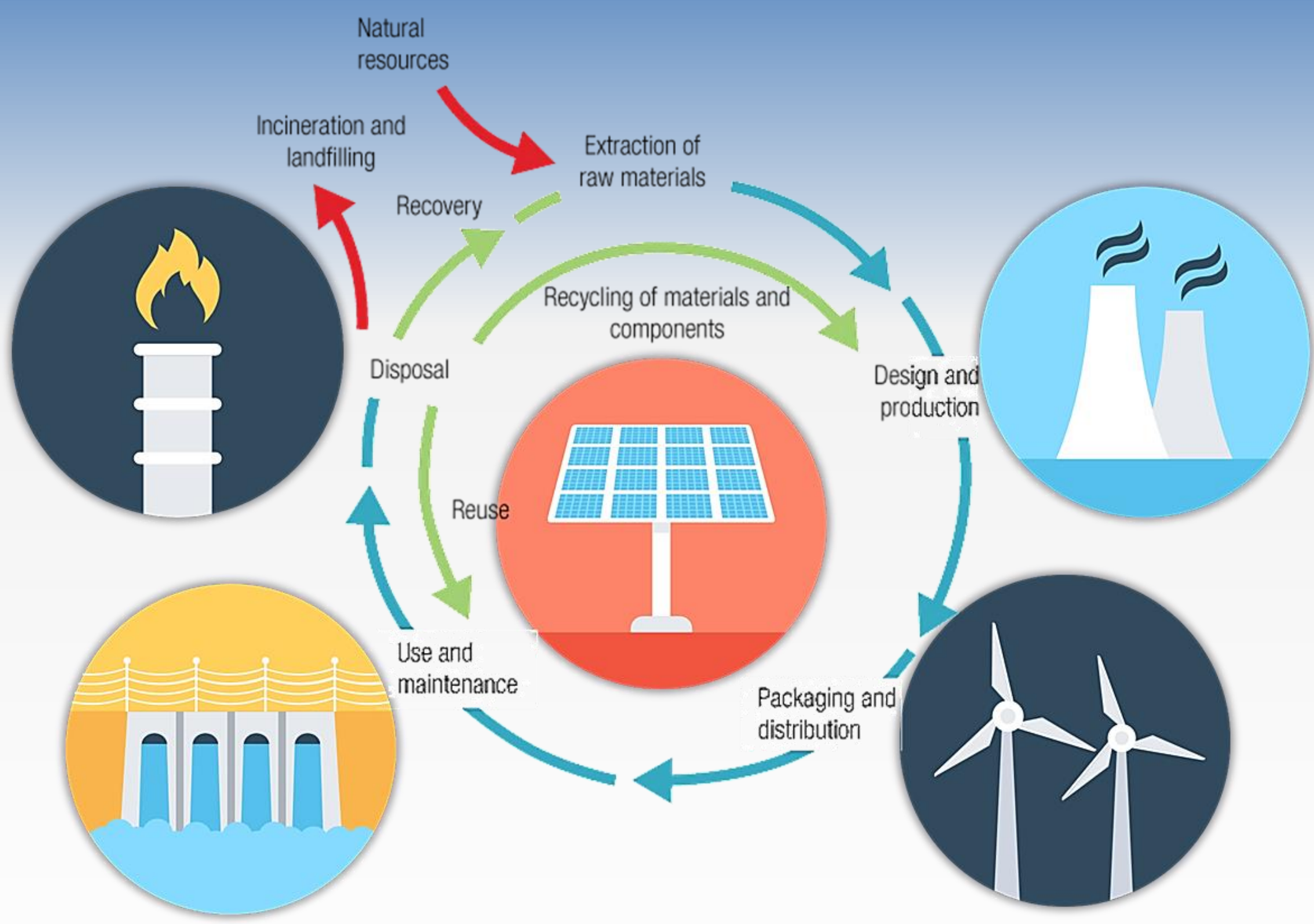


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# LIFE CYCLE SUSTAINABILITY ASSESSMENT OF KEY ELECTRICITY GENERATION SYSTEMS IN PORTUGAL

MSc. Thesis in **Energy for Sustainability**

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**September 2017**

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Universidade de Coimbra

### *Acknowledgements*

I would like to express my sincere gratitude and appreciation to the following people:

First of all to my supervisor; Prof. Fausto Freire; for introducing me to the interesting field of industrial ecology and life cycle assessment; always demanding excellence, encouraging and believing in me, and being supportive and understanding.

To Pedro Marques; for his invaluable technical support, incredible patience, generosity, and good humour. To the other members of the CIE Team: Carla C., Erica, Carla R., Rita, Carlos, Fabiana, Alejandro; for welcoming me to the lab and creating a pleasant working atmosphere; sharing knowledge, advice, encouragement, lunch, and the occasional cafezinho.

To my fellow EfS students: Ariel, Roham, Arnfried, Adrian, Jaqueline, Eduardo, Joao, Danyela, Zuleika, Thiago Thank you all for your friendship and company along this journey; with many fond memories both inside and outside of the classroom. See you in Rio!

To my friends at riverside church; Pastors Joao and Gena and the whole church family. To the international corner of GBU: Natalie, Joe, Beatriz, Simi, Dara, Euna, Tamara, Jeff, Zel. Thanks for your love, prayers and fellowship.

To Dr Sarah. Thanks for visiting me, your messages, support, and prayers

To all of my family in Uganda, and in other parts of the world; for staying in touch despite the distance – all the phone calls, messages. Out of sight has not been out of mind. To my amazing sisters, Tabitha and Agatha: Thank you for your unwavering support, cheerleading, patience, understanding, humour and perpetual encouragement to ‘KOTOMO’.

To my parents, John and Deborah; for always inspiring me with your hard work, love, and for always giving me time, space and support to pursue my ambitions. Mwebaaaaaaaaare!!

Finally, and most of all to God for sustaining me each day and for all the good gifts He gives me; for this great opportunity to explore this field of knowledge, and for the Portugal adventure as a whole.

## *Abstract*

The following thesis presents a multidimensional life cycle sustainability assessment (LCSA) study; carried out to estimate and compare the environmental and socioeconomic impacts associated with six, key electricity generation systems in Portugal namely; coal, natural gas, hydro (large and small), wind, and photovoltaic (PV). In addition to updating the models (i.e. data and assumptions) and impact assessment methods used in an existing life cycle assessment (E-LCA) for the Portuguese context (Garcia et al. 2014), the current study also broadens its scope; assessing critical water use, and applies relevant indicators to account for socioeconomic impacts.

The life cycle assessment (E-LCA) methodology was used to quantify environmental impacts in: metal depletion, fossil fuel depletion, non-renewable primary energy, global warming potential, ozone depletion, terrestrial acidification, freshwater eutrophication, aquatic acidification, freshwater ecotoxicity; as well as human health impacts in toxicity (carcinogenic and non-carcinogenic). In addition to the water use impacts associated to *quality*, the water scarcity footprint of each system was estimated using the AWARE method – to assess the water use impact related to *quantity*. For socioeconomic impacts, a range of empirical methods, and relevant literature were used to estimate impacts in: employment provision (domestic and total), dependence on fossil fuels, capacity factor, and levelised cost of electricity. Within most of the environmental categories, generation based on coal was estimated to have the most negative (i.e. highest) impacts, apart from: metal depletion (wind), ozone depletion (natural gas), water scarcity footprint (large hydro) and freshwater ecotoxicity (PV). For socioeconomic categories, there was more variability as to which system produced the most positive or negative impacts. Coal – previously the worst-performing (environmentally) was estimated to generate the most total employment; had the highest capacity factor; and the second-lowest levelised cost. While PV was estimated to generate the most domestic employment, it had the lowest capacity factor, and the highest non-carcinogenic toxicity towards humans. Overall, small hydro systems appeared to be the most sustainable; both environmentally and socioecomically.

The LCSA methodology (as applied to the current study) is beneficial for holistically considering and quantifying the wider life cycle impacts of systems; across the boundaries of traditional dimensions of sustainability. As a decision support tool, LCSA has provided an overview of the sustainability performance of key electricity generation systems used in Portugal; as well as highlighted areas of either significant *negative* impact – where improvements can be made; or *positive* impact – where opportunities can be exploited. In order to gain the optimum benefit from the available systems or options, it is often necessary for decision makers to consider different trade-offs, depending on the varying (and at times conflicting) priorities of relevant stakeholders.

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**Front Cover Image Sources:**

- https://www.flaticon.com/packs/energy-and-power
- http://www.lifecycleinitiative.org/starting-life-cycle-thinking/what-is-life-cycle-thinking/

### *List of Abbreviations*

| | |
|---|---|
| **AqAc** | Aquatic Acidification |
| **AWARE** | Available Water Remaining (*Water Scarcity Footprint Assessment Method*) |
| **CF** | Characterisation Factor |
| **EF** | Employment Factor |
| **E-LCA** | Environmental Life Cycle Assessment |
| **FFD** | Fossil Fuel Depletion |
| **FWEco** | Freshwater Ecotoxicity |
| **FWEut** | Freshwater Eutrophication |
| **GHG** | Greenhouse Gas (*Emissions*) |
| **GWP** | Global Warming Potential |
| **HTcar** | Human Toxicity (Carcinogenic) |
| **HTnon** | Human Toxicity (Non-Carcinogenic) |
| **ILCD** | International Reference Life Cycle Data |
| **LCIA** | Life Cycle Impact Assessment |
| **LCoE** | Levelised Cost of Electricity |
| **LCSA** | Life Cycle Sustainability Assessment |
| **MCDA** | Multi-criteria Decision Analysis |
| **MD** | Metal Depletion |
| **nREn** | Non-Renewable Energy (Consumption) |
| **OECD** | Organisation for Economic Cooperation and Development |
| **RES-E** | Renewable Energy Systems for Electricity |
| **RJM** | Regional Job Multiplier |
| **SETAC** | Society of Environmental Toxicology and Chemistry |
| **S-LCA** | Social Life Cycle Assessment |
| **TA** | Terrestrial Acidification |
| **UNEP** | United Nations Environmental Programme |
| **WFP** | Water Footprint |
| **WSF** | Water Scarcity Footprint |
| **WSI** | Water Stress Index |
| **WULCA** | Water Use in Life Cycle Assessment |

## 1. *INTRODUCTION*

Energy as a resource is universally recognised as a key factor influencing sustainable development within society today. It may be viewed not only as an enabler of sustainable development (i.e. essential for economic, social, cultural, or technological activities, and progress), but also as a significant platform, on which the principles of sustainability (such as efficiency) may be effectively applied. This multidimensional influence is reflected in one analogy of sustainable energy as "*the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive*" as presented by the former U.N. Secretary-General, Ban Ki-moon [1].

Mekonnen et al. 2015 [2] notes that electricity is the fastest growing form of final energy use; projected to almost double in the two decades following 2012. Understandably, there is significant global interest in the impacts of electricity generation on the social, economic, and environmental welfare of different (and at times conflicting) stakeholders in society. For example, electricity generation may be linked to positive economic growth and prosperity [3], but also to environmental damage [4]. Furthermore, the globalisation of electricity generation value chains has increased the complexity of associated systems; resulting at times in unforeseen effects of specific decisions and actions. Sustainable development, as described by Brundtland et al. (1987) should be "*a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and the institutional changes are made consistent with future as well as present needs*." [5] From this widely adopted definition, it can be inferred that appropriate methods of assessment are essential to systematically identify relevant opportunities, in ensuring that sustainability is achieved.

The environmental life cycle assessment (E-LCA) methodology seeks to comprehensively identify the impacts at each stage of the production, use and disposal of a product, process or system, in order to avoid the shifting, or ignoring of associated burdens. This methodology has been adapted to have a holistic, multidimensional perspective; thus creating Life Cycle Sustainability Assessment (LCSA) [6]. As a decision support tool, the LCSA is suitable for the case of electricity generation, due to system complexities which may transcend single sustainability dimensions and boundaries. By reviewing the existing methods and indicators used for LCSA of electricity generation, one can adapt and apply these to assess a particular case or scenario and where possible, enhance a system's overall sustainability. Since the impacts that originate from the electricity generation phase can differ significantly according to the technology used, comparison between technology options forms a good basis for such assessment.

With this in mind, the following thesis seeks to holistically assess and compare the life cycle impacts of different key electricity generation systems in Portugal (coal, natural gas, hydro, wind and photovoltaic), using a concurrent, multidimensional (environmental, and socioeconomic) approach.

### *1.1 Literature Review*

A literature review was carried out; mainly to identify and examine relevant LCSA frameworks and indicators used for the assessment of electricity generation systems. An understanding of the basis for these has contributed to the methodology applied to the current study – discussed further in Chapter 2. The significance of sustainability assessment of electricity generation is reflected in the steadily growing volume, and variety of related literature. For the current study, the author has considered three main types of literature: international standards; institutional guidelines, and publications (mainly journal articles) on sustainability assessment of electricity systems. Many of the existing frameworks related to life cycle assessment (LCA – and by extension, LCSA) are based on concepts outlined in the International Standard, ISO 14040, 2006: *Environmental Management LCA Principles and Guidelines* [7] and ISO 14044, : *Requirements and Guidelines*. These standards address environmental life cycle assessment (E-LCA) and provide a working definition of LCA as the "*systematic compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle*". Based on this, the standards outline key components deemed necessary for carrying out comprehensive life cycle assessment – which most studies aim to adhere to. Application of these concepts is described further in Chapter 2.

Institutional guidelines have also been developed for LCSA, through multi-stakeholder consultation. The United Nations Environmental Program (UNEP) in collaboration with the Society for Environment, Toxicology and Chemistry (SETAC) have produced general guidelines for LCSA [6] as well as those specifically for *social* life cycle assessment (S-LCA) of products [8]. The latter of these guides proposes several examples of social sustainability indicators – categorised into the following stakeholder groups: workers, local community, society, consumers, and value chain actors. These indicators are presented mainly as examples, without obligation for LCSA practitioners to adopt them in studies. For the specific context of electricity generation, there appears to be little to no correlation between the proposed S-LCA indicators, presented in [8] and the indicators used in previous case studies (Table 1). This may reflect not only the complexity of social sustainability assessment (and the great variety of indicators that one may consider), but also the underdeveloped or emergent nature of S-LCA, and the indicators or methods used within it. Comparatively, there is more consensus within environmental assessment. The International Reference Life Cycle Data System (ILCD) has issued guidelines for both the framework and requirements of an environmental life cycle impact assessment (LCIA) [9] and recommended indicators and methods [10].

Previous LCSA studies on electricity generation systems are summarised in **Table 1** below. Studies which only assessed the impacts of electricity generation for a particular sustainability dimension or technology (e.g. environmental impacts of global technologies [11], economic impacts of RES-E systems through job creation [12] or social impacts of concentrated solar plants [13]), are not addressed in Table 1, as the current study only focussed on cases for which a wider, multidimensional perspective was adopted, to assess different technologies. By this approach, the most significant indicators and LCSA methods could be identified in a comprehensive and efficient way. Also, methods which were used for subsequent integration of impacts from different dimensions (through trade-offs) could be considered.

LCSA studies have been carried out to assess electricity generation systems in Turkey [14], UK [15][16], Mexico [17][18], Australia [19], and Germany [20]. Other observed studies dually considered the environmental and economic impacts in UK [21], Nigeria [22], and Singapore [23]. In addition to the common sustainability dimensions, a technical/technological dimension was also considered in some studies e.g. [16], [24]–[26]. It is worth noting that sustainability dimension divisions may be regarded as somewhat arbitrary, and LCSA frameworks may assign similar impacts and indicators to different dimensions, according to the objectives of their study, as commented on by Maxim in [24]. In addition to assessing and comparing the range of technologies in respective national mixes, some studies also considered the variation of the mix (and its associated impacts) over time [15], as well as possible future electricity mix scenarios [16],[17].

The studies presented in Table 1 used environmental life cycle assessment (E-LCA) to assess impacts related to climate change, resource depletion, and polluting emissions. Of the 25 environmental indicators used across the range of studies (presented in Table 1), the most commonly assessed environmental impacts were *global warming potential*, *land use*, *acidification* and *eutrophication*. For the economic dimension, most studies adopted life cycle costing; within which *levelised cost of electricity*, and *capital costs* were the most widely used of the 12 indicators identified. Among social sustainability assessments there was significant variability, with 37 distinct indicators identified. *Employment* and *human health* were the most commonly assessed impacts. It was observed that some social indicators are directly quantifiable (e.g. for employment-related impacts) while others are linked to environmental metrics or indicators e.g. *human health* – linked to toxicity potential in [17]. It may be noted that while higher impacts within the environmental and economic dimension were generally regarded as negative (i.e. costs to be avoided/mitigated), the indicators expressing social impacts were more variable, and could be either promoted; e.g. *proportion of local staff* in [15] or avoided, as with *noise and local disturbance* in [25].

Within the reviewed studies [14]–[16], [18]–[20], LCSA practitioners based their selection of respective sets of sustainability indicators on the following considerations:

- Reviews of previous studies for similar contexts
- Review of relevant government and industry reports, policy objectives, strategy documents
- Engagement and dialogue with stakeholders from industry, government, academia, non-governmental organizations etc.
- Relevance of indicators for the assessment of specific generation methods (e.g. indicators related to radioactivity for nuclear power stations)
- Relevance of indicators to the goal and scope of the study

The multidimensional nature of LCSA recognises that trade-offs and compromises are required between stakeholder interests, to facilitate holistic decision-making. A number of studies have considered methods for the integration of sustainability indicators, thus enhancing LCSA as a decision support tool. These include multi-criteria decision analysis (MCDA) methods, such as multi-attribute value theory (MAVT) in [14], SWING in [24], and PROMETHEE in [27]. The scope of the current study does not include the integration of impact assessment results across sustainability dimensions. However, an un-weighted comparative summary of the assessed impacts is presented in Chapter 3.

For the context of Portugal, existing literature related to the sustainability assessment of electricity generation systems was reviewed. Within these, research gaps were identified which the current study seeks to address. An E-LCA was carried out by Garcia et al. 2014 [28], which assessed and compared environmental impacts between different generation technologies, as well as the historical evolution of the supply mix (generation and transmission) from 2003 to 2012. This study observed an overall reduction in environmental impacts associated with the electricity system in Portugal over this period. Significant contributions to this reduction were attributed to improvements to emissions cleaning, and decommissioning of fossil power plants; in conformance with the large combustion plant EU Directive [29]. Also noted was a reduction in overall electricity generation share from renewable sources between 2010 and 2012, despite an increase in installed generation capacity. This was due to meteorological and hydrological variability; adversely affecting hydro generation which constituted a significant share of total electricity generated (around 30% in 2014). A planned reduction in the share of dependence on hydroelectricity generation is projected by IEA, 2016 [30]. The current study thus aims to address research gaps in the existing E-LCA for the Portuguese context [28] by expanding the scope to consider socioeconomic impacts; employing additional sustainability indicators for water use impact (described further below); as well as reviewing and updating the system models, LCIA methods and databases used. The selected timeframe for the current study (2012–2016) also serves as a chronological extension of the one presented in Garcia et al. 2014 (2003 – 2012).

The impact of electricity generation on water resources is a significant concern within sustainability assessment, as part of the critical concept of the water–energy nexus [31]. The international standard on water footprint assessment: ISO 14046 [32] reflects this; by requiring studies to comply with certain key guidelines. In addition to adopting a life cycle perspective, the results for water footprint should include impact assessment (i.e. not only volumetric estimation) and address regional issues, such as water scarcity. Furthermore, the assessment methods used should account for the impact of water use; on both quality *and* quantity of water resources. Within the literature, several studies assessed the impact of electricity generation systems on water *quality* (along with other environmental impacts), using indicators such as: *eutrophication*, *acidification* and *ecotoxicity* (refer to Table 1). However, due to the apparent complexity of assessing water use impact related to *quantity*, other studies tended to address water consumption (of different systems) as a standalone impact.

Macknick et al. 2014 [33] provided a review and harmonisation of water consumption estimates for electricity generators, from other related literature, while Spang et al. 2014 [34] and Mekonnen et al. 2016 [2] assessed and compared the water consumption of different technologies globally, per unit of electricity generated. The latter of these adopted a life cycle (LC) perspective (as recommended by ISO 14046); accounting for the respective impacts of particular LC phases. It was noted that [33] and [34] excluded hydropower from their analyses; due to the complexity involved in assessing water balance, the effects of evapotranspiration, and accounting for other reservoir functions. It was noted that all of these studies which compared multiple generation technologies only considered the *volumetric* consumption of water; without accounting for geographical variation or impact assessment, as recommended by ISO 14046 [32]. In contrast, studies which included impact assessment beyond volumetric consumption for water use, only evaluated single technologies. Pfister and Scherer carried out studies to estimate the water scarcity footprint (WSF) for reservoir-based hydropower [35], [36]; using water stress indices (WSI) [37]. This thesis compares water use of different systems more comprehensively, applying impact assessment – described in Section 2.3.3

One of the key socioeconomic impacts assessed in the literature was *employment provision*. For the context of Portugal, studies have been carried out by Henriques et al. [38] and Oliveira et al. [12], to estimate the impact that the implementation of renewable-based generation systems (RES-E) might have on employment. Both of these studies used a 'top-down', input-output analysis approach.. Notwithstanding that the most recent input-output table for Portugal is from 2008 (and may be out-of-date), the IOA method is based on industry-wide effects, and may not allow for accurate comparison of specific technologies, and life cycle phases occurring outside of Portugal. This thesis considers a different approach applying a new method presented in Rutovitz et al. 2015 [39]; which involves a 'bottom-up', empirical approach to estimate the employment created in Portugal using historical generation data – described further in Section 2.3.3.

