European Commission

IRENA
International Renewable Energy Agency

Renewable Energy Prospects for the European Union

Based on REmap analysis
conducted by the International Renewable Energy Agency
in co-operation with the European Commission

February 2018

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

About REmap

IRENA's REmap programme determines the potential for countries, regions and the world to scale up renewables.REmap assesses renewable energy potential assembled from the bottom-up, starting with country analyses done in collaboration with country experts, and then aggregating these results to arrive at a global picture.

Acknowledgements

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Disclaimer

FOREWORD

The European Union (EU) is at the forefront of the global energy transformation. Its steadfast commitment and long-term vision combined with today's cost-effective renewable energy options has enabled the region to nearly double the share of renewable energy from 2005 to 2015. As a result, the EU is on track to meet its 2020 renewables target, and its 2030 target of a 27% share of renewable energy is well within reach. Although impressive progress has been achieved as a result of the ambition and vision of the EU to meet climate targets, more effort will be needed to meet long-term decarbonisation objectives.

This report, Renewable Energy Prospects for the European Union (REmap EU), identifies cost-effective renewable energy options for all EU Member States – spanning a wide range of sectors and technologies – to accelerate the deployment of renewables towards 2030. The study also identifies areas where further action could be taken to unleash the full renewable energy potential identified.

The REmap analysis – conducted by IRENA in close collaboration with the European Commission, as well as with national and international experts – concludes that the EU can double the renewable share in its energy mix from some 17% in 2015 to 34% in 2030 if the right enabling frameworks are put in place. The findings of the report show that this is possible with today's technologies and it makes strong economic sense. Reaching a 34% renewable share by 2030 will also help the EU reduce emissions and meet the objectives of the Paris Agreement. Furthermore, renewables present an opportunity for the EU and all its Member States, to boost economic growth, maintain industrial leadership and create jobs, while delivering substantial social and environmental benefits to European citizens.

In 2018, the EU will make critical decisions about its energy future. By taking the necessary steps now, it will ultimately succeed in its goal to make energy "more secure, affordable and sustainable." IRENA stands ready to contribute toward making this vision a reality.

Adnan Z. Amin

Director-General

IRENA


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ABBREVIATIONS

Abbreviation	Description
°C	Degrees Celsius
ACE	ASEAN Centre for Energy
ACEA	European Automobile Manufacturers Association
ADEME	Agence de l'Environnement et de la Maîtrise de l'Énergie (The French Environment and Energy Management Agency)
AEBIOM	The European Biomass Association
AEE INTEC	Arbeitsgemeinschaft Erneuerbare Energie (Renewable Energy Work Association) Institute for Sustainable Technologies
BNEF	Bloomberg New Energy Finance
CCGT	Combined-cycle gas turbine
CHP	Combined heat and power
CO_2	Carbon dioxide
CSP	Concentrated solar power
DECC	Department of Energy & Climate Change of the United Kingdom
DH	District heating
E3M Lab/ICCS	E3M-Lab of the Institute of Communication and Computer Systems at the National Technical University of Athens
ECV	Electrically chargeable vehicles
EEA	European Environment Agency
EFKM	Energi- Forsynings-og Klimaministeriet (Danish Ministry of Energy, Utilities and Climate)
EJ	Exajoule
ENEA	Agenzia Nazionale per le Nuove Tecnologie, L'energia e lo Sviluppo Economico Sostenibile (Italian National Agency for New Technologies, Energy and Sustainable Economic Development)
ENTSO-E	European Network of Transmission System Operators
EU	European Union
EUR	Euro
Excl.	Excluding
FP	Federaal Planbureau, Brussels (Federal Planning Bureau of Brussels)
g	Gram
GFEC	Gross final energy consumption
GHG	Greenhouse gas
GJ	Gigajoule
GW	Gigawatt
GWh	Gigawatt-hour
HEV	Hybrid-electric vehicles
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis

Abbreviation	Description
Incl.	Including
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
kWh	Kilowatt-hour
LCOE	Levelised cost of energy
MESDE	Ministry of Ecology, Sustainable Development and Energy, France
Mt	Million tons
MW	Megawatt
MWh	Megawatt-hour
NREAP	National Renewable Energy Action Plan
NREL	US National Renewable Energy Laboratory
NTUA	National Technical University of Athens
OCGT	Open-cycle gas turbine
PJ	Petajoule
PV	Photovoltaic
RED	Renewable Energy Directive
SEforAll	Sustainable Energy for All
SHIP	Solar Heat for Industrial Processes
TFEC	Total final energy consumption
TWh	Terawatt-hour
UK	United Kingdom
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
VRE	Variable renewable energy
vs	versus
yr	year

COUNTRY CODES

Short name	Official name	Country code
Austria	Republic of Austria	AT
Belgium	Kingdom of Belgium	BE
Bulgaria	Republic of Bulgaria	BG
Croatia	Republic of Croatia	HR
Cyprus	Republic of Cyprus	CY
Czech Republic	Czech Republic	CZ
Denmark	Kingdom of Denmark	DK
Estonia	Republic of Estonia	EE
Finland	Republic of Finland	FI
France	French Republic	FR
Germany	Federal Republic of Germany	DE
Greece	Hellenic Republic	EL*
Hungary	Hungary	HU
Ireland	Ireland	IE
Italy	Italian Republic	IT
Latvia	Republic of Latvia	LV
Lithuania	Republic of Lithuania	LT
Luxembourg	Grand Duchy of Luxembourg	LU
Malta	Republic of Malta	MT
Netherlands	Kingdom of the Netherlands	NL
Poland	Republic of Poland	PL
Portugal	Portuguese Republic	PT
Romania	Romania	RO
Slovakia	Slovak Republic	SK
Slovenia	Republic of Slovenia	SI
Spain	Kingdom of Spain	ES
Sweden	Kingdom of Sweden	SE
United Kingdom	United Kingdom of Great Britain and Northern Ireland	UK**

** The code "EL" follows the European Commission's Europa guidelines. Greece (the Hellenic Republic) is also known internationally by the ISO code "GR".*

*** The code "UK" follows the European Commission's Europa guidelines. The United Kingdom of Great Britain and Northern Ireland is also known internationally by the ISO code "GB".*

KEY FINDINGS

- The EU could double the renewable share in its energy mix, cost effectively, from 17% in 2015 to 34% in 2030.
- All EU countries have cost-effective potential to use more renewables.
- Renewables are vital for long-term decarbonisation of the EU energy system.
- The European electricity sector can accommodate large shares of solar PV and wind power generation.
- Heating and cooling solutions account for more than one third of the EU's untapped renewable energy potential.
- All renewable transport options are needed to realise long-term EU decarbonisation objectives.
- Biomass will remain a key renewable energy source in 2030 and beyond.

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EXECUTIVE SUMMARY

BACKGROUND

For more than two decades, the European Union (EU) has been at the forefront of global renewable energy deployment. The adoption of long-term targets and supporting policy measures has resulted in strong growth in renewable energy consumption across the region, from a 9% share in 2005 to 16.7% in 2015. Currently, the EU is on track to meet its 20% target established for 2020.

In October 2014, the European Council agreed on a new set of energy and climate targets for the period up to 2030 (European Council, 2014), including a minimum target of 27% for the share of renewable energy consumed in the EU. This agreement was followed by the Energy Union framework strategy of February 2015, which aims to make the EU "the world leader in renewable energy" (European Commission, 2015a).

The European Union ratified the Paris Agreement, which established the goal to limit the rise in global temperatures this century to "well below 2°C" compared to pre-industrial levels. In practice, this entails reducing global carbon emissions from energy use to zero by 2060 and maintaining that level until the end of the century. This long-term decarbonisation objective has profound implications for European climate and energy objectives in the 2030 timeframe. Early climate action is key to ensure an efficient transition in all aspects of energy use, avoiding the need for more dramatic emission reductions after 2030, and minimising stranded assets. Accelerated deployment of renewables can play a key role towards this transition.

For the crucial 2020–2030 period, the European Commission tabled the "Clean Energy for All Europeans" package in November 2016. The package proposes a regulatory framework to support renewable energy deployment (European Commission, 2016a). The International Renewable Energy Agency (IRENA), at the Commission's request, has carried out an assessment of the renewable energy prospects of the European Union to 2030 to support discussion on this proposal. The study, conducted in close collaboration with the Commission, also forms part of REmap – IRENAs' renewable energy roadmap.

The resulting REmap EU study aims to identify cost-effective renewable energy options across all Member States, sectors, and technologies, in order to meet – and potentially exceed – the proposed 27% renewables target for 2030.

IRENA's analysis, furthermore, aims to provide an open platform for EU Member States to assess at an aggregated level the impacts of their national renewable energy plans; to provide insights into the environmental and economic impacts of further deployment of renewables in the EU; and to further highlight the role that renewables could play in the long-term decarbonisation of the European energy system.

APPROACH AND SCOPE

REmap is IRENA's methodology to assess the potential for scaling up renewables in countries, across regions and around the world. The REmap analysis identifies renewable technology options in all sectors of the energy system, assessing them both in terms of costs and required investments as well as their contribution to climate and environmental objectives.

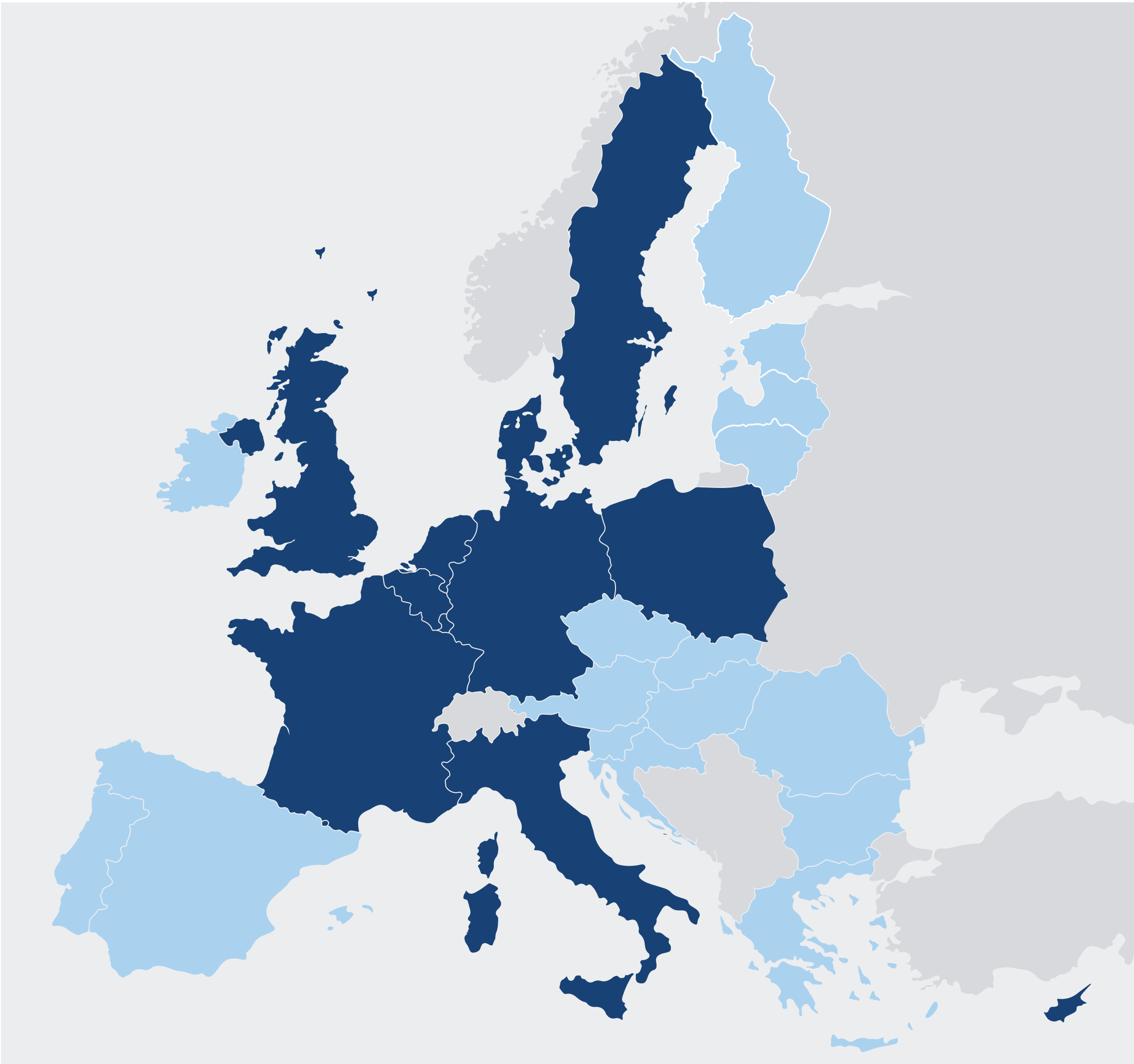
REmap includes 70 countries worldwide, accounting for around 90% of global energy use. It is unique in that participating countries nominate national experts to work jointly with IRENA to determine their renewable energy potential, resulting in roadmaps developed in close consultation with countries themselves.

In recent years, IRENA has applied the REmap approach in several regional analyses.[1] A regional approach is useful to assess the aggregated impact of multiple national efforts, as well as in identifying synergies for cost effective renewable deployment and opportunities for co-operation.

The REmap study for the EU is based on deeper analysis of existing REmap studies for 10 EU Member States (accounting for 73% of EU energy use), complemented and aggregated with high-level analyses for the other 18 EU Member States.

Participation of EU Member States in IRENA's REmap programme[2]

The boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.
The term "country" as used in this material also refers, as appropriate, to territories or areas.



Background map: OpenStreetMap®

1. *A first regional REmap report looked at Africa (IRENA, 2015). This was followed by an analysis of Southeast Asia in co-operation with the ASEAN Centre for Energy (IRENA and ACE, 2016).*

2. *Countries in dark blue have joined the REmap programme and have an existing detailed REmap analysis; those in light blue comprise the rest of the EU-28, which are not part of the REmap programme but have been added as part of the EU study. (Spain is a REmap country but the REmap analysis is not yet complete.)*

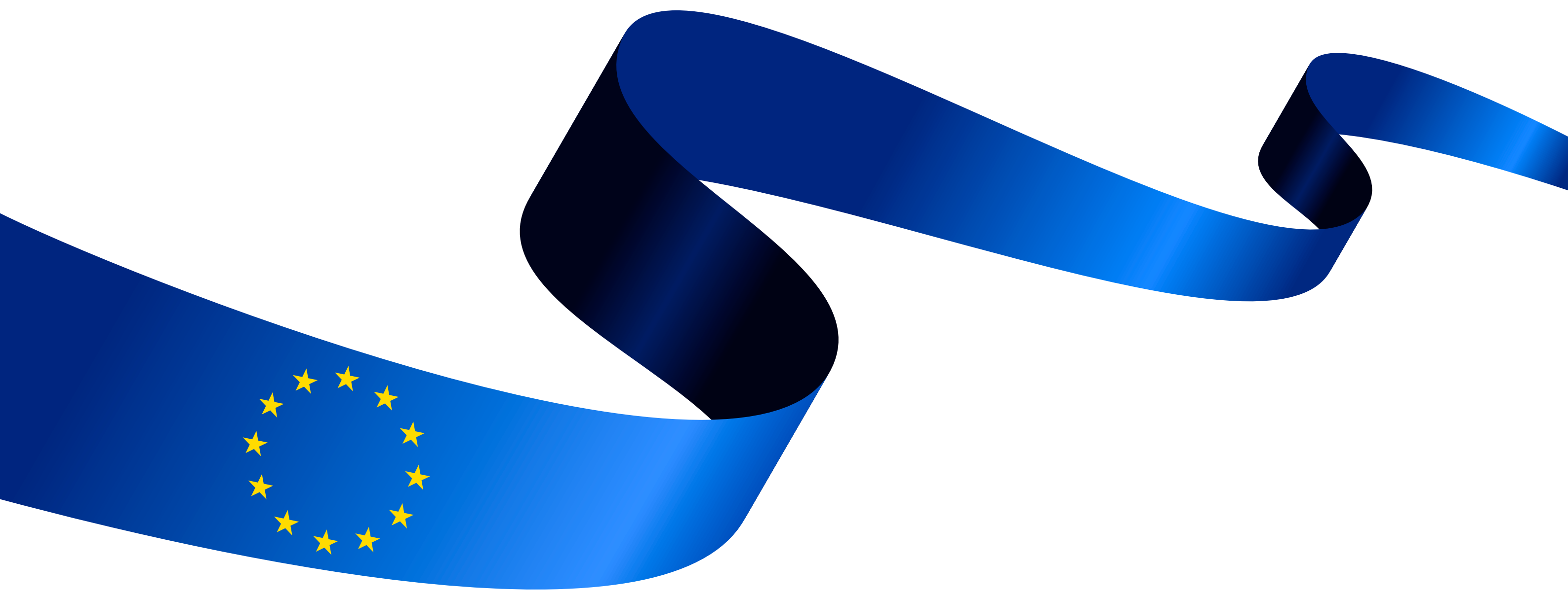
The study analyses the expected deployment of renewables in the EU by 2030 under a Reference Case scenario (which assumes the continuation of existing and planned policies) and through REmap Options (*i.e.* realisable renewable-based technology potential) at a country level, aiming to identify what is possible beyond the Reference Case.

These renewable energy options are characterised in terms of their levelised cost of energy (LCOE) and compared with a conventional technology alternative to determine the 'costs of substitution'. The study covers all sectors, including energy supply (power and district heat) and end-use sectors (buildings, industry and transport).

IRENA's REmap study is not intended as a prediction of the expected evolution of the EU's energy system but rather an analysis of what is technically possible and cost-effective from a societal perspective by 2030, based on today's best knowledge. The future of the European energy sector is subject to multiple uncertainties of a technical, economic and social nature. Their impacts on the findings – both positive and negative – have been mapped as part of this study.

Although the total economic and technical potential of renewables identified in the REmap study is considered a robust finding, technology developments are subject to high levels of uncertainty. REmap analysis considers the rising technical potential and falling costs of renewable energy technologies; the additional potential identified, beyond the proposed 27% target for 2030, can be attributed largely to the rapid progress of such technologies, which has occurred faster than expected at the time the target was set in 2014.

IRENA's REmap analysis for the EU was carried out in consultation with Member State representatives by means of several workshops and sectoral webinars. The analysis of the operation of the power sector was carried out in co-operation with University College Cork. The final results of the REmap study were reviewed and benchmarked against other scenarios for the region by the European Commission's Joint Research Centre.



SUMMARY OF RESULTS

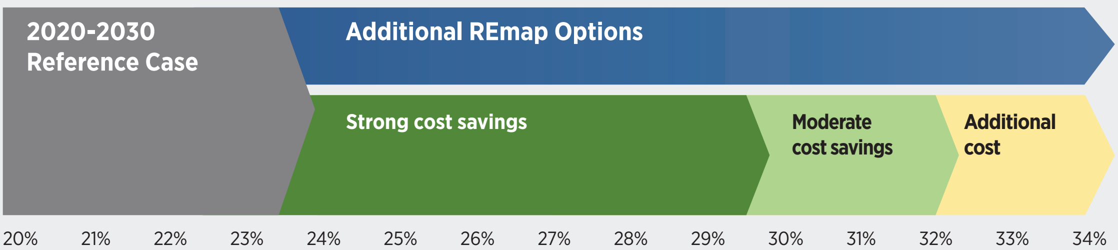
Since the adoption of the 27% target in 2014, much has changed in the energy sector. Key renewable technologies such as solar PV and offshore wind have achieved spectacular cost reductions, exceeding expectations both in terms of their speed and extent. As these technologies improve, so does the renewable potential that can be harvested cost-effectively.

Technological development has also accelerated in end-use sectors; for example, electric vehicles are quickly reaching commercial maturity and could play a key role in the deployment of larger shares of renewables in the EU by 2030, both in the transport and power sectors. Meanwhile, new information and communication technologies are revolutionising the way we design and operate our energy systems. **Thanks to these favourable developments, the 27% renewable target agreed in 2014 may be regarded as a conservative objective for the EU.**

The EU could double the renewable share in its energy mix, cost effectively, by 2030

The analysis shows that there are various cost-effective combinations of renewable energy options to meet the 27% target; however, the REmap analysis identifies additional potential to exceed this share. The full implementation of all renewable energy options under a reference demand scenario would increase the share of renewables to 33% by 2030. If the realisation of the proposed 30% energy efficiency target[3] is considered, the same renewable energy use under the REmap case would represent a share of 34%. If more ambitious energy efficiency targets are considered, the resulting share of renewables could be even higher for the same level of deployment.

Renewable energy options to exceed the 27% target for 2030



IRENA analysis

Strong cost savings
- Wind power
- Solar power
- Solar thermal in buildings
- Hydro power
- Geothermal power

Moderate cost savings
- Heat pumps
- Electric vehicles
- Biodiesel
- Geothermal district heating
- Solar thermal in industry

Additional cost
- Biomass in industry
- Conventional bioethanol
- Biomass in power and district heat
- Advanced bioethanol
- Biokerosene

3. As part of the "Clean Energy for All Europeans" package of November 2016, the European Commission proposed a binding EU-wide target of 30% for energy efficiency by 2030 (European Commission, 2016a).

Current plans and policies for renewable energy deployment would result in a share of 24% by 2030. The additional potential beyond this Reference Case can be broadly split into three categories: the first category comprises different forms of renewable power generation (wind, solar, hydro, geothermal) as well as solar thermal in buildings. The second category includes electrification of heat and transport by means of heat pumps and electric vehicles (in combination with renewable power generation), as well as biodiesel for transport, solar thermal in industry and geothermal in district heating systems. The third category comprises different forms of biomass use across sectors.

The first category yields strong cost savings compared to conventional technologies, the second delivers cost-neutrality to moderate savings and the third comes at additional cost; however, the **full implementation of all identified options would result in estimated net cost savings of USD 25 billion per year by 2030**, as the savings from the cheapest options outweigh the additional costs of the most expensive ones.

Additional costs for the modernisation of power grids, or a potential scenario of low or stagnating fossil fuel prices, could reduce these estimated savings; however, the potential additional costs are outweighed by the benefits when health and environmental externalities are considered. Today, about 400 000 people die prematurely in Europe each year because of air pollution (EEA, 2017a). The REmap savings from **avoided health damage** alone are estimated at **between USD 19 billion and 71 billion per year by 2030**, while the **environmental costs** avoided with the deployment of REmap Options are estimated at **between USD 8 billion and 37 billion per year by 2030**. When the savings from a pure cost–benefit analysis are aggregated with avoided health and environmental externality costs, the accelerated deployment of renewables would result in **total savings of between USD 52 billion and USD 133 billion per year** by 2030.

After peaking in 2011, **new investments in renewable energy in Europe have slowed down significantly compared to other major regions around the world**. Reaching a 34% renewable share by 2030 would require an estimated average investment in renewable energy of USD 73 billion per year.[4] The incremental, accumulated investment additional to the Reference Case would amount to **USD 433 billion until 2030, representing an average annual contribution of 0.3% of current EU28 gross domestic product**, before accounting for additional activity triggered in other sectors. The overall macroeconomic benefits would be more significant because of this multiplier effect. Previous IRENA analysis indicates a multiplier of a factor of two on a global scale, while for fossil-fuel importing regions such as Europe, the multiplier is probably larger (IRENA, 2017a).

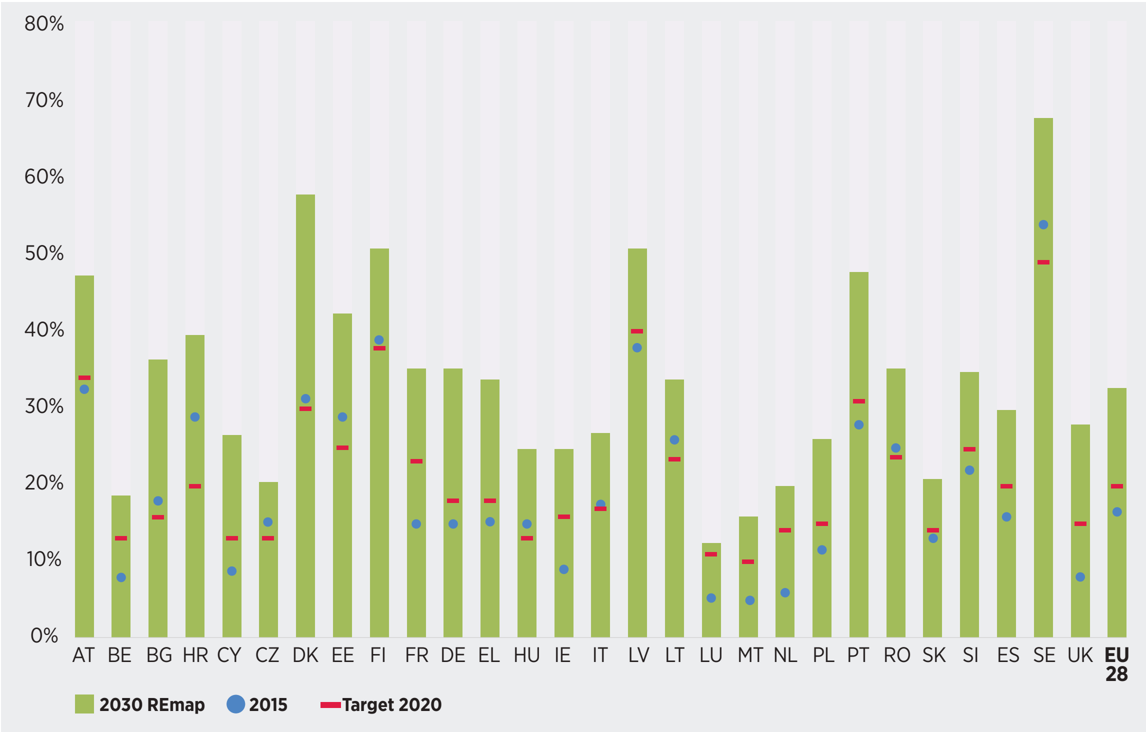
The additional investment in renewables would also have a positive effect in terms of job creation. Today the renewable sector employs about 1.2 million people in Europe (IRENA, 2017b). This figure would increase substantially with a doubling of the renewable share by 2030.

All EU countries have cost-effective potential to use more renewables

In 2015, the renewable energy shares in EU Member States varied from 5% to 54%. Variations will persist to 2030, reflecting multiple factors such as different starting points, available resource potentials, existing and planned policies, as well as the specific market conditions for renewables in each country; however, these differences may narrow by 2030 as Member States with lower initial shares have the potential to grow faster.

4. Current levels of investment in the EU-28 are estimated between USD 50 billion and USD 56 billion in 2016 (Frankfurt School-UNEP Centre/BNEF, 2017).

Renewable energy share in gross final energy consumption – 2015, 2020 target and 2030 potential with accelerated uptake of renewables (REmap)



Sources: REmap 2030: IRENA analysis; Renewable share in 2015: Eurostat (2017a); Targets for 2020: Renewable Energy Directive (2009/28/EC)

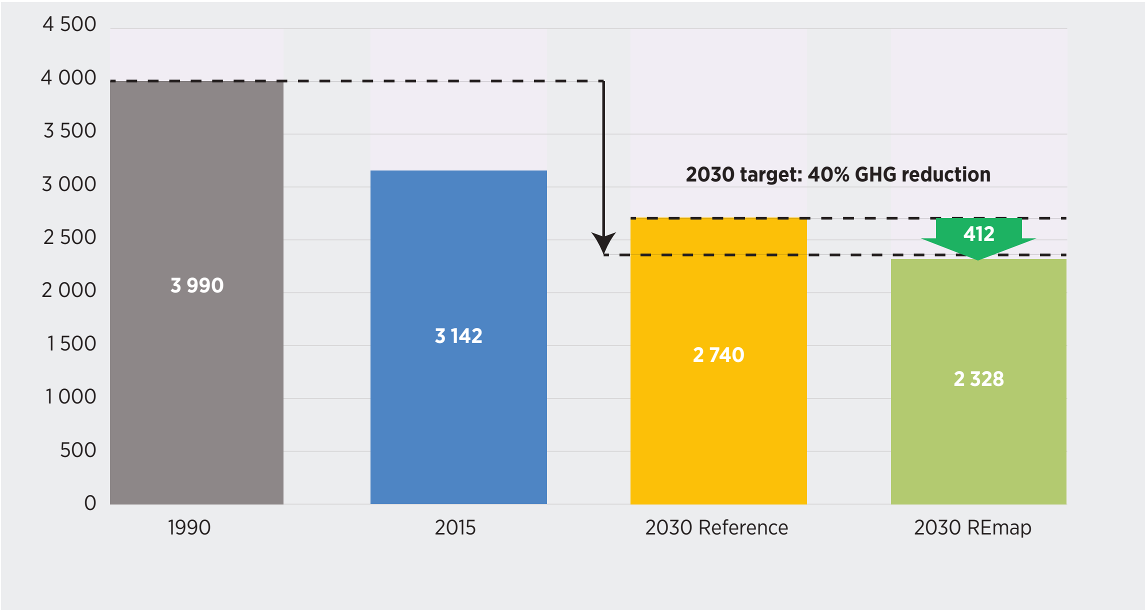
The aggregate share of renewables that would result from existing Member State plans and projections to 2030 falls short of the 27% EU goal; thus, additional commitments will be required from Member States to reach or exceed the proposed 2030 target.

Renewables are vital for long-term decarbonisation of the EU energy system

The EU is well on track to achieve its 2020 emissions reduction target; however, additional effort will be required to align long-term energy system trends with 2050 decarbonisation goals, particularly in end-use sectors (buildings, industry and transport), where progress has been slow in the past. Even if the EU were to realise its 40% emission reduction target by 2030, much deeper reductions (two to three times larger than those required between current and 2030 levels) would be needed between 2030 and 2050 (EEA, 2017b).

The full deployment of REmap Options would deliver a reduction of 412 Mt CO2 (15%) compared to the Reference Case in 2030, an amount comparable to Italy's total emissions today. This scenario would result in a 42% reduction in emissions in the energy sector compared to 1990 levels, in line with the EU's 40% GHG emission reduction objective by 2030 and enabling a deeper decarbonisation pathway conducive to the "well-below" 2°C target in the Paris Agreement (once energy efficiency and other mitigation measures are factored in). This illustrates the key contribution of renewables in meeting EU climate objectives and the need for close alignment between energy and climate policies.

EU energy-related CO_2 emissions (Mt CO_2/year) – 1990, 2015, 2030 Reference Case and 2030 with accelerated uptake of renewables (REmap)



IRENA analysis based on EEA source data for 1990 and 2015 values (EEA, 2017c)

HIGHLIGHTS BY SECTOR

Under the REmap case, the share of renewable energy in the power sector would rise to 50% by 2030 (compared to 29% in 2015), while in end-use sectors renewables would account for shares[5] of 42% in buildings, 36% in industry and 17% in transport.

The European electricity sector can accommodate large shares of solar PV and wind power generation

Solar PV and wind power account for the bulk of capacity additions in the power sector under the REmap case. The potential identified would result in 327 gigawatts (GW) of installed capacity for wind (+97 GW compared to the Reference Case) and 270 GW of solar PV (+86 GW compared to the Reference Case), while other technologies, including biomass, hydropower, geothermal, concentrated solar power (CSP) and marine, contribute a further 23 GW.

The REmap case results in a high share of variable renewable generation (29%), which will pose new challenges for the operation of EU power systems. A key question is whether there will be sufficient power system flexibility[6] in 2030 to deal effectively with the increased variability in generation expected. To assess this, an EU-wide model[7] was developed to simulate the operation of the power sector in 2030, assuming full deployment of the generation mix resulting from the REmap case.

5. Expressed in final energy consumption terms, including renewable electricity and district heating.

6. Flexibility in power systems can be defined as the ability to constantly keep power supply and demand in balance, responding to (quick and large) changes in either. Flexibility can be provided by generators (fossil but also dispatchable renewable), consumers, storage systems, networks or even system operation rules.

7. A dispatch model based on Plexos software and developed in co-operation with University College Cork (www.ucc.ie/en)

The modelling simulations indicate that the **REmap scenario could be technically feasible considering the interconnection infrastructure planned for 2030; however, they also reveal challenges that will need to be addressed.** Firstly, multiple EU interconnectors are expected to operate under high levels of congestion by 2030 regardless of the renewable deployment scenario considered. This indicates a need for additional infrastructure and cross-border market integration efforts to enable the efficient trade of electricity, which is a key element for a cost-effective EU-wide deployment of renewables. Secondly, the simulations show that variable renewable generation plants would capture prices lower than the average in wholesale markets, as their low marginal generation costs place downward pressure on prices when they are in operation. This effect is most pronounced for solar PV plants, as their generation concentrates in the central hours of the day and during summer. A decreasing economic value for solar PV generation could be a barrier to investment in new capacity, which could be mitigated by enabling additional energy storage and incentivising demand-side flexibility across EU markets.

The accelerated adoption of heat pumps and electric vehicles would result in a substantial increase in the use of electricity in end-use sectors. Under REmap, electricity would represent 27% of total final energy consumption, up from 24% in the Reference Case. This requires generation of 230 TWh/year of additional power, an amount comparable to Spain's electricity demand today.

Heating and cooling solutions account for more than one third of the additional renewable energy potential identified through IRENA's REmap analysis

Heating and cooling accounts for about half of the energy demand in the EU today; however, progress in the deployment of renewables has been slower than in the power sector. **The share of renewables in heating and cooling could reach 34% by 2030 with faster renewable energy uptake (as per REmap), compared to 25% in the Reference Case.**

More than two-thirds of the additional renewable heating and cooling options identified are cheaper than the conventional alternative. The REmap analysis reveals significant potential to accelerate the deployment of heat pumps – which could account for about 9% of heating needs – as well as solar water heaters and direct use of biomass in industry and buildings. Today, district heating systems provide about 9% of the EU's heating needs (European Commission, 2016b); however, the bulk is produced with natural gas and coal. The conversion of district heating systems to use renewables is an option to accelerate renewable deployment in the heating and cooling sector.

All renewable transport options are needed to realise long-term EU decarbonisation objectives

The EU has made limited progress on the deployment of renewable energy in the transport sector over the last decade. **The quick adoption of electric vehicles will be key to accelerating renewable deployment by enabling the use of renewable electricity in road transport.** By 2030 most passenger vehicles sold could be fully electric or hybrids, and electric vehicles could potentially account for 16% of the overall car stock in Europe; however, even with such quick adoption of electric vehicles, renewable power would only account for about 3% of the energy consumption in the sector by 2030. Liquid biofuels – both advanced and conventional – will still be needed for the existing stock of vehicles with internal combustion engines and for transport modes where electrification is still not an option. The use of liquid biofuels could triple by 2030 compared to 2010 levels to reach ~66 billion litres.

