

Methodology background document:

**Development of a decarbonisation pathway for the global
energy system to 2050**

*A country-by-country analysis for the G20 based on IRENA's
REmap and Renewable Energy Benefits programmes*

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List of abbreviations

°C	degrees Celsius
Btu	British thermal unit
CAPEX	capital expenditure
CCS	carbon capture and storage
CO ₂	carbon dioxide
CSP	concentrated solar power
DLR	Deutsche Luft- und raumfahrt (German Aerospace Center)
EJ	exajoule
EU	European Union
EV	electric vehicle
G20	Group of Twenty
GBPN	Global Buildings Performance Network
GDP	gross domestic product
GEA	Global Energy Assessment
GEIDCO	Global Energy Interconnection Development and Cooperation Organization
GW	gigawatt
GW _{th}	gigawatt-thermal
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISF	Institute for Sustainable Futures at the University of Technology Sydney
km	kilometre
kt	kilotonne
kW	kilowatt
LT-RM	Sustainable long-term renewable market potential
MJ	megajoule
MW	megawatt
MWh	megawatt-hour
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-operation and Development
PJ	petajoule
PM	particulate matter
PPP	purchasing power parity
PV	photovoltaic
UK	United Kingdom
US	United States
USD	US dollar
VRE	variable renewable energy
yr	year

1. Introduction

The International Renewable Energy Agency (IRENA) has been tasked by the German government to prepare a scenario for decarbonisation of the global energy system by 2050. The study will inform the Germany 2017 G20 presidency, and its main aim is to identify how to operationalise the aims of the Paris Climate Agreement. The decarbonisation analysis is based on IRENA's global renewable energy roadmap (REmap) approach. The macroeconomic analysis is based on IRENA's analysis *Renewable Energy Benefits: Measuring the Economics*, using the E3ME model¹.

This background document provides an overview of the methodology used for the IRENA analysis that is presented in the joint IRENA-IEA report *Perspectives for the energy transition: Investment needs for a low-carbon energy system* (IRENA and IEA, 2017). This background document only overviews the methodology and sourcing used for the IRENA scenarios presented in that report. It does not detail the methodology or sources used by the IEA for its analysis.

The IRENA scenario analysis was led by the REmap team at IRENA's Innovation and Technology Centre. The Institute for Sustainable Futures (ISF) at the University of Technology Sydney has supported IRENA in assessment of the renewable energy potential and markets for G20 countries and the world. The main purpose of this paper is to document the methodology and data sources which contributed to the development of the REmap Case.

The REmap approach and analysis includes a number of steps:

- Development of a baseline (the "Reference Case" scenario) to 2050 based on national energy plans of the G20 countries; this provides a view of expected developments in energy demand and supply, and subsequently in greenhouse gas emissions to 2050.
- Assessment of the additional potential (compared to the Reference Case) of low-carbon technologies, namely renewable energy, material and energy efficiency, and carbon capture and storage (CCS).
- Development of a decarbonisation scenario (the "REmap" Case) that fulfils a carbon budget in line with the Paris Agreement to limit the global average surface temperature increase to below 2 degrees Celsius (°C) with a 66% probability.
- Analysis of the cost, benefits and investment needs of the additional implementation of low-carbon technologies required for the REmap Case.

2. The REmap approach and tool

IRENA has published renewable energy roadmaps for specific countries and regions since 2014 as part of its REmap programme (IRENA, 2014a, 2016a). IRENA's REmap programme determines the potential for countries, regions and the world to scale up renewables in order to ensure an affordable and sustainable energy future. REmap Cases represent worldwide renewable energy potential assembled from the bottom up, starting with separate country analyses done in collaboration with country experts, and then aggregating these results to arrive at a global picture. As of early 2017, these analyses cover 70 countries, representing 90% of global energy use.

¹ Developed by Cambridge Econometrics. More information at www.e3me.com

The REmap analyses assume two trajectories of energy system development:

- 1) **Reference Case** (a.k.a., baseline, or business as usual) based on national energy plans or similar reputable sources that forecast expected developments for the energy demand for a country.
- 2) **REmap Case**, a decarbonisation scenario based on the REmap technology options assessment approach. In the main report, this case may sometimes also be called the REmap scenario.

The assessment of both the Reference Case and the REmap Case is referred to in the whole as **the REmap approach**, while the additional potential of accelerating renewable energy, energy efficiency and other decarbonisation options is generally referred to as **the REmap Options**. This differs from normal REmap reports and analysis in that the normal approach only assess additional renewable energy technology potential with the aim of increasing solely renewable energy, whereas this study was conducted with the aim of decarbonising energy overall and includes additional measures beyond just renewable energy, such as energy efficiency, materials efficiency and other decarbonisation approaches that also include CCS and nuclear.

The analysis is based on a sectoral and technology-based bottom-up approach at the individual country level using an internally developed REmap tool. The bottom-up approach is complemented with a top-down global demand assessment done at the sectoral and sub-sectoral level with high technology resolution. A combination of both an iterative bottom-up country approach and a top-down sectoral approach allows for better representation of country plans in energy use forecasts, but also for a more cohesive global set of technology development assumptions and costs relating to decarbonisation technologies.

The standard IRENA REmap analysis is for the year 2030. In developing the 2030 country analyses, IRENA engages nominated experts from each REmap country who review and provide feedback on the analysis and findings. For the purpose of this assessment, IRENA has expanded the analysis for G20 countries to the year 2050. These analyses are completed for the G19 countries (which include the four large EU countries: Germany, the United Kingdom, France and Italy) plus the remaining EU countries. These results are compiled and scaled to a global level based on factors derived from IRENA's REmap global analysis.

2.1. Reference Case

The Reference Case has been constructed from projections for energy demand and supply, which reflect policies in place or anticipated in each country and incorporate expected market developments. The Reference Case, also referred to as the baseline, is broadly considered to be a business-as-usual case. For this analysis, IRENA has collected data for the G20 countries about their national energy plans, energy targets and forecasts for future years. This information is collated at the country level, and data gaps relating to coverage or time horizon are bridged using credible third-party scenarios (*e.g.*, the International Energy Agency, IEA), authoritative country sources (*e.g.*, energy projections carried out by local universities or research organisations) or IRENA internal analysis. Table 1 presents an overview of the source data by country for the Reference Case.

This Reference Case reflects country Nationally Determined Contributions (NDCs) if they are already an integral part of the country's energy plan, which is the case for around two-thirds of countries. It is important to note that some renewable energy and energy efficiency improvements already are accounted for in the Reference Case, depending on the level of ambition that each country has set in its national energy policy or NDC plans.

Table 1. Reference Case sources

	Main source(s) ¹ used to develop Reference Case for 2030-2050 ²	Consistent with NDC? ³
Argentina	IRENA analysis	N/A
Australia	BREE, 2014	N
Brazil	EPE, 2014, 2015	N
Canada	NEB, 2016	Y
China	CNREC, 2016	Y
EU-28	E3M-Lab, IIASA and Eurocare, 2016	Y
France	E3M-Lab, IIASA and Eurocare, 2016	Y
Germany	BMW, 2014	Y
India	IEA, 2016	Y
Indonesia	BPPT, 2015	Y
Italy	E3M-Lab, IIASA and Eurocare, 2016	Y
Japan	APEC, 2016	Y
Mexico	APEC, 2016	Y
Republic of Korea	APEC, 2016	Y
Russian Federation	APEC, 2016	N/A
Saudi Arabia	KA care, n.d.	N/A
South Africa	IRENA analysis	Y
Turkey	IRENA analysis	Y
United Kingdom	E3M-Lab, IIASA and Eurocare, 2016	Y
United States	EIA, 2016	N

¹ A comprehensive list of sources for the 40 countries that participated in the second version of the global REmap report can be found at http://www.irena.org/remap/IRENA_REmap_2016_edition_country_tables_march.pdf.

² The basis of all country Reference Cases covering the period until 2030 is IRENA's REmap (IRENA, 2016a).

³ Consistency was checked by comparing the greenhouse gas emission reduction target as indicated in the country's NDC and the level achieved in the Reference Case.

N/A = not able to determine

Source: IRENA analysis; UNFCCC, 2017

2.2. REmap Case (decarbonisation scenario)

The REmap Case explores low-carbon technology pathways to achieve a carbon budget in line with the Paris Agreement to limit the global average surface temperature increase to below 2°C with a 66% probability. Technologies considered in the REmap scenario include the following:

- Renewable energy technologies² for energy
- Renewable energy feedstocks for production of chemicals and polymers
- Energy efficiency measures, including electrification
- Material efficiency technologies such as recycling
- CCS for industry.

Energy demand by energy carrier is grouped into three demand sectors: buildings (including residential, commercial and public), industry (including agriculture) and transport. These three grouped sectors are called the end-use sectors. Two supply sectors are also analysed for power and district heat generation. The REmap Case gives preference to renewable energy and energy efficiency

² Solar, wind, hydro, biomass, geothermal and ocean.

technologies and sector-coupling solutions, such as electric vehicles (EVs), district heating and cooling, heat pumps, etc., ahead of other decarbonisation approaches such as CCS and nuclear energy.

The end-use analysis is carried out at a sub-sectoral level. Activity-level growth rates were estimated for the period between 2015 and 2050. Each end-use sector is divided into the main energy-consuming applications – for example, steel production. For energy efficiency and materials efficiency the analysis combines this with technology options to reduce energy use for a given level of production. The technology potential of renewable energy also is analysed at the sub-sectoral level – for example, the potential of a renewable energy technology to provide water heating in the building sector. This potential of the relevant low-carbon technologies for each application was estimated based on market growth rates, resource availability and other constraints³.

To assess interactions between the demand and supply sectors, specifically the power sector, additional analysis was carried out. For European Union (EU) countries the PLEXOS dispatch model was used to model capacity requirements in a high-renewables scenario (IRENA, 2017a; Collins *et al.*, 2016). For other large countries, the analysis relies on studies and modelling by other institutions (NREL, 2012; CNREC, 2015).

The carbon dioxide (CO₂) emissions have been estimated for both the Reference and REmap Cases by country, sector and fuel for 2015 and 2050.

2.2.1. Industry sector assessments

The following five energy-intensive sub-sectors have been considered in the analysis: iron and steel, cement, chemical and petrochemical, pulp and paper, and aluminium. All other sectors (food, textiles, etc.) have been assessed together. The energy efficiency improvement potential beyond the Reference Case is based on an earlier assessment carried out by Kermeli *et al.* (2014) and Saygin (2012).

2.2.2. Assessment of CCS potential

The potential for CCS has been considered at a global level only for three major CO₂-emitting industries: iron and steel, cement, and chemical and petrochemical production. CCS is not considered for electricity generation. The potential is considered only for the REmap Case, with no CCS deployment included in the Reference Case. Assessment for these industry-based uses is based mainly on Kuramochi *et al.* (2012) and Saygin *et al.* (2013).

2.3. Assessment of the renewable energy potential

IRENA provided the Reference Case to 2050 based on the method described in section 2.1, and the REmap Case to 2030 based on analysis for G20 countries carried out as part of the ongoing REmap programme work. Therefore, a gap existed in the analysis for 2050 relating to the decarbonisation potential. To fill this gap, the Institute for Sustainable Futures at the University of Technology Sydney conducted an analysis for G20 renewable energy trajectories to 2050 (except Germany, the UK, Saudi Arabia and Indonesia) by extending the IRENA 2030 REmap scenario to 2050. The 2050 trajectories achieve a pathway to stay within a global carbon budget of 790 gigatonnes of energy-related CO₂ emissions, consistent with a maximum 2°C temperature increase with a 66% probability compared to pre-industrialisation levels.

