IRENA

A Renewable Energy Roadmap (REmap 2030)

REmap 2030
A Renewable Energy Roadmap

Cost Methodology

2014

1. Introduction

One of the methods of displaying results of International Renewable Energy Agency's (IRENA) global renewable energy roadmap (REmap 2030, June 2014) are in the technology cost-supply curves. The cost-supply curve shows the cost difference per unit of final energy consumed if one replaces conventional energy technologies - assumed to be in place in 2030 in the Reference Case - with renewable energy (RE) technologies. This so-called "average substitution cost" [1] is calculated for each RE technology on a country level or in some cases a regional level with a country.

The aim of this document is to discuss the methodology for calculating substitution costs in more detail, and to explain how this methodology is translated into the REmap tool. The document is subdivided into two sections: Section 2 discusses the methodology for collecting data and calculating the substitution costs in more detail, and provides some specific examples for different sectors. Readers interested in understanding the costing methodology should focus on this section. Section 3 explains how the methodology is translated into the REmap tool, including an overview of the formulas used in the different worksheets. The intended user for Section 3 is a national REmap expert who is using the REmap tool to create their own technology cost-supply curves.

2. Substitution cost methodology in REmap 2030

2.1. Collection of cost data

For each country, IRENA prepares several cost-supply curves as a means of visually displaying the results of the substitution analysis. These country curves are then aggregated to generate a global cost supply curve (see Figure 1). However the country specific curves, which are released in REmap country specific reports, are the most appropriate in understanding the substitution costs as it pertains to the competitions and potential of renewable energy technologies.

IRENA's cost-supply curve approach summarizes the substitution costs (in US Dollars per gigajoule (GJ) of final renewable energy) of RE technologies (referred to as "REmap Options") as a function of the total RE share in that country's total final energy consumption (TFEC). The substitution cost of RE technologies is thereby plotted as cumulative frequency curves in ascending order of substitution costs, starting with the most cost-effective technology and ending with the least cost-effective one. The shape of the cost-supply curve is determined by the distribution of the substitution costs and the potential (in %) of the RE technology. Figure 1 illustrates the technology cost-supply curve for the 26 REmap countries aggregated for all RE technologies that was published in the June 2014 global report.

[1] Referred to as "substitution cost" throughout this document.

