Regional Life Cycle Sustainability Assessment on Decentralised Electricity Generation Technologies in the Northeast Region of England

Thesis by

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Abstract

A sustainability assessment framework combines life cycle and triple bottom line approach is proposed in this study; and a life cycle sustainability assessment model that is generic and suitable to examine and compare sustainability performance of decentralised electricity technologies on a regional scale is designed under the proposed framework. The assessment model is designed based on the context of Northeast region of England; the framework is generic, and the model can be tailored to be suitable to assess different technologies in different regions. In the proposed model, sustainability performance is evaluated using three sets of nineteen indicators in total, with five examining the techno-economic impact, twelve measuring the environmental impact and two assess the social impact of selected energy technologies.

Three decentralized energy technologies were assessed in this thesis, they are solar photovoltaic (PV), onshore wind and biomass. Three types of most commonly deployed solar photovoltaic electricity generation systems are considered to represent the current technology, they are: monocrystalline (s-Si), polycrystalline (p-Si) and Cadmium telluride (CdTe) thin film. Three wind turbines with highest installation capacity are considered to be representative for present day onshore wind technology, they are: Vesta V80, Vesta V90, and Repower MM82; For biomass technology, the largest biomass combined heat and power plant both within the region and the UK –Wilton 10 is considered to be representative of state of art for the technology.

Results obtained from the assessment is then ranked and compare against each other to conclude the sustainability performance of each assessed technology. ReCiPe method is also applied as part of sensitivity analysis; and finally data quality assessment is carried out using criteria produced by Stamford and Azapagic (2012, p. 415).

The study reveals that no technology is superior to another; the sustainability performance needs to be expressed in relation to the resource availability and regional development strategy. The common belief that renewable energy is totally emission free is because the significant environmental impacts associated with upstream manufacturing and end-of-life process are not accounted for. For example solar PV is almost emission free during electricity generation but production of the system components do pose significant environmental impact; its merit resides

being an effective tool to alleviate fuel poverty due to its ability to reduce energy bills for the system host and its low capital cost.

Since sustainability is a dynamic process, the choice for the most sustainability electricity options will also progress over the time; depending on the need of society and resource availability. Planning for a sustainable energy future requires holistic review of suitable energy options and strategic energy planning.

Acknowledgements

Here finally comes the day for me to write up this acknowledgement.

Firstly, my deepest gratitude goes to my supervisors Dr Yaodong Wang and Professor Tony Roskilly, for their fatherly guidance, for their acceptance and for their faith in me. Without their encouragement this book would have not been made possible. I would also like to thank Dr. Laurence Stamford and (soon to be Dr.) Thomas Bradley, for their unconditional support, and guiding me into the (forever-confusing and somehow wonderful) world of LCA.

Secondly, I would like to thank my parents and grandparents, who had forever signed their name in lower case but have been and forever will be the capital;

And also the presence of my sisters and friends, in which, both tears and laughter sublimates;

It goes without saying that I am deeply grateful of my examiners, for their kind advice, and most importantly, their generous approval.

And finally, to the once 25-year old myself: be patient, *tout va bien se passer;* and to the 30-year old myself: thank you for being so brave and never gave up.

Let me not pray to be sheltered from dangers,
But to be fearless in facing them.

Let me not beg for the stilling of my pain, but
For the heart to conquer it.

Let me not crave in anxious fear to be saved,
But hope for the patience to win my freedom.

-- Rabindranath Tagore

And then, a new chapter of life begins...

Contents

Abstract...i

Acknowledgements iii

List of Figures.. vii

List of Tables ix

List of abbreviations xi

Chapter 1 Introduction...1

Chapter 2 Literature Review 5

2.1 Conceptualisation of sustainability...5

2.2 Sustainability assessment models 7

2.4 Summary...13

Chapter 3 Methodology 15

3.1 Sustainability Assessment Framework. 15

3.2 Sustainability Assessment indicators...16

  3.2.1 Techno-economic Indicators 16

  3.2.2 Environmental Indicators..19

  3.2.3 Social Sustainability Indicators..25

3.3 Ranking of scores..26

3.4 Quality assurance..27

3.3 Summary 28

Chapter 4 Solar Photovoltaics 31

4.1Introduction..31

4.2 Assumptions...32

  4.2.1 Key technical parameters 32

  4.2.2 Environmental parameters...33

  4.2.3 Social Assumptions 35

4.3. Results..35

  4.3.1 Techno-economic performance...35

  4.3.2 Environmental performance 36

  4.3.3 Social impacts 40

4.3.4 Summary of solar PV technology comparison 43
4.4. Discussion 44
4.4.1 Economic assumptions...44
4.5.2 Policy support 45
4.5.3 End of Life..45
4.5.4. Sensitivity analysis..46
4.5.5 Sustainable supply chain 49
4.5.6 Data quality assessment...49
4.6 Summary..50
Chapter 5 Onshore wind 52
5.1 Introduction...52
5.2 Assumption 55
5.2.1 Key techno-economic parameters..56
5.2.3 Environmental parameters..59
5.2.4 Social parameters 60
5.3 Result 60
5.3.1 Techno-economic performance 60
5.3.2 Environmental performance 62
5.3.3 Social..75
5.3.4 Summary of comparison...75
5.4 Discussion...78
5.4.1 Noise...78
5.4.2 Visual impact 79
5.4.3Impact on wildlife...79
5.4.4 Radio interference 80
5.4.5 Sensitivity analysis...80
5.4.6 End of life 84
5.4.7 Data quality assessment..85
5.5 Summary..86
Chapter 6 Biomass CHP..88
6.1 Introduction...88
6.1.1 Wilton 10 power plant...90

6.2 Assumption 92
6.2.1 System boundary 92
6.2.2 Product impact allocation 93
6.2.3 Carbon neutrality 93
6.2.4 Techno-economic assumptions 94
6.2.3Environmental assumptions 95
6.2.4 Social parameters 97
6.3 Results 97
6.3.1 Techno-economic performances 97
6.3.2 Environmental performances 98
6.3.2 Social performances 103
6.4 Discussion 103
6.4.1 Uncertainty in results 104
6.4.2 Sensitivity analysis 104
6.4.3 Domestic installation 108
6.4.4 Supply chain 108
6.4.5 Data quality assessment 109
6.5 Summary 111
Chapter 7 Discussion 112
7.1 Comparison of three assessed technologies 112
7.2 Energy mix scenarios 116
7.3 Summary 120
Chapter 8 Summary 121
8.1 Policy recommendations 121
8.2 Recommendation for future work 122
Reference 123

List of Figures

Figure	1.1	Impact of sustainability assessment scale	3
Figure	3.1	Design process of proposed sustainability assessment framework	16
Figure	3.2	Application of sustainability assessment process	29
Figure	4.1	Solar irradiation in the UK and Ireland (PVGIS,2014)	33
Figure	4.2	Life cycle stages of solar PV	34
Figure	4.3	Techno-economic performance of solar PV systems	38
Figure	4.4	Environmental performance of Silicon and CdTe solar PV systems	40
Figure	4.5	Manufacture process of silicon-based (top) and thin film (down) solar PV systems (Peng et al. 2013)	41
Figure	4.6	Bill reduction rate achieved by s-Si,p-Si and CdTe solar PV systems	42
Figure	4.7	End of life treatment of retired CdTe solar PV panels (p. Sinha,2012)	47
Figure	4.8	Environmental impact of silicon and CdTe solar PV using ReCiPe method	60
Figure	5.1	Map showing installation of wind farms within the Northeast region of England	50
Figure	5.2	System boundaries of assessment on onshore wind turbines	52
Figure	5.3	Capacity factor for three assessed wind turbines	57
Figure	5.4	Levelised cost for three assessed wind turbines	57
Figure	5.5	Environmental impact assessment of three selected wind turbines	60
Figure	5.6	Material composition of three selected wind turbines	61
Figure	5.7	Energy consumption for manufacturing Vestas V80	61
Figure	5.8	Energy consumption for manufacturing Repower MM82	62
Figure	5.9	Energy consumption for manufacturing Vestas V90	62
Figure	5.10	Environmental impact assessment of Repower MM82 at different life cycle stages	63
Figure	5.11	Environmental impact assessment of Vestas V80 at different life cycle stages	64