³ For example, a switch to new iron-making processes reduces availability of blast furnace slag as a clinker substitute. Also biomass scarcity has been accounted for across all possible applications.

The global trajectory as well as the national/regional trajectories for Brazil, Canada, China, the EU, France, India, Italy, Japan, South Africa and the US build on the approach for 1.5 °C -2°C scenarios for the *Energy [R]evolution* series developed by the German Aerospace Center (DLR-GPI, 2015). The *Energy [R]evolution* series is target-oriented scenarios using a “bottom-up” approach (technology-driven), with assumed growth rates for population, gross domestic product (GDP), specific energy demand and the deployment of renewable energy technology as important inputs. The supply scenarios were calculated using a model developed by DLR on the basis of the commercial database software Mesap/PlaNet⁴.

The DLR model does not use a cost optimisation approach; instead, it requires a consistent exogenous definition of feasible developments in order to meet the overall target. Using assumptions and background information about technical and structural options for the transformation of the energy system, and taking into account – as far as possible – premises about economic, political and social realities, interests, and the resulting barriers and incentives, consistent development paths are defined and integrated into the model database. The model as accounting framework then calculates the energy balances of the future for all sectors as well as related investments and costs in the power sector.

In the Australian REmap Case, renewable energy trajectories are taken from a 100% renewable energy scenario developed by ISF (UTS-ISF, 2016). For Germany, the climate plan based on the Projection Report was used for the 2050 REmap Case (BMUb, 2015). Individual assessments for the remaining countries, including Saudi Arabia, Indonesia and the UK, were done by IRENA.

The structure and initial parameterisation of the energy system for each region and/or country are extracted from the extended energy balances published in 2014 by the IEA (“Energy balances of non-OECD countries” and “Energy balances of OECD countries” (IEA, 2014a, 2014b)). The calculation of potential renewable energy market development has been limited only by technical constraints, such as access to required electricity grid capacities; it is assumed that favourable energy and climate policies are in place in all G20 countries.

The main input parameters are:

- The Reference Case scenarios for national demand, from IRENA (2016a).
- Current market volumes for renewable energy, taken from IRENA estimates.
- The regional/national technical potentials for renewable energy, taken from literature. ISF extended the projections contained in REmap 2030 to 2050 (IRENA and IEA 2017), taking into account previous growth rates, market sizes and cost assumptions.
- Energy efficiency indicators for building and transport sector from literature and published scenarios.

Energy efficiency indicators from literature were used to modify the Reference Case energy demand projections from the IRENA trajectories in the low-emission case.

The mix of renewable energy technologies and their installed capacities for the last year of this analysis (2050) were developed by reviewing published scenarios – mainly from the DLR *Energy [R]evolution* series VI (see *Bibliography – Scenarios*). ISF has not undertaken a power system analysis for the

⁴ Mesap (2015). Commercial software from Seven2one Informationssysteme GmbH. Karlsruhe, Germany.

generation mix to take into account system security with regard to variable renewables, as this was not within the scope of the study.

2.3.1. Renewable energy potential

Renewable energy potential is used to set a ceiling for the development of renewable energy trajectories to 2050. Five different types of renewable energy resource potentials are documented in the literature, originally developed by the German Advisory Council on Global Change (WBGU, 2003) and established as an international standard by the Intergovernmental Panel on Climate Change (IPCC) for its *Special Report on Renewable Energy and Climate Change Mitigation* (IPCC, 2011). The five types of potentials are:

1. **Theoretical potential:** The physical upper limit of the energy available from a certain source. For solar energy, for example, this would be the total solar radiation falling on a particular surface.
2. **Conversion potential:** Derived from the annual efficiency of the respective conversion technology, this is not a strictly defined value, since the efficiency of a particular technology depends on technological progress.
3. **Technical potential:** This takes into account additional restrictions regarding the area realistically available for energy generation. Technological, structural and ecological restrictions and legislative requirements are accounted for.
4. **Economic potential:** The proportion of the technical potential that can be utilised economically. Biomass, for example, is included if it can be exploited economically in competition with other products and land uses.
5. **Sustainable potential:** The potential of an energy source is limited based on an evaluation of ecological and socio-economic factors.

ISF used a combination of the technical potential and the sustainable long-term market potential to create a new definition for potential and use it to determine the accelerated renewable projections for the assessment. This new definition for potential utilises technical potentials obtained from the literature, while developing a market potential perspective used for this assessment:

6. **Sustainable long-term renewable market potential (LT-RM):** This category of potential is discussed in detail in section Table has been reproduced from Ecofys (2007; 2008).

7. 2.3.3.

Sustainable long-term renewable market (LT-RM) potential calculation

Technical potential is defined as the amount of renewable energy output resulting from full implementation of the technology, taking into account the primary resource, the socio-geographical constraints and the technical losses in the conversion process. The theoretical and conversion potentials inevitably overestimate practical implementation pathways, as they do not take into account constraints, while the current economic and sustainable potentials do not account for the changing conditions resulting from an imperative to keep the global temperature rise under 1.5°C.

The technical potential depends on a number of parameters. For instance, a technology breakthrough could have a dramatic impact, changing the technical potential assessment within a very short time

frame. More recent data, such as significantly increased average wind turbine capacity factors and output, would increase the technical potentials still further. A wide range of estimates is provided in the literature, but studies have consistently found that the total global technical potential for renewable energy is substantially higher than both current and projected future global energy demand.

Solar has the highest technical potential among the renewable energy sources, but substantial technical potential exists for all forms of renewables. The various types of renewable energy potentials cannot necessarily be added together to estimate a total, because each type is estimated independently of the others (for example, the assessment did not take into account land-use allocation: solar photovoltaics (PV) and concentrating solar power (CSP) cannot occupy the same space when a particular site is suitable for either).

Due to the large number of studies and sources used as part of this assessment and described in this document, the Annex A: Sources for energy efficiency and infrastructure costs

Sector	Measure	Sub-sector	Parameters	References
Industry	Energy efficiency	Iron and steel	Additional CAPEX, fossil fuel/electricity savings	US EPA, 2012
		Cement		US EPA, 2010
		Pulp and paper		Martin and Anglani, 2000
		Chemicals		IEA, 2014d
		Aluminium		Kermeli <i>et al.</i> , 2015
		Motors	Energy savings and cost, CO ₂ savings	UNIDO, 2010
	Technology	Iron and steel	Renewable and capital CAPEX, operation & maintenance cost	IEA, 2015; IRENA, 2014c; IRENA and IEA-ETSAP, 2013a, 2015a; IRENA and IEA-ETSAP, 2013b; Smolinka <i>et al.</i> , 2016
		Cement		IEA, 2009
		Pulp and paper		Broeren <i>et al.</i> , 2013; IEA, 2008, 2009
		Chemicals		
		Aluminium		IEA, 2009
Transport	Energy efficiency	Passenger light-duty vehicles and road freight	Additional CAPEX, primary fuel savings	IEA, 2014d
		Light-duty vehicles	Improvement potential	ICCT, 2016; US DOE, 2013
	Technology	Passenger and freight (all modes)	Technology cost/performance, commodity prices	IRENA, 2013, 2015a, 2016b, 2017c; IRENA and IEA-ETSAP, 2013a; IRENA and IEA-ETSAP, 2013b
	Infrastructure	Hydrogen station	CAPEX	Melaina and Penev, 2013
		Electric vehicle charging station		US DOE, 2015a
Buildings		Insulation	Additional CAPEX, fuel cost savings, CO ₂ savings, lifetime	Breithaupt, 2015; NIA, 2016
		Windows		DECC, 2012; Breithaupt, 2015
		Reflective roof		RoofingCalc, 2016; US DOE, 2015b
		Appliances – demand side		The co-operative energy, 2013
		Appliances – improved efficiency	Additional CAPEX, energy savings	Wada <i>et al.</i> , 2012

	Energy efficiency	Lighting		
		Smart home system		DECC, 2012; Breithaupt, 2015
		Boilers	Additional CAPEX, lifetime, energy savings	Breithaupt, 2016; IRENA, 2017d
		Heat pumps		
		Renovation cost for building types – space heating and cooling	Additional CAPEX	GBPN and ABUD, 2015
Power	Infrastructure	Transmission grid, storage, curtailment, utilisation	Average integration Cost, discount rate, lifetime	IRENA and IEA-ETSAP, 2015b; Scholz <i>et al.</i> , 2016; SMASH, 2013
		Distribution network		IEA, 2014c
	Technology	Renewable generation costs and forecasts	Generation costs	IRENA, 2015b, 2016e
General	Technology	Global costs	Technology cost/performance, commodity prices	IRENA, 2016c
		REmap country-specific costs		IRENA, n.d.
		Technology brief		IRENA and IEA-ETSAP, n.d.
		Bioenergy	Feedstock cost	IRENA, 2014b

Bibliography section at the end of the paper provides a large list of sources broken down by technology or topic.

2.3.2. Technical potential in the G20 countries

The technical potential for renewable energy in the G20 countries for the year 2050 has been estimated based on regional resource assessments by Ecofys (2007; 2008), the IPCC (2011) and the Global Energy Assessment (GEA, 2012); those potentials are in line with other sources. The technical potential is subject to technical developments and can increase via improvements. For example, the technical potential for offshore wind would change if the availability of floating foundations improved, as that would increase the area of application for this technology.

Table 2. Technical renewable energy potential of G20 countries for 2050

Country	Technical potential EJ/year electric power							EJ/year heat		EJ/year primary
	Solar CSP	Solar PV	Hydro power	Wind onshore	Wind offshore	Ocean	Geothermal electric	Geothermal direct uses	Solar water heating	Biomass residues
Australia	169	216	1	51	1	14	4	296	2	1
Argentina	3	34	2	1	1	50	2	146	6	3
Brazil	9	105	6	4	0	11	5	447	19	10
Canada	10	36	2	78	2	53	3	312	11	8
China	261	332	3	13	0	1	2	468	5	3
France	1	3	0	1	0	1	0	25	1	0
Germany	1	2	0	1	0	0	0	16	1	0
India	89	114	1	4	0	1	1	160	2	1
Indonesia	52	66	1	3	0	11	0	93	1	1
Italy	1	2	0	1	1	3	0	14	0	0
Japan	10	13	0	1	0	1	0	18	0	0
Mexico	2	24	1	1	0	14	1	103	4	2
Republic of Korea	3	3	0	0	0	0	0	5	0	0
Russia	44	107	11	42	5	27	10	772	26	15
South Africa	1	4	0	2	0	1	0	22	0	0
United Kingdom	1	2	0	1	1	3	0	11	0	0
United States	10	35	2	75	1	16	3	301	11	8
Saudi Arabia	1	7	0	4	0	1	0	38	0	0
Turkey	2	5	1	2	0	0	0	35	1	1
Global	992	1 693	47	379	22	321	45	4 955	123	73

Table has been reproduced from Ecofys (2007; 2008).