Biomass will remain a key renewable energy source

Provided that sustainability concerns are considered, biomass will remain key for the energy transition until 2030 and beyond. This is especially the case for uses that are not easily converted to electricity or other carriers in the short and medium term (*e.g.* high temperature processes in industry, advanced biofuels for road freight, etc.). Overall deployment of bioenergy in the REmap scenario would double from today's levels; however, its share in the total consumption of renewables would decline from 67% in 2010 to 55% in 2030 as the growing contribution of other renewables outpaces bioenergy.

LOOKING AHEAD

IRENA's REmap analysis identifies significant renewable energy potential beyond the proposed 2030 target of 27%. **Tapping the additional potential to reach 34% is cost-effective**, even before considering the very significant economic value of the associated health and environmental benefits.

A faster deployment of renewables by 2030 is **technically feasible with today's technologies**. All EU Member States have renewable potential beyond the Reference Case that could be harvested economically. While an EU-wide target represents an important declaration of intent, **national-level commitments and implementation will hold the key** to achieving this objective cost-effectively at the regional level.

To fulfil its aspiration to become the global leader in renewables, Europe will need to maintain a growing domestic market. **The additional investments required to reach a 34% share by 2030 would help Europe maintain its leading role while deriving substantial macroeconomic benefits in terms of growth and balance of trade, as well as creating a new industrial base around the renewables sector.**

Accelerating the deployment of renewables would have much **broader social benefits for the EU and its Member States.** It can boost economic activity and create new jobs. Moreover, the decentralised nature of many renewable energy technologies and the increased uptake of domestic biomass production under the REmap scenario could be a **driver for economic development among structurally weak regions and rural areas.** Combined with energy efficiency measures, renewables can also be a key **contributor to reducing energy poverty in the EU.**

Finally, tapping the additional renewable energy potential identified in the REmap study would bring the EU closer to a **decarbonisation pathway compatible with the "well-below" 2°C objective** established in the Paris Agreement, **while substantially improving the health of citizens.**

1 INTRODUCTION

THE EUROPEAN UNION, A KEY PLAYER FOR THE GLOBAL ENERGY TRANSITION

In December 2015, the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement, which established the goal to limit the rise in global temperatures this century to "well below 2°C" compared to pre-industrial levels. In practice, keeping the temperature increase below 2 degrees Celsius (°C) means that carbon dioxide (CO_2) emissions from energy use need to fall to zero by 2060 and to stay at this level thereafter to achieve this objective by the end of the century (IRENA, 2017a).

Accelerated deployment of renewable energy and energy efficiency measures are the key elements of the energy transition. IRENA's analysis shows that by 2050, renewables and energy efficiency could meet the vast majority of emission reduction needs (90%). Renewable energy would be the largest source of energy supply in 2050, representing two-thirds of the energy mix. This requires an increase in renewables' share of about 1.2% per year, a seven-fold acceleration compared to recent years (IRENA, 2017a).

Global renewable energy use has grown to account for 18% of the world's total final energy consumption (TFEC) in 2014 (IRENA, 2016a)[1]. If the energy plans and targets of all countries participating in IRENA's global renewable energy roadmap (REmap) that are currently in place and under consideration are aggregated, the global renewable energy share would reach only 21% by 2030. This is a minor growth over today's levels and a continuation of past trends in growth of the renewable energy share. However, IRENA's REmap programme shows that a doubling of the global share of renewable energy is possible by 2030.

The latest REmap global report shows that if the world were to double its renewable energy share by 2030, the European Union (EU) would represent 14% of the total final renewable energy demand globally, and it would be the third largest user of renewables following China and the United States.

As part of the Renewable Energy Directive (2009/28/EC), by the end of June 2010 all EU Member States had put in place binding renewable energy targets as well as National Renewable Energy Action Plans (NREAPs) with renewable energy targets by sector and technology to 2020. When all NREAPs are aggregated, the renewable energy share of the EU would reach 20% of total gross final energy consumption (GFEC)[2] by 2020. Besides the renewable energy targets, the other two components of the EU's "20-20-20" targets aim at reducing the region's energy demand by 20% (compared to the projected use of energy in 2020) and achieving a 20% reduction in greenhouse gas emissions compared to 1990 levels.

1. TFEC includes total combustible and non-combustible energy use from all energy carriers as fuel (for the transport sector) and to generate heat (for industry and buildings) as well as electricity and district heat. It excludes non-energy use, which is the use of energy carriers as feedstock to produce chemicals and polymers. However, it includes blast furnace and coke oven consumption by the iron and steel sector (SEforALL, 2013).

2. GFEC includes the energy commodities delivered for energy purposes to industry, transport, residential, commercial and public, agriculture, forestry and fishery sectors. This includes the consumption of electricity and heat by the energy sector for electricity and heat production, as well as electricity and heat distribution and transmission losses (Directive 2009/28/EC).

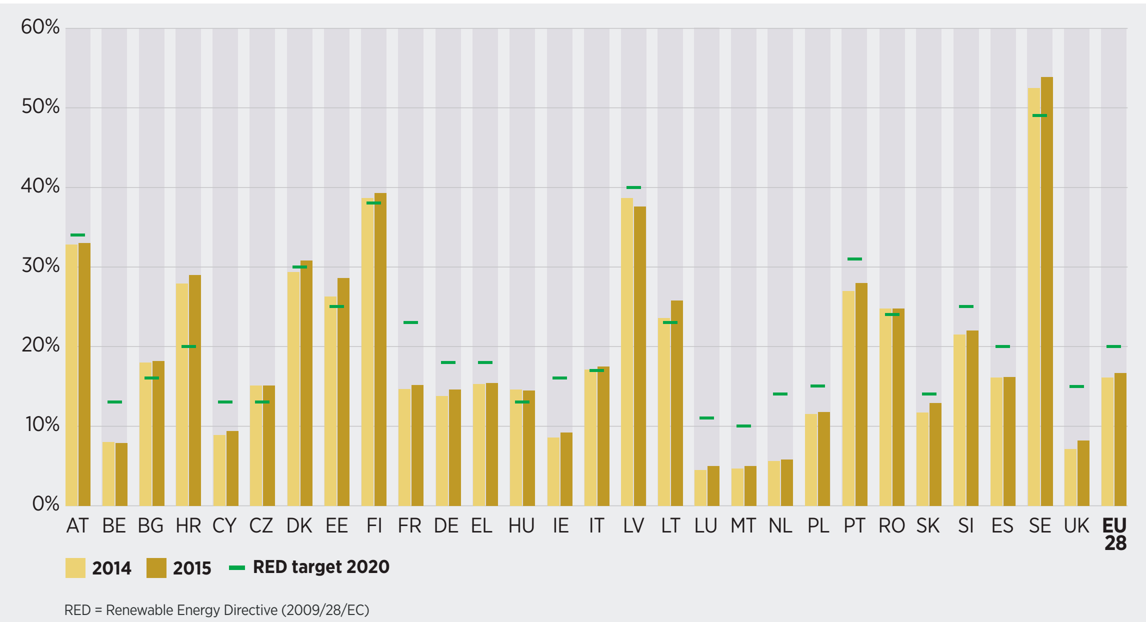
EU PROGRESS TOWARDS THE 2020 RENEWABLE ENERGY TARGET

According to the latest progress report of the European Commission, the EU as a whole is well on track to reach its 20% renewable target by 2020 (European Commission, 2017a). The renewable energy share in the EU reached 16.7% in 2015, up from 16.1% in 2014[3]. Figure 1 shows the change in renewable energy share for each EU Member State between 2014 and 2015, and their respective gaps towards reaching the 2020 targets.

The comparison with the historical progress in the development of renewable energy shares shows that most Member States can be expected to meet their renewable energy shares targets by 2020; however, for some Member States – such as France, Ireland, Luxembourg, Malta, the Netherlands and the United Kingdom (UK) – this may be more challenging. These countries will need a renewables growth rate of more than 1 percentage point per year, higher than the growth that they have achieved in previous years.

For the aggregate EU objective, it is especially important for large energy consuming countries to meet their targets as they also account for a large share of EU's projected total gross final renewable energy consumption by 2020. As of 2015, some Member States already had renewable shares that were larger than their 2020 target.

Figure 1: Renewable share in gross final energy consumption by EU Member State, 2014, 2015 and 2020 target



Source for 2014 and 2015 data: Eurostat (2017a). Targets for 2020: Renewable Energy Directive (RED) (2009/28/EC)

3. Data released in January 2018 shows that the share of renewables in energy consumption in the EU reached 17% in 2016. Source: Eurostat (2018).

EU RENEWABLE ENERGY OBJECTIVES BY 2030

In January 2014, the European Commission proposed a new policy framework for climate and energy to expand the EU 20-20-20 objectives from the year 2020 to the year 2030. In October 2014, the European Council reached an agreement resulting in three higher EU-wide targets to be achieved by 2030: 1) a 40% cut in greenhouse gas emissions compared to 1990 levels, 2) at least 27% of renewable energy in gross final energy consumption, and 3) at least 27% energy savings compared with the business-as-usual scenario (European Council, 2014).

The European Council agreement on the 2030 targets in 2014 was followed by the release of the Energy Union Framework Strategy in February 2015, aimed at ensuring secure, affordable and climate-friendly energy for Europe. One of the objectives of the Energy Union is to make the EU "*the world leader in renewable energy*" (European Commission, 2015a).

In November 2016, the European Commission published the package of legislative proposals "Clean Energy for All Europeans" for the period 2020 to 2030 – commonly referred to as the "Winter Package" – aimed at bringing EU legislation in line with 2030 targets. This package covers energy efficiency, renewable energy, the design of the electricity market, security of supply and governance rules for the Energy Union (European Commission, 2016a). A proposal for a revision of Directive 2009/28/EC on the promotion of the use of energy from renewable sources was released as part of the Winter Package. The proposal does not include national renewable energy targets, but it is up to the Member States to collectively ensure that the binding target at the EU-level of at least 27% is realised.

The proposed legislative package and the 2030 renewable targets are currently under discussion in the EU Parliament, Council and Commission. The final 2030 targets and legislation are expected to be adopted in 2018.

AIM AND SCOPE OF THE REMAP EU ANALYSIS

The EU Council decision of October 2014 established a renewable energy target of at least 27% by 2030 for the EU; however, the specific contributions of countries, sectors and technologies towards this target are not yet determined. In understanding how such a regional target can be operationalised at these levels, IRENA's renewable energy roadmap – REmap – has been deployed.

In close collaboration with the European Commission, IRENA carried out a REmap analysis for the EU to show how the currently proposed renewable energy share target of at least 27% by 2030 can be realised, as well as which cost-effective renewable energy technology options are available for the EU to go beyond this target.

The analysis includes both the energy supply (power generation and district heat) and end-use sectors (buildings, industry and transport) for the period between 2010 and 2030. The standard REmap methodology[4] is complemented with an additional high-level analysis of the potential impacts of accelerated deployment of renewables in the EU power systems of 2030, by means of a power sector dispatch model.

This report is structured as follows: In chapter 2 we describe the methodology and scope of the analysis, as well as the tools used and the main assumptions. Chapter 3 presents the main findings of the REmap analysis for the EU. Chapter 4 provides further discussion of the findings for each sector as well as policy recommendations.

4. The REmap methodology is explained in section 2 of this report. More information on REmap-related publications and methodologies is available at: http://irena.org/remap/

2 METHODOLOGY

2.1 REMAP: A TRANSPARENT AND INCLUSIVE ANALYTICAL APPROACH

REmap is IRENA's renewable energy roadmap that focuses on identifying the realistic potential of renewable energy to the year 2030 and beyond, in all sectors of the energy system. It assesses renewable energy in terms of its costs and investments, as well as its contribution to climate and environmental objectives.

The REmap programme has grown to include 70 countries making up around 90% of global energy use. The programme is unique in that participating countries nominate national experts to work jointly with IRENA to determine their renewable energy potential, resulting in a renewable energy roadmap developed in close consultation with countries.

The REmap analysis generates renewable energy alternatives for decision makers to consider. It is a technology options analysis that quantifies renewable energy potential by sector and by country for the year 2030 and beyond. It is a bottom-up approach, where each country makes a different contribution to achieve higher renewable energy uptake at the regional or global level.

REmap analyses two forward-looking scenarios. The first one, called the "**Reference Case**", is a baseline featuring current national energy plans and goals to 2030; the second, called "**REmap**", is an accelerated renewable energy scenario to 2030 (IRENA, 2016a).

Based on the energy mix projected by a country in the Reference Case, the REmap analysis focuses on identifying cost-effective alternatives to supply energy with renewables instead of conventional technologies/resources. These alternatives are named "**REmap Options**", and are based on the realistic renewable energy potential at the sector and technology levels, realisable to 2030.

REmap Options are assessed for energy supply – *i.e.,* electricity and district heat production – and for end-use sectors including heating and cooling in industry and buildings (*i.e.,* residential, commercial and public buildings) as well as electrification and biofuels in the transport sector.

REmap Options aim to close an important knowledge gap for many countries by helping policy makers to have a clearer understanding of renewable energy opportunities before them. Several factors are considered in identifying and analysing REmap Options, including resource availability, access to finance, human resource needs and supply, manufacturing capacity, policy environment, available infrastructure, annual capacity additions, the age of existing capital stock as well as the costs of technologies by 2030[1].

The cornerstone of the REmap methodology is co-operation and consultation with countries. IRENA works with the nominated country experts in developing the Reference Case and investigating the REmap Options. IRENA has developed a spreadsheet tool (the "REmap Tool") that allows country experts to evaluate and create their own REmap analyses, providing a transparent and dynamic

1. For further details on the REmap methodology and metrics please consult the Appendix of the Global REmap report 2016 edition (IRENA, 2016a), which can be downloaded at www.irena.org/remap.

accounting framework to evaluate and verify Reference Case developments and REmap Options within a country. Results of this analysis are displayed in a REmap-specific energy balance.

The process of the REmap analysis for a country can be summarised in the following steps:

1) **Building the Reference Case:** The energy balance of the country is determined for the base year, 2010, and for 2030, derived from national energy plans whenever available and considering any relevant renewable or energy efficiency objectives that the country deems appropriate.

2) **Assessment of REmap Options:** Once the Reference Case is determined, the additional realistic potential of renewables is identified by sector and by technology/source: REmap Options. Each REmap Option is characterised by its renewable energy contribution and its costs and is used to substitute an equivalent amount of energy (and related capacity) provided by conventional (fossil-fuel based and nuclear) technology.

3) **Building the REmap case:** The scenario resulting from the substitution of conventional technologies – from the Reference Case – with the identified REmap Options is called REmap case. This is reflected in an alternative energy balance of the country in 2030.

4) **Compilation of cost-supply curve:** Both the renewable energy potential and the cost of each REmap Option compared to the conventional technology are compiled into a cost-supply curve, allowing evaluation of the available cost-effective potentials and the level of renewable energy penetration that can be achieved with different options. The costs represented in the cost-supply curve do not consider the savings due to externalities. These are estimated separately to calculate the net costs/savings of the energy transformation.

5) **Validation of the REmap analysis:** The analysis goes through an iterative process of consultation and review with national energy experts, starting from the definition of the Reference Case, followed by the identification of the REmap Options and lastly with validation of the level of ambition of the REmap case.

6) **Estimation of costs and benefits of the REmap case:** Once the REmap analysis is completed, the overall costs and benefits of the REmap case compared to the Reference Case are calculated. These include the impact of the energy system costs, investments, environmental, climate and human health externalities. Further details of cost metrics and calculations are provided below.

The objective of the REmap programme is not to set renewable energy targets; however, the findings can inform target setting. The political feasibility and challenges to implement each option in different sectors and countries vary depending on the countries' national circumstances as well as on the level of commercialisation that technologies have reached.

Key costs and benefits metrics of the REmap approach

Each REmap Option is characterised by its renewable energy potential in terms of final energy and its "**substitution cost**", which is expressed in USD[2] per energy unit (typically in gigajoules, GJ) of final renewable energy. The substitution cost is the difference between the annualised costs of the REmap Option and a non-renewable energy technology used to produce the same amount of energy (*e.g.,* electricity, heat), then divided by the total renewable energy use in final energy terms. It is based on the capital, operation and maintenance and fuel costs in 2030, and considers technological learning as well as energy price changes between now and 2030.

2. The base year for the REmap analysis is 2010. All USD figures reported in this study reflect USD values as of 2010.

When the substitution costs of all REmap Options are multiplied by their energy potential (in petajoules, PJ, per year), the resulting figure reflects the impact of additional renewable deployment on "**energy system costs**". The resulting costs/savings are estimated for the whole energy system and at the sector level.

No further assumptions are made with regard to infrastructure needs (*e.g.*, transmission grids, charging infrastructure for electric mobility, etc.) beyond what countries plan, and the assessment of any related costs is also excluded from the study.

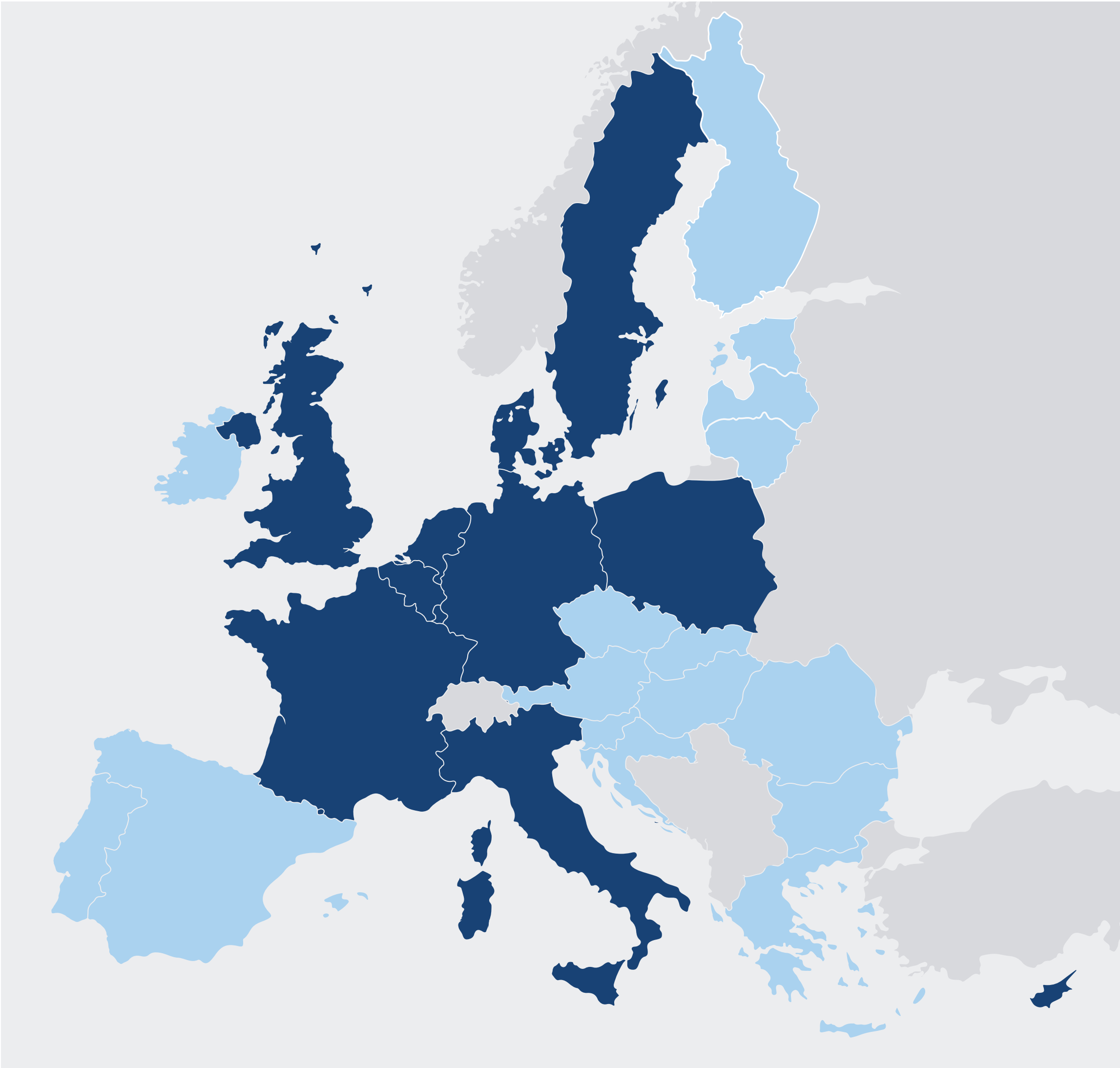
The calculation of benefits of renewable energy in REmap includes the estimation of avoided externalities of CO_2 emissions and emissions of air pollutants, as well as their impact on human health and agricultural crops. A range of USD 17 to USD 80 per tonne of CO_2 is assumed for carbon prices and a wide range of unit external costs is assumed for air pollutants (IRENA, 2016b).

Lastly, in this REmap analysis, costs are estimated from a government perspective. For this reason, the assumed energy prices exclude taxes and subsidies. To account for broad societal goals, a discount rate of 4% is used in the energy cost calculations.

2.2 REMAP STUDY FOR THE EU-28

The REmap study for the EU-28 has been developed by integrating two sets of results: 1) the results of existing in-depth REmap analyses for 10 EU Member States that are part of the REmap programme, and 2) the results of a high-level analysis of 18 EU Member States for which a REmap analysis is not available to date. As shown in Figure 2, IRENA has completed full REmap analyses for Belgium, Cyprus, Denmark, France, Germany, Italy, Poland, Sweden, the Netherlands and the UK.

Figure 2: Participation of EU member states in IRENA's REmap programme[3]



The boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.
The term "country" as used in this material also refers, as appropriate, to territories or areas.

Background map: OpenStreetMap®.

Reference Case

For the purposes of the REmap EU analysis, the Reference Case for the 28 EU Member States has been developed using the following approach:

- For the 10 Member States that already have a REmap analysis (together accounting for 73% of the total final energy consumption of the EU), their Reference Case in 2030 was developed based on the latest national energy plans and renewable energy targets. If the required data were not available or the suggestion was made by countries to use other sources, data that originate from the most comprehensive energy supply and demand projections that fit the country projections were used. A list of the sources that are the basis of the analysis can be found in Annex A.

3. Countries in dark blue have joined the REmap programme and have an existing detailed REmap analysis; those in light blue comprise the rest of the EU-28, which are not part of the REmap programme but have been added as part of the EU study (Spain is a REmap country but the REmap analysis is not yet complete).

- For the other 18 EU Member States for which no REmap analysis was available (together accounting for 27% of the total final energy consumption of the EU), the EU Reference Scenario 2016 (E3MLab *et al*., 2016) was used to develop the Reference Case in 2030.

REmap Options

With the Reference Case in place, the additional realistic potential of renewables can then be identified for each country and sector: the so-called REmap Options. REmap Options are determined based on several authoritative sources that assess renewable energy potential, including industry, technology and sector roadmaps. The full list of consulted sources for the REmap country analyses is shown in Annex A.

More specifically, for the EU-28, REmap Options were determined as follows:

- **REmap Options in end-use sectors in countries with REmap analysis:** For the 10 countries with an existing REmap analysis, several factors were considered, including resource availability, access to finance, available infrastructure, cost developments, etc. Once the process was completed, REmap Options were reviewed by country experts.

- **REmap Options in end-use sectors in countries without REmap analysis:** For the remaining 18 countries, a quick-scan of renewable technology options was performed. Resource availability was taken as a base and several indicators were used to determine the realistic contribution of REmap Options, such as increase in renewable energy share by sector/technology, share of rooftop covered by renewable technologies (*i.e.,* photovoltaic (PV) panels or solar thermal collectors), capacity additions compared to countries with similar conditions, etc.

- **REmap Options for the power sector:** At the time when the REmap EU study started, only 10 EU countries were part of the REmap programme; therefore, REmap Options for the power sector were available only for these countries (countries in dark blue in Figure 2). The assessment of REmap Options considered all the factors mentioned in the REmap methodology in the previous section and were validated in consultation with country experts. The analysis of the remaining 18 EU Member States was developed based on the 2016 Reference Scenario results from the PRIMES model (E3MLab *et al*., 2016) modified with increased renewable energy uptake based on a high-level assessment of the renewable energy resource potential and technology development trends within these countries. The REmap Options for the power sector were further validated through a detailed power system dispatch of the REmap case, explained in the next section.

Once the analyses for each of the 28 EU Member States were ready, these were aggregated into an EU-28 Reference Case and REmap case, which shows the results at the EU level. From this, the EU-wide renewable energy cost-supply curve was derived enabling assessment of the cost-effective renewable energy potential and the level of ambition that the EU can attain with different renewable energy technologies. The estimated potential in REmap by country and sector were aggregated to draw policy conclusions for the entire EU. This can be compared at the country or regional level as well.

Consultative process

The development of the REmap analysis for the EU-28 study benefited from a consultative process with the European Commission, Member States and other EU representatives and stakeholders. Several EU representatives at the Member State and EU levels provided feedback on the analysis and draft report. Several events have taken place to discuss findings at different stages of the study:

- First consultation workshop with Member States and the European Commission to discuss preliminary results – Brussels, 20 October 2016.
- Sectoral webinars to discuss interim results at the EU and country levels for each sector:
  - Power – 19 December 2016
  - Heating and cooling – 9 January 2017
  - Transport – 9 February 2017
- Second workshop with Member States and the European Commission to receive feedback on the interim results of the REmap analysis and to discuss the key policy topics to be addressed in the report – Brussels, 27 March 2017.
- Panel discussion at EU Sustainable Energy Week, hosted by IRENA and the European Commission, with the participation of Member States and European Parliament representatives and attendance of other relevant stakeholders – Brussels, 22 June 2017.
- Final workshop with participation of Member States, Parliament, industry, non-governmental organisations and other stakeholders to present findings and discuss policy recommendations – Brussels, 25 October 2017.

The final results of the REmap study were reviewed and benchmarked against other scenarios for the region by the European Commission's Joint Research Centre (JRC). A summary of findings is provided in Annex F.

2.3 POWER SECTOR ANALYSIS

Wind and solar power account for more than three quarters of the REmap Options identified in the power sector. These are considered "variable renewable energy" (VRE) sources, as their production levels are uncertain in both the short and long term. An increased share of VRE has implications for the operation of EU power systems. This study aims to scrutinise the flexibility of the European power system in 2030 and its ability to absorb the high levels of variable renewables resulting from the full implementation of REmap Options.

For this purpose, both the Reference Case and REmap were analysed within the context of a full 28 Member State[4] European electricity dispatch model (Collins *et al.*, 2017). The analysis is based on detailed simulations of unit commitment and economic dispatch using the modelling tool PLEXOS® Integrated Energy Model (Energy Exemplar, 2016) developed in cooperation with University College Cork. Further detail about the model and assumptions can be found in Annex E.

This power sector analysis adds new insights to REmap findings by quantifying expected levels of curtailment, electricity trade, interconnector congestion, wholesale market price changes, and effects on market clearing (*e.g.*, merit order, marginal unit) and other metrics. The value of these additional insights is in the improved understanding of the robustness of a transitional low carbon electricity sector and in identifying challenges and operational concerns which may accompany that transition.

4. Switzerland and Norway are also included in the boundaries of the analysis. The power system characterized for these countries in the model (i.e. installed generation mix and electricity demand profile) is based on the conservative "Slowest Progress" Vision 1 scenario of the European Transmission system operator's, ENTSO-E's, scenario development report (ENTSO-E, 2016), used to inform the 2016 Ten-Year Network Development Plan.

The modelling approach applied is based on a soft-linked methodology as initially described in Deane *et al.* (2012) and Giannakidis *et al.* (2015), namely, taking a scenario that includes the power generation capacity mix that is defined through application of an energy system model and subsequently simulating the optimal dispatch for that mix via another dispatch model. Such methodology has been applied in an assessment of European power system policy development in Brouwer *et al.* (2015) and Collins *et al.* (2017). Each country was represented as a node, and only interconnection transmission capacity with other countries was considered[5].

The model developed for this REmap EU study ran at hourly resolution for the target year of 2030 using localised electricity demand and wind and solar generation profiles, simulating the cost-optimal operational dispatch of both scenarios for this year:

- Localised national wind profiles used were those of the EMHIRES dataset developed by the European Commission's Joint Research Centre (Gonzalez Aparicio *et al*., 2016).
- Localised national solar profiles were developed through the use of the US National Renewable Energy Laboratory's (NREL) PVWatts tool (NREL, n.d.) (Dobos, 2013).
- Hourly electricity demand profiles for the EU-28 were generated by scaling historic 2012 hourly profiles provided by the European Network of Transmission System Operators for Electricity (ENTSO-E) to the demand anticipated in both dispatch model scenarios respectively for 2030 (ENTSO-E, 2012).
- Interconnector capacities between countries used for this work are in line with ENTSOE's Reference Capacities for 2030 as defined in the scenario development report that informed the *2016 Ten-Year Network Development Plan* (ENTSO-E, 2016).

A few aspects of power system operation are excluded from this analysis, namely trading strategies, risk management, reserves and ancillary services. This choice was made due to data availability reasons; while all of these elements must be analysed in-depth in a full operational assessment of the power sector, their exclusion is expected to have limited impact on our high-level results in terms of the potential feasibility of the REmap case from a power sector perspective.

5. This application of the approach is exactly as was implemented in Collins et al. (2017).

3 RENEWABLE ENERGY PROSPECTS FOR THE EU BY 2030

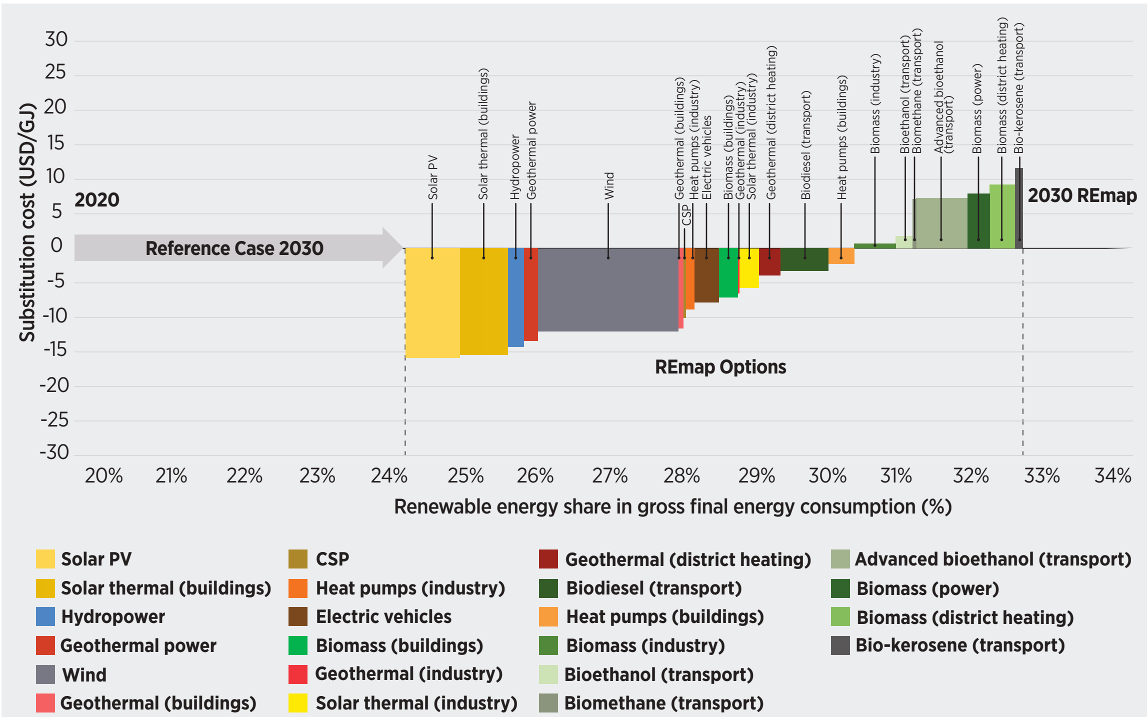
3.1 OVERALL RESULTS

3.1.1 DEPLOYMENT OF RENEWABLES: REMAP VERSUS REFERENCE CASE

In 2010, soon after the adoption of the current Renewable Energy Directive (2009/28/EC), the share of renewable energy as a fraction of total energy consumption in the EU-28 was 12.9%. Since then, this share has grown to reach 16.7% in 2015[1]. The latest European Commission renewable energy progress report, released in February 2017, indicates that the EU-28 is on track to reach a 20% share of renewables by 2020 (European Commission, 2017a).

Under the Reference Case – *i.e.,* assuming the continuation of existing and planned policies – IRENA estimates that the EU-28 would reach a 24% renewable energy share by 2030. This is below the currently proposed 27% target and would represent a substantial deceleration in the rate of renewable energy deployment compared to the previous decade. The REmap analysis identified significant cost-effective renewable energy potential that could be realised by 2030 to reach the proposed 27% target and go beyond. Figure 3 shows the cost-supply curve[2] of available renewable energy options

Figure 3: Cost-supply curve of renewable energy options to go beyond the 27% target for 2030



Note: PV = photovoltaic; CSP = concentrated solar power

1. *Data released in January 2018 shows that the share of renewables in energy consumption in the EU reached 17% in 2016. (Eurostat, 2018)*

2. *Horizontal axis represents renewable energy deployment, with REmap Options organised by cost from left to right. Vertical axis represents 'substitution costs' i.e. differences between the Levelised Cost of Energy (LCOE) for the renewable and the conventional technology it substitutes. REmap Options with negative substitution costs are cheaper than conventional technologies.*

(REmap Options) across all sectors (power and district heat, buildings, industry, and transport), resulting from the REmap analysis for the EU.

The results show that there are various cost-effective combinations of renewable energy options to meet the 27% target; however, the REmap analysis identifies additional potential to exceed this share.

The full implementation of all renewable energy options under a reference demand scenario would increase the share of renewables to 33% by 2030. If realisation of the proposed 30% energy efficiency target[3] is considered, the same renewable energy use under the REmap case would represent a share of 34%. If more ambitious energy efficiency targets are considered, the resulting share of renewables could be even higher for the same level of deployment. An analysis of the sensitivity of the resulting shares of renewables for different demand scenarios and degrees of deployment of REmap Options is shown in Annex D.