Figure 5.12 Environmental impact assessment of Vestas V90 at different life cycle stages 65
Figure 5.13 Environmental impact assessment of Repower MM82 67
Figure 5.14 Environmental impact assessment of Vestas V80 68
Figure 5.15 Environmental impact assessment of Vestas V90 69
Figure 5.16 Environmental impact of three assessed turbines using ReCiPe method 78
Figure 5.17 Comparison of terrestric ecotoxiciy of Vestas V80 turbine using CML and ReCiPe methods 79
Figure 5.18 Comparison of terrestric ecotoxiciy of Repower MM82 turbine using CML and ReCiPe methods 79
Figure 6.1 Map showing maximum energy crop yield in the England and Wales (Bauen *et al.*, 2010) 84
Figure 6.2 Map showing maximum yielding biomass type in the England and Wales (Bauen et al., 2010) 85
Figure 6.3 Location of Wilton 10 power station 87
Figure 6.4 Photo of Wilton 10 power station 87
Figure 6.5 Schematic of Wilton 10. (McIlveen-Wright *et al.*, 2013) 88
Figure 6.6 System boundary for Wilton 10 89
Figure 6.7 Composition of total levelised cost for biomass CHP plant 94
Figure 6.8 Environmental impact of Wilton 10 at life cycle stages 96
Figure 6.9 Environmental impact of Wilton 10 at installation stage 97
Figure 6.10 Environmental impact of Wilton 10 at manufacture stage 98
Figure 6.11 Environmental imapct of Wilton 10 using ReCiPe method 101
Figure 6.12 Environmental impact of Wilton 10 at manufacture stage using ReCiPe method 102
Figure 6.13 Environmental impact of Wilton 10 at installation stage using ReCiPe method 103

List of Tables

Table 3.1 Material recycling rate in the UK 22
Table 3.2 Data quality assessment criteria (Stamford and Azapagic,2012, p.415) 28
Table 3.3 Proposed sustainability assessment framework with indicators and life cycle stage considered 30
Table 4.1 Key techno-economic parameters for solar PV 35
Table 4.2 Material consumption and waste for treatment of solar PV systems 36
Table 4.3 Recoverable mass for wo assessed solar PV 36
Table 4.4 Sustainability assessment results for selected solar PV system 43
Table 4.5 Summarised sustainability ranking of solar PV systems 44
Table 4.6 Data quality assessment result for solar PV 62
Table 5.1 Installation of wind farms within the Northeast region of England 68
Table 5.2 Techno-economic parameters of assessed wind turbines 54
Table 5.3 Material consumption for three assessed wind turbines 55
Table 5.4 Recoverable mass of three assessed wind turbines 56
Table 5.5 Emission per tonne of Steel production (kg/ton) (EcoinventCentre, 2017a) 66
Table 5.6 Emission road construction (kg/meter annual) (EcoinventCentre, 2017a) 70
Table 5.7 Table 5.7 Summarised sustainability ranking of assessed wind turbines 72
Table 5.8 Sustainability assessment results for three assessed wind turbines 73
Table 5.9 A list of wind farm community fund within County Durham 74
Table 5.10 Ranking of environmental impacts of three assessed turbines using ReCiPe method 80
Table 5.11 Data quality assessment result for onshore wind 82
Table 6.1 Key techno-economic parameters for Wilton 10 91
Table 6.2 Material composition and recyclability of Wilton 10 (t/system) 92
Table 6.3 Materia composition and recyclability of Wilton 10 during installation stage 92
Table 6.4 Sustainability assessment results of Wilton 10 99
Table 6.5 Data quality assessment result for biomass CHP 106
Table 7.1 Sustainability performance of three assessed technologies: solar PV, onshore wind and biomass CHP 110
Table 7.2 Sustainability performance ranking of three assessed technologies: solar PV, onshore wind and biomass CHP 111

Table 7.3 Summary of scenarios considered in this analysis 112

Table 7.4 Sustainability performance results of three assessed scenarios 114

Table 7.5 Ranking of sustainability performance for three assessed scenarios 115

List of abbreviations

LCA	life cycle assessment
Solar PV	solar photovoltaic
CHP	combined heat and power
CdTe	cadmium telluride
p-Si	poly-silicon
s-si	single-silicon
ROC	renewable obligation certificate
FiT	feed in tariff
AP	acidification potential
EP	eutrophication potential
FAETP	freshwater aquatic ecotoxiciy potential
GWP	global warming potential
HTP	human toxicity potential
MAETP	marine aquatic ecotoxiciy potential
ODP	ozone layer depletion potential
POCP	photochemical ozone creation potential
TETP	terrestric ecotoxiciy potential

List of publications

1. Li, T., Roskilly, A.P., Yaodong Wang., (2016) 'A Life Cycle Approach to Sustainability Assessment on Community Energy Projects in the UK', ACEEE Summer Study on Energy Efficiency in Buildings. *American Council for an Energy-Efficient Economy, CA, United State.*

2. Li, T., Roskilly, A.P. and Wang, Y., (2017) 'A Regional Life Cycle Sustainability Assessment Approach and its Application on Solar Photovoltaic'. *Energy Procedia, 105, pp.3320-3325.*

3. Li, T., Roskilly, A.P., Yaodong Wang (2017) 'Measuring Sustainability: Life Cycle Approach to Sustainability Assessment on Electricity Options. 'The International Conference for Students on Applied Engineering, United Kingdom, 2016. *IEEE Xplore*

4. Li, T., Roskilly, A.P., Yaodong Wang (2018) 'Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England', *Applied Energy Special Issue: Transformative Innovations for a Sustainable Future – Part III*

Chapter 1 Introduction

Sustainability is commonly known as the developmet gives balanced attention to the needs of both present and future generations (WCED, 1987).The “three pillars” of sustainability, also known as “triple bottom line” referring to equal presentation of environment, economy, and social values is the core component of sustainable development (Hopwood *et al.*, 2005). Since the concept of sustainability was first defined in the Brundtland report, there is increasing interest in developing methods to better understand sustainability. Sustainability assessment is an appraisal methodology that can assist decision making to adhere to the sustainability values; and the approach to sustainability assessment varies depending on the objectives, scale and scope of decision making (Devuyst *et al.*, 2001, p. 9; Cinelli *et al.*, 2014; Kamali *et al.*, 2018). Life cycle approach, also known as life cycle thinking, encourages considering a product’s impact throughout every stage of its life cycle, is increasingly incorporated in the field of sustainability management and research (Blass and Corbett, 2018; Ekener *et al.*, 2018). The combination of sustainability assessment and life cycle approach forms the Life Cycle Sustainability Assessment (LCSA), is recommended by the United Nations Environment Programme and Society of Environmental Toxicology and Chemistry for its ability to enable decision-makers, stakeholders, enterprises and consumers to organise complex sustainability related information in a structured form and therefore identifying weakness which enable future improvements of a product life cycle (UNEP, 2012).

