A Global Renewable Energy Roadmap: Comparing Energy Systems Models with IRENA's REmap 2030 Project

Ruud Kempener, Edi Assoumou, Alessandro Chiodi, Umberto Ciorba, Maria Gaeta, Dolf Gielen, Hiroshi Hamasaki, Amit Kanudia, Tom Kober, Maryse Labriet, Nadia Maïzi, Brian Ó Gallachóir, Deger Saygin, Júlia Seixas, Nicholas Wagner and Evelyn Wright

Abstract In 2014, the International Renewable Energy Agency (IRENA) published a global renewable energy roadmap—called REmap 2030—to double the share of renewables in the global energy mix by 2030 compared to 2010 (IRENA, A Renewable Energy Roadmap, 2014a). A REmap tool was developed to facilitate a transparent and open framework to aggregate the national renewable energy plans and/or scenarios of 26 countries. Unlike the energy systems models by IEA-ETSAP teams, however, the REmap tool does not account for trade-offs between renewable

R. Kempener (✉) · D. Gielen · D. Saygin · N. Wagner
International Renewable Energy Agency, IRENA Innovation and Technology Centre, Bonn, Germany
e-mail: rkempener@irena.org

D. Gielen
e-mail: dgielen@irena.org

D. Saygin
e-mail: dsaygin@irena.org

N. Wagner
e-mail: nwagner@irena.org

E. Assoumou · N. Maïzi
Centre for Applied Mathematics, MINES ParisTech, PSL Research University, Paris, France
e-mail: edi.assoumou@mines-paristech.fr

N. Maïzi
e-mail: nadia.maizi@mines-paristech.fr

A. Chiodi · B. Ó Gallachóir
Energy Policy and Modelling Group, Environmental Research Institute, University College Cork, Cork, Ireland
e-mail: a.chiodi@ucc.ie

B. Ó Gallachóir
e-mail: b.ogallachoir@ucc.ie

G. Giannakidis et al. (eds.), *Informing Energy and Climate Policies Using Energy Systems Models*, Lecture Notes in Energy 30,
DOI 10.1007/978-3-319-16540-0_3

energy and energy efficiency activities, system planning issues like path dependency and investments in the grid infrastructure, competition for scarce resources—e.g. biomass—in the commodity prices, or dynamic cost developments as technologies get deployed over time. This chapter compares the REmap tool with the IEA-ETSAP models at two levels: the results and the insights. Based on the results comparison, it can be concluded that the REmap tool can be used as a way to explicitly engage national experts, to scope renewable energy options, and to compare results across countries. However, the ETSAP models provide detailed insights into the infrastructure requirements, competition between technologies and resources, and the role of energy efficiency needed for planning purposes. These insights are particularly relevant for countries with infrastructure constraints and/or ambitious renewable energy targets. As more and more countries are turning to renewables to secure their energy future, the REmap tool and the ETSAP models have complementary roles to play in engaging policy makers and national energy planners to advance renewables.

U. Ciorba · M. Gaeta
ENEA—Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Central Unit Studies and Scenarios, Rome, Italy
e-mail: umberto.ciorba@enea.it

M. Gaeta
e-mail: maria.gaeta@enea.it

H. Hamasaki
Japan and Centre for International Public Policy Studies, Fujitsu Research Institute, Tokyo, Japan
e-mail: hiroshi.hamasak@jp.fujitsu.com

A. Kanudia
KanORS-EMR, Noida, India
e-mail: amit@KanORS.com

T. Kober
Policy Studies Department, Energy research Centre of the Netherlands (ECN), Petten, The Netherlands
e-mail: kober@ecn.nl

M. Labriet
Eneris Environment Energy Consultants, Madrid, Spain
e-mail: maryse.labriet@enerisconsultants.com

J. Seixas
CENSE, Departamento de Ciências e Engenharia do Ambiente, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Lisbon, Portugal
e-mail: mjs@fct.unl.pt

E. Wright
Sustainable Energy Economics, Rosendale, NY, USA
e-mail: evelyn.l.wright@gmail.com

1 Introduction

In 2012, the UN Secretary General initiated the Sustainable Energy for All (SE4ALL) initiative with a political call to double of the share of renewable energy in the global energy mix by 2030 compared to 2010. The International Renewable Energy Agency (IRENA) joined the SE4ALL initiative as the hub for renewable energy in the same year. With the United Nations General Assembly declaring 2014–2024 the decade of Sustainable Energy for All, the SE4ALL initiative is now formalized and supported by a global facilitation team.

As an intergovernmental organisation, IRENA was asked by its Members to explore potential pathways to achieve this aspirational target of doubling the share of renewable energy in the global energy mix. This request resulted in the development of a global renewable energy roadmap—REmap 2030—launched in January 2014 (IRENA 2014a).

The main challenge in developing a global roadmap is that the starting point and the potentials to accelerate the deployment of renewables are different per country and per region. For example, the USA and Tonga are two of the REmap countries, but their energy systems are very different from each other. Furthermore, the level of expertise and studies available to explore renewable energy options differs substantially among the IRENA Member countries. Third, the methods used to define renewable energy, renewable energy targets and renewable energy plans differ across countries.

To ensure an accurate representation of country-specific challenges, IRENA developed an analytical framework based on a bottom-up analysis of renewable energy potential in individual country members. In each country, existing renewable energy plans and additional renewable energy options in the 2010–2030 timeframe are identified, and then aggregated at a global level. The 26 countries selected account for around 75 % of global energy consumption, and are representative of different continents.

The tool developed to support this exercise is a relative simple accounting framework. The tool allows national experts to identify additional renewable energy options on top of existing renewable energy expansion plans up to 2030. The advantage of this tool is that it can be applied to all countries and that it provides a transparent way to communicate results with the national experts. However, it does not take into consideration any system constraints, path dependencies or competition for resources that affect both the potential and costs of additional renewable energy (RE) deployment.

There are, however, other tools available to provide a far more detailed analysis of the evolution of energy systems. Among the most widely applied tools are those developed by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agency of the International Energy Agency (IEA). Established in 1976, the programme functions as a consortium of member country teams, mainly using MARKAL and TIMES models to compile long-term energy scenarios. These ETSAP models are bottom-up system engineering tools using least-cost optimisation to satisfy certain system constraints and/or policy objectives. The models can investigate scenarios for the evolution of the energy system, and can also be used to explore which pathway of renewable energy technologies achieves a national renewable energy target with the lowest overall system costs. 20 out of the 26 countries analysed under REmap actually have institutions within their country that are using ETSAP tools.

The ETSAP models are technically far more sophisticated than the REmap tool, but there are a number of specific commonalities and differences between the REmap tool and the ETSAP models that make this comparison of interest. First, both methods are based on technology-specific data, but the REmap tool is limited to energy-supply technologies and electricity-consuming heat and transportation options in the end-use sectors. In contrast, the MARKAL and TIMES models also include the whole range of energy-consuming technologies as well as energy system technologies, like transmission and distribution lines, storage options, etc. Furthermore, in TIMES models, technology deployment in one sector (and region in the case of mult-regional models) will have impacts on deployment levels in the other sectors, while in the REmap tool deployment options are chosen independently. Second, the REmap tool only examines three time instances: 2010, 2020 and 2030. The ETSAP models create time series and the TIMES models even allow for user-defined and flexible length time periods. Third, the TIMES models allow the user to model the construction phase and dismantling of facilities that have reached their end of life internally. The REmap tool assumes that considerations of life time and construction lead times are conducted prior to the selection of additional renewable energy options. Fourth, the ETSAP models allow for multiple regions to be coupled to construct geographically integrated instances, whilst the REmap tool can only be applied to individual countries. Fifth, in the REmap tool energy demand and commodity prices are set exogenously, whilst ETSAP models may include elastic energy demand in the end-use sectors as well as endogenous price setting of commodity prices and energy costs.

The aim of this study is twofold. The first aim is to understand whether the simplified REmap tool creates comparable results with the more sophisticated ETSAP models. The second aim is to understand the appropriateness and complementarity of the usage of both the REmap tool and ETSAP models.