The additional potential beyond the Reference Case can be broadly split into three categories: the first category comprises different forms of renewable power generation (wind, solar, hydro, geothermal) as well as solar thermal in buildings. The second category includes electrification of heat and transport by means of heat pumps and electric vehicles (in combination with renewable power generation), as well as biodiesel for transport, solar thermal in industry and geothermal in district heating systems. The third category comprises different forms of biomass use across sectors. The first category yields strong cost savings compared to conventional technologies, the second delivers cost-neutrality to moderate savings and the third comes at additional cost.

The main renewable energy options in terms of their contribution to the additional potential beyond the Reference Case shown in Figure 3 are: wind power, transport biofuels (both first and second generation), solar thermal in industry and buildings, biomass in industry and buildings, and solar PV.

The total incremental costs of REmap Options is represented by the area below the cost-supply curve shown in Figure 3. The options below the curve represent savings, while the options above the curve bring additional costs. About three quarters of the identified REmap Options are cheaper than the conventional technology substituted, whereas the remaining one-quarter comes at an additional cost. However, the full implementation of all identified REmap Options is cost-effective, as the volume of economic savings of the most competitive options far outweighs the costs of the least-competitive ones.

The full implementation of all identified renewable energy options would result in estimated net cost savings of USD 25 billion per year by 2030 compared to the Reference Case.

Additional costs for the modernisation of power grids, or a potential scenario of low or stagnating fossil fuel prices, could reduce these estimated savings. However, these potential additional costs are still outweighed by the benefits when health and environmental externalities are considered. A more detailed analysis of the overall economic impacts of the REmap case is provided in section 3.1.2.

3. As part of the "Clean Energy for All Europeans" package of November 2016, the European Commission proposed a binding EU-wide target of 30% for energy efficiency by 2030 (European Commission, 2016a).

Box 1 **Solar thermal energy in the EU**

About half of the energy consumption in the EU is used to produce heat. Solar thermal technology is a highly cost-effective renewable solution, that can be used for multiple heating applications, including hot water and space heating for buildings, as well as low and medium temperature process heat in the industrial sector. However, the economic potential for solar thermal technology in the EU remains largely untapped.

Only a handful of EU countries have reached substantial levels of solar thermal technology deployment. Cyprus is the leader, with approximately 0.8 square metres of solar panels installed per capita, followed by Austria, Greece and Denmark. Across the EU, the average level of deployment is estimated at approximately 0.1 square metres of solar panels per capita, resulting in an almost negligible contribution to final energy consumption and well below the realistic potential for this technology in the region.

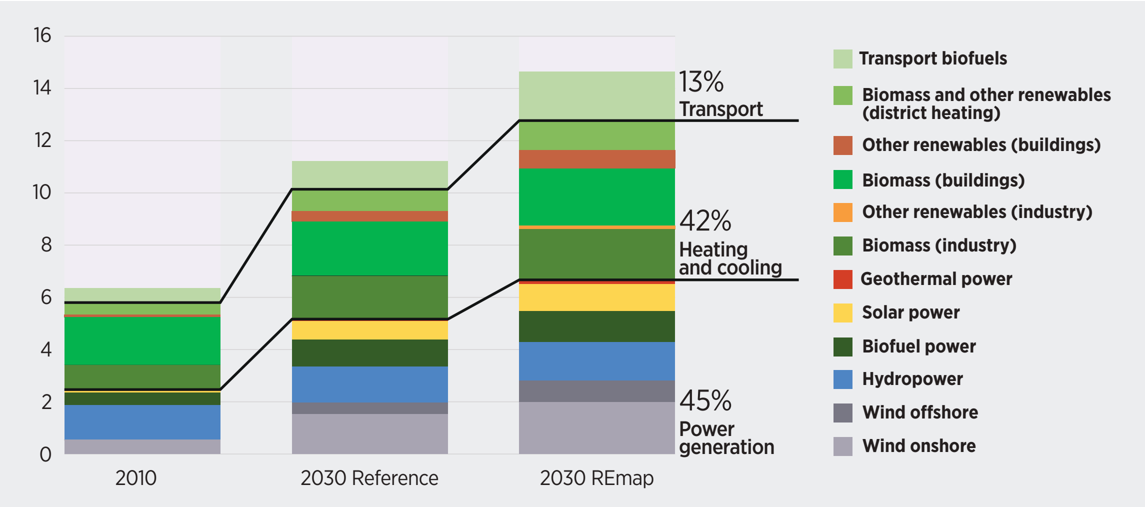
The REmap analysis identifies very significant cost-effective potential to upscale the use of solar thermal in the EU - both for buildings and industry - to account for more than 3% of final heat demand.

Renewable energy deployment by source and application in 2030

In 2010, the reference year for this analysis, bioenergy accounted for about two-thirds of all final renewable energy use, followed by hydropower (21%) and wind power (9%). In terms of the breakdown per application, more than half of the total renewable energy use was for heating and cooling purposes (buildings and industry). Power accounted for about 39% of the total renewable energy use, followed by the transport sector with 9%.

Figure 4 shows the breakdown of EU-28 gross final renewable energy consumption by source and application for 2010 and 2030 (for both the Reference Case and REmap).

Figure 4: Breakdown of gross final renewable energy consumption[4] in the EU-28 by source and application in 2010 and 2030 (PJ) (Reference Case versus REmap)



4. *Renewable power for heating & cooling and transport is shown under the power generation sector. The category "other renewables" includes solar thermal and geothermal.*

In the Reference Case, the renewable energy mix is already projected to change substantially by 2030. Wind and solar PV are the technologies with the largest relative growth expected compared to 2010. Wind power generation (including onshore and offshore) would more than triple, while solar PV generation is expected to grow more than eight-fold to account for 6% of total renewable energy use. While bioenergy also grows substantially in absolute terms, its relative weight in total final renewable energy use would decrease to 60%. Similarly, the share of hydropower is expected to decrease to 12% of total renewable energy consumption.

In terms of the breakdown per application, renewable power would increase in weight under the Reference Case to account for about 46% of the gross final renewable energy consumption in the EU-28. The contribution of transport would remain almost unchanged (at between 9 and 10%), while that of heating and cooling would decrease to 45% of total renewable energy use.

In REmap, the main renewable energy options contributing to the additional potential in 2030 are: wind power (239 TWh or 860 PJ), transport biofuels (both first and second generation) (786 PJ), solar thermal in industry and buildings (420 PJ), biomass in industry and buildings (377 PJ) and solar PV (93 TWh or 333 PJ).

The share of wind and solar PV combined would account for 21% of the gross final renewable energy consumption. On the other hand, the share of bioenergy would decrease to 55%. In terms of the breakdown per application, the REmap case increases the weight of transport biofuels as a fraction of total renewable energy use to 13%. Conversely, the relative weight of the heating and cooling sector would decrease to 42%.

Renewable energy deployment by sector in 2030

Table 1 shows the renewable energy consumption and shares by sector in 2030. Under the REmap case, the share of renewable energy in the power sector would rise to 50% (compared to 41% in the Reference Case), while in the end-use sectors renewables would account for shares of 42% in buildings, 36% in industry and 17% in transport. Detailed analysis and results per sector are provided in sections 3.2 and 3.3.

Table 1: Overview of renewable energy consumption and shares by sector in the EU-28 in 2010 and in 2030 (Reference Case and REmap)

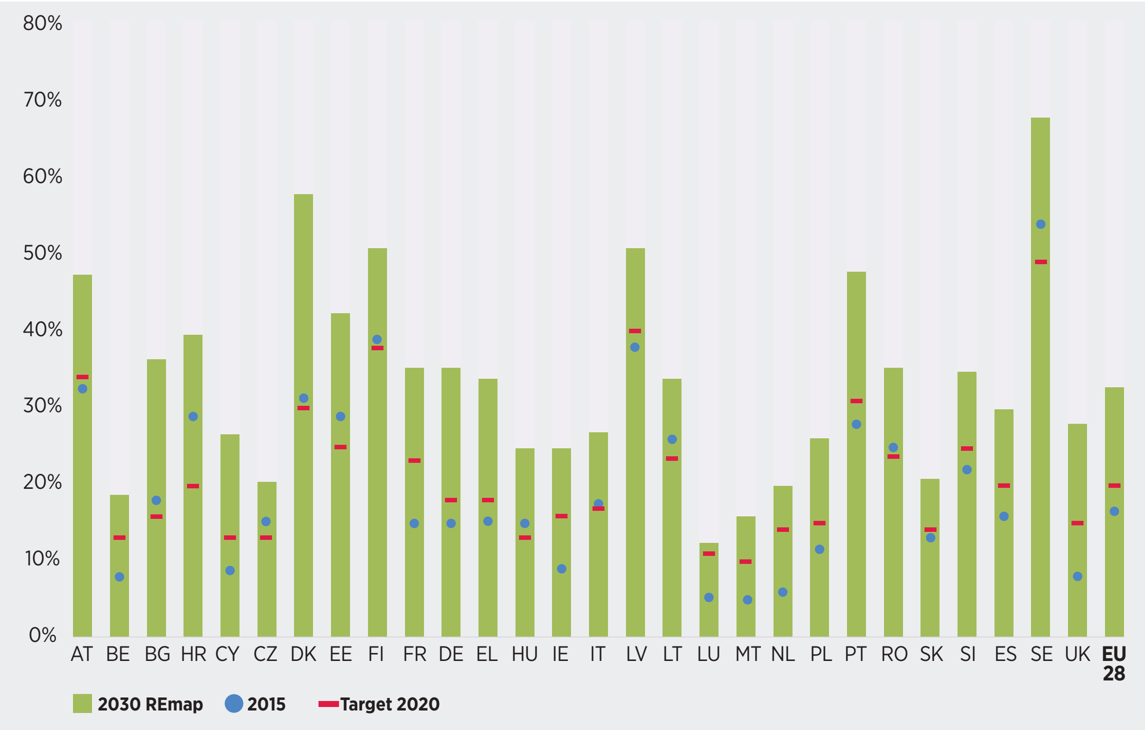
SECTOR		RENEWABLE ENERGY SHARE			RENEWABLE ENERGY CONSUMPTION		
		2010	REmap 2030	REmap 2030	2010	REmap 2030	REmap 2030
		(%)	(%)	(%)	(PJ/year)	(PJ/year)	(PJ/year)
Transport	Excl. electricity (D)	4%	8%	14%	550	1 066	1 852
	Incl. electricity (A)	4%	9%	17%	598	1 255	2 227
Industry	Excl. electricity & DH (F)	13%	22%	28%	966	1 686	2 074
	Incl. electricity & DH (B)	15%	28%	36%	1 825	3 520	4 389
Buildings	Excl. electricity & DH (G)	15%	26%	37%	1 920	2 477	2 928
	Incl. electricity & DH (C)	17%	32%	42%	3 433	5 448	6 787
Power generation (H)		20%	41%	50%	2 453	5 133	6 687
District heat generation (I)		16%	29%	38%	470	845	1 132
GFEC	Incl. electricity & DH (=D+F+G+H+I)	13%	24%	33%	6 359	11 207	14 674
TFEC	Excl. electricity & DH (=D+F+G)	10%	17%	24%	3 436	5 229	6 855
	Incl. electricity & DH (=A+B+C)	12%	23%	32%	5 856	10 223	13 403

Note: DH = district heating.

Renewable Energy Deployment by Member State in 2030

In 2015, the renewable energy shares in EU Member States varied from 5% to 54%. Variations will persist to 2030, reflecting multiple factors such as different starting points, available resource potentials, existing and planned policies, as well as the specific market conditions for renewables in each country. However, these differences may narrow by 2030 as Member States with lower initial shares have the potential to grow their renewable shares faster. Figure 5 compares the situation in 2015 with each of the 2020 targets as well as the realisable potential by 2030 under the REmap Case.

Figure 5: Renewable energy share in gross final energy consumption by EU Member State – 2015, 2020 target and 2030 potential with accelerated uptake of renewables (REmap)

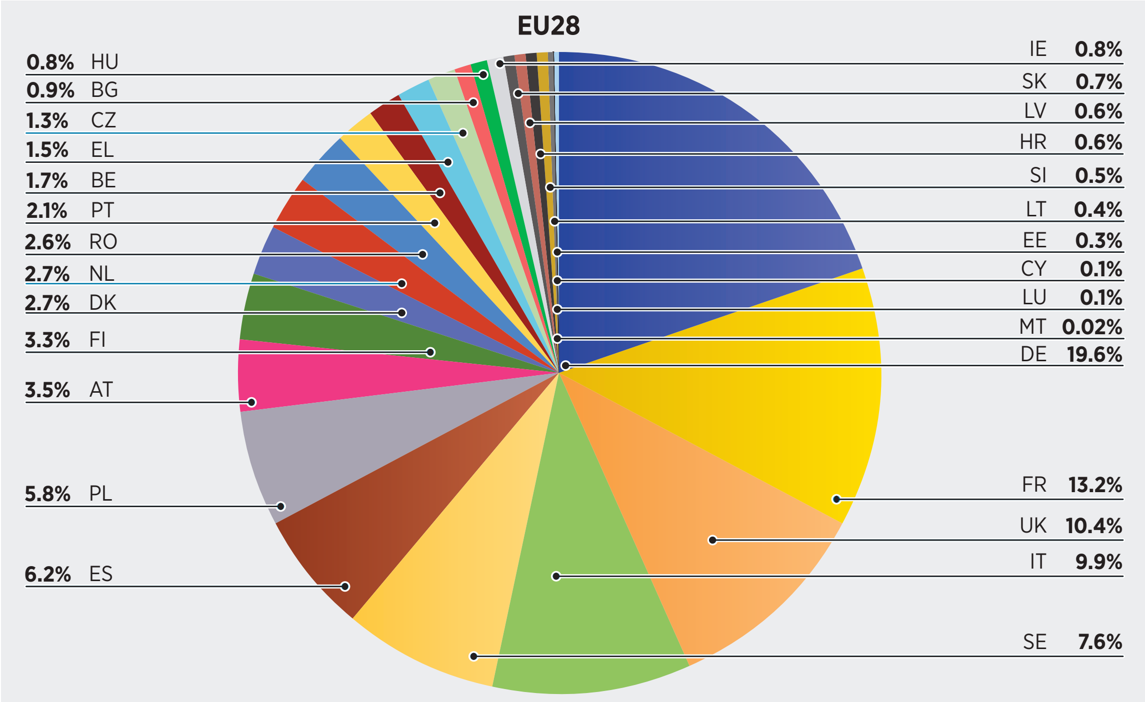


Sources: REmap 2030: IRENA analysis; Renewable share in 2015: Eurostat (2017a); Targets for 2020: Renewable Energy Directive (2009/28/EC)

As indicated above, the Reference Case analysis shows that the aggregation of existing Member State plans or projections to 2030 would fall short from a 27% share at the EU level. Thus, additional efforts will be needed from Member States to reach the proposed EU-wide 27% renewable target by 2030. One underlying reason is that most countries focus on accelerating the uptake of renewable energy in the power sector. By comparison, the end-use sectors (transport, industry, buildings) receive less policy attention in most Member States.

In terms of the total volumes of renewable energy consumption in the REmap case, Germany and France would be by far the largest users of renewable energy by 2030, accounting for 20% and 13% respectively. Together with the United Kingdom and Italy, these four countries would represent more than half of the total gross final renewable energy consumption in 2030 (see Figure 6).

Figure 6: Breakdown of gross final renewable energy consumption by Member State in 2030 under REmap



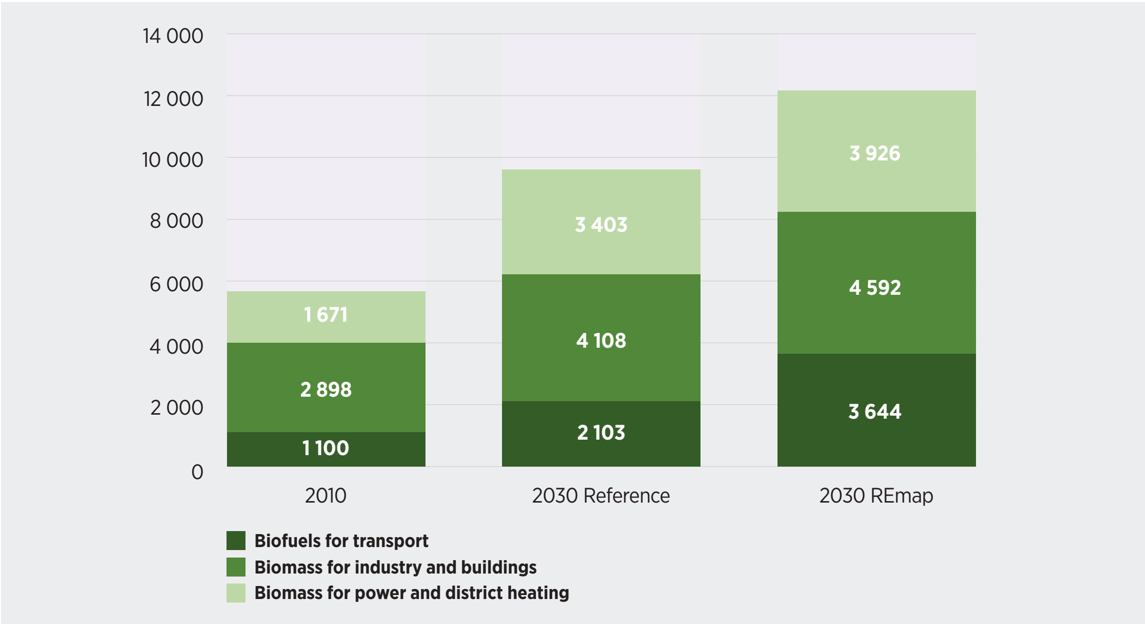
The role of bioenergy

Bioenergy is the largest source of renewable energy in the EU. In 2010, the reference year for this analysis, bioenergy accounted for roughly two thirds of the final renewable energy consumption in the region. In terms of primary energy, biomass accounted for 5.7 exajoules (EJ), equivalent to 8% of the total energy supply of the EU. Most biomass was allocated to direct uses in the buildings and industry sector (49%, 2 801 PJ). Power and district heat generation accounted for 29% of biomass demand (1 671 PJ). Biofuels in the transport sector accounted for the remaining 22%.

Biomass will remain a key energy source for the EU in 2030, as it is needed to enable the region to progress on the decarbonisation of energy uses for which no other cost-effective solutions are available. Biomass is the main source of renewable energy for industry, providing a feedstock for chemicals production and delivering process heat at high temperatures. For transport, biomass is the main source of renewable energy besides electrification. In the power sector, it enables flexibility in renewable electricity generation.

Figure 7 shows primary energy biomass in 2010 and 2030, under both the Reference Case and REmap. Under the Reference Case, biomass demand is expected to grow substantially to reach 9.6 EJ by 2030. If the potential of all REmap Options is implemented, biomass demand would grow further to reach 12.2 EJ, roughly a twofold increase from 2010 to 2030. The biggest growth would come from liquid biofuel deployment in the transport sector. However, the bioenergy share in the EU's final renewable energy consumption would decrease from 67% in 2010 to 55% under REmap in 2030, as the contributions from other sources (*e.g.,* wind and solar) grow faster.

Figure 7: Total primary energy supply of biomass in the EU-28 in 2010 and in 2030 under the Reference Case versus REmap (PJ)



Today, the EU meets a large share of its bioenergy demand domestically. Imports from outside of the EU represent about 4% of the gross inland consumption of bioenergy (AEBIOM, 2015). A recent study prepared for the European Commission (VITO *et al.*, 2017) estimates that the supply potential of domestic bioenergy in the EU-28 by 2030 ranges from 14.1 EJ to 16.4 EJ.

While the total domestic biomass supply potential in the EU-28 exceeds the projected demand under REmap by 2030, a sizeable portion of this supply potential may be more expensive than imported alternatives or hard to mobilise into the energy sector. This is especially the case when considering a shift from conventional biomass feedstocks derived from vegetable oils and sugars to novel biomass feedstocks derived from agricultural and forestry residues. Technologies for the conversion of such novel biomass feedstocks into gasoline and diesel substitutes exist, but they come at a higher cost when compared to their fossil counterparts. Thus, the EU may benefit from substantial biomass imports from other countries – where biomass supply might be cheaper – to help contain costs.

Also within the EU, not all Member States have the domestic feedstock supply potential to meet their growing demand. This will require the creation of internal bioenergy markets and the related trade infrastructure to ensure that all countries meet their demand potential.

In both cases – imports from outside the EU-28 and trade within EU-28 countries – sustainability of biomass supply can be addressed by appropriate legislation that establishes minimum sustainability criteria that need to be met by the biomass supply chain to ensure that bioenergy pathways do not cause negative impacts on biodiversity, food prices and land ownership.

Box 2 Biogas in the EU

Biogas and its refined form, biomethane, represent an interesting alternative in the future supply of renewable energy. Compared to other renewable energy sources, biogas has the advantage that it can be used to provide flexible power production, including in times of low wind and solar intensity, and it also can provide an option for the decarbonisation of natural gas grids. In 2015, the total production of biogas in the EU-28 corresponded to 653 PJ, or 4% of the region's primary supply of gaseous fuels (natural gas and biogas) (Eurostat, 2017b) and came mainly from dedicated crops (51%) and manure (22%) (CE Delft *et al.*, 2016). Electricity generation was the predominant use corresponding to 62% of the biogas production.

The production of biogas has the potential to increase to 1 683 PJ in 2030 (CE Delft *et al.*, 2016) from the use of available organic waste streams and with the potential of biogas capture from landfill sites. The largest growth potentials are found to be in liquid and solid manure, and in organic wastes. The existence, stability and reliability of the policy framework and support schemes appears to be the number one driver in all countries. National targets and goals also are identified as an important driver for the sector, as is the availability of suitable feedstocks (and waste collection processes) for biogas production. Biogas is supported mainly in the electricity sector, while support for biomethane has its focus on the transport sector.

Effects on fossil fuel consumption

The shift away from imported fossil fuels towards renewable energy is one of the key objectives of the Energy Union. Most of the fossil fuels consumed in the EU are imported from third countries. Oil products and natural gas have by far the highest external dependency rate at 90% and 69%, respectively (European Commission, n.d.).

Fossil fuels currently account for about 71% of the EU's primary energy supply. Under the Reference Case, IRENA estimates that by 2030 total consumption of fossil fuels would decrease by 16% compared to current levels, and these fuels would represent 62% of the primary energy supply. If the potential of all the REmap Options is implemented, the weight of fossil fuels in the EU's energy supply could be reduced further to represent just 54% of the region's primary energy supply by 2030.

Figure 8 shows the effect of the additional renewable energy deployment under the REmap Case for the consumption[5] of coal, oil products and natural gas in the EU-28 in 2030. Coal would experience the largest reduction[6] (19% below the Reference Case), driven by the penetration of large amounts of solar PV and wind in the power sector. Reductions in oil consumption (14% below the Reference Case) are mostly driven by the introduction of biofuels and electric vehicles in the transport sector. Consumption of natural gas under the REmap case would be 12% lower than in the Reference Case, with the largest reductions happening in the buildings sector.

5. *Excluding non-energy use in industry and consumption of the energy branch.*

6. *After completion of the REmap analysis for the EU, 10 EU Member States agreed to phase out existing traditional coal power and place a moratorium on any new traditional coal power stations without operational carbon capture and storage in the context of the "Powering Past Coal Alliance" launched at the 2017 United Nations Climate Change Conference held in Bonn in November 2017.*

Figure 8: Consumption of fossil fuels in the EU-28 in 2030. Reference Case versus REmap (PJ)

Electrification of end-use sectors

Some applications that consume energy in transport, industry and buildings, which currently are supplied through direct use of fossil fuels, can be converted to work with electricity. This "electrification" of end-uses will be a key element of the long-term transition towards a low carbon energy system as it can trigger very substantial energy efficiency gains while enabling the use of renewable power[7], avoiding the combustion of fossil fuels.

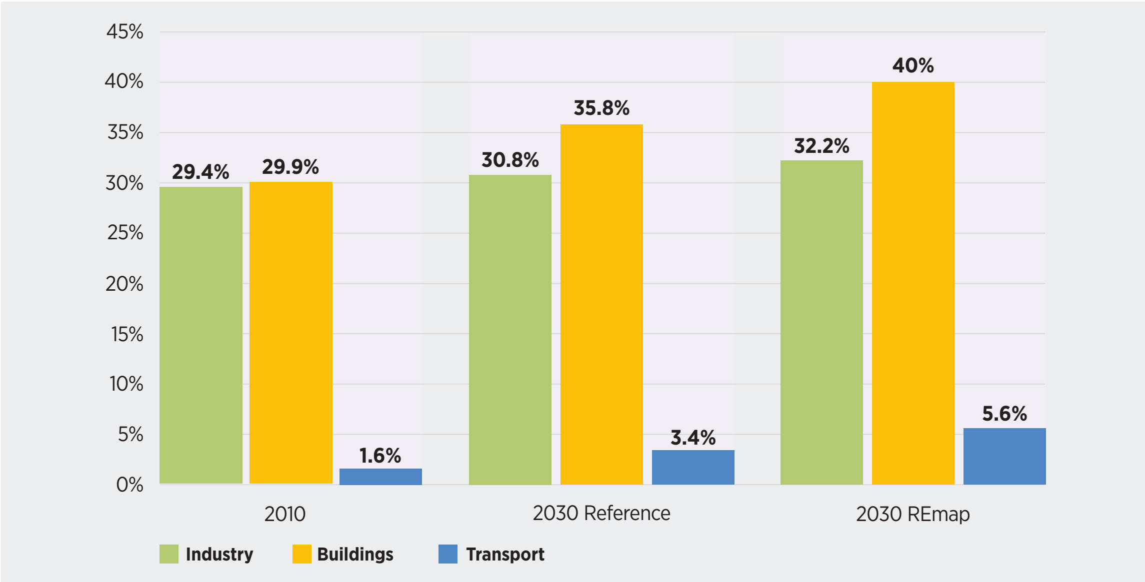
In the transport sector, increased electrification can be achieved, for example, with the deployment of electric or hybrid vehicles or the conversion of diesel trains to electric. In the buildings and industrial sectors, electric heat pumps can provide low-temperature heat for multiple applications.

In 2010, the base year of this analysis, electricity accounted for 21% of the final energy consumption of the EU. The accelerated adoption of heat pumps and electric vehicles under REmap would result in a substantial increase in the use of electricity in end-use sectors by 2030. Under REmap, electricity would represent 27% of total final energy consumption, up from 24% in the Reference Case. This requires generation of 230 terawatt-hours (TWh) per year of additional power, an amount comparable to Spain's electricity demand today.

Figure 9 shows the degree of electrification (expressed as a percent of final energy consumption) for each of the end-use sectors in 2010 and 2030 under both the Reference Case and REmap.

7. The REmap methodology includes electric vehicles and heat pumps as renewable energy options as they enable the efficient use of renewable power for transport and for heating purposes in buildings and industry. Only the renewable fraction of the power consumed is accounted towards the renewable share in these sectors.

Figure 9: Degree of electrification of end-use sectors in the EU-28 in 2010 and in 2030 (Reference Case versus REmap)



3.1.2 ENVIRONMENTAL AND ECONOMIC IMPACTS

Greenhouse gas emissions

Over the last two decades, the EU has been a key international player in raising awareness of and advancing policy action against the global challenge of climate change.

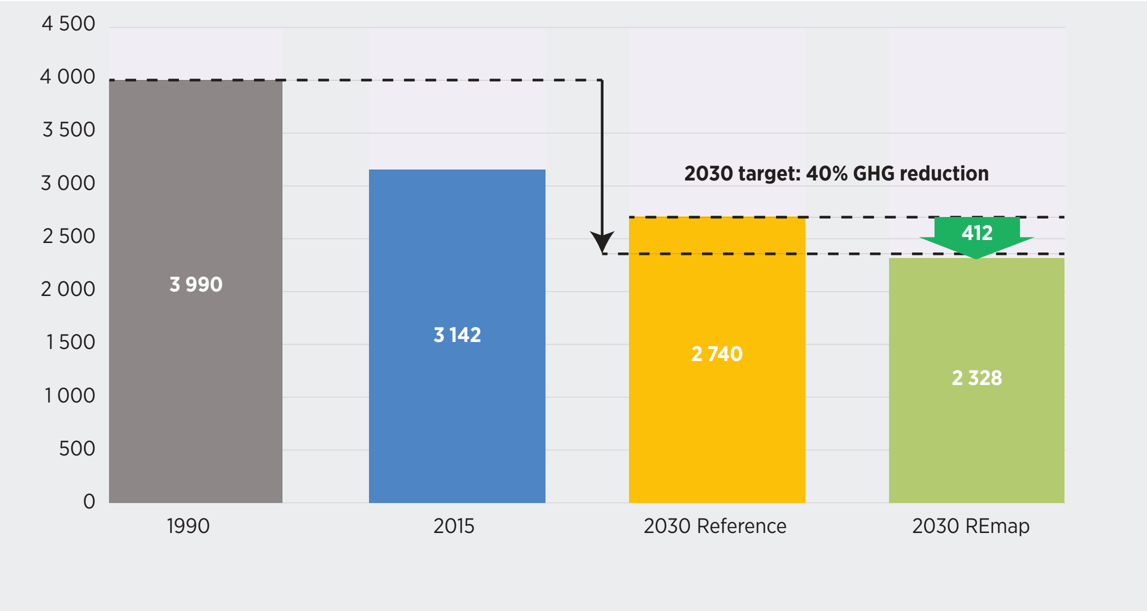
The EU committed to reduce its greenhouse gas emissions by 20% compared to 1990 levels by 2020, as part of its climate and energy "20-20-20" target package, adopted in 2009. In 2011, the EU adopted the *"Roadmap for moving to a competitive low carbon economy in 2050"* (European Commission, 2011). This roadmap outlines EU action to meet the objective of reducing greenhouse gas emissions by 80% to 95% by 2050 compared to 1990. It also establishes emission reduction milestones of 40% and 60% below 1990 levels by 2030 and 2040, respectively.

In 2014, the EU agreed on a new climate and energy framework for 2030, including a target to cut emissions by at least 40% below 1990 levels. Then in October 2016, the EU ratified the Paris Agreement, which established the goal to limit the rise in global temperatures this century to "*well below 2* °C" compared to pre-industrial levels.

The latest progress report of the European Environment Agency (EEA) shows that the EU is well on track to achieve its 2020 emissions reduction target. However, the report also indicates that the long-term trends are not in line with the EU's 2050 decarbonisation goals. Even if the EU would realise its 2030 target, much deeper reductions (two to three times larger than those from current levels to 2030 levels) would be needed between 2030 and 2050 (EEA, 2017b).

IRENA estimates that under the Reference Case, the energy-related CO_2 emissions of the EU would decrease to 2 740 million tonnes of CO_2 by 2030, equivalent to a 31% reduction compared to 1990 levels (see Figure 10).

Figure 10: Energy-related CO_2 emissions in the EU-28 in 1990, 2015 and 2030 under the Reference Case and with accelerated uptake of renewables (REmap) (Mt CO_2/year)



Source: IRENA analysis based on EEA source data for 1990 and 2015 values (EEA, 2017c)

The full deployment of REmap Options would deliver 412 million tonnes of additional CO_2 mitigation, a 15% reduction compared to the Reference Case. Under the REmap case, emissions in the energy sector would be 42% below 1990 levels, bringing the EU in line with its 2030 greenhouse gas objective.

The additional emission reductions that can be realised through the accelerated deployment of renewable energy under the REmap case – together with additional energy efficiency efforts – will be key to set Europe in line with a long-term emissions pathway compatible with the 2 °C objective established in the Paris Agreement.

Economic benefits

After a period of very strong growth, where investments almost doubled from USD 67 billion in 2007 to a peak of USD 124 billion in 2011, new investments in renewable energy in Europe[8] have declined and then stabilised at about USD 60 billion per year over the period 2013-2016 (Frankfurt School-UNEP Centre and BNEF, 2017).

Reaching a 34% renewable share by 2030 as per REmap would require an estimated average investment in renewable energy of USD 73 billion per year. The incremental, accumulated investment additional to the Reference Case would amount to USD 433 billion until 2030, representing an average annual contribution of 0.3% of the current EU-28 gross domestic product, before accounting for additional activity triggered in other sectors[9]. The overall macroeconomic benefits would be more significant because of this multiplier effect.

8. Investment data includes countries within the European region, outside the EU-28. Levels of investment in the EU-28 in 2016 are estimated between USD 50 billion and USD 56 billion (Frankfurt School-UNEP Centre and BNEF, 2017).

9. Previous IRENA analysis indicates a multiplier of a factor of two on a global scale, while for fossil-fuel importing regions such as Europe, the multiplier is probably larger (IRENA, 2017a).

Besides the impact on economic growth, the additional investment in renewables would have much broader social benefits for the EU and its Member States. Today the renewable sector employs about 1.2 million people in Europe (IRENA, 2017b). This figure would increase substantially with a doubling of the renewable energy share by 2030. Moreover, the decentralised nature of many renewable energy technologies and the increased uptake of domestic biomass production under the REmap scenario could be a driver for economic development in structurally weak regions and rural areas. Combined with energy efficiency measures, renewables also can be a key contributor to reducing energy poverty in the EU.

The REmap case results in an EU energy system with a reduced need for consumption of (mostly imported) fossil fuels, which in turn could deliver very substantial economic savings for EU citizens. About three quarters of the identified REmap Options are cheaper in terms of levelised cost of energy than the conventional technology substituted, while the remaining one-quarter comes at an additional cost. However, the full implementation of all REmap Options is cost-effective, with associated savings estimated at USD 25 billion per year by 2030 (approximately USD 165 billion accumulated over the period 2020-2030).

Additional costs for the modernisation of power grids, or a potential scenario of low or stagnating fossil fuel prices, could reduce these estimated savings[10]. However, the potential additional costs are outweighed by the benefits when the avoided externalities of a fossil-based system are considered.

The REmap methodology accounts for two types of externalities: the cost of damages of air pollutant emissions from the combustion of fossil fuels on human health and agriculture crops and the environmental cost of CO_2 emissions in the context of climate change.

The positive impact that renewable energy can have on the health of citizens is usually overlooked in the energy debate, despite being very significant. Today, about 400 000 people die prematurely in Europe each year because of air pollution driven by the combustion of fossil fuels (EEA, 2017a). The economic value from the avoided health damages with accelerated deployment of renewables as per REmap is estimated at between USD 19 billion and 71 billion per year by 2030.

Similarly, the environmental costs related to climate change avoided with the deployment of the REmap Options are very substantial. These are estimated at between USD 8 billion and USD 37 billion per year by 2030. Overall, the total avoided costs of externalities – greenhouse gas emissions and health impacts – are estimated at USD 27 to USD 108 billion per year by 2030.