**Table 1: Summary of indicators used in recent LCSA studies for electricity generation systems**

| Sustainability Indicators used in recent LCSA studies for Electricity Generation Systems | Indicator Units | Recent LCSA studies for Electricity Generation Systems | | | | | | | | | | | Indicator Frequency |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (Atilgan & Azapagic 2016) | (Santoyo-Castelazo & Azapagic 2014) | (Maxim 2014) | (Stamford & Azapagic 2014) | (Troldborg et al. 2014) | (Stamford & Azapagic 2012) | (Stamford & Azapagic 2011) | (Evans et al. 2009) | (Genoud and Lesourd 2009) | (May and Brennan 2006) | (Hirschberg et al. 2004) | |
| | **Literature Reference** | [14] | [17] | [24] | [16] | [27] | [16] | [40] | [25] | [26] | [19] | [20] | |
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | |
| **ENVIRONMENTAL INDICATORS** | | | | | | | | | | | | | |
| Global Warming Potential | $kgCO_2$ eq./kWh | X | X | | X | X | X | X | X | | X | X | 10 |
| Land Use/Occupation | m2/kWh | | | X | X | X | X | X | X | X | | X | 8 |
| Acidification | $kgSO_2$ eq./kWh | X | X | | X | | X | X | | | X | | 7 |
| Eutrophication | $kgPO_4$ eq./kWh | X | X | | X | | X | X | | | X | | 7 |
| Abiotic Depletion (Elements) | kgSb eq./kWh | X | X | | | | X | X | | | X | | 6 |
| Fresh Water Aquatic Eco-Toxicity | kgDCB eq./kWh | X | X | | X | | X | X | | | X | | 6 |
| Ozone Layer Depletion | kgCFC-11eq./kWh | X | X | | X | | X | X | | | | | 6 |
| Photochemical Oxidants Creation | $kgC_2H_4$ eq./kWh | X | X | | X | | X | X | | | | | 6 |
| Abiotic Depletion (Fossil Fuels) | MJ/kWh | X | | | | | X | X | | | X | | 5 |
| Marine Aquatic Eco-Toxicity | kgDCB eq./kWh | X | X | | X | | X | | | | X | | 5 |
| Terrestrial Eco-Toxicity | kgDCB eq./kWh | X | X | | X | | X | | | | X | | 5 |
| Human Toxicity | kgDCB eq./kWh | X | X | | | | | | | | X | | 3 |
| Recyclability of input materials | % | | | | X | | X | X | | | | | 3 |
| Water consumption | m3/kWh | | | | | | | | X | | X | | 2 |
| Emissions of Particulates | kg/kWh | | | | | | | | | X | X | | 2 |
| Solid Wastes | kg/kWh | | | | | | | | | | X | X | 2 |
| Greenfield Land Use (proportion of new development on previously undeveloped land relative to total land occupied) | % | | | | | | X | | | | | | 1 |
| External Costs (Environmental) | Qualitative (1-5) | | | X | | | | | | | | | 1 |
| Impacts on amenity | Qualitative (1-5) | | | | | X | | | | | | | 1 |
| Emissions of $CO_2$, NOx, $SO_2$, VOC, Cd, $CH_4$ | kg/kWh | | | | | | | | | X | | | 1 |
| Biochemical Oxygen Demand | N.S. | | | | | | | | | X | | | 1 |
| Radioactivity | N.S. | | | | | | | | | X | | | 1 |
| Noise Pollution | N.S. | | | | | | | | | X | | | 1 |
| Energy Payback (EROI) | N.S. | | | | | | | | | X | | | 1 |
| Regional environmental impact | $km^2$/kWh | | | | | | | | | | | X | 1 |
| **ECONOMIC INDICATORS** | | | | | | | | | | | | | |
| Levelised Costs (of Electricity) | €/year | X | X | X | X | X | X | X | X | X | | | 9 |
| Capital Costs | € | X | X | | X | | X | X | | | X | X | 7 |
| Fuel Costs | €/kWh | | | | X | | X | X | | | | | 3 |
| Economic Dispatchability (Ratio of capital cost to total levelised generation cost) | Percentage (%) | | | | X | | X | X | | | | | 3 |
| Operation and Maintenance Costs | €/kWh | | | | X | | X | X | | | | | 3 |
| Total Annualised Costs | €/kWh | X | X | | | | | | | | | | 2 |
| Financial incentives and assistance (e.g. ROCs, taxpayer burdens) | €/kWh | | | | | | X | X | | | | | 2 |
| Contribution to economy | Qualitative (1-5) | | | | | X | | | | | | | 1 |
| Wealth Generation | N.S.[d] | | | | | | | | | | X | | 1 |
| Long-term sustainability: Energy-based | Years | | | | | | | | | | | X | 1 |
| Long-term sustainability: non-energy based | kg/kWh | | | | | | | | | | | X | 1 |
| Geopolitical factors | Relative scale | | | | | | | | | | | X | 1 |
| | | | | | | | | | | | | | |
| **TECHNOLOGICAL/OTHER INDICATORS** | | | | | | | | | | | | | |
| Ability to respond to demand/Technical Dispatchability | Summed Rank | | | X | X | | X | X | | X | | | 5 |
| Availability Factor | Percentage (%) | | | | X | | X | X | X | | | X | 5 |
| Capacity Factor | Percentage (%) | | | X | X | | X | X | | | | | 4 |
| Fuel price sensitivity (ratio of fuel cost to total levelised generation cost) | Dimensionless | | | | X | | X | X | | | | X | 4 |
| Efficiency | Percentage (%) | | | X | | | | | X | X | | | 3 |
| Lifetime of global fuel reserves at current extraction rates | Years | | | | X | | X | X | | | | | 3 |
| Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or thermal/ +C281 thermochemical H2 production) and operational lifetime | Years−1 | | | | X | | X | X | | | | | 3 |
| Time of plant start-up to construction | Months | | | | X | | X | X | | | | | 3 |
| Potential total power generation | TWh/year | | | | | X | | | | | | | 1 |

| Sustainability Indicators used in recent LCSA studies for Electricity Generation Systems | Indicator Units | Recent LCSA studies for Electricity Generation Systems | | | | | | | | | | | Indicator Frequency |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (Atilgan & Azapagic 2016) | (Santoyo-Castelazo & Azapagic 2014) | (Maxim 2014) | (Stamford & Azapagic 2014) | (Troldborg et al. 2014) | (Stamford & Azapagic 2012) | (Stamford & Azapagic 2011) | (Evans et al. 2009) | (Genoud and Lesourd 2009) | (May and Brennan 2006) | (Hirschberg et al. 2004) | |
| | **Literature Reference** | [14] | [17] | [24] | [16] | [27] | [16] | [40] | [25] | [26] | [19] | [20] | |
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | |
| Technology maturity | Qualitative (1-5) | | | | | X | | | | | | | 1 |
| Renewability | Qualitative (1-5) | | | | | | | | | X | | | 1 |
| Possibility of Growth | Qualitative (1-5) | | | | | | | | | X | | | 1 |
| Peak load response | Relative scale | | | | | | | | | | | X | 1 |
| **SOCIAL INDICATORS** | | | | | | | | | | | | | |
| Total employment (direct + indirect)/ Job Creation | Person-years/TWh | X | | X | X | | X | X | | X | X | | 7 |
| Human Health Impacts (based on Human Toxicity Potential, excl. Radiation) | kgDCB eq./kWh[a] | | X | X | X | | X | X | X | | | X | 7 |
| Direct employment | Person-years/TWh | X | | | X | | X | X | | | X | X | 6 |
| Fatalities due to large accidents | No.fatalities/TWh | X | | | X | | X | X | | | X | X | 6 |
| Worker Injuries | No.injuries/TWh | X | | | X | | X | | | | X | | 4 |
| Imported fossil fuel potentially avoided | toe/kWh[b] | X | | | X | | X | X | | | | | 4 |
| Diversity of fuel supply mix | Score(0–1) | X | | | X | | X | X | | | | | 4 |
| Long-lived Hazardous (Radioactive) Waste to be stored | $m^3$/kWh | | X | | X | | X | X | | | | | 4 |
| Long-lived Hazardous (Liquid CO2) Waste to be stored | $m^3$/kWh | | X | | X | | X | X | | | | | 4 |
| Spending on local suppliers relative to total annual spending | Percentage (%) | | | | | | X | X | | X | | | 3 |
| Fuel storage capabilities (energy density) | GJ/$m^3$ | | | | X | | X | X | | | | | 3 |
| Social Acceptability (based on existing surveys) | Qualitative | | X | X | | X | | | | | | | 3 |
| Mitigation of Climate Change (based on Global Warming Potential) | $kgCO_2$ eq./kWh | | X | | X | | | X | | | | | 3 |
| Depletion of Fossil Fuel Reserves (Based on Abiotic Depletion) | MJ/kWh | | X | | X | | | X | | | | | 3 |
| Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium | Score (0–3) | | | | X | | X | X | | | | | 3 |
| Proportion of staff hired from local community relative to total direct employment | Percentage (%) | | | | | | X | X | | | | | 2 |
| Direct investment in local community as proportion of total annual profits | Percentage (%) | | | | | | X | X | | | | | 2 |
| Reliability of supply | Percentage (%) | | X | | | X | | | | | | | 2 |
| Worker Human health impacts from radiation | DALY/GWh[c] | | | | | | X | X | | | | | 2 |
| Total human health impacts from radiation (workers and population) | DALY/GWh[c] | | | | X | | X | | | | | | 2 |
| External Supply Risk | Relative scale | | | X | | | | | | X | | | 2 |
| Involvement of countries in the life cycle with known corruption problems (based on Transparency International Corruption Perceptions Index) | Score (0–10) | | | | | | X | X | | | | | 2 |
| Noise/ Local Disturbance | Relative scale | | | | | | | | X | | | X | 2 |
| Depletion of fossil fuel reserves (Abiotic Depletion) | MJ/kWh | | X | | | | | | | | | | 1 |
| Import dependency (Abiotic Depletion of National Reserves) | MJ/kWh | | X | | | | | | | | | | 1 |
| Availability of renewable energy resources | Percentage (%) | | X | | | | | | | | | | 1 |
| Safety Risks | Relative scale | | X | | | | | | | | | | 1 |
| Bird Strike Risk | No./kWh | | | | | | | | X | | | | 1 |
| Visual Amenity | N.S.[d] | | | | | | | | X | | | | 1 |
| Effect on Agriculture and Seismic Activity | $m^2$/kWh | | | | | | | | X | | | | 1 |
| Odour | N.S.[d] | | | | | | | | X | | | | 1 |
| River Damage | N.S.[d] | | | | | | | | X | | | | 1 |
| Notion of Public Good | N.S.[d] | | | | | | | | | X | | | 1 |
| Proliferation | Relative scale | | | | | | | | | | | X | 1 |
| Critical waste confinement | Thousands of years | | | | | | | | | | | X | 1 |
| Risk Aversion | Max. fatalities/accident | | | | | | | | | | | X | 1 |
| Total waste | tonne/kWh | | | | | | | | | | X | | 1 |

**Legend**: [a] DALY – Disability-Adjusted Life Year [b] toe – Tonnes of Oil Equivalent [c] DCB – Dichlorobenzene [d] N.S. – Not Specified

## 1.2 *Electricity Generation System in Portugal*

The total installed power capacity in Portugal was 19.5 GW by the end of 2016 [41], having increased 9.7% since 2013, as presented in Figure 1 below. A slight reduction in capacity (4%) between 2012 and 2013 was due to the decommissioning of small thermal plants. In 2016, the total annual electricity generation was around 56 TWh [41] representing a 31% increase since 2012. Different technologies contributed the following shares to the total generation: hydro: 29.8%, wind: 21.8%, coal: 20.9%, natural gas: 20.7%, biomass: 4.8%, photovoltaic: 1.4%, and other methods 0.6%. There was a notable reduction in hydro generation in 2015, due to low precipitation in the previous year. Further details of the generation mix are also presented in Appendix I.

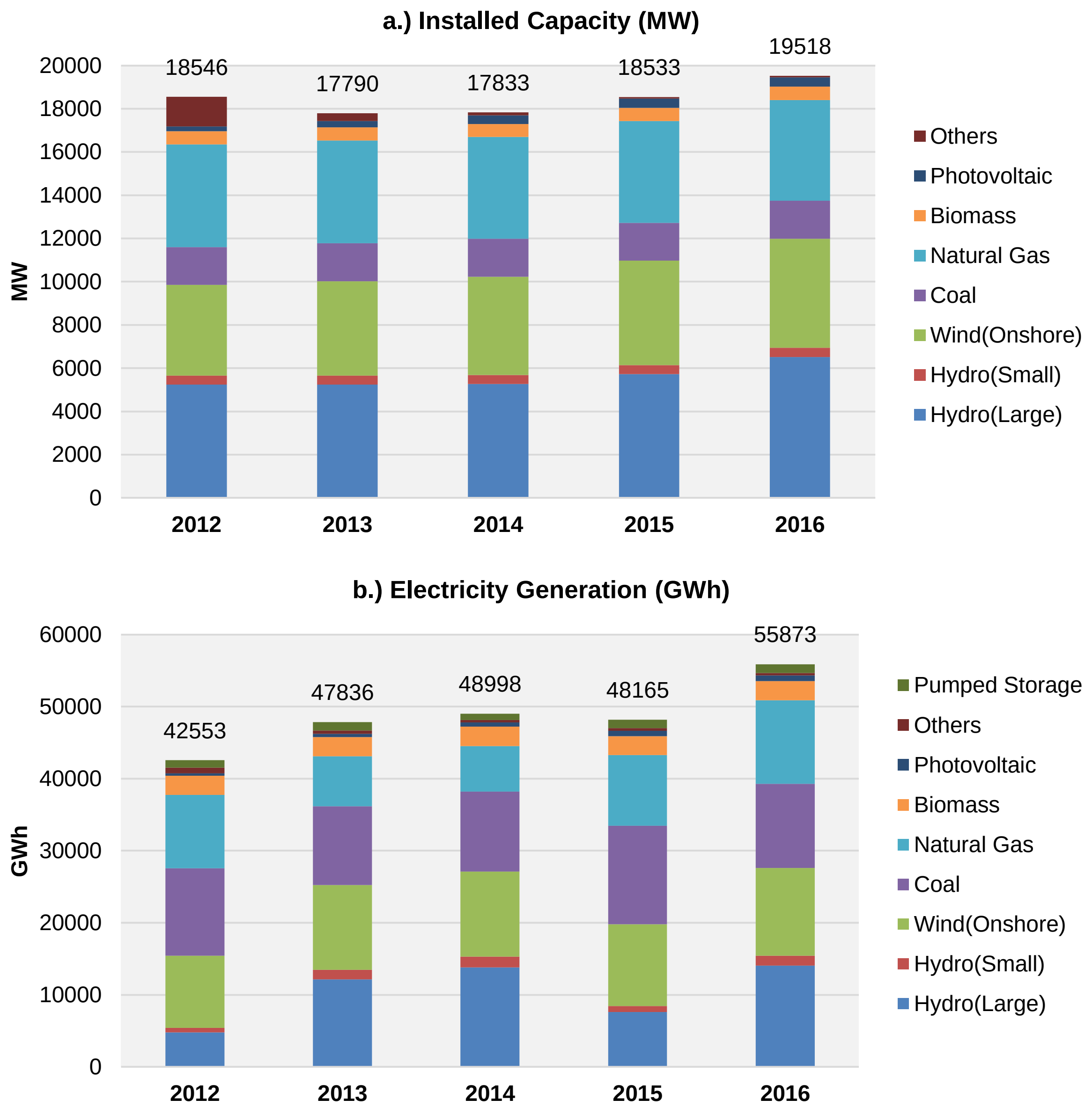



**Figure 1: Annual installed capacity and generation from 2012 to 2016 – REN Data** [41]–[45]

Renewable energy sources represent approximately 57% of Portugal's total electricity generation [41]. This is considerably higher than the equivalent renewable electricity generation shares in OECD and EU-28 countries of 23% and 27.5% respectively [46]. Non-renewable energy sources represent 43% of total electricity generation in Portugal, compared to 77% and 72.5% in OECD and EU-28 countries respectively.

Portugal has been widely commended for its ambitious, large-scale adoption of renewable energy [47]. Globally, Portugal ranks second-highest behind Denmark in terms of share of electricity generated from wind power [30], and among the top 20 worldwide for installed capacity. Globally it ranks fifth-highest in terms of electricity per capita from non-hydro renewable sources [3]. Notwithstanding Portugal's favourable geographical and climatic conditions for exploiting available resources (e.g. wind, solar, hydro), the success in deploying significant renewables in electricity generation can equally be attributed to actions in the implementation of European Union (EU) policies. These include the EU Renewable Energy Sources (RES) Directive [48], the EU Large Combustion Plant Directive [29] and the EU Cogeneration Directive [49]. Among EU nations, Portugal has set the 5$^{th}$ most ambitious target for gross final energy consumption from renewables - 31% in 2020 (the EU's overall target being 20%). As part of this, a sector-specific target of 60% of electricity generated from renewable resources has been set for 2020; which is on track at 57%[41].

Portugal does not have domestic reserves of fossil fuels. For electricity generation coal is sourced from Colombia (88.1%), USA (6.6%), South Africa (3.5%), and Ukraine (1.8%), while Natural Gas originates from Nigeria (46%), Algeria (35%), and other sources (19%), as documented in [30]. From the LCSA perspective, the physical origins of fossil fuels is important to consider; as its extraction (and associated activities) can result in unforeseen upstream impacts e.g. socioeconomic impacts of employment, as discussed in Chapter 2.

### 1.3 Research Objectives and Areas of Novelty

Based on the preliminary ideas and findings outlined previously in this chapter (related to LCSA of electricity generation systems), the overall research objective of this thesis is to estimate and compare the environmental and socioeconomic impacts associated with six, key electricity generation systems in Portugal namely; coal, natural gas, hydro (large and small), wind, and photovoltaic (PV).

Within this, the current study aims to achieve a number of specific objectives, including:

- Comprehensive review of the current available LCSA literature and knowledge, exploring sustainability indicators and assessment methods relevant to electricity generation
- Suitable application of indicators and methods to perform a LCSA study in the Portuguese context
- Identifying areas of most significant impact for the recent existing generation portfolio, and also considering the effects of temporal variation
- Identifying opportunities for sustainability enhancement based on the assessment results
- Assessing the applicability of LCSA methodology to electricity generation and its contribution towards forming a reliable decision-making support tool

In achieving these research objectives, the current study aims to contribute to the field of knowledge with the following aspects of novelty:

- Updating the models and methods for the previous E-LCA of the Portuguese electricity generation systems, carried out by Garcia et al. 2014 [28]
- Comparative impact assessment of water scarcity footprint between a range of Portugal’s key generation technologies (in addition to volumetric consumption)
- Application of multi-indicator social life cycle assessment (S-LCA) to the Portuguese electricity generation context to assess relevant sustainability impacts concurrently, and holistically

## 2. *METHODS AND MATERIALS*

The following chapter presents the methodology adopted for developing multidimensional sustainability assessment models; describing how the selected issues, indicators and methods were applied.

### *2.1 Sustainability Assessment Framework*

The assessment framework for the current study (as summarised in
Figure 2 below) was adapted from the environmental life cycle assessment (E-LCA) methodology, as presented in ISO 14040, 2006 [7]. In addition to previously defined, key E-LCA stages, such as goal and scope definition, development and analysis of life cycle inventories, and interpretation of results, the current framework also recognises preliminary stages (literature review, and characterisation of electricity generation systems – described previously in Chapter 1), which are essential for understanding the context of the assessment and developing suitable, holistic models.

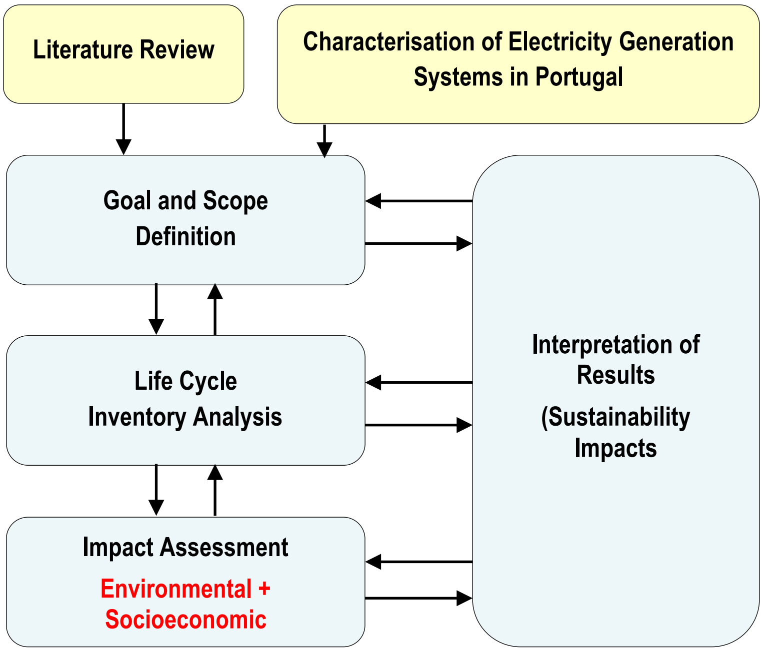



**Figure 2: Framework for current LCSA on electricity generation – adapted from** [7]

The remaining sections of this chapter discuss the goal and scope, life cycle inventories and impact assessment, while results are presented in Section 3, with other aspects of results interpretation and validation presented beyond that. The LCSA framework above also illustrates the iterative nature of the LCSA process; as different aspects are reviewed and revised over the course of the study, to achieve its overall goal.

### 2.2 Goal and Scope Definition

The goal of the current study is to estimate and compare the life cycle sustainability impacts associated with the generation of electricity from key technologies in Portugal; with a view to identify potential opportunities for efficiency, or sustainability improvement. In terms of scope, the assessment was carried out on a full life cycle basis ('cradle-to-grave'), adopting a multidimensional perspective; considering environmental and socioeconomic impacts.

As summarised in Figure 3 below, the life cycle phases accounted for included: materials production and component assembly; extraction, processing and transportation of fuels; plant construction; plant operation and maintenance; and plant decommissioning, waste treatment and disposal. The life cycle phases were categorised as part of either a foreground system (based on specific data for systems in Portugal); or the background system (based on global upstream processes and systems). The data and assumptions relating to this are discussed further in Section 2.3. The functional unit for the current study is 1 MWh of electricity generated.

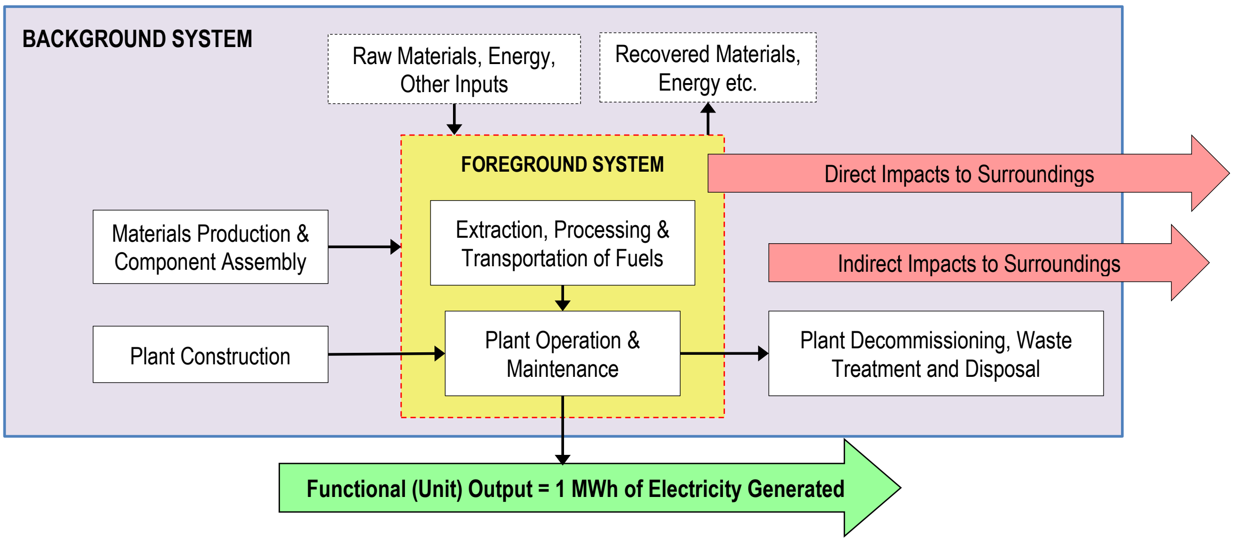



**Figure 3: Life cycle phases for LCSA of electricity generation**

The downstream stages of the electricity supply value chain (i.e. distribution, transmission, and retail) are not relevant in terms of the comparison of generation systems, are outside the scope of the current study. The reference year for the current study is 2016. As well as comparing the impacts associated with individual systems in this year the period from 2012 to 2016 is also considered for certain indicators. By adopting a timeframe of more than a single year, the study takes into account the variability of generation (and associated impacts) from one year to another. This may be influenced by a combination of factors, such as: response to demand, changing weather and hydrological patterns, policy amendments, fluctuation of fuel prices etc. In addition to considering variability, this approach also serves as an extension to the E-LCA study carried out by Garcia et al. on the Portuguese electricity mix, where the timeframe considered was 2003 to 2012 [28].

### 2.2.1 Selection of Generation Technologies

As described in Chapter 1, the electricity generation mix of Portugal is based on a diverse range of primary energy sources. The current study has assessed the life cycle sustainability impacts for the following key generation technologies: coal, natural gas, hydro (large and small), wind, and photovoltaic (PV). These technologies constituted over 90% of both the total installed capacity, and generation in 2016 [41]. Other generation technologies (biomass, geothermal, fuel oil, etc.), were omitted from the study as they represent a significantly smaller share of installed capacity in the existing generation mix. While PV systems do not currently represent a large share of generation, they were included based on significant evidence for expected future growth.

In spite of significant trends and policies towards increased deployment of renewables (as discussed in Chapter 1) the inclusion of fossil fuel systems not only recognises their sustained importance within the electricity generation mix (as dispatchable, and base load generation systems), but also allows for the recognition and assessment of wider impacts, associated with the importation of fossil fuels. Since Portugal does not have domestic fossil fuel reserves, the life cycle stage for extraction, processing and transportation of fuels does not occur within Portugal. The impacts related to this critical phase might otherwise be overlooked if the system boundaries did not include the origins of these fuels, or if the study omitted fossil fuels completely. The data sources and assumptions for each of the selected technologies are described further in Section 2.3 as part of the life cycle inventories.

### 2.2.2 Selection of Sustainability Indicators and Assessment Methods

As mentioned in the literature review, the selection of sustainability issues, indicators and assessment methods is a critical step in the development of LCSA models. The final form and trend of the assessment results are directly determined by these selections. This can influence not only the overall *perceived* sustainability performance of the elements or systems being assessed, but also the subsequent recommendations and decisions towards sustainability improvement. Thus, it is essential to understand the basis upon which these selections are made; in order to avoid potential bias, and acknowledge methodological limitations. In light of this, the following selection criteria were considered:

i. **Recommendations from relevant guidelines.** The International Reference Life Cycle Data (ILCD) system handbook [10] provides a set of suggested environmental indicators and recommends suitable assessment methods to be used (based on the robustness of these methods); which were taken into consideration. For the socioeconomic dimension, social LCA guidelines from the UNEP/SETAC initiative [8] were considered, however it was noted that the suggested social indicators were more product-based than system-based; and hence were not deemed suitable to be applied to the context of the current study.

ii. **Applicability to goal and scope.** The relevant system boundaries and characteristics of technologies were considered. For example (within the current study), under the socioeconomic dimension, indicators for *employment generation* were included, whereas those for *health effects of radioactive waste* were omitted. The latter of these is typically applied to nuclear power e.g. in Stamford and Azapagic, 2011 [40], which is outside the scope of the study.

iii. **Compatibility or coherence with previous LCSAs or sustainability studies.** By selecting indicators and methods related to those used in previous assessments (e.g. academic studies, government and industry reports, etc.), one is able to validate methods used, as well as verify results obtained through comparison with studies of similar systems. This is particularly relevant, as the application of LCSA to electricity generation is not particularly well-developed.

iv. **Availability of reliable data sources**. The availability of reliable data sources for different electricity generation technologies, as well as different life cycle stages was essential for developing accurate assessment models. Where reliable data were not available, assumptions were made, as required. This is discussed further in Section 2.3, under life cycle inventories.

v. **Comparability between elements under study**. Considering the inherent differences between the technologies within the current study, type-specific issues and indicators were avoided, in favour of more general, comparable ones. For example, Evans et al. 2009 [25] uses the indicator *bird strike risk* to assess social sustainability, which is strongly associated with wind turbines. Although wind power is within the scope of the current study – constituting a significant share of both installed capacity and generation (22%) *bird strike risk* was omitted, as it has disproportionately high sensitivity to wind power generation, compared to other technologies, and thus cannot reasonably be compared.