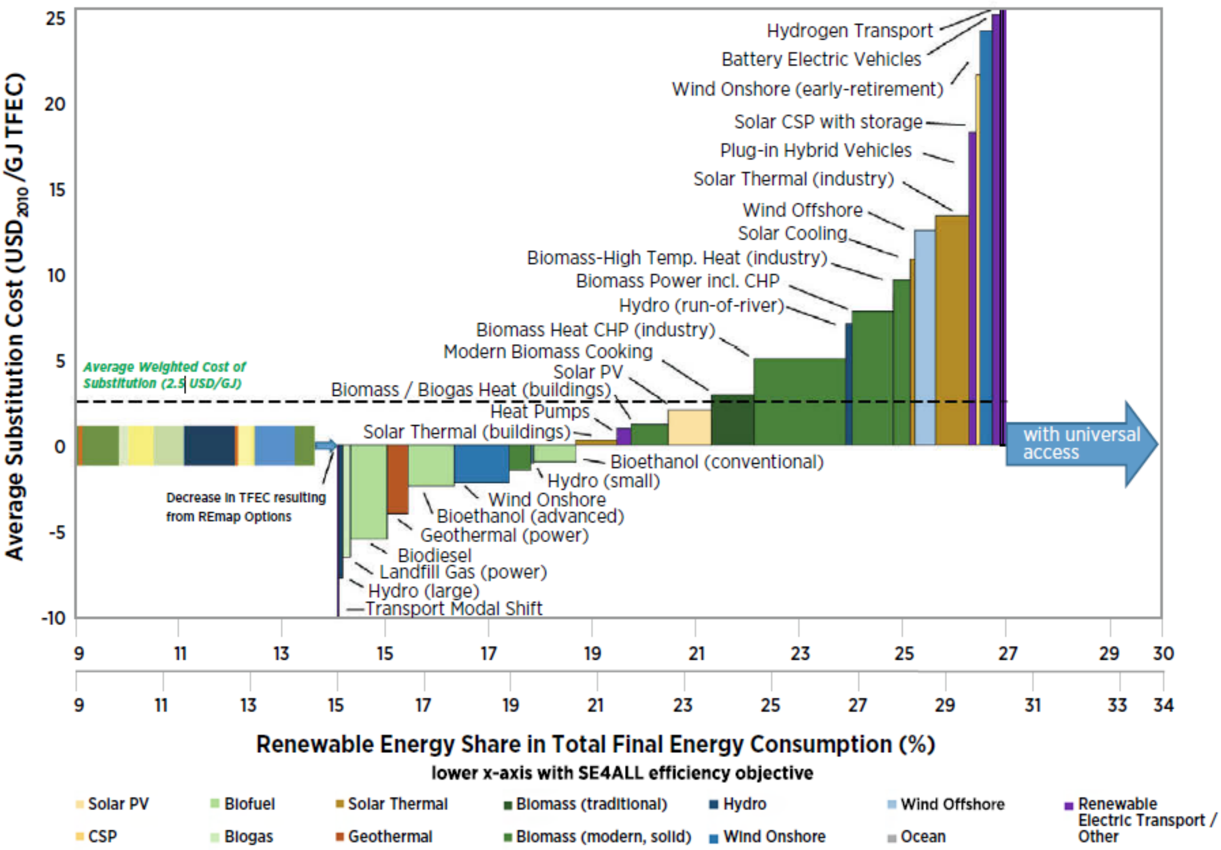

Figure 1: REmap Options cost supply curve for 26 REmap countries

Note: Information on *x*-axis and *y*-axis show the substitution cost and the share of RE in the TFEC, respectively.
Source: IRENA (2014)

For each country two types of cost-supply curves are created, namely a national (called business perspective) and an international (called government perspective). Both curves are based on national projections for capital, operational and maintenance (O&M) costs and the technical performance of conventional and RE technologies.

In the government perspective, international commodity costs exclude energy taxes and subsidies, and a standard 10% discount rate. This approach allows for a comparison across countries and for a country cost-benefit analysis; it shows the cost of the transition as governments would calculate it. For the business perspective, the process was repeated to include national prices (including, for example, energy taxes, subsidies and the local cost of capital) in order to generate a localised cost curve including taxes, subsidies and the cost of capital for individual countries[1]. This approach shows the cost of the transition as businesses or investors would calculate it[2].

[2] For coal, natural gas, biomass and electricity, exceptions were made as it is not possible to assign global values which are representative for all countries. Coal and natural gas prices are distinguished between

The basis for the national cost and performance projections for conventional and renewable energy technologies are national planning study. If available, the 2030 cost projections for both conventional and renewable energy technologies are taken from these national studies. Ideally, the national analysis includes the 2030 projections for capital costs, O&M costs, and capacity factors for all conventional and RE technologies that are used in the REmap analysis. Furthermore, national economic data to generate national curves are taken from these national studies. If more than one study is available, the choice between different cost projections is decided by the national REmap experts.

If no national data is available, IRENA provides regionalized cost data. For conventional energy technologies, regionalized cost data projections for 2030 are derived from the IEA-ETSAP technology briefs. For RE technologies, regionalized cost data projections are derived from IRENA's costing studies and IRENA-ETSAP technology briefs.

Consistency checks based on learning curves

For IRENA capital cost projections the concept of 'learning curve' is used. The 'learning curve' concept quantifies the effects of learning-by-doing on the capital cost of technologies. The learning curve is an empirical concept and it models the capital costs of technology as a function of the installed cumulative capacity (plotted as a power-law function). The concept assumes that capital costs of technologies reduce at a constant rate with each doubling of the installed cumulative capacity. For both *energy supply* (*e.g.*, wind turbine) and *energy demand* (*e.g.*, refrigerators, heat pumps) technologies, observed learning rates are generally between 10% and 20% (Weiss et al., 2010) which means that capital costs reduce by between 10% and 20% with each doubling of the installed cumulative capacity.

For national data, IRENA uses the learning rates available from literature to estimate the capital cost reductions which could be achieved between 2010 and 2030 if the cumulative installed capacity according to the REmap Options is implemented. For the O&M cost projections, IRENA uses its extensive database on RE projects to evaluate differences in the costs of installing, operating, and maintaining RE technologies within a given country. Learning effects related to the O&M costs are excluded.