2 Methodology

This methodology section discusses the REmap tool as well as the methodology used to compare the results of ETSAP models with the REmap results.

2.1 REmap Methodology

REmap is based on a bottom-up analysis of existing renewable energy plans and additional renewable energy options between 2010 and 2030 in 26 countries located

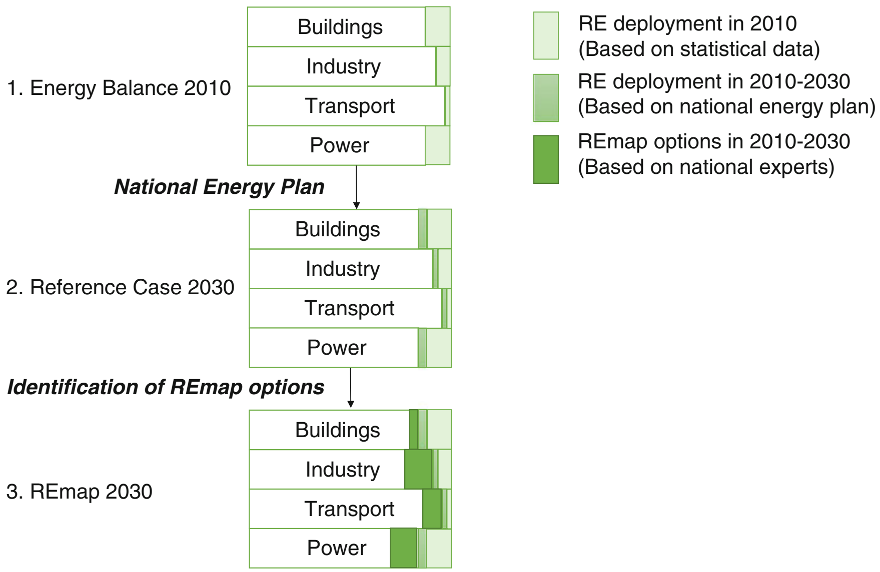

Fig. 1 The analytical steps to develop the REmap analysis

on five different continents (Saygin et al. 2015). For each country analysis, IRENA works together with a REmap expert nominated by the country. Figure 1 shows the three steps in the REmap process. First, data on the national energy balance in 2010 is collected by IRENA and verified by the country expert. Second, the REmap expert provides information on existing renewable energy plans between 2010 and 2030. Based on this information, a national energy balance for 2030 is derived. This is called the **Reference Case**. If no national energy plans are available, IRENA works with national REmap experts to make a business-as-usual projection based on data collected from literature and other sources. Third, together with the national REmap experts and based on existing reports and studies, additional renewable energy options are identified. These are called the **REmap Options**. The technical feasibility of each additional REmap Option is assessed based on resource availability, constraints in the local supply chain, and policies in place promoting or inhibiting further growth of renewables.

At each step, the renewable energy share for both the national energy system and the different subsectors of buildings, industry, power and transport is calculated. The renewable energy share is measured as a percentage of total final energy consumption (TFEC) within a given country or region or sector.[1] Within TFEC—in particular in

[1] The approach is in line with the Global Tracking Framework (GTF) of the SE4ALL initiative, but differs from the EU Directive on Renewable Energy (Article 5, 2009/28/EC) which calculates the RE share based on **gross** final consumption, which includes any RE based electricity and/or heat transmission and distribution losses, including in-house load in power plants.

the IEA statistics used as the basis for the national energy balances—heat and electricity are reported directly in the form ready for consumption although other primary energy sources (for example, fossil fuels and bioenergy used for heating in the residential sector) are still reported in terms of their fuel content. Furthermore:

- Electricity consumption for aerothermal, geothermal and hydrothermal heat pumps is included in TFEC, but the approach excludes the heat energy captured by these pumps.
- RE that is exported is not included within the RE share.
- TFEC excludes non-energy uses of energy sources such as their use as raw material for the production of plastics and chemicals.
- TFEC is computed according to the aggregation used by the IEA statistics.

The identification of additional renewable energy options is the most important step of the process. For each additional renewable energy option, the REmap expert has to determine what conventional energy technology option will be replaced. For example, additional wind power generation capacity will result in less coal, gas, or nuclear power generation capacity (or a combination) built in the period between 2010 and 2030. For each replacement, the tool calculates the so-called 'substitution costs', which is based on the difference in costs of the conventional energy technology—assumed to be in place in 2030—and the renewable energy option that has replaced the conventional energy technology.

Based on this approach, each country analysis results in the creation of a cost supply curve (Fig. 2). The x-axis represents the share of RE in final energy consumption in 2030. The y-axis represents the cost difference per unit of energy consumed [in real 2010 US Dollars per gigajoule (USD_{2010}/GJ)] between renewable and conventional energy technologies. This so-called "annualized incremental cost of substitution"[2] is calculated for each RE technology based on the costs to substitute one unit of final energy generated by non-RE technologies with the costs of one unit of final energy generated by the RE technology. The costs are based on national projections for the capital and operational and maintenance (O&M) costs, and the technical performance of conventional and RE technologies.

To allow for comparison and aggregation of results across multiple countries, standardized energy commodity prices for oil, gas and coal (without any subsidies, taxes, or levies),[3] a standardized cost calculation for electricity prices (based on the maximum RE penetration in 2030), and a fixed 10 % discount rate based on IRENA's costing studies (IRENA 2013) are used to calculate the annualized costs of both RE and conventional technologies. The fixed discount rate (for all countries and technologies) is chosen to allow for comparable results, whereby 10 % is

[2] Referred as "substitution cost" throughout this report.

[3] For coal, natural gas, biomass and electricity, exceptions were made as it is not possible to assign global values that are representative for all countries. Coal and natural gas prices are distinguished between exporting and importing countries. Biomass prices are determined at a regional level with a breakdown by energy crops, residues and waste. Electricity prices are determined for each country.

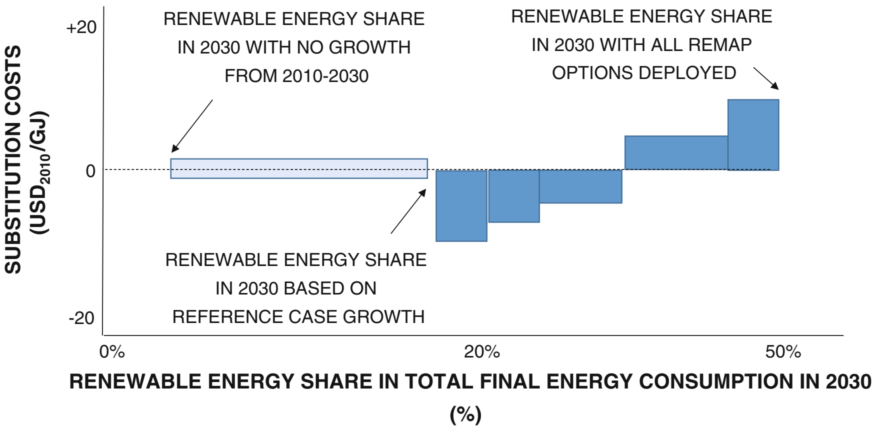

Fig. 2 The REmap cost supply curve

chosen as a middle ground between the costs of capital for energy projects in developing countries (indicative range of 15–20 %) and OECD countries (indicative range of 6–12 %). The costs are expressed in USD_{2010}/GJ.

In the electricity and heat sector, one unit of final energy generated by an RE technology substitutes the same amount of energy produced by a non-RE technology. In other words, one MWh of coal-based electricity production would be replaced by one megawatt-hour (MWh) of solar-based electricity production. For the end-use sectors, one unit of final energy used by an RE technology substitutes the units of final energy which would have been otherwise used by a non-RE technology to deliver the same amount of useful energy. Electricity consumption of heat pumps to generate heat (e.g. for space heating) from various sources including air, geothermal, hydrothermal, is included in the TFEC of the respective end-use sectors (e.g. residential sector). However, heat consumed by the end-use sectors is not reported separately in the TFEC. Substitution costs of heat pumps are expressed in USD per GJ of heat produced. To estimate heat production, the co-efficient of performance (COP) is used. The costs are calculated as follows:

Substitution cost of an RE technology for the energy transformation sector is estimated as "*(annualized costs of RE technology to generate 1 petajoule (PJ) of electricity or heat—annualized costs of non-RE technology to generate 1 PJ of electricity or heat)/total RE electricity or heat generated*".