2.3.3. Sustainable long-term renewable market (LT-RM) potential calculation

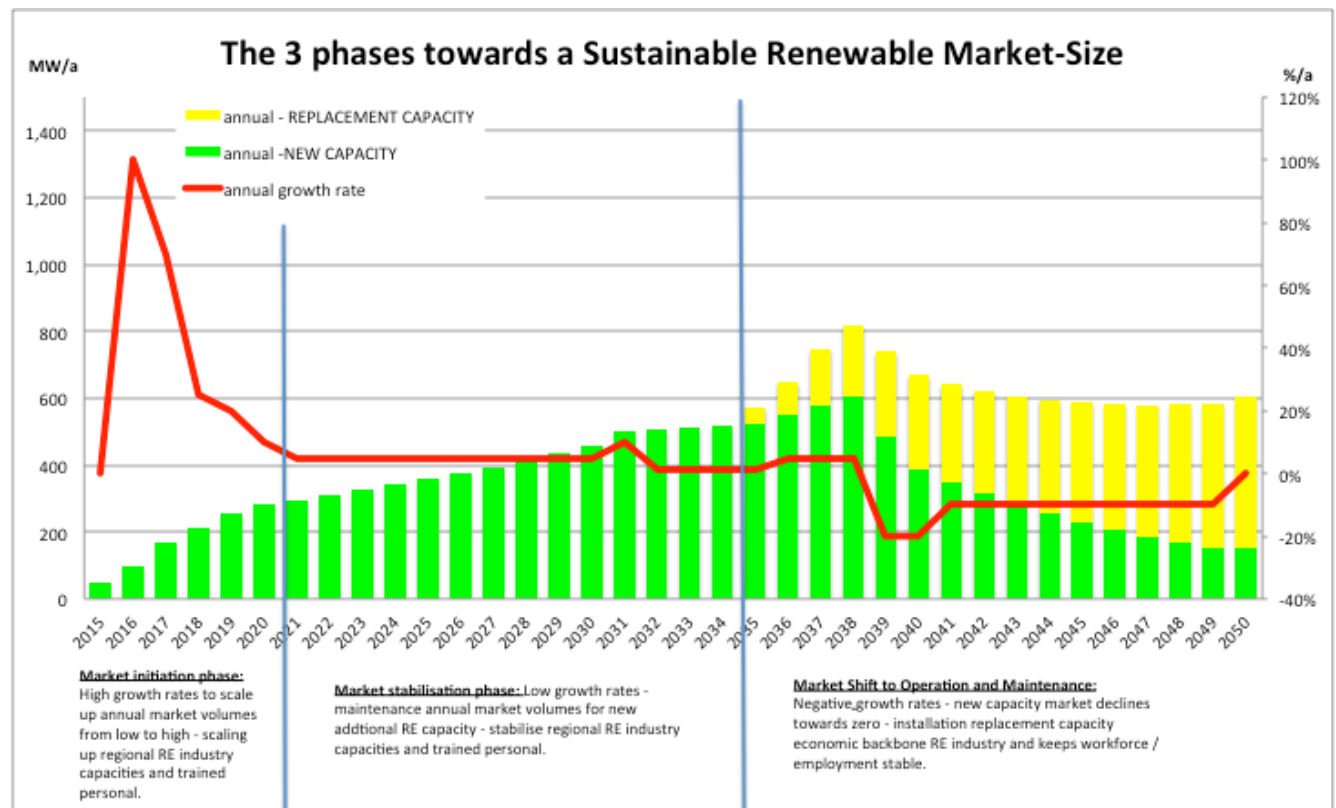
ISF developed a new indicator for renewable energy potential – *the sustainable long-term renewable market potential* – to find a sustainable market development pathway for ambitious renewable energy expansion that avoids boom-and-bust cycles with the associated job losses. Such a pathway requires realistic time frames for the expansion of manufacturing and installation infrastructure, as well as allowing time for training and education of personnel.

Although the final installed capacities for each technology for the year 2050 are based on published scenarios (primarily the *Energy [R]evolution* series; see *Bibliography – Scenarios*), the sustainable growth rates have been developed for the assessment described in this document. The time frames

required to develop infrastructure for manufacturing and installation, as well as for training personnel, are based on historical experience as documented in renewable industry publications (see *Bibliography – Technology pathways*).

The *sustainable long-term renewable market potential* has been calculated as that which would provide stable market conditions for the entire scenario period to 2050, to support the development of sustainable national and regional renewable industries. Market development has been divided into three phases (see Figure 1). The figure is based on the LT-RM for Argentina's solar PV market between 2015 and 2050.

Figure 1. The three phases in development of a sustainable renewable energy market for solar PV, 2015-2050



Source: The figure shows one example based on the LT-RM solar PV projection for Argentina.

The three phases have different calculation methods for potential, with the formula developed by ISF presented below.

1. Initiation phase:

Renewable energy policy provides secure market conditions to enable high growth rates. In the initiation phase, the renewable energy industry needs to scale up manufacturing capacities, purchase infrastructure (for example, offshore cranes for offshore wind) and develop local knowledge, such as trained workforces. Furthermore, the G20 renewable market potential needs to take into account constraints such as training needs, regional know-how, development of local manufacturing and maintenance services, and the required financial services. The social license to operate requires public acceptance, which in turn requires good communication and public consultation, and also limits the speed of expansion to some extent. These constraints cannot be calculated in a mathematical formula but require a further in-depth, on-site analysis.

The growth rate for the initiation phase is calculated from experiences in comparable countries and on published market development projections, which are exogenous input parameters (for details and references see *Bibliography – Technology pathways*).

$$P_{AM-IP} = P_{AM-yr-1} * GR_{yr-IP}$$

$$GR_{yr-IP} = (P_{IP} / P_{CC-REF}) / T_{IP}$$

$$GR_{IP} = (P_{IP} / P_{CC-REF})$$

where:

P_{AM-IP} :	Renewable capacity; annual market volume – initiation phase	[MW/yr]
P_{CC-REF} :	Cumulative installed capacity; reference year	[MW/yr]
$P_{AM-yr-1}$:	Renewable capacity; annual market volume – previous year	[MW/yr]
P_{IP} :	Target cumulative renewable capacity for entire period	[MW/yr]
GR_{IP} :	Total growth rate – initiation phase	[%]
GR_{yr-IP} :	Annual growth rate – initiation phase	[%/yr]
T_{IP} :	Period length – initiation phase	[yr]

2. Stabilisation phase:

The renewable energy market stabilisation phase requires stable and long-term energy policies in order to achieve a consistent increase in renewable energy shares. Growth rates decline and are similar to other mature industries. The renewable energy industry restructures towards the end of this period towards operation and maintenance and repowering if it is to maintain stability.

$$P_{AM-SP} = P_{AM-yr-1} * GR_{yr-SP}$$

$$GR_{yr-SP} = (P_{SP} / P_{CC-IP-end}) / T_{SP}$$

$$GR_{SP} = (P_{SP} / P_{CC-IP-end})$$

where:

P_{AM-SP} :	Renewable capacity; annual market volume – stabilisation phase	[MW/yr]
$P_{CC-IP-end}$:	Cumulative installed capacity; last year – initiation phase	[MW/yr]
$P_{AM-yr-1}$:	Renewable capacity; annual market volume – previous year	[MW/yr]
P_{SP} :	Target cumulative renewable capacity for entire period	[MW/yr]
GR_{SP} :	Total growth rate – stabilisation phase	[%]
GR_{yr-SP} :	Annual growth rate – stabilisation phase	[%/yr]
T_{SP} :	Period length – stabilisation phase	[yr]

3. Market saturation phase:

Further increase in new additional capacities of this specific renewable energy technology in the analysed country is not possible any more. The industry has restructured successfully and aims to maintain technology market shares. Repowering of capacities that reached the end of their technical lifetime replaces new additional capacities, while annual installation volumes remain the same as during the stabilisation phase. The long-term market size for new capacities remains relatively stable as repowering capacities at the end of the technical lifetime repeat market volumes.

$$P_{AM-SA} = P_{AM-yr-1} * GR_{yr-SA} + P_{yr-LT}$$

$$GR_{yr-SA} = (P_{SA} / P_{CC-SP-end}) / T_{SA}$$

$$GR_{yr-SA} = (P_{SA} / P_{CC-SP-end})$$

where:

P_{AM-SA} :	Renewable capacity; annual market volume – saturation phase	[MW/yr]
$P_{CC-IP-end}$:	Cumulative installed capacity; last year – saturation phase	[MW/yr]
$P_{AM-yr-1}$:	Renewable capacity; annual market volume – previous year	[MW/yr]

P_{SA} :	Target cumulative renewable capacity for entire period	[MW/yr]
GR_{SA} :	Total growth rate – saturation phase	[%]
GR_{SA-yr} :	Annual growth rate	[%/yr]
T_{SA} :	Period length – saturation phase	[yr]
P_{yr-LT} :	Renewable capacity; annual market volume LT year ago	[MW/yr]
LT:	Technical lifetime renewable energy technology	[yr]

With the following assumed life times:

Solar PV:	25 years
Wind – onshore:	20 years
Wind – offshore:	30 years
Bioenergy – power:	20 years
Bioenergy – heat:	20 years
Geothermal – power:	20 years
Geothermal – heat:	20 years
Hydropower:	100 years

2.3.4. Renewable energy technical and market potential for G20 countries

Power sector technologies

REmap trajectories include the following eight renewable power generation technologies:

- 1) solar PV
- 2) CSP
- 3) onshore wind
- 4) offshore wind
- 5) bioenergy power plants
- 6) geothermal power plants
- 7) hydropower
- 8) ocean power

While the first six technologies are mature with established markets, ocean energy is under development. Thus low market shares are assumed until 2030, increasing in the second half of this century. This section provides an overview of the key assumptions and references for the REmap Case.

Solar PV

The IRENA G20 decarbonisation study results in more than 6 000 gigawatts (GW) of installed solar PV capacity in REmap by 2050. Under the market potential trajectories of ISF, the global solar PV market will increase significantly from a cumulative capacity of 227 GW in 2015, with 50 GW installed during 2017, to around 3 000 GW by 2030 and over 6 000 GW by 2050. The main source for the global projection was the DLR-GPI 2015 study that projected a possible increase in global solar PV capacity to over 800 GW by 2020 and up to 9 300 GW in 2050.

This study reduces the 2050 projection to take into account the market potential, in order to achieve stable industry development. ISF projects that the initiation phase capacity will reach 175 GW by 2020, an order of magnitude similar to that projected by the solar PV industry for the initial market development phase between 2016 and 2020 (Schmela, 2016).

The long-term solar PV market size, including replacement capacities after 20 years of technical lifetime, could grow to approximately 500 GW in 2040 and then remain at this level until the end of

the modelling period. Although the G20 countries are currently the most important market for the PV industry, the global market is expected to diversify and expand beyond this region. However, the G20 countries alone could maintain a stable long-term market of 100 GW from 2025 onwards.

CSP

The IRENA G20 decarbonisation study results in more than 700 GW of installed CSP capacity in REmap by 2050. Under the market potential trajectories of ISF, the trajectory for CSP plants focuses on countries within the global sunbelt that have more than 2 000 sunshine hours per year. The annual CSP market in 2015 was 0.5 GW, significantly smaller than the market for solar PV. However, CSP technology has technical advantages which offer significant growth opportunities, as CSP can provide energy storage as well as steam that can be used for industrial process heat. The ISF pathway for CSP would lead to a sharp increase in the annual market up to 40 GW by 2025 and a stable market of around 100 GW from 2030 onwards.

G20 countries are currently the most important market for CSP. Although the global market is expected to diversify, the G20 region is expected to remain significant for the next two decades, with G20 market shares of 80% and 60%, respectively. The total annual market volume for CSP is projected to grow to 200 GW per year if repowering is included. The global cumulative CSP capacity increases to more than 1 100 GW by 2035 – equal to the current hydropower capacity – and rises to 2 500 GW in 2050.