2.2. Estimation of the substitution costs

This section provides the definition of substitution costs and the methodology to estimate these costs. The substitution costs are estimated based on three steps:

(i) **Substitution:** REmap analysis starts with the identification of the RE technology potentials that can be implemented in addition to business as usual developments ("Reference Case") (shown in petajoules (PJ) per year). RE potential is evaluated at the *final energy*

exporting and importing countries. Biomass prices are determined at country level with a breakdown by energy crops, residues and waste. Electricity prices are determined for each country.

level. According to the International Energy Agency (IEA) energy balances, there are two main groups of sectors which use energy (IEA, 2005).

The first group is the energy transformation sector which use different types of energy carriers (*e.g.*, natural gas, biomass, coal) and technologies (*e.g.*, hydro power plant, solar photovoltaic) to generate electricity and district heat. Primary energy is used in power and district heat (DH) plants to generate secondary energy in the form of electricity and heat. Generated electricity is transferred through power transmission lines to substations and thereon is delivered to customers such as industry facilities or households. District heat follows a similar path. District heat is transferred to a substation and subsequently to the heating system of the building or plant.

The second group is the end-use sectors which use different types of energy carriers (*e.g.*, coal, electricity) and technologies (*e.g.*, biomass boilers, solar thermal) to generate useful energy (*e.g.*, hot water, cooking heat)[3]. The largest energy using end-use sectors are the manufacturing industry, transport and buildings (residential and commercial). These sectors account for more than 90% of the total final energy consumption of most countries. The remainder of energy use is covered by the agriculture/forestry sector, fishing and other small-sectors. A total of fuels, electricity and district heat input to the technologies to generate useful energy are regarded as *final energy*.

According to the approach followed in the REmap analysis, the RE potential of the energy transformation sectors is estimated based on the share of electricity and district heat generated from RE technologies. For the end-use sectors, the RE potential is based on the amount of renewable fuels, electricity or district heat consumed to generate useful energy.

For the energy transformation sectors, one unit of electricity or district heat generated by a RE technology substitutes the same amount of electricity or district heat produced by a non-RE technology.

To estimate the total primary energy (*e.g.*, total energy input to a power plant to generate one unit of electricity) substituted by producing 1 PJ of RE electricity or heat, total generated amount should be divided by the conversion efficiency[4] of the non-RE technology.

[3] According to the Global Energy Assessment (GEA, 2012), useful energy is defined as the last measurable energy flow before the delivery of energy services (e.g., industrial process heat generated by a steam boiler).
[4] For energy transformation sectors, we mean by "conversion efficiency" the ratio of 1 PJ of electricity or heat generated to the total PJ of primary energy required to generate this amount. For end-use sectors, it is the ratio of 1 PJ of useful energy generated to the total PJ of final energy required to generate this amount.

For the end-use sectors, one unit of final energy used by a 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.

1 PJ of RE would generate “1 * η_{RE}“ PJ of useful energy where η_{RE} is the conversion efficiency of the RE technology (in %). 1 PJ of RE would substitute “1 * *SF*“ PJ of non-RE final energy which would have otherwise been used by a non-RE technology to deliver the same amount of useful energy. The substitution factor *SF* (unitless) is estimated as “η_{RE} / η_{NRE} “ where η_{NRE} is the conversion of the non-RE technology (in %).

For solar water heaters, solar photovoltaic, wind, etc, the conversion efficiency is 100%. are Exceptions to this rule are geothermal-based power and heat generation with their conversion efficiencies are set at 10%, and CSP which is set at 33%, both based on IEA (2005).

(ii) **Annualized cost of a technology and the annual final energy:** REmap estimates the annualized cost of each RE and non-RE technology (in real 2010 USD/yr/technology). Annualized cost of a technology includes its capital, O&M, fuel and electricity costs which are required to generate an unit of electricity, heat (for the energy transformation sectors) and useful energy (for end-use sectors). Therefore, it takes into account the nameplate capacity (in megawatt (MW) thermal *or* electricity), capacity factor (*i.e.*, annual utilization rate of the capacity, in hours/year) and the conversion efficiency of each technology.