Substitution cost of an RE technology for the end-use sectors is estimated as "*(annualized costs of RE technology to generate 1 PJ of useful energy—annualized costs of non-RE technology to generate 1 PJ of useful energy) /total RE final energy used to generate 1 PJ of useful energy*".

The cost supply curve contains two separate sets of data (Fig. 2). The first part of the curve represents the increase in the renewable energy share between 2010 and 2030 based on the Reference Case. Since the existing national energy plans are assumed to be the baseline, no costs are associated with the renewable energy expansion in the Reference Case. The second part of the curve shows the REmap Options. The width of each REmap Option is determined by the absolute amount of renewable energy consumption entering the system, and is represented on the x-axis as an increase in the renewable energy share in 2030. For each REmap options, the substitution costs are determined by the conventional energy option being replaced.

2.2 Comparing REmap and ETSAP Modelling Results

For the comparison of the results, IRENA provided the ETSAP modellers with the following data:

- Data sources for Reference Case and REmap Options;
- Total energy consumption and RE deployment in the Reference Case per sector, expressed in PJ or GWh;
- The assumed commodity prices and discount factors for 2030. These assumptions impact the cost calculations;
- List of REmap Options, expressed in PJ and with associated substitution costs;
- RE shares in the end-use sectors in 2030 in the Reference Case as well as after the REmap Options.

Based on this information, the ETSAP modellers performed clusters of multiple model runs for the year 2030 for the specific purpose of this chapter. The first model run targets the RE share in 2030 as suggested by the Reference Case. Each subsequent model run increases the RE share by a certain percentage up to the RE share achieved by the REmap Options. The RE share are only applied at a national level, and not to individual subsectors.

The approach is illustrated with the Irish TIMES model (Ó Gallachóir et al. 2012). The x-axis shows the total share of RE in TFEC by 2030, while the y-axis shows the system cost difference of each REmap scenario from the *Reference Case*. For each target scenario pathway, a scenario file has been created (e.g. in the case of Ireland, as shown in Fig. 3 we have the *Reference Case* with 16 % by 2020, and 16 % by 2030; the *REmap-18* case with 16 % by 2020, 18 % by 2030, etc.). The supply curve was built comparing differences in total system costs between scenario runs. The costs of additional RE options are only positive (incremental), because, unlike in the REmap analysis, the negative costs (savings) are already embedded in the *Reference Case* (objective minimization of total system cost).

Given the nature of MARKAL-TIMES models (vertical and horizontal competition), multiple substitution technologies and/or efficiency measures are selected as the model optimizes for an increasing share of renewables in the system. The contributions of individual renewable energy technologies (and the conventional technologies that have been substituted) are identified afterwards from results analysis, as shown in Fig. 3.

Furthermore, each scenario is run individually, which means that the system changes (i.e. electrification of the transport sector) under a 16 % scenario target

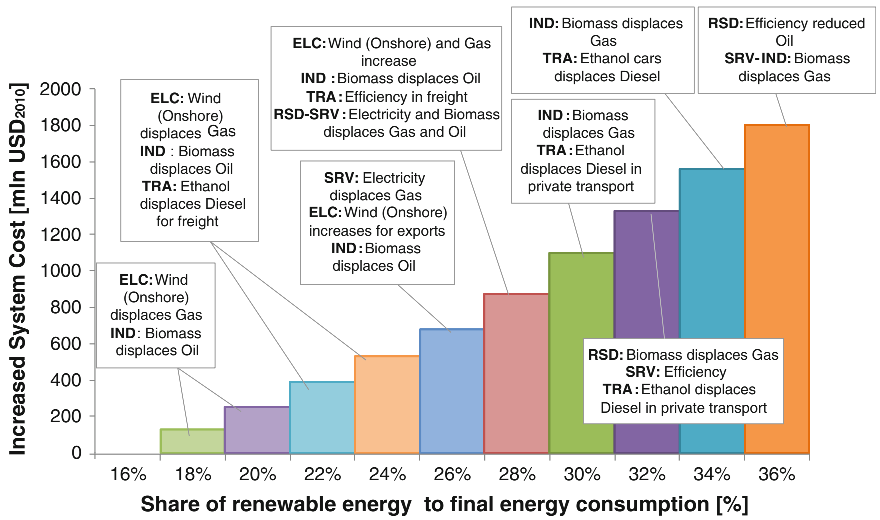

Fig. 3 Illustrative cost supply curve for Ireland. Information on the x-axis and y-axis show the share of RE in TFFC and the increased system costs, respectively

might not apply to the 18 % scenario target. Furthermore, some system changes might be reversed at a later stage. Any discontinuities are highlighted in the results analysis.

Implementation of REmap scenarios in the Irish TIMES model

The implementation in single MARKAL-TIMES models strongly depends on the model structure. In Irish TIMES the cost supply curve has been built performing a cluster of 11 model runs with the Reference Case as a starting point, in which Ireland's energy system must deliver at least 16 % renewable energy penetration by 2020 (the EU RE Directive target for Ireland for the year 2020), and is then assumed to maintain this share in the period 2020–2030. Each individual *REmap* scenario run then increases the RE share by 2 percentage points resulting in a final scenario of 36 % RE share by 2030 (Fig. 3).

Furthermore, the amount of RE consumed (measured as a share of total final energy consumption, or TFEC) was simply evaluated as the sum of green certificates produced by renewable technologies in the electricity generation sector and the end use sectors. In Irish TIMES green certificates are automatically generated by the model when renewable fuels are consumed in electricity, heat and transport sectors. The EU Directive sectoral specific target of 10 % renewables in the transport sector (with different weightings for different biofuels) was excluded in the Irish TIMES *REmap scenarios*.

Table 1 Overview of ETSAP models and the assessed range of RE share in TFEC in 2030

Model	Country/Region	RE share in Reference Case (%)	RE share with REmap Options (%)
TIAM-ECN	Global	18	36
TIAM-WORLD	Global	18	37
TIMES-FR	France	27	42
Irish TIMES	Ireland	16	36
TIMES-Italy	Italy	9.5	19
JMRT[a]	Japan	20	44
TIMES-PT	Portugal	33	62
FACETS	USA	8.3	16.7

[a] *Japan Multi-regional Transmission Model* RE shares are for electricity sector only

Table1 provides an overview of the models for which the results were compared with the REmap analysis. The starting point for each model has been the RE share in the Reference Case. For the case of Ireland and Portugal, the Reference Case was based on the EU RE Directive target for 2020 and extended towards 2030. For the case of Italy, the government's new energy strategy (*Strategia Energetica Nazionale*, SEN) was used as the *Reference Case* and the ETSAP model was used to identify and quantify the REmap Options.

In the following two subsections, the results of these comparative analyses are used to explore the aims and main questions outlined at the outset of this chapter:

1. How do the REmap Options identified by national experts compare to the renewable energy deployment identified in ETSAP models (Sect. 3)?
2. How can the different insights derived from the ETSAP models and the REmap tools be used to support policy makers (Sect. 4)?

3 Comparing Results

This section answers the question of whether the results of the simplified REmap tool are in line with the results of the more sophisticated ETSAP models. The results of the REmap tool and the ETSAP models are compared on three levels:

- Deployment of renewable energy technologies (in PJ or GWh) in 2030 (Sect. 3.1);
- The sequence with which renewable energy technologies are deployed to increase the share of RE (Sect. 3.2);
- The additional overall system costs compared to the Reference Case (Sect. 3.3).