Wind power

The IRENA G20 decarbonisation study results in more than 4 800 GW of installed wind power capacity in REmap by 2050. Under the sustainable market potential trajectories of ISF, the annual wind market capacity in 2015 reached 63 GW, the largest capacity of all renewable power technologies. Onshore wind dominates the global wind power market, although the offshore wind market is starting to expand as costs decline. However, the onshore wind market is assumed to remain dominant over the entire modelling period. The ISF trajectory for wind power would double the current market every five years until 2025 and remains at around 250 GW to 2050. The market shares of G20 countries will drop from over 80% currently to 50% in 2030 and less than 40% by 2050.

The overall global cumulative capacity of wind power increases from 433 GW in 2015 to 8 000 GW at the end of the modelling period. Thus wind power and solar PV will have comparable total capacities and are expected to dominate all other renewable power technologies.

Geothermal power

The IRENA G20 decarbonisation study results in more than 280 GW of installed geothermal power capacity in REmap by 2050. Under the sustainable market potential trajectories of ISF, the market for geothermal power generation – contrary to geothermal heating – is concentrated in countries with high geothermal temperatures close to the surface, mainly around the Pacific “ring of fire” and at the edge of continental plates. To date G20 countries host around 50% of the total installed geothermal power plant capacity. The ISF development would lead to a sharp increase in capacity from 3 GW in 2015 to 25 GW in 2025, where it reaches a stable market size until 2050. To reach the projection for 2050, the cumulative capacity of geothermal power plants needs to increase from 13 GW in 2015 to 700 GW (equal to the total solar PV and wind capacities of 2015 combined) in 2050.

Bioenergy

The IRENA G20 decarbonisation study results in more than 400 GW of installed bioenergy capacity in REmap by 2050. Under the sustainable market potential trajectories of ISF, the 2015 market volume

for bioenergy power generation, at around 5 GW, is almost twice as large as for geothermal power plants. G20 countries hold a 25% share of the global market – a threshold that increases to around 50% over the entire modelling period of the ISF pathway. The annual market would increase to a stable size of around 15 GW, leading to an increase in the cumulative capacity from 100 GW in 2015 to 620 GW in 2050.

Hydropower

The IRENA G20 decarbonisation study results in more than 1 600 GW of installed hydropower capacity in REmap by 2050. Under the sustainable market potential trajectories of ISF, the market for hydropower is assumed to be mature, and market saturation already has been reached in most industrialised countries. However, the market for new hydropower plants remains significant with an annual volume of around 30-40 GW per year – within the order of magnitude of solar PV and wind power for the past 5-7 years. New capacities are specifically installed in China and other emerging and/or developing economies. China is by far the largest market but is expected to reach the end of its technical potential within the next 10 years; therefore, the annual market volume declines sharply after 2025. Total cumulative capacity increases by 50% from around 1 100 GW in 2015 to 1 500 GW in 2050.

Ocean energy

The IRENA G20 decarbonisation study results in 80 GW of installed ocean energy capacity in REmap by 2050. Under the sustainable market potential trajectories of ISF, ocean energy is assumed to be at a development stage equal to the wind industry in the 1980s, and future developments are difficult to predict. It remains unclear if ocean energy will be able to compete with solar and wind in specific applications. Potentially this technology could be combined with offshore wind installations for dispatch power supply. Thus ocean energy is the “wild card” under the renewable power generation group, with an annual market potential of around 20-30 GW over the next decades. ISF includes this technology due to its advantages for island power supply and for coastal communities that have strong tidal ranges or ocean currents.

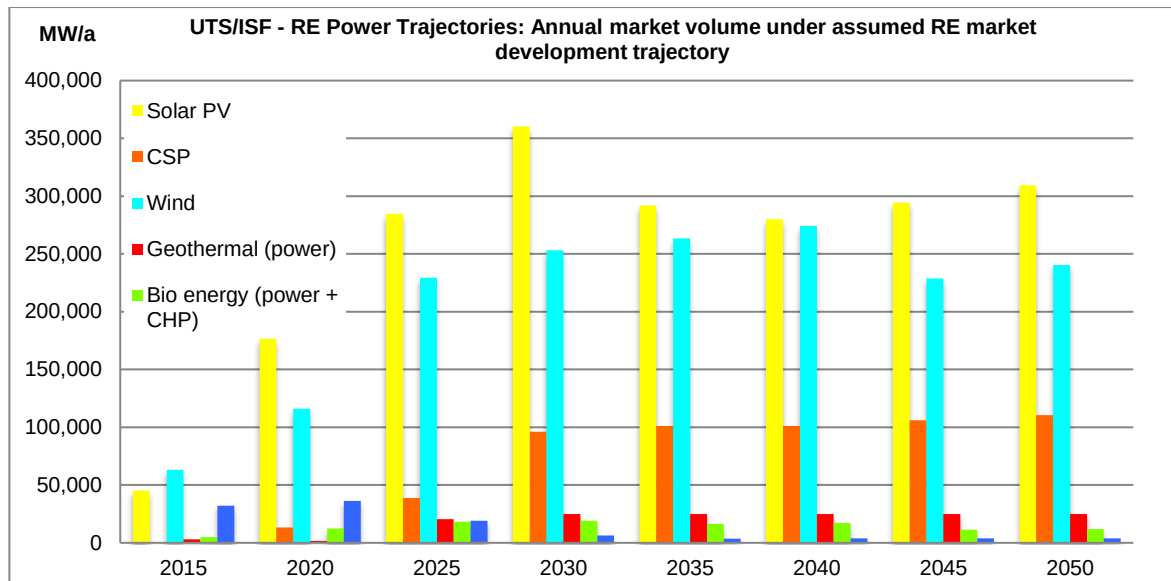
Global renewable power market capacity trajectories

This section provides an overview of the renewable power market trajectories calculated by ISF.

The 2050 capacity is established by taking into account the technical capacity, the capacity which may be achieved using stable market trajectories, the 2050 demand from the IRENA Reference Case, and a reasonable balance of supply types based on literature sources for technical potential at 2050. The ramp rate from current installations to the end point is calculated using the *sustainable long-term renewable market potential* growth rates derived for this study.

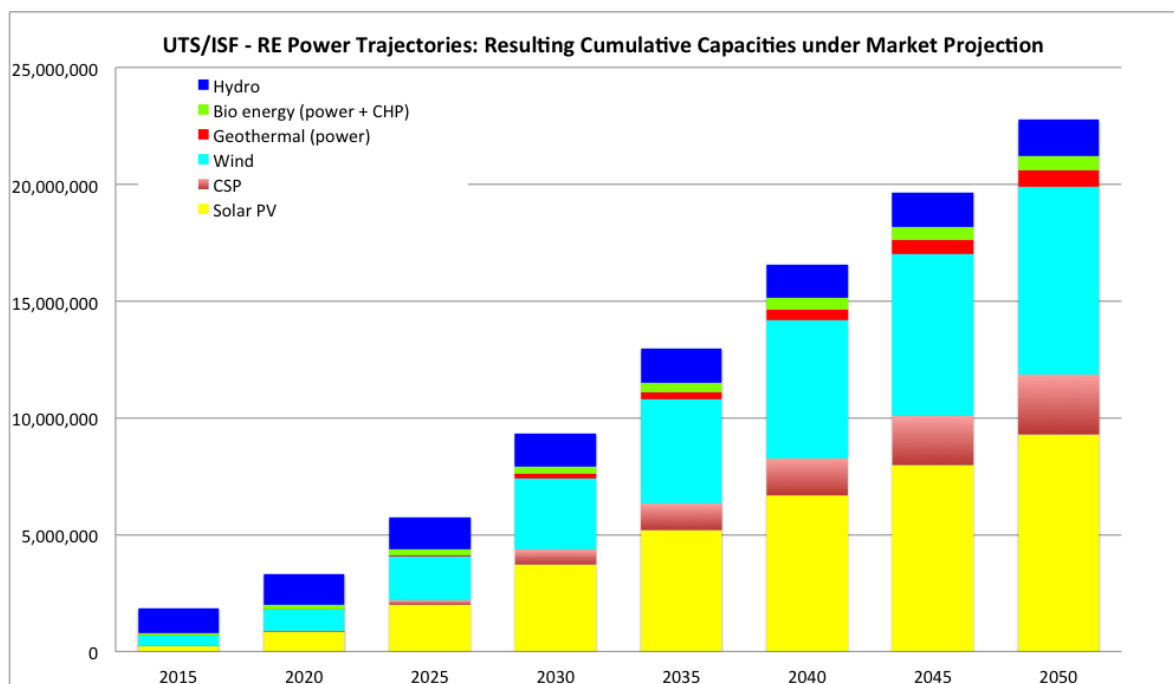
The global renewable power market is expected to remain dominated by solar PV and wind power in the foreseeable future in all ISF trajectories. Hydropower continues to be the third most important technology for the next decade, with regard to both cumulative capacities and the annual market. CSP may exceed the annual market volume of hydropower after 2025, and it could surpass the cumulative capacity of hydropower around 2040. Cumulative installed capacity for geothermal and bioenergy generation grow to equal levels under the ISF market projection – used mainly for dispatch power or in combination with heat production as co-generation plants (combined heat and power, or CHP).

Figure 2. Global annual renewable power market development, including replacement capacities, 2015-2050



Source: ISF projection

Figure 3. Cumulative global renewable power capacity, 2015-2050



Source: ISF projection

Heating sector

The ISF analysis includes three renewable heating resources: solar, bioenergy and geothermal energy. However, in contrast to the power sector, the technologies available for these resources are very diverse. Solar energy can be used for solar collectors to heat service water (washing, showers, etc.), for space heating as well as for industrial or commercial process heat. Geothermal energy can be used via high-temperature applications, or in low-temperature applications such as geothermal heat pumps, which is a very large market. Bioenergy, with conversion technologies for solid, liquid and gaseous fuels, represents the largest market segment in heating to date. The trend to electrify heating

applications might lead to a decrease in traditional thermal heating technologies, with regard to both fossil fuel and renewable energy sources.

Solar heating

Currently China dominates the market for solar heating collectors with a market share of over 80%. China installed 30 GW in 2015, mainly glazed evacuated tube collectors. Turkey came second with a total of 1.5 GW installed during 2015; all other countries installed between 1 GW and a few hundred MW. There is currently a trend towards electrification of the heating sector, so it is assumed that established markets remain and that the new markets will likely be in Europe and North America, while other regions might leapfrog directly to higher shares of electric heating systems. In the ISF trajectory, market volumes increase by a factor of 10 by 2030 and remain at that level until 2050, including the increase in annual replacement capacity after 2030. However, the IRENA assessment assumes additional growth after 2030 until 2050, driven in part by increased adoption of solar thermal low- and medium-temperature systems in industry.

Geothermal heating

The geothermal heat market is based mainly on heat pumps and benefits from the electrification trend of the heating sector which is assumed after 2030. Direct geothermal heating systems are assumed to grow more slowly than heat pumps. The overall geothermal heating market under the ISF trajectories increases from 0.3 GW in 2015 to around 30 GW between 2030 and 2050.

