Renewable Energy 89 (2016) 649–657

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Renewable electricity in Turkey: Life cycle environmental impacts

Burcin Atilgan, Adisa Azapagic*

School of Chemical Engineering and Analytical Science, The Mill, Room C16, Sackville Street, The University of Manchester, Manchester M13 9PL, UK

ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form
19 November 2015
Accepted 29 November 2015
Available online 24 December 2015

Keywords:
Electricity generation
Environmental impacts
Life cycle assessment
Renewable energy
Turkey

ABSTRACT

This paper applies a life cycle approach to evaluate for the first time the environmental impacts of renewable electricity in Turkey. There are 305 power plants utilising hydro, wind and geothermal resources, all of which are considered in the study. The results indicate that the impacts from large reservoir hydropower are lower than for the small reservoir (by 45%–72%) and run-of-river hydropower (by 74%–84%). The exceptions are the global warming potential (GWP) and summer smog which are two times and 45% higher for large than small reservoir, respectively. Onshore wind is the worst option overall, with nine out of 11 impacts higher than for hydropower and geothermal. However, its GWP is 9 times and 11% lower than for geothermal and large reservoir, respectively. Acidification from geothermal is 281 times higher than for wind power. Geothermal is the best option for six impacts. Large reservoir has the lowest depletion of elements and fossil resources as well as acidification. Small reservoir and run-of-river plants are the best and geothermal the worst options for the GWP. The majority of the annual impacts from the renewable electricity mix are from hydropower with the exception of acidification which is largely from geothermal electricity.

1. Introduction

Turkey has a significant potential for a variety of renewable energy resources, including solar, wind, geothermal, bioenergy and hydropower. Despite this, the country's energy sector is still dominated by imported fossil fuels with only around 10% of the total energy consumption supplied by renewable sources in 2010 [1]. The majority of this was from hydropower (4%) and biomass (3%). The contribution from other sources was low, ranging from 1.1% for animal and vegetable waste, 0.5% for geothermal, 0.3% for wind to 0.1% for solar energy [1,2]. The share of renewables in the primary energy mix has been declining since the 1970s, particularly biomass, mainly because of deforestation and other environmental concerns [1,3]. The country also imports twice as much energy as it generates: 109,266 kt of oil equivalent (ktoe) of primary energy was consumed in 2010, of which only 32,493 ktoe was generated domestically and the rest was imported [1].

Hydropower is currently the most common renewable energy source and plays an important part in Turkey's electricity sector. The theoretical viable hydroelectric potential of the country has been estimated at 433 TWh/year, nearly 1% of the total hydropower potential of the world [4,5]. However, when technological limitations are considered, this potential decreases to 216 TWh/year. The country's economically viable hydroelectric potential is 140 TWh/year which is equal to 16% of Europe's economically viable hydroelectric potential [4,5]. In 2010, the total hydropower installed capacity was 15,831 MW, generating an average of 51,795 GWh/year. This is nearly 24% of the technical and 37% of the economically viable hydroelectric potential of the country.

Turkey also has a significant potential for wind energy, estimated at approximately 48,000 MW with an annual production capacity of 130 TWh/year [6]. Currently, only a fraction of the wind potential is utlised: in 2010, the installed onshore wind power capacity was 1320 MW producing 2916 GWh per annum; there are no offshore installations.

Turkey is one of the richest countries in the world in terms of geothermal energy resources, with the overall potential of 31.5 GW [6]. Like wind, only a fraction of the geothermal potential is realised at present, with the installed electrical capacity of 94.2 MW which in 2010 generated 668 GWh [7]. The majority of the installations are flash (62.4%) and the rest are binary cycle plants [8].

Electricity demand has been increasing rapidly in Turkey [1]. The total installed capacity in 2010 reached 49,524 MW [9,7], generating 211,208 GWh, almost seven times higher than in the mid-80s [7]. As indicated in Fig. 1, the large majority (73.6%) of electricity was generated by fossil fuels, with the rest contributed

* Corresponding author.
E-mail address: adisa.azapagic@manchester.ac.uk (A. Azapagic).

http://dx.doi.org/10.1016/j.renene.2015.11.082

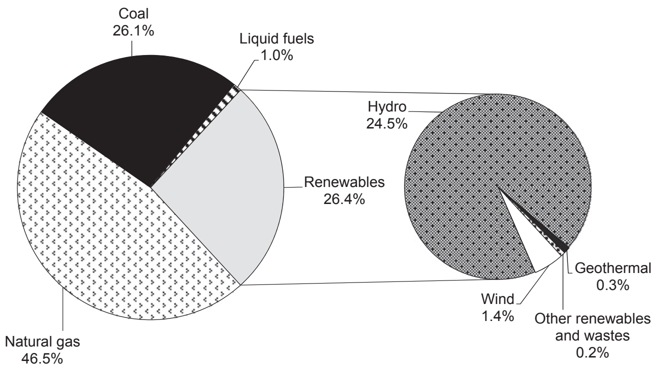

Fig. 1. Turkey's electricity mix in 2010 [9].

mainly by hydropower (24.5%).

In an attempt to reduce the country's dependence on imports and maximise use of the domestic energy potential, Turkish government has set a target for 30% of the electricity generation to be provided from renewable resources by 2023 [10]. This includes a target for 20,000 MW of wind and 600 MW of geothermal power. The government is also encouraging expansion and the utilisation of solar energy for electricity generation. To stimulate investment in renewables, various incentive schemes have been introduced [11,12]. For example, renewable energy plants with an installed capacity of 500 kW or less are exempt from licencing obligations [13]. Legal entities applying to obtain a licence from the Energy Market Regulatory Authority (EMRA) to generate electricity from renewable sources are required to pay an initial 1% of the total licencing fee and then they are exempt from the annual licencing costs for the first eight years from the facility completion date [11]. Furthermore, the fees to be paid for planning permission, rent, right of access or usage permission are reduced by 85% during the first 10 years. Government also guarantees to buy electricity from renewable power plants that started operation between 18 May 2005 to 31 December 2015, offering a feed-in tariff of 7.3 US$ cent/kWh for wind and hydropower, 10.5 US$ cent/kWh for geothermal and 13.3 US$ cent/kWh for solar and biomass (including landfill gas) plants [12].