Sustainable energy is one of the sustainable development objectives identified by the United Nations (United, 2015). Electricity is the fastest growing among all energy sources (Roinioti and Koroneos, 2019) and is projected to overtake oil products become the largest final energy carrier (IEA, 2017). Although fossil fuel still remains a significant source of electricity at present days, the path to a non-fossil fuel based electricity future is widely agreed upon. In investigating what this sustainable future entails and how to achieve the sustainability transition, numbers of LSCA have been proposed to compare the sustainability performance of electricity technologies. Majority of the studies carried out the comparison by forming scenarios of electricity technology mix (e.g. (Stamford and Azapagic, 2014; Rehman and Deyuan, 2018)) or applying Multi-criteria

Decision Analysis to give scores and rankings to assessed technologies (e.g. (Roth *et al.*, 2009; Santoyo-Castelazo and Azapagic, 2014)).

Research team led by Professor Adisa Azapagic had carried out the most extensive rearch on sustainability of electricity options in the UK; and the assessment proposed by Stamford and Azapagic (2012) is by far the most comprehensive in this context, where five technoloiges including coal, nuclear, natrual gas, biomass, hydro were compared using 43 indicators covering techno-economic, environmental and social aspects; despite its comprehensiveness, however, the focus of this research remains at a national level where questions reflecting how the regional characteristic were not inquired. For example. in case of biomass, does the region have sufficient biomass resource or it has to rely on importing from elsewhere? In addition, the trend renewable electricity in the UK is moving centralised towards decentralised supply[1], however due to scope of the study, decentralised technologies were not considered as an option.

As illustrated in Figure 1.1, increased geographical scale of assessment may compromise the level of detail; on the other hand, downscaled assessment narrows the assessment scope (Ulgiati *et al.*, 2011), and regional level is where social institution, ecological boundaries and economic phenomena overlap (Graymore *et al.*, 2008; Graymore *et al.*, 2010; Lein, 2014). Therefore, a regional based assessment on decentralised energy technoloiges can offer a more detailed view on sustainability performance of electricity options.

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[1] Driven by the development post industrial revolution, a nationally connected electricity grid was constructed in the UK since 1926 to connect the large power plants and the end users Lehtonen, M. and Nye, S. (2009) 'History of electricity network control and distributed generation in the UK and Western Denmark', *Energy Policy*, 37(6), pp. 2338-2345.. Due to lack of upgrade, the aging national grid is increasinly struggling with addition of intermiddent renewable electricity when the demand is much lower than the supply; several wind farms were ordered to switch off during low demand periods to avoid reverse voltage incurred blackout Gosden, E. (2016) 'UK will have too much electricity this summer, National Grid forecasts', *The Telegraph*edn). (Accessed: 20/03/2019).

Consequently, any renewable electricity generator applied to join the grid is required to pay a network upgrade fee, in addition the application can take up to two years. Therefore, many generators have opted to not join the grid and remain a decentralised generator.

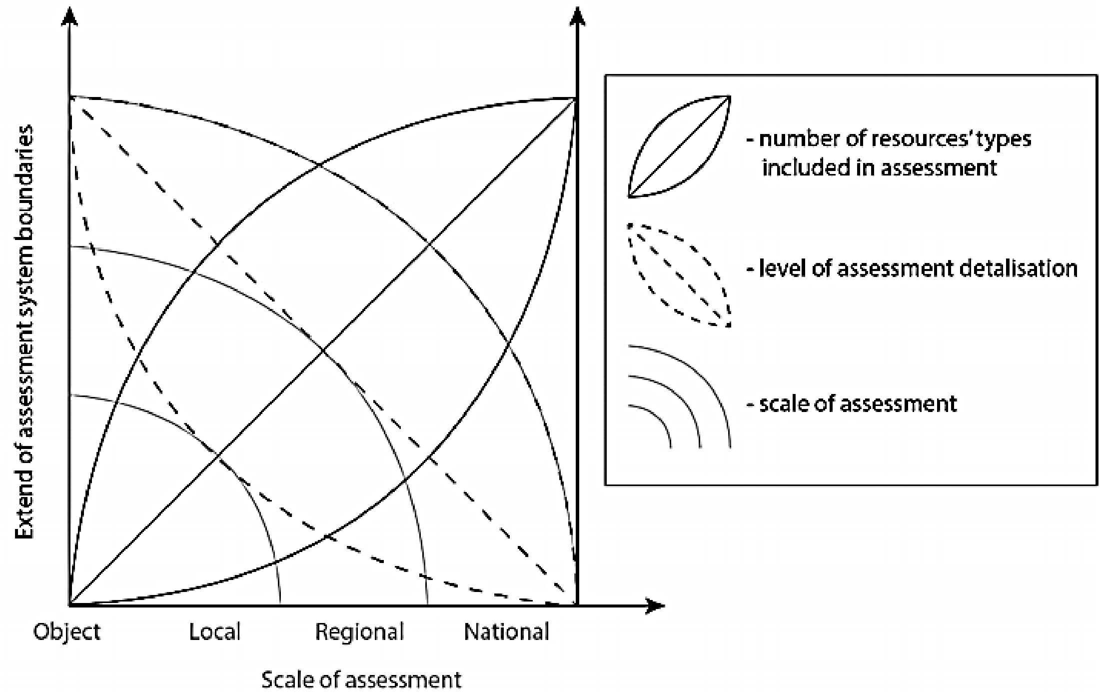

Figure1.1 Impact of sustainability assessment scale (Hay et al., 2014)

1.1 Aims and Objectives

Aim of this study is to design a regional sustainability assessment model combing life cycle and triple bottom line approaches based on the characteristics of Northeat region of England, to assess and compare the sustainability performance of existing decentralised electricity options within the region.The task is devided into following objectives:

1. Carry out literature survey on existing assessment methods;
2. Construct assessment framework and model based on the goal and scopes of this study;
3. Carry out assessment to compare the sustainability performance of selected technologies;
4. Provide policy recommendation and advise on future works.

1.2 Novelty of the thesis

Novelty of this study can be concluded as following:

I. The designed assessment method is the first sustainability assessment framework developed to examine and compare electricity technologies with regional scope;

II. The proposed model can be applied to compare electricity options in other regions not restricted to the UK. Modification on indicator selection can be made to be suitable for the context following the International Guideline on Life Cycle Assessment ISO14040 listed in page16;

III. As part of this study, the author modified the designed model, and applied the assessment on community energy projects in the UK (Li *et al.*, 2016a);

IV. This study proposed a novel indicator to examine a technology or product's circularity, to author's knowledge this is first time circularity is included in sustainability assessment on energy technologies;

V. Three widely established technologies were assessed in this thesis based on their performance within the region

1.3 Thesis structure

This thesis contains 8 chapters. Literature survey is analysed in chapter 2, and methodology is explained in chapter 3. Chapter 4-6 covers the assessment of the selected electricity generation technologies. Chapter 7 discusses the results obtained from chapter 4-6, and finally chapter 8 summarises the study and provide recommendation to policy and future works.

Chapter 2 Literature Review

This chapter first explores the conceptualisation of the sustainability, then reviews the existing methods for assessing sustainability. It is sometimes argued that sustainability and sustainable development do not share the same definition where sustainability refers to a state and sustainable development concerns with the process(Aras and Crowther, 2009). To avoid confusion, the term sustainability and sustainable development are used interchangeably in this thesis.

2.1 Conceptualisation of sustainability

The concept of sustainability was brought into the public realm in 1980 in the World Conservation Strategy(IUCN, 1980); in 1987 it was officially introduced in the Brundtland Report, as “the development that meet[s]the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987, p. 43). Despite the idea was progressive for the time, due to the ambiguity of its definitely, the term sustainability became an article of faith that was often used, but little explained (Loorbach *et al.*, 2009; Tolba, 2013); for a long period of time sustainability was adopted by politicians and organizations as a the new jargon phrase in the development business (Conroy and Litvinoff, 1988). Some scholars even argued that sustainability is a contradiction in terms as it only serves as symbolic rhetoric with competing interests each redefining it to suit their own political agendas, and decision makers use the term to their advantage (Beatley, 1997; Biely *et al.*, 2018).