3.1 Comparing Results: Deployment Levels in 2030

Table 2 presents some comparative deployment numbers in the ETSAP models and REmap results for France, Japan and the world (Ireland and Portugal were not part of the initial set of 26 REmap countries).

These results show that considering the differences in the overall RE share in 2030 (ranging between 0 and 5 %) in each country, the deployment levels of individual renewable energy technologies between the ETSAP models and the REmap results are comparable. In the case of France and Japan, the national REmap experts have assumed higher deployment levels of hydropower but lower levels of solar photovoltaics than the ETSAP models. This might be due to the fact that in the ETSAP models the deployment levels are a function of their techno-economic characteristics in 2030, whilst the deployment levels in the REmap tool is a deliberate choice of the national experts. For technologies like solar photovoltaics that are currently at a relative low deployment level, it might be difficult for these national experts to envision their rapid growth of deployment. Similarly, the biggest difference can be found in solar photovoltaics deployment at a global level, but this might also be explained by the fact that the TIAM-WORLD model targets 37 % RE share, whilst the REmap analysis only achieves 28 %.

3.2 Comparing Results: Substitution Choices

The comparison of absolute deployment levels in Sect. 3.1 provides a static picture of the deployment levels in 2030. The REmap model, through its cost supply curve, and the ETSAP models also allow for a comparison of the relative costs of different RE options. In the case of the REmap cost supply curve, individual RE options

Table 2 Comparison of deployment levels of renewable power generation in ETSAP models and the REmap tools in 2030

	TFEC (EJ)	RE share (%)	Hydro (TWh)	Wind (TWh)	Solar PV (TWh)
TIMES-FR	5.1	42	67	89	33
REmap France	5	40	83	89	30
TIMES-IT[a]	115.8	40	48	29.3	28.7
REmap Italy[a]	115	40	50	29.4	29
JMRT[b]	4	43.7	93	188	146
REmap Japan[b]	4	40	127	113	121
FACETS	68	16.7	251	650	361
REmap USA	66	27	430	994	235
TIAM-WORLD	491	37	5673	4043	3150
REmap World	448	28	5907	5279	1807

[a] TIMES-IT was used to populate the REmap tool for Italy

[b] Power sector only

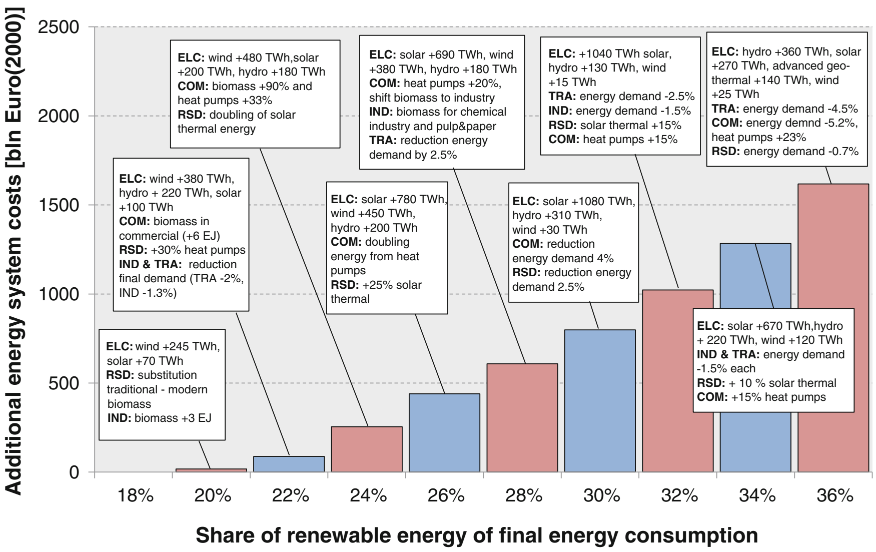

Fig. 4 Global marginal cost curve for the renewable energy share of gross final energy consumption in 2030 based on TIAM-ECN. *N.B.* (1) additional system costs refer to the Reference Case with a renewable energy share in 2030 at today's level of 18 %. (2) Descriptions in the boxes refer to effects of the incremental increase. (3) Abbreviations for sectors *ELC* elcectricity, *IND* industry, *COM* commercial and agriculture, *RSD* residential, *TRA* transport

contributing to the RE share in 2030 are displayed in order of increasing costs. The ETSAP models, by virtue of their economic cost optimization, choose the most economic options contributing to an increasing RE share. This means that the REmap Options on the left side of the curve (the cheaper options) would also be the first options that would be chosen by the ETSAP models to increase the RE share. A key difference between the REmap tool and the ETSAP models is that the latter also may choose energy efficiency options or structural changes to the energy system to increase the RE share.

Figures 4 and 5 show the sequences of RE options identified by the TIAM-World and TIAM-ECN models as the RE share increases from 18 to 36 %. These results can be compared to the global REmap cost supply curve.

The TIAM-ECN [for model description see Rösler et al. (2011), Keppo and van der Zwaan (2012), Kober (2014)] model shows that early opportunities to increase the RE share arise from the shift of biomass from traditional use to modern biomass use in the residential sector, but also an increased biomass use in the commercial sector and in industry.[4] Additional least cost opportunities to accelerate RE growth in the residential and commercial sectors include heat pumps and solar thermal appliances for room

[4] Traditional uses of biomass is not included in the renewable energy share, hence a shift to modern uses of biomass increases the share of RE.

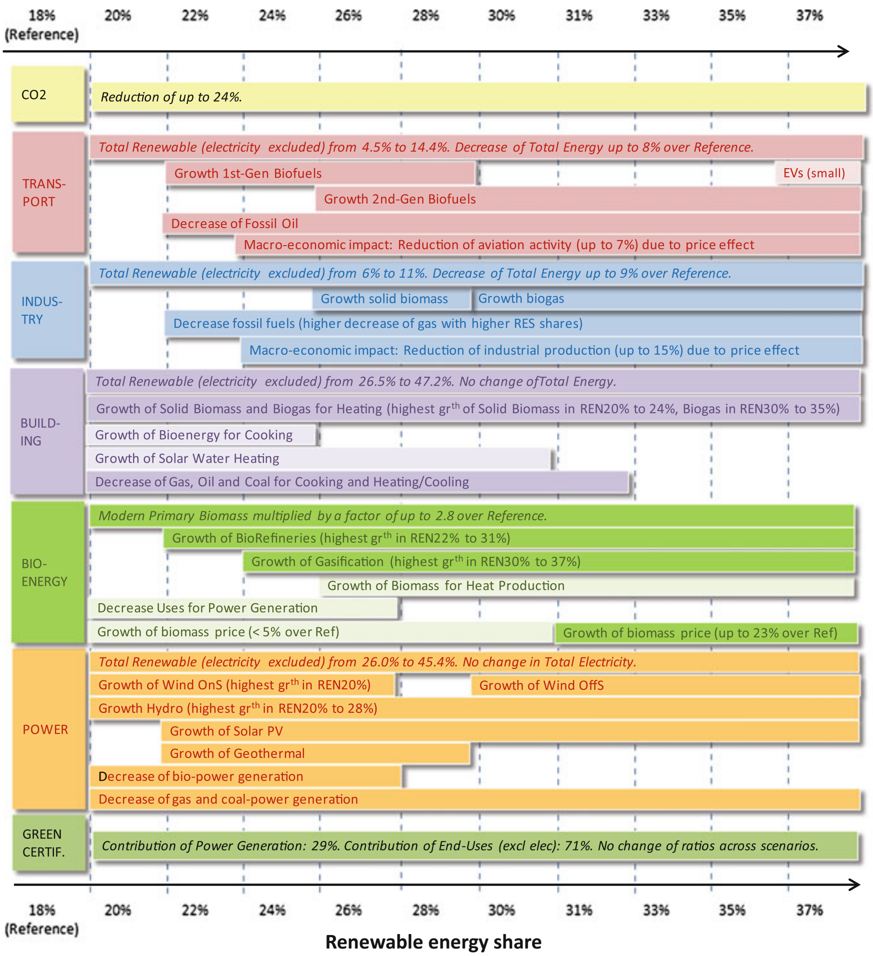

Fig. 5 Technology options with increasing RE share in the TIAM-WORLD model

heat and warm water production. For electricity generation from RE, wind offshore technology represents the least cost option, and contributes with additional 1000 TWh to increase the RE share of gross final energy consumption from 18 to 26 %.