Turkey is also concerned about the greenhouse gas (GHG) emissions which are rising rapidly: in 2010, they reached 403.5 Mt CO_2-eq., a two-fold increase on 1990 levels [14]. Of this, 71% was emitted by the energy sector [15] to which electricity generation contributed 25% or 99 Mt CO_2-eq [16]. While Turkey still has the lowest GHG emission per capita (5.6 t CO_2-eq.) in Europe (9.4 t CO_2-eq. in the EU28) [14], they are set to increase owing to the growing energy demand. Given the country's large potential for renewable energy, a significant amount of GHG emissions could be avoided. However, at present it is not known how much and also how some other environmental impacts may be affected by the planned expansion of renewables. For that reason, this paper sets out to explore the environmental sustainability of current renewable electricity generation in Turkey, to provide a baseline for future planning. Taking a life cycle approach, the study considers environmental impacts of electricity generation from reservoir and run-of-river hydropower, wind and geothermal power plants. As far as the authors are aware, this is the first time such a study has been carried out for renewable electricity in Turkey. The following section details the methodology, assumptions and data sources. This is followed in Section 3 by a discussion and comparison of the results with literature. The conclusions and recommendations are summarised in Section 4.

2. Methodology

The environmental impacts of electricity generation from renewable sources in Turkey have been estimated using life cycle assessment (LCA), following the ISO 14040 and 14044 methodology [17]. The software package GaBi v.6 [18] has been used to model the power options and estimate the environmental impacts. The following sections describe the goal and scope of the study as well as the systems considered.

2.1. Goal and scope definition

The main goal of the study is to estimate the life cycle environmental impacts of electricity generation from the renewable power systems in Turkey. A further aim is to compare the impacts from large and small reservoir, run-of-river, wind and geothermal power plants to help inform future energy planning. The year 2010 has been chosen as the time reference since this is the year for which the most complete data are available.

Two functional units are considered:

i generation of 1 kWh of renewable electricity; and
ii annual generation of renewable electricity, in this case 55,379 GWh generated in 2010.

The scope of the study for all electricity options is from cradle to grave, comprising the following life cycle stages: operation to generate electricity, plant construction and decommissioning at the end of their useful lifetime. Fig. 2 outlines the life cycle system boundaries for each technology considered. Since the functional units are related to generation of electricity, its distribution, transmission and consumption are outside the system boundary.

2.2. Data and assumptions

There are 55 reservoir hydropower, 205 run-of-river hydropower, 39 onshore wind and six geothermal power plants in Turkey all of which are considered in this study; for details, see Supplementary material. The primary data for this study have been obtained from the Turkish Ministry of Energy and Natural Resources (MENR), Turkish Electricity Transmission Company (TEIAS), Turkish Electricity Generation Corporation (EUAS), the Directorate General of State Hydraulic Works (DSI), Turkish Wind Energy Association (TUREB) and Energy Market Regulatory Authority (EMRA). Additional information and data have been gathered from government and industrial reports, academic literature as well as through personal communication with members from the Turkish Ministry of Energy and Natural Resources (MENR). All data sources are detailed further below.

The data for the renewable power plants for the year 2010 are summarised in Table 1; for details for the individual plants see Supplementary material. The inventory data and assumptions used to model the hydro and wind plants can be found in Table 2 and Table 3.

The background life cycle inventory data for reservoir hydropower plants have been sourced from Ecoinvent [19] and ESU [20]. Since the data for construction materials for reservoir plants in these sources correspond to smaller plants (175.6 MW in Ecoinvent and 95 MW in ESU), the size of plants has been scaled up to estimate the materials needed for bigger plants (see Table 2 for details). All life cycle data for the run-of-river hydropower plants are from ESU [20]. The size of the plant has been scaled up from 8.6 MW to 13.5 MW. The construction data set for large and small reservoir as well as run-of-river plants includes manufacturing, processing and transportation of construction materials and energy requirements

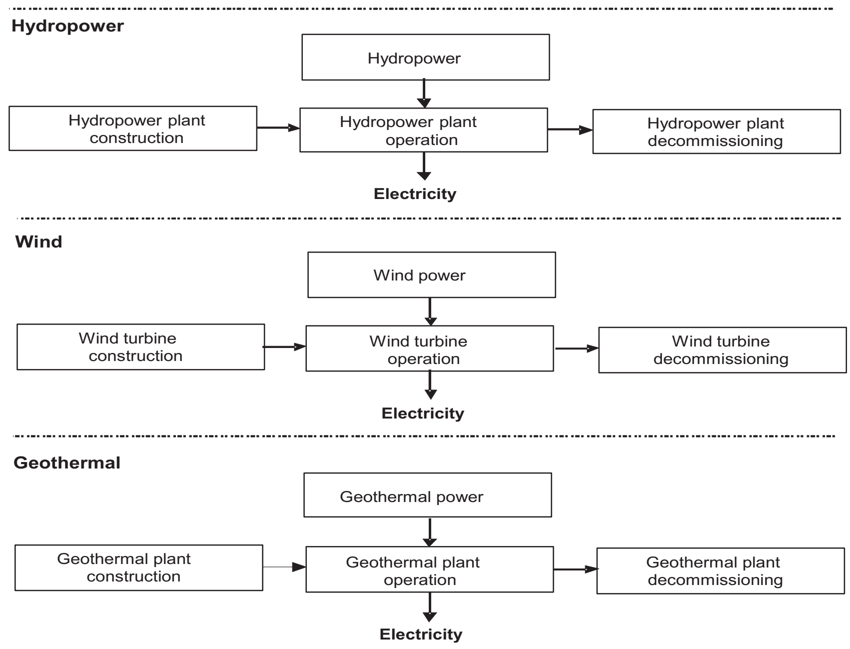

Fig. 2. The life cycle of renewable electricity from cradle to grave.

Table 1
Renewable power plants in Turkey in 2010.

Type of power plant	Number of plants	Installed capacity (MW)	Annual generation (GWh)	Percentage of total renewable electricity generation (%)
Large reservoir hydropower (capacity >500 MW)	8	8459	30,583	55.2
Small reservoir hydropower (capacity <500 MW)	47	4608	13,885	25.1
Run-of-river hydropower	205	2764	7327	13.2
Onshore wind	39 (682 turbines)	1320	2916	5.3
Geothermal	6	94	668	1.2
Total		**17,245**	**55,379**	**100**

for construction. Construction materials are assumed to be transported 200 km by rail and 100 km by lorry. During the operation of the hydropower plants, no resources are used except lubrication oil. At the end of the useful lifetime, the plant construction waste is recycled assuming that 50% of metals and concrete and 20% of plastics is recycled (Table 2); the system has been credited for the recycled materials.

The inventory data for onshore wind turbines are taken from a model for 2 MW turbines [21], based on the Vestas V80 turbine. The size of the turbine has been scaled down from 2 MW to 1.94 MW. Both fixed (tower and basement) and moving parts (rotor, nacelle, mechanics, cabling and electronics) are considered for the construction of the turbines, taking into account manufacturing of construction materials, transportation and energy requirements for installation. Construction materials are assumed to be transported 100 km by lorry and 100 km by rail; the turbine is transported at a distance of 2000 km by rail and 150 km by lorry to the installation location (see Table 3). Lubrication oil is used during maintenance and operation of the turbines. Transportation for operation and maintenance purposes is also included in the model. At the end of its service life, the turbine is dismantled and components are recycled using the same recycling rates as for the hydro-plants.