The “triple bottom line” concept of sustainability was brought into discussion by Elkington (1994) whom tirelessly advocates that the bottom line of sustainability shall rest on the social, economic, and environmental aspects, these are also known as the three pillars of sustainability. Although these three aspects are commonly agreed upon in present days, the difference in interpretation of sustainability divides the scientific community.

School of weak sustainability believes that in order to achieve growth, trade-offs between these three aspects should be allowed. This idea was first proposed by scholars such as Pearce and Atkinson (1993) and Costanza *et al.* (1997) who suggested that the service of ecological systems can be assigned with an economic value, which contribute to the total economic value of the planet and affects the quality of human welfare. In this way, sustainability can be quantified and managed; and income obtained from the use of nonrenewable resources should be invested back to generate and maintain renewable sources in order to prevent social-wellbeing from declining overtime (Hartwick, 1990); in addition, the non-declining capital needs to be maintained cross generations (Dasgupta and Mäler, 2001; Hamilton *et al.*, 2006). The school of weak sustainability generally acknowledges that given the trend of technological advancement, future generations can maximize their wellbeing with minimal consumption of natural resources; therefore some economic aspects can be temporarily traded off for environmental aspects. This idea is challenged by the school of strong sustainability. Mainstream advocates of strong sustainability concept does not agree with the trade-offs since each of these three aspects serves the human wellbeing in different way and they are not substitutable; and after all, future technology may not guarantee solutions for sustainability (Ekins *et al.*, 2003; Pelenc and Ballet, 2015; Biely *et al.*, 2018).

In recent years, researchers such as Davies (2013) and Koirala *et al.* (2011)are searching for a middle ground between the weak and strong sustainability debate. One argument is that sustainability has a temporal dimension as described by Grossman and Krueger (1991) using the Environmental Kuznets Curve, which refers to the inverted –U relationship between environmental degradation and economy-social development; that pollution increases in the initial level of development and then until the development reaches a turning point were enlightenment of environmental value occurs the pollution subsequently decreases (López-Menéndez *et al.*, 2014). For example, in the case of the western world, the general public's environmental awareness was improved through a series of events such as the Clean Air Act in 1956 and the Stockholm Conference in 1972, and this is partially achieved by heightened social development at the time; thus there is a shift on what sustainability entails depending the priorities of society at the time.

Another argument is that although the widely discussed weak and strong sustainability concepts have their roots in economics (Hartwick, 1990), ethical and philosophical values are also associated with how sustainability is practiced in reality. This can be observed from how the "end-of-pipe" solution to pollution control have led many developed countries displaces pollutive activities to developing countries, for example Japan is among the global frontier at forest protection, but it imports forest resources from other countries for the production and packaging for consumer goods (Baker, 2006; Davies, 2013).

Regardless of the difference in interpretations, one common ground can be established that sustainability is not an end state but a dynamic process that is continuously evolving (Gaziulusoy et al., 2013). This dynamic process involves complex interactions between components within the human-nature network at different organizational and spatial levels, from technosphere to biosphere; and these interactions evolve as even more complex adaptive systems (Levin, 1998). To understand sustainability, is to regard the dynamic process as an integrated entity instead of separate aspects of economic, environmental and social values, and to understand the interaction between the components within the system using an integrated approach, which requires cutting across boundaries and blending ideas from various disciplines (Cheng *et al.*, 2009; Lam *et al.*, 2014).

2.2 Sustainability assessment models

There is increasing need for individuals and organisations to find models and metrics to pin-point what activates are not sustainable. As defined by Ness *et al.* (2007), the purpose of sustainability assessment is to provide decision makers with information on impact of an activity or a plan in order to determine which actions should or should not be taken in an attempt to make society sustainable. The U.S. National Research Council (1999) advised three components needs to be addressed in sustainability assessment, they are: what is to be sustained, what is to be developed, and the impact on intergenerational equality.

The key questions of sustainability assessment are addressed by Kates *et al.* (2001, p. 641) :

1. “How can today's operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition towards sustainability?”

2. “How can today's relatively independent activities of research planning, monitoring, assessment, and decision support be better integrated into systems for adaptive management and societal learning?”

Defining the goal and scopes of sustainability assessment may appear easy but it is crucial for selection and development of indicators; as concluded by Singh *et al.* (2012), alignment of goal with identified indicators become more difficult when measurement is made on multi-dimensions and aggregated into single values. The goals and scope can decide what assessment tools are appropriate for the context. There are two major categories of sustainability assessment tools: one is product related assessment which provides information on material use and energy flow of products or anything can be regarded as a product (e.g. cycle assessment, life cycle costing, exergy analysis etc.); another category is prospective and integrated assessment, they examine the impact of policy or products that may occur at a future time (e.g. cost-benefit analysis, environmental impact assessment etc.) (Ness *et al.*, 2007).

Many of the product related tools originated from elaboration of Life Cycle Assessment (LCA). LCA was initiated as an internal study in 1969 for the Coca-Cola Company in a comparison of different beverage containers to identify the option with lowest environmental impact; a few years later, similar study was also conducted by Sundström (1979). A few years later in 1997 the first international LCA standard ISO 1400 was published by ISO (1997); and LCA was then increasingly used to support policy making, especially in bioenergy performance related regulations. The well-known carbon footprint standards were formed based on the LCA methodology; other tools such as Life Cycle Costing (LCC) and social life costing were also developed later (Clift and Druckman, 2015). The broadening of LCA’s environmental scope by joining it with other aspects of sustainability forms the Life Cycle Sustainability Assessment (LCSA). The term LCSA was first used by Zhou *et al.* (2007) by evaluate and compare sustainability of six fossil fuel options, but the assessment only considers life cycle costing, climate change and resource depletion impacts, other impacts such as social aspect were absent from the study; and the exclusion of social impact is common among the early LSCA studies. For example Afgan and Carvalho (2008) employed only one social indicator NOx emission to compare the sustainability of renewable hybrid energy systems. Indeed NOx emission do have impact on human health such as increased risk in respiratory diseases, but gaseous emission is normally considered to be under environmental impact categories. Shortly after Zhou *et al.* (2007), definition of LCSA were proposed as model combining LCA, LCC, and Social Life Cycle Assessment (SLCA), this definition is sometimes presented as LCSA=LCA+LCC+SLCA (Kloepffer, 2008). Guinee *et al.* (2010) suggests that LCSA should be regarded as a framework rather than a model after reviewing the question proposed by Zamagni *et al.* (2009) as part of the EU FP6 CALCAS (Co-ordination Action for innovation in Life Cycle Analysis For Sustainability) project, on whether LCSA should be conducted in segments of LCA, LCC and SLCA, i.e. LCSA as the sum of three separate analysis; or should it be carried out as examining a system in three ways using environmental economic and social indicators, i.e. design LCSA model using three sets of indicator. The difference between these two approaches leads to further questions such as, if LCSA acts as sum of three models, how to ensure these models share the same goal and scope, and system boundary[2]? Some scholars also argue that the method of combing three models may risk overlooking some sustainability issues (Jørgensen *et al.*, 2013; Onat *et al.*, 2014), for example Kucukvar and Tatari (2013)uses the LCSA=LCA+LCC+SLCA method to investigate the sustainability of building materials in the US, and concluded that the assessment is a “starting point for more comprehensive LCSA of buildings since no study in this kind had been found”, but aggregated data are unavoidably used in supply chain SLCA, which may not share the same system boundary with the LCC or LCA analysis.

Benoît and Mazijn (2009) reviewed Over 150 social sustainability indicator, and reveals that only a few indicators can be directly assessed to products or processes. Vinyes *et al.* (2013) discovered the difficulty of quantification on social indicators through the application of LCSA on used cooking oil waste; the author is not alone in facing this difficulty. Hu *et al.* (2013) also experienced problematic implementation of LCSA while compare sustainability of various concrete recycling scenarios, because many social indicators that were developed in SLCA method are qualitative and therefore it is difficult to link these indicators to unit process and functional units.