The more costly options for increasing the RE share, which are deployed at shares higher than 26 %, include measures and technologies to diminish the total final energy demand, such as more efficient engines for road transport, and also more expensive options for the production of RE-based electricity. For RE-targets above 28 %, electricity generation from wind (onshore and offshore) is almost fully deployed (in total about 1300 GW), and additional capacity from RE technology is commissioned based on solar (mainly CSP and PV at sites with lower full load hours), small hydro power plants and advanced geothermal power plants.

At high levels of RE shares, strong reductions in energy demand use (−4.5 % in the transport sector, −5 % in the commercial and agricultural sectors) are the most cost-effective options to increase the RE share. In the TIAM-ECN model, most of the reductions in energy demand in the transport sector are realised through improvements of energy efficiency, such as more efficient engines, low resistant tires and improved aerodynamics for cars. In the commercial sector, energy savings are achieved through energy efficiency. The introduction of renewable energy targets failed to provide sufficient incentive for more substantial technology switches, such as electric cars, hydrogen vehicles or fuel cell technology in the commercial sector.

In the TIAM-WORLD model [see recent applications in Kanudia et al. (2014); Labriet et al. (2012)], bioenergy also plays a crucial role in increasing the RE share, especially in the end-use sectors. More specifically, biomass-based power generation decreases up to 26 % whilst modern biomass and biofuels increase. At higher RE shares (>30 %), biogas use in industry and for heating purposes in the building sector increase strongly (Fig. 5).

In the power sector, hydropower and onshore wind exhibit the highest growth levels at low RE shares. At higher RE shares, offshore wind and solar photovoltaics are used to increase the RE share. Similar to the TIAM-ECN model, solar water heating is one of the early technologies that is used to increase the RE share. Battery electric vehicle are only deployed at RE shares above 35 %.

In comparison, Fig. 6 shows the technology options of the REmap global cost supply curve. The brackets above each option indicate the number of countries in which the RE options is deployed. Similar to the ETSAP models, biomass options

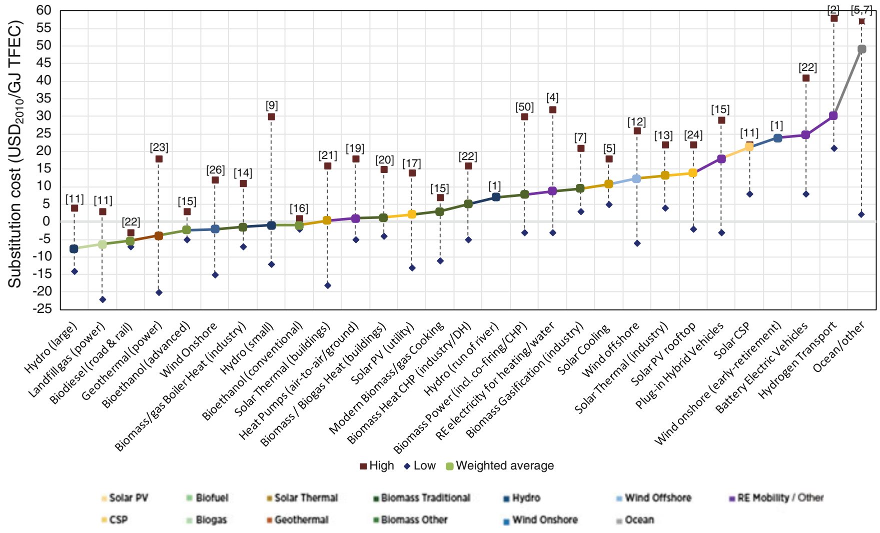

Fig. 6 Ranges of substitution costs of REmap Options in the 26 REmap countries based on the perspective of governments in 2030

are among the least-cost options to increase the RE share of modern energy use, except for biomass gasification. Solar thermal and heat pumps are cost-effective options in the buildings sector. In the power sector, hydro, wind and geothermal are the least cost options followed by solar photovoltaics. The more expensive options are solar photovoltaics on rooftops, solar concentrated solar power, and the upgrading/repowering of existing wind parks [indicated as "wind onshore (early retirement)"]. Similar to the TIAM-WORLD model, battery electric vehicles are one of the most expensive options to increase the RE share.

A similar analysis is possible at a country level. Figure 7 shows the REmap cost supply curve of the USA (IRENA 2014b). Figure 8 shows the RE options contributing to an increasing RE share in the FACETS model (for model description see Wright and Kanudia (2014) and http://facets-model.com).

The results from the FACETS model and the REmap tool show that the main contributors (wind, solar PV, biomass heat and electricity production, and biofuels) to an increasing renewable energy share are the same, but they differ in terms of the sequence with which they are deployed. These differences are partly due to the different RE targets for 2030. Wind power (nr. 4 in Fig. 7) is one of the cheaper options in the REmap tool, but is only chosen at a later stage in the FACETS model. Similarly, biofuels seem to be a technology option that is relatively cheap in the REmap tool (nr. 7 in Fig. 7), deployed at later stages in the FACETS model.

One explanation for the differences is the explicit choice for substitution technologies that is offered by the REmap tool. In the USA analysis, national REmap analysts determine that the additional renewable power generation would mainly

