images/stories/normativa/20130314_Strategia_Energetica_Nazionale.pdf (accessed on 10 September 2014).
60. APEC. *Energy Demand and Supply Outlook*, 5th ed.; APEC, IEEJ: Tokyo, Japan, 2013. Available online: http://publications.apec.org/publication-detail.php?pub_id=1389 (accessed 10 September 2014).
61. CFE (Comision Federal de Electricidad). *Programa de Obras e Inversiones del Sector Electrico 2011–2025*; Comision Federal de Electricidad: Distrito Federal, Mexico, 2013. Available online: http://aplicaciones.cfe.gob.mx/aplicaciones/otros/POISE2011_2025%20WEB.ZIP (accessed on 10 September 2014).
62. MEMEE (Ministere de l'Energie, des Mines, de l'Eau et de l'Environment). *Etude Prospective de la Demande D'energie a L'horizon 2030*; Ministere de l'Energie, des Mines, de l'Eau et de l'Environment: Rabat, Morocco, 2013. Available online: http://www.mem.gov.ma/SitePages/GrandsChantiers/DOPPROSP203008–01–13.pdf (accessed on 10 September 2014).
63. K.A. Care (King Abdullah City for Atomic and Renewable Energy). *Saudi Arabia's Renewable Energy Strategy and Solar Energy Deployment Roadmap*; King Abdullah City for Atomic and Renewable Energy: Riyadh, Saudi Arabia, 2013. Available online: http://www.irena.org/DocumentDownloads/masdar/Abdulrahman%20Al%20Ghabban%20Presentation.pdf (accessed on 10 September 2014).
64. SA DoE (Republic of South Africa, Department of Energy). *Integrated Resource Plan for Electricity 2010–2030*; Revision 2, Final report; Republic of South Africa, Department of Energy: Pretoria, South Africa, 2011. Available online: http://www.energy.gov.za/IRP/irp%20files/IRP2010_2030_Final_Report_20110325.pdf (accessed on 10 September 2014).
65. KPX. *Present & Future of NRE: The 3rd National NRE Basic Plan*; Ministry of Trade, Industry and Energy: Sejong, Korea, 2011.
66. TEIAS (Turkish Electric Transmission Company). *Turkiye Elektrik Enerjisi 10 Yillik Uretim Kapasite Projeksiyonu (2012–2021)*; Turkish Electric Transmission Company: Ankara, Turkey, 2012. Available online: http://www.teias.gov.tr/YayinRapor/APK/projeksiyon/KAPASITEPROJEKSIYONU2012.pdf (accessed on 10 September 2014).
67. SAEE (State Agency for Energy Efficiency and Energy Saving of Ukraine). *National Renewable Energy Action Plan (NREAP) through 2020*; Draft. State Agency for Energy Efficiency and Energy Saving of Ukraine: Kiev, Ukraine, 2012. Available online: http://saee.gov.ua/documents/NpdVE_eng.pdf (accessed on 10 September 2014).
68. UNAS. *Investment Requirements and Benefits Arising from Energy Efficiency and Renewable Energy Policies in Ukraine*; UNAS: Kiev, Ukraine, 2013. Available online: http://www.iea-etsap.org/web/Workshop/Paris_Jun2013/1_4%20PodoletsDiachuk_TIMESUA.pdf (accessed on 17 June 2013).
69. IRENA/MI. *Renewable Energy Prospects: United Arab Emirates, REmap 2030 Analysis*; IRENA/Masdar Institute: Abu Dhabi, UAE, 2015.
70. DECC (Department of Energy & Climate Change). *Pathways to 2050: Key Results*; Department of Energy & Climate Change: London, UK, 2011. Available online: https://www.gov.uk/government/publications/pathways-to-2050-key-results (accessed on 11 May 2011).

71. DECC. *UK Renewable Energy Roadmap*; Department of Energy & Climate Change: London, UK, 2011. Available online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48128/2167-uk-renewable-energy-roadmap.pdf (accessed on 10 September 2014).
72. DECC. *Updated energy and emissions: 2012*; Department of Energy & Climate Change: London, UK, 2012. Available online: https://www.gov.uk/government/publications/2012-energy-and-emissions-projections (accessed on 15 October 2012).
73. US EIA. *Annual Energy Outlook 2013*; U.S. Energy Information Administration, U.S. Department of Energy: Washington, DC, USA, 2013. Available online: http://www.eia.gov/forecasts/aeo/pdf/0383(2013).pdf (accessed on 10 September 2014).