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[2] There are four phases in an LCA study, they are: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation of assessment results. In any LCA study, functional unit defines the amount, weight and quality of the assessed product, and system boundary defines what processes in the product life cycle is considered for the assessment.

Using research derived from findings of EU project PROSUITE, Blok *et al.* (2013) proposed a life-cycle based sustainability assessment framework with five main areas to be addressed when assessing sustainability of technologies, they are:

1) Impacts on human health;
2) Impacts on social wellbeing, such as impact on safety and equal opportunities of the public etc. ;
3) Impacts on prosperity, this includes labor, capital and resource productivity, and new market development etc. ;
4) Impacts on natural environment;
5) Impacts on exhaustible resources.

The main challenge of the project is the identification and quantification of indicators that can sufficiently examine impacts of the above five areas. The author discovered that the methodologies for examining environmental impacts is most well established and methodologies for assessing the impact on social well-being is still in early age; most of the time there is no sufficient primary data for existing social indicators.

Some researchers avoid these difficulties by only taking a qualitative approach and not include any quantitative indicators; for example in assessing renewable energy use in Austria, Madlener *et al.* (2007) examines the social aspect of energy technologies using qualitative measures such as social cohesion, smell, social justice and empowerment etc., results for these indicators were obtained relying author’s interpretation of stakeholder interviews, and thus these results are very unlikely to be reproducible by future studies.

Zamagni *et al.* (2013) believes that the lack of quantitative indicators is because LCSA framework is still at the conceptual level, and future research should focus on making it practical and operational. Additional case studies are still required to move the LCSA into the practical realm from theoretical research. This conclusion is confirmed by Hu *et al.* (2013), whom also believe there is weak understanding on the interdependence of the three pillars and to improve practicality of LCSA, the modeling technological system should start from local and regional level, and then scale it up using knowledge gained from studies at higher level of analysis (e.g. global policy analysis).

On the other hand, there are cases where quantifiable measures are evaluated in qualitative measures. For example, cost of electricity product is one of the most commonly used indicator in LCSA studies on energy technologies, it is a useful indicator as it allows direct comparison between energy technology options; de Souza *et al.* (2016) evaluated system's economic feasibility using two indicators, they are: direct and indirect costs, and profit and avoided costs, author obtained the results by interpreting on stakeholder's opinions on these two measures, which introduced unnecessary uncertainties to the analysis.

Begić and Afgan (2007) compared sustainability of a range of energy technologies including solar photovoltaic (PV), biomass, wind turbine and natural gas combined cycle; although author employed quantitative measures such as quantitative measure such electricity generation cost, but only focus on cost involved in electricity generation stage and therefore the result could be biased towards technologies such as natural gas combined cycle where cost involved in constructing the plant is higher than operate and maintain the plant. In comparison, the levelised cost method which accounts for the unit cost of electricity over the lifetime, is more appropriate on providing information on cost-effectiveness of energy technologies (Ouyang and Lin, 2014; Stamford and Azapagic, 2014).

A high upfront cost is commonly associated with renewable energy technologies; and thus financial subsidy plays important role in implementation of these technologies, especially in the cases of large scale installation (Painuly, 2001). Therefore, subsidies received should also be accounted for in levelised cost estimation.

Over the past decade, investor's perception of risk and return on renewable energy technologies is becoming detrimental for deployment of these technologies (Salm *et al.*, 2016). Globally, the primary concern in this area is the payback period (Reddy and Painuly, 2004; Adams *et al.*, 2011). According to Salm *et al.* (2016), over 60% of the retail investors interviewed in Germany perceive renewable energy as high risk profile investment, similar to the risk of investing into a high-risk start-up company, and over 81% of the interviewees feel this way because of the long holding period of investment.

On the other hand, renewable energy technologies are more than just an investment options, it is also a solution to combat fuel poverty. UK is one of the most affluent countries in the world, and it has an ongoing fuel poverty issue where 11.1% of its household is fuel poor[3]. Fuel poverty results from several factors, the four main issues are: low incomes, rising fuel prices, poor housing stock and house under-occupancy (Hills, 2012; Liddell *et al.*, 2012; Boardman, 2013). Series actions are taken by the UK government, and community energy groups were set up to combat this issue locally. Decentralized renewable energy technologies like rooftop solar PV are seen as practical option for their relatively low overall cost compare to other energy technologies and their easiness to install (Walker, 2008), these technologies have been made available through various schemes to provide affordable and accessible energy to underprivileged communities.

In the assessment of building materials in the US, Onat *et al.* (2014) employed government tax as a positive sustainability indicator for social welfare under the presumptions that collected taxes will be used for supporting the national health and education systems, public transportation, highways, and other civil infrastructures; and this idea is challenged by Gilbert (2017), who argues it is the increased welfare expenditure that improves the social wellbeing instead of tax collected. Another indicator also has debatable direction of preference is "human-machine interaction time" proposed by Khan *et al.* (2004) which is defined as the percentage of time where machines need to be operated by human, where lower value is preferred as it indicates advanceness of the technology and hence cost reduction; while on the other hand, it can be argued that lower human-machine interaction time implies reduced workforce, and hence less employment opportunity created which does not have positive social impact.

In terms of environmental sustainability, trend of assessment approach is slowly moving from over simplifying, where only few indicators are involved and the impacts are inadequately

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[3] According to the latest report DBEIS (2018a) *ANNUAL FUEL POVERTY STATISTICS REPORT.*, fuel poverty in England is now measured using the Low Income High Costs indicator, under this indicator, a household is considered be in fuel poverty if:

1. they have required fuel costs that are above the national median level;
2. Were they to spend that amount, they would be left with a residual income below the official poverty line.

The report also pointed out three important elements in determining fuel poverty, they are:

1) Household income,
2) Household energy requirements

assessed, towards more comprehensive and life-cycle oriented approach. For instance, in an earlier study on development of wind park in Troizina carried out by Polatidis and Haralambopoulos (2007), only four indcators were considered in the environmental impact category where one of them being qualitatively assessing the aesthetic impact on the local landscape, and another three quantitative indicators are landuse, noise creation and contribution to mitigating climate change. Clearly these four indicators are not sufficient to demonstrate the envirnmental impact of a wind park; in addition,author did not specify what was the purpose of landuse prior to installation of and wind farm and whether the purpose of land use is altered due to the installation, if the case was that the location was abondonded land then installation of wind farm does not create negative environmental impact on local environment. In comparison, a recent study of LCSA on the Greek electricity system took a more comprehensive life cycle approach, where six environmental indicators were proposed in line with LCA methodologies, exmaining the the global warming potential, acidification potential, tropospheric ozone precursor potential, eutrophication potential, photochemical oxidation potential, and ozone depletion potential of the electricicity system (Roinioti and Koroneos, 2019).

2.4 Summary

In this chapter the concept of sustainability reviewed and sustainability assessment methods are explored. The findings can be concluded as following:

1. The definition of sustainability is often criticized for being blurred (Biely *et al.*, 2018), while on the other hand this leaves flexibility for a customized working definition of sustainability reflecting the needs and priorities of a society.
2. Sustainability is an evolving process requires the balance between economic, environment and social development.
3. Indicators serves as message carriers and it facilitates the communication between sustainability research and practice. Sustainability assessment is moving towards a life cycle based assessment method with balanced attention given the three pillars of sustainability. This needs be reflected in the assessment indicators.

4. Methodologies for sustainability assessment should be made transparent and feasible with consideration for feasibility of data collection.