Since no Turkish data were available for geothermal power, the model available in the GaBi database [18]. The installed capacity of the power plant is 30 MW and it generates 250 GWh/year using a flash steam design. It consists of geothermal production wells with well head and spencer, power plant buildings and the collection pipes that transport the hot water and steam. As it was not possible to alter the model to Turkish conditions owing to a lack of data, the data were used without any changes. However, the geothermal power contributes only about 1% of the renewable electricity generation in Turkey (see Table 1), so that this limitation is not deemed significant. Moreover, the GaBi model is representative of standard, widely adopted geothermal plant designs.

As mentioned above and shown in Table 2, the data for the size of reservoir and run-of-river hydropower plants and wind turbines have been scaled in order to match the average plant capacity in Turkey. The approach used in scaling up process plants [22] has been used for these purposes, as adapted by Greening and Azapagic [23]:

$$E_2 = E_1 x \left(\frac{C_2}{C_1}\right)^{0.6}$$

where:

E_1 – environmental impacts of the larger plants
E_2 – environmental impacts of the smaller plants
C_1 – capacity of the larger plant
C2 – capacity of the smaller plant

Table 2
Assumptions and summary of inventory data for renewable sources.

Life cycle stage	Reservoir	Run-of-river	Onshore wind
Plant construction	*Large reservoir* • See Table 1 for details • Data based on Ecoinvent[a,b] with the average size of 175.6 MW plant and scaled up to 1057 MW plant • Lifetime: 150 years[a,c] Small reservoir • See Table 1 for details • Data based on ESU[c] with the average size of 95 MW plant and scaled up to 98 MW plant • Life time: 150 years[a,c]	• See Table 1 for details • Data based on ESU[c] with the average size of 8.6 MW plant and scaled up to 13.5 MW plant • Life time: 80 years[a,c]	• See Table 1 for details • Data based on the average size of 2 MW turbine[d] and scaled down to 1.94 MW turbine • Lifetime: 40 years for fixed parts and 20 years for moving parts
Plant operation	*Large reservoir* • Lubricating oil: 7 mg/kWh Small reservoir • Lubricating oil: 0.03 mg/kWh	• Lubricating oil: 0.12 mg/kWh	• Lubricating oil: 43.1 mg/kWh
Plant decommissioning[e]	• Metals and concrete: 50% recycled, 50% landfilled • Plastics: 20% recycled, 80% landfilled	• Metals and concrete: 50% recycled, 50% landfilled • Plastics: 20% recycled, 80% landfilled	• Metals and concrete: 50% recycled, 50% landfilled • Plastics: 20% recycled, 80% landfilled

[a] Source [24].
[b] Source [25].
[c] Source [20].
[d] Source [21].
[e] The system has been credited for recycling. The recycling rates are assumed due to a lack of data.

Table 3
Summary of transport modes and distances.

	Transport mode	Distance[b]
Large and small reservoir hydropower		
Construction materials[a]	Freight train	200 km
	Lorry >16 tonne	100 km
Run-of-river hydropower		
Construction materials[a]	Freight train	200 km
	Lorry >16 tonne	100 km
Onshore wind turbine		
Construction materials	Freight train	100 km
	Lorry >16 tonne	100 km
Turbine	Freight train	2000 km
	Lorry >16 tonne	150 km
Maintenance	Passenger car	100 person·km/year

[a] It is assumed that gravel is extracted at the construction site.
[b] Estimated by using online mapping.

0.6 – scaling factor

Further detail on the assumptions related to large and small reservoir, run-of-river and wind plants is provided below.

3. Results and discussion

The CML 2001 impact assessment method [26], November 2010 update, has been used to estimate the environmental impacts via GaBi software [18]. The following impacts are considered: abiotic depletion potential (ADP elements and fossil), acidification potential (AP), eutrophication potential (EP), fresh water aquatic ecotoxicity potential (FAETP), global warming potential (GWP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical oxidants creation potential (POCP), also known as summer smog, and terrestrial ecotoxicity potential (TETP).

The results are shown in Figs. 3–7 and are discussed in the following sections, first per kWh of electricity and then for the total electricity generation from renewables in 2010.

3.1. Environmental impacts per kWh of electricity generated

The life cycle environmental impacts per kWh of electricity generated by different renewable technologies are compared in Fig. 3. The impacts from large reservoirs are lower than for small reservoirs, ranging from 45% lower ADP fossil to 72% lower ADP elements. Large reservoir hydropower also has lower impacts than run-of-river plants, ranging from 74% lower TETP to 84% lower ADP elements. The exceptions to this are the GWP and POCP. The former is around two times higher for large than for the small reservoir and run-of-river hydropower. This is largely due to the greenhouse gases emitted by the flooded biomass and soil, mainly dependent on the type of plant, reservoir size, water depth and climate. The POCP for small reservoir is 45% lower than for the large reservoir and run-of-river plants. This is because the large reservoir has higher biogenic emissions of methane while run-of-river has higher impact from construction than small reservoir plants.

The results also indicate that electricity from onshore wind is the worst option overall, with nine out of 11 impacts higher than for hydroelectricity and geothermal power. This is due to the impacts from the life cycles of construction materials. However, the GWP of wind power is 88% and 11% lower than for geothermal electricity and large reservoir hydropower, respectively. On the other hand, the acidification potential of geothermal power is around 280 times higher than from wind power because of the air emissions of hydrogen sulphide (99.9%). Overall, geothermal power is the best option for six impacts (eutrophication, ozone layer depletion and all the toxicity categories). Large reservoir hydropower has the lowest depletion of elements and fossil resources as well as acidification. Small reservoir and run-of-river plants are the best and geothermal power worst options for the global warming potential.