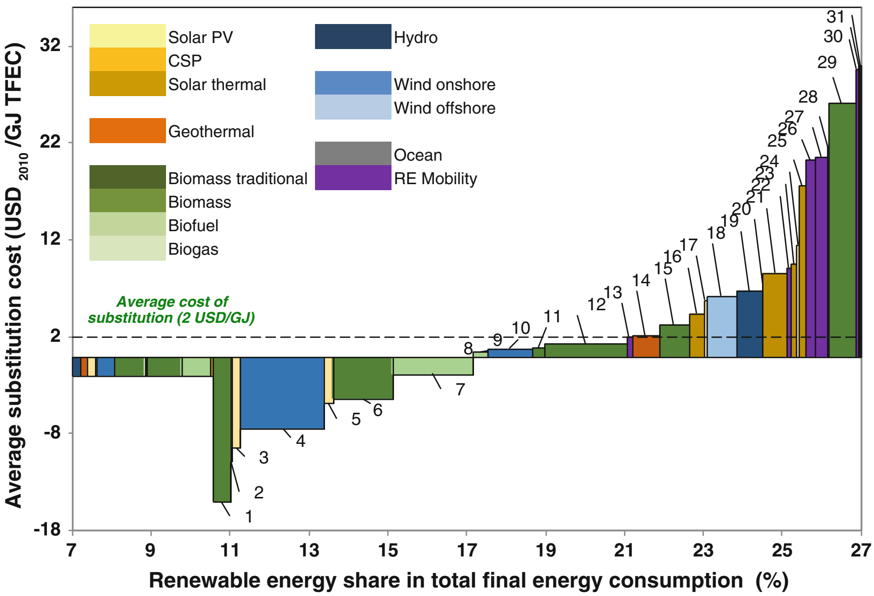

Fig. 7 REmap Options cost supply curve, government perspective, by resource

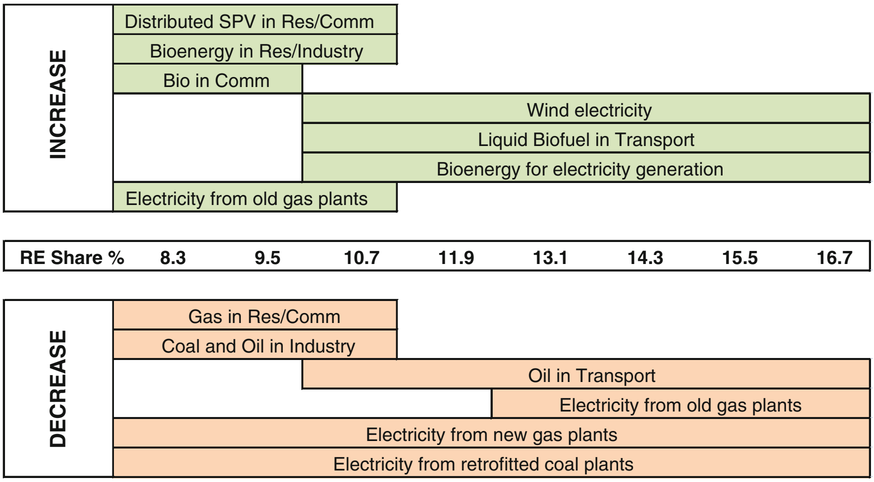

Fig. 8 RE technology options in the FACETS model

replace United States Environmental Protection Agency (EPA) compliant conventional coal (89 %), new nuclear (6 %) and advanced coal carbon capture and storage (CCS) (5 %). In contrast, the FACETS model chooses to rely on electricity production from old inefficient gas plants to support the variable renewable power generation production from distributed solar photovoltaics, and replace both new and old gas plants as the renewable energy share is increased. In the industry sector, the substitution choice is also different with the FACETS model replacing coal and oil, whilst the national experts replaced mainly natural gas usage.

3.3 Comparing Results: System Costs

The third indicator to compare the REmap results with the ETSAP models are the total system costs for a transition towards renewables. This comparison, however, should be made cautiously as:

- The REmap tool only examines the year 2030, and assumes linear deployment rates for RE deployment between 2010 and 2030;
- The REmap tool only examines the substitution costs of the renewable energy technologies, and does not consider the costs of energy efficiency improvements;
- The REmap tool does not consider costs in transmission and distribution networks, or other infrastructural investments, required to support the additional renewable energy deployment (Table 3).

The comparison at a global level shows that the estimated system costs are in the same order of magnitude, although it is clear from the limitations of the REmap tool that ETSAP models are better suited for an assessment of system costs. For the year

Table 3 Comparison of incremental systems costs over the Reference Case for the ETSAP models and the global REmap results

Model	Incremental system costs (USD_{2010})[a] (billion)	Discount rate (%)
Global REmap	1450	10
TIAM-ECN	1980	10
TIAM-WORLD	5582	5
TIMES-FR	58	10
Irish TIMES	1.8	6
TIMES-PT[b]	5.6	10
FACETS	865	5

[a] The costs are converted into USD_{2010} using the official exchange rates and consumer price indexes provided by the World Bank (http://data.worldbank.org/indicator/PA.NUS.FCRF and http://data.worldbank.org/indicator/FP.CPI.TOTL)
[b] For decentralized solar PV on residential rooftops, a discount rate of 17.5 % was used to reflect family decisions

2030, the REmap tool estimates total additional system costs of USD_{2010} 145 billion. An approximate level of additional system costs over the 2010–2030 period would be USD_{2010} 1450 billion assuming linear increasing deployment levels of renewables.[5] In comparison, the total additional energy system costs estimated by the TIAM-ECN model are around USD_{2010} 1980 billion, and for the TIAM-WORLD model USD_{2010} 5580 billion (discount rate of 5 %). The higher system costs observed in TIAM-WORLD are explained by the lower discount rate (system costs obtained with a 10 % discount rate are in the range of USD_{2010} 1340 billion.

The incremental system costs for the national models highly depends on the system size, national cost assumptions, absolute deployment levels as well as the different financial indicators used. More detailed information would be required to make a one by one comparison across the national results.

4 Comparing Insights

The second question is how the different insights derived from the ETSAP models and the REmap tools can be used to support policy makers, and when and where the REmap tool and ETSAP models are appropriate to use. One clear advantage of the ETSAP models is their ability to examine changes at each time step, whilst the REmap tool only provides results for a single year (essentially assuming that all

[5] For a proper comparison, additional assumptions would be required in terms of the energy commodity prices (oil, coal, gas, biomass, electricity, etc.), and capital and operational cost development for both renewable and conventional energy technologies over the 2010–2030 period.

system changes occur instantaneously). However, there are also a number of other features that are included in the ETSAP models but excluded from the REmap tool:

- The inclusion of infrastructural systems to examine the transition towards renewables (Sect. 4.1);
- The dynamic interaction and competition between different renewable energy technologies and resources (Sect. 4.2);
- The inclusion of both energy efficiency and renewable energy options (Sect. 4.3).

Furthermore, we explore the use of ETSAP models as input into the REmap tool.

4.1 Comparing Insights: Infrastructural Features

The REmap tool assumes that any costs associated with infrastructural investments that will take place in the Reference Case will also support the deployment of renewable energy options. In the ETSAP models, these infrastructural requirements can be explicitly modelled and taken into consideration. The results of the JMRT model show this most clearly (Hamasaki and Kanudia 2013). The model comprises 10 grids with weak inter-grid connections, using geographically specific resource data and GIS data to calculate distances to and from roads and grids, as well as seabed depth. In Japan, the greatest potential for onshore wind lies in the Northern regions, while the Southern region has great demand but limited potential, resulting in geographical supply-demand mismatch. Given the current state of Japan's power grids, the full potential of onshore wind in the north cannot be tapped without new interconnecting facilities.

Grid expansion changes the portfolio of renewable energy technologies selected under a 44 % renewable energy target. Onshore wind deployment levels increase and geothermal and offshore wind decrease (±10 % on deployment levels). The model also shows that despite the increased costs for the interconnecting facilities, the overall system costs will be marginally lower with grid expansion.

The impacts of infrastructure on the deployment levels of renewable energy technologies is an important insight for policy makers, especially since in the case of Japan they substantially alter perspectives for onshore versus offshore wind deployment. However, the JMRT model also shows that substantial model enhancements are needed to address these issues, including the introduction of subregions, increased data requirements and higher computing power.

In general, it seems that the inclusion of infrastructural constraints increases the insights provided by the ETSAP models, but the demand for model development and data requirements are also substantially higher than the REmap tools. As the renewable energy shares, especially those of wind power and solar photovoltaics, increase, the insights from the ETSAP models on infrastructural requirements and investments will become more important for policy makers.

4.2 *Comparing Insights: Competition of Technologies and Resources*

The REmap tool allows the national policy makers to identify additional individual renewable energy options to be deployed above and beyond the Reference Case. The deployment levels for these additional RE options should be based on an assessment of the available resources, energy demand, supply chain constraints and political barriers for each of the individual RE options. However, the REmap tool does not force the analyst to consider competition between different REmap Options, except for the fact the overall deployment levels are limited to the energy demand within a given sector.

In the ETSAP models, there is endogenous competition between the different RE technologies to satisfy the RE share that is set for the year 2030 most cost effectively. Figure 9 shows this competition for the case of TIMES-FR (Assoumou and Maïzi 2011). The results show the difference in deployment levels between the *Reference Case* to achieve a 27 % RE share, and higher RE shares. The results show increasing levels of solar heating deployed to satisfy the increasing shares of RE. However, beyond 36 % it becomes more cost-effective to deploy solar photovoltaics systems rather than solar water heaters. Due to space limitations associated with rooftops, this leads to a decrease in the deployment of solar water heaters. Similarly, the results show that to achieve higher shares of RE the deployment levels of biofuels in the transport sector drop in favour of biomass usage for heat and power. Furthermore, additional biogas production based on energy crops is used to increase biomass usage at higher renewable energy shares.