When the savings from a pure cost–benefit analysis are aggregated with the economic value of avoided health and environmental externalities, the accelerated deployment of renewables as per REmap would result in total savings of between USD 52 billion and USD 133 billion per year in 2030.

10. A sensitivity analysis has been carried to assess how variations on assumptions on fossil fuel prices would affect the results on energy systems costs/savings and share of cost-effective renewable energy options. Results are detailed in Annex C.

Table 2: investment needs and economic benefits of REmap[11]

Average total yearly investment needs in renewable technologies until 2030 under REmap case (Reference + REmap)	**USD 73 billion/year**
Accumulated, incremental investments beyond Reference for the period until 2030 (Δ REmap - Reference)	**USD 433 billion**
Net system savings of REmap versus Reference Case (difference between LCOE of renewable energy options versus conventional)	USD 25 billion/year in 2030
Estimated avoided health damages	USD 19 – 71 billion/year in 2030
Estimated avoided environmental costs related to climate change	USD 8 – 37 billion/year in 2030
Total savings REmap versus Reference Case	**USD 52 – 133 billion/year in 2030**

Source: IRENA analysis

Box 3 VRE integration costs

The net savings to the energy system in 2030 reported in this study reflect the differences in the LCOEs between conventional technologies in the Reference Case versus renewable technologies in the REmap case. The LCOE is a commonly accepted metric for the comparison of the costs of energy. However, it does not account for system effects that could be derived from the variability of renewable sources, for example the need for additional back-up generation capacity, storage, curtailment or grid expansions.

Variable renewables pose new challenges to the operation of power systems, and these challenges increase as the VRE shares in the system increase. However, the overall costs of these challenges can be overestimated if the impacts on specific elements of the system – for example, operation of conventional plants, interconnectors, etc. – are assessed in isolation. Instead, a system-wide view is required to capture the whole range of possible cost-effective solutions. Investing in a diversified portfolio of power system flexibility options – including for example flexible generation, demand response, storage and interconnectors – results in important benefits in terms of system costs (Andrey *et al.*, 2017). Integration costs also can be reduced greatly with the adoption of best practices in system and market operation, adapted to the intrinsic nature of VRE technologies.

A recent review of studies suggests that the additional costs that VRE generation imposes upon electricity systems can remain relatively modest (Heptonstall *et al.*, 2017). This conclusion is in line with an increasing body of practical experience demonstrating that markets with large shares of variable renewables incurred significantly lower integration costs than expected, as a result of technology cost declines and the ability of markets to exploit low cost flexibility options (IRENA, 2017a).

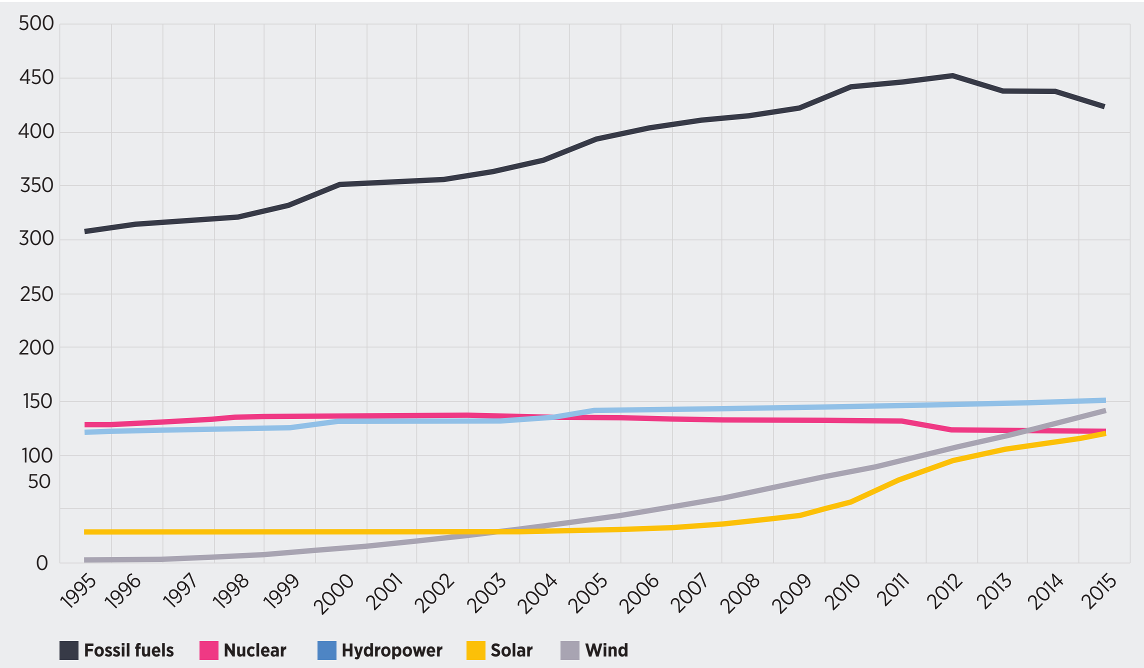
11. For more details on the definitions of the metrics for investments and savings, please consult the Appendix on REmap Methodology and Data of the Global REmap report, edition 2016 (IRENA, 2016a).

3.2 RENEWABLES IN THE POWER SECTOR

3.2.1 GENERATION AND CAPACITY MIX IN 2030: REMAP VERSUS REFERENCE CASE

In 2010, the base year of the REmap analysis, the EU power sector was dominated by nuclear, coal and natural gas, which together accounted for almost 80% of the total generation. The largest renewable contributor was hydro power (11% of total generation), followed by wind power (4%) and biomass (4%). Since then, the bulk of the newly installed power generation capacity in the EU has come from renewable technologies, while the installed capacity of fossil-fuelled generation has stagnated or declined (see Figure 11).

Figure 11: Electricity generation capacity by source in the EU-28, 1995-2015 (GW)



Source: Eurostat (2017c)

Renewable power generation technologies are quickly becoming cheaper than conventional technologies at a much faster pace than expected just a few years ago. Offshore wind and solar PV are two prominent examples. Over the last two years the costs of offshore wind have shown a steep decline with recent auctions in The Netherlands, Denmark and the UK awarded at record low prices of around 6 Eurocents per kilowatt-hour (kWh). In the case of solar PV, module prices in Europe have declined by about 80% from 2010 to 2016 (IRENA, 2016c). These reductions enable competitive generation costs even in countries with low solar resources. A utility-scale solar PV auction in Germany in June 2017 yielded an average cost of 5.6 Eurocents per kWh.

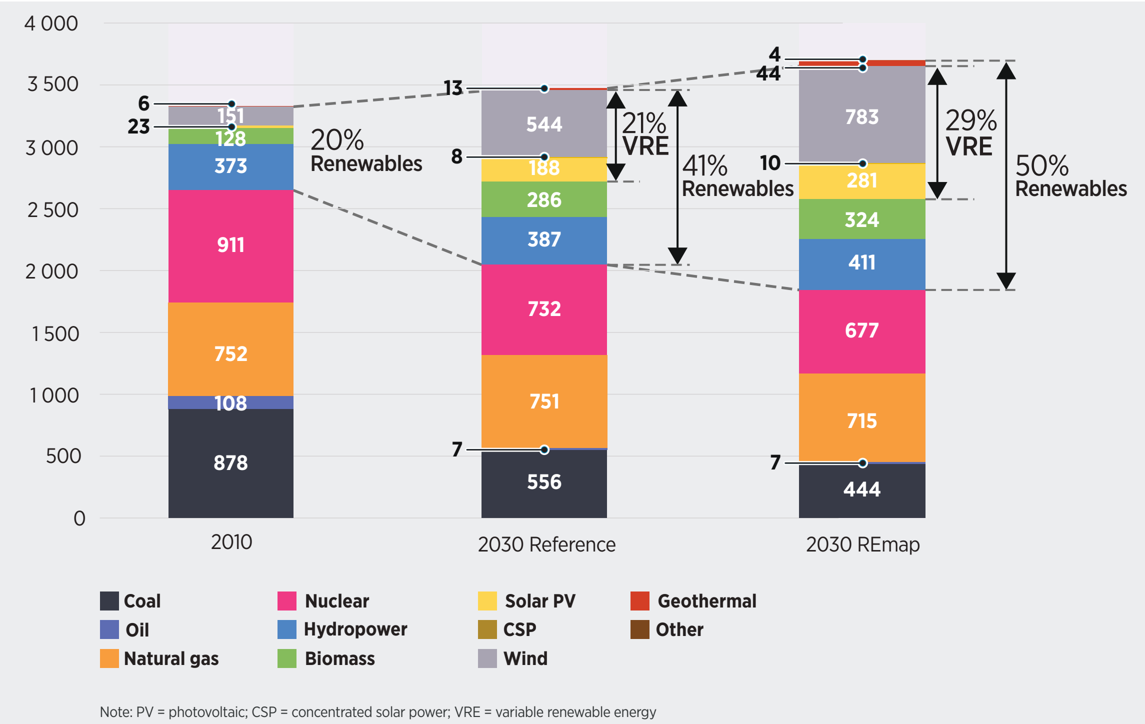
Furthermore, renewable power technologies keep improving, resulting not only in a reduction of costs, but also in an expansion of the volumes of renewable energy that can be harvested cost-effectively. Capacity factors of onshore wind turbines have increased steadily in the past and could increase further by about five percentage points[12] – from 27% in 2014 to 32% in 2025 – as a result of higher hub heights, larger swept areas, and improved blade design and controls.

In the case of offshore wind, there is also a clear trend towards larger machines, which can capture much more wind resource. Most offshore turbines operational at the end of 2015 were in the 2 megawatt (MW) to 4 MW range, with rotor diameters between 90 metres and 120 metres. Today's state-of-the-art, commercially deployed turbines are 6 MW machines. The commercialisation of 10 MW turbines is expected by 2020 (IRENA, 2016c). Furthermore, the technical experience accumulated from deploying offshore turbines in increasingly deeper waters will enable accessing larger volumes of renewable potential than expected a few years ago.

This trend is expected to continue towards 2030, resulting in very deep structural changes in the EU power generation mix. IRENA estimates that under the Reference Case, renewables could account for 41% of total generation, with variable renewable energy (mainly solar PV and wind) accounting for 21% of total generation.

The REmap analysis identified further potential for deployment of additional renewable power generation beyond the Reference Case, to reach 50% of total electricity generation in the EU. The share of variable renewable energy also would increase under the REmap case, reaching 29% of total generation. The main renewable technologies contributing to the growth beyond the Reference Case are wind power (both onshore and offshore), which could account for 21% of total power generation, and solar PV, which could provide 8% of total electricity in the EU by 2030.

Figure 12: Power generation by technology in the EU-28 in 2010 and in 2030 under the Reference Case versus REmap (TWh)



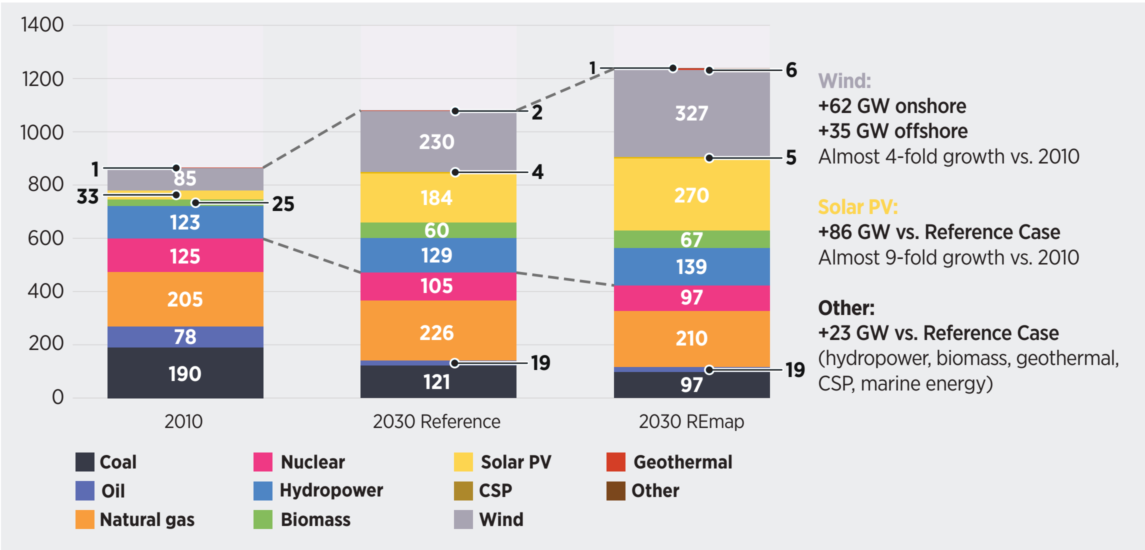
Source: IRENA and University College Cork analysis

12. Expressed as weighted global average.

Total installed power generation capacity in the EU-28 is expected to increase from 864 GW in 2010 to 1 079 GW in the Reference Case and to 1 237 GW in REmap by 2030. Capacity additions come from renewable technologies, which would grow from 266 GW installed in 2010 to 608 GW under the Reference Case and 814 GW under the REmap case. On the other hand, the share of conventional capacity would decrease significantly under both the Reference Case and REmap.

In REmap, the installed capacity of coal plants in the EU would almost halve from 190 GW in 2010 to 97 GW in 2030. Similarly, installed nuclear power would decrease significantly from 125 GW to 97 GW in 2030. The installed capacity of natural gas plants in 2030 would be similar to 2010 levels, with 210 GW installed.

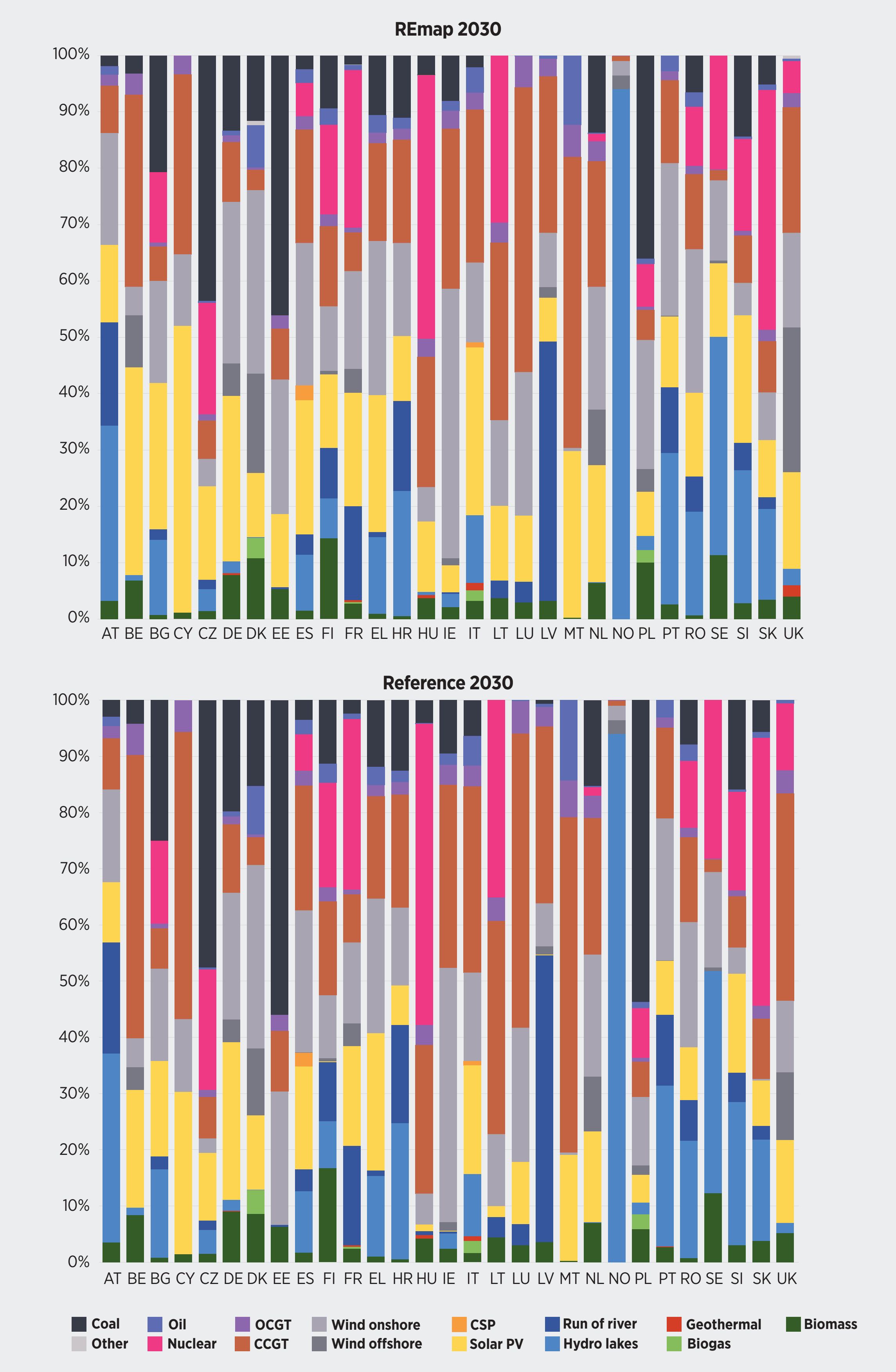
Figure 13: Installed power generation capacity by source in the EU-28 in 2010 and in 2030 under the Reference Case versus REmap (GW)



Source: IRENA and University College Cork analysis

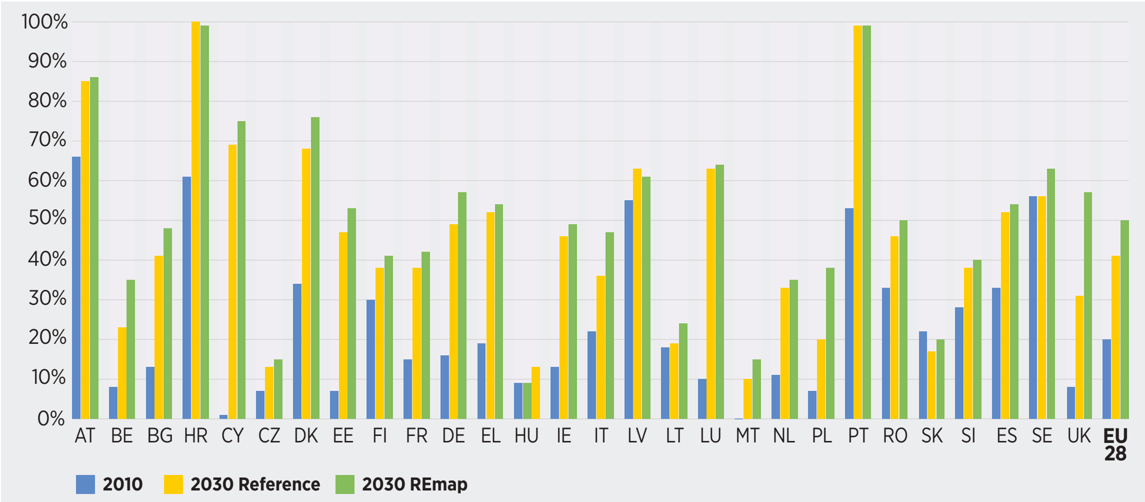
Figure 14 shows this power generation capacity breakdown in 2030 for each Member State under both the Reference Case and REmap. Figure 15 and Figure 16 compare the renewable and VRE shares in total electricity generation by Member State in 2030 according to the Reference Case and REmap.

Figure 14: Breakdown of installed power generation capacity by technology and EU Member State in 2030 under the Reference Case versus REmap



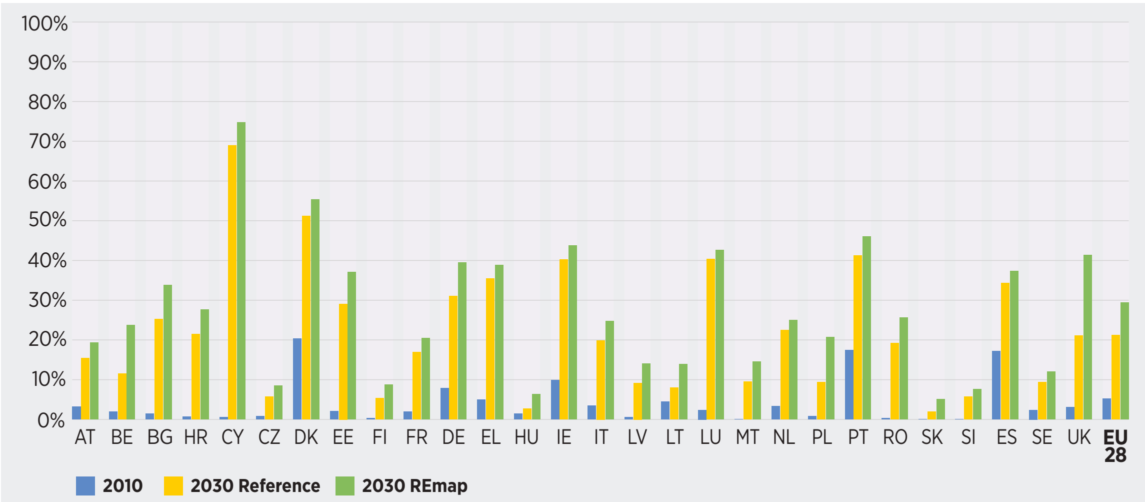
Source: IRENA and University College Cork analysis. Note: open-cycle gas turbine (OCGT), combined-cycle gas turbine (CCGT).

Figure 15: Renewable energy share in electricity generation by EU Member State in 2010 and in 2030 under the Reference Case versus REmap



Source: IRENA and University College Cork analysis

Figure 16: Variable renewable energy share in total electricity generation by EU Member State in 2010 and in 2030 under the Reference Case versus REmap



Source: IRENA and University College Cork analysis

3.2.2 IMPLICATIONS FOR THE EU POWER SYSTEMS OF 2030

The REmap case results in high shares of variable renewable generation (29%). This could potentially create challenges for the operation of EU power systems. A key question is whether the sources of power system flexibility[13] available by 2030 will be sufficient to deal effectively with the expected increased variability in generation.

In this section, we present the results of our assessment of the potential effects of the generation mix derived from the REmap EU analysis on the operation of the European power systems by 2030. To carry out this assessment, an EU power system model was developed to analyse generator unit commitment and economic dispatch assuming full deployment of the generation mix resulting from the REmap case by 2030. These results were then benchmarked against a similar simulation of the Reference Case. More details about the methodology and assumptions for this modelling analysis can be found in section 2.3 and Annex E.

This assessment provides additional insights to the REmap findings. It quantifies expected levels of curtailment of renewables, electricity trade across Member State's boundaries, interconnection congestion, changes in wholesale market prices and in the operation of conventional generation units, and the carbon intensity of the EU grids. Results for each of these elements are detailed in the following subsections.

This analysis should be interpreted as a first plausibility check of an EU power system under the REmap case assumptions. However, it does not constitute a full system operational analysis, nor a detailed forecast of EU power sector operation by 2030. Member States are treated as a single network node for simplicity purposes; therefore, a full system reliability analysis could not be carried out. Some elements of power sector operation – *e.g.,* analysis of reserves, short term stability, and generation forecast errors – were excluded from this analysis[14]. More detailed studies, including a better representation of these elements, are needed to assess the full implications of the REmap case as well as the additional power system flexibility options that would need to be deployed to operate a system under such conditions.

Impact on curtailment of variable renewable energy

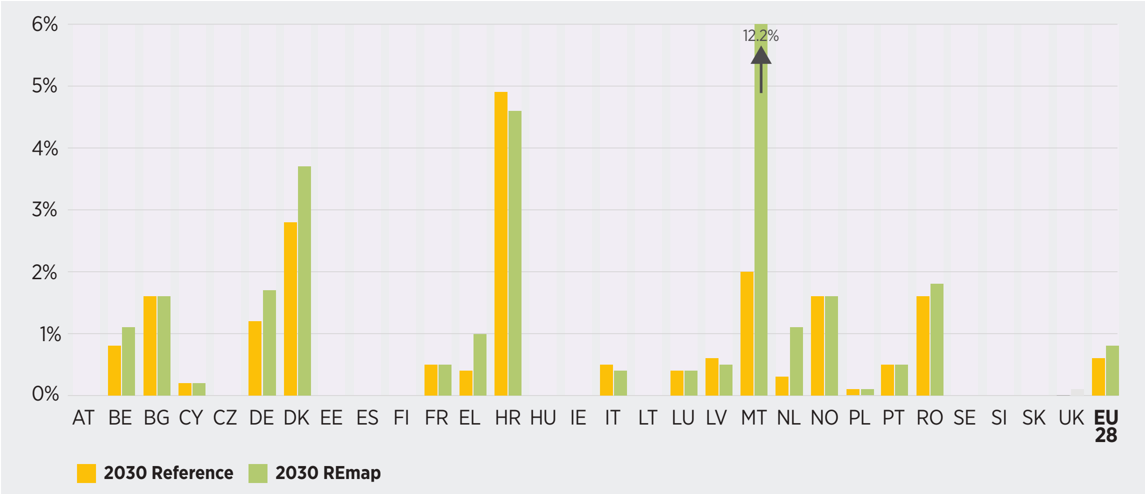
One of the challenges to the operation of a system with high shares of variable renewable energy is to avoid curtailment of renewable generators. The risk of curtailment of variable renewable generation is an important barrier for further deployment of technologies such as solar PV and wind power, as it introduces uncertainty about future revenues for project developers, increasing the difficulties in making projects bankable.

Curtailment of VRE occurs when excess supply of wind and solar PV power cannot be consumed within a market nor exported to neighbouring markets. High levels of curtailment of VRE are indicative of insufficient flexibility in power systems to accommodate the variability of these technologies. Figure 17 shows the levels of curtailment of VRE resulting from the model simulation in different EU Member States.

13. Flexibility in power systems can be defined as the ability to constantly keep power supply and demand in balance responding to (quick and large) changes in either of them. Flexibility can be provided by generators, consumers, storage systems, networks or even system operation rules. For more details about modelling assumptions with regards to each of these flexibility components, please see Annex D.

14. Forced and maintenance outages are included in the model.

Figure 17: Renewable energy curtailment rate by EU Member State in 2030 (Reference Case versus REmap)



Source: IRENA and University College Cork analysis

The model simulation shows that levels of curtailment are expected to remain low at the EU level (0.8% under REmap and 0.6% under the Reference Case).

These results indicate that the EU power systems of 2030 could, in principle, accommodate the expected shares of variable renewables under the Reference and REmap case by using existing or already planned sources of flexibility, *i.e.*, interconnectors, pumped hydro storage and flexible generation. However, these results should be interpreted as a low-end estimation of potential curtailment. Curtailment levels could increase because of congestion in transmission lines within Member States, which cannot be captured in this analysis.

Several Member States show higher levels[15] than the EU average (Malta, Croatia, Denmark, Romania, Germany, Bulgaria, the Netherlands and Greece). In these cases, additional cost-effective sources of flexibility (*e.g.* storage, demand side response, interconnection expansion) could be deployed by 2030 to accommodate larger shares of renewables while minimising curtailment. In some conditions, curtailment itself also can be a cost-effective source of system flexibility if the operation rules and compensation schemes are clear, transparent and known upfront to minimise revenue risk for renewable power producers.

Impact on cross-border electricity exchange among Member States

A key element of a fully integrated EU power market is the ability to trade power effectively across Member State borders. An efficient exchange of power beyond national borders becomes even more important in systems with high penetrations of variable renewables, as in the REmap case. The capacity to export and import power is a key source of flexibility to the power system, enabling the integration of larger volumes of renewables by diluting their intrinsic variability into a larger power system.

The model simulation shows that under the Reference Case, 568 TWh of electricity would be traded

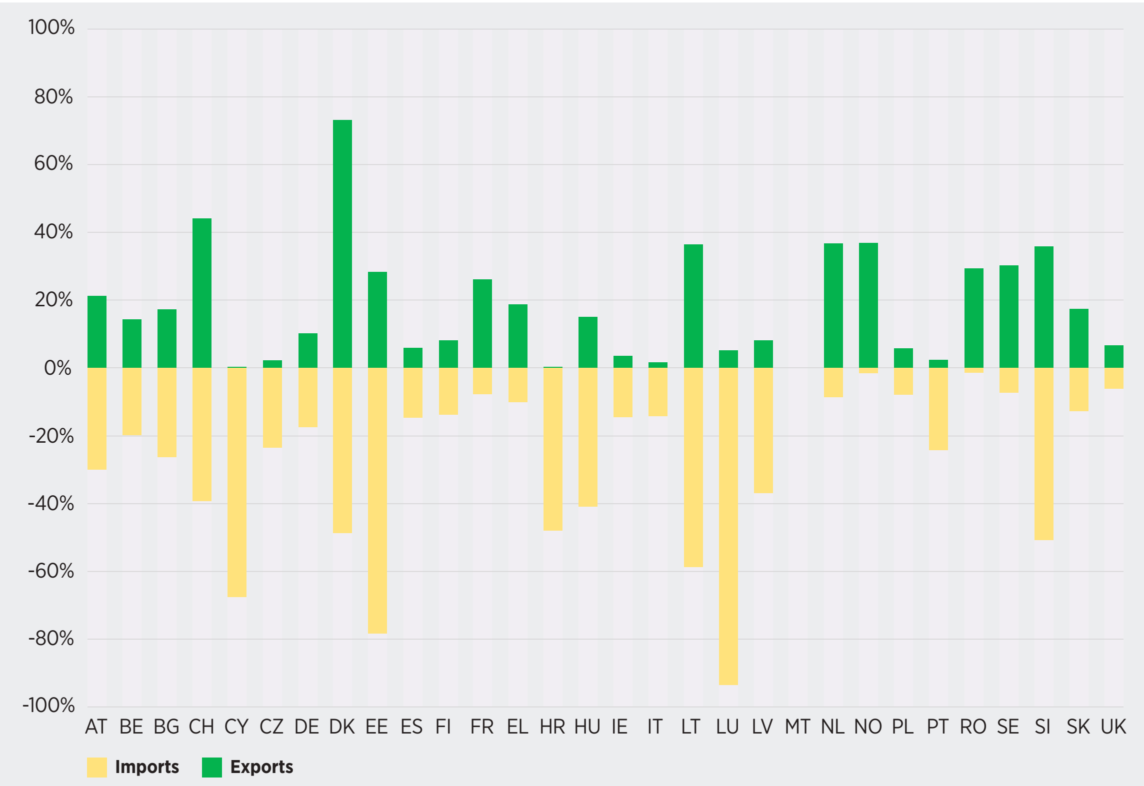
15. Simulations show the highest levels of curtailment for Malta. These are explained primarily by the small size and isolated nature of Malta's power system.

across Member State borders by 2030. This is equivalent to 16% of the expected final electricity consumption in the EU-28. The larger shares of (variable) renewable power generation and the increase in electricity demand from electric vehicles and heat pumps under the REmap case trigger an increase in power trade across Member States' boundaries to reach 583 TWh, *i.e.* a 2.8% growth compared to the Reference case. Figure 18 shows the volume of imports and exports of electricity for different Member States as a share of internal power consumption.

The exchange of power across Member State borders relies on the availability of sufficient interconnection infrastructure. The EU has set a target[16] of 10% electricity interconnection by 2020, which has been extended with a proposed 15% target by 2030.

In this analysis, the ENTSO-E reference capacities for 2030 were used for the simulation of both the Reference Case and REmap. These are defined in the scenario development report that informed ENTSO-E's *2016 Ten Year Network Development Plan*. These capacities would meet the 10% interconnection target for all Member States except Malta and the 15% target for most Member States, except Ireland, Italy, Poland, Romania, Spain and the UK.

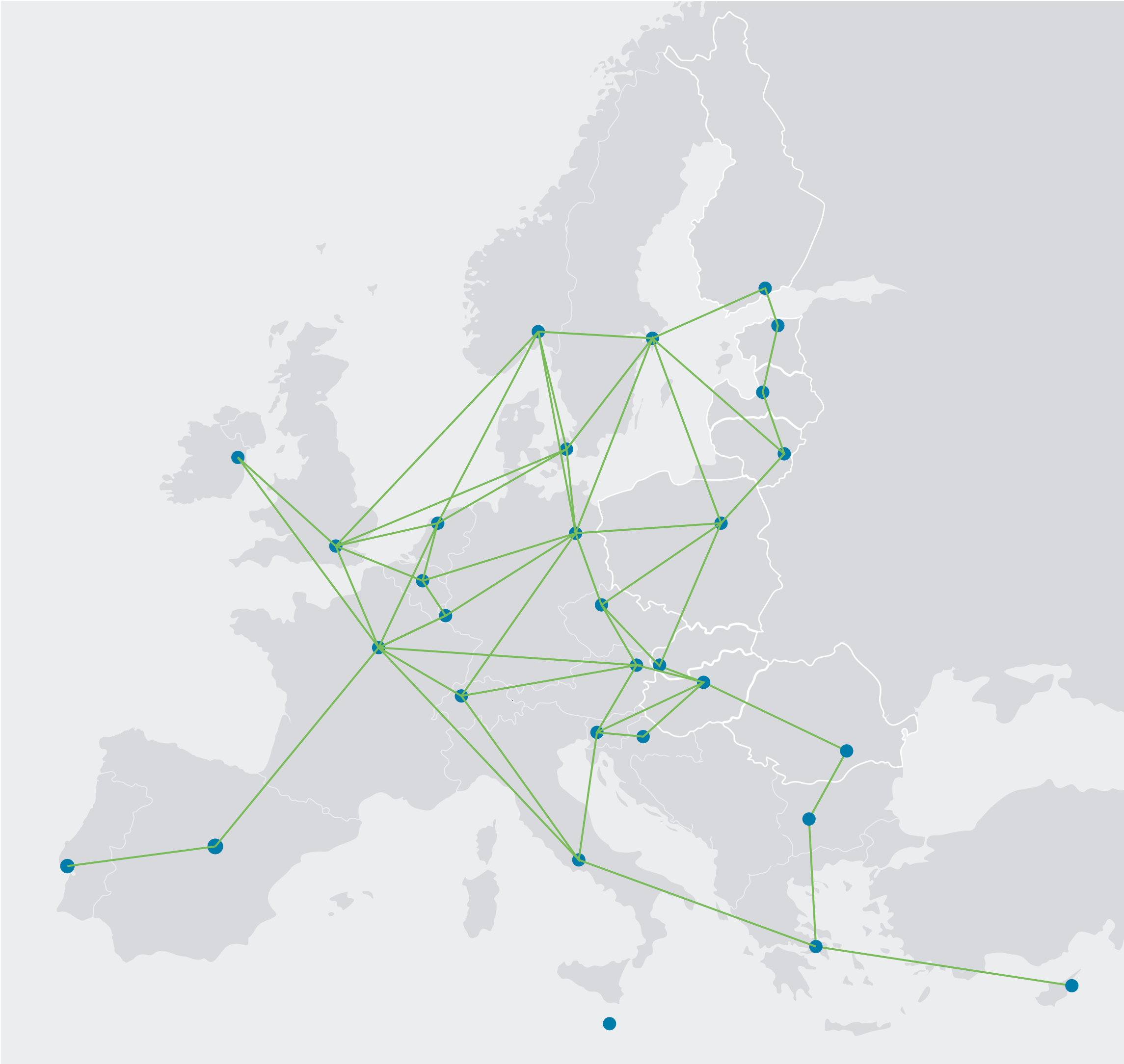
Figure 18: Power imports and exports by EU Member State in 2030 under REmap



Source: IRENA and University College Cork analysis

16. The Third Report on the State of the Energy Union indicates that 11 EU Member States have not yet reached their 2020 target and need to continue their efforts. Four Member States (Cyprus, Poland, Spain and the UK) are expected to remain below the 10% electricity interconnection target in 2020 (European Commission, 2017b) .