As mentioned previously, the selected issues and indicators were categorised according to sustainability dimension, as either environmental or socioeconomic. However, these divisions may be regarded as somewhat arbitrary, due to the inherent interaction and interconnection between different issues and respective indicators. The following sub-sections of this chapter describe (in more detail) the selected environmental and socioeconomic indicators; as well as methods that were used to estimate them, and their relevance for the context. A summary of this is presented in Table 2 below.

**Table 2: Selected sustainability issues, indicators and assessment methods**

| Issues | Indicators | Units | Assessment Method (Reference) |
|---|---|---|---|
| **ENVIRONMENTAL** | | | |
| Resource Depletion | Metal Depletion | kg Fe eq./MWh | ReCiPe (Midpoint) (H) V1.11/EU |
| | Fossil Fuel Depletion | kg oil eq./MWh | (Huijbregts et al. 2017) [50] |
| Energy Demand | Non-Renewable Primary Energy | $MJ_{prim}$/MWh | CED V1.09 (Hischier et al. 2010) [51] |
| Climate Change | Global Warming Potential | kg $CO_2$ eq./MWh | IPCC 2013 GWP 100a (IPCC, 2014) [52] |
| Air and Soil Pollution | Ozone Depletion | kg CFC-11 eq./MWh | ReCiPe (Midpoint) (H) V1.11/EU |
| | Terrestrial Acidification | kg $SO_2$ eq./MWh | (Huijbregts et al. 2017) [50] |
| Freshwater Use Impact | Freshwater Eutrophication | kg $PO_4^{3-}$ eq./MWh | ReCiPe (as above) |
| | Aquatic Acidification | kg $SO_2$ eq./MWh | Impact 2002+ v2.12 (Jolliet et al. 2003) [53] |
| | Freshwater Ecotoxicity | CTUe/MWh | USETox v1.04 (Rosenbaum et al. 2008) [54] |
| | Freshwater Scarcity Footprint | world $m^3$eq./MWh | AWARE (Boulay et al. 2017) [55]; ReCiPe (above) |
| **SOCIOECONOMIC** | | | |
| Employment Generation | Domestic Employment | person-years/TWh | *Calculating Global Energy Sector Jobs* |
| | Total Employment | person-years/TWh | (Rutovitz et al. 2015) [39] |
| Health and Safety | Human Toxicity (Carcinogenic) | CTU/MWh | USETox (Rosenbaum et al. 2008) [54] |
| | Human Toxicity (Non-Carcinogenic) | CTU/MWh | ” |
| Energy Security | Dependence on Fossil Fuels | % relative to coal-based generation | Based on CED V1.09 (Hischier et al. 2010) [51] |
| Energy Availability | Capacity Factor | % | Ratio of Actual to Potential Generation |
| Energy Cost | Levelised Cost of Electricity | USD/MWh | *Projected Costs of Elec. Gen.* (IEA, 2015) [56] |

### *2.2.3 Environmental Considerations*

The E-LCA component followed the guidelines in standards ISO 14040 [7] and ISO 14044 ; as well as ISO 14046 [32] for freshwater use impact. As outlined in Table 2 above, five environmental issues were assessed, namely: resource depletion, energy demand, climate change, pollution to air, soil and water, and freshwater use impact. The nine environmental indicators which were used to address these issues are described in more detail below, along with their respective impact assessment methods (descriptions based on [57]). In all cases where the ReCiPe impact assessment method [50] was used, a hierarchist, midpoint (problem-oriented) approach was adopted, rather than an endpoint (damage-oriented) method. This is due to the higher uncertainty within the results obtained using the latter approach: related to the weighting of impacts and associated damage assessment.

#### *2.2.3.1 Metal Depletion and Fossil Fuel Depletion*

The depletion of abiotic resources through the extraction of metals and fossil fuels (due to system inputs) is based on concentration of reserves and their respective rates of de-accumulation. These have been characterised in kilograms of iron equivalent (kg Fe eq.) and kilograms of oil equivalent (kg oil eq.) for metals and fossil fuels respectively, using the ReCiPe method.

#### *2.2.3.2 Non-Renewable Primary Energy*

The requirement of non-renewable primary energy throughout the life cycle of the key electricity generation systems (due to system inputs), has been characterised in megajoules of primary energy using the Cumulative Energy Demand (CED) method [51]. This indicator relates closely to fossil fuel depletion, described above. The two indicators are particularly significant for E-LCA in the current context, as Portugal relies entirely on foreign imports for fossil fuels. In addition to assessing environmental impact, these indicators can be used to assess the issue of energy security and import dependency within the socioeconomic dimension – discussed further in Section 2.2.4.

#### *2.2.3.3 Global Warming*

The emission of greenhouse gases into the atmosphere from system outputs has been characterised in kilograms of carbon dioxide equivalent (kg $CO_2$ eq.) using the Intergovernmental Panel on Climate Change 2013 (IPCC) method [52], for the time horizon of 100 years (GWP100). In the context of E-LCA for electricity generation, global warming potential is one of the most widely used indicators (present in 9 out of 11 of the previous LCSA studies considered – refer to Table 1) reflecting a significant environmental concern for LCSA practitioners and other stakeholders.

#### 2.2.3.4 Ozone Layer Depletion

The emission of gases which are likely to destroy the stratospheric ozone layer has been characterised in kilograms of trichlorofluoromethane equivalent (kg CFC-11 eq.) using ReCiPe.

#### 2.2.3.5 Terrestrial Acidification

The emission of various soil–acidifying substances (including their fate and deposition) has been characterised in kilograms of sulfur dioxide equivalent (kg $SO_2$ eq.) using ReCiPe.

#### 2.2.3.6 Freshwater Degradation

The first component of freshwater use impact accounts for the reduction in *quality* of freshwater stocks, caused by direct pollution. It has been assessed using the following impact categories, as recommended by ILCD [10]:

**i.** *Freshwater Eutrophication* – excessive levels of macro-nutrients characterised in kilograms of phosphates equivalent (kg $PO_4^{3-}$ eq.) using the ReCiPe method.

**ii.** *Freshwater Acidification* – emission of acidifying substances to freshwater stocks characterised in kilograms of sulfur dioxide equivalent (kg $SO_2$ eq.) using the Impact 2002+ method.

**iii.** *Freshwater Eco-toxicity* – emission of substances toxic to humans and ecosystems, characterised in Comparative Toxic Units ecosystems (CTUe) using the USETox method.

#### 2.2.3.7 Freshwater Scarcity Footprint

The second component of freshwater use impact accounts for the *quantity* of freshwater consumed, as a result of system inputs. This has been assessed using AWARE characterisation factors, as presented by Boulay et al. 2017 [55], which considers the relative available water remaining in a watershed area, after the demand of humans and aquatic ecosystems has been met. As mentioned in Chapter 1, previous studies which compared the water consumption for multiple electricity generation systems only adopted a volumetric approach, without assessment of the impact of water consumption.

In contrast, the AWARE method aims to account for water use impact more comprehensively, by taking into account the geographical location of the point of consumption, and likelihood of water deprivation in that area. This recognises the potential (and at times, significant) variability of water use impact, depending on regional context. For the current study, water consumption was estimated using ReCiPe (under the category water depletion), and thereafter characterised in world cubic metres equivalent (world $m^3$ eq.) using AWARE regional characterisation factors for different parts of Portugal. Details of the data and assumptions used in this method are discussed in Section 2.3.3

### 2.2.4 Socioeconomic Considerations

Within the socioeconomic dimension of this study, five issues were addressed, namely: employment provision, health and safety, energy security, energy availability, and energy cost. The six socioeconomic indicators which were used to address these issues are described below; along with their respective impact assessment methods.

#### 2.2.4.1 Domestic and Total Employment

The amount of employment that is created throughout the life cycle of selected systems has been assessed using two indicators; domestic employment (i.e. within Portugal) and total employment (which includes non-domestic). These have been estimated in person-years per TWh generated, using the operational method presented by Rutovitz et al. 2015, [39]; by assigning employment factors to different life cycle phases, based on their technology and location. Application of this method and relevant assumptions are discussed further in Section 2.3.2. The unit TWh was used instead of the standard functional unit (MWh) to avoid results of a very small order of magnitude, which are difficult to conceptualise and compare.

#### 2.2.4.2 Human Health Impacts

The impacts of electricity generation on human health (due to the toxic emissions from system outputs) have been assessed using two indicators: carcinogenic- and non-carcinogenic human toxicity. These have been characterised in comparative toxic units, (CTUh) using the USETox method with recommended characterisation factors. Other occupational health impacts such as those resulting from workplace accidents, injuries, or exposure to hazardous substances were not included in this impact category.

#### 2.2.4.3 Dependence on Fossil Fuels

This indicator has been used to assess and compare the relative energy security for selected systems, based on a hypothetical scenario in which Portugal produces all of its electricity from coal power. It is derived from the impact category for consumption of non-renewable fossil energy (see Eq. 1 below). The current study considers a higher dependence on fossil fuels less secure, due to the required importation of fossil fuels.

$$\boldsymbol{Dependence\ on\ Fossi\ Fuels}\ (\%) = \frac{Non\ Ren. Prim. Energy\ Consumption_t\ (MJ/MWh)}{Non. Ren. Prim. Energy\ Consumption_{\ Coal\ Power}\ (MJ/MWh)} \times 100$$

***(Eq. 1)***

#### 2.2.4.4 Capacity Factor

This indicator has been used to assess the operational energy availability within selected systems. Following convention (as in [15], [16], [24], [40]), the capacity factor was calculated as the ratio of annual actual electricity generation to the theoretical potential maximum generation, assuming the system was operating continuously at full nameplate capacity for the one year, such that:

$$\boldsymbol{Annual\ Capacity\ Factor}\ (\%) = \frac{Average\ Annual\ Generation\ (MWh)}{Installed\ Capacity\ (MW) \times\ 8760\ (total\ annual\ hours)} \times 100$$

***(Eq. 2)***

Historical generation data for the timeframe of the study (2012-2016) was used to establish an average value, to account for annual variations which may have occurred due to factors such as: changes in operational costs (mainly due to fuel prices); changes in temporal load patterns (due to demand variation); differences in efficiency of generation technologies; and resource availability constraints (especially within renewable generators). In order to account for partial-year generation effect (i.e. where generators installed mid-year, and not providing a full year's production), an average annual value for installed capacity was used in calculations.

#### 2.2.4.5 Levelised Cost of Electricity

This indicator has been used to assess the cost of energy over the lifetime of the generation system. It refers to the total cost of building (capital expenditure) and operating (operational expenditure) a power plant over its lifetime, calculated at a discount rate, to account for the time value of money. Data was obtained from an International Energy Agency report to compare the selected systems [56]

## 2.3 Life Cycle Inventories and Modelling

### 2.3.1 General Data and Assumptions

The inventory data used to construct the life cycle models for the current study were collected from a number of sources, based on the power plants operating in Portugal. The technical details and characteristics of plants based on renewable energy were obtained from the *e2P – Endogenous Energies of Portugal* online database [58]. The data relating to fossil fuel power production were obtained from the environmental declarations for *Sines* [59] and *Ribatejo* [60], representing coal and natural gas respectively; as well as from key fuel suppliers e.g. *Galp* [61]. Operational data regarding the installed capacity and electricity generation of the power plants were obtained from the statistics database (*centro de informaçao* [62]), and annual technical data reports [41] and [42]–[45]; published by Portugal's electricity transmission system operator, REN (*Redes Energeticas Nacionais*). A summary of the characteristics of existing systems is presented in Table 3 below.

**Table 3: Details of power plants considered in current study**

| Type of Power Plant | Number of Plants | Installed Capacity (MW) | 2016 Generation (GWh) |
|---|---|---|---|
| Coal | 2 | 1756 | 11698 |
| Natural Gas | 4 | 3829 | 11571 |
| Hydro (Large) | 45 | 6522 | 14081 |
| Hydro (Small) | 162 | 423 | 1332 |
| Wind | 253 (2599 Turbines) | 5046 | 12188 |
| Photovoltaic [a] | 90+ | 439 | 781 |

***Note:*** *[a] Only utility scale PV plants were documented in e2P* [58] *however total installed capacity from REN* [41] *includes commercial and domestic (self-consumption) scale plants connected to the grid.*

The following simplifying assumptions were made for the generation technologies being assessed:

i. System characteristics and conditions (e.g. annual generation conversion efficiency, fuel and raw material origins etc.) were assumed to be constant throughout the plant lifetime, and for the duration of the timeframe where temporal variation was accounted for.

ii. Variations in efficiency or system performance due to the age of equipment or geographical location of power plant (which might affect availability of resources e.g. solar irradiance and wind speed) have been assumed to be negligible. Regional variation in water scarcity has been accounted for in the assessment of water use impact (refer to Section 2.3.3)

iii. Due to lack of data about the specific origins and supply chains of system components for all technologies, background data from the Ecoinvent 3.0 database was used for modelling.

The data sources and assumptions for specific generation technologies are described in subsequent sections. A summary of key inventory data and assumptions for selected systems is also presented in Table 4 below.

**Table 4: Key inventory data and assumptions**

| | Coal | Natural Gas | Hydro (Large) | Hydro (Small) | Wind | PV Solar |
|---|---|---|---|---|---|---|
| **FUELS** | | | | | | |
| **Fuel Type (& LHV)** | Hard Coal (18.59 MJ/kg) | Natural Gas (35.61 MJ/$m^3$) | n/a | | | |
| **Fuel Origin** | Colombia (88%) | Nigeria (46%) Algeria (35%) | n/a | | | |
| **Transportation** | Freight Ship 7000km Freight Train 400km | Pipeline –1800km (29%) Freight Ship – 7000km (71%) | n/a | | | |
| **Generation Unit Characteristics** | | | | | | |
| **Type/Technology** | Boiler and Steam Turbine | CCGT | Reservoir | Run-of-River | Onshore | Ground-mounted |
| **Power (MW)** | 300 | 400 | 95 | 8.6 | 7 classes (0.5 - 3.5) Average 2 | 3.4; 5.5; 11 |
| **Plant Lifetime (years)** | 30 | 30 | 150 | 80 | 25 | 25 |
| **Avg. Capacity Factor 2012-'16** | 77.4% | 21.7% | 21.9% | 30.8% | 28.0% | 20.7% |
| **Efficiency** | 36% | 58% | 78% | 82% | 93% | n/a |
| **LCI Data Sources** | EMAS 2016; Treyer & Bauer 2016 [63] | EMAS 2015; Treyer & Bauer 2016 [63] | Flury et al. 2012 [64] | | Treyer & Bauer 2016 [63] | Jungbluth et al. 2012 [65] |

### 2.3.2 Modelling of Electricity Generation Systems

The LCA software, Simapro v8.0 was used to model the selected electricity generation systems, and estimate their respective life cycle environmental impacts. As mentioned in Section 2.2, foreground data was obtained from sources relating directly to systems operating in Portugal, as of 2016. This data was used to modify existing Ecoinvent processes, in order to be as representative of the average conditions of selected generation technologies as possible. Background data (relating to upstream systems and processes) were obtained from the Ecoinvent v3.0 database [66].

#### 2.3.2.1 Coal

The two coal power plants operating in Portugal were modelled based on technical data from the environmental declarations issued for *Sines* [59]. As discussed in Garcia et al. 2014 [28], flue gas cleaning measures were implemented in 2008 to remove sulfur dioxide, nitrous oxides, and particulate matter from power plant emissions. These measures were taken into account in the current model. An electrical conversion efficiency of 36% was assumed for the system. As a simplification, all coal fuel was assumed to originate from Colombia (actual share – 88%) [30]; and thereafter transported to Portugal by freight train and ship. The lifetime of the coal power system was assumed to be 30 years, based on Ecoinvent data [67].

#### 2.3.2.2 Natural Gas

The four natural gas power plants were modelled based on the environmental declaration issued for *Ribatejo* [60]. The origin shares of natural gas were modelled as 45% from Algeria (actual share 35%) transported via pipeline, and 55% from Nigeria (actual share 46%), shipped as liquefied natural gas [61]. Venting and flaring of methane at the point of extraction was accounted for, as documented by Safaei et al. 2015 [68], and 2017 [69]. A conversion efficiency of 58% was assumed, based on the use of combined cycle gas turbine (CCGT) technology in larger NG power plants. The lifetime of the natural gas power system was assumed to be 30 years, based on Ecoinvent data [67].

#### 2.3.2.3 Hydro (Large and Small)

The modelling for large hydro generation was carried out based on the 45 power plants documented in e2P [58]. The majority of these were reservoir-type power plants. Hence, the large hydro system was modelled as a reservoir power plant of average power 96 MW. In the same way, small hydro was modelled as a run-of-river system (average power of 8.6MW), as this technology made up the majority of the 162 power plants which were documented. The lifetime of the hydro plants were assumed to be 150 years for large, and 80 years for small systems, based on the inventory report for hydroelectric power generation [64].

### 2.3.2.4 Wind

A total of 2599 wind turbines were documented, across 253 wind farms [58]. These were grouped and modelled in seven power classes (Figure 4 below); by proportionally adjusting material inputs within the relevant Ecoinvent process. This approach is based on the assumption that material inputs are proportional to the size and power of the turbine. The operation and maintenance inputs of processes remained constant across all classes.

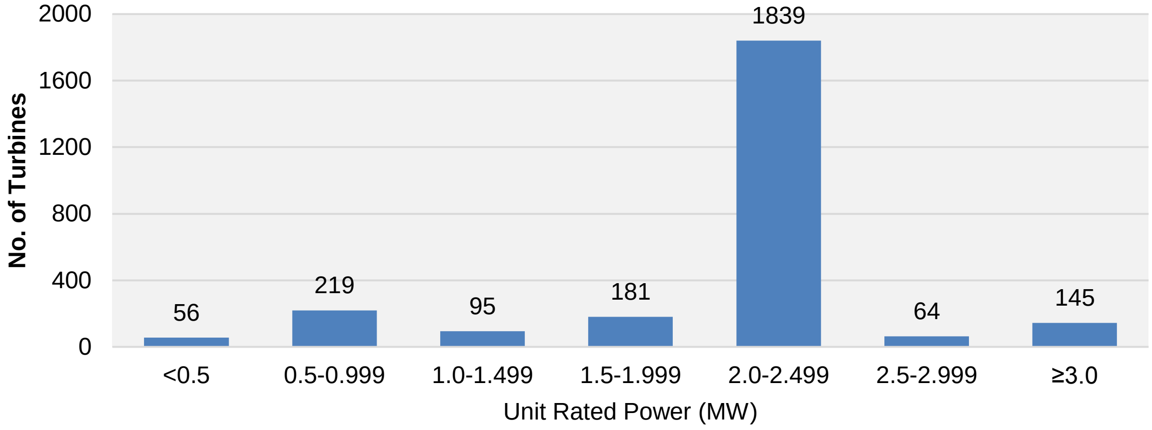



**Figure 4: Distribution of wind turbines operating in 2016 by unit rated power** [58]

The wind power generation system for Portugal was modelled by combining the processes of different power classes, according to their respective shares of the total number of turbines. For this, the average annual generation rate (or wind speed) was assumed to be the same across Portugal. The lifetime of the system was assumed to be 25 years, based on the Ecoinvent data [67]

### 2.3.2.5 Photovoltaic

The PV panels used in generators [58] are based on three main cell technologies, namely: polycrystalline silicon (multi-Si), monocrystalline silicon (mono-Si), and thin-film cells. For each of these cell types, the average power plant capacity was used to adjust material inputs of related PV processes from the Ecoinvent database. The PV system in Portugal was then modelled by combining these processes, according to the respective share of total installed capacity that each cell technology group represented. Due to lack of comprehensive data regarding the composition of the PV portfolio in Portugal, a mix was assumed based on annual PV cell production, as presented by ISE, 2017 [70]. Within this, multi-Si represented the most significant contribution, with 70% of installed capacity, while mono-Si and thin-film cells represented 20% and 10% respectively. Within this approach, it was assumed that the average annual solar irradiance is the same across Portugal. The variation in efficiency due to age or equipment model was not modelled due to lack of data. The PV generation system is assumed to have a lifetime of 25 years, based on inventory report for photovoltaics [65].

### 2.3.3 Modelling for Specific Indicators

The following subsection describes in more detail the data, assumptions and methods which were used for calculating specific sustainability indicators which were not evaluated using the E-LCA results from the modelling processes described above.

#### 2.3.3.1 Freshwater Scarcity Footprint

As mentioned previously, the freshwater consumption (i.e. the volumetric difference between freshwater inputs and outputs) for the processes within the life cycle of each generation technology was estimated using the *water depletion* (WD) impact category, (ReCiPe method). From this, the water scarcity footprint (WSF) was obtained by multiplying these estimates by the relevant AWARE characterisation factors (CFs), according to the geographical location where the life cycle activity took place, such that:

$$W\boldsymbol{ater\ Scarcity\ Footprint}\ for\ technology\ t, \boldsymbol{WSF_t}\ (worldm^3)\ =\ \boldsymbol{WD}\ (m^3)\ \times\ \boldsymbol{CF_{AWARE}}$$

***(Eq. 3)***

The AWARE method considers the available water remaining in a watershed after the demands of humans and aquatic ecosystems have been met. This is based on the assumption that the more water there is in a particular area, the less likely other users will be deprived of it [55]. Within this method, the characterisation factors are inversely proportional to the remaining water, such that:

$$\boldsymbol{A}vailable\ \boldsymbol{Wa}ter\ \boldsymbol{Re}maining\ =\ Availability - Demand\ (\boldsymbol{AMD})\ \text{ and } \qquad \boldsymbol{CF} = fn\ (\frac{1}{\boldsymbol{AMD}})$$

***(Eq. 4)***

From this general formula CFs are calculated relative to a world average, such that:

$$CF_{AWARE} = \frac{AMD_{world\ avg}}{AMD_i} = \frac{0.0136\ m^3world/m^2month}{(Availability - Human\ and\ Ecosystem\ Demand)/m^2month}$$

***(Eq. 5)***

AWARE characterisation factors (based on hydrological model data from 2016) were obtained from the WULCA website [71]. Due to the lack of data and limited time to consider the exact location of different fossil fuel sources, the national annual average CFs were applied for the fuel extraction, processing and transportation life cycle phase. In the case of coal, the non-agricultural CF for Colombia (0.77) was applied; while a weighted average of the national annual CFs for Nigeria (10.38) and Algeria (36.21) was applied in the case of natural gas, according to the respective (assumed) share of gas production from each origin.

For the remaining life cycle phases which are not directly related to fuel extraction (refer to Figure 3), the characterisation factors used were based on conditions in Portugal. Due to the variation in the hydrological conditions (and hence availability of water) across Portugal, it was deemed necessary to disaggregate the AWARE annual national CF (15.33) to account for the distribution of power plants in different locations. The annual CFs for each of the 20 districts and autonomous regions of Portugal were obtained using the AWARE Google earth layer [71] as shown in Figure 5 below.

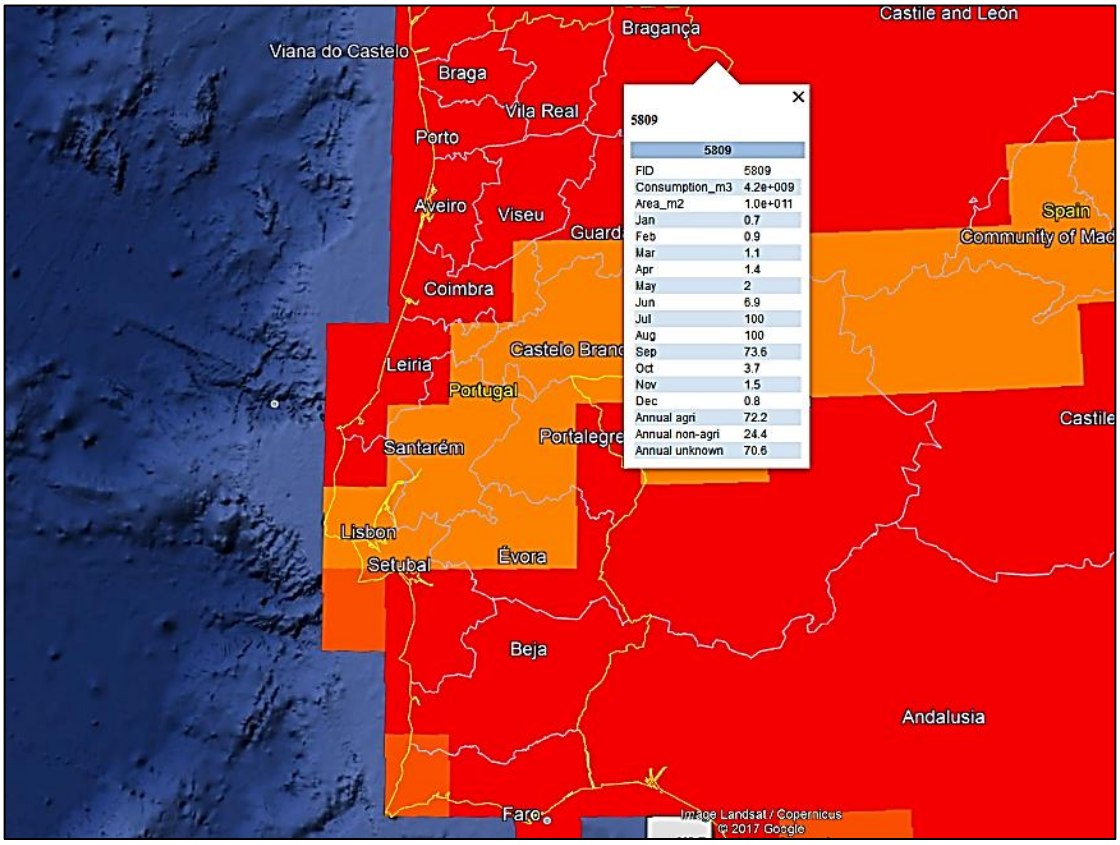



**Figure 5: Map showing regional variation of AWARE CFs in Portugal - WULCA 2017** [71]

A weighted average annual CF was then calculated for each generation technology, based on the respective share of installed capacity contained within each district or autonomous region. This modelled the water scarcity of a particular technology in terms of how its associated power plants are distributed throughout Portugal.