Fig. 3 also shows that construction of the power plants is the main contributor to the environmental impacts. Recycling of

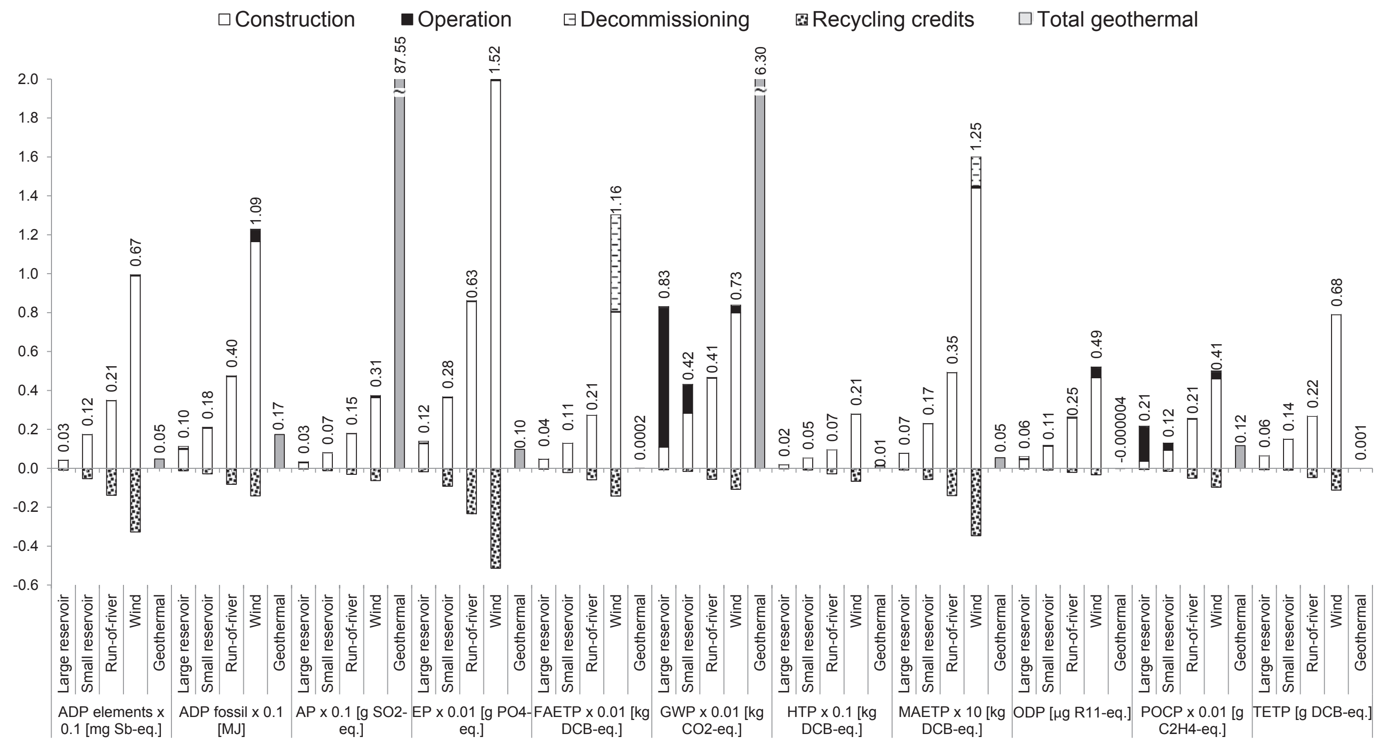

Fig. 3. Environmental impacts from different renewable electricity options in Turkey. [All impacts expressed per kWh of electricity generated. For geothermal, the breakdown by life cycle stage is not available so that only total impacts are shown. The values shown on top of each bar represent the total impact after the recycling credits for the plant construction materials have been taken into account ADP elements: Abiotic depletion of elements; ADP fossil: abiotic depletion of fossil resources; AP: acidification potential; EP: eutrophication potential; FAETP: fresh water aquatic ecotoxicity potential; GWP: Global warming potential; HTP: human toxicity potential; MAETP: marine aquatic ecotoxicity potential; ODP: ozone layer depletion potential; POCP: photochemical oxidants creation potential; TETP: terrestrial ecotoxicity potential.].

materials after decommissioning reduces the impacts by up to 40% (based on the assumptions made in this study). These results for each impact are discussed in more detail below. Note that all the results incorporate the credits for material recycling.

3.1.1. Abiotic depletion potential of elements (ADP elements)

The depletion of elements for large reservoir hydropower is estimated at 3 μg Sb-eq./kWh. This is four times lower than the impact for small reservoir plants and seven times smaller than for the run-of-river option (see Fig. 3). Almost all of the impact is incurred in the construction stage (>97%) for all three types of hydroelectricity. Recycling of construction materials reduces depletion of elements by 21% for large reservoir and 40% for run-of-river.

The wind turbine plants deplete 67 μg Sb-eq./kWh of abiotic elements. Similar to hydropower options, power plant construction is almost entirely (99.7%) responsible for the elements depletion because of the use of metals such as chromium (35%), copper (29%), molybdenum (14%) and nickel (12%). Some reduction (33%) in the impact is also due to the credits for the recycled materials.

The depletion of elements from geothermal power is estimated at 5 μg Sb-eq./kWh, mainly because of the depletion of natural gypsum (29%), lead (25%), chromium (22%), molybdenum (13%) and copper (6%).

3.1.2. Abiotic depletion potential of fossil resources (ADP fossil)

This impact for all the options is mainly due to the energy used for the extraction and processing of construction materials. Large reservoir hydropower consumes 10 kJ/kWh of fossil resources. By comparison, the amount depleted by the small reservoir is 18 kJ/kWh and that by the run-of-river plants is 40 kJ/kWh. However, the worst option is wind power which consumes 109 kJ/kWh, almost six times more than the small reservoir hydropower and geothermal electricity.

3.1.3. Acidification potential (AP)

Large reservoir hydropower has the lowest AP, with a value of 3 mg SO_2-eq./kWh. The impact from small reservoir hydroelectricity is around two times higher (7 mg SO_2-eq./kWh) than for large reservoir hydroelectricity (Fig. 3). The emissions of SO_2 and NO_x contribute respectively 53% and 44% to the total impact from reservoir hydropower. At 15 mg SO_2-eq./kWh, the AP from run-of-river is five times higher than from large reservoir and is due to the emissions of NO_x (51%) and SO_2 (47%), generated largely during the construction of the plant. The onshore wind AP is estimated at 31 mg SO_2-eq./kWh, around 10 times higher than for large reservoir. Almost all of the impact is due to the emissions of SO_2 (72%) and NO_x (25%), mainly from the production of the metal components. Geothermal power is significantly worse than any other option considered here, with the AP of 8755 mg SO_2-eq./kWh and almost all of the impact (99.9%) is due to the air emissions of hydrogen sulphide.