Bioenergy heating

The bioenergy heat market is based mainly on stand-alone boiler and biomass-fuelled co-generation plants. The ISF projections assume a reduced use of bioenergy for heating and power and a shift towards transport fuels and industrial processes after 2030. The global annual market volume was 5 gigawatts-thermal (GW_{th}) in 2015 (REN21, 2016). Under the ISF trajectory the annual market increases to 9.5 GW_{th} by 2030 and remains at this level until the end of the modelling period.

2.4. Assessment of the energy efficiency potential

2.4.1. Buildings

High-resolution, country-level data on the energy efficiency potential of buildings are very limited, and no consistent dataset exists even for the G20 countries. A combination of the different datasets therefore has been used to provide input parameters for the IRENA REmap model to calculate energy efficiency potentials for buildings. The main source of data is the Global Buildings Performance Network (GBPN) online database and analysis tool. GBPN is a global organisation that provides policy expertise and technical assistance to advance building energy performance. The data collection and analysis tool has been developed at the Centre for Climate Change and Sustainable Energy Policy (3CSEP) at the Central European University in Budapest, Hungary.

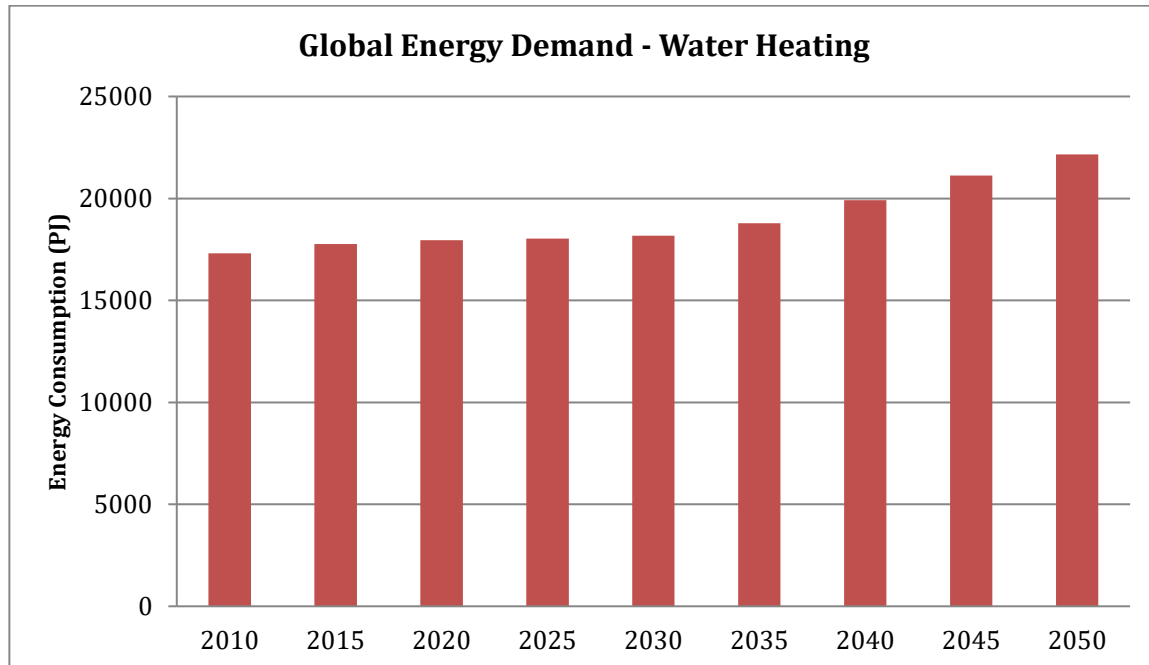
Three datasets of the GBPN analysis tool have been used, for space heating, cooling and water heating. Values (in petajoules, PJ) were given for 13 regions of the world for the period 2010 to 2050, in five-year increments. Deep-efficiency and moderate-efficiency values were given for each region and period, for the three categories of residential, commercial and all buildings.

Potential savings were determined using the following formula:

$$\text{Efficiency potential (\%)} = \frac{(\text{Moderate eff. energy use (PJ)} - \text{deep eff. energy use (PJ)})}{\text{Moderate eff. energy use (PJ)}}$$

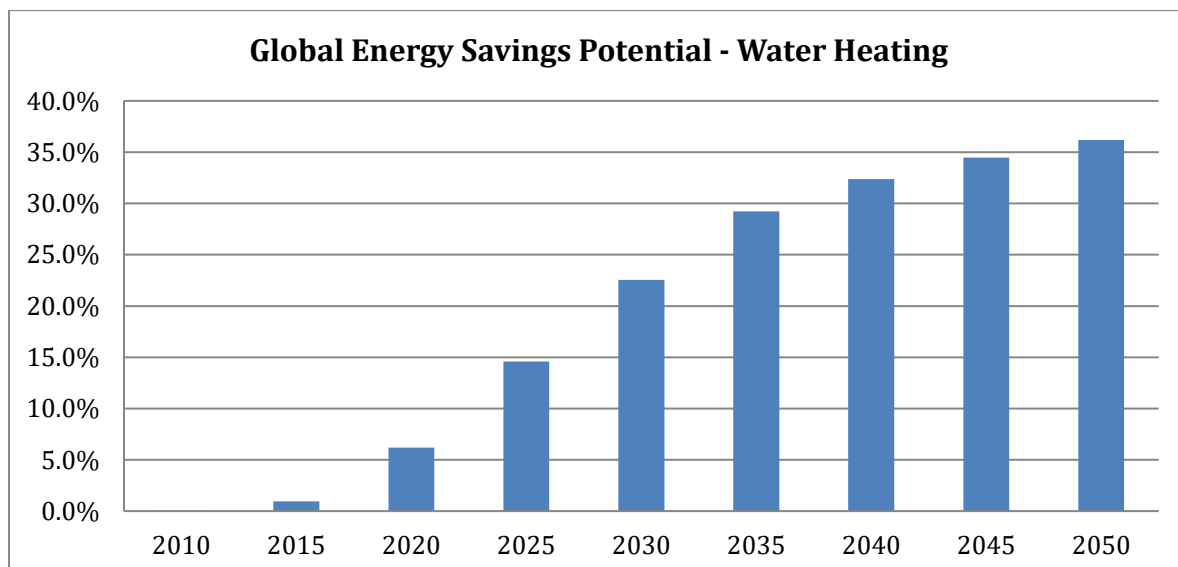
where efficiency potential describes the total percentage of energy in that area that theoretically could be saved each year; moderate efficiency use describes the energy demand for each region in PJ for that application where moderate efficiency measures are put in place; and deep efficiency describes the energy use where very high efficiency goals are met.

Figure 4. Global energy demand for water heating, 2010-2050



Source: Calculated based on GBPN data.

Figure 5. Global energy savings potential for water heating, 2010-2050



Source: Calculated based on GBPN data.

2.4.2. Transport

The REmap scenario assumes that sustainable transport technologies are needed to decarbonise, just as much as a shift to renewable electricity and heat production. A transition from fossil fuels to renewable energy sources is necessary, achieved either by means of direct use of electricity for transport or via synthetic fuels.

Trajectories for energy demand for the transport sector by country and region are calculated on the basis of annual kilometres per person (for the transport of people) and per kilogram for freight transport, specific energy demand per kilometre and technology market shares. The data for the transport segment contain transport information for the road, rail, aviation and navigation sectors.

The assumptions and data are based on a research project by DLR's Institute of Vehicle Concepts, which analysed the entire global transport sector based on the 10 IEA world regions with the intent to achieve 100% emission-free energy by 2050 (DLR, 2012), as well as on additional DLR research that focused on the latest developments in land-based transport systems, especially for megacities (DLR, 2015). The technology shift towards efficient transport technologies includes a sharp increase in electric drives that leads to significantly higher electricity demand for transport.

A three-step approach was taken to decarbonising the transport sector:

- Reducing transport demand
- Shifting transport “modes” (from high to low energy intensity) and
- Improving efficiency via technology development.

This section provides an overview of inputs, data sources and calculations to estimate transport energy demand for the road, rail, aviation and marine sectors for the REmap Case.

Although some transport technologies can greatly increase efficiency, technology modification will not be enough to achieve the required emission reductions. The movement of people, especially in urban areas, will have to be re-organised almost entirely, and individual transport must be complemented or even substituted by public transport systems. Car sharing and public transport on demand are only the beginning of the transition to a system that carries more people more quickly and conveniently to their destination while using less energy, as DLR demonstrated in its research.

Around 14% of all fossil transport fuel is used for “bunker fuel”, meaning transport energy for international shipping and international air transport. To replace bunker fuels entirely with renewables, a combination of energy efficiency and renewable fuels is required. Biofuels and synthetic fuels – produced with renewable electricity – are currently the only renewable energy option for planes for at least the next decade. For ships, new wind-based drives, such as new generation sails and Flettner rotors, are needed to replace a proportion of engine fuels. However, research remains at a very early stage.

Formulas for the calculation of transport energy requirements:

$$P_T = P_{road} + P_{rail} + P_{navigation} + P_{aviation}$$

$$P_{TM} = \sum_n (P_{specific-TT1} * M_{annual-TT1}) + (P_{specific-TT2} * M_{annual-TT2}) + \dots + (P_{specific-TTn+1} * M_{annual-TTn+1})$$

with

$$M_{annual-TT} = M_{annual-TM} * D_{TT-year}$$

P_T : Energy demand transport in [MJ/yr]

P_{TM} :	Energy demand per transport mode	in [MJ/yr]
$P_{specific-TM}$:	Specific energy demand per transport mode	in [MJ/km]
$M_{annual-TT}$:	Annual mileage per transport technology	in [km/yr]
$M_{annual-TM}$:	Annual mileage per transport mode	in [km/yr]
$D_{TT-year}$:	Market distribution per transport technology	in [%]

Road transport

Assumptions:

For transport of people, a modular shift towards increased market shares of electric public transport systems such as light rails, e-buses and trains is assumed. EVs replace cars with internal combustion engines almost entirely over the next three decades. For freight it is assumed that the road transport market share decreases, whereas the market shares of rail transport systems increase. Biofuels are used only for land-based transport technologies that cannot operate with electric drives, such as heavy-duty trucks or mining vehicles.

Formulas for the calculation of road transport energy requirements:

$$P_{road} = \sum ((P_{specific-TT-RO1} * M_{annual-TT-RO1}) + (P_{specific-TT-RO2} * M_{annual-TT-RO2}) + \dots + (P_{specific-TT-Ron} * M_{annual-TT-Ron}))$$

with

$$M_{annual-TT-RO} = M_{annual-TT-RO} * D_{TT-RO-year}$$

P_{road} :	Energy demand road transport	in [MJ/yr]
$P_{specific TT-RO}$:	Specific energy demand per road transport technology	in [MJ/km]
$M_{annual-TT-RO}$:	Annual mileage per road transport technology	in [km/yr]
$D_{TT-RO-year}$:	Market distribution per road transport technology by year	in [%]

Rail transport

Assumptions:

The rail transport sector is assumed to move towards efficient electric drives with a gradual phase-out of diesel fuels and a significant reduction of combustion engines. The remaining combustion engines are converted to biofuels or synthetic fuels. The overall market share for land transport increases at the expense of road transport.