Within this approach, the simplifying assumption is made such that the electricity generation rate (determined by wind speed, solar irradiance, hydraulic river flow rate, etc.) for each system remains constant across the country. It is also assumed that the specific conditions which determine water scarcity and hence the characterisation factors in a particular region (such as hydrological or climatic conditions) remain constant over the entire lifetime of the electricity generating systems. Refer to Appendix II for further details of the calculations described above.

#### *2.3.3.2 Employment Provision*

Employment was assessed using the empirical method presented in Rutovitz et al. 2015 [39]. This method was developed to estimate the amount of direct employment (i.e. not including indirect or induced) which is created annually in the energy sector of a specific country or region. When applied to electricity generation, it takes into account the operational characteristics of different technologies; the average labour intensity of related activities; and the average labour productivity of the location where the activities occur. While this method already considers equivalent LC phases to those used in the current study (refer to Figure 3), it has been adapted (as described below) to account for employment over the entire lifetime of the generation systems under study, not only a single year. The annual employment (in person-years) for a particular generation technology t, is calculated as the sum of the employment in each of the life cycle phases occurring in a specific year, such that:

$$\boldsymbol{Annual\ Employment}\ (person\ years) = \boldsymbol{AM}_t + \boldsymbol{PC}_t + \boldsymbol{FE}_t + \boldsymbol{OM}_t + \boldsymbol{PD}_t,$$

***(Eq. 6)***

where equation terms represent employment for: $\mathbf{AM}_t$ = Component Assembly/Materials Production; $\mathbf{PC}_t$ = Plant Construction; $\mathbf{FE}_t$ = Fuel Extraction, Processing and Transportation; $\mathbf{OM}_t$ = Plant Operation and Maintenance; $\mathbf{PD}_t$ = Plant Decommissioning, Waste Treatment and Disposal. The annual employment in each of these phases is calculated as the product of plant capacity (new, cumulative, or decommissioned) or fuel extracted; multiplied by an employment factor, and a regional job multiplier. Thus, the model developed by [39] may be presented as follows:

| | | | | | | |
|---|---|---|---|---|---|---|
| Component Assembly/ Materials Production (**AM**t) | = | New Installed Capacity (MW) | × | **EF** for $AM_t$ (*py/MW*) | × | **RJM** for $AM_t$ |
| Plant Construction (**PCt**) | = | New Installed Capacity (MW) | × | EF for $PC_t$ (*py/MW*) | × | **RJM** for $PC_t$ |
| Fuel Extraction Processing and Transport (**FEt**) | = | Fuel Extracted (PJ) | × | **EF** for $FE_t$ (*py/PJ*) | × | **RJM** for $FE_t$ |
| Plant Operation & Maintenance (**OMt**) | = | Cumulative Operating Capacity (MW) | × | **EF** for $OM_t$ (*py/MW*) | × | **RJM** for $OM_t$ |
| Plant Decommissioning and Disposal (**PDt**) | = | Decommissioned Capacity (MW) | × | **EF** for $PD_t$ (*py/MW*) | × | **RJM** for $PD_t$ |

**Figure 6: Calculation of annual employment – based on Rutovitz et al.** [39]

where:

- **EF** for $XX_t$= **Employment Factor** for life cycle phase XX of technology *t* (labour intensity i.e. number of persons per unit of capacity/fuel extracted)
- **RJM** for $XX_t$ = **Regional Job Multiplier** for life cycle phase XX of technology *t* (indicator of labour productivity of region relative to the OECD – a higher RJM reflects lower productivity)

The employment factor (Table 5 below) and regional job multipliers for the current study were obtained from Rutovitz et al. 2015 [39], and are based on average values from previous labour and employment studies on power plants. The RJM was assumed to be 1.0 (equivalent to OECD), except for employment related to coal and natural gas extraction; 3.4 for South America (Colombia) and 5.7 for Africa (Algeria and Nigeria).

**Table 5: Employment factors used for current study by life cycle phase (Rutovitz et al. 2015)**

| Type of Power Plant | Construction and Installation (person-years/MW) | Manufacturing (person-years/MW) | Operation and Maintenance (person-years/MW) | Fuel Extraction and Processing (person-years/PJ) |
|---|---|---|---|---|
| Coal | 11.2 | 5.4 | 0.14 | 15.4 |
| Natural Gas | 1.3 | 0.93 | 0.14 | 7.4 |
| Hydro (Large) | 7.4 | 3.5 | 0.2 | - |
| Hydro (Small) | 15.8 | 3.5 | 1.0 | - |
| Wind | 3.2 | 4.7 | 0.3 | - |
| Photovoltaic | 13.0 | 6.7 | 0.7 | - |

In order to estimate the employment over the *lifetime* of the generation systems, the model in Rutovitz et al. 2015 was adapted to account for the duration of each life cycle phase (determined by inventory data and assumptions), as presented in Figure 7 below:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Component Assembly/ Materials Production (**AM**tl) | = | New Installed Capacity (MW) | × | **EF** for $AM_t$ (*py/MW*) | × | **RJM** for $AM_t$ | × | Duration of $AM_t$ (years) |
| Plant Construction (**PCtl)** | = | New Installed Capacity (MW) | × | EF for $PC_t$ (*py/MW*) | × | **RJM** for $PC_t$ | × | Duration of $PC_t$ (years) |
| Fuel Extraction Processing & Transport (**FEtl**) | = | Fuel Extracted (PJ) | × | **EF** for $FE_t$ (*py/PJ*) | × | **RJM** for $FE_t$ | × | Duration of $FE_t$ (years) |
| Plant Operation & Maintenance (**OMtl**) | = | Cumulative Operating Capacity (MW) | × | **EF** for $OM_t$ (*py/MW*) | × | **RJM** for $OM_t$ | × | Duration of $OM_t$ (years) |
| Plant Decommissioning and Disposal (**PDtl**) | = | Decommissioned Capacity (MW) | × | **EF** for $PD_t$ (*py/MW*) | × | **RJM** for $PD_t$ | × | Duration of $PD_t$ (years) |

**Figure 7: Calculation of total lifetime employment – adapted from Rutovitz et al. 2015** [39]

Thus, the total employment over the lifetime of technology t, was calculated as:

$$\boldsymbol{Total\ \ Lifetime\ Employment}\ (person\ years) = \boldsymbol{AM}_{tl} + \boldsymbol{PC}_{tl} + \boldsymbol{FE}_{tl} + \boldsymbol{OM}_{tl} + \boldsymbol{PD}_{tl}$$

***(Eq. 7)***

The lifetime electricity generation was calculated as:

$$\boldsymbol{Lifetime\ \ Generation}\ (TWh) = Annual\ Generation\ (TWh/year)\ \ \times Plant\ lifetime\ (years)$$

***(Eq. 8)***

By combining *Eq.7* and *Eq.8*, the life cycle employment has been calculated as:

$$\boldsymbol{Life\ Cycle\ Employment}\ (person\ years/TWh) = \frac{Total\ Employment\ \ (person\ years)}{Lifetime\ Generation\ (TWh)}$$

***(Eq. 9)***

This method assumes that the operational conditions are maintained throughout the lifetime of the electricity generation system. For the current study a timeframe of 5 years (2012-2016) is considered (to account for system variability), and hence the life cycle employment for technology t ($\mathbf{LCE_t}$) was calculated for each of these five years, based on the equations above. From these results, an average life cycle employment ($\mathbf{LCE_{t.avg}}$ – see equation below) was obtained, as well as a range of results, showing variability between different years.

$$\boldsymbol{LCE_{t.avg.}}\ (person\ years/TWh) = \frac{\sum_{y=2012}^{y=2016} \boldsymbol{LCE_t}}{5}$$

***(Eq. 10)***

Employment was designated as either domestic or non-domestic based on system boundaries, where domestic employment accounted for roles within the construction, operation, and disposal of generation infrastructure, while total employment also includes the non-domestic roles within manufacturing and fuel provision (refer to Figure 3). One of the benefits of disaggregation in this way is that it enables stakeholders to compare employment levels across life cycle phases, and identify opportunities for promoting local employment, which is usually more of a priority.

As a simplifying assumption, the operational system characteristics used in this model (fuel origins, conversion efficiency etc.) remained constant over the lifetime of the systems. Details of the calculations carried out for employment generation are presented in Appendix III.

# 3. *RESULTS AND DISCUSSION*

This chapter presents the life cycle impact assessment results, obtained for the current study. Environmental and socioeconomic impacts are discussed in sections 3.1 and 3.2, respectively.

## *3.1 ENVIRONMENTAL IMPACTS*

The charts in Figure 8 (pg. 31) present the estimated life cycle environmental impacts, calculated per MWh of electricity generated; comparing generation technologies. Disaggregation of results has been carried out to identify the specific contributions that power plant *infrastructure* and *operation* each make towards each impact category. In terms of life cycle phases (refer to Figure 3), infrastructure comprises: component assembly, plant construction, decommissioning, and waste disposal, while operation comprises: extraction, processing and transportation of fuels, as well as operation and maintenance. Details of the substance contributions from each technology, for each impact category are presented in Appendix III with brief discussion in the sections below.

### *3.1.1 General Observations*

Overall, fossil fuel-based systems exhibited higher environmental impacts than renewable-based systems (in 8 out of 12 impact categories considered, namely: FD, nREn, GWP, OD, TA, FWEut, AqAc, and HTnon). For all categories, impacts in fossil fuel-based power plants were mainly attributable to plant operation while in renewable-based plants, impacts originated mostly from plant infrastructure.

### *3.1.2 Resource Depletion (Metal and Fossil Fuels)*

Metal element depletion was estimated to be highest in wind and PV systems, which reduce existing reserves by 18.6 kg and 13.9 kg Fe eq. respectively, for each MWh of electricity generated. Natural gas power plants exhibited the lowest impacts in this category, with 1.1 kg Fe eq. per MWh. This trend can be attributed to a higher relative share of metal components in the infrastructure of wind and PV systems, as well as shorter lifespan and lower electricity production, compared to other systems. Iron and manganese contributed most to this impact in fossil fuel-based systems, while copper, nickel, and chromium were the most significant substances in renewable-based systems.

Fossil fuel depletion was highest in coal and natural gas systems, with 243.6 kg and 154.8 kg oil eq. respectively per MWh. Large and small hydro exhausted the least amount of fossil fuels, with 1.3 and 0.9 kg oil eq. respectively per MWh. In terms of substance contribution, coal and natural gas were significant for all systems; as operating fuels for fossil fuel-based systems but also as primary energy for the manufacturing of renewable system infrastructure (e.g. metal ore smelting, composite plastic forming etc.). Within hydro systems, crude oil was most significant due to use of lubricants.

### *3.1.3 Energy Demand and Climate Change*

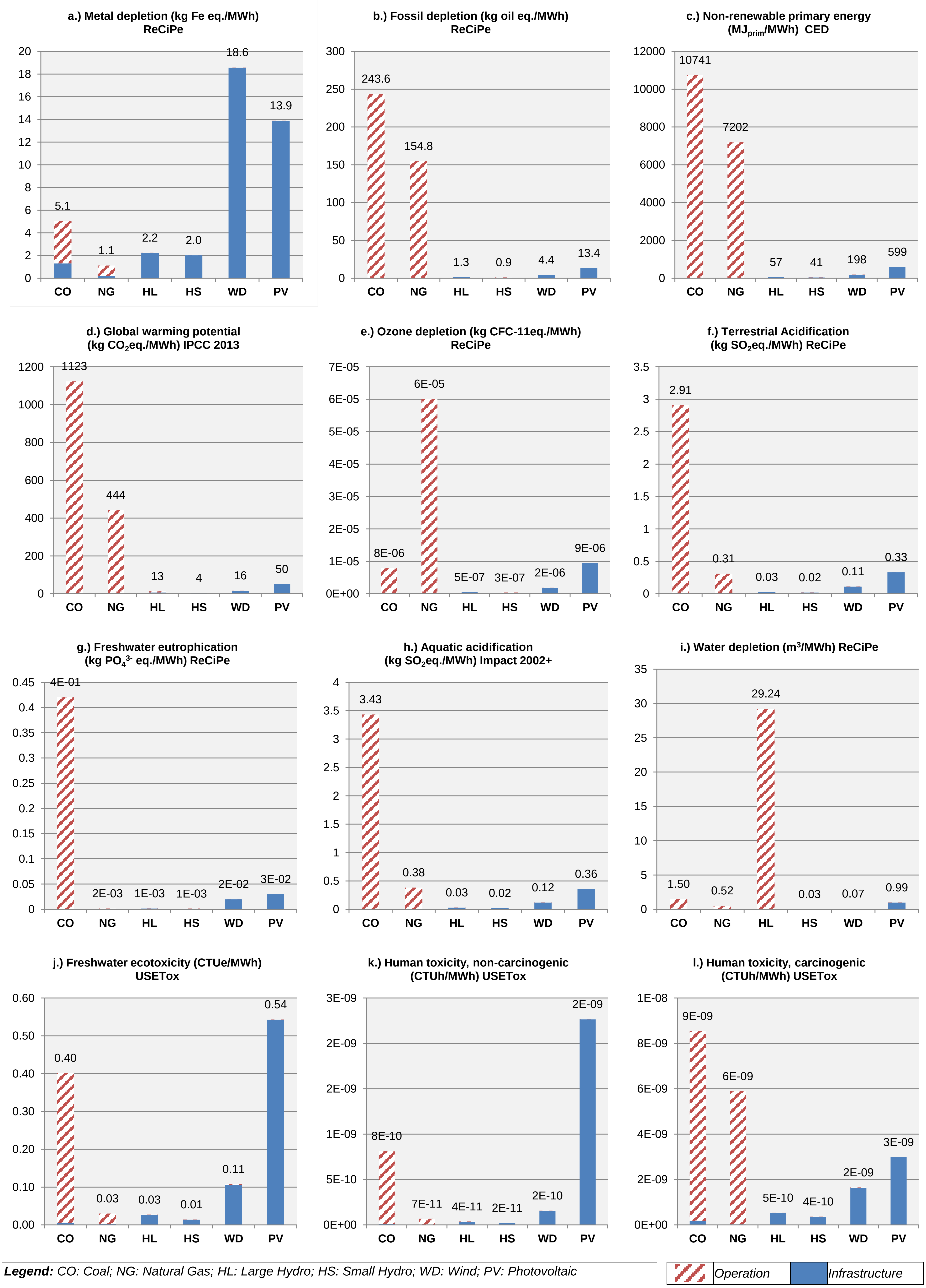
In terms of energy demand, fossil fuel-based systems consume the most non-renewable primary energy over their life cycle, with coal and natural gas estimated at 10741 MJ and 7202 MJ respectively, per MWh generated. Large and small hydro power consumed the least; 57 MJ and 41 MJ respectively. Between the fossil fuel-based plants, coal systems consume more primary energy than natural gas, due to their lower electrical conversion efficiency (36% for coal versus 58% for CCGT). Coal and natural gas were the significant contributors for most systems, with crude oil representing the highest share in hydro systems.

Following the trend from the two previous impact categories, fossil fuel-based power plants (due to their requirement for combustible fuels) also produce the highest global warming potential (GWP) via greenhouse gas emissions; with coal and natural gas producing 1123 kg and 444 kg $CO_2$ eq. respectively per MWh generated. Large and small hydro plant generation resulted in the lowest GWP (13 kg and 4 kg $CO_2$ eq. per MWh). The substances which contributed the most towards this impact category were carbon dioxide (in emissions from flue gases and flaring); and methane (from venting of natural gas wells). Biogenic methane (due to the anaerobic decomposition of submerged, organic matter) also represented a significant share (~45%) of GWP in large (reservoir) hydro systems.

### *3.1.4 Pollution to Air and Soil*

Generation from natural gas causes the highest ozone depletion (OD), with $6\times10^{-5}$ kg CFC-11eq. per MWh. This is attributed to the use of bromotrifluoromethane (more commonly known as *Halon 1301*) as a fire suppression measure during the extraction and processing of highly flammable natural gas.

Within emissions to soil, coal power plants cause the highest levels of terrestrial acidification (TA) with 2.91 kg $SO_2$eq. per MWh. Sulfur dioxide ($SO_2$) and nitrogen oxides (NOx) are the substances which contribute the most to this impact; occurring as a result of the oxidisation of fuel impurities during combustion. The results account for the effects of flue gas treatment systems (consisting of desulfurization, denitrification, and particulate removal) which were installed in coal power plants in 2008, as discussed in Garcia et al. 2014 [28].




***Legend:*** *CO: Coal; NG: Natural Gas; HL: Large Hydro; HS: Small Hydro; WD: Wind; PV: Photovoltaic* | *Operation* | *Infrastructure*

**Figure 8: Environmental life cycle assessment impacts**

### 3.1.5 Freshwater Use Impact

#### 3.1.5.1 Freshwater Degradation

The impact of freshwater eutrophication was estimated to be highest in coal power plants at $4 \times 10^{-1}$ kg $PO_4^{3-}$ eq. per MWh. The main contributing substances were phosphates. Coal power also produced the highest levels of aquatic acidification with 3.43 kg $SO_2$ eq. per MWh. The substances most significant to this impact were nitrogen oxides for most technologies, and sulfur dioxide for wind and PV systems – due to emissions from generation of the electricity used in manufacturing, which likely occurs in countries where coal is used. PV systems produced the highest freshwater ecotoxicity with 0.54 CTUe per MWh, and small hydro at 0.01 CTUe. This was mainly attributed to diflubenzuron and chlorothalonil; both pesticides used in agricultural activities. Overall, coal has the highest impacts towards freshwater degradation, while small hydro has the lowest.

#### 3.1.5.2 Freshwater Scarcity Footprint

The life cycle water consumption of each technology was estimated based on water depletion using the ReCiPe method, with preliminary results presented in Figure 8i.). These estimates were multiplied by AWARE characterisation factors (CFs) as described in Section 2.3, to obtain the freshwater scarcity footprint (WSF) for each technology. Overall the application of AWARE CFs increased the estimates of water use impact (as presented in Figure 9 below), apart from a minor reduction in the operation phase for coal, due to a low CF (0.77) at the fuel origin, Colombia. Large hydro is estimated to have the highest WSF at 615.71 world $m^3$, while wind has the lowest; 0.07 world $m^3$ per MWh.

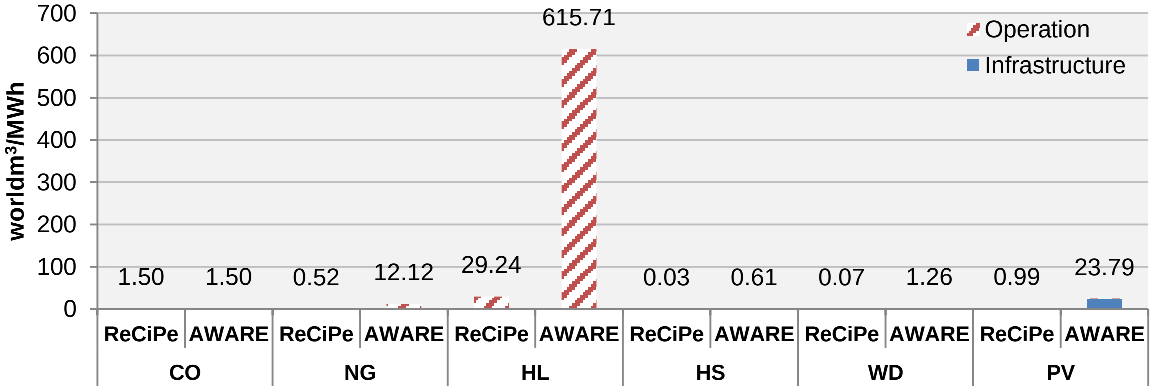


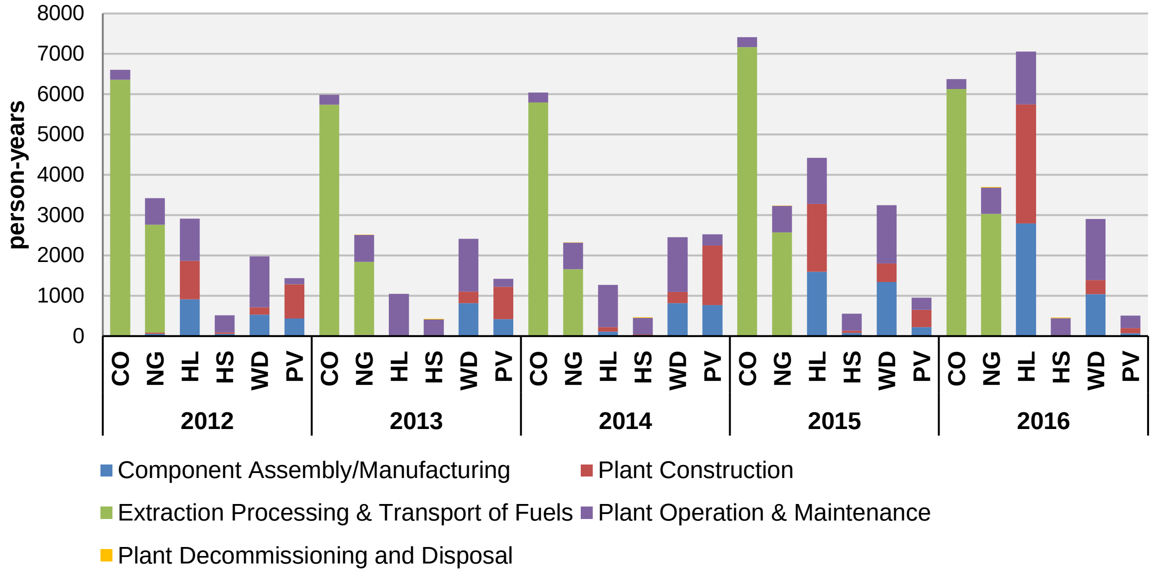

**Figure 9: Comparison of life cycle water depletion and freshwater scarcity footprint**

There has been discussion in recent literature regarding appropriate methods for the assessment of water consumption in reservoir power plants, and how to account for factors such as surface evapotranspiration, flow alteration, etc. These issues are discussed further as part of the results comparison in Section.

### 3.2 SOCIOECONOMIC IMPACTS

#### 3.2.1 Employment Generation

The amount of employment created by selected systems was estimated using the method presented by Rutovitz et al. 2015. [39], as described in Section 2.3. As shown in Figure 10 below, there was an estimated increase in total employment, annually from 2013. This corresponds to the successive overall increase in both installed capacity and generation (refer to Figure 1), following recovery from a national economic downturn around 2012/2013. Coal power is estimated to have contributed the most towards annual employment between 2012 and 2015; ranging between 5980 and 7407 person-years; while large hydro generated the most employment in 2016, with 7050 person-years. Small hydro generated the least employment across all years, ranging between 426 and 554 person-years.




*CO: Coal; NG: Natural Gas; HL: Large Hydro; HS: Small Hydro; WD: Wind; PV: Photovoltaic*

**Figure 10: Estimated annual employment by generation technology (person-years)**

For fossil fuel-based systems, extraction, processing and transportation of fuels is estimated to have generated the most employment across all years. This can be attributed to relatively high electricity production from these base-load systems during the timeframe, as well as the high employment factors (

Table 5) assigned to activities carried out at the fuel origins (Colombia for coal; Algeria and Nigeria for natural gas); indicative of the lower labour productivity assumed in these regions. Within systems based on renewable energy, there is greater variability as to which life cycle phase generates the most employment. The operation and maintenance phase generally contributed the most towards employment, apart from years where significant new capacity was installed e.g. in 2013/2014 for PV, and 2015/2016 for large hydro.

The average *life cycle* employment was calculated for each of the years within the timeframe (2012-2016), as described in Section 2.3. Figure 11 below presents a comparison of the life cycle employment between different generation technologies; showing the relative contribution of each life cycle phase towards the average life cycle employment (columns), as well as variability between results within the timeframe (error bars). A summary of average life cycle employment by life cycle phase is also presented in Table 6 below.