3.1.4. Eutrophication potential (EP)

The EP of electricity from the run-of-river plants is equal to 6.3 mg PO_4-eq./kWh. This impact from large reservoir is around five times lower (1.2 mg PO_4-eq./kWh) and for small reservoir around two times lower (2.8 mg PO_4-eq./kWh) than for run-of-river hydropower. Plant construction is the main hotspot, contributing between 89% for large reservoir and 99% for run-of-river power, owing to the emissions of phosphates to freshwater and NO_x to air. Electricity from onshore wind emits 15.2 mg PO_4-eq./kWh with 97%

arising from the plant construction stage and particularly the emissions of phosphates to freshwater related to the copper and steel production chain. As can be seen in Fig. 3, recycling of construction materials reduces the impact by around 25% for the wind and the hydro-plants, except for the large reservoir (12%). Despite these reductions, the best option is geothermal power with 1 mg PO_4-eq./kWh. The main contributors (86%) to the EP from geothermal power are NO_x emissions to air.

3.1.5. Freshwater aquatic ecotoxicity potential (FAETP)

Large reservoir hydropower has an estimated FAETP of 0.4 g dichlorobenzene (DCB)-eq./kWh and small reservoir 1.1 g DCB-eq./kWh, nearly three times higher. Both values are still lower than for run-of-river hydropower which is equivalent to 2.1 g DCB-eq./kWh (Fig. 3). The majority of the impact for all three hydroelectricity options is due to the emissions of metals to fresh water associated with the construction materials, including nickel, beryllium, cobalt and vanadium. This FAETP from wind power is estimated at 11.6 g DCB-eq./kWh, around 10 times higher than for small reservoir hydroelectricity. Emissions of copper (38%), nickel (36%), cobalt (8%) and beryllium (5%) to fresh water are the main contributors to this impact. The estimated value for the FAETP for geothermal power is 0.002 g DCB-eq. per kWh of generated electricity, caused largely by emissions of copper, vanadium and nickel.

3.1.6. Global warming potential (GWP)

Large reservoir has a GWP of 8.3 g CO_2-eq./kWh. As can be seen in Fig. 3, the biggest contributor (87%) is operation of the power plant and in particular emissions of CO_2 (12.8%) and CH_4 (86.6%) from the degradation of biomass submerged in the water. The GWP for small reservoir and run-of-river hydropower is two times lower, estimated at 4.2 and 4.1 g CO_2-eq./kWh, respectively. For the small reservoir, the GHG emissions during plant construction (64%) and operation (35%) are the biggest contributors while for the run-of-river, almost all of the impact (99%) is from plant construction. The emissions from operation of the run-of-river plants are the smallest as the water is stored for a short time.

For wind power, the GWP of 7.3 g CO_2-eq./kWh is mainly due to the emissions associated with the energy used to manufacture the turbine components. This is nine times lower than the GWP from geothermal power (63.0 g CO_2-eq./kWh) which is the worst option for this impact. The CO_2 emissions account for 91% of the total GWP for wind and 99% for geothermal power.

3.1.7. Human toxicity potential (HTP)

The HTP for electricity from large reservoirs is estimated at 2 g DCB-eq./kWh, 2.5 times lower than for small reservoir (5 g DCB-eq./kWh) and 3.5 times smaller than for run-of-river hydropower (7 g DCB-eq./kWh). As indicated in Fig. 3, almost all of this impact for the hydropower technologies is due to the plant construction (99%) and particularly as a result of emissions of chromium, selenium, arsenic and nickel. Onshore wind is the worst option for this impact, with a value of 21 g DCB-eq./kWh. Turbine manufacture is responsible for almost all HTP primarily because of the emissions to air and water of chromium (72%), arsenic (8%) and selenium (5%). The HTP for geothermal power is 21 times lower (1 g DCB-eq./kWh) than for wind power. The main contributor is the emission of hydrogen sulphide (93%) to air.

3.1.8. Marine aquatic ecotoxicity potential (MAETP)

Electricity from large reservoir hydro-plants emits 0.7 kg DCB-eq. per kWh. The impact from run-of-river hydropower is 3.5 kg DCB-eq./kWh, twice as high as from small reservoirs (1.7 kg DCB-eq./kWh). Emissions of beryllium, cobalt, selenium, vanadium and nickel to water and hydrogen fluoride emissions to air are the main burdens contributing to this category for all three hydroelectricity technologies. Wind power is the worst option for this impact, with a value of 12.5 kg DCB-eq./kWh, mainly caused by construction (87%) and decommissioning (12%) of the turbine. Similar to hydroelectricity, the main contributors are emissions to water of beryllium (27%), cobalt (9%), vanadium (10%), copper (7%) and selenium (4%) as well as air emissions of hydrogen fluoride (17%). Crediting the system for the recycled materials reduces the MAETP of wind power by 22% (Fig. 3). Geothermal power is the best option with 0.5 kg DCB-eq./kWh, caused almost entirely (99%) by hydrogen fluoride emissions.

3.1.9. Ozone layer depletion potential (ODP)

The ozone layer depletion for the hydro options ranges from 0.06 μg R11-eq./kWh for large reservoir to 0.25 μg R11-eq./kWh run-of-river (see Fig. 3). The impact from wind power is twice as high as the worst hydro option (0.49 μg R11-eq./kWh). The main contributors for both wind and hydropower are halons (1301 and 1211) used as fire suppressants during the production of construction materials such as glass fibre, concrete, chromium and steel as well as transport of the parts. The ODP from geothermal power is negligible ($-4x10^{-6}$ μg/kWh).

3.1.10. Photochemical oxidants creation potential (POCP)

The POCP is similar for large reservoir and run-of-river, estimated at 2.1 mg C_2H_4-eq./kWh. This is higher than for small reservoir hydropower (1.2 mg C_2H_4-eq./kWh). The majority of the POCP for large reservoirs is due to the biogenic CH_4 (81%). For small reservoirs, the biggest contributors are plant construction and operation, particularly the emissions of biogenic CH_4 (30%), non-methane volatile organic compounds (NMVOCs) (27%), NO_x (15%), SO_2 (13%) and CO (10%). By contrast, almost all of the impact (98%) for the run-of-river plants is from construction as a result of emissions of NMVOCs (40%), NO_x (21%), CO (20%) and SO_2 (14%). The POCP of wind power is 4.1 mg C_2H_4-eq./kWh and it is mainly due to the construction stage (90%) with CO, NO_x, SO_2 and NMVOCs contributing 91%. Geothermal power has the same impact as small reservoir power (1.2 mg C_2H_4-eq./kWh), caused by the emissions of NMVOCs (54%), CO (21%), NO_x (16%) and SO_2 (10%).

3.1.11. Terrestrial ecotoxicity potential (TETP)

The TETP of large reservoir hydropower is equivalent to 0.06 g DCB-eq./kWh and that of small reservoir to 0.14 g DCB-eq./kWh; the impact from run-of-river hydropower is 1.6 times higher than the latter (0.22 g DCB-eq./kWh). Emissions to air and soil of mercury, chromium and arsenic are the main cause of this impact for all three options. At 0.68 g DCB-eq./kWh, wind power is the worst option for this impact, with chromium (81%) and mercury (14%) emissions being the main contributors. As for the other toxicity categories, geothermal power is the best options with 1 mg DCB-eq./kWh, which is around two orders of magnitude lower than for wind power.