Formulas for the calculation of rail transport energy requirements:

$$P_{rail} = \sum ((P_{specific-TT-RA1} * M_{annual-TT-RA1}) + (P_{specific-TT-RA2} * M_{annual-TT-RA2}) + \dots + (P_{specific-TT-Ran} * M_{annual-TT-Ran}))$$

with

$$M_{annual-TT-RA} = M_{annual-TT-RA} * D_{TT-RA-year}$$

P_{rail} :	Energy demand rail transport	in [MJ/yr]
$P_{specific TT-RA}$:	Specific energy demand per rail transport technology	in [MJ/km]
$M_{annual-TT-RA}$:	Annual mileage per rail transport technology	in [km/yr]
$D_{TT-RA-year}$:	Market distribution per rail transport technology by year	in [%]

Aviation transport

Assumptions:

Fossil fuel-based kerosene is replaced with biofuels and synthetic fuels. No electric drives are assumed for the aviation sector.

Formulas for the calculation of aviation transport energy requirements:

$$P_{aviation} = \sum ((P_{specific-TT-A1} * M_{annual-TT-A1}) + (P_{specific-TT-A2} * M_{annual-TT-A2}) + \dots + (P_{specific-TT-An} * M_{annual-TT-An}))$$

with

$$M_{annual-TT-A} = M_{annual-TT-A} * D_{TT-A-year}$$

$P_{aviation}$:	Energy demand aviation transport	in [MJ/yr]
$P_{specific-TT-A}$:	Specific energy demand per aviation transport technology	in [MJ/km]
$M_{annual-TT-A}$:	Annual mileage per aviation transport technology	in [km/yr]
$D_{TT-A-year}$:	Market distribution per aviation transport technology by year	in [%]

Navigation transport

Assumptions:

Analog to the aviation sector, diesel fuels will be replaced by biofuels – efficiencies are assumed to develop equal to efficient diesel systems.

Formulas for the calculation of navigation transport energy requirements:

$$P_{navigation} = \sum ((P_{specific-TT-M1} * M_{annual-TT-M1}) + (P_{specific-TT-M2} * M_{annual-TT-M2}) + \dots + (P_{specific-TT-Mn} * M_{annual-TT-Mn}))$$

with

$$M_{annual-TT-M} = M_{annual-TT-M} * D_{TT-M-year}$$

$P_{navigation}$:	Energy demand navigation transport	in [MJ/yr]
$P_{specific-TT-M}$:	Specific energy demand per marine transport technology	in [MJ/km]
$M_{annual-TT-M}$:	Annual mileage per marine transport technology	in [km/yr]
$D_{TT-M-year}$:	Market distribution per marine transport technology by year	in [%]

3. Costs and capital investment

A number of economic indicators have been used to characterise the impacts of decarbonisation. The analysis looks at the incremental system cost of the REmap technology pathway, including any co-benefits. A number of co-benefits have been estimated, including health impacts of air pollution⁵. The analysis also quantifies the investment needed to realise the REmap technology pathways.

Investment costs included direct capital investments in generation technology and other system-related costs – namely integration costs associated with variable renewable energy, and stranded assets.

3.1. Capital investment for generation technologies

Energy sector capital investment (excluding transport) is calculated for both the Reference Case and the REmap Case. The investment level in the REmap Case is higher than in the Reference Case due to the increased deployment of renewable technologies which, on average, have higher capital costs than non-renewable energy technologies. The principle behind the approach is the product of capital investment in each year (in USD/kW by technology) and the deployment of that low-carbon technology in that year, to arrive at total annual investment needs. The total capital investment for each year is then summed over the period 2015 to 2050 to arrive at a cumulative investment need. The incremental investment need is also calculated, equal to the sum of the differences between the total investment costs for all technologies, renewable and non-renewable energy, in the REmap Case and the Reference Case for the period 2015 to 2050.

The approaches taken for the power and end-use sectors differ by the availability of data. For the end-use sectors, the investment analysis starts with a detailed assessment of the “additional investment needs” of each low-carbon technology deployed in each end-use sector. Based on this estimate and on the extent to which technologies are deployed in the Reference Case, the investment needs for both the REmap Case and the Reference Case have been estimated. The analysis for the power sector has been carried out in more detail, by taking into account the capital stock turnover for each technology type. Infrastructure needs for EV charging equipment, hydrogen infrastructure, transmission and distribution capacity (including super grids and specific needs for integration of variable renewable energy) and battery storage have been estimated based on the deployed capacity of both renewable and non-renewable technologies between 2015 and 2050.

3.2. Integration costs for variable renewable energy

Integration costs associated with variable renewable energy (VRE) in the power sector are calculated. They are based on average system cost (USD/MWh of VRE) estimates for four categories – utilisation⁶, transmission grid, storage and curtailment – with respect to different levels of VRE shares (solar and wind proportions in the power system (Scholz *et al.*, 2016). These estimates for Europe have been used as a proxy to calculate average system integration costs relating to VRE in 2050 in other countries and regions. Incremental VRE generation between 2015 and 2050 in REmap compared to the Reference Case is applied to estimate the incremental system integration cost.

VRE integration costs for Europe range from USD 10 to USD 35 per MWh, depending on the VRE share and on the respective solar and wind generation. Integration costs for each of the analysed categories

⁵ A detailed description of IRENA REmap costs and externality methodology can be found online (IRENA, 2016c).

⁶ Accounting for the reduced use of dispatchable power plants, given that their capacity factor is reduced with increasing VRE shares.

are found to increase almost linearly with respect to VRE share in total generation up to 80%. The study also finds that at VRE shares up to 40%, average integration costs are dominated by the utilisation costs, whereas curtailment and storage become increasingly important at higher VRE shares. Storage, curtailment and utilisation costs are strongly influenced by scenarios with high solar shares.

Total transmission grid (including super grids⁷) and storage investments also were derived from the cost approach used in Scholz *et al.* (2016) and the ADVANCE project (SMASH, 2015). Distribution network investments are calculated based on the cost estimates to integrate PV rooftop generation to distribution grids, provided by the IEA (2014c).

3.3. Stranded assets

Stranded assets also are quantified. IRENA defines stranded assets as the remaining book value⁸ of assets substituted before the end of their anticipated economic lifetime and without recovery of any remaining value to achieve 2050 decarbonisation targets. This definition emphasises that assets become stranded because of the requirement to reduce fossil fuel use to achieve a deeply decarbonised energy system by mid-century⁹.

Technology cost assumptions are taken from a variety of sources including IRENA's own cost assessments, country plans, the learning rate approach and other sources. Fossil fuel prices are taken from either country studies or credible sources (IEA, 2016) and applied at a country level (when available), or by using regional assumptions (see *Bibliography*).

3.4. Substitution cost and system costs

Each REmap Option is characterised by its costs, with the main metric represented by its substitution cost. Based on the substitution cost, inference can be made as to the effect on system costs. This indicator is the sum of the differences between the total capital and operating expenditures of all energy technologies based on their deployment in a given year for the REmap Case and the Reference Case.

3.5. Other assessed parameters and metrics

Sensitivity analysis was conducted for the key economic inputs (*e.g.*, discount rates, energy prices) and technology parameters (*e.g.*, biomass feedstock availability, efficiency improvement rates).

Table 3 provides the key macroeconomic and energy price assumptions used for the purposes of this assessment. It is off these median values that the sensitivity assessment is done by either increasing or decreasing variables to see their effect on the costs of the REmap Case.

⁷ IRENA estimates based on announcements from State Grid Corporation of China and on data from the Global Energy Interconnection Development and Cooperation Organization (GEIDCO).

⁸ Book value is defined here as the cost of an asset, minus the accumulated depreciation.

⁹ A detailed paper for IRENA's stranded assets assessment can be found online (IRENA, 2017b).

Table 3. Key assumptions

	Unit	2015	2050
Population	[million]	7 350	9 700
GDP PPP	[trillion USD per year]	113	315
Energy prices			
Coal	[USD per GJ]	2.5	3
Crude oil	[USD per barrel]	50	80
Natural gas	[USD per million Btu]	7	11
Biomass feedstock	[USD per GJ]	-	8
Discount rates	[%]	-	10% all sectors

The energy efficiency measures in end-use sectors (buildings/industry/transport) based on various applications were identified from different sources (see *Bibliography – Energy efficiency technology and infrastructure costs*). The investment needs (capital expenditures, or CAPEX) along with the energy savings data (primary fuel savings, electricity savings) are extracted from these sources for each identified energy efficiency measure. The annual additional investment (CAPEX) is estimated by applying the annuity rate (for different discount rates for sectors) and energy prices for fossil fuels (from Table 3).

By applying emission factors for fuel types over saved primary fuel, savings in CO₂ emissions is estimated, which in turn is used over net annual additional cost (difference between annualised additional investment (additional CAPEX) and annual saved primary fuel cost) to arrive at the annual CO₂ mitigation cost range (sector and technology level).

4. Benefits

4.1. Externality analysis for air pollution

This section explains the methodology used to estimate the externality costs associated with the consumption of energy carriers (*e.g.*, fossil fuels, modern bioenergy and traditional uses of bioenergy). The external costs estimated are those arising from the use of fuels and include both combustion and non-combustion emissions, but they do not take into account the life cycles by which these fuels are produced, transported, used to generate energy and finally disposed of.

The external costs from generation of electricity, heat and mechanical energy for transport arise from the emissions produced in the form of fine particulate matter (PM_{2.5}), mono-nitrogen oxides (NO_x), sulphur dioxide (SO₂), volatile organic compounds (VOCs) and ammonia (NH₃). In this assessment, three emission effects were covered: 1) health effects arising from outdoor exposure, 2) health effects arising from indoor exposure in the case of traditional use of bioenergy and 3) effects on agricultural yields. Additionally, the external costs associated with social and economic impacts of CO₂ are estimated.

The methodology to estimate external costs consists of three key calculations, carried out in sequence:

- 1) **Emission factors for local pollutants by sector.** Emission factors reflect the emissions of different pollutants in kilotonnes per petajoule (kt/PJ) of energy used. This calculation is done for 2030 and 2050, for each pollutant, country and sector. Emission factors change over time on account of changes in technology. An analysis of these changes is carried out, showing where (in which countries and sectors) to expect changes in emissions per unit of energy.

- 2) **Costs per tonne of fuel.** This part of the methodology involves updating estimates of external costs in USD per tonne. This step, based on the “ExterneE” methodology, takes into account recent work on health and other external costs and the subsequent costs of carbon (OECD, 2012; US Government, 2013). The estimates are made first for local air pollutants in EU countries, where the original ExterneE estimates of cost per tonne were made, and subsequently for all other REmap countries. As a separate exercise, the external costs of carbon are estimated. A range of values is derived from the most recent work in this area (US Government, 2013).
- 3) **External costs from fossil fuels.** This final step involves applying the updated costs to the estimates of emissions from fuel use by sector and country. This is done for the year 2014 (the base year of REmap analysis) and again for each of the two case scenarios in 2030 and 2050, to derive estimates of the total external costs of fossil fuel use by country.

Further information can be found online (IRENA, 2016c).

4.2. Macroeconomic benefits

IRENA’s macroeconomic analysis has been carried out by feeding the REmap energy mixes developed for this report into a global macroeconometric model that takes into account the linkages between the energy system and the world’s economies within a single and consistent quantitative framework.