Figure 19: Interconnections in the 2030 EU power system model



Source: IRENA and University College Cork based on ENTSO-E (2016). Background map: OpenStreetMap®

An indicator of the need for additional interconnection between two countries is the level of congestion of the line (the number of hours that the interconnector is operating at maximum capacity). Figure 20 shows the resulting hours of congestion for the EU interconnectors in the model simulation under the Reference Case and REmap.

These results indicate that a sizeable portion of European interconnectors would operate under high levels of congestion by 2030, in both the Reference Case and REmap. On average, European interconnectors are expected to operate at full capacity 39% of the time under the Reference Case. The REmap case results in additional use of EU interconnectors over the Reference Case, with a 1.8% increase in the average level of congestion across the EU.

While the observed increase in usage under the REmap case is moderate, the effect on some already congested interconnectors would require more attention. The high level of usage of all Norwegian interconnectors shows the value of Norway's hydro resource to balance the variability of VRE in neighbouring countries.

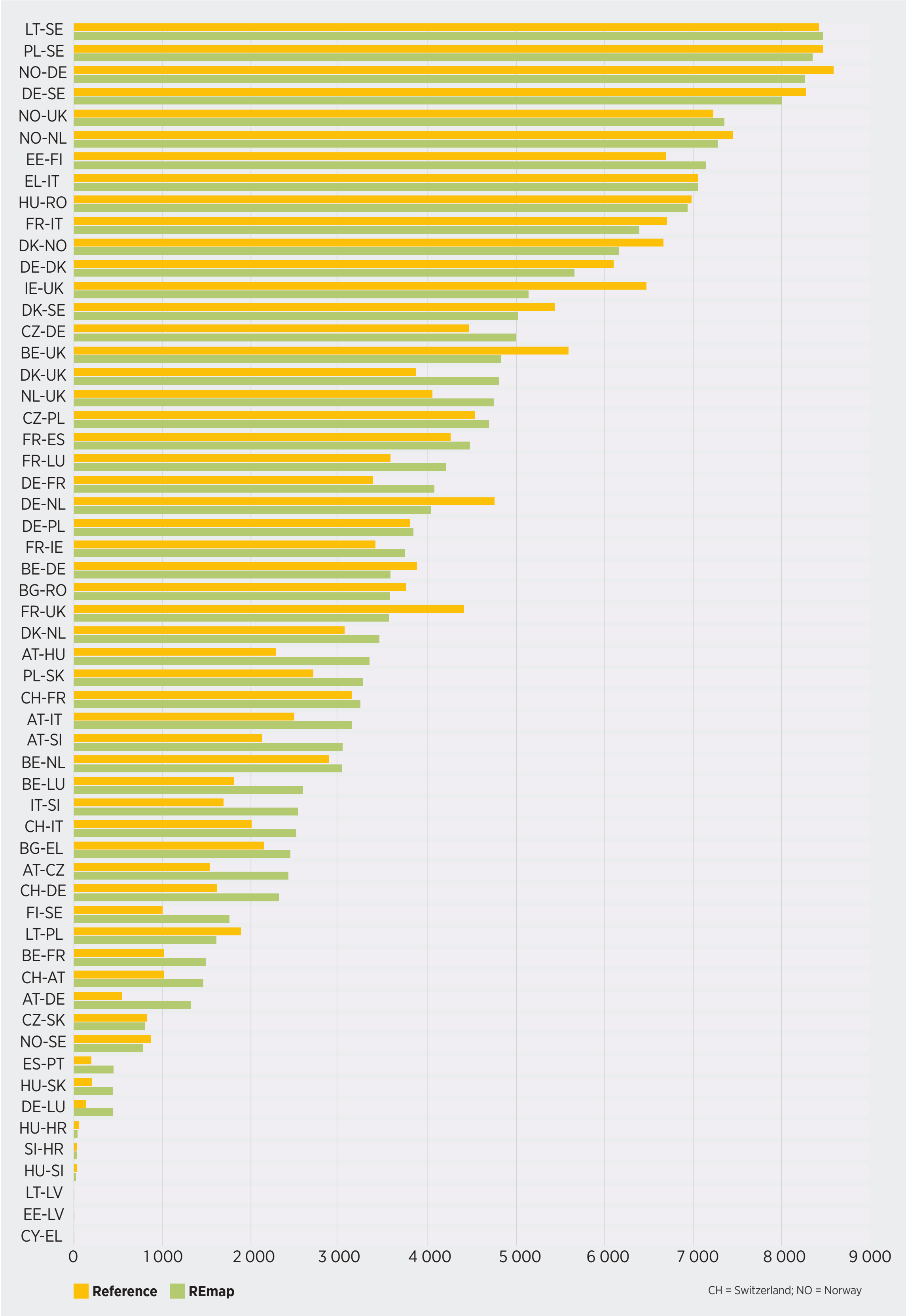
The levels of congestion resulting from this analysis indicate a need for increased interconnection capacity beyond what is already planned by 2030. Congestion is already high under the Reference Case, which indicates that the EU power system may encounter significant challenges even under reference conditions. Notably, the congestion identified on interconnectors in this analysis cannot all be appropriated to the increased penetration of renewables; it also may indicate pre-existing infrastructural inadequacy.

The expansion of the most congested interconnectors would facilitate higher penetration of variable renewables while mitigating the risk of increased levels of VRE curtailment. However, investment decisions in additional interconnection infrastructure need to be balanced with other alternatives to increase the flexibility of power systems (demand response, storage, flexible generation, etc.)

Impact on wholesale electricity prices

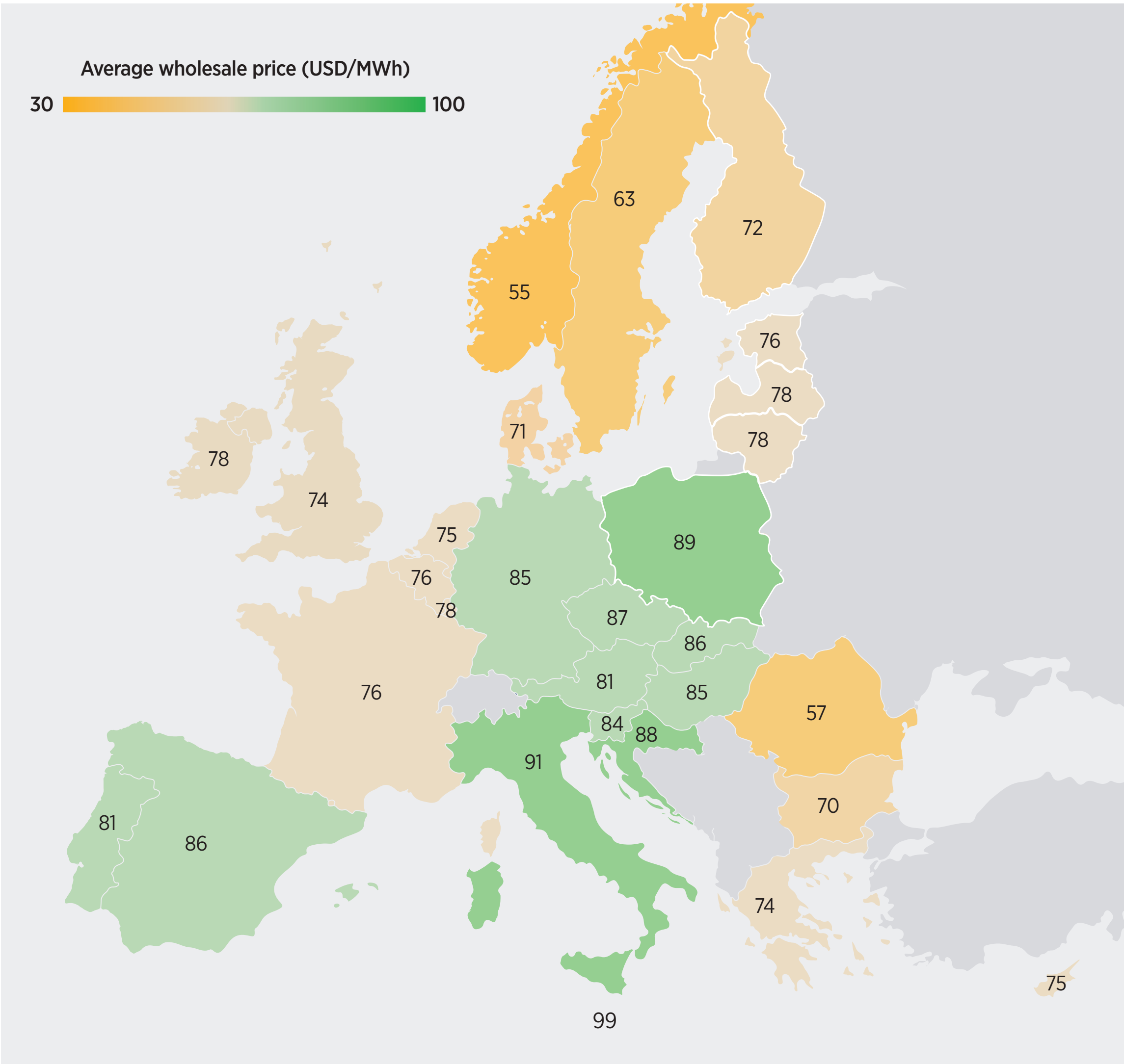
The hourly simulation of power system dispatch enables analysis of the resulting wholesale market prices by Member State. Figure 21 shows the expected average wholesale market prices under the Reference Case in 2030. Prices range between USD 57 per megawatt-hour (MWh) in Romania and USD 99 per MWh in Malta.

Figure 20: Interconnector congestion in the EU-28 in 2030. Reference Case versus REmap



Source: IRENA and University College Cork analysis

Figure 21: Average wholesale market prices by EU Member State in 2030 under the Reference Case (USD/MWh)



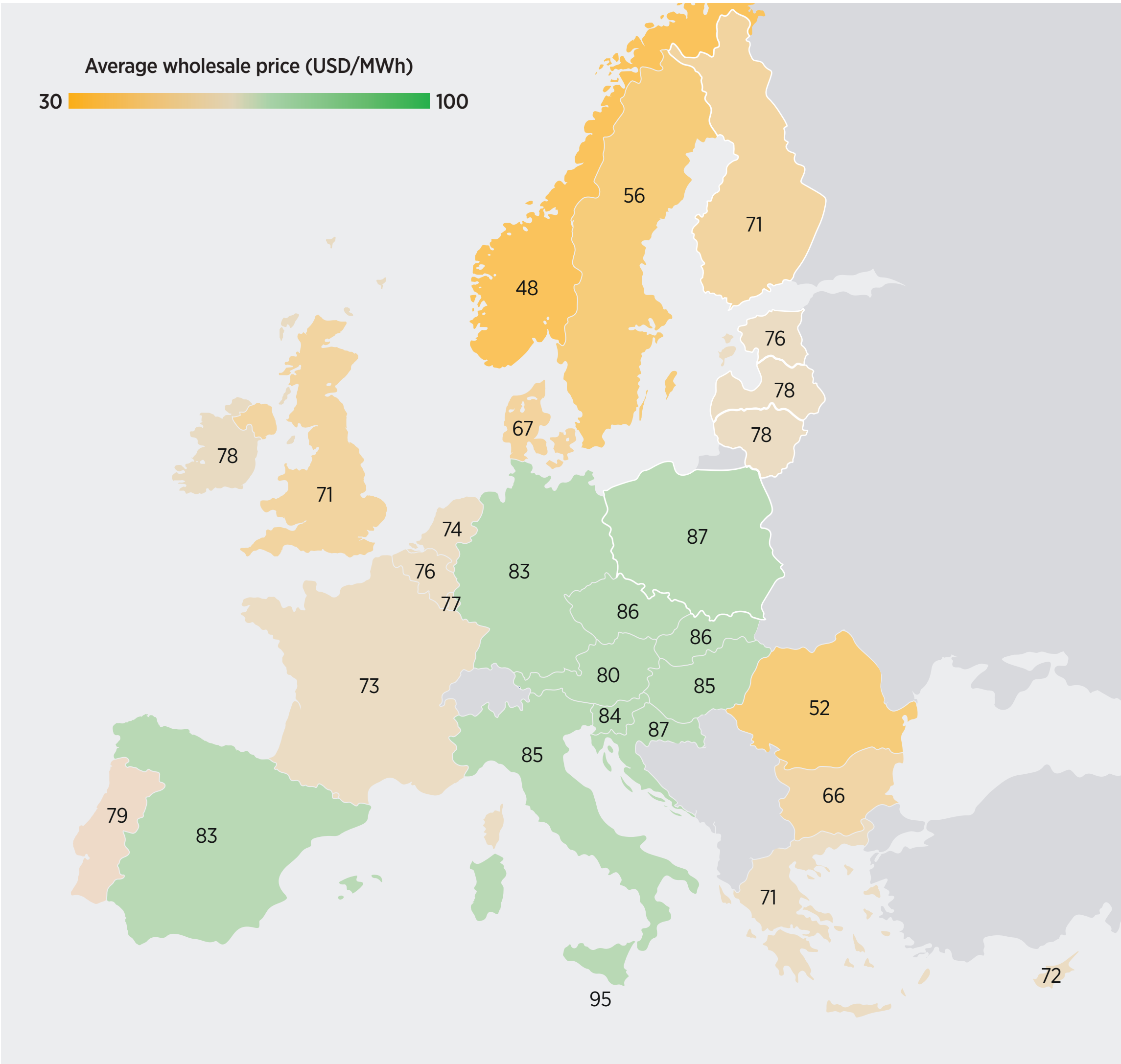
Source: IRENA and University College Cork analysis. Background map: OpenStreetMap®
Norway, although not part of the EU-28, is factored into some aspects of IRENA's power sector analysis

The higher penetrations of variable, low-marginal-cost renewable generation across the EU in the REmap case leads to systematic but moderated decreases in wholesale market prices compared to those of the Reference Case. The underlying dynamic for price reduction is the "merit-order" effect triggered by the additional low-marginal-cost renewables in the REmap generation mix. However, this effect is mitigated by the additional power demand driven by the increased electrification of end-use sectors in REmap. Figure 22 shows the expected average wholesale market prices.

On average, the REmap case leads to a 3.6% reduction in prices across the EU compared to the Reference Case. However, reductions differ across Member States, depending on several factors, including the generation mix, fuel prices and levels of interconnection with neighbours. Prices range between USD 52 per MWh in Romania and USD 94 per MWh in Malta.

Although positive from the point of view of the consumer, the downward pressure on prices created by low marginal cost renewables should not be overlooked if additional VRE deployment is considered

Figure 22: Average wholesale market prices by EU Member State in 2030 under REmap (USD/MWh)



Source: IRENA and University College Cork analysis. Background map: OpenStreetMap®
Norway, although not part of the EU-28, is factored into some aspects of IRENA's power sector analysis

beyond the REmap case. On the one hand, further systematic reductions in prices could endanger the viability of conventional and dispatchable generation, which are required for security of supply, frequency regulation etc. On the other hand, lower prices could undermine the business case for the further deployment of renewables themselves.

The model simulation shows that solar PV and wind power would capture lower prices than the average. This is due to the "cannibalisation" effect triggered by the resource-driven, low-marginal cost nature of these technologies. The low marginal cost that is characteristic of solar PV and wind means that sunny and windy periods tend to be low-price periods in markets with large penetration of these technologies.

Because both technologies are also resource-driven, they tend to capture from the market precisely those low prices that they contribute to create. This effect is most pronounced for solar PV plants, as their generation concentrates in the central hours of the day and during the summer.

In the REmap case, the weighted average market value for solar PV across the EU is 20% lower than the average price. For onshore wind, this reduction is much smaller (4% below the average market price). The substantial reduction in market value for solar PV is indicative of a need for increased flexibility in EU power systems and markets to mitigate the cannibalisation effect described above. In turn, this need for additional flexibility could be an opportunity for new business models – for example, price “arbitrage” by means of storage technologies.

Impact on the operation of conventional plants

The larger shares of renewables under the REmap case lead to a reduction in the overall hours of operation of conventional plants compared to the Reference Case. Coal- and natural gas-based generation decrease by 20% and 5% respectively compared to the Reference Case.

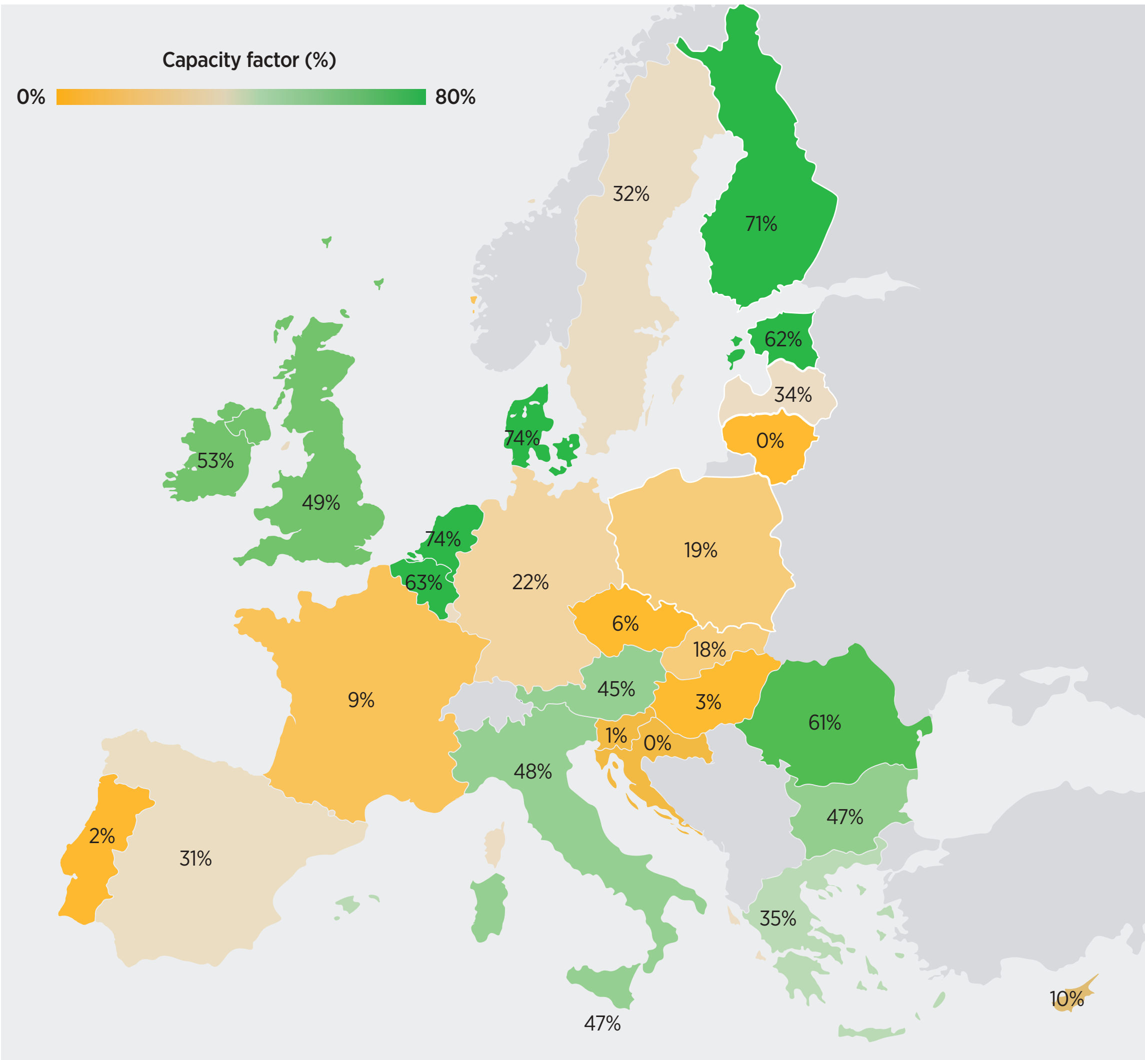
Under REmap, coal plants would operate at an average capacity factor of 52% across the EU (approximately 4 570 equivalent full load hours). However, there are large differences across Member States. While in some Member States coal plants are expected to operate at relatively high capacity factors (for example France, Italy, the Netherlands, Greece, Poland, Germany, Finland, Slovakia and Slovenia) in other Member States (for example Austria, Belgium, Bulgaria, Estonia, Croatia, Hungary and Romania), the remaining coal capacity would be hardly in operation, with capacity factors below 10% in some cases.

The analysis of the plants’ capacity to recover full generation costs from the markets is beyond the scope of this study; however, the low capacity factors resulting from the simulation for some Member States indicate that their economic viability could be potentially at risk[17].

Under the REmap case, the average natural gas plant in the EU-28 would operate at an average capacity factor of 39% (approximately 3 400 equivalent full load hours per year). However, as in the case of coal, there are large differences across Member States (see Figure 23).

17. After completion of the REmap analysis for the EU, 10 EU Member States agreed to phase out existing traditional coal power and place a moratorium on any new traditional coal power stations without operational carbon capture and storage in the context of the “Powering Past Coal Alliance” launched at the 2017 United Nations Climate Change Conference celebrated in Bonn in November 2017.

Figure 23: Average capacity factors for combined-cycle gas plants by EU Member State in 2030 under REmap



Source: IRENA and University College Cork analysis. Background map: OpenStreetMap®
Norway, although not part of the EU-28, is factored into some aspects of IRENA's power sector analysis

As in the case of coal generation, the simulation results indicate low capacity factors in gas plants for some Member States. Low capacity factors could be a risk for the economic viability of these type of plants in some conditions – for example, if market revenues from the provision of flexibility are insufficient to compensate for the lower capacity factors, or if generators are insufficiently flexible to provide such services.

While the overall volume of power generation from gas plants is reduced under the REmap case, these generators still will be needed to guarantee the operation of the system by 2030. The model simulation shows that gas plants will operate fewer hours and start and stop more frequently to bridge the increased variability introduced by resource-driven renewable energy plants.

This observed increase in cycling also would be relevant for dispatchable renewable generators – for example biogas or solid biomass plants. Heavier cycling of plants is an additional cost to the system due to increased fuel consumption (during plant start-ups and because of plants operating below optimal load range) as well as higher operations and maintenance costs.

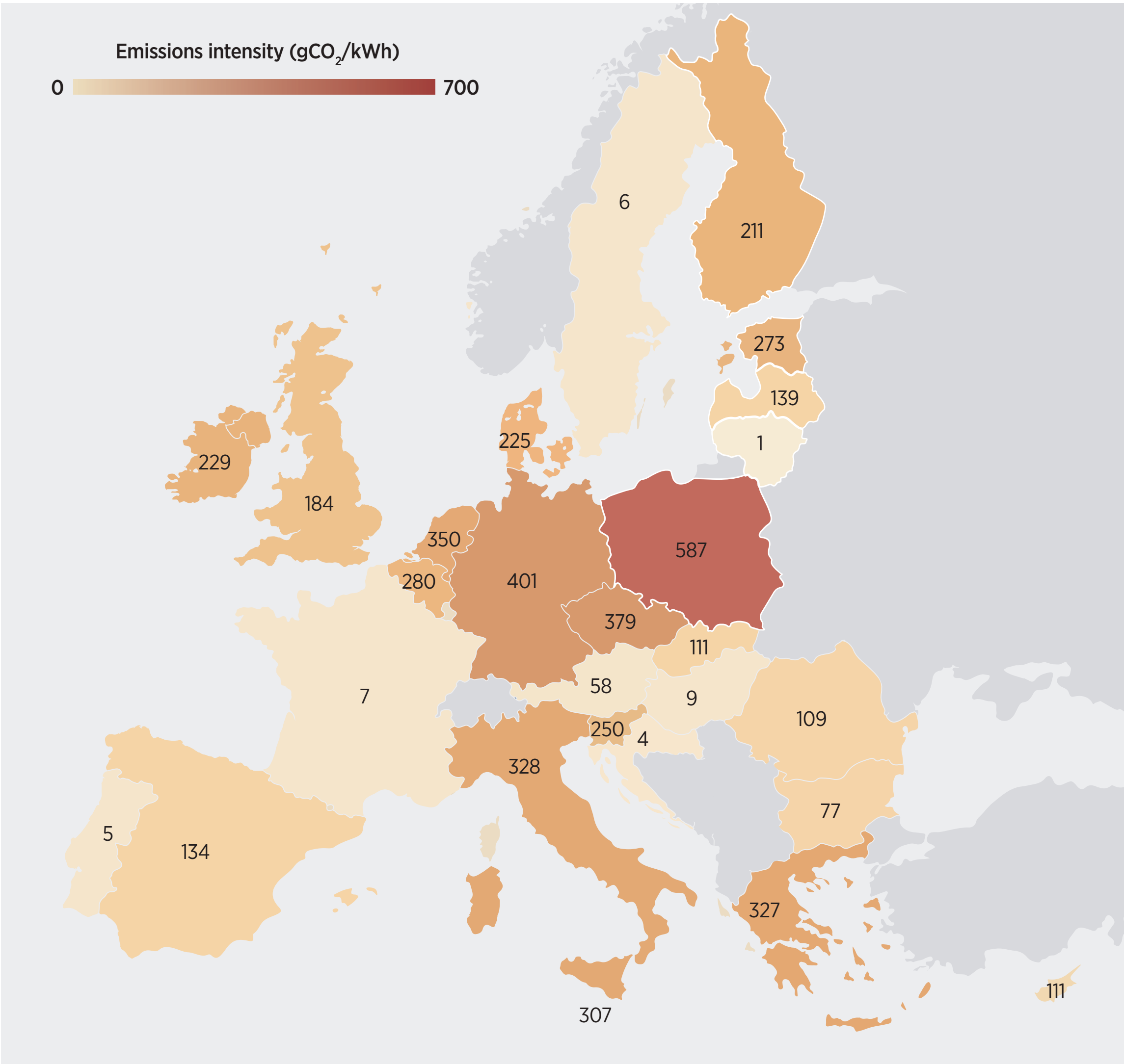
Emissions intensity

In 2015, the average emissions intensity of EU-28 electricity grids was 304 grams of CO_2 per kWh. The model simulation shows that by 2030 this emissions intensity would be reduced by 28% compared to 2015, to reach 219 grams of CO_2 per kWh under the Reference Case.

There are large differences in carbon intensity of power generation across EU Member States. Figure 24 shows the wide range of results – from almost carbon-neutral generation in Lithuania, Croatia, Portugal, Sweden and France to highly carbon-intensive generation in Poland, Germany, Czech Republic and the Netherlands.

The model simulation results show that the REmap case is effective in the decarbonisation of the EU power sector. The significant increase in variable renewable generation and reduction in fossil fuelled generation under the REmap case leads to an overall reduction in emissions of 14% across the EU-28 countries compared to the Reference Case simulation.

Figure 24: Emissions intensity of power generation by EU Member State in 2030 under the Reference Case

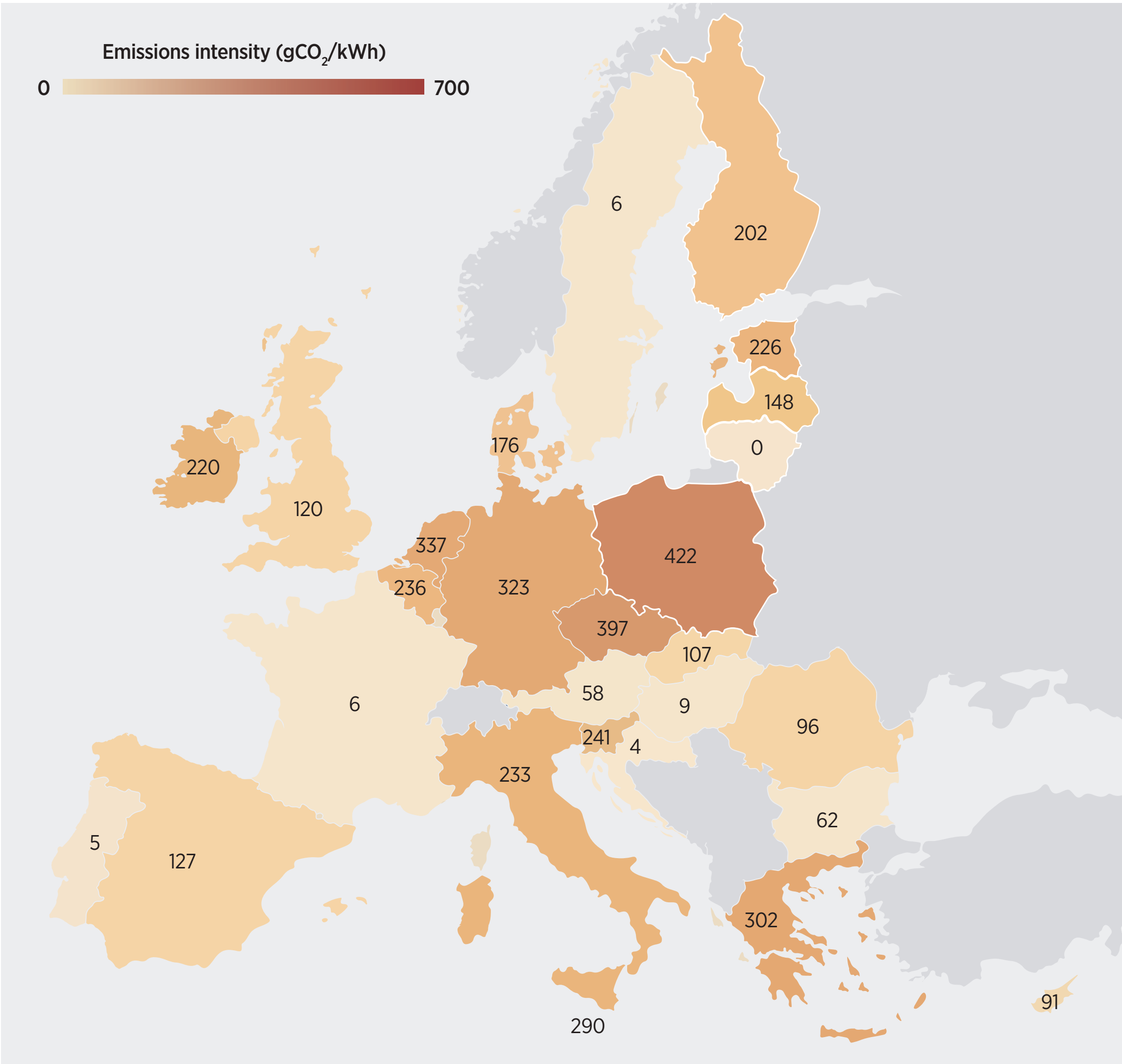


Source: IRENA and University College Cork analysis. Background map: OpenStreetMap®
Norway, although not part of the EU-28, is factored into some aspects of IRENA's power sector analysis

While the regional distribution of carbon intensity is similar to that of the Reference case, some countries with high emissions intensity in the Reference Case also show substantial reductions – for example, Poland (-28%), Italy, (-29%) and Germany (-19%). Figure 25 shows the emission intensities per Member State in 2030 under the REmap case.

The average emissions intensity for the EU-28 countries would reach 177 grams of CO_2 per kWh under the REmap case. This represents a 19% reduction in carbon intensity compared to the Reference Case and a 42% reduction compared to 2015 levels. In comparison, a coal-fired power plant with assumed 40% efficiency produces electricity with an emission intensity of 850 grams of CO_2 per kWh.

Figure 25: Emissions intensity of power generation by EU Member State in 2030 under REmap



Source: IRENA and University College Cork analysis. Background map: OpenStreetMap®
Norway, although not part of the EU-28, is factored into some aspects of IRENA's power sector analysis

Impact on system reliability and reserves

The aggregated geographical resolution of the EU model built for this analysis and the assumption of no uncertainty in power demand, VRE generation, or plant outages do not allow for drawing conclusions about power system reliability. The model simulations do not show reliability issues at a high level. However, a full operational analysis of the system would be required to provide full assurance that the REmap case is technically feasible from an operational perspective.

Similarly, reserve requirements were not analysed in this modelling exercise. For this reason, the impact of the full implementation of REmap on reserve requirements could not be quantified. The main impact of realisation of the REmap case on reserve requirements would be related to forecast errors from renewable generators. Forecasting is a crucial and cost-effective tool for integrating variable renewable energy resources such as wind and solar into power systems. Improvements in forecasting are anticipated to lead to reductions in reserve costs (Marquis *et al*., 2011). Surprisingly, in the case of Germany wind and solar capacity has tripled since 2008, but reserves have been reduced by 15%, and balancing costs by 50% (Hirth and Ziegenhagen, 2015). This shows that allowing existing and affordable sources of flexibility to participate in the reserves market can be more than compensated by the cost reductions brought by sources of reserves that are able to affordably provide them.

Box 4 Impact of electric vehicles and stationary batteries in VRE integration

The modelling analysis discussed in section 3.2.2, considers pumped hydro reservoirs as the only form of electricity storage available in EU power systems by 2030. The fleet of electric vehicles deployed both in the Reference Case and REmap is analysed as an electric load, unresponsive to electricity prices in the market and unable to discharge electricity back to the grid.

Smart charging of electric vehicles – *i.e.* charging responsive to price signals in power markets – as well as allowing electric vehicles to feed electricity back into the grid when profitable, acting as stationary electricity storage (*i.e.* "vehicle to grid") – could play an important role in the cost-effective integration of variable renewable sources in the power sector in 2030. Stationary batteries can also contribute towards this goal.