5. System boundary needs to be consistent across indicators; quantitative measures not only enhances the reproducibility of research also reduces the unnecessary uncertainty of results.

Chapter 3 Methodology

This chapter introduces the sustainability assessment framework proposed in this research, with detailed explanation on how the indicators shall be quantified.

3.1 Sustainability Assessment Framework.

In proposed framework electricity generated is regarded as the final product, and sustainability performance of this product is examined throughout its entire life cycle (including manufacture electricity system components, installation of the system, electricity generation and end of life stages) using three sets of indicators reflecting the product's economic, environmental and social impacts.

Two stages are involved in designing the assessment model. First stage is establishing the goal and scope of the assessment, which to assess and compare the sustainability performance of existing decentralised electricity options within the Northeast region of England.

Stage two is to design the assessment model within the established framework, where indicators are selected and designed to examine the aspects of sustainability issues. Stakeholder (including experts in the industry, local council and academic researchers) opinions were sought in this stage.

The international guideline on life cycle assessment studies ISO14040 studies is adopted as the basis of indicator selection criteria[4], as follows:

1. Relevancy to energy technologies
2. Avoid double counting.
3. Indicators must be quantifiable
4. Feasibility of application

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[4] It shall be noted that weighing method which includes applying the value of importance onto results of indicators is not recommended as stated in ISO14040. Therefore weighing is not considered in this proposed model.

The designed model is demonstrated in table 3.2. A total of nineteen indicators were selected, with five examining the techno-economic impact, twelve measuring the environmental impact and two assess the social impact of selected energy technologies; the life cycle stages considered for each indicator is also listed in the table.

3.2 Sustainability Assessment indicators

The selected sustainability assessment indicators are explained in this section in three categories: techno-economic indicators, environmental indicators and social indicators. Techno-economic category examines the reliability, cost and financial feasibility of a technology.

The environmental category examines the circularity, energy payback period and specific environmental impact including: acidification potential, eutrophication potential, freshwater and marine aquatic ecotoxiciy potential, global warming potential, ozone layer depletion potential, photochemical ozone creation potential and terrestric ecotoxiciy potential. CML impact assessment method[5] (Guinée, 2002) is applied in this study to calculate the environmental impacts, for it is the most well-established mid-point methodology and it is regional valid for European based cases(Handbook, 2010). Therefore the indicators (except circularity and energy payback indicator) included in this category are named in accordance with the CML methodology.

3.2.1 Techno-economic Indicators

The techno-economic performance of an energy technology is examined in four categories: reliability, dispatchability, levelised cost of generation and profitability.

Reliability of the technology is measured through two indicators: availability factor and capacity factor. *Availability factor* is the ratio of time in which a plant is available to generate electricity over its maximum working hours (IEEE, 2006), over a certain period, and is calculated as (1):

$$Availability\ Factor = \frac{T_{output}}{T_{max}} \times 100(\%) \tag{1}$$

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[5] CML methodology, is named after where it was first developed, the Centrum voor Milieuwetenschappen (Faculty of science, University of Leiden), is an impact assessment method which restricts quantitative modelling to midpoint analysis, and also provides best practice for midpoint assessment following the ISO14040 standards.

Where,

$$T_{output} - Total\ hours\ the\ energy\ system\ is\ available\ to\ deliver\ power$$

$$T_{max} - Maximum\ annual\ working\ hours\ of\ the\ energy\ system$$

Capacity factor is the ratio of a plant's actual output in comparison to its potential maximum output at full production capacity over a given period. This ratio varies in time and also depends on the availability of resources particularly in cases of intermittent technology such as solar and wind. It is calculated as (2):

$$Capacity\ Factor = \frac{E_{output}}{E_{max}} \times 100(\%) \tag{2}$$

Where,

$$E_{output} - The\ total\ electricity\ output\ of\ a\ system$$

$$E_{max} - Plant\ maximum\ capacity$$

Dispatchability of an energy technology is its ability to increase or decrease output according to demand. Most of the conventional energy technologies are dispatchable, means their output can be controlled by the operator in response to demand. This is an important characteristic, because electricity is difficult and expensive to store at present days, therefore having a power plant that is able to reduce electricity output when the demand is low and able to ramp up output when the demand is high is both economically attractive and essential for electricity network to respond to peak demand. Most of the renewable technologies such as solar and wind energy are considered to be intermittent source of supply, because their output cannot be controlled in response to demand, and their output cam vary from day to day, or from hour to hour. Dispatchability of a technology is measured using method proposed by Stamford and Azapagic (2012), that the ramp-up rate, ramp-down rate, minimum up time and minimum down time should be ranked and summed to make up to a total of dispatchability ranking, where the higher the score is less dispatchable a technology is. It is calculated as follows as follows:

$$Dispatachbility = R_{up} + R_{down} + Ru_{min} + RD_{min} \tag{3}$$

Where

$$R_{up} - Ranking\ for\ ramp\ up\ rate$$

$$R_{up} - Ranking\ for\ ramp\ down\ rate$$

$$RU_{min} - Ranking\ for\ minimum\ up\ time$$

$$RD_{min} - Ranking\ for\ minimum\ downtime$$

Levelised cost of generation stands for the totalised cost of energy technology throughout lifetime. It is included in capital cost as well as operational expense totals. Capital costs cover expenses at both the construction stage and decommissioning stage of an energy project, whereas operational costs cover costs generated for operation and maintenance of an energy project and expenditures on waste disposal. The total levelised costs are the sum of capital costs and operational costs. A discount rate of 3.5 is applied according to the Green Book. (Book, 2003)

The formula for this indicator is an integration of methods by Stamford and Azapagic (2011) and IEA and NEA (2015, p. 28), as (4):

$$Levelised\ Cost = \frac{\sum_{n=1}^{N} \frac{CC + M_t + F_t}{(1+r)}}{\sum_{n=1}^{N} \frac{E_{output}}{(1+R)^n}} \tag{4}$$

Where,

$CC_t - Capital\ cost$

M_t- *Maintenance cost*

$F_t - Fuel\ cost$

$r - Discount\ rate$

Renewable energy in the UK generates income through two main streams, renewable incentives offered by the government (e.g. feed in tariff) and export of electricity. Except for CHP, any installation with less than 2MW capacity benefits from Feed in Tariff

(FiT) [6]approximate 4.39pence/kWh[7]; any electric exported to the distribution grid, the host also receives payment for the amount of electricity at the export rate (approximately 4.85pence/kWh) . (DECC, 2015)

For installations with capacity large than 2MW each unit of electricity generated is eligible for one renewable obligation certificate (ROC). Each energy supplier is obliged to produce certain proportion of renewable electricity or they will be penalised by Office of Gas and Electricity Markets (Ofgem); therefore when the generation falls short the suppliers will have to purchase auctioned ROCs on the trading system (such as eROC) to make up to the requirement; the ROCs are sold in auction, ranges between £45-£50 per ROC. The payment received for trade in the ROCs is another income stream for hosts of larger scale renewable energy installations. [8]

Financial feasibility of energy technology is examined using payback period, the amount of time for income generated through a technology to break even with total capital and operational expenditure. The payback period is calculated as (5):

$$Payback\ Period = \frac{CC + M_t + F_t}{In_t} \tag{5}$$

Where,

$$In_t - Total\ income\ generated$$

3.2.2 Environmental Indicators

One of the many strengths of LCA is its ability to produce results that are based on scientific data; there are two ways to calculate and visualise these results: mid-point and end-point methods. These two approaches examine different stages in the cause-effect chain to calculate the environmental impact. End-point methodology examines impact at the end of the cause-effect chain such as the impact on human health, ecosystem quality, etc., while mid-point methodology examines impact at the earlier end of the cause-effect chain before the end is reached. Although

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[6] The FiT will stop accepting new applications after 31st March, 2019. FiT rates are adjusted annually in accordance with the Retail Price Index. Latest FiT is published on ofgem website: www.ofgem.gov.uk

[7] FiT varies depending on the type and size of installations, this figure was the average FiT for technologies assessed in this study. The FiT rate for assessed technologies had changed by the time of submitting this thesis. For period 1 January 2019 to 31 March 2019, the FiT for assessed solar PV technology is 3.41pence/kWh.