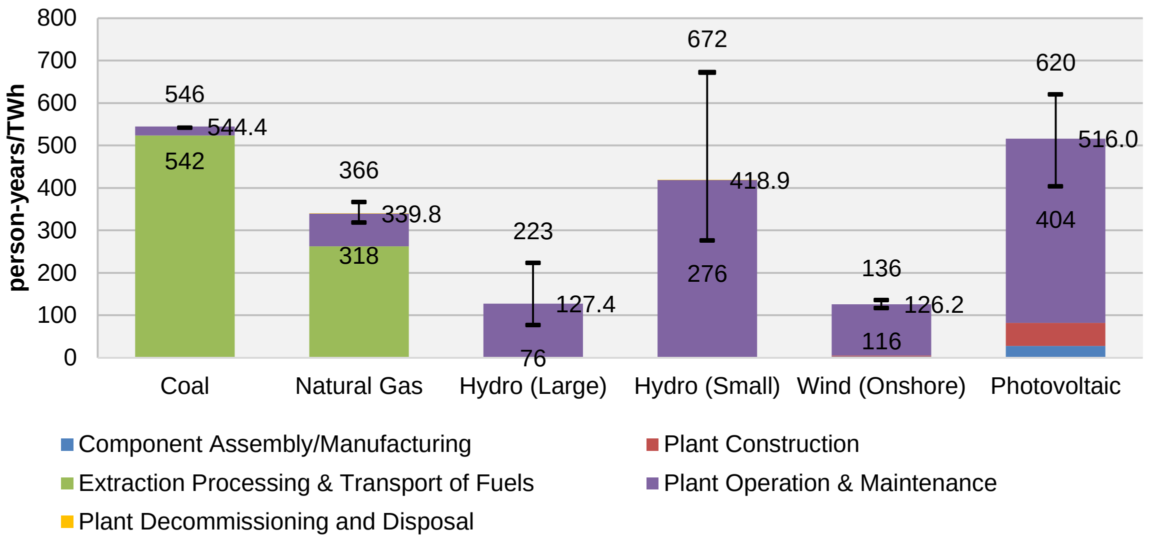



**Figure 11: Estimated life cycle employment showing variability (person-years/TWh generated)**

As mentioned in Section 2.3, employment was designated according to life cycle phase. PV and small hydro systems have been estimated to generate the most *domestic* life cycle employment (488.0) due to relatively low production; while coal systems generate the least (20.78) due to small the number of large, high-production plants with fewer personnel. Conversely, coal systems are estimated to generate the most *total* life cycle employment (544.4) due to high labour in the fuel extraction phase, while wind (126.19) and large hydro (127.38) systems generate the least. The greatest variability of results is observed with small hydro systems due to large variation in electricity production, while base-load systems like coal and wind exhibit low variability.

**Table 6: Average life cycle employment per life cycle phase (person-years/TWh generated)**

| | | CO | NG | HL | HS | WD | PV |
|---|---|---|---|---|---|---|---|
| Component Assembly/Manufacturing | | *0.00* | *0.05* | *0.74* | *0.41* | *3.14* | *27.99* |
| **Plant Construction** [D] | | 0.00 | 0.07 | 1.56 | 0.59 | 2.14 | 54.30 |
| Extraction Processing & Transport of Fuels | | *523.60* | *262.61* | *0.00* | *0.00* | *0.00* | *0.00* |
| **Plant Operation & Maintenance** [D] | | 20.78 | 77.05 | 125.08 | 417.82 | 120.92 | 433.69 |
| **Plant Decommissioning** [D] | | 0.00 | 0.03 | 0.00 | 0.10 | 0.00 | 0.00 |
| **Total Employment** | | **544.4** | **339.8** | **127.4** | **418.9** | **126.2** | **516.0** |
| Domestic Employment | | 20.8 | 77.2 | 126.6 | 418.5 | 123.1 | 488.0 |

[D] - *Indicates Domestic Employment*

### 3.2.2 Human Health Impacts

Two impact categories were used to assess the effects of generation systems on human health, namely: carcinogenic- and non-carcinogenic human toxicity (Figure 12 below). For carcinogenic toxicity, coal-based generation produced the highest impacts ($8.5\times10^{-9}$ CTUh per MWh) while large hydro produced the lowest ($3.6\times10^{-10}$ CTUh per MWh). The substances contributing the most to this impact were: 2, 3, 7, 8-Tetrachlorodibenzo-p-dioxin (TCDD) and formaldehyde; which are emitted during the combustion of organic compounds, such as hydrocarbons in fossil fuels. For non-carcinogenic toxicity, PV systems are estimated to cause the highest impact ($2.3\times10^{-9}$ CTUh per MWh) while large hydro cause the lowest ($2.1\times10^{-11}$ CTUh per MWh). Within this impact, propylene oxide (used in manufacture of polyurethane plastic materials) and aldrin (used as a pesticide – refer to Section 3.1.5) were identified as most significant substances.

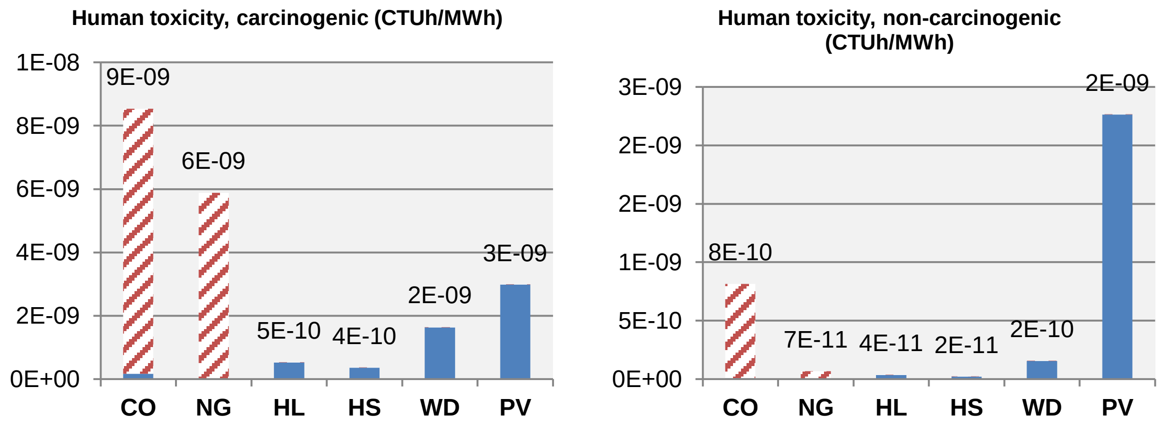



**Figure 12: Human health impacts by generation technology**

### 3.2.3 Dependence on Fossil Fuels

Dependence on fossil fuels was used to assess energy security: expressed as a percentage of non-renewable primary energy consumed by each technology (per MWh generated), relative to that of coal – the highest consumer. As presented in Figure 13 below, natural gas power is estimated to consume 67.1% of the fossil primary energy resources that coal does. This is attributed to the higher energy conversion efficiency for natural gas (58%) compared to coal (36%). The lowest dependence on fossil fuels is for small hydro with 0.5% of the non-renewable primary energy requirement of coal-based electricity.

As discussed in Section 3.1.3; in fossil fuel-based systems, the operational phase contributes the most to fossil fuel dependence, while in renewable systems, the infrastructure is most significant. While this indicator gives an overall comparison of the performance of different systems, in terms of energy security for the context of Portugal where all fossil fuels are imported, its limitations are acknowledged.

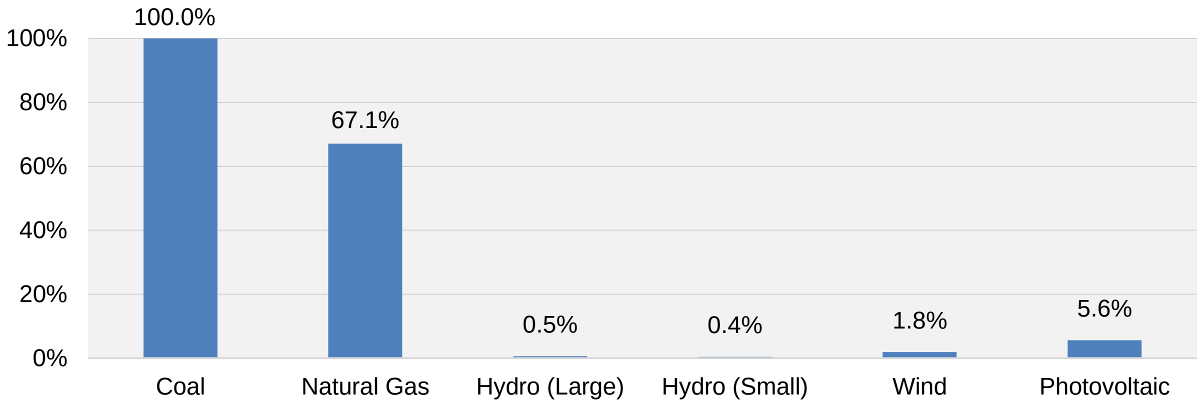



**Figure 13: Comparison of relative dependence on fossil energy by generation technology**

### *3.2.4 Capacity Factor*

As described in Section 2.2.4 the availability of energy has been assessed and compared between different systems using the ratio of the actual electricity generated to the maximum theoretical electricity that could have been generated, over the same time period. Figure 14 below presents a comparison between the average capacity factor of generation technologies (*columns*), as well as variability between results within the timeframe of the current study, 2012 – 2016 (*error bars*).

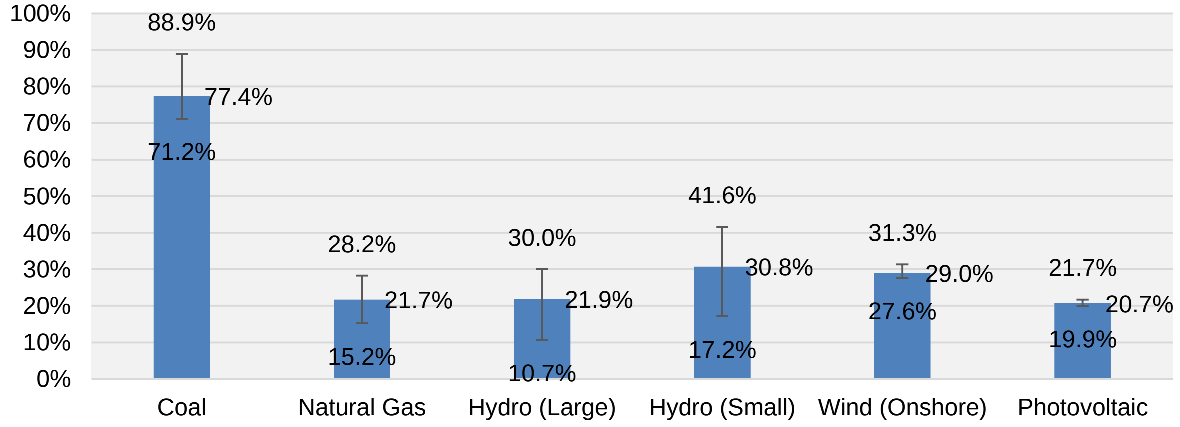



**Figure 14: Comparison of capacity factor by generation system – REN Data** [41]–[45]

As a key base load generation technology, coal power exhibited the highest average capacity factor (77%) while PV (with an intermittent primary energy resource) has the lowest (21%). The highest variability was observed in small hydro with capacity factors ranging from 17% to 42%. This can be attributed to variability in generation patterns due to annual hydrological changes, since the installed capacity of small hydro did not change significantly over this timeframe. The author recognises that capacity factor may not be regarded as a conclusive indicator for the comparison of the performance of all generation technologies, due to its apparent bias against systems based on renewable resources like wind and PV, which are inherently intermittent and cannot practically generate electricity continuously – as is assumed in *(Eq. 2* on pg. 19). The current study justifies the use of capacity factor as a measure of energy availability rather than technical efficiency of energy conversion.

### 3.2.5 Levelised Cost of Electricity

The levelised cost of electricity (LCOE), as obtained from IEA 2015 [56] for the context of Portugal, is presented in Figure 15 below for different generation technologies, considering different discount rates (3, 7, and 10%). Wind power is estimated to be the cheapest, at between USD 61.0 and USD 99.0 per MWh, for the range of discount rates. Electricity from large hydro exhibits the highest overall LCOE of USD 283.0 per MWh for the commonly applied discount rate of 10%. This can be attributed to high initial capital costs and also the very long assumed lifetime of hydro power facilities.

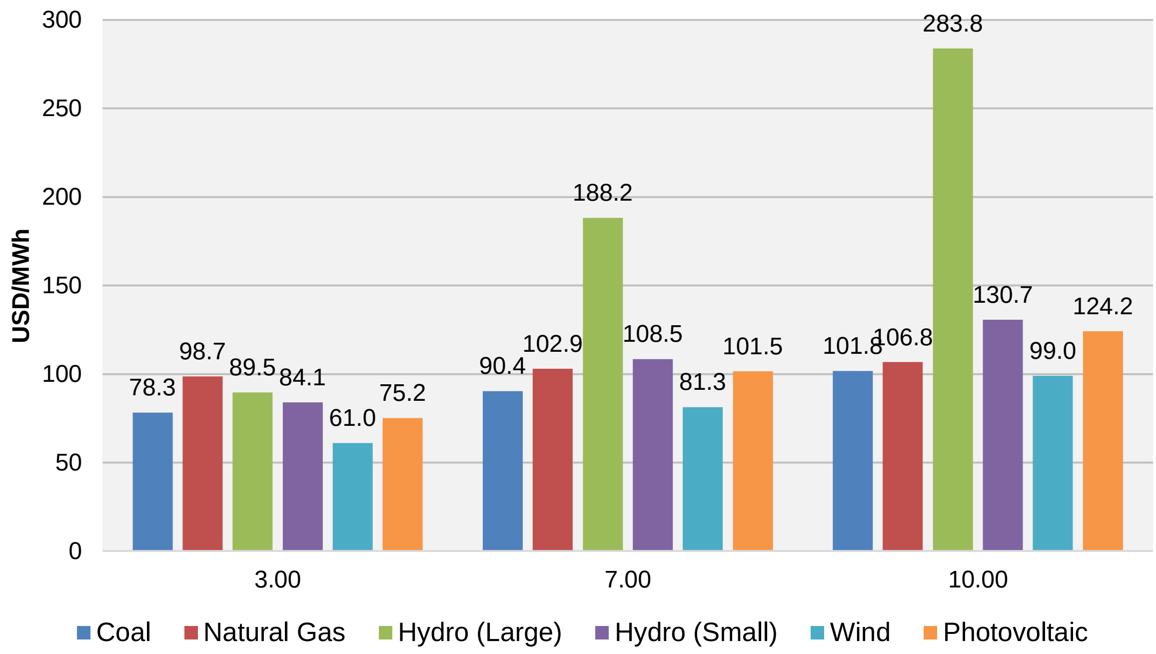



**Figure 15: Levelised cost of electricity for different discount factors – IEA 2015** [56]

## 3.3 Summary of Results

A comparative summary of the results discussed earlier in this chapter is presented in Table 7 below. This provides a global overview of sustainability performance; by ranking each generation technology within each impact category along an un-weighted colour gradient scale, such that higher/more negative impacts are highlighted in red, while lower/more positive impacts are highlighted in green. Overall coal power exhibits the highest environmental impacts and appears to be the least sustainable of generation technologies, while small hydro exhibits the lowest, suggesting best sustainability performance.

**Table 7: Comparison of life cycle impacts per MWh generated**

| Indicator | Unit | CO | NG | HL | HS | WD | PV |
|---|---|---|---|---|---|---|---|
| Non-Ren. Prim Energy | MJ prim | 10741 | 7202 | 57 | 41 | 198 | 599 |
| Global Warming Potential | kg $CO_2$ eq. | 1123 | 444 | 13 | 4 | 16 | 50 |
| Metal Depletion | kg Fe eq. | 5.1 | 1.1 | 2.2 | 2.0 | 18.6 | 13.9 |
| Fossil Fuel Depletion | kg oil eq. | 243.6 | 154.8 | 1.3 | 0.9 | 4.4 | 13.4 |
| Ozone Depletion | kg CFC-11 eq. | 8E-06 | 6E-05 | 5E-07 | 3E-07 | 2E-06 | 9E-06 |
| Terrestrial Acidification | kg $SO_2$ eq. | 2.91 | 0.31 | 0.03 | 0.02 | 0.11 | 0.33 |
| Freshwater Eutrophication | kg $PO_3^{4-}$eq. | 4E-01 | 2E-03 | 1E-03 | 1E-03 | 2E-02 | 3E-02 |
| Water Depletion | $m^3$ | 1.50 | 0.52 | 29.24 | 0.03 | 0.07 | 0.99 |
| Water Scarcity Footprint | world.$m^3$ | 1.50 | 12.12 | 615.71 | 0.61 | 1.26 | 23.79 |
| Aquatic Acidification | kg $SO_2$ eq. | 3.43 | 0.38 | 0.03 | 0.02 | 0.12 | 0.36 |
| Freshwater Ecotoxicity | CTUe | 0.40 | 0.03 | 0.03 | 0.01 | 0.11 | 0.54 |
| Total Employment | pers.yrs/TWh* | 544.4 | 339.8 | 127.4 | 418.9 | 126.2 | 516 |
| Domestic Employment | pers.yrs/TWh* | 20.8 | 77.2 | 126.6 | 418.5 | 123.1 | 488 |
| Non-Carcinogenic Toxicity | CTUh | 8E-10 | 7E-11 | 4E-11 | 2E-11 | 2E-10 | 2E-09 |
| Carcinogenic Toxicity | CTUh | 9E-09 | 6E-09 | 5E-10 | 4E-10 | 2E-09 | 3E-09 |
| Fossil Fuel Dependence | Relative % | 100.0% | 67.1% | 0.5% | 0.4% | 1.8% | 5.6% |
| Capacity Factor | % | 77.4% | 21.7% | 21.9% | 30.8% | 29.0% | 20.7% |
| Levelised Cost of Electricity | USD | 101.77 | 106.75 | 283.83 | 130.7 | 98.97 | 124.16 |

| ←More Positive | Lower Impacts | | | More Negative | Higher Impacts→ |
|---|---|---|---|---|---|

***Legend:*** *CO: Coal; NG: Natural Gas; HL: Large Hydro; HS: Small Hydro; WD: Wind; PV: Photovoltaic*

Regarding socioeconomic indicators, there is more variability in the summary of results. While small hydro power exhibits mostly positive impacts, other technologies which may be regarded as less sustainable perform better in certain areas; e.g. coal in *total employment* and *levelised cost of electricity*. By presenting impact results in this way, a decision-maker/policy-maker has a global perspective of the technologies under study, and can easily identify areas of hotspots (i.e. significant impacts) as well as starting points for possible areas of sustainability/efficiency improvement.

### *3.4 Comparison with Previous Studies*

Previous studies related to the environmental assessment of electricity generation have been used for comparison against the results of the current study; as a way of validation of the methods and indicators used. The following subsection presents these comparisons; for key applicable indicators

### 3.4.1 Garcia et al. 2014 (Portuguese Context)

As mentioned previously, Garcia et al. carried out an E-LCA for the context of Portugal [28]. Due to significant differences in assessment methods used for certain impacts, not all results were directly comparable to those obtained in the current study. For example, Garcia et al. assessed the issue of resource depletion using *abiotic depletion* within the CML 2 v2.05 [72] method; which estimates a single aggregated impact. In contrast, the more recent ReCiPe method which was used for the current study [50], disaggregates *metal*- and *fossil fuel depletion*. Without further analysis of how the different methods estimate these impacts (which is outside the scope of this study), direct comparison is not feasible. Incidentally, the most recent version of the CML method – CML-IA [73] *also* disaggregates; into element- and fossil depletion; reflecting the evolving nature of LCIA methods, in response to the requirements of E-LCA practitioners to better understand components of a particular impact.

***Legend:*** *CO: Coal; NG: Natural Gas; HL: Large Hydro; HS: Small Hydro (Results of 'Run-of-River' Hydropower from Garcia et al. 2014 used); WD: Wind; PV: Photovoltaic;*

Figure 16 below presents a comparison of three selected impacts (nREn, GWP and TA); between Garcia et al. 2014 and the current study Overall the trend of the estimated impacts is maintained, with both sets of results within the same order of magnitude for each technology. For non-renewable primary energy (***Legend:*** *CO: Coal; NG: Natural Gas; HL: Large Hydro; HS: Small Hydro (Results of 'Run-of-River' Hydropower from Garcia et al. 2014 used); WD: Wind; PV: Photovoltaic;*

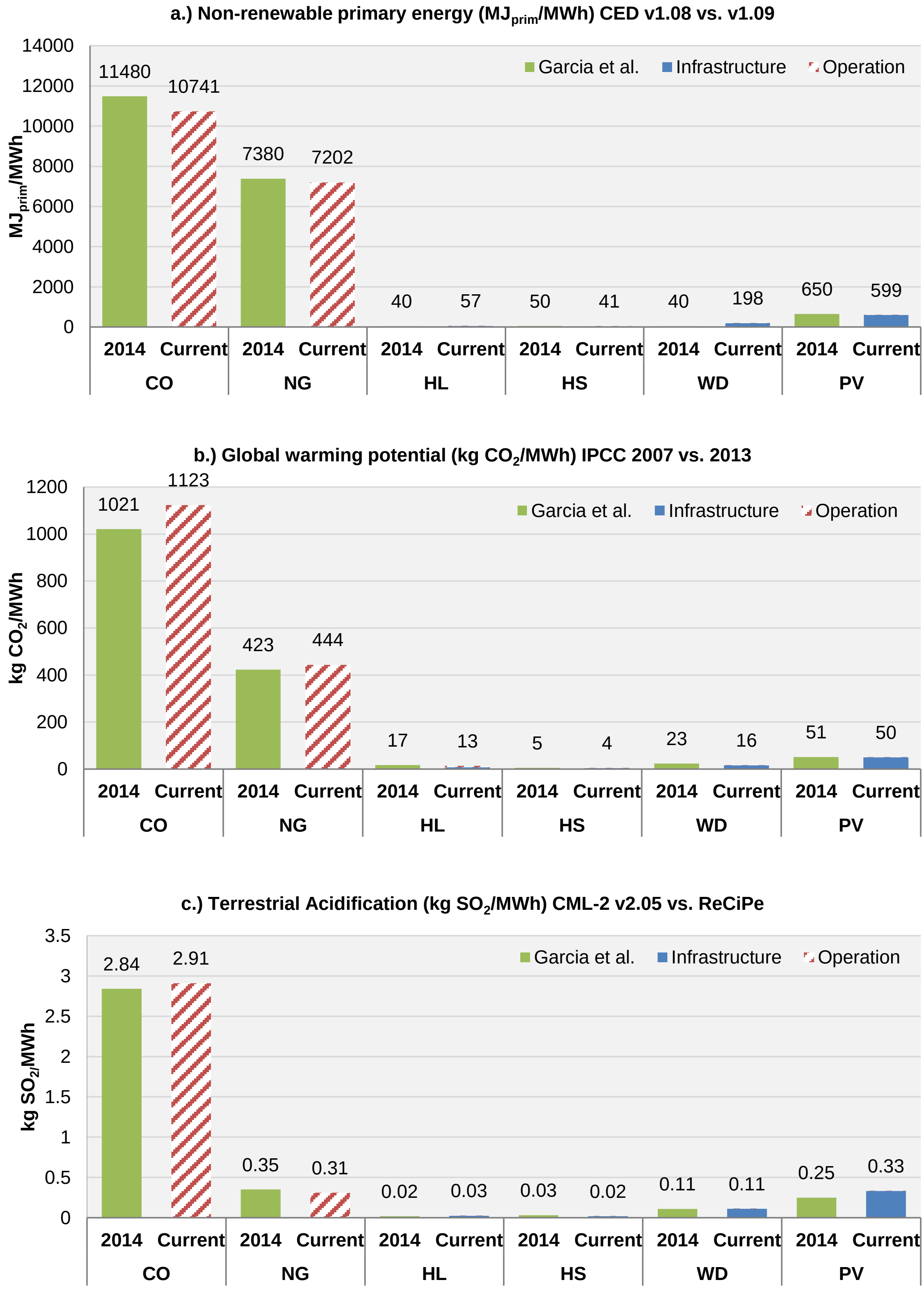
Figure 16a.), slightly lower impacts were calculated, compared to the previous study. This was due to an improvement in the energy conversion efficiency, as accounted for in the updated Ecoinvent v3.0 database [66]. For the case of wind generation, the significant increase (from 40 to 198 $MJ_{prim}$/MWh) was due to more comprehensive modelling of the wind system composition, as discussed in Section 2.3.2.

For global warming potential (***Legend:*** *CO: Coal; NG: Natural Gas; HL: Large Hydro; HS: Small Hydro (Results of 'Run-of-River' Hydropower from Garcia et al. 2014 used); WD: Wind; PV: Photovoltaic;*

Figure 16b.) there is an *increase* in coal and natural gas GHG impacts, despite consuming less primary fossil energy (described above). This can be attributed to updated background data in the newer Ecoinvent database; which accounts for controlled fires in the coal extraction phase, as well as flaring and venting in natural gas (discussed by Safaei et al. [68], [69]) – both of which lead to higher quantities of GHGs per MWh of electricity generated.