3.2. Comparison of results with literature

As far as the authors are aware, there are no other studies on life cycle environmental impacts of renewable electricity generation in Turkey so direct comparison of the results is not possible. However, quite a few studies of renewable electricity technologies based in other countries are available in LCA databases [19,27] and academic literature; therefore, the current results are compared to these sources for each electricity option considered here. As can be seen from Figs. 4–6, a wide range of values has been reported for each impact across different studies. This is primarily due to the different background data and different assumptions, such as geographical regions, installed capacities, capacity factors, recycling rates and lifetimes.

There are very few LCA studies of reservoir hydropower plants and most do not distinguish between the large and small reservoir. For this reason, the values for the large and small reservoir plants obtained in the current study (Fig. 3) have been averaged and are compared in Fig. 4 to the range of values found in the literature. As can be seen, the average values for the GWP, AP, EP, ODP, POCP and TETP estimated here fall within the range reported in other studies [19,27,28]. For example, the GWP ranges between 2.7 and 11.6 g CO_2-eq./kWh in the literature, which compares well to this study's average of 6.9 g CO_2-eq./kWh for reservoir hydropower in Turkey. On the other hand, the results for the ADP elements, ADP fossil, FAETP, HTP and MAETP fall below the range of values in the existing databases [19,27]. This is mainly because the size of the large reservoir plant assumed in this study is six times bigger than the one reported in Ecoinvent (see Table 2 for further details). Consequently, a lower amount of construction materials is required per kWh of energy generated and the associated impacts are lower. The large hydropower plants in Turkey also have a higher capacity factor than is assumed in some studies, further reducing their impacts per kWh.

As opposed to the reservoir, a number of LCA studies of run-of-river hydropower plants have been carried out [19,27,29–33]. As indicated in Fig. 5, all the environmental impacts obtained in the present study are comparable to the values reported in the literature. For example, the GWP reported in the literature is between 0.3 and 5.2 g CO_2-eq./kWh, compared to the value of 4.1 g CO_2-eq./kWh obtained in the current work.

There are also a number of LCA studies of onshore wind turbines [19,34–39]. As shown in Fig. 6, the impacts range widely between the studies and the estimates in this study are well within the values reported in the literature.

3.3. Annual environmental impacts

The annual environmental impacts from renewable electricity generated in Turkey in 2010 have been estimated using the impacts per kWh discussed in Section 3.1 and the total electricity of 55,379 GWh generated that year by the power plants (see Supplementary material); the results are shown in Fig. 7. For example, the annual GWP is estimated at 404 kt CO_2-eq., of which large reservoir plants contribute 62.5%, small reservoir 14.3%, geothermal 10%, run-of-river 7.5% and wind 5.3%. By comparison, the total annual GWP from fossil fuel plants in Turkey is estimated at 109 Mt CO_2-eq. [40]. This is 270 times higher than the impact from renewable electricity, although fossil fuels supply only 2.7 times more electricity (153,190 GWh/year). The difference in the impacts is even starker for some other impacts such as eutrophication which is around 2900 times higher and marine ecotoxicity which is almost 2400 times greater for the fossil-based electricity.

The majority of the impacts from renewable electricity are from hydropower, whose contribution ranges from 5% for acidification to 88% for summer smog. This is despite the hydropower plants generating around 18 and 78 times more electricity than the wind and geothermal plants, respectively. The exception to this is acidification which is mainly (94%) due to geothermal electricity because of the previously-mentioned emissions of hydrogen sulphide.

4. Conclusions

This study represents a first attempt to analyse the life cycle environmental impacts of renewable electricity in Turkey. Eleven environmental impacts have been estimated for large and small reservoir, run-of-river, onshore wind and geothermal power. The results suggest that per kWh of electricity generated, onshore wind is the worst option overall, with nine out of 11 impacts higher than for geothermal and hydropower. This is due to the related impacts from the extraction and processing of the construction materials. On the other hand, its GWP is 88% and 11% lower than for geothermal and large reservoir hydropower, respectively. The acidification potential of geothermal electricity is 281 times higher than for wind power. The findings suggest that large reservoir plants are environmentally more sustainable than small reservoir and run-of-river plants for nine out of 11 environmental categories. However, the GWP for large reservoirs is around two times higher than for small reservoir and run-of-river hydropower. Furthermore, the potential for summer smog is 45% lower for the small than large reservoir plants.

Geothermal power is the best option for six impacts: eutrophication, ozone layer depletion, human toxicity and all ecotoxicity categories. Large reservoir hydropower has the lowest depletion of elements and fossil resources as well as acidification. Small reservoir and run-of-river plants are the best and geothermal

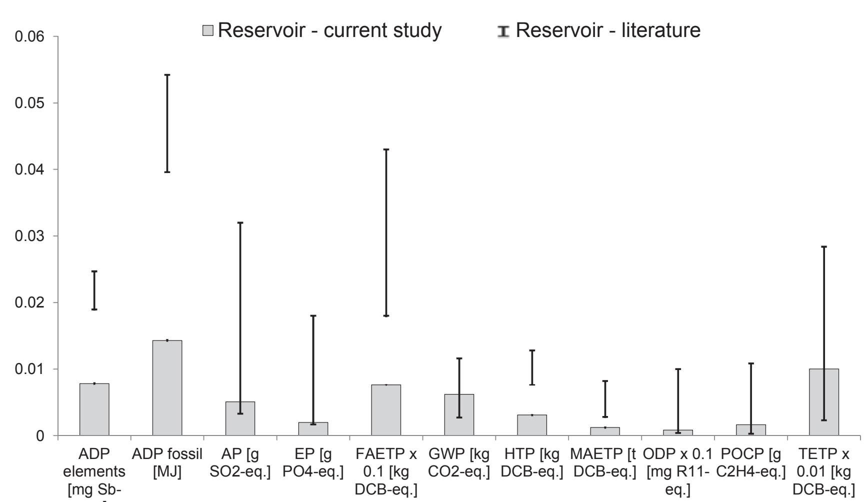

Fig. 4. Comparison of results from the current study with the literature for reservoir hydropower. [All impacts expressed per kWh of electricity generated. The current study results present the average values for large and small reservoir. Literature data from: [19,27,28]. All impacts estimated using the CML 2001 method. For impacts nomenclature, see Fig. 3.].