Annualized costs are estimated as “annuity * overnight capital cost * installed capacity + annual O&M cost + annualized fuel and electricity costs” where annuity (in yr^{-1}) is defined as the “discount rate / (1 – (1+discount rate) ^ lifetime)”, discount rate is expressed in % and lifetime in years. Overnight capital cost is expressed in USD per MW capacity, installed capacity in MW and the annual O&M, fuel and electricity costs are expressed in USD/yr.

Annual electricity (in megawatt-hour (MWh) per year) or district heat (in PJ per year) generation is estimated as the product of the total installed capacity and the capacity factor. Annual final energy of the end-use sector technologies refers to the total quantity of final energy used to generate useful energy. It is estimated as the product of the total annual activity in physical terms (*e.g.*, distance travelled by a passenger vehicle in tonnes-km/yr, iron production of a blast furnace in megatonnes (Mt) per year) and the specific energy consumption (SEC) (*e.g.*, GJ final energy required to produce one tonne of iron).

(iii) **Substitution cost:** For energy transformation sectors, substitution cost (in USD per GJ) is defined as the additional annualized costs required to invest in a RE technology relative to its non-RE counterpart for delivering the same amount of electricity or district heat.

For end-use sectors, substitution cost (in USD per GJ) is defined as the additional annualized costs required to invest in a RE technology relative to its non-RE counterpart to deliver the same amount of useful energy.

Substitution cost of a RE technology for the energy transformation sector is estimated as " (annualized costs of RE technology to generate 1 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 a 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".

Assessment of all additional costs related to complementary infrastructure are excluded from this study (*e.g.*, grid reinforcements)

3. Cost calculations and the cost-supply curve in the REmap tool

This section provides an overview of the general formulas used in the REmap tool to estimate the annualized costs of the system and the production costs of electricity, district heat and useful energy from these systems (Section 3.1). It continues with the methodology used to estimate the substitution costs of replacing conventional technologies with their RE equivalents (Section 3.2). In Section 3.3, the methodology used to prepare the cost-supply curve is explained.

This section builds on a detailed description of the REmap tool that is overviewed in the REmap tool manual, available upon request. All background technical and cost data required to estimate the annual system costs and the production costs are provided in tabs WS2a and WS2b of the REmap tool. As explained in Section 2, all substitution costs are estimated based on final renewable energy. Users enter the absolute potentials of final RE energy (in PJ/yr) to the sectoral worksheets (tabs WS3 through WS7). Tab WS8 provides a summary of the Reference case and REmap 2030. Based on the summary information, cost supply curves are created in tab WS8.

3.1. Annualized costs of the systems

In tabs WS2a and WS2b, for each RE and non-RE technology, REmap tool provides the following information:

- Type of energy carrier,
- Capacity factor (%),
- Lifetime (years),
- Reference capacity (MW electricity, MW heat),
- Unit activity of vehicles (passenger- or tonne-km per year per vehicle),
- Overnight capital cost (refers to specific fixed capital investment costs) (USD per kilowatt (KW) electricity, USD/kW heat, USD/vehicle),
- O&M costs (USD/kW/year heat, USD/kW/year electricity, USD/vehicle/yr) which are often estimated as % of the overnight capital cost,

- Fuel and power demand (GJ/kW electricity per year, GJ/kW heat per year, megajoule (MJ) fuel per passenger- or tonne-km),
- Conversion efficiency (%)

First, the methodology for the power, industrial and building sector technologies is explained.

Fuel is used for combustion technologies. Small quantities of electricity is also used to meet the auxiliary needs. Electricity is also used to meet the auxiliary needs of RE technologies which do not require fuels, such as solar water heaters, and geothermal heat-pumps. Fuel use is estimated based on the conversion efficiency of the technology as

(reference capacity * capacity factor * 365 * 24 / conversion efficiency) / reference capacity

Electricity is used as the main energy carrier in electricity-based technologies such as heat pumps or electric water heaters. Electricity use of electricity-based technologies are estimated as

(reference capacity * capacity factor * 365 * 24 / conversion efficiency) / reference capacity

Annualized costs of a system (both RE and non-RE) (in USD/yr) for its reference capacity is estimated as

(annuity * overnight capital cost + annual O&M cost + fuel price * annual fuel use + electricity price * annual electricity use) * reference capacity

Production cost of electricity, heat or useful energy from a system (both RE and non-RE) (in USD/GJ) is estimated as

(annuity * overnight capital cost + annual O&M cost + fuel price * annual fuel use + electricity price * annual electricity use) * reference capacity / (reference capacity * capacity factor * 365 * 24)

Second, the methodology for the transport sector technologies is explained.