The impacts for acidification (***Legend:*** *CO: Coal; NG: Natural Gas; HL: Large Hydro; HS: Small Hydro (Results of 'Run-of-River' Hydropower from Garcia et al. 2014 used); WD: Wind; PV: Photovoltaic;*

Figure 16c.) are also noted to have increased for coal (due to the release of impurities like sulfur in coal fuel through combustion – described above). For PV, acidification impacts also increase within the infrastructure phase, due to a database change, which accounts for the change in the manufacturing origin of panels (and other components); i.e. from Europe to countries where coal is more prominent in the electricity generation mix (e.g. China, India, and the U.S.)




***Legend:*** *CO: Coal; NG: Natural Gas; HL: Large Hydro; HS: Small Hydro (Results of 'Run-of-River' Hydropower from Garcia et al. 2014 used); WD: Wind; PV: Photovoltaic;*

**Figure 16: Comparison of impacts with results from Garcia et al. 2014** [28]

### 3.4.2 *Water Consumption for Large Hydro*

As mentioned previously, the assessment of life cycle water consumption in reservoir hydro systems has been recognised as a complex task, due to the lack of methodological consensus on how to estimate evapotranspiration from open reservoir surfaces [33], as well as the allocation of water losses to other functions which reservoirs might provide, apart from electricity generation [34]. In light of these complexities, the results have been compared with existing literature. Figure 17 below presents a comparison of the water scarcity footprint results from the current study (Section 3.1.5), against those from recent studies on hydropower systems; by Mekonnen and Hoekstra 2012 [74], Mekonnen et al. 2015 [2], and Scherer and Pfister 2016 [35]; showing average water consumption (columns), as well as the range of estimates (error bars) for water consumed per MWh electricity generated.

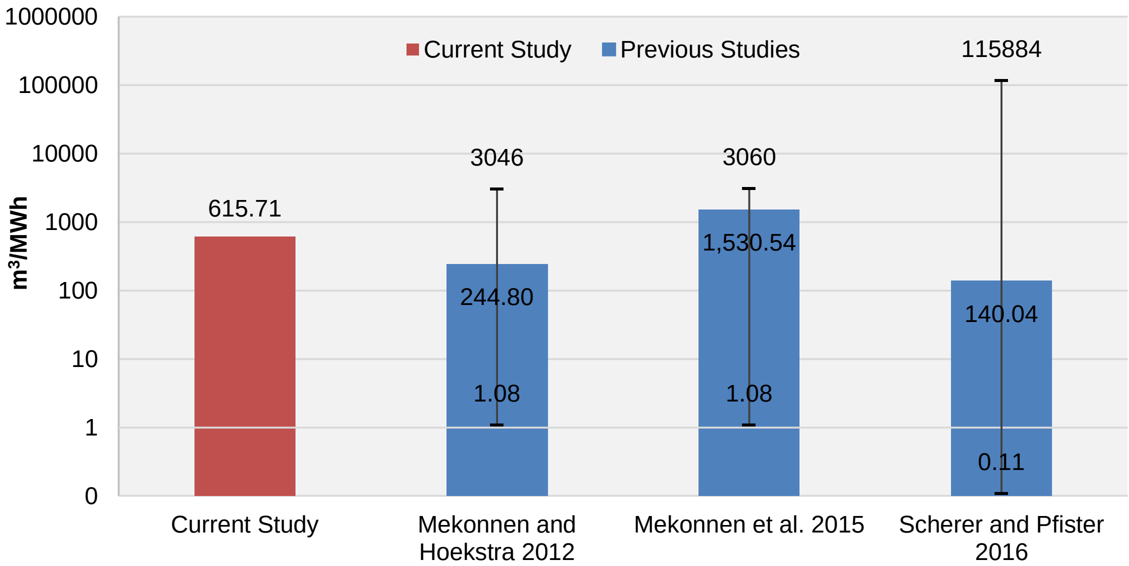



**Figure 17: Comparison of large hydro WSF against recent studies** [2], [35], [74]

The estimate of water scarcity footprint for the current study (615.71 world $m^3$/MWh) is within the ranges of all three of the previous studies. However, the variability in the methods used in previous studies should be noted. For example, Scherer and Pfister [35] used net water consumption estimates; and accounted for allocation towards other hydrological functions of the reservoir, as well as geographical water scarcity using the WSI. On the other hand, the other previous studies used gross values for water consumption, and did not account for allocation, or consider geographical issues related to water scarcity. For the specific aim of the current study (i.e. assessing and comparing between different key technologies), the results which were obtained appear to be sufficient; in identifying the significant impact of large hydro systems in terms of water use.

# 4. *LIMITATIONS AND FUTURE WORK*

## *4.1 Limitations*

Over the course of the current study, the following limitations were recognised:

- For the assessment of water scarcity footprint, the variation of hydrological conditions over time within a particular water catchment area was not accounted for, i.e. water scarcity CF was assumed to be constant over the entire life time of the generation system. This approach was also taken in previous studies which considered water scarcity [35], [36]
- For the assessment of employment provision; variations in labour productivity (EF), labour intensity (RJM), and changes in the value chain of the generation systems (e.g. fuel origins) were not accounted for. The other previous study which used this model to estimate employment [14] also followed this approach.
- The use of average values of electricity generated for Portugal rather than detailed disaggregated generation data for specific power plants (assuming constant conditions across the country), results in scale distortion in the modelling of systems

## *4.2 Future Work*

A number of subsequent future, research and assessment studies may be considered following this thesis, including:

- Application of multi-criteria decision analysis (MCDA) to systematically consider the trade-offs between different impact categories and sustainability dimensions
- Applying LCSA to the other electricity generation systems present in Portugal, which have not been considered in this thesis, namely: biomass,
- Expanding socioeconomic models to assess issues more comprehensively e.g. for energy security using higher resolution of data for the fuel value chains, and focusing on fewer socioeconomic issues in greater depth
- Incorporating uncertainty and variability associated with the estimated impacts for different generation systems

## 5. *CONCLUSIONS*

A multidimensional life cycle sustainability assessment was carried out to estimate and compare the environmental and socioeconomic impacts of key electricity generation technologies in Portugal. To the best of the author's knowledge this is the first time that an LCSA has been carried out for this particular context. The current study has applied relevant indicators and methods to account for different socioeconomic impacts. In addition to this, it has assessed critical water use impacts, and updated the models (i.e. data and assumptions) and impact assessment methods which were developed in the previous E-LCA for the Portuguese context (Garcia et al. 2014),

The LCSA methodology (as applied to the current study) is beneficial for holistically considering and quantifying the wider life cycle impacts of systems; across the boundaries of traditional sustainability dimensions. As a decision support tool, LCSA has not only provided an overview of the sustainability performance of key electricity generation systems used in Portugal; but also highlighted areas (hotspots) of either significant *negative* impacts – where improvements can be made; or *positive* impacts – where opportunities can be exploited. For example, wind systems (which represent a large share of Portugal's generation mix) have been identified as having a significant impact towards metal resource depletion. In addition to promoting the use of recycled metals in the infrastructure of these systems (to avoid the impacts involved in mining virgin material), the responsible stakeholder may use the findings of this (or another) LCSA study to promote methods to mitigate the negative impacts caused during upstream phases in the value chain of wind systems. From a socioeconomic perspective, the increasing adoption of PV systems in Portugal (discussed previously in Chapter 2) could be promoted further, and also justified on the basis of its estimated potential to create high levels of *domestic* employment. By applying LCSA (rather than only an economic study) to this particular context, the challenge of mitigating the significant environmental impacts of PV (toxicity towards ecosystems and humans) would also be recognised concurrently.

The LCSA methodology also reveals the importance of *context* in considering the sustainability of systems. In order to comprehensively answer the key research question of this thesis: "Which electricity generation system is the most sustainable in Portugal?" the assumptions and data relevant to Portugal are essential. Furthermore, in order to gain the optimum benefit from the available systems or options (based on the results of the LCSA), it is important for decision makers to consider trade-offs, depending on the different (and at times conflicting) priorities of relevant stakeholders.

Fossil fuel-based systems were found to produce the most negative (i.e. highest) impacts within most environmental categories. Coal was estimated to have the highest impacts in several categories notably; nREn consumption (10741 MJ/MWh, and by extension FFD – 243.6 kg oil eq./MWh) due to fuel combustion; GWP (1123 kg $CO_2$ eq./MWh) due to GHG emissions; as well as TA and AqAc due to emissions of acidifying substances like $SO_2$ and NOx in waste gases. Natural gas produced the highest impacts towards OD due to auxiliary systems within the fuel extraction process. While renewable systems generally produced lower environmental impacts, certain technologies registered the highest in categories such as: metal depletion (wind – 18.6 kg Fe eq./MWh), freshwater ecotoxicity (PV) and water scarcity footprint (large hydro – 615.71 worldm$^3$/MWh). For all categories considered, the impacts within fossil fuel-based systems were mainly attributable to plant operation (fuel extraction, and operation and maintenance); while in renewable-based systems, the impacts originated mostly from plant infrastructure – the only exception to this being water scarcity footprint in large hydro systems for which the operation phase was more significant. For socioeconomic impacts, there was more variability as to which systems produced the most positive or negative impacts. Coal – previously the worst-performing (environmentally) was estimated to generate the most total employment (544.4 person-years/TWh); had the highest average capacity factor (77.4%); and the second-lowest levelised cost (USD 101.77/MWh). While PV was estimated to generate the most domestic employment (488.0 person-years/TWh), it had the lowest capacity factor (20.7%), and the highest non-carcinogenic toxicity towards humans. Overall, small hydro systems appeared to be the most sustainable; both environmentally and socioecomically.

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### *Appendix I Details of Generation and Installed Capacity in Portugal (2012 – 2016)*

| | 2012 | | | | 2013 | | | | 2014 | | | | 2015 | | | | 2016 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Generation | Variation from previous year | Installed Capacity | Variation from previous year | Generation | Variation from previous year | Installed Capacity | Variation from previous year | Generation | Variation from previous year | Installed Capacity | Variation from previous year | Generation | Variation from previous year | Installed Capacity | Variation from previous year | Generation | Variation from previous year | Installed Capacity | Variation from previous year |
| | **GWh** | **GWh** | **MW** | **MW** | **GWh** | **GWh** | **MW** | **MW** | **GWh** | **GWh** | **MW** | **MW** | **GWh** | **GWh** | **MW** | **MW** | **GWh** | **GWh** | **MW** | **MW** |
| **Hydro(Large)** | 4780 | -5441 | 5239 | 259 | 12146 | 7366 | 5239 | 0 | 13805 | 1659 | 5269 | 30 | 7637 | -6168 | 5724 | 455 | 14081 | 6444 | 6522 | 798 |
| **Hydro(Small)** | 623 | -396 | 417 | 5 | 1337 | 714 | 413 | -4 | 1509 | 172 | 415 | 2 | 816 | -693 | 422 | 7 | 1332 | 516 | 423 | 1 |
| **Wind(Onshore)** | 10012 | 1009 | 4194 | 113 | 11751 | 1739 | 4368 | 174 | 11813 | 62 | 4541 | 173 | 11334 | -479 | 4826 | 285 | 12188 | 854 | 5046 | 220 |
| **Coal** | 12136 | 3008 | 1756 | 0 | 10953 | -1183 | 1756 | 0 | 11066 | 113 | 1756 | 0 | 13677 | 2611 | 1756 | 0 | 11698 | -1979 | 1756 | 0 |
| **Natural Gas** | 10214 | -4153 | 4739 | 52 | 6908 | -3306 | 4758 | 19 | 6321 | -587 | 4717 | -41 | 9807 | 3486 | 4698 | -19 | 11571 | 1764 | 4657 | -41 |
| **Biomass** | 2630 | 64 | 618 | 15 | 2692 | 62 | 610 | -8 | 2697 | 5 | 601 | -9 | 2618 | -79 | 613 | 12 | 2687 | 69 | 615 | 2 |
| **Photovoltaics** | 357 | 95 | 220 | 65 | 446 | 89 | 282 | 62 | 592 | 146 | 396 | 114 | 760 | 168 | 429 | 33 | 781 | 21 | 439 | 10 |
| **Others** | 757 | -517 | 1363 | -865 | 446 | -311 | 364 | -999 | 336 | -110 | 138 | -226 | 356 | 20 | 65 | -73 | 318 | -38 | 60 | -5 |
| ***From Pumped Storage*** | 1044 | | | | 1157 | | | | 859 | | | | 1160 | | | | 1217 | | | |
| ***Pump Consumption*** | -1388 | | | | -1458 | | | | -1079 | | | | -1467 | | | | -1519 | | | |
| ***Import Balance*** | 7894 | | | | 2782 | | | | 900 | | | | 2266 | | | | -5082 | | | |
| ***Imports (Commercial)*** | 8297 | | | | 5229 | | | | 4084 | | | | 4549 | | | | 1973 | | | |
| ***Exports (Commercial)*** | 403 | | | | 2447 | | | | 3184 | | | | 2283 | | | | 7055 | | | |
| **Total Production** | 42553 | -6331 | 18546 | -356 | 47836 | 5283 | 17790 | -756 | 48998 | 1162 | 17833 | 43 | 48165 | -833 | 18533 | 700 | 55873 | 7708 | 19518 | 985 |
| **Net Local Demand** | 49059 | | | | 49160 | | | | 48819 | | | | 48964 | | | | 49272 | | | |

***Data Sources:*** *REN Centro de informaçao* [62], *and REN Technical Reports* [41]–[45]

## *Appendix II  Calculation for AWARE Water Scarcity Characterisation Factors*

| District/Autonomous Region | AWARE Annual CFs | | | Installed Capacity (MW by District/Autonomous Region) | | | | | | Share Installed Capacity (% by District/Autonomous Region) | | | | | | Technology and Region-Specific Water Scarcity CFs [a.)] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AGRI | NON-AGRI | UNKNOWN | CO | NG | HL | HS | WD | PV | CO | NG | HL | HS | WD | PV | CO | NG | HL | HS | WD | PV |
| **Aveiro** | 61.40 | **18.80** | 58.70 | 0.0 | 0.0 | 0.0 | 11.5 | 42.1 | 4.7 | 0.0% | 0.0% | 0.0% | 2.5% | 0.8% | 1.5% | 0.00 | 0.00 | 0.00 | 0.47 | 0.16 | 0.28 |
| **Beja** | 62.80 | **22.60** | 62.20 | 0.0 | 0.0 | 500.0 | 21.3 | 74.4 | 104.7 | 0.0% | 0.0% | 7.7% | 4.6% | 1.5% | 33.6% | 0.00 | 0.00 | 1.73 | 1.04 | 0.33 | 7.59 |
| **Braga** | 67.60 | **17.60** | 64.30 | 0.0 | 0.0 | 187.0 | 53.3 | 147.9 | 2.4 | 0.0% | 0.0% | 2.9% | 11.5% | 2.9% | 0.8% | 0.00 | 0.00 | 0.51 | 2.03 | 0.52 | 0.14 |
| **Braganca** | 72.20 | **24.40** | 70.60 | 0.0 | 0.0 | 1659.4 | 44.8 | 74.0 | 0.1 | 0.0% | 0.0% | 25.5% | 9.7% | 1.5% | 0.0% | 0.00 | 0.00 | 6.22 | 2.36 | 0.36 | 0.01 |
| **Castelo Branco** | 10.70 | **4.30** | 10.30 | 0.0 | 0.0 | 108.0 | 25.3 | 482.2 | 0.0 | 0.0% | 0.0% | 1.7% | 5.5% | 9.6% | 0.0% | 0.00 | 0.00 | 0.07 | 0.24 | 0.41 | 0.00 |
| **Coimbra** | 60.30 | **17.60** | 58.00 | 0.0 | 826.0 | 384.4 | 13.6 | 689.2 | 4.4 | 0.0% | 21.6% | 5.9% | 2.9% | 13.7% | 1.4% | 0.00 | 3.80 | 1.04 | 0.52 | 2.40 | 0.25 |
| **Evora** | 10.70 | **4.30** | 10.30 | 0.0 | 0.0 | 0.0 | 1.4 | 0.0 | 40.9 | 0.0% | 0.0% | 0.0% | 0.3% | 0.0% | 13.1% | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.56 |
| **Faro** | 64.47 | **29.70** | 63.20 | 0.0 | 0.0 | 0.0 | 1.1 | 220.7 | 43.0 | 0.0% | 0.0% | 0.0% | 0.2% | 4.4% | 13.8% | 0.00 | 0.00 | 0.00 | 0.07 | 1.30 | 4.09 |
| **Guarda** | 72.20 | **24.40** | 70.60 | 0.0 | 0.0 | 295.7 | 43.8 | 452.1 | 0.0 | 0.0% | 0.0% | 4.5% | 9.5% | 9.0% | 0.0% | 0.00 | 0.00 | 1.11 | 2.31 | 2.19 | 0.00 |
| **Leiria** | 59.80 | **19.60** | 54.60 | 0.0 | 0.0 | 44.0 | 0.5 | 203.4 | 0.0 | 0.0% | 0.0% | 0.7% | 0.1% | 4.0% | 0.0% | 0.00 | 0.00 | 0.13 | 0.02 | 0.79 | 0.00 |
| **Lisboa** | 10.70 | **4.30** | 10.30 | 0.0 | 1176.0 | 0.0 | 0.0 | 362.5 | 24.6 | 0.0% | 30.7% | 0.0% | 0.0% | 7.2% | 7.9% | 0.00 | 1.32 | 0.00 | 0.00 | 0.31 | 0.34 |
| **Portalegre** | 10.70 | **4.30** | 10.30 | 0.0 | 0.0 | 132.0 | 14.4 | 8.2 | 0.0 | 0.0% | 0.0% | 2.0% | 3.1% | 0.2% | 0.0% | 0.00 | 0.00 | 0.09 | 0.13 | 0.01 | 0.00 |
| **Porto** | 72.20 | **24.40** | 70.60 | 0.0 | 990.0 | 257.0 | 21.8 | 65.1 | 2.0 | 0.0% | 25.9% | 3.9% | 4.7% | 1.3% | 0.6% | 0.00 | 6.31 | 0.96 | 1.15 | 0.31 | 0.16 |
| **R.A. Acores** | n/a | **n/a** | n/a | 0.0 | 0.0 | 0.0 | 8.3 | 34.2 | 0.0 | 0.0% | 0.0% | 0.0% | 1.8% | 0.7% | 0.0% | n/a | n/a | n/a | n/a | n/a | n/a |
| **R.A. Madeira** | 100.00 | **61.70** | 95.50 | 0.0 | 0.0 | 24.0 | 26.8 | 49.8 | 17.8 | 0.0% | 0.0% | 0.4% | 5.8% | 1.0% | 5.7% | 0.00 | 0.00 | 0.23 | 3.58 | 0.61 | 3.52 |
| **Santarem** | 10.70 | **4.30** | 10.30 | 576.0 | 837.0 | 280.7 | 0.0 | 158.9 | 18.7 | 32.8% | 21.9% | 4.3% | 0.0% | 3.1% | 6.0% | 1.41 | 0.94 | 0.19 | 0.00 | 0.14 | 0.26 |
| **Setubal** | 94.00 | **43.60** | 93.50 | 1180.0 | 0.0 | 0.0 | 3.0 | 18.7 | 48.3 | 67.2% | 0.0% | 0.0% | 0.6% | 0.4% | 15.5% | 29.30 | 0.00 | 0.00 | 0.28 | 0.16 | 6.75 |
| **Viana do Castelo** | 67.60 | **17.60** | 64.30 | 0.0 | 0.0 | 696.1 | 13.8 | 342.6 | 0.2 | 0.0% | 0.0% | 10.7% | 3.0% | 6.8% | 0.1% | 0.00 | 0.00 | 1.88 | 0.53 | 1.19 | 0.01 |
| **Vila Real** | 72.20 | **24.40** | 70.60 | 0.0 | 0.0 | 1588.4 | 62.7 | 679.5 | 0.0 | 0.0% | 0.0% | 24.4% | 13.6% | 13.5% | 0.0% | 0.00 | 0.00 | 5.95 | 3.31 | 3.29 | 0.00 |
| **Viseu** | 60.30 | **17.60** | 58.00 | 0.0 | 0.0 | 357.6 | 95.1 | 940.7 | 0.1 | 0.0% | 0.0% | 5.5% | 20.6% | 18.6% | 0.0% | 0.00 | 0.00 | 0.97 | 3.62 | 3.28 | 0.00 |
| | | | | | | | | | | | | | | | | | | | | | |
| | | | TOTAL | **1756** | **3829 [b.)]** | **6514.3** | **462.49** | **5046.17** | **311.81** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **30.71** | **12.37** | **21.06** | **21.66** | **17.75** | **23.96** |
| | | | | | | | | | | | | | | | | | | | | | |

***Legend:*** *CO: Coal; NG: Natural Gas; HL: Large Hydro; HS: Small Hydro; WD: Wind; PV: Photovoltaic; n/a: data not available*

**Notes:**

a) **Water scarcity CFs** calculated by multiplying the **relative share of installed capacity** in each district/autonomous region by the **AWARE Non-Agricultural CF** for that region (based on hydrological model data from 2016), and adding the results for each technology. AWARE CFs for districts were obtained from Google Earth Layer, developed by WULCA [71]. Installed capacity per district obtained from e2P database [58] and environmental declarations from fossil fuel plants [59]

b) Geographical distribution of installed capacity for NG was based on utility scale power plants only. Discrepancy between total capacity (3829 MW) and overall NG capacity (4657 MW – see Appendix I) represents smaller, cogeneration plants.