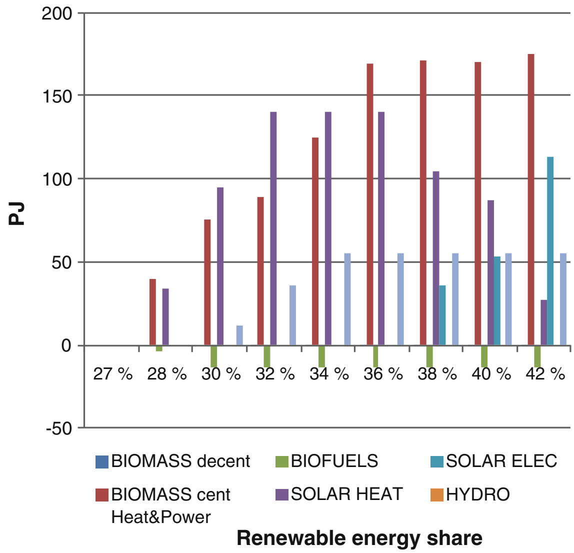

Fig. 9 Increase of renewables per source (vs. 27 % case) in TIMES-FR

Similar dynamics can be observed in the Irish TIMES model (Fig. 3). In that particular case, the deployment levels of biomass in the commercial sector decreases in favour of increased levels of biofuel usage in the transport sector as the renewable energy share increases from 30 to 32 %.

The competition between renewable energy resources and technologies is an important insight that can be gained from the ETSAP models, and that can inform the deployment levels of renewable energy technologies considered in the REmap tool. These insights seem to be particularly relevant for biomass, which is a renewable energy technology that can be used in the power sector as well as all of the end-use sectors. Consequently, countries that have high levels of biomass use should complement any REmap analysis with more detailed ETSAP models to understand how competition between the different end-use sectors may affect both the prices of biomass commodities as well as the deployment levels.

4.3 Comparing Insights: Energy Efficiency and Rational Use of Energy

Energy efficiency can substantially contribute to higher shares of renewables by reducing overall energy consumption. The REmap tool only considers energy efficiency measures that have been considered in the Reference Case, and as such determine the national energy balance in 2030. In contrast, the ETSAP models explicitly consider additional energy efficiency measures to increase the share of renewables.

All of the ETSAP models show that energy efficiency measures and the reduction of energy service demand are very important tools to increase the RE share, especially when RE shares are reaching levels above 30 %. Figure 10 shows such results at a national level for the TIMES-PT model created for Portugal (Simoes et al. 2008), whilst Fig. 11 shows the impact of energy efficiency options at a global level.

The results derived from a national model with elastic demand show that the total system costs decrease with an increasing share of renewables from 40 to 41 %. This is due to a reduction of energy service demand with impact in the total system costs. For other RE targets, this impact is not visible since other costs like investment costs are high enough to hide the effect of the reduction of services demand.

In Fig. 11, the contribution of renewable energy and energy efficiency options in each step increase of the RE share is examined. From 26 to 34 %, the share of RE increases primarily due to an increase in consumption of electricity and district heat generated from RE, which replace non-RE electricity. In this range of RE targets, we see a change in the generation mix on the supply side rather than substantial changes on the consumption side, including relatively small changes in the total final energy consumption. As a consequence, increasing RE supply outweighs demand-reduction-effects. With respect to the drivers for demand reductions, the model approach does not allow for a strict distinction between technology-related energy efficiency improvements, energy saving measures and demand reductions due to changes in the

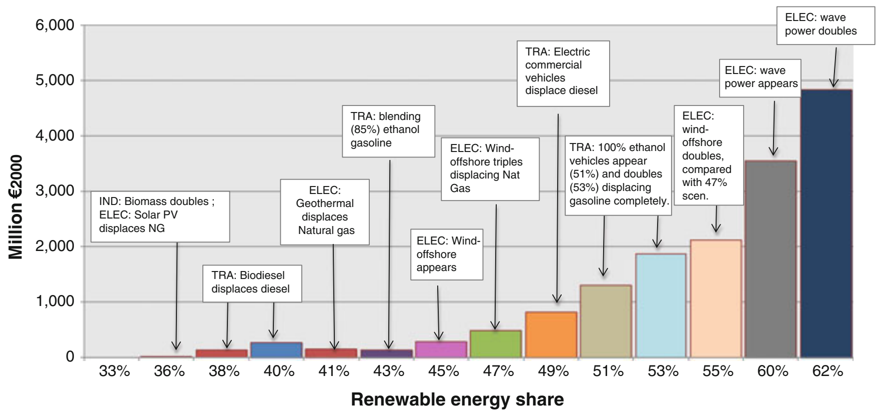

Fig. 10 National cost supply curve for Portugal from the TIMES-PT model

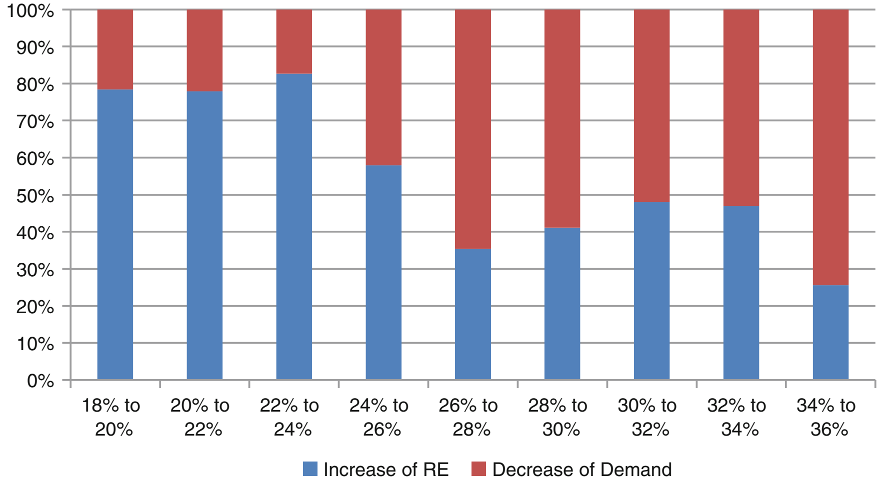

Fig. 11 Decomposition of RE and demand (TFEC) effects for each step to increase the RE share in the TIAM-ECN model

demand pattern. However, in general two thirds can be allocated to reductions in energy services demand, which also include energy saving measures, and one third to technology-based energy efficiency uptake.

In conclusion, the REmap tool seems to be sufficient to examine and explore deployment levels of renewable energy options up to around 30 % of TFEC. However, as countries are moving towards higher shares of renewables they simultaneously need to consider additional energy efficiency options available to decrease overall energy consumption and therefore increase the renewable energy share.

4.4 Comparing Insights: ETSAP Models as Input into the REmap Tool

An alternative way to use the ETSAP models is to populate the REmap tool. For the case of Italy, the TIMES-Italy model (Gaeta and Baldissara 2011) was used to estimate the substitution costs for individual renewable energy technologies (in EURO/GJ) by running multiple scenarios towards a set RE share in 2030, and removing or decreasing constraints on a specific RE technology group one at a time. For each scenario, the incremental system costs were computed, and attributed to the RE technology group. Figure 12 shows the results of this analysis.

These results show that the substitution costs per renewable energy option are comparable to the substitution costs identified in other REmap countries and at a global level. For example, Fig. 12 shows that the range of substitution costs between −10 and +50 USD/GJ in the case of Italy falls within the range of substitution costs from −20 to +60 USD/GJ identified in the REmap tool (Fig. 6). The renewables share at the x-axis does not include traditional biomass, as in the IRENA methodology.