For the transport sector, fuel and electricity use data is based on literature estimates.

Annualized costs of a system (both RE and non-RE) (in USD/yr) for its reference capacity is estimated as

(annuity * overnight capital cost + annual O&M cost + annual fuel or electricity use * fuel or electricity price * unit activity of the vehicle)

Cost of one unit of passenger- or tonne-km (both RE and non-RE) (in USD/passenger- or tonne-km) is estimated as

(annuity * overnight capital cost + annual O&M cost + annual fuel or electricity use * fuel or electricity price * unit activity of the vehicle) / unit activity of the vehicle

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3.2. Substitution costs

Substitution costs are estimated in the worksheet of each sector. All substitution costs are estimated based on final energy. It is estimated in three steps:

(i) For energy transformation sectors, total RE electricity and district heat generated from RE technologies are entered (in PJ/yr).
For end-use sectors, total RE energy which is used in the RE technologies are entered (in PJ/yr).

Based on these final energy values, capacity factors and the conversion efficiencies of each RE technology, the required capacity for the RE technology is estimated. Subsequently, the substituted total capacity of the non-RE technology and the quantities of non-RE fuels are estimated (see the examples in Section 2).

(ii) Based on these estimates, the annualized costs of the RE technology and the substituted non-RE technology are estimated (see Section 3.1).

(iii) The difference between the annualized costs of the RE and the non-RE technology is divided by the final RE energy to estimate the substitution costs.

3.3. Cost-supply curve

Cost-supply curves plot the substitution costs of each RE technology as a function of the cumulative renewable energy share between REmap 2030 and the Reference Case.

1) The renewable energy use between REmap 2030 and the Reference Case for heating and cooling technologies is estimated as (in PJ/yr)

$\sum_{i=1}^{n} T_i$ for *n* number of heating and cooling technologies where T_i is the energy use of renewable energy technology *i* (in PJ/yr).

2) The renewable energy use between REmap 2030 and the Reference Case for electricity generation technologies is estimated as (in PJ/yr)

$E_1 * \frac{\sum_{j=1}^{m} P_j}{R_2+F_2}$ for *m* number of electricity generation technologies where P_j is the energy use of renewable energy technology *j* (in PJ/yr) and where E_1 is total electricity use in Reference Case (in PJ/yr), but by accounting for the changes in total electricity demand from the deployment of additional RE technologies (heating, cooling, electricity generation) relative to the conventional technologies (e.g., difference in auxiliary electricity demand of a solar water heater relative to a coal-based steam boiler to generate the same amount of useful energy). R_2 and F_2 are the total renewable and fossil fuel-based electricity production in REmap 2030, respectively. The same methodology is also repeated for district heat generation technologies in the heat sector.

3) The renewable energy use between REmap 2030 and the Reference case for electricity-based technologies (*e.g.,* heat pumps, electric vehicles, electric cook stoves) is estimated as (in PJ/yr)

$\sum_{k=1}^{l} E_k * \frac{R_2}{R_2+F_2}$ for *k* number of electricity generation technologies where E_k is the energy use of renewable energy technology *l* (in PJ/yr)

The share of renewable energy of REmap 2030 is estimated as (in %)

$\left(RE + \sum_{i=1}^{n} T_i + E_1 * \frac{\sum_{j=1}^{m} P_j}{R_2+F_2} + \sum_{k=1}^{l} E_k * \frac{R_2}{R_2+F_2}\right) \Big/ TFEC$ where RE is total renewable energy use in Reference Case (in PJ/yr) and TFEC is total final energy consumption of the REmap 2030 (in PJ/yr). The cost-supply curve plots for each technology *i*, *j* and *k* the cumulative renewable energy share between the Reference case and the REmap 2030.

References

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