To explore the potential benefits of these applications, a complementary modelling simulation was carried out, building on the REmap case simulation. A detailed list of modelling assumptions is provided in Annex E.

The results of the simulation show a reduction in curtailment of variable renewable generation across the EU from 0.8% in the REmap case to 0.7% with an active role of electric vehicles and stationary batteries. This reduction in curtailment is most beneficial for those countries with the highest curtailment rates (*e.g.* Malta sees VRE curtailment rates reduced from 12% to 6%).

In addition to reduced curtailment, a very positive impact is observed with regards to the revenues for solar PV plants. Batteries can store electricity at times when solar power is abundant and prices low, contributing to protect the market value of solar PV generation. In the REmap case, the weighted average market value for solar PV across the EU is 20% lower than the average price. The value loss is reduced to 13% below average price in the simulations considering additional battery storage.

3.3 RENEWABLES IN END-USE SECTORS

3.3.1 TRANSPORT

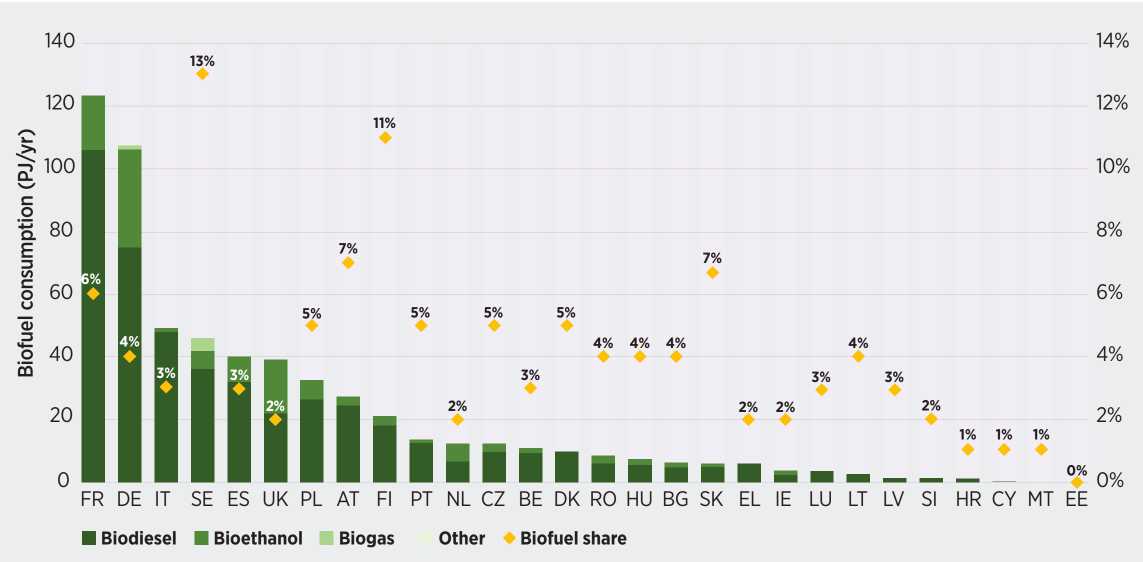
Recent trends

Transport remains the sector with the lowest penetration of renewable energy in the EU energy system. In 2015 the share of renewable energy in transport was below 7% (Eurostat, 2017a).

The main source of renewables in the transport sector is liquid biofuels. Biodiesel dominates the market, accounting for 80% of the biofuel consumption in the EU. Bioethanol is the second largest, with 19% of the EU biofuel market. Biogas accounted for a much smaller fraction (1%), concentrated mainly in Sweden and Germany[18] (Eurostat, 2017b).

France and Germany are by far the largest consumers of biofuels in the EU in absolute terms. Together, they account for 39% of EU biofuel consumption. However, Sweden and Finland are the EU countries with the highest share of biofuels in their respective transport sectors. Figure 26 shows the biofuel consumption across EU Member States, as well as the biofuel share by market.

Figure 26: Biofuel consumption and shares by EU Member State in 2015



Source: IRENA analysis based on Eurostat (2017b)

Driven by various policy incentives, the demand for biofuels in the EU grew very rapidly from 81 PJ in 2002 to a peak of 608 PJ in 2012. Since then, demand has declined slightly to 600 PJ in 2015.

The use of food crops for biofuel production, and the direct and indirect effects on greenhouse gas emissions over the life cycle of biofuels, has raised concerns in the EU. This has resulted in defining sustainability criteria which has been reflected in EU legislation. All liquid biofuels consumed in the EU today must meet a 35% greenhouse gas emission reduction requirement with the threshold set to increase to 60% by 2018.

18. Shares are expressed in terms of energy content.

While biofuels have been the largest renewable contributor to EU transport so far, electric mobility solutions could play a key role in the long-term evolution of the sector. Electricity accounted for just 1.5% of the final energy consumption in EU transport by 2015. Most of this electricity (77%) was used in trains. Road transport accounted for just 8% of the electricity consumption in the sector (0.1% of total final energy consumption for transport) [19].

Electric vehicles still represent a very small fraction of total vehicle sales in the EU. In 2015, electric passenger cars accounted for 1.2% of new sales, accumulating a 0.15% share on the overall active car fleet. The Netherlands, the UK, Germany, France, Sweden and Denmark accounted for nearly 90% of all electric vehicles sales in 2015. Battery electric vans accounted for a 0.5% share of new vans sold in EU. About 500 battery electric buses were deployed in the EU by 2015 (EEA, 2016b).

While the level of adoption of electric vehicles in the EU is still in the early stages, the sector shows early signs of a very deep transformation. Sales of new electric cars follow an exponential trend with very strong growth factors. Registrations of electrically chargeable vehicles (ECV) and hybrid-electric vehicles (HEV) grew by 46% and 61%, respectively, in the second quarter of 2017, compared to the same period in 2016 (ACEA, 2017).

Several EU countries – for example, France and the UK – have announced long-term plans or regulations to support this ongoing transformation[20]. On the private sector side, several manufacturers have announced plans to include electric vehicles in their product lines, to substantially increase current production levels or to fundamentally change their portfolios towards these vehicles. Examples include Volvo Cars[21], Volkswagen[22] and BMW[23]. Furthermore, multinational companies are increasingly committing to a shift towards electric mobility – deploying electric vehicles and the required infrastructure – through initiatives such as The Climate Group's EV100[24]. All of these factors point towards an acceleration of electric vehicle adoption in Europe in the coming years.

The adoption of electric vehicles has multiple benefits, including a much more efficient overall use of energy compared to internal combustion vehicles, zero tailpipe emissions (and hence less local air pollution) and, depending on the power generation mix, lower overall CO_2 emissions. In terms of the impact on renewables, the increased penetration of electric vehicles in transport enables higher shares of renewables by enabling the use of (renewable) electricity for an application currently dominated by fossil fuels, but also by reducing the total energy demand in the sector. Furthermore, the potential positive effects of electric vehicles for renewables extend beyond the transport sector. The aggregated battery storage in these vehicles could be used to enable higher shares of renewables in the power supply – for example, by storing excess solar and wind electricity and returning it to the grid at times of higher demand.

19. IRENA analysis based on Eurostat (2017b)

20. France has pledged to end sales of gasoline and diesel vehicles by 2040 as part of a plan to meet its targets under the Paris Agreement. Similarly, the UK has announced plans to ban combustion engine car and van sales by 2040 as part of its "Plan for tackling roadside nitrogen dioxide concentrations", released in July 2017.

21 Volvo Cars announced in July 2017 that every new model it launches from 2019 onwards will have an electric motor, placing electrification at the core of its future business (Volvo Car Group, 2017).

22. Volkswagen plans to invest more than EUR 20 billion by 2030 in electric vehicles and has requested producers to submit proposals to supply cobalt for up to 10 years from 2019 (Reuters, 2017). This would serve the company's objective to put 30 new electric vehicle models in the market and meet its sales target of 2-3 million vehicles by 2025 (Volkswagen, 2016).

23. BMW announced its expansion on production of electric vehicles (Electrek, 2017).

24. Part of the efforts of the EV100 initiative (The Climate Group, 2017) are reflected on the wide adoption plans of the Streetscooter for delivery vehicles of DHL (DHL, 2017).

Renewable prospects for 2030

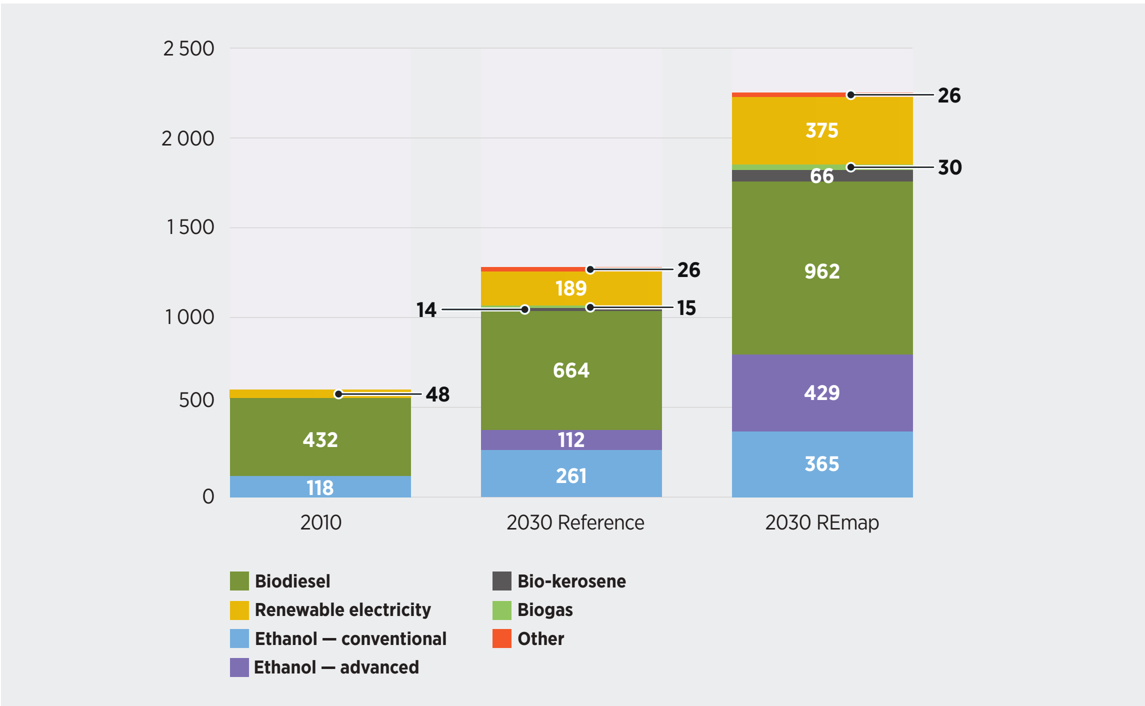
IRENA estimates that renewable energy consumption in transport would reach 1 280 PJ by 2030 (including renewable electricity) under the Reference Case. Under the REmap case, this amount could almost double, to reach 2 252 PJ. This is equivalent to almost quadrupling the level of renewable energy use in 2010 (see Figure 27).

The main renewable energy carriers would be biodiesel, bioethanol (both conventional and advanced) and electricity, with smaller shares of other carriers such as biokerosene, biogas[25] or hydrogen.

In the Reference Case, the use of renewable electricity would amount to 53 TWh (189 PJ) by 2030, equivalent to 1.4% of the total final consumption of the sector. REmap analysis estimates that up to 60% of light-duty vehicle sales in the EU could be fully electric or hybrid by 2030. This is consistent with a strong penetration of electric vehicles in the EU market to reach the equivalent of 40 million light-duty electric vehicles on EU roads by 2030.

Under the REmap case, the consumption of renewable electricity would double compared to the Reference Case, to reach 104 TWh (375 PJ), equivalent to 2.8% of final energy consumption in the sector.

Figure 27: Final renewable energy consumption by source in the EU-28 transport sector in 2010 and in 2030 under the Reference Case versus REmap (PJ)



25. The development of biogas use in transport has the potential to grow beyond the 30 PJ allocated under REmap if the adoption of gaseous fuels in the transport sector expands.

Box 5 **Biofuel targets in the EU**

The existing Renewable Energy Directive (2009/28/EC), adopted in 2009, established a sector-specific target for transport to reach a 10% renewable share by 2020. While multiple renewable carriers can count towards the realisation of the transport target, in practice liquid biofuels have been the renewable energy option with the largest deployment to date.

In 2015, responding to concerns about potential indirect land-use change (ILUC) issues, the EU adapted the legislation that established a limit of 7% for the share of biofuels from crops grown on agricultural land that can be counted towards the 2020 renewable energy targets.

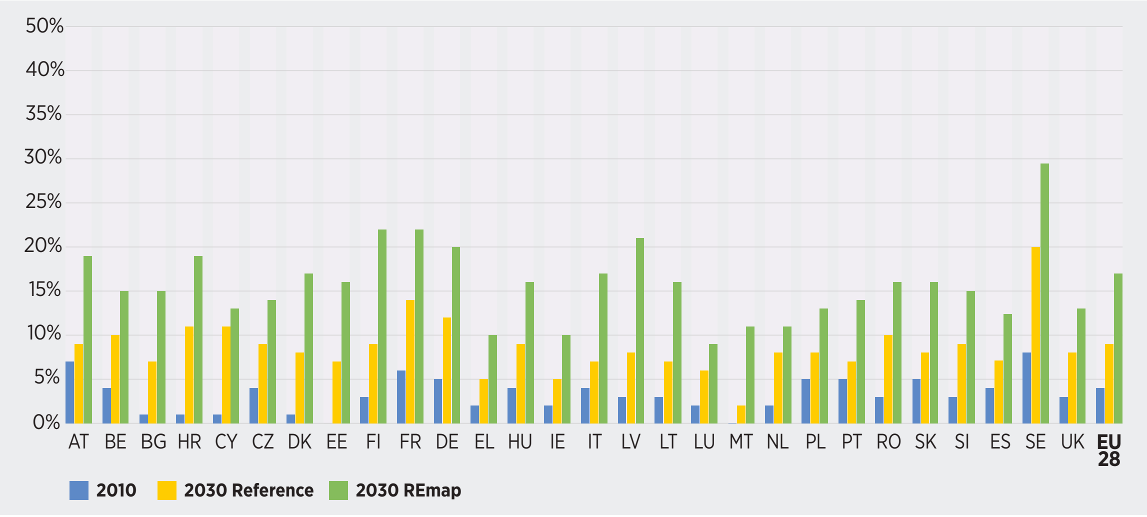
The European Commission's proposal for a new Renewable Energy Directive (European Commission, 2016c) introduces a phase-out of food and feed-based biofuels from 7% to 3.8% in 2030. It also proposes a minimum share of advanced biofuels (not food based), to be increased gradually from at least 0.5% in 2021 to at least 3.6% in 2030.

While the REmap case considers a strong electrification potential for transport in the EU, biofuels still will be needed in the short and medium term to continue the decarbonisation of the sector for the existing stock of vehicles equipped with internal combustion engines.

Despite the challenges around transport biofuels, the EU has potential for significant uptake: in the Reference Case, the renewable energy share in transport associated with biofuels (*i.e.,* excluding renewable electricity use in the sector) would be around 8% by 2030, up from around 4% in 2015. The REmap case identifies potential to go beyond this, to reach 14%.

In terms of the distribution across Member States, the REmap analysis identified additional potential to increase the renewable share in transport across all EU Member States. This is shown in Figure 28.

Figure 28: Renewable energy share in transport by EU Member State in 2010 and in 2030 under the Reference Case versus REmap



3.3.2 INDUSTRY

Recent trends

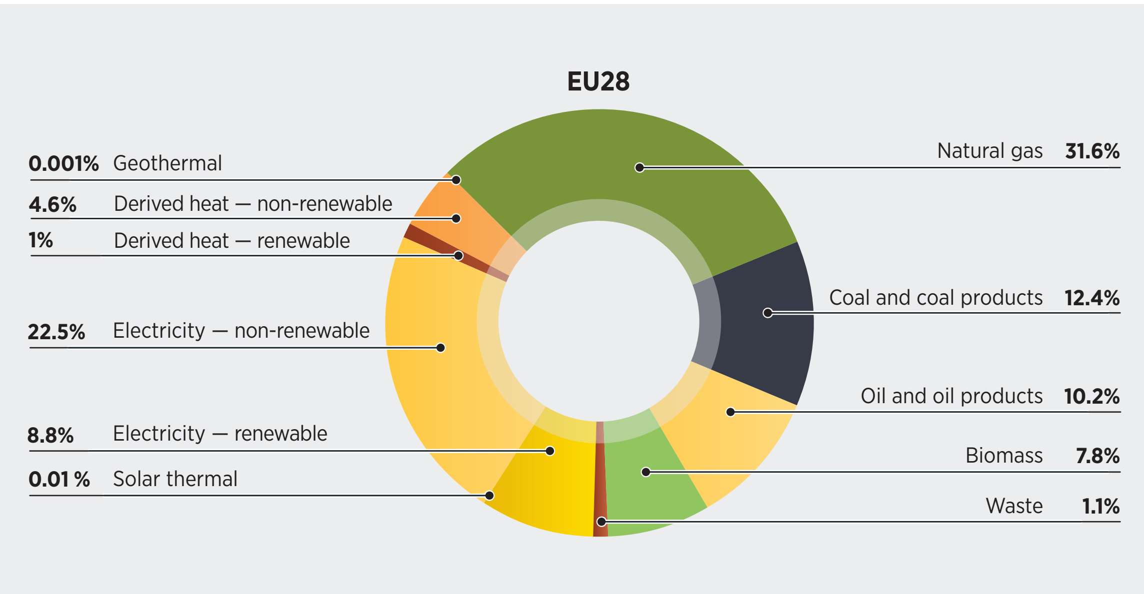
The industrial sector represents about one third of the EU's total final energy consumption[26]. Total energy demand in the sector reached 15.3 EJ (366 million tonnes of oil-equivalent) per year in 2015 (Eurostat, 2017b).

The sector is characterised by several sub-sectors that manufacture various materials and goods, including steel, cement, food and chemicals. Production processes require energy in the form of process heat, steam, or direct heat and electricity. Different processes operate under different temperature levels. The temperature level of production processes and other process characteristics (*e.g.,* pressure level of steam) determine the type of technology and energy carrier that can be used.

Renewables represented 18% of the EU's total industrial energy demand in 2015. Half of this was split into direct uses of renewables, including the combustion of biomass and a very small fraction of heat generated from solar thermal and geothermal. The other half was the consumption of electricity and district heat derived from renewable energy sources.

Sweden, Finland and Germany are the largest consumers of renewable energy in the industrial sector, representing nearly half of the total demand for renewables in the EU-28 (excluding the consumption of electricity and derived heat). Baltic and Scandinavian countries lead in the share of renewable energy used in the sector, due to large shares of biomass. In most other Member States, the renewable energy share in the sector is typically below 10%.

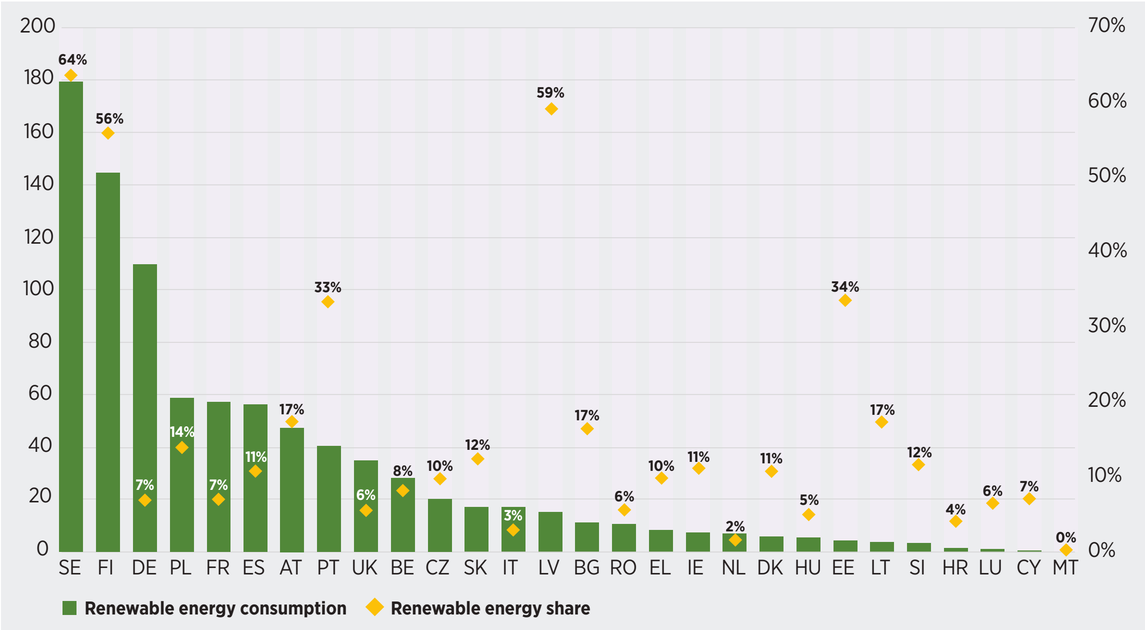
Figure 29: Breakdown of industrial energy use in the EU-28 by energy carrier (excluding non-energy use), 2015



Source: Eurostat (2017b)

26. Including non-energy use of fuels as feedstocks, which represents about a quarter of its total.

Figure 30: Total renewable energy consumption (PJ) and renewable share in the industrial sector by EU Member State, 2015



Source: IRENA analysis based on Eurostat (2017b). Note: Excludes renewable power and district heating.

Biomass is by far the largest source of renewable energy in the sector as it can deliver heat to all levels of process temperatures, from the generation of hot water (<100°C) to high-temperature direct heat applications in cement making (>1 000°C). The largest users are the pulp and paper and food sectors.

Electricity, if provided by renewable energy sources, can play a key role in raising the industry sector's renewable energy share. In Germany, Italy and the UK, more than half of all renewable energy use is related to renewable electricity. Corporate sourcing of renewable power can be a driver for increasing shares of renewables in the sector. The market for corporate renewable power purchase agreements has grown strongly in recent years. In 2017, more than 1GW of new contracts were signed in Europe (BNEF, 2018).

Electricity-based process heating technologies, such as heat pumps, can help industry raise its electricity share, enabling a higher penetration of renewables. However, these technologies are limited by the level of temperature of process heat (up to 250°C). For sectors that require high-temperature process heat levels and that dominate industrial energy use (*e.g.,* iron and steel, chemicals) electricity-based technologies are only at the research and development stage and are not commercialised.

Renewable prospects for 2030

IRENA estimates that the renewable energy share in the EU-28 industry would reach 28% by 2030 under the Reference Case (including electricity and district heat).

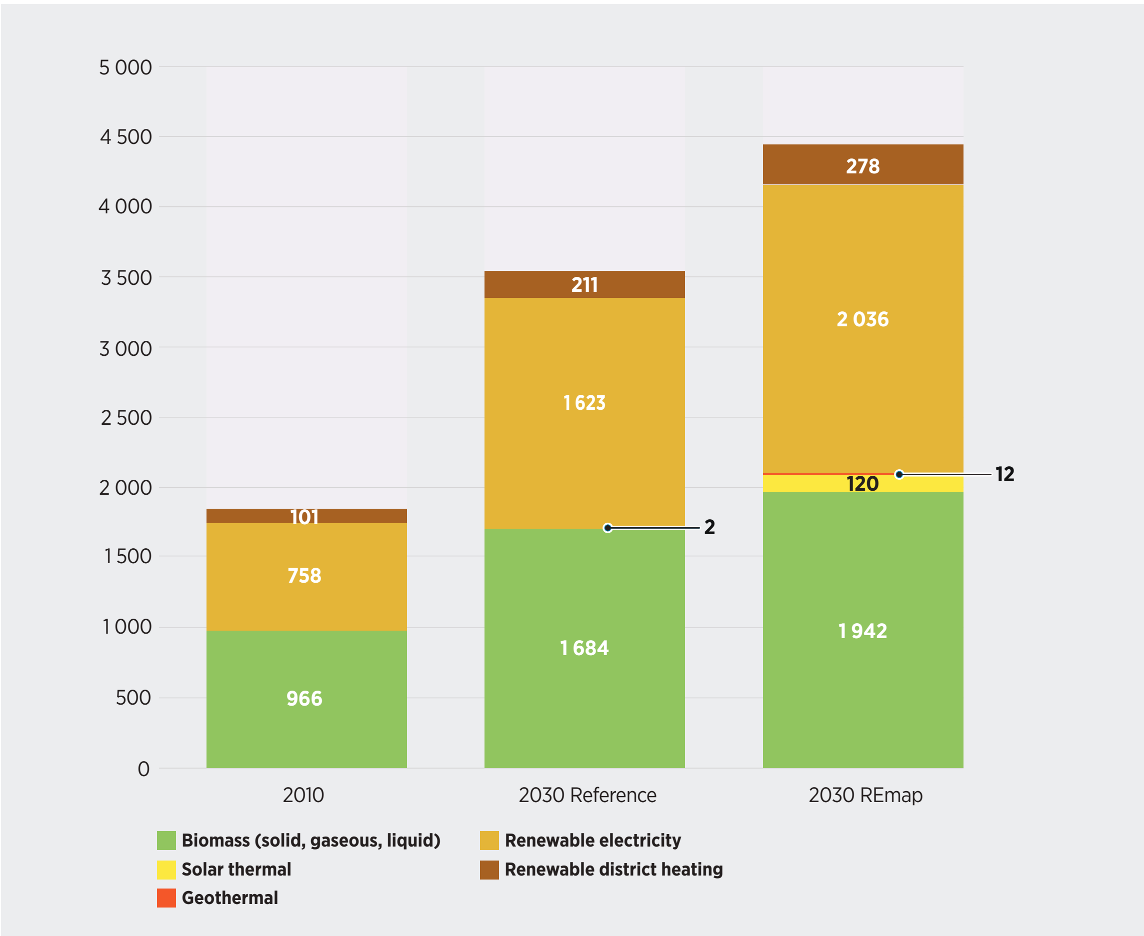
In terms of the technology breakdown, expected growth in the direct end-use of renewable energy comes primarily from a significant increase in the use of bioenergy. The main reason for the high share of bioenergy use is because it can provide process heat at all temperature levels. On the other hand, the shares of solar thermal and geothermal heating are low, limited by their higher initial investment costs, their ability to deliver only low-medium temperature heat and in most cases the need for modification of production processes that bring additional costs.

REmap identified significant additional potential for deployment of renewables in the EU industrial sector, to realise a 36% share (including electricity from renewable sources). Figure 31 shows the final consumption of renewable energy in industry in the EU. Total renewable energy consumption could increase by 25% under REmap compared to the Reference Case (869 PJ additional) – representing 140% growth from 2010 levels.

The largest contributor to the additional potential beyond the Reference Case is the consumption of renewable electricity (115 TWh or 413 PJ additional). The deployment of heat pumps plays a role here, enabling 105 PJ of the additional renewable electricity consumption under REmap versus the Reference Case. The second largest contributor is biomass combusted in stand-alone boilers or combined heat and power (CHP) plants to provide various levels of process heat temperature (258 PJ of additional potential). Solar water heaters for low- or medium-temperature industry processes could provide 119 PJ additional beyond the Reference Case.

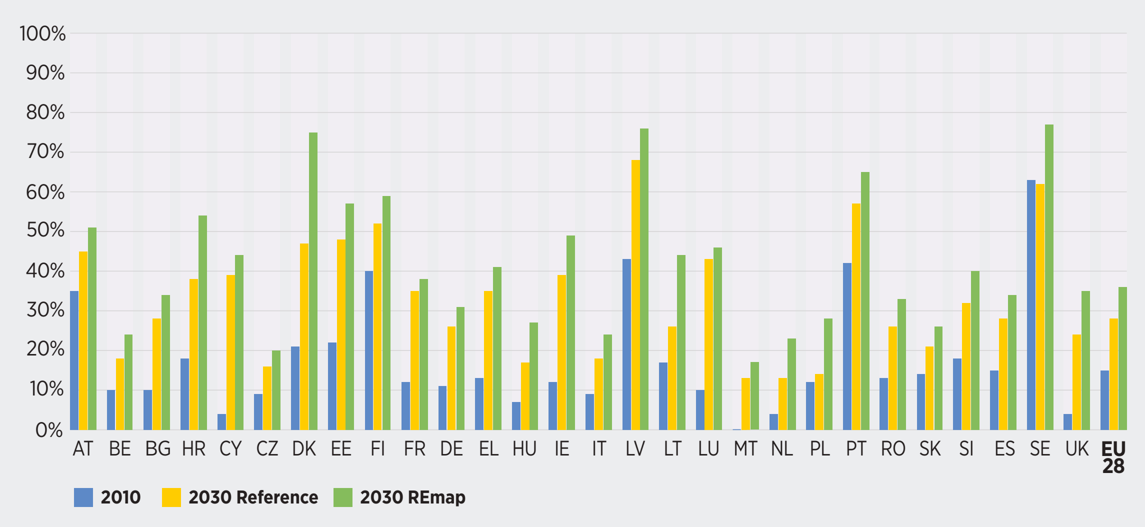
The potential for renewables under the REmap case is larger than in the Reference Case, but the additional potential and technology mix differs across countries. Figure 32 below shows the renewable share per Member State in 2010 and in 2030 (under both the Reference Case and REmap).

Figure 31: Final renewable energy consumption by source in the EU-28 industry sector in 2010 and in 2030 under the Reference Case versus REmap (PJ)



Only in a few Member States – for example, Sweden and Poland – are significant additional potentials for bioenergy in industry identified. This is because these countries still have additional supply potential that can be combusted to co-generate heat and electricity. In other countries, either biomass feedstocks are used for other sectors, or the consumption of feedstocks already has reached the estimated availability of supply.

Figure 32: Renewable energy share in industry by EU Member State in 2010 and in 2030 under the Reference Case versus REmap



3.3.3 BUILDINGS

Recent trends

In 2015, buildings accounted for nearly 40% of all energy demand in the EU-28 (Eurostat, 2017b). Around two-thirds of this total is related to the residential sector, and one-third to the services sector. The share of energy use in buildings reaches 40% or higher in Cyprus, Luxembourg, Malta, Portugal, Slovakia and Sweden, countries characterized by either low heating demand in the residential sector or by a large service-based (commercial, public, etc.) economy.

Total energy demand in buildings in the EU reached 17.6 EJ (approximately 421 million tonnes of oil-equivalent) per year in 2015. Natural gas accounted for 34% of the total final energy demand. The share of oil and coal combined was less than half of the share of natural gas. A large share of the final demand was in the form of electricity used for household appliances, lighting, office equipment, etc.

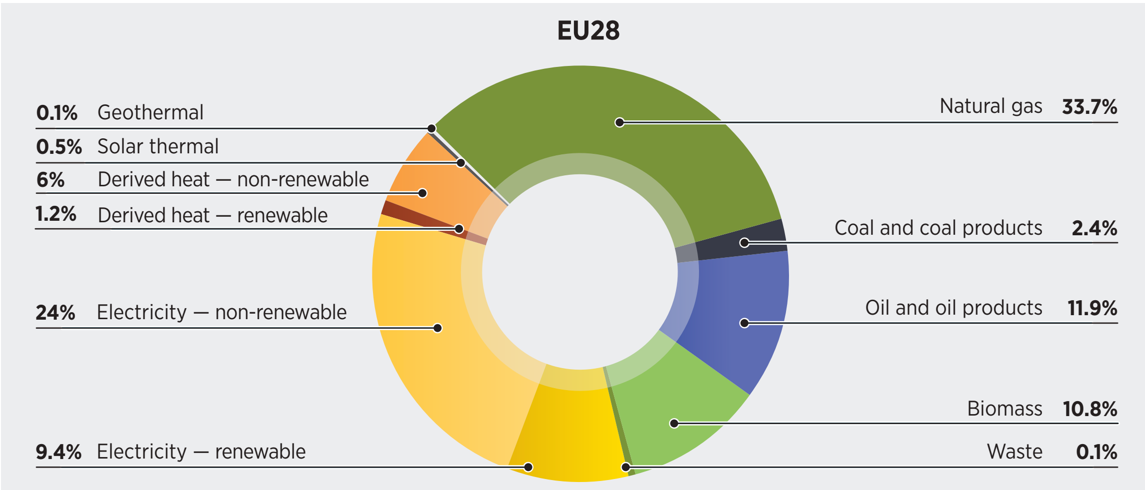
Space and water heating demand accounts for roughly two-thirds of all energy demand in the households of the EU. The current share of cooling is small, but demand from both households and the commercial sector is rising during the summer period in several countries, for example in Bulgaria, Croatia, Germany, Italy and Spain.

Renewables contributed 22% of the total final energy demand in buildings. Approximately half of this was biomass and the other half was renewable electricity and district heat derived from renewable energy sources. The contribution of solar thermal was relatively small (2% of renewable consumption).

Raising the share of renewable energy in the sector can be achieved by increasing the use of renewables for direct heating and cooling applications through decentralised units and by increasing the share of renewable energy in the fuel mix of the power and district heat sectors.

Multiple technologies can provide renewables-based heating and cooling and have been used in various EU countries for many years. Wood pellet boilers typically are used by many households in Austria, Germany and various Scandinavian countries. Markets also exist in the central European countries.

Figure 33: Breakdown of final energy use in the EU-28 buildings sector, 2015



Source: Eurostat (2017b)

Austria and Cyprus are among the world leaders in the use of solar water heaters. Geothermal heating (mainly through centralised systems) is widely used in France. In Finland, a new project with a total capacity of 40 MW with seven-kilometre-deep wells is under construction.

Heat pumps enable higher shares of renewables in buildings by converting heating applications – currently mostly supplied with fossil fuels – to electricity, and by capturing free renewable heat from ground, water or aerothermal sources. Heat pumps also consume much less input energy for the same heat output than boilers, multiplying their positive effect in the renewable share of final energy consumption. The largest markets for heat pumps in Europe (in terms of renewable heat captured) are Italy, France, Sweden and Germany (Eurostat, 2017a).

The uptake of renewable energy technologies depends on several factors, including building stock turnover. About half of the EU-28 building stock was built before 1970, with limited energy efficiency considerations and no renewable energy requirements. These buildings will either need to be renewed or some of their equipment retrofitted over time. The potential for renewables will depend on the technology characteristics and the choice made for the future of the building. When equipment is retrofitted, old boilers can be replaced easily with biofuel boilers. If there is roof space available, solar water heaters or solar PV panels can be integrated into the buildings. Renewables are easier to introduce in newly constructed buildings[27], as the design can be made in accordance with the renewable energy technology requirements, and energy demand is typically lower.