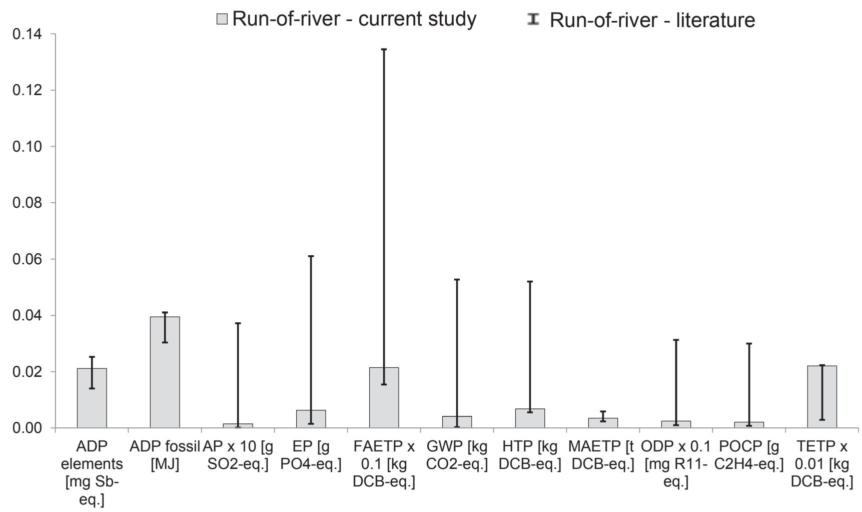

Fig. 5. Comparison of results from the current study with the literature for run-of-river hydropower. [All impacts expressed per kWh of electricity generated. Literature data from: [19,27,29–33]. All impacts estimated using the CML 2001 method. For impacts nomenclature, see Fig. 3.].

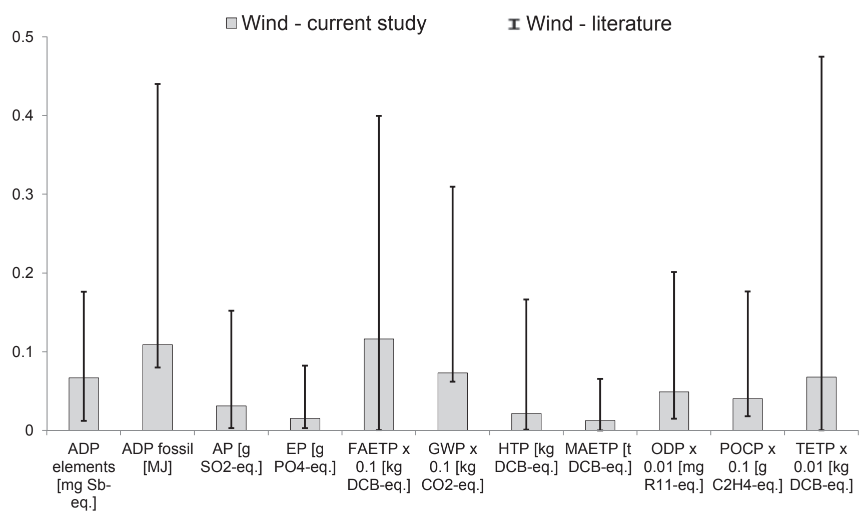

Fig. 6. Comparison of results from the current study with the literature for wind power. [All impacts expressed per kWh of electricity generated. Literature data from: [19,34–39]. All impacts estimated using the CML 2001 method. For impacts nomenclature, see Fig. 3.].

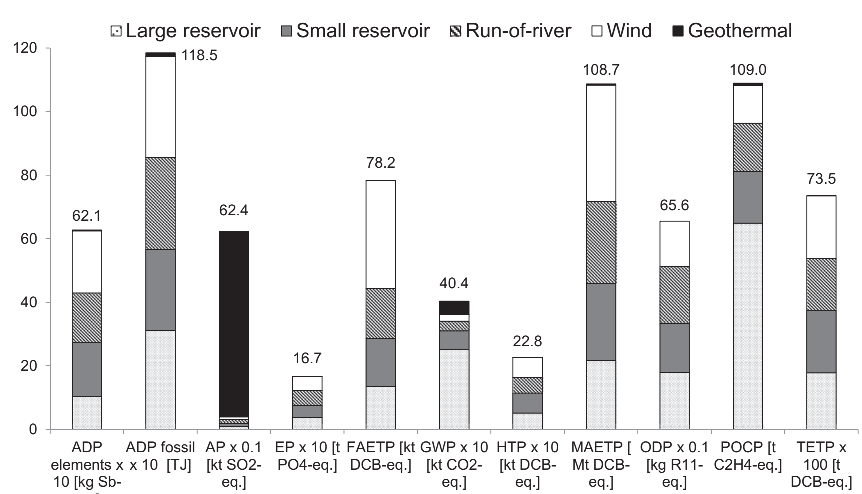

Fig. 7. Annual environmental impacts from renewable electricity generated in Turkey in 2010. [For impacts nomenclature, see Fig. 3.].

power worst options for the global warming potential.

Construction of the power plants is the main contributor to the impacts for all the options considered. Recycling of materials at the end of the plant lifetime reduces the impacts by up to 40%.

The results also indicate that generation of renewable electricity in Turkey emits around 404 kt CO_2-eq. per year. The majority of the impacts are from hydroelectricity owing to the amount of electricity generated by hydropower plants which is 18 and 78 times higher than from wind and geothermal plants, respectively.

A greater penetration of renewable energy sources into the grid as an alternative to fossil fuels is important for Turkey to reduce the dependence on imported energy, provide security of supply and reduce the environmental impacts from the electricity sector. For example, the GWP of fossil-fuels electricity is around 109 Mt CO_2-eq./year, 270 times higher than for renewable electricity, despite the fossil-based plants generating only 2.7 times more electricity. Therefore, the government should encourage and possibly incentivise further increasing the share of renewables in the electricity mix as well as diversifying the portfolio of technological options to include offshore wind and solar power. However, renewable electricity options should be chosen with care. For example, increasing the proportion of geothermal power in the electricity mix would increase some of the life cycle impacts such as acidification and GWP compared to increasing the share of hydropower and wind. Nevertheless, these would still be several orders of magnitude lower than from fossil-fuels electricity.

Acknowledgements

This work was funded by the Republic of Turkey Ministry of National Education as well as by the Engineering and Physical Sciences Research Council, EPSRC (Grant no. EP/K011820/1). This funding is gratefully acknowledged.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2015.11.082.