[8] ROC application is closed for new applications post 31st March 2017, this change does not affect any existing installations that is already under the scheme, and therefore does not alter the results of this study.

the end-point methodology is favoured by decision makers for its simplicity in communicating LCA information, however, due to its high level of uncertainty the mid-point methodology is chosen for this study. Software GaBi professional v6.115 and Ecoinvent 3.4 integrated database (EcoinventCentre, 2017a) are used for producing the environmental results

The idea of circularity originates from the concept of "circular economy". In contrast to the current economic paradigm of a "linear economy" where the production chain depends on the extraction of virgin material resources, a circular economy calls for an economy that sustains on the finite resources available by treating waste as resource and opportunity instead of a burden. The idea of the circular economy was first introduced in the 1960s (Boulding, 1966), and further developed in the fields of industrial ecology (Erkman, 1997), the blue economy (Pauli, 2010) and cradle-to-cradle (McDonough and Braungart, 2010). Many countries such as Netherlands and China have integrated this concept into national policies and development strategies (Yuan *et al.*, 2006; Bastein *et al.*, 2013). The integration of first Circular Economy Strategy as part of sustainable development policy in 2015 was the European Commission's response to the need of a regional circular economy (Commission, 2015), and in 2016 the Ellen MacArthur Foundation introduced a first official methodology for measuring material circularity (EMF, 2016). As the first European-level official response to material circularity, this method has received mixed reviews. Criticism mainly surrounds its complexity of application, and also for its "Euro-centricicity" data requirement for carrying out the assessment (Griffiths and Cayzer, 2016). A novel indicator for *circularity* of material use and fuel in energy technologies is introduced in this study, to broaden the horizon of existing sustainability assessment. To the author's knowledge this indicator is first of its kind to be applied in sustainability assessment for energy technologies.

In this study, the circularity is measured using two indicators, material circularity which examines the circularity of all the material consumed; and fuel circularity examines the circularity of the fuel used for electricity production. *Material circularity* is calculated as in (6):

$$Material\ Circularity = \frac{\sum_{j}^{J}(\ MR_{in} + MR_{waste})}{2 * M_{total}} \times 100(\%) \tag{6}$$

Where,

$$MR_{in} - Total\ of\ recovered\ material\ for\ energy\ system$$

$$MR_{waste} - Amount\ of\ recoverable\ waste\ generated\ in\ life\ cycle\ j$$

$$M_{total}\ - Total\ amount\ of\ material\ required\ for\ energy\ system$$

And *fuel circularity* is calculated as follows:

$$Fuel\ Circularity = \sum_{j}^{J} \frac{RF}{F_{total}} \times 100(\%) \tag{7}$$

Where,

$$RF - Amount\ of\ input\ fuel\ as\ recoverable\ material$$

$$F_{total} - Total\ fuel\ required\ for\ power\ generation$$

Down-cycled material can be included in the reusable material category if it can be used as feedstock. For example, a particular aluminium and plastic material mix can in theory can be re-used, but in reality that there is currently no market mechanism that supports such a process, and material as such cannot be considered as re-usable material.

Ideally material recycle rate should be calculated using site specific data. However, due to unavailability of this data, the recycling rate of materials is calculated using UK current recycling rate, as this is considered to be the most accurate available information. They are shown in table 3.1 below:

Material	Recycle rate	Source
Aluminium	96.0%	(CSI, 2010)
Copper	57.4%	(DEFRA, 2015)
Board box	86.5%	(DEFRA, 2015)
Wood	60%	(WRAP, 2017)
Glass fibre reinforced plastic, polyamide	10.0%	(Asokan *et al.*, 2009)
Polyethylene terephthalate	60.0%	(RECOUP, 2016)
Silicon product	85.0%	(DEFRA, 2015)
Glass	67.8%	(DEFRA, 2015)
Steel	52.0%	(UNEP, 2015)
Unrefined semiconductor material	95.0%	(P. Sinha, 2012)
Plastic	26.0%	(Al-Salem *et al.*, 2014)

Table 3.1 Material recycling rate in the UK

The *energy payback period* measures the timespan (years) that an energy system require to break-even with the energy required to produce the system. It is calculated as (8):

$$Energy\ Payback\ Period = \frac{E_{in}}{E_{out}} \tag{8}$$

Where,

$E_{in} - Energy\ consumption\ for\ the\ energy\ system$

$E_{out} - Annual\ energy\ output\ from\ the\ energy\ system$

Lifetime energy consumption is estimated using Ecoinvent 3.4 database (EcoinventCentre, 2017a), including the end of life treatment for both recoverable and unrecoverable waste, and it is in line with existing literature(Peng *et al.*, 2013).

All activities involved in the life cycle of electricity production emit acidic gases such as Sulphur dioxide, nitrogen oxides, ammonia and hydrogen chlorides, which all contribute to the acidification of water bodies and thus increase the mortality rate of aquatic organisms. *The acidification potential* of each acidic chemical is interpreted as per kg of Sulphur dioxide equivalent. The acidification potential of the energy technology is calculated as (9):

$$Acidification\ Potential = \sum_{x}^{X} AP_x \times M_{ax}\ (kgSO_2\ eq./MWh) \tag{9}$$

Where,

$AP_x - Acidification\ potential\ (per\ kgSO_2\ eq.) of\ emission\ x$

$M_{ax} - Total\ mass\ of\ acidic\ emission\ x\ per\ unit\ electricity\ generated$

Eutrophication potential measures the excessive richness of nutrient in waterbodies introduced by the assessed energy technology, which promotes excessive growth of biomass in the ecosystem. It is calculated as (10):

$$Eutrophication\ Potential = \sum_{x}^{X} EP_x \times M_{ex}\ (kgPO_{-4}^{2}\ eq./MWh) \tag{10}$$

Where,

$EP_x - Eutrophication\ potential\ (\ per\ PO_{-4}^{2}\ eq.)\ of\ nutrient\ substancex$

$M_{nx} - Total\ mass\ of\ nutrient\ substance\ x\ per\ unit\ electricity\ generated$

Emission of toxic substance to the environment can lead to ecotoxiciy, three indicators are proposed in this research to examine the toxicity impact on the ecosystem, expressed as 1,4-dichlorobenzene (DCB) per MWh electricity generated, categorized as different medium where the toxic mechanism take place, they are *fresh water aquatic ecotoxity potential, marine aquatic ecotoxiciy potential,* and *terrestric ecotoxiciy potential.* Similarly, the direct effect of toxic substance on human environment is also expressed as 1,4-DCB equiv.kg/MWh electricity generated, These indicators are calculated as follows (11-14):

$$Freshwater\ Aquatic\ Ecotoxicity\ Potential = \textstyle\sum_{x}^{X} FAETP_x \times M_t\ (kg1{,}4 - DCB\ eq./MWh) \tag{11}$$

$$Marine\ Aquatic\ Ecotoxicity\ Potential = \sum_{x}^{X} MAETP_x \times M_t\ (kg1{,}4 - DCB\ eq./MWh)$$

(12)

$$Terrestric\ Ecotoxicity\ Potential = \sum_{x}^{X} TEP_x \times M_t\ (kg1{,}4 - DCB\ eq./MWh)$$

(13)

$$Human\ Toxicity\ Potential = \sum_{x}^{X} HTP_x \times M_t\ (kg1{,}4 - DCB\ eq./MWh)$$

(14)