Dwelling type, tenure status and location in urban versus rural areas also play a role in increasing the integration of renewable energy technology into buildings. Single-family houses can require up to two times more energy than, for example, apartment flats, but they may have more space and therefore would allow easier integration of renewable energy equipment.

Continuing urbanisation and expansion of urban areas provide an important potential for renewables, particularly for district heating and cooling. District heating provides about 9% of the EU's heating needs (European Commission, 2016b). Several Member States already consume considerable amounts of renewable energy in district heating networks, such as Sweden, Finland, Denmark, Poland and Germany. However, the bulk of district heating in the EU is still produced using natural gas and coal.

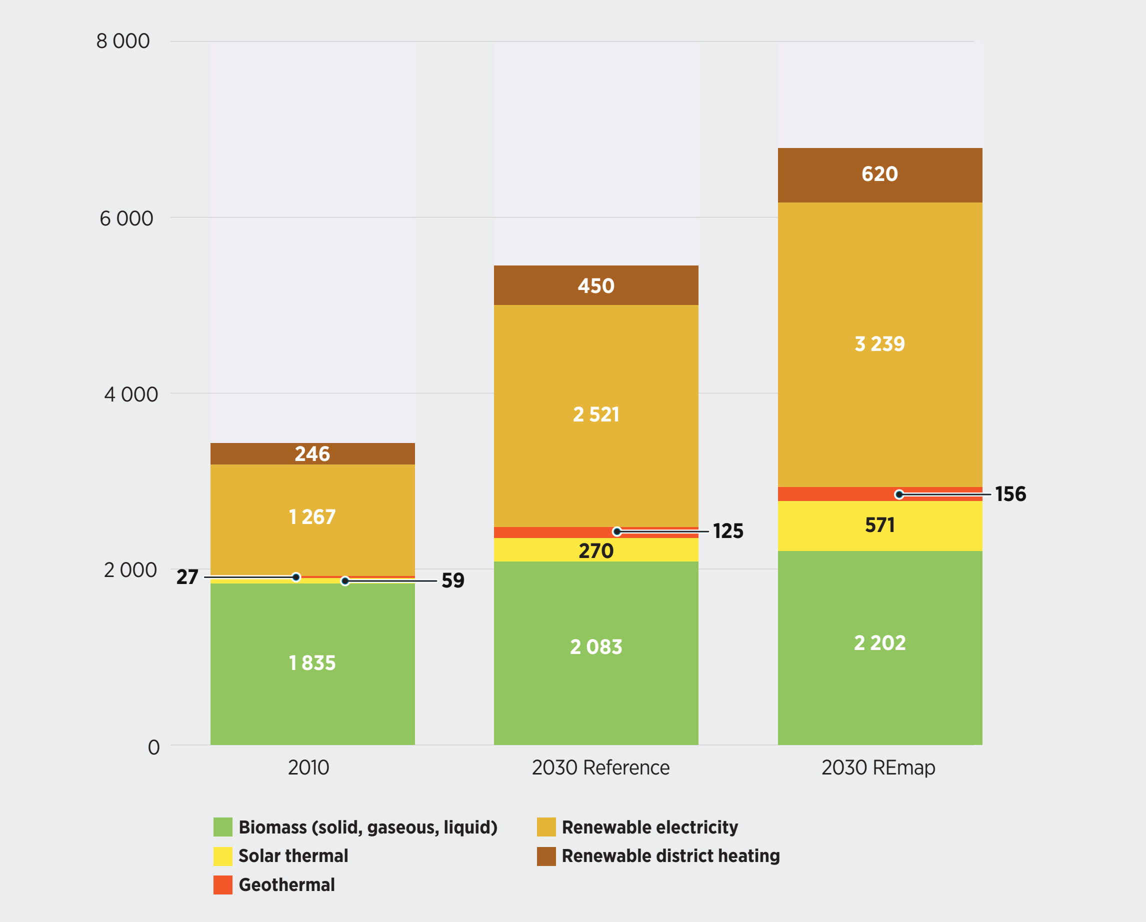
Renewable prospects for 2030

IRENA estimates that the renewable energy share in buildings would reach 32% by 2030 (including electricity) under the Reference Case. The REmap analysis identified significant additional potential for deployment of renewables to realise a 42% share.

Figure 34 shows the breakdown of the use of renewable energy in the sector. Final consumption of renewable energy in buildings in the EU could double by 2030 under the REmap case compared to 2010 levels. This represents a 25% increase over the Reference Case.

27. The EU Energy Performance of Buildings Directive (2010/31/EU) requires all new buildings to be nearly zero-energy by the end of 2020. All new public buildings must be nearly zero-energy by 2018.

Figure 34: Final renewable energy consumption by source in the EU-28 buildings sector in 2010 and in 2030 under the Reference Case versus REmap (PJ)

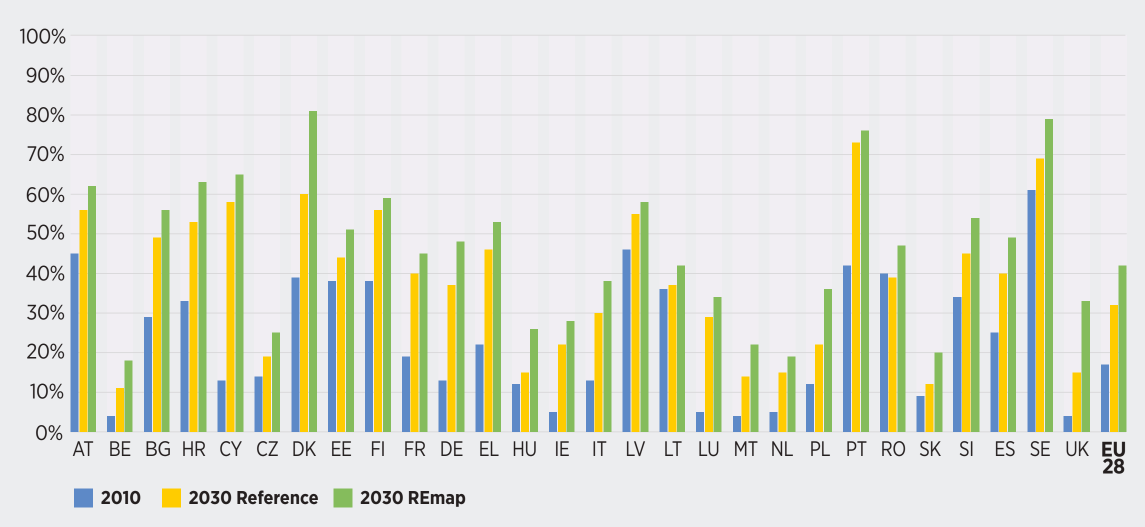


The largest contributor to the additional potential beyond the Reference Case is renewable electricity (718 PJ). The increased electrification of heating in buildings through deployment of heat pumps plays a key role, accounting for 157 PJ of the additional renewable electricity consumption versus the Reference Case (and substituting more than 1 000 PJ of fuels). The other large contributors to the additional renewable potential are solar thermal (300 PJ), renewable district heat (170 PJ) and biomass (120 PJ).

Figure 35 shows the renewable share by Member State in 2010 and in 2030 (under both the Reference Case and REmap). Electrification paired with deployment of heat pumps and increased use of district heating supplied with renewable energy play a key role in many countries. There is also significant additional potential for deployment of solar water heaters in most EU Member States. In some countries, particularly in those where demand for heating is significant (*e.g.,* central European and Baltic countries), the potential for additional bioenergy consumption is considerable as well.

Denmark and Sweden could reach the highest shares, driven by very high penetration of renewable-based district heating systems and high shares of renewables in the power sector. Portugal also could reach very high shares due to a high degree of electrification of energy consumption in buildings and large penetration of direct biomass use.

Figure 35: Renewable energy share in buildings by EU Member State in 2010 and in 2030 under the Reference Case versus REmap



Box 6 Renewable heating and cooling in the EU

Article 23 of the European Commission's proposal for a new Renewable Energy Directive (European Commission, 2016c) establishes that each EU Member State *"shall endeavour to increase the share of renewable energy supplied for heating and cooling by at least 1 percentage point every year, expressed in terms of national share of final energy consumption".*

Progress in the deployment of renewables for heating and cooling applications has been slower than in the power sector in the past. Under the Reference Case – *i.e.,* assuming the continuation of current plans and policies – IRENA estimates that most EU Member States would fall behind the above-mentioned objective, with average yearly growth of approximately 0.5% per year at the EU level. The full deployment of heating and cooling options in the REmap case results in yearly growth rates in line with the proposed target, assuming reference energy demand conditions. If additional efficiency measures are considered, higher growth rates could be realised in the sector with the same level of renewable energy deployment.

Heating and cooling solutions account for more than one third of the additional renewable energy potential identified through IRENA's REmap analysis, and more than two-thirds of the additional renewable heating and cooling options identified are cheaper than the conventional alternative. REmap analysis reveals significant potential to accelerate the deployment of heat pumps – which could account for about 9% of heating needs – as well as solar water heaters and direct use of biomass in industry and buildings. Today, district heating systems provide about 9% of the EU's heating needs (European Commission, 2016b); however, the bulk is produced with natural gas and coal. The conversion of district heating systems to use renewables is an option to accelerate renewable deployment in the heating and cooling sector.

Under the Reference Case, IRENA estimates that the share of renewables in heating and cooling would reach 25.2% by 2030, up from 18.6% in 2015. With the full deployment of REmap Options this share could grow further to reach 33.7%.

4 DISCUSSION AND RECOMMENDATIONS

IRENA's REmap analysis shows that in the Reference Case the EU is expected to reach a renewable energy share of 24% of its final energy consumption by 2030. Thus, additional commitments from EU Member States will be needed to realise and go beyond the proposed 27% EU-wide target.

The 27% EU-wide target was initially agreed at the EU Council in 2014. Since then, much has changed in the energy sector. Key renewable technologies such as solar PV and offshore wind have shown spectacular cost reductions, much faster and to much lower levels than expected. Furthermore, technology keeps improving and expanding the renewable potential that can be harvested cost-effectively, as illustrated by the rising trend in capacity factors of wind turbines, improved PV module efficiencies and the expanded horizon of technically feasible offshore wind projects. Technology developments also have accelerated in the end-use sectors: electric vehicles are quickly reaching commercial maturity and could play a key role in the deployment of larger shares of renewables in the EU by 2030, in both the transport and power sectors.

Under these more favourable circumstances, the 27% renewable target agreed in 2014 may be considered a conservative objective for the EU today. IRENA's REmap analysis shows that Europe has cost-effective opportunities available to accelerate deployment towards 2030, maintaining a global leading role in renewables rooted in a growing domestic market. The full implementation of REmap Options under reference energy demand conditions would increase the renewable share to 33% by 2030. If on the demand side the realisation of the proposed 30% energy efficiency target is considered, then renewable energy use under the REmap case would result in an even higher renewable share (34%).

In terms of greenhouse gas mitigation, the full deployment of identified REmap Options would deliver a reduction of 412 million tonnes of CO_2 (15%) in 2030 compared to the Reference Case, an amount comparable to the total greenhouse gas emissions of Italy today. Such a scenario would result in a 42% emissions reduction below 1990 levels in the energy sector – in line with the EU's 40% greenhouse gas emission reduction objective by 2030. It also would enable deeper decarbonisation conducive to a 2°C compatible pathway once energy efficiency and other mitigation measures are factored in. This illustrates the key contribution of renewables for Europe to meet climate objectives, as well as the need for close alignment between energy and climate policy.

Reaching a 34% renewable share by 2030, as per REmap, would require an estimated average investment in renewable energy of USD 73 billion per year[1]. The incremental, accumulated investment additional to the Reference Case would amount to USD 433 billion until 2030, representing an average annual contribution of 0.3% of the current EU-28 gross domestic product.

1. Levels of investment in the EU-28 were estimated at between USD 50 billion and USD 56 billion in 2016 (Frankfurt School-UNEP Centre and BNEF, 2017).

About three-quarters of the identified REmap Options are cheaper than the conventional technology substituted, while the remaining one-quarter comes at an additional cost. However, the full implementation of all REmap Options is cost-effective, delivering very substantial savings to the EU energy system compared to the Reference Case. These savings are mostly related to reduced fossil fuel imports and would reach USD 25 billion per year by 2030 (approximately USD 165 billion accumulated over the period 2020-2030). When the costs of externalities – greenhouse gas emissions and health impacts – are considered, the savings derived from the accelerated deployment of renewables are much larger, estimated at USD 52 billion to USD 133 billion per year by 2030. Savings related to avoided health damages alone would account for an estimated USD 19 billion to USD 71 billion per year by 2030.

4.1 POWER SECTOR

Electricity consumption currently accounts for about one-fifth of total final energy use and one-third of the energy-related emissions of the EU. The share of renewables in the EU power sector reached almost 29% by 2015 (Eurostat, 2017a). Under the Reference case, this share would increase to 41% by 2030.

The overall share of renewable energy generation in the power sector could reach 50% by 2030 under the REmap case. Solar PV and wind power account for the bulk of the additions under the REmap case. Solar PV could catch up with onshore wind in installed capacity at 270 GW by 2030. Offshore wind could also become a large player by 2030, with 72 GW installed in the REmap case compared to 37 GW expected in the Reference Case.

Cost-competitiveness of renewable energy

Renewables are quickly becoming cheaper than conventional power generation technologies. While fossil fuel prices have fallen in recent years, renewables costs have fallen much further and more quickly. Offshore wind is one prominent example, with recent auctions in the Netherlands, Denmark and the UK awarded at record low prices, around 6 Eurocents per kWh. Another example is solar PV: module prices in Europe have declined by about 80% from 2010 to 2016 (IRENA, 2016c). These reductions enable competitive generation costs even in countries with low-quality solar resources. A utility-scale solar PV auction in Germany in June 2017 yielded an average cost of 5.6 Eurocents per kWh.

➤ Power generation costs for renewables are – already today – comparable or lower to those of conventional technologies. The need for economic support for new capacity will continue to fall over the period 2020-2030.

Under these new conditions, creating a favourable regulatory environment will be essential to unleash market-driven investments in new renewable energy generation. A critical element of such a regulatory environment is the level and predictability of long-term renewable targets, aimed at providing a strong and reliable signal to investors. Furthermore, policies and regulations can accelerate renewable energy deployment by reducing barriers to enter the market – such as costly grid connections or administrative procedures – where these barriers are still present.

Appropriate carbon pricing – in line with the real costs of the externality – and the elimination of existing subsidies for carbon-intensive conventional generators also are key building blocks of a level playing field for renewables to compete on equal footing in the EU power markets.

Power markets with high shares of renewable energy

The REmap case results in higher shares of variable renewable energy in the power sector (*i.e.,* mainly wind and solar PV), which would account for 29% of overall power generation across the EU. The modelling analysis of such a system indicates that the REmap case could be technically feasible considering the interconnection infrastructure already planned for 2030. However, the model simulations also show some potential challenges:

Firstly, while the renewable curtailment rate resulting from the analysis is very low at the EU level, some Member States could experience higher (non-trivial) curtailment rates. These are indicative of a need for deployment of more power system flexibility options in those markets.

Secondly, the simulations show that solar PV and wind power would capture lower prices than the average wholesale market price. This happens because both technologies have low marginal generation costs, putting downward pressure on prices when they operate. This means that sunny and windy periods tend to be periods of low wholesale prices in markets with high penetration of these technologies.

This phenomenon is an indication of the additional need for market flexibility in order to respond to periods of cheap available solar and wind generation by increasing demand. If not mitigated, this effect could have an impact on the market value of renewable generation and become a serious barrier for additional investments.

- ➤ European power systems and markets will need to be progressively adapted to the intrinsic nature of variable renewable energy sources, which will represent the bulk of the capacity additions over the period 2020-2030.

  A key element to integrate large shares of variable renewable sources will be the creation of appropriate price signals for all market actors to contribute to increasing the levels of flexibility in the system. Flexibility can come from both generators and consumers, but also from the deployment of energy storage, the expansion of interconnection capacity with neighbouring Member States and the adaptation of power market rules.

  Until recently, flexibility in European systems was provided mostly by power generators. However, there is significant untapped potential to increase system flexibility on the demand side. Consumers can contribute to system flexibility by shifting demand to times of low prices. This requires, firstly, the adaptation of regulations (to expose consumers to the hourly fluctuations of market prices) and, secondly, the deployment of infrastructure (*e.g.,* smart meters and appliances) for consumers to be able to react to such signals.

  Energy storage solutions also may play an important role in providing the required additional flexibility to the system by absorbing excess power production at times of excess supply of (variable) renewables and releasing it back to the grid at times of higher demand.

  Changes in power market operation regulations also can contribute to the integration of larger shares of renewables – for example, by reducing the size of dispatch periods and "gate closure" times to minimise balancing costs, or by enabling the participation of renewable generators in ancillary services markets.

- Increased integration of the power sector with end-use sectors ("sector coupling") also can contribute to improving power system flexibility and the integration of higher shares of renewables in the power sector.

  The heat sector can contribute to power sector flexibility – for example, through the smart use of electric heat pumps at times when electricity is cheap (high supply of variable renewables). Similarly, in the transport sector, batteries in electric cars can be used to balance renewable energy variability in the power system. In addition to the benefits for the power system, the electrification of heating and transport is beneficial for the integration of renewables and the decarbonisation of the heat and transport sectors themselves by enabling the use of renewable electricity for applications that today are supplied mostly with fossil fuels.

Integration of EU power markets

Integration of electricity markets with neighbouring countries has multiple benefits, including a more efficient use of renewable resources across Member States as well as enhanced security of supply by enabling Member States to use capacity from a larger pool of options when needed.

A key element of an integrated EU power market is the ability to trade power across Member State borders effectively. Increasing the volumes of electricity trade will require efficient regional co-operation of institutions and market actors. Cross border flow of electricity in the EU has been growing in recent years at a faster rate than total generation of electricity in the same period. This illustrates the EU's progress towards integration of power markets; however, market fragmentation across European countries remains an issue.

The REmap power model simulations for 2030 show that an increase in renewable shares in the EU triggers an increased need for power trade across Member States' borders. Furthermore, simulations show that a sizeable portion of European interconnectors would operate under high levels of congestion, in both the Reference Case and REmap, indicating a need for increased interconnection capacity beyond what is already planned by 2030.

- Further integration of EU power markets will be key to realising or going beyond the 2030 renewable targets and improving security of supply cost-effectively.

  This requires, on the one hand, progress towards further convergence of EU power system operation and market rules across Member States to facilitate cross-border trade of electricity. This includes not only day-ahead market coupling, but also rules for the operation of infrastructure, and shared methodologies for, for example, the evaluation of power system adequacy.

  On the other hand, the expansion of cross-border interconnection capacity will be key to facilitating higher penetration of variable renewables up to and beyond 2030. However, specific investment decisions regarding additional interconnection infrastructure need to be weighted on a case-by case basis against other alternatives (additional demand response, storage, additional flexible generation, etc.).

4.2 END-USE SECTORS

Transport

Transport remains the sector with the lowest share of renewable energy in the EU energy system. In 2015, the share of renewable energy was less than 7% (Eurostat, 2017a). REmap identified significant potential for an increase in renewable energy use. Under the REmap case, the renewable energy share in the transport sector would reach 17% by 2030, compared to 9% in the Reference Case.

Electric mobility has emerged in recent years as a promising technology for the long-term decarbonisation of road transport. Benefits of electric vehicles include a much more efficient overall use of energy compared to internal combustion vehicles, zero tailpipe emissions (and hence less local air pollution) and, depending on the power generation, lower overall CO_2 emissions. REmap estimates that with the right policy incentives in place, up to 60% of passenger vehicles sales in the EU could be fully electric or hybrid by 2030; This is consistent with a strong penetration of electric vehicles in the EU market to reach the equivalent of 40 million light-duty electric vehicles on the EU roads by 2030 (a 16% of current stock).

- A cost-effective transition towards electric mobility can be accelerated with the adoption of clear and reliable long-term objectives for the decarbonisation of the sector (to provide industry with a clear and reliable long-term investment signal) as well as with the implementation of supporting policies, including EV purchase incentives, support to charging infrastructure roll-out, emission standards and exemptions on congestion charges for electric vehicles in cities, among others.

Despite the positive outlook for electric mobility, replacement of the existing vehicle stock will take a couple of decades. Furthermore, there are transport modes for which commercially viable electric solutions still do not exist, such as aviation, shipping, etc. Thus, a substantial increase in biofuel consumption (both conventional and advanced) will be required to progress in the decarbonisation of the sector in the period up to 2030.

The biofuel sector has faced difficulties in the EU in recent years. The harsh economic environment after the 2008 crisis triggered reductions in support in several Member States. This was followed by a decline in oil prices after 2014. Furthermore, uncertainty about future policies hindered additional investments. Thus, growth of production and consumption of biofuels in the EU has slowed down and several advanced biofuels projects have been subject to delays or cancelled.

- Current production of advanced biofuels in the EU is limited to a handful of first of a kind demonstration or small-scale commercial plants. In view of sustainability concerns about conventional liquid biofuels, significant additional policy effort needs to be allocated to accelerate investments in advanced biofuel production in the EU from now until 2030. A balanced portfolio of policies will be required to address the support needs of technologies at different stages of maturity, to scale up deployment while containing the costs imposed on consumers.
- Over the transitional period while advanced biofuels cannot supply the volumes required to meet EU renewable energy and decarbonisation targets, EU policies should maintain support for the production and use of sustainably sourced first-generation biofuels.
- Given resource constraints, allocation of biofuels should prioritise those uses for which there are no renewable technology alternatives available, *e.g.,* road freight, aviation and shipping.
- Transport is the main sector where renewables deployment is impacted by low crude oil prices. Biofuels producers need to be protected from price volatility and changing market trends by long-term stable and predictable policies. On the supply side, measures are necessary to supply affordable, reliable and sustainable feedstocks.

Industry

The industrial sector represents about one-third of the EU's total final energy consumption (including non-energy use of fuels as feedstocks, which represents about a quarter of its total). The renewable energy share[2] of EU-28 industry is expected to reach 28% by 2030 under the Reference Case. REmap identified significant additional potential for deployment of renewables in the EU industry, to realise a 36% share.

About two-thirds of energy use in industry is for heating purposes. Renewable energy growth potential in the REmap case comes primarily from an increase in the use of bioenergy, as it can provide process heat at all temperature levels. However, its availability is subject to competition with demand from other sectors.

2 Including electricity

In addition to biomass, solar water heaters and geothermal can be used for low- and medium-temperature industry processes. Deployment has been limited so far due to higher initial capital costs, their limitations in terms of temperature ranges, lack of awareness of the technology, and in many cases, the need for modifications in production processes, which bring additional risks and costs to such projects.

- Given resource constraints and competing demand from other sectors, biomass use for energy purposes in industry should be allocated primarily to applications that require medium- and high-temperature heat, preferably in CHP installations to maximise conversion efficiency.

- As in the power sector, appropriate carbon pricing – in line with the real costs of the externality – and the elimination of existing subsidies for carbon-intensive fuels (where those still exist) are key to create a level playing field for renewable technologies to compete on equal footing in the industrial sector.

- There is a need to accelerate the uptake of other renewable energy technologies such as solar thermal and geothermal. Policies should address existing barriers for further deployment, while ensuring affordable process heat generation, which is essential for the competitiveness of several industrial sectors.

The conversion of heat processes into electricity can play a key role in raising the industry sector's renewable energy share. Electricity-based process heating technologies, such as heat pumps, can help industry sector raise its electricity share but these technologies face limits in terms of process heat temperature (less than 250°C). For sectors that require high-temperature process heat levels and that dominate industrial energy use (*e.g.,* iron and steel, chemicals) electricity-based technologies are only at the research and development stage and are not commercialised.

- The possibility of further electrification of the sector for heating needs should be considered. More efforts on innovation and research and development are necessary to bring electrification technologies to commercial readiness.

In recent years, corporations have shown increasing interest in sourcing renewable electricity by means of own-installations for self-consumption in their facilities, renewable energy certificates or power purchase agreements with third parties. Corporate sourcing of renewable energy can be a driver for increasing shares of renewables in the industrial sector while providing a strong signal to market actors, and thereby improving the conditions for investment in renewable generation in the power sector.

- Policies should aim at creating suitable conditions for investment in renewable electricity sourcing. This means removing existing regulatory barriers for self-consumption installations or corporate power purchase agreements with renewable energy generators and establishing and maintaining transparent and stable renewable energy certification schemes.

Finally, industry as a sector often goes beyond the boundaries of countries when ownership is multinational. Hence more sectoral approaches instead of country-specific action are needed to address the untapped renewable potential.

Buildings

In 2015, buildings accounted for nearly 40% of all energy demand in the EU-28. The decarbonisation of the sector will require strong improvements in energy efficiency paired with increased deployment of renewable energy technologies. REmap identified significant potential for additional deployment of solar water heaters, direct use of biomass and electrification of heat applications by means of heat pumps. Under the REmap case, the renewable energy share[3] in buildings could reach 42%, compared to 32% in the Reference Case.

About half of the EU-28 building stock was built before 1970, with limited energy efficiency considerations and no renewable energy requirements. Most of these buildings will still be in place for decades to come. Renovation of buildings is an opportunity to upgrade their energy performance and to substitute old fossil-based heating and cooling equipment. However, the current pace of building renovation in the EU is low, between 0.4% and 1.2% per year (European Commission, 2015b).

- ➤ Policies should aim at accelerating current renovation rates, and guaranteeing that when such renovations take place, investors have the right incentives, information, and support to install renewable technologies for heating and electricity, while maximising energy efficiency performance levels.

District heating provides about 9% of the EU's heating needs (European Commission, 2016b). Several Member States already consume considerable amounts of renewable energy in district heating networks, such as Sweden, Finland, Denmark, Poland and Germany. However, the bulk of district heating in the EU is produced using natural gas and coal.

- ➤ The conversion of fossil-fuelled district heating systems into renewables is an option to scale up renewable share uptake in the buildings sector. Several renewable technologies can be used to feed district heating networks, including biomass, solar thermal, heat pumps in combination with renewable power, and geothermal.

Some technologies, such as heat pumps, enable higher shares of renewables in buildings, but also deliver substantial efficiency gains. Heat pumps can deliver more than three times useful heat than (renewable) electricity consumed, resulting in a much more efficient use of energy compared to boilers. However, heat pumps face several barriers to implementation, including higher initial investments and difficulty to access finance, landlord-tenant issues and insufficient knowledge of the advantages of the technology.

- ➤ Energy efficiency and renewable energy policies should be co-ordinated to recognise this complementarity and support the deployment of heat pumps by mitigating existing barriers for implementation, so that the abovementioned synergies can be tapped.

3 Including renewable electricity and district heat

4.3 CROSS-SECTORAL

The role of bioenergy

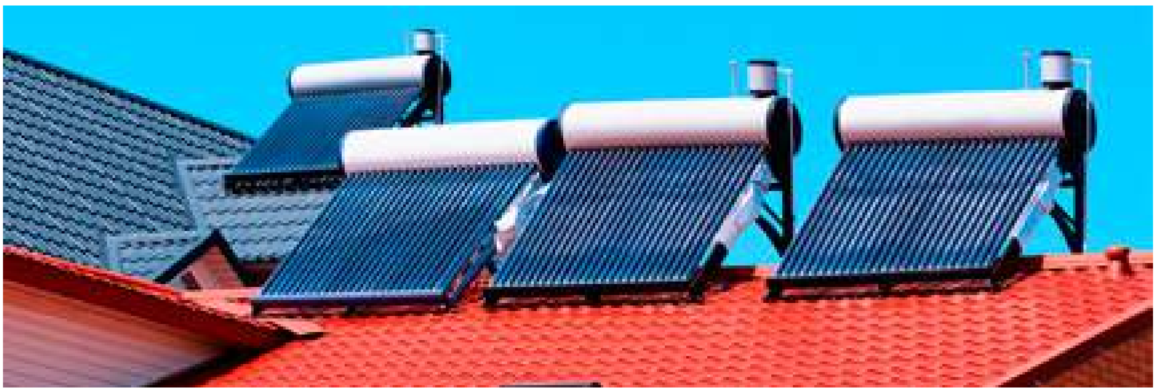
Biomass will remain a key renewable energy source for the EU to 2030. If the potential of all REmap Options is implemented, it will be the largest renewable source, growing twofold from 2010 to 2030; However, bioenergy's share in the EU's final renewable energy consumption would decrease from 67% in 2010 to 55% in 2030, as the contributions from other sources such as wind and solar can grow faster.

Provided that sustainability concerns are considered, bioenergy is a key renewable energy resource that has complementarity to other renewable energy technology options. It is the main source of renewable energy for industry because it provides a feedstock for chemicals production and can deliver process heat at high temperatures. For transport, bioenergy is the main source of renewables aside from electrification coupled with renewable power supply. In buildings, it is among the key renewable energy technologies, and in the power sector biomass can be a source of dispatchable capacity.

Although the total domestic biomass supply potential in the EU-28 exceeds the projected demand by 2030 under REmap, a sizeable share of this supply potential may be more expensive than imported alternatives or hard to mobilise for use in the energy sector. Thus, the EU would need substantial biomass imports from other countries. Imports of sustainably sourced biomass enable a deeper and more cost-effective short- and medium-term decarbonisation of applications for which other alternatives still do not exist or are more expensive.

Also within Europe, not all EU Member States have the domestic feedstock supply potential to meet their growing demand. This will require the creation of regional bioenergy markets and the related trade infrastructure to ensure that all countries meet their demand potential.

- Given global biomass resource constraints, the consumption of biomass should be progressively directed towards applications where it is the most valuable for the energy transition. This includes processes that are hard to convert to electricity or other carriers in the short and medium term, such as high temperature processes in industry, road freight, aviation, etc.
- Bioenergy trade within the EU and with countries outside of the EU will be increasingly important. Trade opens opportunities to widen the availability of supply of cost-efficient feedstocks and to diversify the bioenergy mix. Appropriate monitoring of supply chains will be key to ensure sustainability. Creating links with various trading partners also will be important to diversify trade dependency, since some feedstocks are seasonal and supply volumes may change while demand remains roughly constant throughout the year.



5 LOOKING AHEAD

IRENA's REmap analysis identifies significant renewable energy potential beyond the proposed 2030 target of 27%. **Tapping the additional potential to reach 34% is cost-effective**, even before considering the very significant economic value of the associated health and environmental benefits.

A faster deployment of renewables by 2030 is **technically feasible with today's technologies**. All EU Member States have renewable potential beyond the Reference Case that could be harvested economically. While an EU-wide target represents an important declaration of intent, **national-level commitments and implementation will hold the key** to achieving this objective cost-effectively at the regional level.

To fulfil its aspiration to become the global leader in renewables, Europe will need to maintain a growing domestic market. **The additional investments required to reach a 34% share by 2030 would help Europe maintain its leading role while deriving substantial macroeconomic benefits in terms of growth and balance of trade, as well as creating a new industrial base around the renewables sector.**

Accelerating the deployment of renewables would have much **broader social benefits for the EU and its Member States.** It can boost economic activity and create new jobs. Moreover, the decentralised nature of many renewable energy technologies and the increased uptake of domestic biomass production under the REmap scenario could be a **driver for economic development among structurally weak regions and rural areas.** Combined with energy efficiency measures, renewables can also be a key **contributor to reducing energy poverty in the EU.**

Finally, tapping the additional renewable energy potential identified in the REmap study would bring the EU closer to a **decarbonisation pathway compatible with the "well-below" 2°C objective** established in the Paris Agreement, **while substantially improving the health of citizens.**

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ANNEXES

ANNEX A: SOURCES FOR REMAP COUNTRY ANALYSES

This section presents the list of sources that have been used to develop the underlying REmap country analyses for the EU Member States. The table below shows a list of the key reports and studies that served to extract energy use and supply projections and to estimate additional renewable potential for the 10 EU Member States with an in-depth REmap analyses:

Table 3: Data for REmap country analysis

Member State	Reference Case 2030	REmap 2030
Belgium	Federal Planning Bureau (2014)	Devogelaer *et al.* (2013) Duerinck *et al.* (2017)
Cyprus	IRENA (IRENA, 2015b)	IRENA (2015b)
Denmark	EFKM (2010)	EFKM (2011)
France	MESDE (2015)	ADEME (2015, 2009)
Germany	PROGNOS, EWI & GWS (2014)	IRENA (2015c)
Italy	ENEA (2014)	IRENA analysis based on industry, technology and sector roadmaps (IRENA, 2017c, 2016a, 2016d, 2016e, 2015d, 2014a, 2014b,) (IRENA and IEA-ETSAP, 2015a, 2015b, 2015c)
Netherlands	Schoots *et al.* (2016)	
Poland	IRENA (2015d)	
Sweden	Regeringskansliet (2009)	
United Kingdom	DECC (2015)	

For the remaining 18 EU Member States, the basis of the Reference Case in 2030 is the PRIMES Reference Scenario (E3MLab, 2016) which is explained in detail in Annex B. For the estimation of additional potential and indicators for the REmap scenario for these countries, the analysis is based on IRENA's expertise, technology and sectoral studies, and complementary information and data has been extracted from the following reports:

- Best Available Technologies for the Heat and Cooling Market in the European Union (JRC, 2012)
- Electric Vehicles in Europe (EEA, 2016b)
- Energy efficiency trends for households in the EU (Lapillonne et al., 2015)
- ENTRANZE - Policies to Enforce the Transition to Nearly Zero-Energy Buildings in the EU-27 – Scenario Results (ENTRANZE, n.d.)
- Estimating Rooftop Suitability for PV: A Review of Methods, Patents, and Validation Techniques (NREL, 2013)

- Growing for Good? The European Heat Pump Market - Status and Outlook (EHPA, 2017)
- Heat Pump Implementation Scenarios until 2030 (Ecofys, 2013)
- Heat Pumps Barometer 2016 (Eurobserver, 2016)
- Heat Roadmap Europe 2: Second Pre-Study for the EU27 (Aalborg University, 2013)
- Heating and Cooling - Facts and Figures (Heat Roadmap Europe, 2017)
- Power 2030: A European grid for 3/4 renewable electricity by 2030 (Greenpeace, 2014)
- Solar Heat Worldwide Edition 2012 - Markets and Contribution to the Energy Supply 2010 (AEE INTEC, 2012)
- Solar Heat Worldwide Edition 2016 - Markets and Contribution to the Energy Supply 2014 (AEE INTEC, 2015)
- Solar Thermal Plants Database for Solar Heat for Industrial Processes (SHIP) (AEE INTEC, n.d.)