References

[1] MENR, Mavi Kitap (Blue Book), Ministry of Energy and Natural Resources, Ankara, 2012.
[2] WEC, Turkiye Enerji Raporu, World Energy Council, Turkish National Committee, Ankara, 2011.
[3] WEC, Turkey Energy Balance Table (1970–2004): World Energy Council Turkish National Committee, 2005 [Online]. Available from: http://www.dektmk.org.tr/incele.php?id=MTQ3.
[4] DSI, Turkey Water Report 2009 Ankara: State Hydraulic Works, 2010 [Online]. Available from: http://www2.dsi.gov.tr/english/pdf_files/TurkeyWaterReport.pdf.
[5] DSI, Annual Activity Report of 2010, State Hydraulic Works, Ankara, 2011.
[6] EMRA, RE: Data on Energy Potential of Turkey, Republic of Turkey Energy Market Regulatory Authority, Ankara, 2014 [Personel communication, 15.06.2014].
[7] TEIAS, Electricity Generation & Transmission Statistics of Turkey Ankara: Turkish Electricity Transmission Corporation [Online]. Available from: http://www.teias.gov.tr/TurkiyeElektrikIstatistikleri.aspx, 2012.
[8] M. Parlaktuna, O. Mertoglu, S. Simsek, H. Paksoy, N. Basarir, Geothermal Country Update Report of Turkey (2010-2013) European Geothermal Congress 2013, 2013 (Pisa, Italy).
[9] Ecoinvent, Ecoinvent Database v2.2, Swiss Centre for Life Cycle Inventories, St Gallen, Switzerland, 2010.
[10] SPO, Elektrik Enerjisi Piyasası Ve Arz Güvenliği Strateji Belgesi, Turkish State Planning Organization, Ankara, 2009.
[11] F.C. Kilic, Recent renewable energy developments, studies, incentives in Turkey, Energy Educ. Sci. Technol. Part A 28 (1) (2011) 37–54.
[12] H.A. Simsek, N. Simsek, Recent incentives for renewable energy in Turkey, Energy Policy 63 (0) (2013) 521–530.
[13] K. Baris, S. Kucukali, Availibility of renewable energy sources in Turkey: Current situation, potential, government policies and the EU perspective, Energy Policy 42 (0) (2012) 377–391.
[14] EEA, European Environment Agency, Greenhouse Gas Data Viewer: European Environment Agency, 2012 [Online]. Available from: http://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer.
[15] TUIK, National Greenhouse Gas Inventory Report, 1990-2010, Turkish Statistical Institute, Ankara, 2011.
[16] FutureCamp, Baseline Emission Calculations. Verified Carbon Standard (VCS), Version 3, Turkey, Ankara, 2011.
[17] ISO, ISO 14044: Life Cycle Assessment - Requirements and Guidelines, International Standard Organization, Geneva, Switzerland, 2006.
[18] PE International, GaBi Version 6, Echterdingen, Stuttgart, 2013.
[19] EUAS, Annual Report, Turkish Electricity Generation Company, Ankara, 2011.
[20] K. Flury, R. Frischknecht, Life Cycle Inventories of Hydroelectric Power Generation. ESU Database, Uster: Öko-Institute e.V, 2012.
[21] V. Kouloumpis, L. Stamford, A. Azapagic, Decarbonising electricity supply: Is climate change mitigation going to be carried out at the expense of other environmental impacts? Sustain. Prod. Consum. 1 (2015) 1–21.
[22] J.M. Coulson, R.K. Sinnott, J.F. Richardson, Coulson & Richardson's Chemical Engineering, Butterworth Heinemann Ltd, Oxford; Boston, 1993.
[23] B. Greening, A. Azapagic, Environmental impacts of micro-wind turbines and their potential to contribute to UK climate change targets, Energy 59 (2013) 454–466.
[24] R. Dones, C. Bauer, R. Bolliger, B. Burger, M. Faist Emmenegger, R. Frischknecht, T. Heck, N. Jungbluth, A. Röder, M. Tuchschmid, Ecoinvent Report: Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland, 2007.
[25] C. Bauer, R. Bolliger, Ecoinvent Report: Wasserkraft, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland, 2007.
[26] J.B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. Koning, Life Cycle Assessment: an Operational Guide to the ISO Standards: Part 2a, Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), The Netherlands, 2002.
[27] ESU, ESU Database, ESU-services Ltd.: Öko-Institute e.V, 2012.
[28] S. Arnøy, Hydroelectricity from Trollheim Power Station. Environmental Product Declaration ISO 14025, OSLO: Østfoldforskning AS, 2013.
[29] S. Arnøy, I.S. Modahl, Life Cycle Data for Hydroelectric Generation at Embretsfoss 4 (E4) Power Station: Background Data for Life Cycle Assessment (LCA) and Environmental Product Declaration (EPD), EB Kraftproduksjon LCA Vasskraft. Ostfold Research, 2013.
[30] A. Pascale, T. Urmee, A. Moore, Life cycle assessment of a community hydroelectric power system in rural Thailand, Renew. Energy 36 (11) (2011) 2799–2808.
[31] H.L. Raadal, L. Gagnon, I.S. Modahl, O.J. Hanssen, Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power, Renew. Sustain. Energy Rev. 15 (7) (2011) 3417–3422.
[32] O. Schuller, S. Albrecht, Year. Setting up life cycle models for the environmental analysis of hydropower generation, considering technical and climatic boundary conditions, in: Life Cycle Assessment VIII, 2008. Seattle, USA.
[33] W. Suwanit, S. Gheewala, Life cycle assessment of mini-hydropower plants in Thailand, Int. J. Life Cycle Assess. 16 (9) (2011) 849–858.
[34] P. Garrett, K. Rønde, Life Cycle Assessment of Electricity Production from an Onshore V90-3.0 MW Wind Plant, Vestas Wind Systems A/S, Denmark, 2013a.
[35] P. Garrett, K. Rønde, Life cycle assessment of wind power: Comprehensive results from a state-of-the-art approach, Int. J. Life Cycle Assess. 18 (1) (2013b) 37–48.
[36] F. Lahuerta, E. Saenz, Life cycle assessment of the wind turbines installed in Spain until 2008, in: Europe's Premier Wind Energy Conference and Exhibition. Brussels, 2011.
[37] E. Martínez, F. Sanz, S. Pellegrini, E. Jiménez, J. Blanco, Life-cycle assessment of a 2 MW rated power wind turbine: CML method, Int. J. Life Cycle Assess. 14 (1) (2009) 52–63.
[38] B. Palomo, B. Gaillardon, Year. Life cycle assessment of a French wind plant, in: Europe's Premier Wind Energy Event, 2014 (Barcelona, Spain).
[39] J.R.M. Pereg, J.F. Hoz, Life Cycle Assessment of 1 KWh Generated by a Gamesa Onshore Windfarm G90 2.0 MW ECOWIND, 2013.
[40] B. Atilgan, A. Azapagic, Life cycle environmental impacts of electricity from fossil fuels in Turkey, J. Clean. Prod. 106 (2015) 555–564.