***Appendix III Calculations for Employment Generation***

| 2016 | Units | Coal | Natural Gas | Hydro (Large) | Hydro (Small) | Wind (Onshore) | Photovoltaic | *Comments/Data Sources* |
|---|---|---|---|---|---|---|---|---|
| **Actual Generation** | GWh | 11698 | 11571 | 14081 | 1332 | 12188 | 781 | *REN, Technical Data 2016* |
| **Variation from previous year** | GWh | -1979 | 1764 | 6444 | 516 | 854 | 21 | *"* |
| **Installed Capacity** | MW | 1756 | 4657 | 6522 | 423 | 5046 | 439 | *"* |
| **Variation from previous year** | MW | 0 | -41 | 798 | 1 | 220 | 10 | *"* |
| **Expected Lifetime** | years | 30 | 30 | 150 | 80 | 25 | 25 | *Key data and assumptions (Table 4)* |
| **Construction Time** | years | 5 | 2 | 2 | 2 | 2 | 1 | *Rutovitz et al. 2015* |
| **Potential Generation for 2016** | GWh | 15382.6 | 40795.3 | 57132.7 | 3705.5 | 44203.0 | 3845.6 | *REN, Technical Data 2016* |
| **Capacity Factor** | % | 76% | 28% | 25% | 36% | 28% | 20% | *"(Based on max. potential annual generation at 8760 hours)* |
| **Expected Lifetime Generation** | GWh | 350940 | 347130 | 2112150 | 106560 | 304700 | 19525 | *"* |
| **Component Assembly/Manufacturing** | | | | | | | | |
| MW installed per year in region | MW | 0.0 | 0.0 | 798.0 | 1.0 | 220.0 | 10.0 | *REN, Technical Data 2016* |
| Manufacturing employment factor | p-years/MW | 5.4 | 0.9 | 3.5 | 10.9 | 4.7 | 6.7 | *Rutovitz et al. 2015 pg.5* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| % Local Manufacturing | % | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Assumed components manufactured and used locally* |
| | | 0.0 | 0.0 | 2793.0 | 10.9 | 1034.0 | 67.0 | |
| **Plant Construction** | | | | | | | | |
| MW installed per year | MW | 0.0 | 0.0 | 798.0 | 1.0 | 220.0 | 10.0 | *REN, Technical Data 2016* |
| Construction employment factor | p-years/MW | 11.2 | 1.3 | 7.4 | 15.8 | 3.2 | 13.0 | *Rutovitz et al. 2015 pg.5* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Factored for Construction Time | | 0.0 | 0.0 | 2952.6 | 7.9 | 352.0 | 130.0 | |
| Unfactored | | 0.0 | 0.0 | 5905.2 | 15.8 | 704.0 | 130.0 | |
| **Extraction Processing & Transport of Fuels** | | | | | | | | |
| Primary energy demand plus exports | PJ | 117.0 | 71.8 | 0.0 | 0.0 | 0.0 | 0.0 | *1 GWh = 0.0036 PJ; Efficiency Coal 36%, NG 58%* |
| Fuel employment factor for one year | p-years/PJ | 15.4 | 7.4 | 0.0 | 0.0 | 0.0 | 0.0 | *Fuel EF for Colombia (CO), Algeria and Nigeria (NG)* |
| Regional job multiplier for year | n/a | 3.4 | 5.7 | 1.0 | 1.0 | 1.0 | 1.0 | *RJM for Colombia (CO), Algeria and Nigeria (NG)* |
| % Local Production | n/a | 1.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Unfactored | | 6125.1 | 3029.4 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Factored for lifespan | | 183752.2 | 90881.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| **Plant Operation & Maintenance** | | | | | | | | |
| Cumulative capacity | MW | 1756.0 | 4657.0 | 6522.0 | 423.0 | 5046.0 | 439.0 | *REN, Technical Data 2016* |
| O&M employment factor for one year | p-years/MW | 0.1 | 0.1 | 0.2 | 1.0 | 0.3 | 0.7 | *Rutovitz et al. 2015 pg.5 (O&M EF for HS adjusted due to outlier)* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Unfactored | | 245.8 | 652.0 | 1304.4 | 423.0 | 1513.8 | 307.3 | |
| Factored for lifespan | | 7375.2 | 19559.4 | 195660.0 | 33840.0 | 37845.0 | 7682.5 | |
| **Plant Decommissioning** | | | | | | | | |
| MW decommissioned per year | MW | 0.0 | 41.0 | 0.0 | 4.0 | 0.0 | 0.0 | *REN, Technical Data 2016* |
| Construction employment factor | p-years/MW | 2.2 | 0.3 | 1.5 | 3.2 | 0.6 | 2.6 | *Rutovitz et al. 2015 pg.5; Decom. assumed 20% of construction* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| | | 0.0 | 10.7 | 0.0 | 12.6 | 0.0 | 0.0 | |
| **Total Employment in 2016** | p-years | 6371 | 3692 | 7050 | 454 | 2900 | 504 | |
| **Total Lifetime Employment (2016 conditions)** | p-years | 191127 | 110451 | 204358 | 33879 | 39583 | 7880 | |
| **Life Cycle Employment (2016 conditions)** | p-years/TWh | 545 | 318 | 97 | 318 | 130 | 404 | |

| 2015 | Units | Coal | Natural Gas | Hydro (Large) | Hydro (Small) | Wind (Onshore) | Photovoltaic | Comments/Data Sources |
|---|---|---|---|---|---|---|---|---|
| **Actual Generation** | GWh | 13677 | 9807 | 7637 | 816 | 11334 | 760 | *REN, Technical Data 2014* |
| **Variation from previous year** | GWh | 2611 | 3486 | -6168 | -693 | -479 | 168 | *"* |
| **Installed Capacity** | MW | 1756 | 4698 | 5724 | 422 | 4826 | 429 | *"* |
| **Variation from previous year** | MW | 0 | -19 | 455 | 7 | 285 | 33 | *"* |
| **Expected Lifetime** | years | 30 | 30 | 150 | 80 | 25 | 25 | *Key data and assumptions (Table 4)* |
| **Construction Time** | years | 5 | 2 | 2 | 2 | 2 | 1 | *Rutovitz et al. 2015 pg.5* |
| **Potential Generation for 2015** | GWh | 15382.6 | 41154.5 | 50142.2 | 3696.7 | 42275.8 | 3758.0 | *REN, Technical Data 2015* |
| **Capacity Factor** | % | 89% | 24% | 15% | 22% | 27% | 20% | *"(Based on max. potential annual generation at 8760 hours)* |
| **Expected Lifetime Generation** | GWh | 410310 | 294210 | 1145550 | 65280 | 283350 | 19000 | *"* |
| | | | | | | | | |
| **Component Assembly/Manufacturing** | | | | | | | | |
| MW installed per year in region | MW | 0.0 | 0.0 | 455.0 | 7.0 | 285.0 | 33.0 | *REN, Technical Data 2015* |
| Manufacturing employment factor | p-years/MW | 5.4 | 0.9 | 3.5 | 10.9 | 4.7 | 6.7 | *Rutovitz et al. 2015 pg.5* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| % Local Manufacturing | % | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Assumed components manufactured and used locally* |
| | | 0.0 | 0.0 | 1592.5 | 76.3 | 1339.5 | 221.1 | |
| **Plant Construction** | | | | | | | | |
| MW installed per year | MW | 0.0 | 0.0 | 455.0 | 7.0 | 285.0 | 33.0 | *REN, Technical Data 2015* |
| Construction employment factor | p-years/MW | 11.2 | 1.3 | 7.4 | 15.8 | 3.2 | 13.0 | *Rutovitz et al. 2015 pg.5* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Factored for Construction Time | | 0.0 | 0.0 | 1683.5 | 55.3 | 456.0 | 429.0 | |
| Unfactored | | 0.0 | 0.0 | 3367.0 | 110.6 | 912.0 | 429.0 | |
| **Extraction Processing & Transport of Fuels** | | | | | | | | |
| Primary energy demand plus exports | PJ | 136.8 | 60.9 | 0.0 | 0.0 | 0.0 | 0.0 | *1 GWh = 0.0036 PJ; Efficiency Coal 36%, NG 58%* |
| Fuel employment factor for one year | p-years/PJ | 15.4 | 7.4 | 0.0 | 0.0 | 0.0 | 0.0 | *Fuel EF for Colombia (CO), Algeria and Nigeria (NG)* |
| Regional job multiplier for year | n/a | 3.4 | 5.7 | 1.0 | 1.0 | 1.0 | 1.0 | *RJM for Colombia (CO), Algeria and Nigeria (NG)* |
| % Local Production | n/a | 1.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Unfactored | | 7161.3 | 2567.5 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Factored for lifespan | | 214838.3 | 77026.2 | 0.0 | 0.0 | 0.0 | 0.0 | |
| **Plant Operation & Maintenance** | | | | | | | | |
| Cumulative capacity | MW | 1756.0 | 4698.0 | 5724.0 | 422.0 | 4826.0 | 429.0 | *REN, Technical Data 2015* |
| O&M employment factor for one year | p-years/MW | 0.1 | 0.1 | 0.2 | 1.0 | 0.3 | 0.7 | *Rutovitz et al. 2015 pg.5 (O&M EF for HS adjusted due to outlier)* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Unfactored | | 245.8 | 657.7 | 1144.8 | 422.0 | 1447.8 | 300.3 | |
| Factored for lifespan | | 7375.2 | 19731.6 | 171720.0 | 33760.0 | 36195.0 | 7507.5 | |
| **Plant Decommissioning** | | | | | | | | |
| MW decommissioned per year | MW | 0.0 | 19.0 | 0.0 | 0.0 | 0.0 | 0.0 | *REN, Technical Data 2015* |
| Construction employment factor | p-years/MW | 2.2 | 0.3 | 1.5 | 3.2 | 0.6 | 2.6 | *Rutovitz et al. 2015 pg.5; Decom. assumed 20% of construction* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Unfactored | | 0.0 | 4.9 | 0.0 | 0.0 | 0.0 | 0.0 | |
| | | | | | | | | |
| **Total Employment in 2015** | p-years | 7407 | 3230 | 4421 | 554 | 3243 | 950 | |
| **Total Lifetime Employment (2015 conditions)** | p-years | 222214 | 96763 | 176680 | 33947 | 38447 | 8158 | |
| **Life Cycle Employment (2015 conditions)** | p-years/TWh | 542 | 329 | 154 | 520 | 136 | 429 | |

| 2014 | Units | Coal | Natural Gas | Hydro (Large) | Hydro (Small) | Wind (Onshore) | Photovoltaic | Comments/Data Sources |
|---|---|---|---|---|---|---|---|---|
| **Actual Generation** | GWh | 11066 | 6321 | 13805 | 1509 | 11813 | 592 | *REN, Technical Data 2014* |
| **Variation from previous year** | GWh | 113 | -587 | 1659 | 172 | 62 | 146 | *"* |
| **Installed Capacity** | MW | 1756 | 4717 | 5269 | 415 | 4541 | 396 | *"* |
| **Variation from previous year** | MW | 0 | -41 | 30 | 2 | 173 | 114 | *"* |
| **Expected Lifetime** | years | 30 | 30 | 150 | 80 | 25 | 25 | *Key data and assumptions (Table 4)* |
| **Construction Time** | years | 5 | 2 | 2 | 2 | 2 | 1 | *Rutovitz et al. 2015 pg.5* |
| **Potential Generation for 2014** | GWh | 15382.6 | 41320.9 | 46156.4 | 3635.4 | 39779.2 | 3469.0 | *REN, Technical Data 2014* |
| **Capacity Factor** | % | 72% | 15% | 30% | 42% | 30% | 17% | *"(Based on max. potential annual generation at 8760 hours)* |
| **Expected Lifetime Generation** | GWh | 331980 | 189630 | 2070750 | 120720 | 295325 | 14800 | *"* |
| | | | | | | | | |
| **Component Assembly/Manufacturing** | | | | | | | | |
| MW installed per year in region | MW | 0.0 | 0.0 | 30.0 | 2.0 | 173.0 | 114.0 | *REN, Technical Data 2014* |
| Manufacturing employment factor | p-years/MW | 5.4 | 0.9 | 3.5 | 10.9 | 4.7 | 6.7 | *Rutovitz et al. 2015 pg.5* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| % Local Manufacturing | % | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Assumed components manufactured and used locally* |
| | | 0.0 | 0.0 | 105.0 | 21.8 | 813.1 | 763.8 | |
| **Plant Construction** | | | | | | | | |
| MW installed per year | MW | 0.0 | 0.0 | 30.0 | 2.0 | 173.0 | 114.0 | *REN, Technical Data 2014* |
| Construction employment factor | p-years/MW | 11.2 | 1.3 | 7.4 | 15.8 | 3.2 | 13.0 | *Rutovitz et al. 2015 pg.5* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Factored for Construction Time | | 0.0 | 0.0 | 111.0 | 15.8 | 276.8 | 1482.0 | |
| Unfactored | | 0.0 | 0.0 | 222.0 | 31.6 | 553.6 | 1482.0 | |
| **Extraction Processing & Transport of Fuels** | | | | | | | | |
| Primary energy demand plus exports | PJ | 110.7 | 39.2 | 0.0 | 0.0 | 0.0 | 0.0 | *1 GWh = 0.0036 PJ; Efficiency Coal 36%, NG 58%* |
| Fuel employment factor for one year | p-years/PJ | 15.4 | 7.4 | 0.0 | 0.0 | 0.0 | 0.0 | *Fuel EF for Colombia (CO), Algeria and Nigeria (NG)* |
| Regional job multiplier for year | n/a | 3.4 | 5.7 | 1.0 | 1.0 | 1.0 | 1.0 | *RJM for Colombia (CO), Algeria and Nigeria (NG)* |
| % Local Production | n/a | 1.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Unfactored | | 5794.2 | 1654.9 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Factored for lifespan | | 173824.7 | 49646.4 | 0.0 | 0.0 | 0.0 | 0.0 | |
| **Plant Operation & Maintenance** | | | | | | | | |
| Cumulative capacity | MW | 1756.0 | 4717.0 | 5269.0 | 415.0 | 4541.0 | 396.0 | *REN, Technical Data 2014* |
| O&M employment factor for one year | p-years/MW | 0.1 | 0.1 | 0.2 | 1.0 | 0.3 | 0.7 | *Rutovitz et al. 2015 pg.5 (O&M EF for HS adjusted due to outlier)* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Unfactored | | 245.8 | 660.4 | 1053.8 | 415.0 | 1362.3 | 277.2 | |
| Factored for lifespan | | 7375.2 | 19811.4 | 158070.0 | 33200.0 | 34057.5 | 6930.0 | |
| **Plant Decommissioning** | | | | | | | | |
| MW decommissioned per year | MW | 0.0 | 41.0 | 0.0 | 4.0 | 0.0 | 0.0 | *REN, Technical Data 2014* |
| Construction employment factor | p-years/MW | 2.2 | 0.3 | 1.5 | 3.2 | 0.6 | 2.6 | *Rutovitz et al. 2015 pg.5; Decom. assumed 20% of construction* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Unfactored | | 0.0 | 10.7 | 0.0 | 12.6 | 0.0 | 0.0 | |
| | | | | | | | | |
| **Total Employment in 2014** | p-years | 6040 | 2326 | 1270 | 465 | 2452 | 2523 | |
| **Total Lifetime Employment (2014 conditions)** | p-years | 181200 | 69469 | 158397 | 33266 | 35424 | 9176 | |
| **Life Cycle Employment (2014 conditions)** | p-years/TWh | 546 | 366 | 76 | 276 | 120 | 620 | |

| 2013 | Units | Coal | Natural Gas | Hydro (Large) | Hydro (Small) | Wind (Onshore) | Photovoltaic | *Comments/Data Sources* |
|---|---|---|---|---|---|---|---|---|
| **Actual Generation** | GWh | 10953 | 6908 | 12146 | 1337 | 11751 | 446 | *REN, Technical Data 2013* |
| **Variation from previous year** | GWh | -1183 | -3306 | 7366 | 714 | 1739 | 89 | *"* |
| **Installed Capacity** | MW | 1756 | 4758 | 5239 | 413 | 4368 | 282 | *"* |
| **Variation from previous year** | MW | 0 | 19 | 0 | -4 | 174 | 62 | *"* |
| **Expected Lifetime** | years | 30 | 30 | 150 | 80 | 25 | 25 | *Key data and assumptions (Table 4)* |
| **Construction Time** | years | 5 | 2 | 2 | 2 | 2 | 1 | *Rutovitz et al. 2015 pg.5* |
| **Potential Generation for 2013** | GWh | 15382.6 | 41680.1 | 45893.6 | 3617.9 | 38263.7 | 2470.3 | *REN, Technical Data 2013* |
| **Capacity Factor** | % | 71% | 17% | 26% | 37% | 31% | 18% | *"(Based on max. potential annual generation at 8760 hours)* |
| **Expected Lifetime Generation** | GWh | 328590 | 207240 | 1821900 | 106960 | 293775 | 11150 | *"* |
| | | | | | | | | |
| **Component Assembly/Manufacturing** | | | | | | | | |
| MW installed per year in region | MW | 0.0 | 19.0 | 0.0 | 0.0 | 174.0 | 62.0 | *REN, Technical Data 2013* |
| Manufacturing employment factor | p-years/MW | 5.4 | 0.9 | 3.5 | 10.9 | 4.7 | 6.7 | *Rutovitz et al. 2015 pg.5* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| % Local Manufacturing | % | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Assumed components manufactured and used locally* |
| | | 0.0 | 17.7 | 0.0 | 0.0 | 817.8 | 415.4 | |
| **Plant Construction** | | | | | | | | |
| MW installed per year | MW | 0.0 | 19.0 | 0.0 | 0.0 | 174.0 | 62.0 | *REN, Technical Data 2013* |
| Construction employment factor | p-years/MW | 11.2 | 1.3 | 7.4 | 15.8 | 3.2 | 13.0 | *Rutovitz et al. 2015 pg.5* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Factored for Construction Time | | 0.0 | 12.4 | 0.0 | 0.0 | 278.4 | 806.0 | |
| Unfactored | | 0.0 | 24.7 | 0.0 | 0.0 | 556.8 | 806.0 | |
| **Extraction Processing & Transport of Fuels** | | | | | | | | |
| Primary energy demand plus exports | PJ | 109.5 | 42.9 | 0.0 | 0.0 | 0.0 | 0.0 | *1 GWh = 0.0036 PJ; Efficiency Coal 36%, NG 58%* |
| Fuel employment factor for one year | p-years/PJ | 15.4 | 7.4 | 0.0 | 0.0 | 0.0 | 0.0 | *Fuel EF for Colombia (CO), Algeria and Nigeria (NG)* |
| Regional job multiplier for year | n/a | 3.4 | 5.7 | 1.0 | 1.0 | 1.0 | 1.0 | *RJM for Colombia (CO), Algeria and Nigeria (NG)* |
| % Local Production | n/a | 1.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Unfactored | | 5735.0 | 1808.6 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Factored for lifespan | | 172049.7 | 54256.9 | 0.0 | 0.0 | 0.0 | 0.0 | |
| **Plant Operation & Maintenance** | | | | | | | | |
| Cumulative capacity | MW | 1756.0 | 4758.0 | 5239.0 | 413.0 | 4368.0 | 282.0 | *REN, Technical Data 2013* |
| O&M employment factor for one year | p-years/MW | 0.1 | 0.1 | 0.2 | 1.0 | 0.3 | 0.7 | *Rutovitz et al. 2015 pg.5 (O&M EF for HS adjusted due to outlier)* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Unfactored | | 245.8 | 666.1 | 1047.8 | 413.0 | 1310.4 | 197.4 | |
| Factored for lifespan | | 7375.2 | 19983.6 | 157170.0 | 33040.0 | 32760.0 | 4935.0 | |
| **Plant Decommissioning** | | | | | | | | |
| MW decommissioned per year | MW | 0.0 | 41.0 | 0.0 | 4.0 | 0.0 | 0.0 | *REN, Technical Data 2013* |
| Construction employment factor | p-years/MW | 2.2 | 0.3 | 1.5 | 3.2 | 0.6 | 2.6 | *Rutovitz et al. 2015 pg.5; Decom. assumed 20% of construction* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Unfactored | | 0.0 | 10.7 | 0.0 | 12.6 | 0.0 | 0.0 | |
| | | | | | | | | |
| **Total Employment in 2013** | p-years | 5981 | 2515 | 1048 | 426 | 2407 | 1419 | |
| **Total Lifetime Employment (2013 conditions)** | p-years | 179425 | 74293 | 157170 | 33053 | 34135 | 6156 | |
| **Life Cycle Employment (2013 conditions)** | p-years/TWh | 546 | 358 | 86 | 309 | 116 | 552 | |

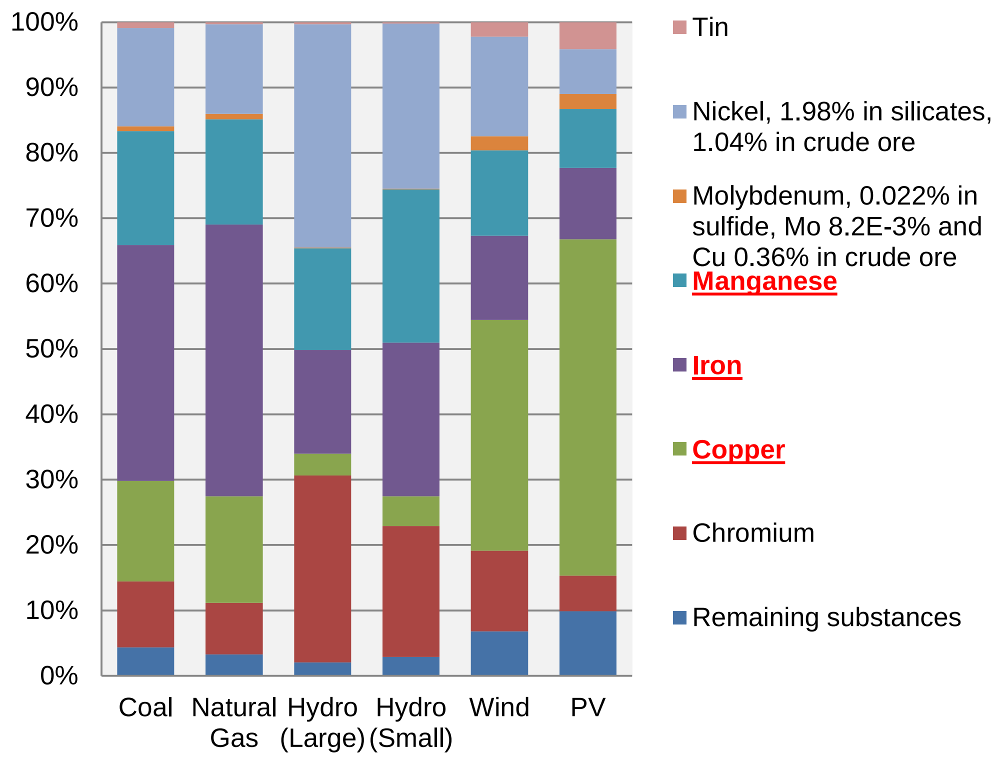
| 2012 | Units | Coal | Natural Gas | Hydro (Large) | Hydro (Small) | Wind (Onshore) | Photovoltaic | *Comments/Data Sources* |
|---|---|---|---|---|---|---|---|---|
| **Actual Generation** | GWh | 12136 | 10214 | 4780 | 623 | 10012 | 357 | *REN, Technical Data 2012* |
| **Variation from previous year** | GWh | 3008 | -4153 | -5441 | -396 | 1009 | 95 | *"* |
| **Installed Capacity** | MW | 1756 | 4739 | 5239 | 417 | 4194 | 220 | *"* |
| **Variation from previous year** | MW | 0 | 52 | 259 | 5 | 113 | 65 | *"* |
| **Expected Lifetime** | years | 30 | 30 | 150 | 80 | 25 | 25 | *Key data and assumptions (Table 4)* |
| **Construction Time** | years | 5 | 2 | 2 | 2 | 2 | 1 | *Rutovitz et al. 2015 pg.5* |
| **Potential Generation for 2012** | GWh | 15382.6 | 41513.6 | 45893.6 | 3652.9 | 36739.4 | 1927.2 | *REN, Technical Data 2012* |
| **Capacity Factor** | % | 79% | 25% | 10% | 17% | 27% | 19% | *"(Based on max. potential annual generation at 8760 hours)* |
| **Expected Lifetime Generation** | GWh | 364080 | 306420 | 717000 | 49840 | 250300 | 8925 | *"* |
| **Component Assembly/Manufacturing** | | | | | | | | |
| MW installed per year in region | MW | 0.0 | 52.0 | 259.0 | 5.0 | 113.0 | 65.0 | *REN, Technical Data 2012* |
| Manufacturing employment factor | p-years/MW | 5.4 | 0.9 | 3.5 | 10.9 | 4.7 | 6.7 | *Rutovitz et al. 2015 pg.5* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| % Local Manufacturing | % | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Assumed components manufactured and used locally* |
| | | 0.0 | 48.4 | 906.5 | 54.5 | 531.1 | 435.5 | |
| **Plant Construction** | | | | | | | | |
| MW installed per year | MW | 0.0 | 52.0 | 259.0 | 5.0 | 113.0 | 65.0 | *REN, Technical Data 2012* |
| Construction employment factor | p-years/MW | 11.2 | 1.3 | 7.4 | 15.8 | 3.2 | 13.0 | *Rutovitz et al. 2015 pg.5* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 pg.15 - EF for OECD (Portugal)* |
| Factored for Construction Time | | 0.0 | 33.8 | 958.3 | 39.5 | 180.8 | 845.0 | |
| Unfactored | | 0.0 | 67.6 | 1916.6 | 79.0 | 361.6 | 845.0 | |
| **Extraction Processing & Transport of Fuels** | | | | | | | | |
| Primary energy demand plus exports | PJ | 121.4 | 63.4 | 0.0 | 0.0 | 0.0 | 0.0 | *1 GWh = 0.0036 PJ; Efficiency Coal 36%, NG 58%* |
| Fuel employment factor for one year | p-years/PJ | 15.4 | 7.4 | 0.0 | 0.0 | 0.0 | 0.0 | *Fuel EF for Colombia (CO), Algeria and Nigeria (NG)* |
| Regional job multiplier for year | n/a | 3.4 | 5.7 | 1.0 | 1.0 | 1.0 | 1.0 | *RJM for Colombia (CO), Algeria and Nigeria (NG)* |
| % Local Production | n/a | 1.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Unfactored | | 6354.4 | 2674.1 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Factored for lifespan | | 190632.3 | 80222.9 | 0.0 | 0.0 | 0.0 | 0.0 | |
| **Plant Operation & Maintenance** | | | | | | | | |
| Cumulative capacity | MW | 1756.0 | 4739.0 | 5239.0 | 417.0 | 4194.0 | 220.0 | *REN, Technical Data 2012* |
| O&M employment factor for one year | p-years/MW | 0.1 | 0.1 | 0.2 | 1.0 | 0.3 | 0.7 | *Rutovitz et al. 2015 pg.5 (O&M EF for HS adjusted due to outlier)* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 - OECD employment factor for Portugal* |
| Unfactored | | 245.8 | 663.5 | 1047.8 | 417.0 | 1258.2 | 154.0 | |
| Factored for lifespan | | 7375.2 | 19903.8 | 157170.0 | 33360.0 | 31455.0 | 3850.0 | |
| **Plant Decommissioning** | | | | | | | | |
| MW decommissioned per year | MW | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | *REN, Technical Data 2012* |
| Construction employment factor | p-years/MW | 2.2 | 0.3 | 1.5 | 3.2 | 0.6 | 2.6 | *Rutovitz et al. 2015 pg.5; Decom. assumed 20% of construction* |
| Regional job multiplier for year | n/a | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | *Rutovitz et al. 2015 - OECD employment factor for Portugal* |
| Unfactored | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| **Total Employment in 2012** | p-years | 6600 | 3420 | 2913 | 511 | 1970 | 1435 | |
| **Total Lifetime Employment (2012 conditions)** | p-years | 198007 | 100243 | 159993 | 33494 | 32348 | 5131 | |
| **Life Cycle Employment (2012 conditions)** | p-years/TWh | 544 | 327 | 223 | 672 | 129 | 575 | |