ANNEX B: PRIMES REFERENCE SCENARIO

The EU Reference Scenario 2016 (E3MLab et al., 2016) has been used to develop the Reference Case of the REmap EU study for Member States lacking a REmap analysis. For this purpose, the following information was extracted:

- Energy demand projections in end-use sectors and district heating generation in 2030 for 18 EU Member States (countries in light blue in Figure 2) for which no REmap analysis had been completed by the beginning of 2017.
- Power generation and capacity to 2030 for 18 Member States (18 countries in light blue in Figure 2).

The PRIMES model

PRIMES is a partial equilibrium model for the EU energy system developed by and maintained at the National Technical University of Athens (NTUA). It is the result of collaborative research under a series of projects supported by the Joule programme of the Directorate General for Research of the EC (E3MLab, 2014).

PRIMES is intended to serve as an energy policy markets analysis tool involving the relationships between energy policy and technology assessment. Being a market oriented modelling system, PRIMES simulates a market equilibrium solution for energy supply and demand in EU member states. It is applied for forecasting, scenario construction and policy impact analysis with medium to long-term horizon coverage (until 2050). PRIMES provides detailed projections of energy demand, supply, prices and investment to the future, covering the entire energy system including emissions for each individual EU member state and for Europe-wide trade of energy commodities. Price-driven equilibrium attained through iterative process is considered in all energy and environment markets, including Europe-wide clearing of oil and gas markets, as well as Europe-wide networks, such as the Europe-wide power grid and natural gas network (E3MLab, 2016)

The distinctive feature of PRIMES is the combination of behavioural modelling following a micro-economic foundation with engineering and system aspects, covering all sectors and markets at a high level of detail. PRIMES focuses on prices as a means of balancing demand and supply simultaneously in several markets for energy and emissions. The model determines market equilibrium volumes by finding the prices of each energy form such that the quantity producers find best to supply matches the quantity consumers wish to use. Investment is generally endogenous in PRIMES and in all sectors, including for purchasing of equipment and vehicles in demand sectors and for building energy producing plants in supply sectors. The model handles dynamics under different anticipation assumptions and projects over a long-term horizon keeping track of technology vintages in all sectors. Technology learning and economies of scale are fully included and are generally endogenous depending on market development. (E3MLab, 2016; NTUA, n.d.)

PRIMES model design is suitable for medium- and long-term energy system projections and system restructuring up to 2050, in both demand and supply sides. The model can support impact assessment of specific energy and environment policies and measures, applied at Member State or EU level, including price signals, such as taxation, subsidies, Emissions Trading System, technology promoting policies, RES supporting policies, efficiency promoting policies, environmental policies and technology standards. PRIMES is sufficiently detailed to represent concrete policy measures in various sectors, including market design options for the EU internal electricity and gas markets. Policy analysis draws on comparing results of scenarios against a reference projection (E3MLab, 2016).

ANNEX C: ENERGY PRICE ASSUMPTIONS

Energy prices

The assumed 2030 energy commodity prices are based on historic prices as of 2010 (base year for this analysis) projected to 2030 using the price growth rates for the relevant carriers obtained from the PRIMES results of the Reference Scenario 2016 (E3MLab et al., 2016).

Table 4: Energy commodity prices excluding taxes in 2030 for EU-28 countries

Commodity	Units	Min	Max	Avg.
Steam coal (industry)	(USD/GJ)	4.6	7.8	5.6
Steam coal (power)	(USD/GJ)	3.5	4.8	4.3
Electricity (buildings)	(USD/kWh)	0.11	0.25	0.17
Electricity (industry)	(USD/kWh)	0.07	0.27	0.13
Natural gas (buildings)	(USD/GJ)	6.9	26.2	18.6
Natural gas (industry)	(USD/GJ)	4.9	16.7	12.5
Natural gas (power)	(USD/GJ)	3.7	12.6	9.4
Petroleum products (buildings)	(USD/GJ)	18.9	30.4	24.3
Petroleum products (industry)	(USD/GJ)	14.8	21.9	19.4
Diesel (transport)	(USD/GJ)	24.9	30.9	27.4
Gasoline (transport)	(USD/GJ)	25.6	29.8	27.5
Kerosene (transport)	(USD/GJ)	25.7	25.7	25.7
Biodiesel (transport)	(USD/GJ)	24.4	24.4	24.4
First generation bioethanol	(USD/GJ)	27.5	29.9	29.8
Second generation bioethanol	(USD/GJ)	35.0	35.0	35.0
Biomethane (transport)	(USD/GJ)	15.7	43.0	26.0
Biokerosene (transport)	(USD/GJ)	35.0	35.0	35.0
Biomass (feedstock average)	(USD/GJ)	5.8	7.1	6.4

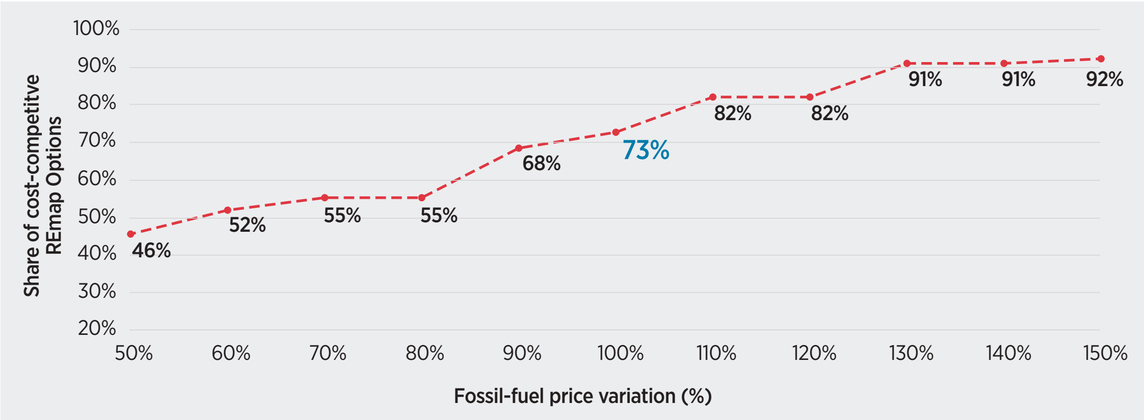
Note: The min and max represent the lowest and highest energy prices of one of the EU Member States.

Sensitivity of results to fossil fuel price scenarios

A sensitivity analysis was carried out to assess how variations on assumptions on fossil fuel prices would affect the results on energy systems costs/savings and share of cost-effective renewable energy options. The sensitivity analysis considers a fossil fuel price variation between 50% to 150% of the central scenario. The results of the sensitivity analysis for the two analysed variables are presented in the figures below.

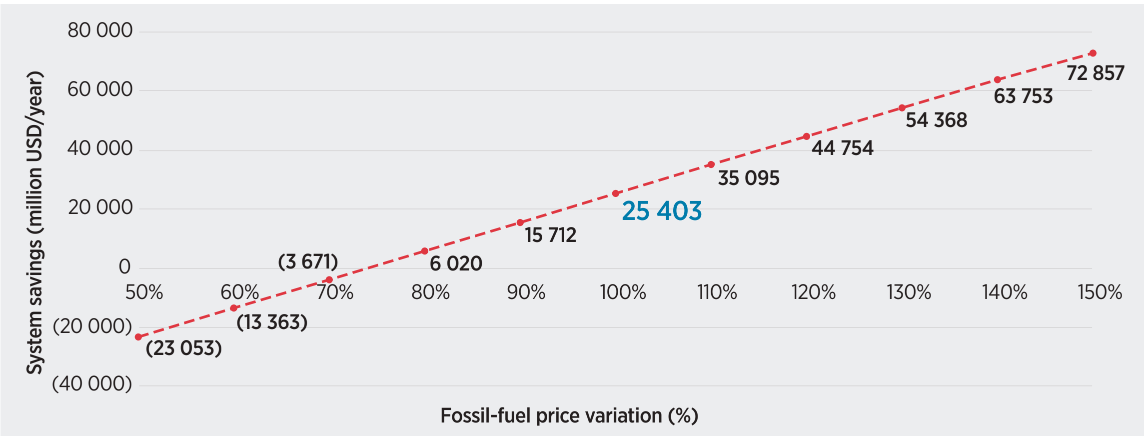
With lower fossil fuel prices, renewable energy becomes less competitive, but even in a scenario with very low energy prices, almost half of the identified REmap Options are still cost competitive.

Figure 36: Share of cost-competitive REmap Options (%) versus fossil fuel price variation (%)



The full implementation of REmap Options would deliver net savings in LCOE terms (excluding all additional savings from reduced externalities) compared to the Reference Case even considering fossil fuel prices 26% lower than the central assumption. Figure 37 below shows the resulting net savings considering fossil fuel price variations between 50% to 150% of the central scenario.

Figure 37: Energy system savings (million USD/year) versus fossil fuel price variation (%)



ANNEX D: RENEWABLE ENERGY SHARES IN 2030 UNDER DIFFERENT ENERGY DEMAND SCENARIOS

IRENA's REmap analysis focuses on the identification of additional potential for the deployment of renewables. The REmap case is built considering reference demand scenarios (*i.e.,* without consideration of additional energy efficiency measures[1].

Under the reference demand scenario, the full implementation of all renewable energy options identified in this study would result in a share of renewables in the gross final energy consumption of the European Union of 33% by 2030; however, the resulting share depends both on the volume of renewable energy consumption and on the energy demand scenario considered. Additional efforts in energy efficiency result in a higher share of renewables for the same volume of renewable energy consumption.

Table 5 below shows the expected shares of renewables by 2030 as a function of 1) the fraction of renewable energy options (REmap Options) deployed by 2030 out of the total renewable potential identified in this study, and 2) the demand scenario according to different energy efficiency targets under discussion in the European Union for the year 2030.

As part of the "Clean Energy for All Europeans" package of November 2016, the European Commission proposed a binding EU-wide target of 30% for energy efficiency by 2030 (European Commission, 2016a). If the realisation of such a target is considered, the full implementation of all renewable energy options identified in this study would represent a renewable energy share of 34%. A similar share of renewables could be achieved with partial deployment of REmap Options (60-70%) if the 2030 efficiency target would be increased to 35%. If more ambitious energy efficiency targets are considered, the resulting share of renewables could be even higher for the same levels of renewable energy deployment.

Table 5: Resulting renewable energy share in gross final energy consumption for different degrees of deployment of REmap Options and demand scenarios

% of REmap Options Implemented →

Energy Efficiency Target ↓	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
IRENA Reference Case	**24%**										
IRENA REmap Case		26%	27%	27%	28%	29%	30%	30%	31%	32%	**33%**
27%	25%	26%	27%	28%	28%	29%	30%	31%	31%	32%	33%
28%	26%	26%	27%	28%	29%	30%	30%	31%	32%	33%	33%
29%	26%	27%	28%	28%	29%	30%	31%	32%	32%	33%	34%
30%	26%	27%	28%	29%	30%	30%	31%	32%	33%	34%	**34%**
31%	27%	28%	28%	29%	30%	31%	32%	32%	33%	34%	35%
32%	27%	28%	29%	30%	30%	31%	32%	33%	34%	35%	35%
33%	27%	28%	29%	30%	31%	32%	33%	33%	34%	35%	36%
34%	28%	29%	30%	30%	31%	32%	33%	34%	35%	36%	37%
35%	28%	29%	30%	31%	32%	33%	34%	34%	35%	36%	37%

1. Except for the efficiency gains resulting from the deployment of heat pumps and electric vehicles.

ANNEX E: EU POWER SYSTEM MODELLING ANALYSIS

PLEXOS Model Description

PLEXOS (Energy Exemplar, 2016) can model various aspects of the power system, including:

- Power Market Simulation, Price Forecasting and Analysis
- Operational Planning, Unit Commitment and Optimisation of Generation and Transmission
- Trading and Strategic Decision Support
- Integrated Resource Plan including Generation and Transmission Expansion and Investment Analysis
- Renewable Integration Analysis and Intermittent Supply
- Co-optimisation of Ancillary Services, Energy Dispatch and Emissions
- Transmission Analysis and Congestion Management
- Portfolio Optimisation and Valuation
- Risk Management and Stochastic Optimisation

Generation Portfolio

For the 10 EU Member States with a completed REmap analysis (as described in sections 2.1 and 2.2) the installed capacities per technology defining the generation portfolio used as input for the power sector model simulations were obtained from the results of the REmap analysis for each country, for both the Reference Case and REmap.

For the remaining 18 EU Member States, the generation portfolio was obtained as follows:

- For the Reference Case, the installed generation mixes were based on the PRIMES reference scenario 2016 for the year 2030.
- For the REmap case, the installed generation portfolios from the PRIMES reference scenario 2016 were used as starting point and adjusted to generate a representative increased renewable uptake scenario akin to that developed for the 10 REmap countries. The process for generating installed capacity mix for the 18 non-REmap countries for the REmap case is based on the following steps:

    i. An initial estimate of REmap Options was made based on their resource availability and installed capacity in 2030 under the Reference scenario. REmap Options in this instance covered only wind and solar PV and their installed generation capacity were scaled up based on a high-level assessment of their respective national potential. This increase in the total VRE capacity between the Reference and REmap scenarios is comparable to that projected in the 10 REmap countries.

    ii. After this initial assessment of the potential, an iterative process was followed to adjust the installed capacity of these VRE sources in these 18 countries. This process involved the simulation of an EU-28 power system dispatch model in PLEXOS for this initial and each subsequent REmap scenario developed. Installed capacities of VRE in non-REmap countries were subsequently revised in countries in an iterative process in line with modelling observations, *e.g.,* curtailment of variable renewable power, interconnector congestion and emissions intensity of generation.

iii. The increased renewable energy capacity introduced under the REmap scenario reduces the need for non-renewable energy capacity from the Reference scenario. For the 18 non-REmap countries, a capacity credit methodology developed by the IEA (IEA, 2015) was applied to determine the level of fossil fuel capacity which could be removed from the generation mix with the introduction of additional variable renewable energy capacity in the REmap scenario[2]. This involved the substitution of the most carbon intensive fossil fuel electricity generation capacity.

This process facilitated the development of a highly renewable power sector scenario for the rest of the EU that is broadly representative of those developed in the 10 REmap countries.

Power system representations in Switzerland and Norway were the same for both REmap and the Reference Case and were based on the conservative "Slowest Progress" Vision 1 scenario of the European Transmission system operator's, ENTSO-E's, scenario development report used to inform the 2016 Ten-Year Network Development Plan.

Generator plant size

The generation portfolio for each country is represented by standard generators with standard characteristics (maximum capacity, minimum stable levels, ramp rates, maintenance rates, forced outage rates, start costs etc.) A selection of these characteristics can be seen in Table 6.

Each disaggregated generation capacity was built up by many identical generators that sum to the total installed capacity as split by technology in the aggregate generation mixes. For natural gas-fired generation, 10% of installed capacity was assigned as open-cycle gas turbine (OCGT) to reflect the impact of the flexibility of these less efficient plants on the power system with the remainder of natural gas fired plants being modelled as combined-cycle gas turbine (CCGT) units. Heat rates for the various types of power plant in the model are defined at country level and are as they appear in the PRIMES reference scenario results.

Table 6: Standard generator characteristics

Fuel Type	Capacity (MW)	Start Cost (€)	Min Stable Factor[3] (%)
Biomass-waste fired	300	10 000	30
Biogas fired	150	12 000	40
Geothermal	70	3 000	40
Hydropower, lakes	150	0	0
Hydropower, run of river	200	0	0
Hydrogen plants	300	5 000	40
Natural gas CCGT	450	80 000	40
Natural gas OCGT	100	10 000	20
Nuclear energy	1 200	120 000	60
Oil fired	400	75 000	40
Coal fired	300	80 000	30

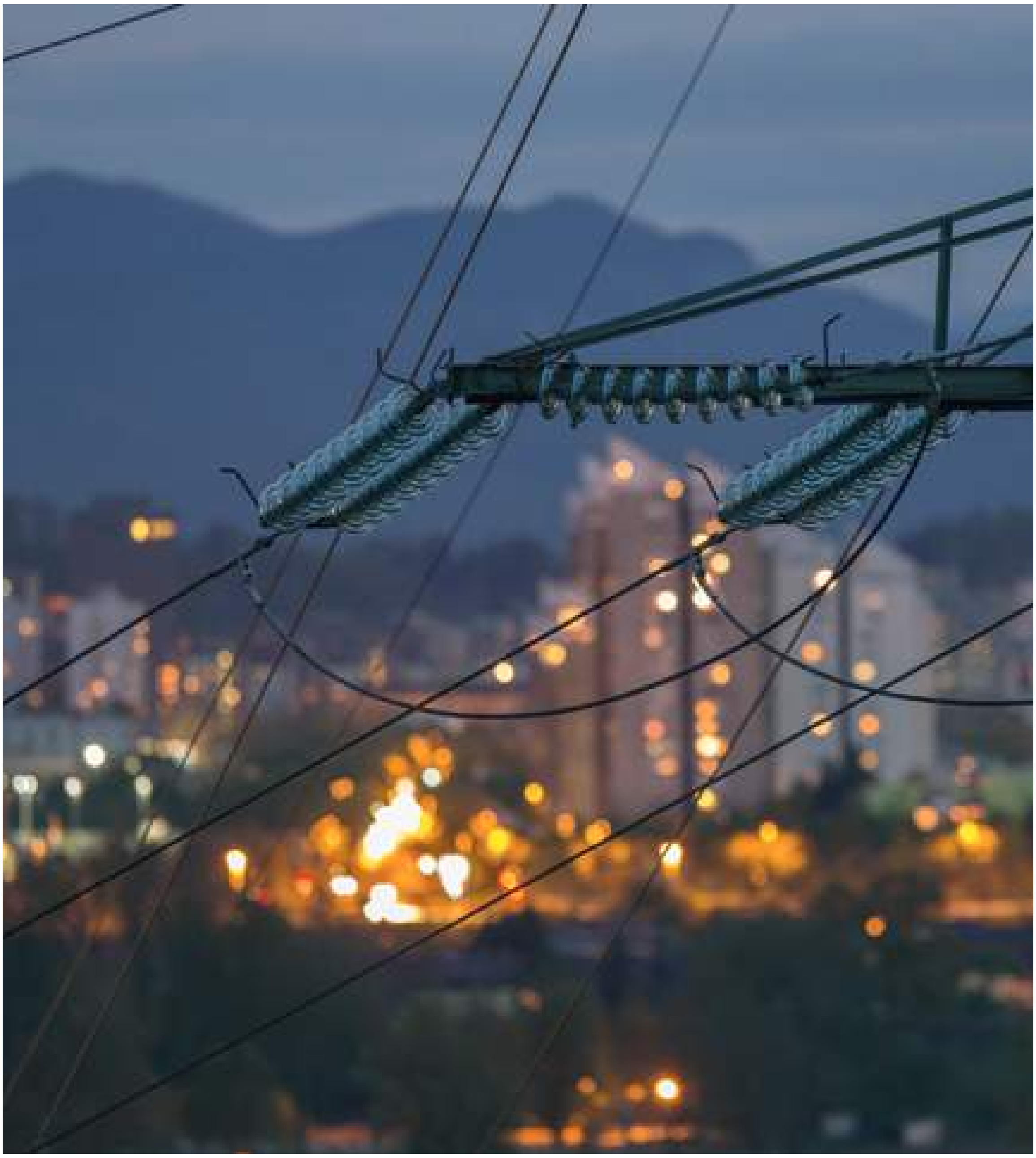
2. For the countries with completed REmap assessments, close collaboration with country experts facilitates the careful substitution of dispatchable fossil fuelled generation with variable renewable sources.

3. Min Stable Factor is the minimum stable generation level defined as a percentage of Max Capacity.

Interconnection

Net power transfer capacities are limited here to interconnection between Member States, *i.e.* no interregional transmission is considered. The electricity network expansion is aligned with the *2016 Ten Year Development Plan* from ENTSO-E (ENTSO-E, 2016), without making any judgement on the likelihood of certain projects materialising.

While greater resolution in terms of transmission capacity would be desirable, this would require greater nodal disaggregation in the model which would lead to substantial increases in data requirements (*i.e.,* require disaggregation of demand, renewables profiles, generation capacity etc. by node). Using these pan-European transmissions capacities provided by the European transmission system operator at a country level provide a reasonable assessment of how the system may develop out to 2030 and allow for a high-level assessment of power system operation in a pan European context.



Demand

The REmap and Reference scenarios were simulated at hourly resolution for each country for the year 2030 and thus required an hourly electricity demand profile. Historic demand profiles from ENTSO-E for the EU[3] in the year 2012 (ENTSO-E, 2012) were used and linearly scaled to 2030 levels with a peak scaling of 1.1. This was done using the tool in PLEXOS software for this purpose and ensured that representative variations in demand by Member State were maintained.

VRE modelling

To assess the flexibility of the European power system in 2030 and its ability to absorb high levels of intermittent renewables, the modelling process must sufficiently capture the effects of the intermittent nature of these modes of generation with localised profiles for each EU-28 Member State:

- *Onshore and offshore wind power*

  Hourly wind generation profiles for each country were derived from the EMHIRES data set developed by the Joint Research Centre of the European Commission that models how hourly energy production from installed wind farms in Europe have produced in every hour over the course of the past 30 years (Gonzalez Aparicio et al., 2016). The profiles provided by the EMHIRES data set are at a national scale based on the 2015 installed fleet of wind farms, and in order to account for technological improvements anticipated to come online by 2030, these were scaled to the capacity factors anticipated by Member State in the PRIMES Reference Scenario of the EU Reference Scenario 2016 (E3MLab et al., 2016).

- *Solar power*

  Localised hourly solar profiles for each EU-28 Member State were created and used within the model. This was done through use of NREL's PV Watts® Calculator web application which determines the electricity production of a grid-connected roof- or ground-mounted PV system based on several inputs regarding the system location and basic system design parameters. The profiles created were then normalised with the generation capacity for each member state as per the Reference Case 2030 results.

Hydropower

The hydropower generation profiles that used in this work were at a monthly resolution and were derived using historic generation profiles provided by ENTSO-E for each individual EU Member State and for Norway. As with wind generation, these generation capacity factors were brought into line with those in the PRIMES Reference Scenario in 2030.

3. In the case of Switzerland and Norway the demand profile used was the projected hourly demand profile from "Slowest Progress" Vision 1 scenario of the European Transmission system operator's, ENTSO-E's, scenario development report used to inform the 2016 Ten-Year Network Development Plan.

Electric vehicles and stationary battery storage

The modelling analysis discussed in section 3.2.2, considers pumped hydro reservoirs as the only form of electricity storage available in EU power systems by 2030. The fleet of electric vehicles deployed in both the Reference Case and REmap is analysed as an electric load, unresponsive to electricity prices in the market and unable to discharge electricity back to the grid.

Box 4 discusses the results of an additional simulation considering an active role of electric vehicles and stationary batteries. REmap considers the deployment of 40 million light duty electric vehicles by 2030, with an estimated aggregated battery storage capacity of 959 gigawatt-hour (GWh). Likewise, stationary battery storage capacity could be significant. An aggregated capacity of 243 GWh across the EU by 2030 is assumed for these simulations.

- *Assumed operation of the electric vehicle fleet:*
  - 50% of the fleet operating under "smart charging" mode *i.e.,* with no generation capability, but able to regulate charging power and be sensible to price signals to charge when energy is cheaper.
  - 50% of the fleet operating under "vehicle-to-grid" mode, *i.e.,* in addition to price sensitivity while charging, they can discharge energy to the grid when connected and profitable to do so.
  - Simultaneity factors: 20% of the electric vehicle fleet connected from 8am until 8pm; 50% of the fleet connected from 8pm until 8am.
- *Assumed operation of stationary batteries:*
  - 20% of total capacity can do energy arbitrage at any time.

Fuel and carbon prices

Fuel prices are available in Annex C. Biomass and Biomethane fuels were priority dispatched in model simulation which means that their actual cost did not feature in the dispatch. The carbon price used in this analysis is EUR 25 per tonne of CO_2 (USD 33.3).

ANNEX F: COMMENTARY BY THE JOINT RESEARCH CENTRE

This Annex reflects the findings of the Joint Research Centre only.

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Commentary on IRENA's Renewable Energy Prospects for the European Union by the Joint Research Centre

The International Renewable Energy Agency (IRENA) used the REmap methodology to conduct an assessment of renewable energy prospects for the EU in 2030. The Knowledge for the Energy Union Unit of the Joint Research Centre (JRC) carried out a meta-analysis by comparing the REmap scenario results on renewable energy deployment with those of other studies for the EU. The REmap scenario results for the EU were benchmarked against other scenarios at a sectoral and systems level. Policy insights derived from the REmap analysis were compared qualitatively with recommendations of other major publications.

The main findings of this meta-analysis are summarised below:

REmap and other long-term energy scenarios:

A large number of global energy scenarios are regularly published by international organisations (e.g. International Energy Agency), consultants (e.g. Bloomberg), industry associations (e.g. Global Wind Energy Council), NGOs (e.g. Greenpeace) and academia (e.g. MIT). These scenarios describe the development of energy demand and supply over longer time periods, typically 20-35 years. The JRC through its Knowledge for the Energy Union Unit monitors such global scenarios to carry out comparative analyses. The dataset used in this note includes publications up to June 2017.

Using exogenous energy demand assumptions, REmap sees the potential for significant growth of renewable energy in all sectors over the next 12 years to reach a RES share of 33%. Based on the REmap methodology, assuming demand trajectories in line with the European Commission's proposal of 30% efficiency savings by 2030 would imply the same volume of renewable energy but a higher RES share of 34%.

Overall, REmap is well in line with estimates of other ambitious scenarios aiming to decarbonise the energy system and meet long term climate targets. RES shares in end-use sectors are also consistent between REmap and other scenarios: by 2030 the buildings sector is in a direction of being halfway decarbonised, the RES share in industry almost doubles compared to 2015 and renewable energy supply in transport is the fastest growing.

*Sectoral and technology details however, point to differences. REmap estimates on **electricity** supply from renewables (RES-E) and related capacity deployment are consistently on the higher-end for all main options (solar, wind and biomass) compared to other scenarios. The REmap scenario sees steep annual growth rates in parallel for both solar PV and wind energy (about 7% and 6%, compared to 2015, respectively). Other scenarios see prominent increase for just one of the two variable RES options (about 7% for solar and 4% for wind or vice versa). Studies currently do not agree on the level of biomass electricity generation. One scenario, which combines bioenergy with carbon capture beyond 2030, sees higher deployment than REmap. The steep increase of RES-E in REmap (4.7% annually) between 2015 and 2030 occurs in an expanding electricity sector (by about 1% per year). Other scenarios see lower demand for electricity in 2030 (by 3% to 14%) compared to REmap, which leads to lower annual* *growth for renewables (by about 0.2% to 1% percent points). Despite different absolute levels, these dynamics lead to comparable results between REmap and other scenarios in electrification of final demand (25% to 27%), RES-E share (49% to 55%) and penetration of variable RES (29% to 33%).*

All scenarios point towards a rapidly increasing electrification of ***transport*** *(9% to 14% annually from 2015 onwards), leading to comparable electricity consumption by 2030. A pronounced difference, however, is found in biofuel consumption, with REmap estimates being higher by up to 30 bn litres of gasoline eq. compared to scenarios with similar renewable energy share in transport. REmap sees potential uptake in advanced, non-food-based biofuels, yet those that account for most consumption are produced from food crops. As such, imports would be required for the EU to meet this additional demand. Another difference is found in the sector's energy demand as REmap assumes higher final consumption by 18% to 40% compared to other ambitious scenarios that also show strong energy efficiency improvements. REmap's final energy consumption in the sector is by about 10% lower in 2030 compared to current levels. Other studies assume even higher reduction already in their business as usual scenarios and such steep reduction may represent a change with respect to recent demand growth trends.*

In the ***industry*** *sector, in line with business as usual scenarios, REmap assumes increase in total energy demand by about 10% in 2030 compared to 2015. Other scenarios, however, show ambitious reduction in energy demand in the order of 20%. New industrial demand in REmap is supplied primarily by additional deployment of renewable energy, with a parallel increase in electrification and district heat. In other studies reduction in demand affects primarily fossil fuels. As such, renewables increase but significantly less than in REmap. Across studies, energy demand in the* ***buildings*** *sector is comparable to 2015 or declines by up to 1.5% per year, and the REmap analysis shows results within this range (reduction at an annual pace of 0.7%). In this sector, REmap shows fast fuel switch. Most other scenarios however phase fossil fuels out faster than they introduce renewables. Overall, across scenarios REmap sees one of the highest transformation rates in industry and buildings (defined as the aggregate of the required annual change).*

The REmap scenario concludes that the EU could double its renewable energy supply (RES) share from 17% in 2015 to 34% in 2030, if the European Commission's proposal on 30% energy efficiency savings is realised. Achieving even more ambitious energy efficiency targets would entail prioritisation of investment needs and furthermore, efficiency options could influence the substitution portfolio of REmap. In addition, if RES supply remains the same but demand for energy decreases, technical barriers may arise. For example, the penetration of variable RES will grow thereby increasing system balancing needs and related costs. Finally, as the contribution of biomass in REmap is prominent in all sectors, further analysis is required in terms of sustainable availability and supply (within and outside the EU), energy security, and emissions.

Policy recommendations:

The REmap report makes a number of recommendations to policymakers on how to realise the identified potentials for renewable energies. In line with the International Energy Agency (IEA) studies, the REmap policy recommendations argue for supporting renewable energy in the electricity, heating, transport or bioenergy subsectors through carbon pricing and long term goals. All studies address the need to unlock flexibility sources through sector coupling and geographical integration, both physically and market wise. Yet REmap does not go as far as to provide concrete recommendations on how investments in the non-renewable part of the electricity system could be ensured during the transition *period. For the bioenergy sector, REmap also sees the need for policies to address potential conflicts for resources by "prioritising the effective use of biomass".*

REmap recommendations focus on renewable energy sources. Thus, opposed to, for example, the IEA's studies (World Energy Outlook, Energy Technology Perspectives), IRENA does not provide recommendations for the advancement of Carbon Capture and Storage (CCS) or nuclear energy. In some deep decarbonisation studies, CCS plays a role in combination with biomass beyond 2030, justifying policy support considerations for this technology.

Finally, REmap is focussed on the supply rather than the demand side. While IRENA recommends supporting the roll-out of EVs and heat pumps, the study does not look in detail into energy efficiency policy mechanisms. Other studies go further in this respect by recommending labelling and standards for appliances and setting minimum standards for vehicle emissions.

Overall, REmap makes a consistent set of policy recommendations for supporting renewable energy without becoming prescriptive or country specific.

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ANNEX G: OVERVIEW OF EU REMAP RESULTS

EU-28			Unit	2010	Reference Case 2030	REmap 2030
Energy production and capacity	Power sector	**Total installed power generation capacity**	***GW***	**864**	**1 079**	**1 237**
		Renewable capacity	*GW*	266	608	814
		Hydropower	*GW*	123	129	139
		Wind - onshore	*GW*	85	194	256
		Wind - offshore	*GW*	0	36	71
		Biofuels (solid, liquid, gaseous)	*GW*	25	60	67
		Solar PV	*GW*	33	184	270
		CSP	*GW*	0	4	5
		Geothermal	*GW*	1	2	6
		Other (Ocean / Tide / Wave / Other)	*GW*	0	0	1
		Non-renewable capacity	*GW*	597	471	423
		Total electricity generation	*TWh*	**3 331**	**3 471**	**3 700**
		Renewable generation	*TWh*	682	1 426	1 858
		Hydropower	*TWh*	373	387	411
		Wind	*TWh*	151	544	783
		Biofuels (solid, liquid, gaseous)	*TWh*	128	286	324
		Solar PV	*TWh*	23	188	281
		CSP	*TWh*	0	8	10
		Geothermal	*TWh*	6	13	44
		Other (Ocean / Tide / Wave / Other)	*TWh*	0	0	4
		Non-renewable generation	*TWh*	2 649	2 045	1 843
	DH	**Total district heat generation**	***PJ***	**2 933**	**2 953**	**2 995**
		Biofuels (solid, liquid, gaseous)	*PJ*	467	803	961
		Geothermal	*PJ*	3	42	171
		Non-renewable DH	*PJ*	2 463	2 108	1 863

EU-28			Unit	2010	Reference Case 2030	REmap 2030
Final energy use - direct uses	Buildings and Industry	**Total direct uses of energy**	**PJ**	**21 300**	**17 570**	**15 823**
		Direct uses of renewable energy	PJ	2 886	4 163	5 003
		Solar thermal - Buildings	PJ	59	270	571
		Solar thermal - Industry	PJ	0	0	120
		Geothermal - Buildings	PJ	27	125	156
		Geothermal - Industry	PJ	0	2	12
		Bioenergy - Buildings	PJ	1 835	2 083	2 202
		Bioenergy - Industry	PJ	966	1 684	1 942
		Non-renewable - Buildings	PJ	11 094	6 946	5 094
		Non-renewable - Industry	PJ	7 320	6 460	5 727
	Transport	**Total fuel consumption**	**PJ**	**14 234**	**13 240**	**12 653**
		Liquid biofuels	PJ	550	1 052	1 822
		Ethanol - conventional	PJ	118	261	365
		Ethanol - advanced	PJ	0	112	429
		Biodiesel - conventional and advanced	PJ	432	664	962
		Biokerosene	PJ	0	14	66
		Other (biogas, methanol, hydrogen)	PJ	0	41	56
		Non-renewable fuels	PJ	13 684	12 147	10 774
Total final energy consumption (electricity, DH, direct uses)			**PJ**	**47 829**	**43 667**	**42 106**
RE shares	RE share in electricity generation			20%	41%	50%
	RE share in district heat generation			16%	29%	38%
	RE share in Buildings - direct uses			15%	26%	37%
	RE share in Buildings - incl. RE electricity and DH			17%	32%	42%
	RE share in Industry - final energy use, direct uses			13%	22%	28%
	RE share in Industry - incl. RE electricity and DH			15%	28%	36%
	RE share in Transport fuels			4%	8%	15%
	RE share in Transport fuels incl. RE electricity			4%	9%	17%
	Share of RE in TFEC			10%	17%	24%
	Share of RE in GFEC			13%	24%	33%
Other	Net incremental system costs [USD bln/yr in 2030]			N/A	N/A	-25
	Avoided CO_2 emissions [Mt CO2/yr]			N/A	N/A	412

European Commission

IRENA
International Renewable Energy Agency