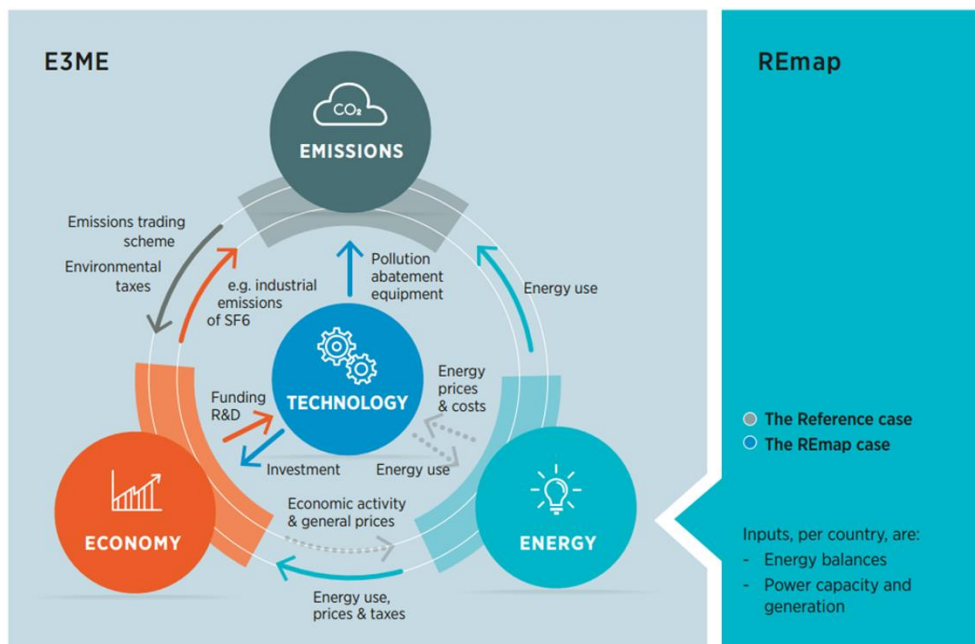
The model used, E3ME¹⁰, covers the complete global economy and therefore is complementary to REmap, which focuses only on the energy sector. E3ME simulates the economy based on post-Keynesian principles, in which behavioural parameters are estimated from historical time-series data. Interactions across sectors are based on input/output relations obtained from national economic statistics (see below for an in-depth description). The model is flexible and can be tailored to different technological, sectoral and geographical disaggregation. The version used includes 24 different electricity generation technologies, 44 economic sectors and 59 countries/regions globally, which have been selected consistently with the REmap G20 analysis.

The model has a proven track record of policy and policy-relevant projects. Those projects include the impact assessments for energy and climate policy carried out by the European Commission; contributions to the Intergovernmental Panel on Climate Change on the economic impacts of climate change mitigation; participation in inter-model comparison exercises in the context of climate change mitigation, both global and regional (e.g. in Latin America); and work on the macroeconomic impacts of energy policy in Japan and in India. In the academic sphere, close to 50 scientific journal and book publications have used the E3ME model.

The basic structure of the version of E3ME used is illustrated in Figure 6. A full description of the energy sector of each country, derived from the REmap analysis, has been fed into the model (right-hand side of the figure). The left-hand side shows how the main components of E3ME fit together, with arrows showing linkages. For the purposes of this analysis, the links feeding into the energy system have been disabled (dotted grey arrows in the figure) to match and fix the energy sector parameters (e.g. installed capacities, energy mixes) obtained from REmap.

¹⁰ Developed by Cambridge Econometrics. More information can be found at www.e3me.com.

Figure 6. E3ME tool structure and input from REmap



In order to strengthen the analysis, IRENA engaged with a panel of seven internationally renowned experts, independent from the modelling team. The experts were strategically selected from diverse countries (Brazil, China, Germany, India, United Arab Emirates, United Kingdom and United States) and from varied backgrounds, (some are experts in fundamentally different modelling approaches, such as computable general equilibrium models [so they can bring different perspectives]). All the experts were requested to critically assess the key assumptions and approach of the analysis, in a review that took place in December 2016. Close to 350 comments were received. Those comments have been incorporated into the macroeconomic analysis and will also inform future work by IRENA.

Compared to the Reference Case, the macroeconomic analysis assumes lower future international fossil fuel prices than the REmap Case. The values used are, respectively, in line with the New Policies Scenario and the 450 Scenario of the *World Energy Outlook 2016* (IEA, 2016). Carbon prices are used and are set consistently with these scenarios (in terms of value, and geographical and sectoral application). The analysis assumes that carbon pricing is revenue neutral for the government, by using the proceeds to reduce income taxes, in a sort of “green tax reform”.

Importantly, a sensitivity analysis has been carried out for the key assumption of crowding out of capital. This is one of the key differences between post-Keynesian and neo-classical approaches to macroeconomic modelling, and is expected to have meaningful effects on the results. Such expectation is grounded on an extensive expert consultation and on previous IRENA analyses with E3ME. While the analysis assumes partial crowding out in the central case, two additional model runs have been done with total and null crowding out¹¹. Further methodological details, from previous IRENA work using E3ME, can be found in *Renewable Energy Benefits: Measuring the Economics* (IRENA, 2016d).

¹¹ Partial crowding out is modelled by forcing savings to be at least 50% of investment. Full crowding out imposes savings to be equal to investment. Null crowding out does not impose any relation between savings and investment.

In-depth description of E3ME

This section provides a summary of the E3ME tool. A more complete description including the full technical manual is available on the tool website www.e3me.com.

Key strengths

E3ME is a computer-based tool of the world's economic and energy systems and the environment.

The key strengths of E3ME are:

- close integration of the economy, energy systems and the environment with explicit linkages between each component;
- detailed sectoral disaggregation in the tool's classifications allowing for the analysis of similarly detailed cases;
- global coverage while allowing for analysis at the national level for major economies;
- bottom-up treatment of the power sector allowing a detailed analysis of the renewables mix. For other sectors, renewable energy is represented with a top-down framework;
- the econometric approach, which provides a strong empirical basis for the tool and means it is not reliant on some of the restrictive assumptions seen in CGE models; and
- the econometric specification of the tool, making it suitable for short and medium-term assessment as well as longer term trends.

Main dimensions of the tool

The main dimensions of E3ME are:

- 59 regions – all major world economies, the EU 28 and EU candidate countries plus other countries' economies grouped;
- 44 or 69 (Europe) industry sectors based on standard international classifications
- 28 or 43 (Europe) categories of household expenditure
- 22 different users of 12 different fuel types
- 14 types of airborne emissions (where data are available) including the six greenhouse gases monitored under the Kyoto protocol

Tool applications

E3ME has recently been used, among others, in the following studies:

- the EU's official assessment of its 2030 climate and energy targets and an assessment of the EU's long-term Energy Roadmap
- assessment of decarbonisation options in Latin America
- assessment of low-carbon policy in East Asia
- assessment of the impacts of phasing out fossil fuel subsidies in India and Indonesia

The tool website provides a full list of academic publications that have used the tool, stretching back to the 1990s.

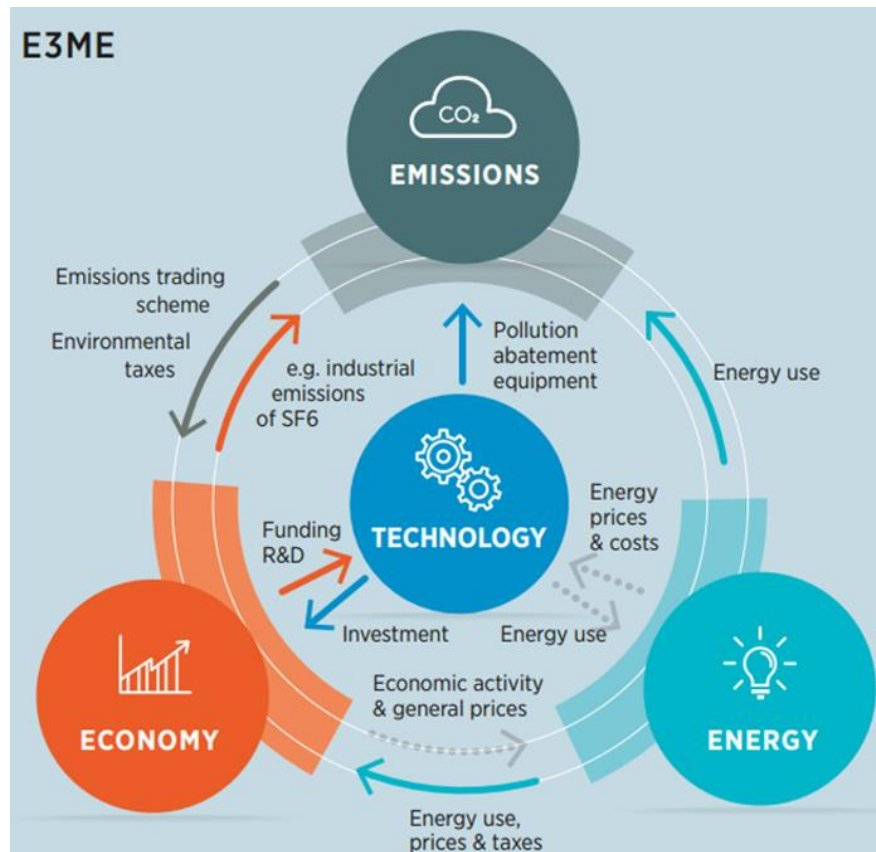
E3ME as an E3 tool

The E3 interactions

Figure 7 below shows how the three components (modules) of the tool – energy, environment (emissions) and economy (i.e. the three Es in an E3 tool) fit together. The linkages between the tool components are shown explicitly by the arrows that indicate which values are transmitted between

components. The dotted arrows show interactions built into the tool but disabled for this report. These affect the energy sector and are fixed to match the results from Remap (as explained above).

Figure 7. Linkages in the E3ME tool



Estimations of energy demand and feedbacks to the economy

The standard version of E3ME includes five sets of equations for energy demand – an aggregate equation set and one set for each of the four main fuel types. However, in this study the equations were not used because energy demand was instead made consistent with the projections in Remap.

However, the linkages to the economy are included. Feedbacks to the economy for the main section occur through the input output relationships in the tool, which determine output levels within the energy extraction and distribution sectors. For example, if the steel sector uses 10% less coal in energy terms, it is assumed that (after correcting for prices) consumption of coal by the steel sector in economic terms also falls by 10%. Production of coal will be affected either in the same country or through the trade relationships described below.

Treatment of renewables

E3ME covers low-carbon technologies in the power sector through the FTT power sector model (Mercure, 2012). Although FTT can provide estimates of renewable shares itself, when considering cases of different renewables penetration rates it can fix the renewables shares as defined in the cases analysed. The tool will then determine an electricity price based on average LCOE of the power mix. The tool will also feedback fuel consumption and the required investment to the economic part of the tool.

Final use of biofuels is also included in the tool's energy equations. The use of other renewables by final energy users (e.g. decentralised solar) is covered by the tool's classifications but at a lower level of detail.

Role of technology

Technological progress plays an important role in the E3ME tool, affecting all three Es: economy, energy and environment. The approach to constructing the measure of technological progress in E3ME is adapted from that of Lee et al. (1990). It adopts a direct measure of technological progress by using cumulative gross investment but this is altered by using data on R&D expenditure, thus forming a quality adjusted measure of investment. The tool's endogenous technical progress indicators appear in nine of E3ME's econometric equation sets including trade, the labour market and prices. Investment and R&D in new technologies also appears in E3ME's energy and materials demand equations to capture energy/resource savings technologies as well as pollution abatement equipment.

As described above, E3ME includes a set of specific technologies for the power sector, including both conventional and renewable options. These options are assigned specific characteristics, relating to cost, build time and intermittency, for instance.

Energy prices

A large global reduction in fossil fuel demand could prompt a fall in global energy prices. In the analysis in this report, fossil fuel prices are set as exogenous across all cases. Cost-supply curves have been used only to determine the source of fuel supplies rather than prices.