***Legend:*** *p-years: person-years;: EF: Employment Factor; RJM: Regional Job Multiplier*

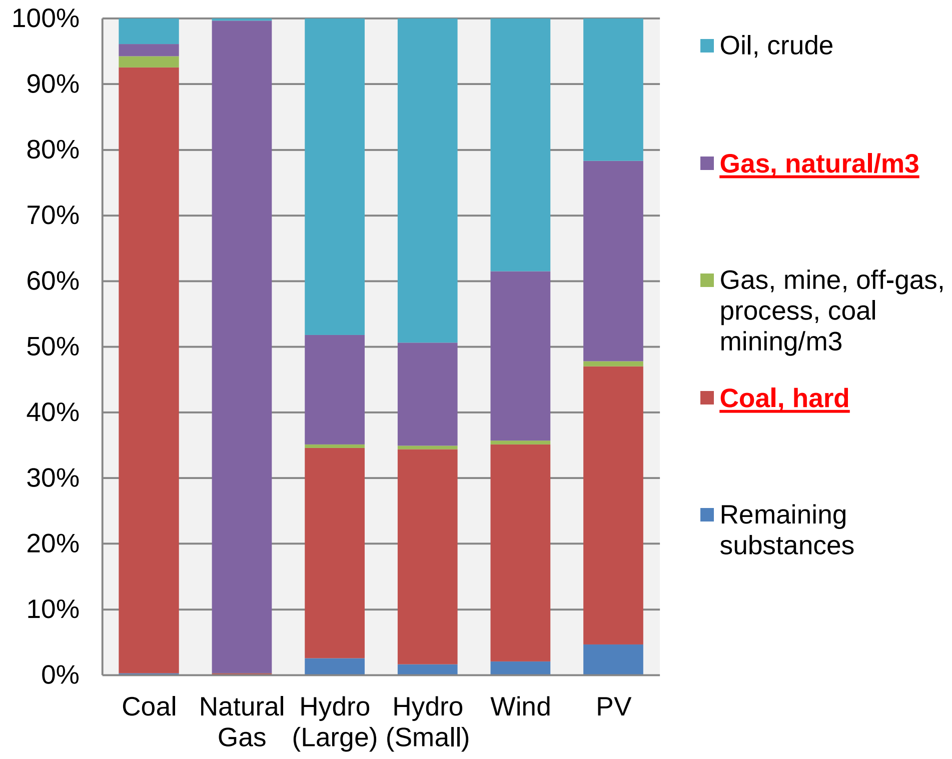
## *Appendix IV Substance Contributions for Environmental Impacts*

Note: Most significant substances shown **bold and underlined**

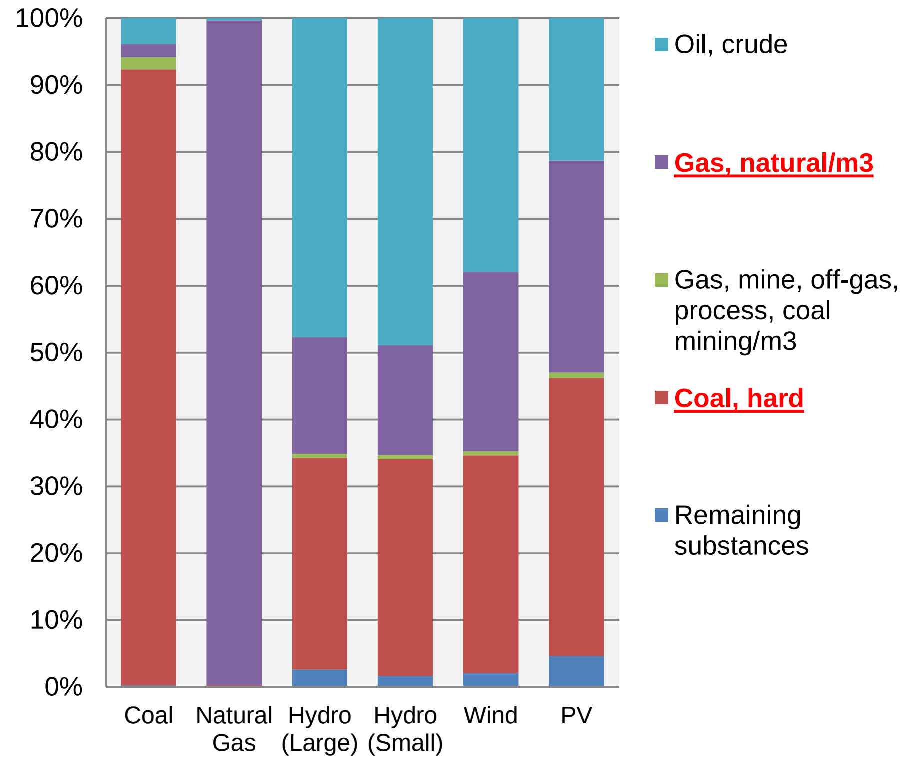
**a.) Metal Depletion (kg Fe eq./MWh) ReCiPe**



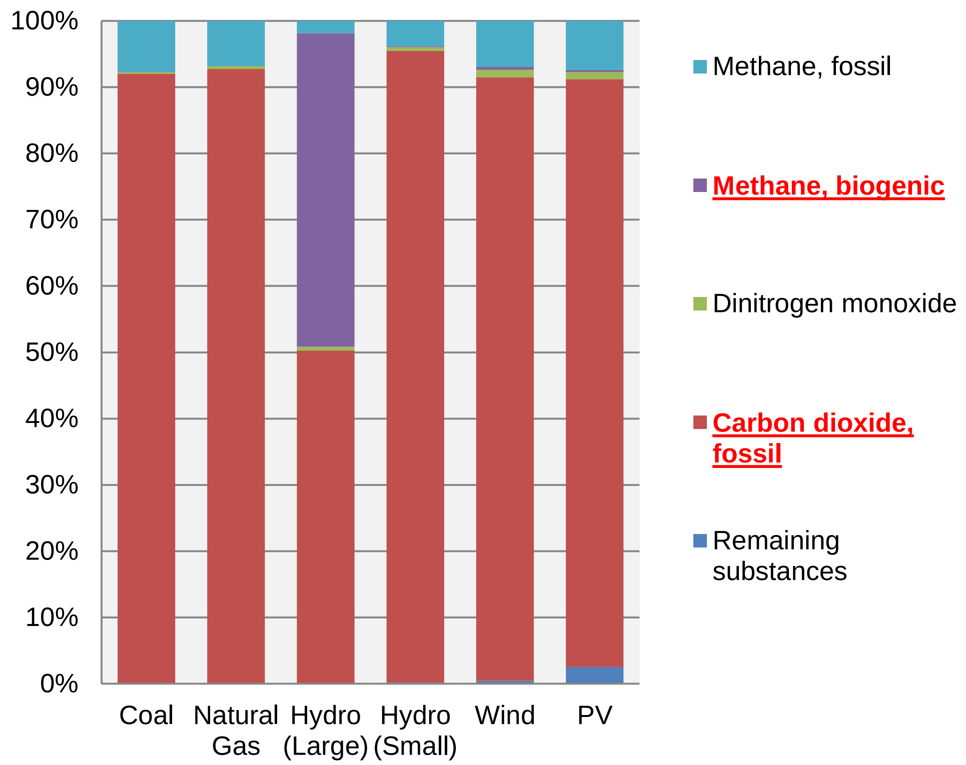

**b.) Fossil Depletion (kg oil eq./MWh) ReCiPe**



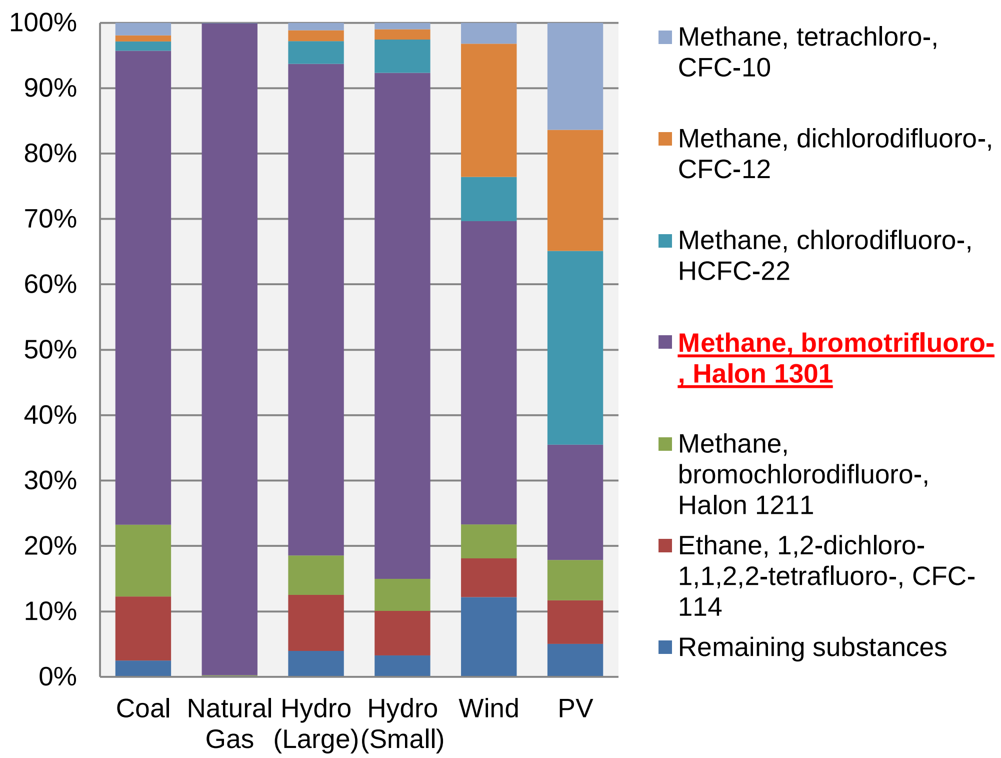

**c.) Non-renewable primary energy ($MJ_{prim}$/MWh) CED**



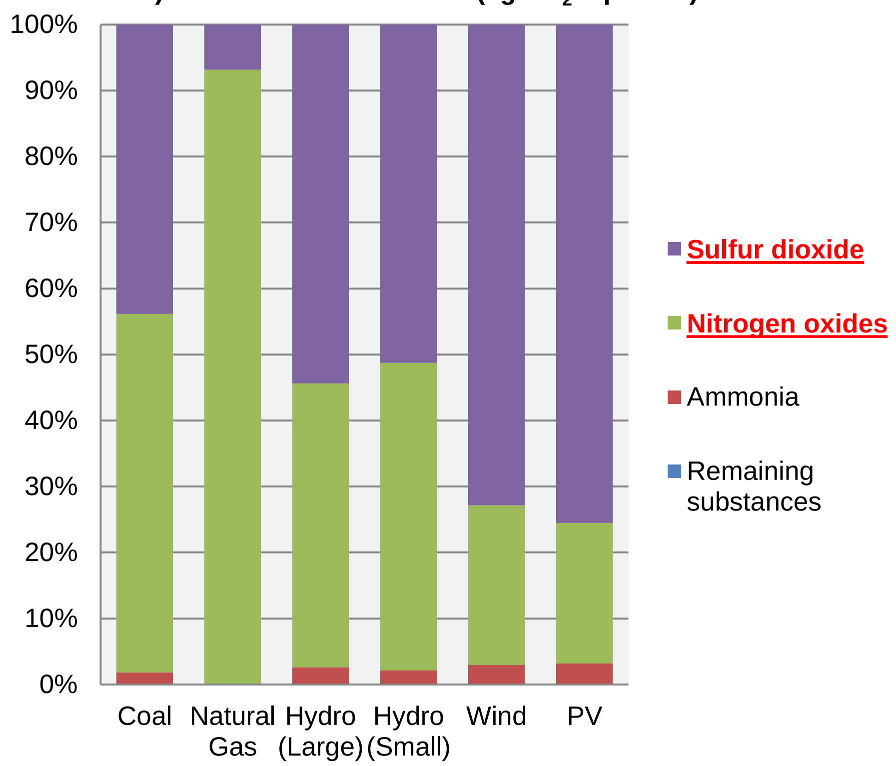

**d.) Global warming potential (kg $CO_2$ eq./MWh) IPCC 2013**

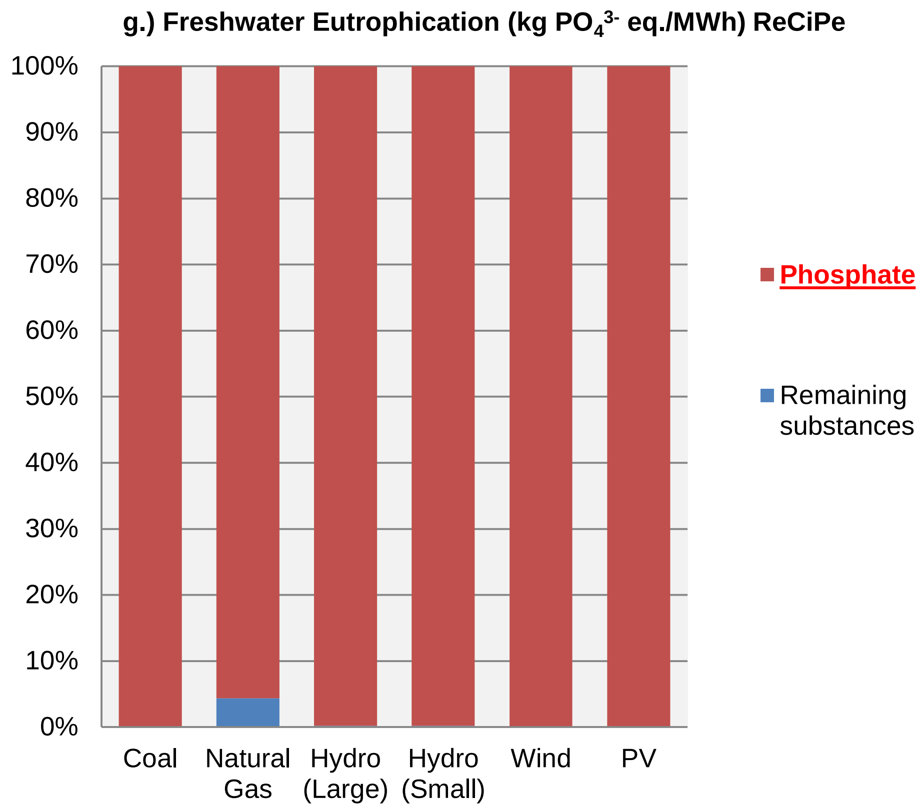


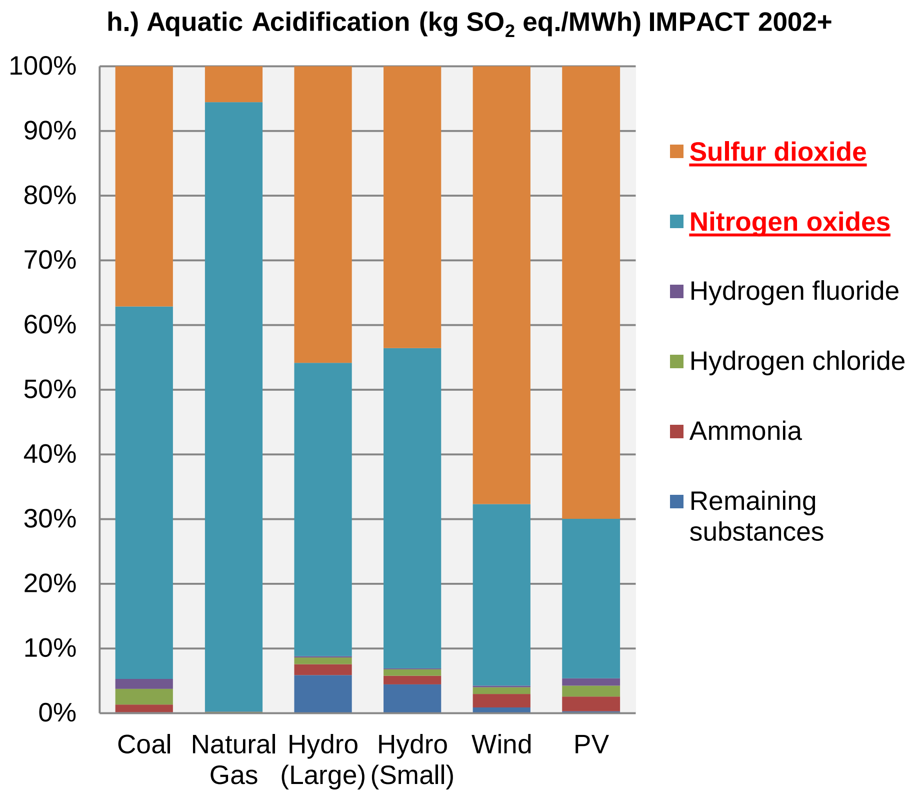

**e.) Ozone depletion (kg CFC-11 eq./MWh) ReCiPe**

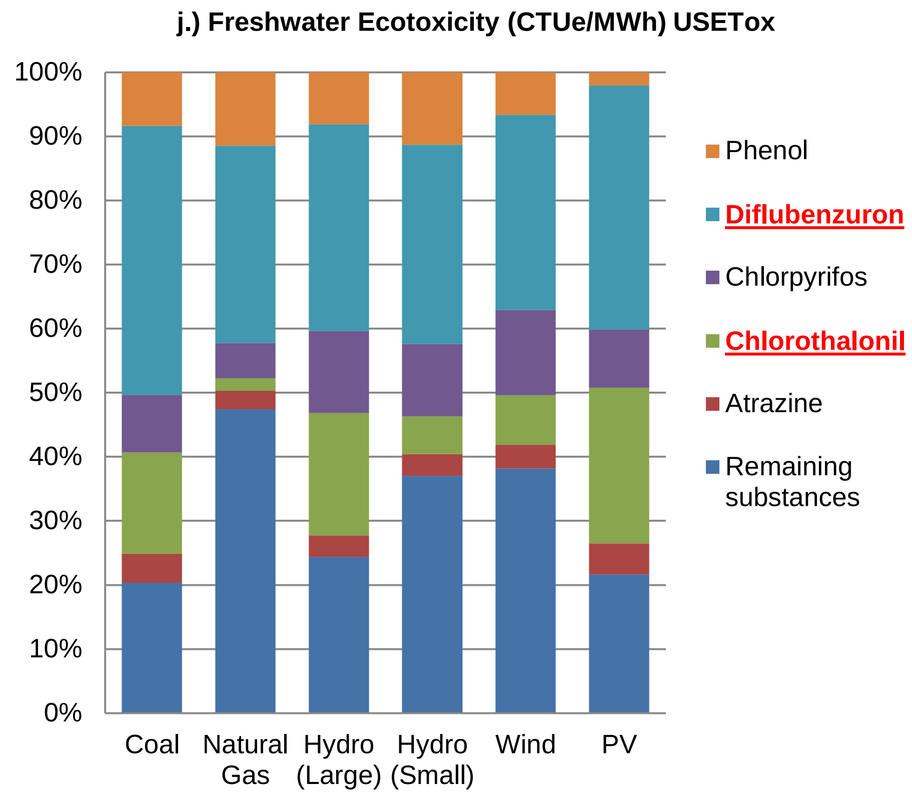


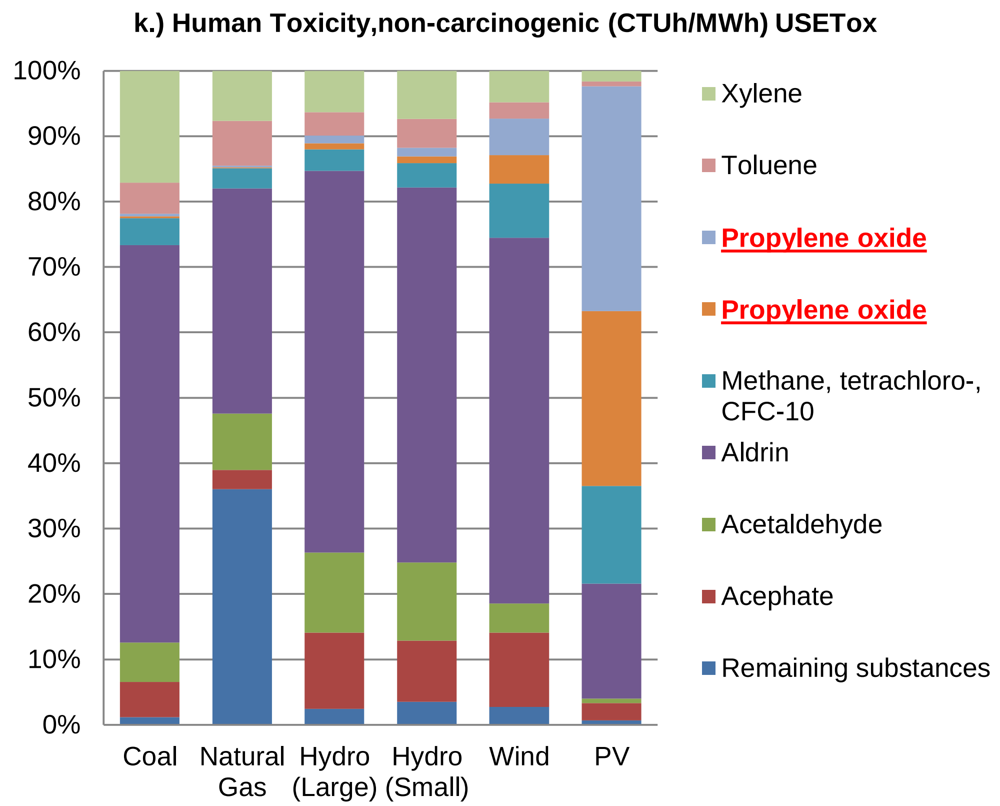

**f.) Terrestrial Acidification (kg $SO_2$ eq./MWh) ReCiPe**

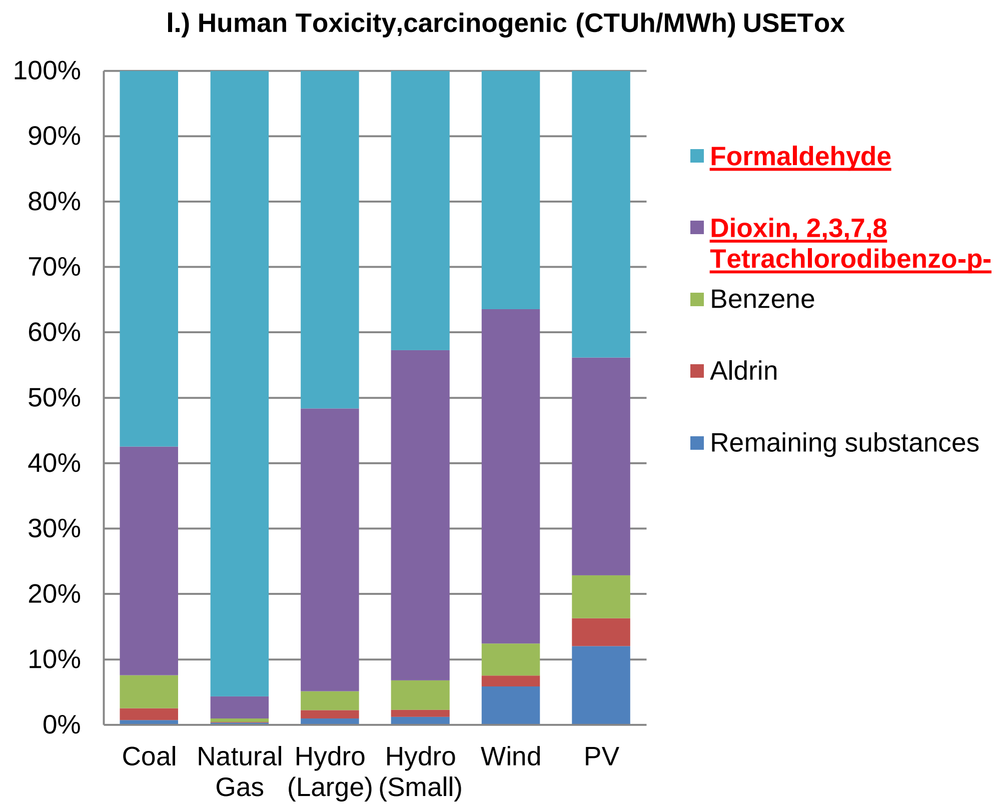



g.) Freshwater Eutrophication (kg $PO_4^{3-}$ eq./MWh) ReCiPe
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Coal
Natural Gas
Hydro (Large)
Hydro (Small)
Wind
PV
Phosphate
Remaining substances


h.) Aquatic Acidification (kg $SO_2$ eq./MWh) IMPACT 2002+
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Coal
Natural Gas
Hydro (Large)
Hydro (Small)
Wind
PV
Sulfur dioxide
Nitrogen oxides
Hydrogen fluoride
Hydrogen chloride
Ammonia
Remaining substances


j.) Freshwater Ecotoxicity (CTUe/MWh) USETox
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Coal
Natural Gas
Hydro (Large)
Hydro (Small)
Wind
PV
Phenol
Diflubenzuron
Chlorpyrifos
Chlorothalonil
Atrazine
Remaining substances


k.) Human Toxicity,non-carcinogenic (CTUh/MWh) USETox
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Coal
Natural Gas
Hydro (Large)
Hydro (Small)
Wind
PV
Xylene
Toluene
Propylene oxide
Propylene oxide
Methane, tetrachloro-, CFC-10
Aldrin
Acetaldehyde
Acephate
Remaining substances


l.) Human Toxicity,carcinogenic (CTUh/MWh) USETox
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Coal
Natural Gas
Hydro (Large)
Hydro (Small)
Wind
PV
Formaldehyde
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-
Benzene
Aldrin
Remaining substances