In the case of Italy, where the ETSAP model is used to develop national renewable energy plans, it made sense to use the ETSAP results to populate the REmap tool. Subsequently, this allowed an aggregation of Italy at a global level. However, many of the more detailed insights of the ETSAP models are lost and substantial efforts are needed to run the multiple scenarios. Therefore, the use of ETSAP models to populate the REmap tool only makes sense if countries' national

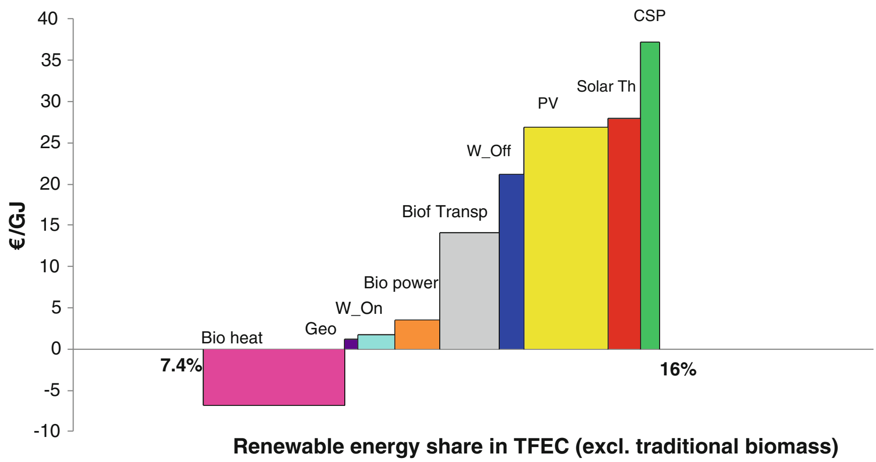

Fig. 12 Substitution costs of REmap Options by TIMES-Italy

renewable energy plans are based on ETSAP models and these plans need to be simplified to compare and aggregate at a global level.

5 Conclusions

In this chapter, we have examined a number of indicators to determine whether the simplified REmap tool creates comparable results with the more sophisticated ETSAP models, and to understand the appropriateness and complementarity of the usage of both the REmap tool and ETSAP models.

For the comparison of the results, we have examined the deployment levels, the substitution choices, and the system costs. The comparison of deployment levels of renewable energy options in 2030 shows that the results are similar. The major difference is in the deployment levels of solar photovoltaics, which could be explained by the reluctance by national REmap experts to envision radical changes in deployment levels. The comparison of substitution choices and the REmap cost supply curve shows that the REmap results correspond with the sequence in which the ETSAP models choose renewable energy options to satisfy an increasing RE share. The difference in results is mainly due to the political choices made by REmap experts. For example, in the case of the USA the national REmap experts choose to only substitute coal-fired power stations, whilst the ETSAP model chooses a mixture of conventional technologies depending on their economics. The results on system costs are far more robust for the ETSAP models than for the REmap tool, mainly because of the single time step (2030) used in the REmap tool. However, the difference in system costs between the two global ETSAP models also shows that system costs are highly affected by parameter choices, such as the discount factors.

From the comparison of results, it can be concluded that the REmap tool is a useful and appropriate tool to engage national experts and policy makers in the assessment and comparison of renewable energy options and renewable energy targets within and across countries. However, the REmap tool is not an appropriate tool for detailed national renewable energy planning. The results of the ETSAP tools show that they can provide far more detailed analyses, including the assessment of uncertainty, required to determine national renewable energy targets and associated policies. Furthermore, the comparison has demonstrated the value of multiple ETSAP model runs to examine progressively higher renewable energy shares as it demonstrates how a specific target may lock-in certain renewable technology options and infrastructures that are less economic for higher shares of variable renewables.

Considering the additional features of the ETSAP models, it is clear that they can provide more detailed insights than the REmap tool. In this chapter, the comparison considered three of these features: the infrastructure requirements for higher shares of renewables in the energy system, the role of competition between renewable energy technologies and resources, and the role of energy efficiency. For the specific case of Japan, the results show that infrastructural changes can have an important impact (±10 %) on the deployment levels of individual RE technologies considered. However, detailed analysis of grid infrastructure impacts requires the ability for inter-regional modelling, is data-intensive and is especially relevant for those countries with grid issues or with high shares of variable renewables.

The comparison also shows that the ability to provide insights on the role of competition between different renewable energy technology options and resource use among sectors is an important feature that is lacking in the REmap tool. In the REmap cost supply curve, the renewable energy options are presented as independent options to increase the renewable energy share within a country. Only through a qualitative discussion of the results can policy makers be informed about the possible interactions between these options. In the ETSAP models, the interaction and competition is made explicit, and this provides a valuable and important mechanism to support policy makers in their energy planning. The results show that this issue is particularly relevant for countries where there is competition for biomass in the different end-use sectors, and for examining different renewable energy options in the residential sector (rooftop photovoltaics versus solar thermal systems versus heat pumps).

The same applies for the insights that the ETSAP models provide on the competition and complementarity between energy efficiency options and renewable energy options to increase the overall RE share with an energy system.[6] Especially at higher levels of RE shares, the ETSAP models show that energy efficiency options become the dominant option to increase RE shares cost effectively.

The overall conclusion of this comparative analysis is that tools need to be geared towards the specific purpose of the exercise, but that it is important to collaborate between the different institutions that are supporting policy makers in their decision making process. The purpose of the REmap process is to explicitly engage national experts in the process of comparing and aggregating national renewable energy plans across a diverse set of countries. However, such an exercise should not be seen in isolation. For detailed national renewable energy planning, any use of the REmap tool should be complemented with ETSAP models as they provide a more flexible and robust tool to examine renewable energy options. In particular, the ETSAP tools can provide insights on system interactions, more detailed insights on the overall system costs, including possible investments in infrastructural changes, and provide insights on the competition of renewable energy options, renewable resources, and energy efficiency options once renewable energy targets have been set. The latter features become particularly relevant as countries continue to move to higher renewable energy targets.

---

[6] Please note that this competition is driven to achieve a certain renewable energy target, which is different from competition to satisfy greenhouse gas emission reductions.

References

Assoumou E, Maïzi N (2011) Carbon value dynamics for France: a key driver to support mitigation pledges at country scale. Energy Policy 39(7):4325–4336

Gaeta M, Baldissara B (2011) Il modello energetico TIMES-ITALIA. Struttura e dati. ENEA report ENEA-RT-2011-09, Rome, Italy

Hamasaki H, Kanudia A (2013) System analysis of Japanese renewable energy. Fujitsu, no. 404. http://jp.fujitsu.com/group/fri/downloads/report/research/2013/no404.pdf. April 2013

IRENA (2013) Renewable power generation costs in 2012: an overview. IRENA. www.irena.org/costing. January 2014

IRENA (2014a) REmap 2030: a renewable energy roadmap. IRENA.www.irena.org/remap. June 2014

IRENA (2014b) Renewable energy prospects: United States of America, REmap 2030 analysis. IRENA. www.irena.org/remap. November 2014

Kanudia A, Labriet M, Loulou R (2014) Effectiveness and efficiency of climate change mitigation in a technologically uncertain World. Special Issue on "The EMF27 Study on Global Technology and Climate Policy", Clim Change 123(3–4):543–558

Keppo I, van der Zwaan BCC (2012) The impact of uncertainty in climate targets and co_2 storage availability on long-term emissions abatement. Env Model Assess 17:177–191

Kober T (2014) Impact of energy efficiency measures on greenhouse gas emission reduction. Energy research Centre of the Netherlands (ECN report ECN-E- 14 -038), Petten, Netherlands

Labriet M, Kanudia A, Loulou R (2012) Climate mitigation under an uncertain technology future: a TIAM-WORLD analysis. Energy Econ 34(Supplement 3):366–377

Ó Gallachóir BP, Chiodi A, Gargiulo M, Deane P, Lavigne D, Rout UK (2012) Irish TIMES energy systems model. EPA climate change research programme 2007–2013. Report Series No. 24. UCC, Johnstown Castle, Co.Wexford, Ireland http://erc.epa.ie/safer/reports

Rösler H, Bruggink JCC, Keppo IJ (2011) Design of a European sustainable hydrogen model—model structure and data sources. Energy research Centre of the Netherlands (ECN) report ECN-E-11-041, Petten, Netherlands

Saygin D, Kempener R, Wagner N, Ayuso M, Gielen D (2015) A renewable energy roadmap for doubling the share of renewables in the global energy mix between 2010 and 2030. Manuscript under review

Simoes S, Cleto J, Fortes P, Seixas J, Huppes G (2008) Cost of energy and environmental policy in Portuguese CO_2 abatement-scenario analysis to 2020. Energy Policy 36(9):3598–3611

Wright E, Kanudia A (2014) Low carbon standard and transmission investment analysis in the new multi-region US power sector model FACETS. Energy Econ 46:136–150