Electricity prices are set using an average LCOE calculation as described above.

Material consumption

The specification of the materials submodel in E3ME follows that of the energy submodel. The units of analysis are thousands of tonnes, and materials demands are split into seven types of material and 16 user groups. The level of material consumption is estimated as a function of economic activity rates, relative prices and technology. Feedbacks are provided to the material extraction sectors (agriculture and mining).

Materials used for energy are not included in the materials demand equations but are instead estimated using a fixed energy-weight ratio. In the analysis in this report, biomass used for energy was not counted in the results for materials demand.

GDP and economic indicators

GDP and output

GDP is formed as the sum of household expenditure, government consumption, investment and international trade (see below). With the exception of government consumption, which is treated as exogenous, there are estimated econometric equations for each component. Each equation includes a combination of quantity and price terms, and tool parameters are estimated using historical datasets covering each year since 1970. They are summarised in turn in the paragraphs below.

The tool also provides estimates of economic output and Gross Value Added by sector. Output by product group is worked out in a similar way to GDP by summing across the components of demand (including intermediate demand). Gross Value Added by industry is calculated by subtracting intermediate costs from output and correcting for net taxes.

Household consumption

Household consumption (or household expenditure) is determined using two sets of econometric equations. The first estimates total household budgets, which are assumed in the long run to move in line broadly with changes in real incomes. However, other factors like demographic development may affect aggregate savings ratios so the relationship is not entirely one-to-one. In the short run, additional factors may also affect rates of consumption. Changes to inflation rates or to unemployment rates may cause households to delay major purchases due to uncertainty over future incomes or prices.

Once the tool has estimated the aggregate consumption, a second set of equations determines spending by product group. In these equations, relative prices are used to estimate spending on each product. Consumption by each product is then scaled to be consistent with the total.

Investment

Investment (Gross Fixed Capital Formation) is one of the most important equation sets within the tool. Following post-Keynesian theory, investment is made by companies in expectation of future profits. Although relative prices and interest rates can also determine rates of investment, there is no explicit representation of finance in E3ME and it is assumed that banks make the necessary money available for lending. This assumption is tested in the crowding out sensitivities in the main report.

Stock building can be an important component of short-term economic growth but is less important in the long term. In E3ME, stock building is treated as exogenous.

Bilateral trade between regions

An important part of the modelling concerns international trade. E3ME solves for detailed bilateral trade between regions (similar to a two-tier Armington model). For most sectors, trade is modelled in three stages:

- econometric estimation of regional sectoral import demand
- econometric estimation of regional bilateral imports from each partner
- forming exports from other regions' import demands

Trade volumes are determined by a combination of economic activity indicators, relative prices and technology.

Trade in fossil fuels

Trade in fossil fuels is modelled using a different approach because the commoditised nature of fuels violates the Armington assumption of differentiated production. A cost-supply curve approach is applied instead. It is assumed that the lowest-cost sources are used first given the existing rates of extraction (as a ratio of reserves) and within a range of uncertainty (i.e. production is not fully optimised). As discussed in the report, this approach provides important insights into the aggregate trade effects.

Economic multipliers and price formation

Multipliers in E3ME

There are several loops of dependency in E3ME, which result in effects similar to multipliers. Supply chains are represented by input-output tables which produce Type I multipliers. There is another loop from output to employment, incomes, household demand and further output, which gives the induced effects associated with Type II multipliers.

However, there are additional feedback loops in E3ME. Expectations of higher future output can lead to additional investment, in turn leading to demand for investment goods (plus supply chain effects).

There are also trade interactions because an increase in GDP in one country will lead to higher demand for imports from other countries (which can feed back to the first country etc.).

It should also be noted that E3ME includes measures of capacity that could limit multiplier effects. The limit is most obvious in the labour market where population places a constraint on participation. Rising wages caused by a tighter labour market could crowd out some employment increases (see labour market section below). In other sectors, implicit capacity constraints are modelled using econometric equations which can affect prices (see below). These equations are described in more detail in the tool manual.

Price formation in E3ME

Aside from wages (see below), E3ME's economic module includes three sets of prices: domestic prices, import prices and export prices. Each is determined in the tool as a mark-up of unit costs.

In the long run it is assumed that all changes in production costs are passed on to final prices unless international competition prevents this from happening (e.g. in commoditised sectors). However, this constraint is not applied in the short run so there is an adjustment path for prices. Other factors that could affect prices included investment and R&D since a higher quality product commands a higher price.

As noted above, the measures of capacity in the tool can also affect price formation. If a sector's output increases towards capacity, firms will have the incentive to increase prices and their rates of profitability. This is typically a short-term effect since in the long run companies will invest in new capacity. Nevertheless, it is important as a determinant of overall output levels.

The labour market

The treatment of the labour market distinguishes E3ME from other macroeconomic models. E3ME includes econometric equation sets for employment, average working hours, wage rates and participation rates. The first three of these are disaggregated by economic sector while participation rates are disaggregated by gender and five-year age band.

Employment is a function of economic output, real wage rates, average working hours and technology. In the results presented in this report, employment impacts are mostly determined by changes in economic output (notably in sectors that produce renewables equipment) and changes in wage rates. Wage rates are determined in the tool using a union-bargaining approach and typically increase when unemployment falls, offsetting some of the initial employment gains.

A full specification of all the E3ME equations is provided in the tool manual.

Unemployment

The labour force is determined by multiplying labour market participation rates by population. Unemployment (both voluntary and involuntary) is worked out by taking the difference between the labour force and employment.

Econometric specification

The econometric techniques used to specify the functional form of the equations are the concepts of cointegration and error correction methodology, particularly as promoted by Engle and Granger (1987) and Hendry et al. (1984). The process involves two stages. The first is a levels relationship, whereby an attempt is made to identify the existence of a cointegrating relationship between the chosen variables. This is selected on the basis of economic theory and a priori reasoning. For example, the list of variables for employment demand contains real output, real wage costs, hours worked,

energy prices and the two measures of technological progress. If a cointegrating relationship exists then the second stage regression is carried out. This is known as the error-correction representation. It involves a dynamic, first difference regression of all the variables from the first stage. This is accompanied by lags of the dependent variable, lagged differences of the exogenous variables and the error-correction term (the lagged residual from the first stage regression).

Stationarity tests on the residual from the levels equation are performed to check whether a cointegrating set is obtained. Due to the size of the tool, the equations are estimated individually rather than through a cointegrating VAR. For both regressions, the estimation technique used is instrumental variables. This is principally because of the simultaneous nature of many of the relationships e.g. wage, employment and price determination. E3ME's parameter estimation is carried out using a customised set of software routines based in the Ox programming language (Doornik et al., 2007). Its main advantage is that parameters for all sectors and countries may be estimated using an automated approach.

Comparison with CGE models

E3ME is often compared to CGE models. In many ways the modelling approaches are similar; they are used to answer similar questions and use similar inputs and outputs. However, beneath the surface there are substantial differences, and it is important to be aware of this when interpreting tool results. The two types of models come from distinct economic backgrounds. They are in general consistent in their accounting and identity balances but differ substantially in their treatment of behavioural relationships.

Ultimately this comes down to assumptions about optimisation. The CGE tool favours fixing behaviour in line with economic theory. For example, it assumes that individuals act rationally in their own self-interest and that prices adjust to market clearing rates. In this way aggregate demand automatically adjusts to meet potential supply, and output levels are determined by available capacity.

By contrast, econometric models like E3ME interrogate historical datasets to determine behavioural factors on an empirical basis. They do not assume optimal behaviour. The tool is demand-driven and makes the assumption that supply adjusts to meet demand (subject to any supply constraints) but at a level likely to be below maximum capacity.

This has important practical implications for scenario analysis, including scenarios of energy policy. The assumptions of optimisation in CGE models mean that all resources are fully utilised and it is not possible to increase economic output and employment by adding regulation. On the other hand, E3ME allows for the possibility of unused capital and labour resources that may be utilised under the right policy conditions. It is therefore possible (although not guaranteed) that additional regulation could lead to increases in investment, output and employment. For example, as demonstrated in this report, the additional investment required to increase renewables capacity could lead to additional job creation and multiplier effects, depending on how the investment is financed.

The econometric specification in E3ME follows an error-correction methodology that estimates both the impacts of short-term shocks and the path that the key tool variables follow towards a long-term outcome. The equations are estimated separately for each sector and region. Further information about the approach is provided in the tool manual.

5. Annex A: Sources for energy efficiency and infrastructure costs

Sector	Measure	Sub-sector	Parameters	References
Industry	Energy efficiency	Iron and steel	Additional CAPEX, fossil fuel/electricity savings	US EPA, 2012
		Cement		US EPA, 2010
		Pulp and paper		Martin and Anglani, 2000
		Chemicals		IEA, 2014d
		Aluminium		Kermeli <i>et al.</i> , 2015
		Motors	Energy savings and cost, CO ₂ savings	UNIDO, 2010
	Technology	Iron and steel	Renewable and capital CAPEX, operation & maintenance cost	IEA, 2015; IRENA, 2014c; IRENA and IEA-ETSAP, 2013a, 2015a; IRENA and IEA-ETSAP, 2013b; Smolinka <i>et al.</i> , 2016
		Cement		IEA, 2009
		Pulp and paper		Broeren <i>et al.</i> , 2013; IEA, 2008, 2009
		Chemicals		
		Aluminium		IEA, 2009
Transport	Energy efficiency	Passenger light-duty vehicles and road freight	Additional CAPEX, primary fuel savings	IEA, 2014d
		Light-duty vehicles	Improvement potential	ICCT, 2016; US DOE, 2013
	Technology	Passenger and freight (all modes)	Technology cost/performance, commodity prices	IRENA, 2013, 2015a, 2016b, 2017c; IRENA and IEA-ETSAP, 2013a; IRENA and IEA-ETSAP, 2013b
	Infrastructure	Hydrogen station	CAPEX	Melaina and Penev, 2013
		Electric vehicle charging station		US DOE, 2015a
Buildings	Energy efficiency	Insulation	Additional CAPEX, fuel cost savings, CO ₂ savings, lifetime	Breithaupt, 2015; NIA, 2016
		Windows		DECC, 2012; Breithaupt, 2015
		Reflective roof		RoofingCalc, 2016; US DOE, 2015b
		Appliances – demand side		The co-operative energy, 2013
		Appliances – improved efficiency	Additional CAPEX, energy savings	Wada <i>et al.</i> , 2012
		Lighting		
		Smart home system		DECC, 2012; Breithaupt, 2015
		Boilers	Additional CAPEX, lifetime, energy savings	Breithaupt, 2016; IRENA, 2017d
		Heat pumps		
		Renovation cost for building types – space heating and cooling	Additional CAPEX	GBPN and ABUD, 2015

Power	Infrastructure	Transmission grid, storage, curtailment, utilisation	Average integration Cost, discount rate, lifetime	IRENA and IEA-ETSAP, 2015b; Scholz <i>et al.</i> , 2016; SMASH, 2013
		Distribution network		IEA, 2014c
	Technology	Renewable generation costs and forecasts	Generation costs	IRENA, 2015b, 2016e
General	Technology	Global costs	Technology cost/ performance, commodity prices	IRENA, 2016c
		REmap country-specific costs		IRENA, n.d.
		Technology brief		IRENA and IEA-ETSAP, n.d.
		Bioenergy	Feedstock cost	IRENA, 2014b

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