Where,

$$FWAETP - The\ freshwater\ aquatic\ toxicity\ potential\ of\ toxic\ subtance$$

$$MAETP - The\ marine\ aquatic\ toxicity\ potential\ of\ toxic\ subtance$$

$$TEP - The\ terristric\ toxicity\ potential\ of\ toxic\ substance$$

$$HTP - The\ human\ toxicity\ potential\ of\ toxic\ substance$$

$$M_t - The\ emission\ of\ toxic\ substance\ to\ the\ environment$$

Global warming potential is the total greenhouse gas emitted throughout the entire life cycle of the energy technology. The calculation follows the CML2001 impact method, as this is the most widely-used method of accounting for the life cycle climate change contribution of a product (Guinée, 2001; Stamford, 2012, p. 80). It is calculated as (15):

$$Global\ Warming\ Potential = \sum_{x}^{X} GWP_x \times M_{gx}\ (kg\ CO_2\ eq./MWh) \qquad (15)$$

Where,

$GWP_x - Global\ warming\ potential (in\ kgCO_2\ eq.) of\ greenhouse\ gas\ x$

$M_{gx} - Total\ mass\ of\ green\ house\ gas\ emission\ per\ unit\ electricity\ generated$

Ozone is a variant of oxygen, an ozone molecule having three atoms of oxygen. The ozone layer coats the earth's stratosphere, protecting the earth against the harmful ultraviolet rays of the sun by absorbing most of the hazardous UV-B radiation. Damage of this layer of ozone exposes the earth's surface to increased UV-B radiation. Emission of chlorofluorocarbons (CFCs) can cause thinning of ozone layers. The majority of ozone depleting substances were banned in the

Montreal Protocol in 1989; however since this protocol does not prohibit non-signatory countries from using products that use CFCs in manufacturing, CFCs along with other halogenated hydrocarbons are still widely used in industrial non-signatory countries. The energy technology's *ozone depletion potential* is calculated as (16):

$$Ozone\ Layer\ Depletion\ Potential = \sum_{x}^{X} OP_x \times M_{ox}\ (kgCFC_{-11}\ eq./kWh) \tag{16}$$

Where,

$OP_x - Ozone\ depletion\ potential\ (\ per\ CFC_{-11}\ eq.)\ of\ emission\ x$

$M_{ox} - Total\ mass\ of\ ozone\ depletion\ substance\ per\ unit\ electrictiy\ generated$

Photochemical oxidant formation (or photochemical smog) refers to a phenomenon that occurs under the influence of ultraviolet light, Volatile Organic compounds (VOCs) and carbon monoxide (CO) undergoing photochemical oxidation with presence of nitrogen oxides (NOx). *Photochemical ozone creation potential* investigates the formation of photo-oxidants, Ozone, derived from activities associated with electricity generation, it is calculated as (17):

$$Photochemical\ ozone\ creation\ potential = \textstyle\sum_{x}^{X} POCP_x \times M_p\ (kgCFC_{-11}\ eq./kWh) \tag{17}$$

Where

$POCP - Photochemical\ ozone\ forming\ potential\ of\ emissions$

$M_p - Emission\ of\ summer\ smog\ creation\ substance$

3.2.3 Social Sustainability Indicators

The social impact of energy technology is measured in two categories; its ability to alleviate fuel poverty, and provision of employment.

An energy technology's ability to reduce fuel poverty is assessed using the energy *bill reduction rate* achieved through the deployment of the chosen energy technology. It is calculated as (18):

$$Bill\ Reduction\ Rate = \frac{E}{E_p} \times 100(\%) \tag{18}$$

Where,

$$E - Savings\ on\ electricity\ expenses\ through\ installation\ of\ energy\ technologies$$

$$E_p - Electricity\ expenses\ prior\ to\ installation\ of\ energy\ technologies$$

Renewable energy is often promoted for its associated effect on job creation. A major social contribution that an energy technology is expected to deliver is *employment provision*, and it is calculated as (19):

$$Employment\ provision = \frac{\sum_i^I LE_i}{E_i} \tag{19}$$

Where,

$$LE_i - Employment\ generated\ at\ life\ cycle\ stage\ i$$

$$E_i - Installed\ capacity$$

3.3 Ranking of scores

The assessment results are organized using a total ranking system to identify the strengths and weakness of each assessed technology. Assuming all indicators are equally important[9], a ranking score from 1 to 3 is assigned to each indicator based on the performance score of the assessed technology at each category; where 1 represents the best performance and 3 accounts for the worst performance. The same ranking score is given to technologies that share the same performance within one category. All the scores are finally summed up to represent the sustainability performance of each technology, where a lower score indicates better performance and a higher score worse performance.[10]

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[9] In accordance to sustainability theory, all three-pillars are considered to be equally important; therefore all indicators are considered to be equally important and no importance ranking score is applied.

[10] The ranking does not take into account that the number of indicators is not evenly distributed among the three sustainability impact categories.

3.4 Quality assurance

In LCA practice data quality issues have been broadly discussed since the 1990s (USEPA, 1995), but robustness of the modelled results is not commonly addressed in the LCAs. Two approaches are employed in this study to examine the sensitivity and degree of uncertainty of the data, they are sensitivity analysis and data quality assessment.

In compliance with ISO 14044(ISO, 2006b, p. 22), additional analysis should be carried out for data quality assurance purpose, and sensitivity analysis is chosen to be appropriate for this study.

ReCiPe method is another both geographically valid and widely applied LCA method where its impact categories had been thoroughly peer reviewed(De Schryver *et al.*, 2009; Handbook, 2010); it is therefore used to cross-check with the environmental result produced using CML method. ReCiPe method involves both mid-point and end-point method, for consistency purpose only mid-point criteria of indicators that emphasizes same environmental impacts are included in this study. The results obtained from ReCiPe method uses same assumption, system boundary and process with that of the CML method.

Data quality assessment is to give an estimate of degree of uncertainties introduced by use of data. A number of data quality assessment criteria have been developed and practiced in the field of carbon foot printing, such as PAS 2050 (BSI, 2011) developed by British Standard Institute and CCaLC(Azapagic, 2011) developed by Manchester university; a modified version the data quality assessment method developed by Stamford and Azapagic (2012) is employed in this study. Each indicator assessed in each case study will have its data assessed using data quality assessment criteria illustrated in table 3.3. The total ranking score for each indicator will be summed and then to give a normalised total. An overall rating of 1 (or 100%) is an indication of perfect quality, and lower score means quality of the data has larger room for improvement

		Time specificity	**Geographical specificity**	**Technological specificity**	**Completeness of data**	**Data source**	**Auditability**
Score	3 (high)	<5 years old; valid for new build	Matches general Northeast England conditions throughout life cycle	Data for the exact technology under question	All significant inputs and outputs considered; whole life cycle considered	Primary or reputable secondary (e.g. data from company or peer-reviewed)	All data sources documented
	2 (medium)	5-15 years old; valid only for current capacity	Partly matches Northeast England conditions throughout life cycle	Data for technology very similar to that under question	Majority of inputs and outputs considered; most of life cycle considered	Mainly secondary; some estimation based on expert judgment	Partly documented
	1 (low)	>15 years old	Geographically generic	More generic data	Missing potentially significant inputs, outputs or life cycle stages	Estimated based on expert judgment	No link to original data

Table 3.2 Data quality assessment criteria (Stamford and Azapagic, 2012, p. 415)

3.3 Summary

This chapter explained the sustainability assessment framework proposed in this study. The assessment process can be simplified into four stages as illustrated in figure 3.2. First of all, the assessed technology is identified, then the sustainability assessment framework (table 3.3) is applied on the selected technologies; the result obtained from the assessment can be ranked against each indicator, the technology with the lower score will have the better ranking; for quality assurance purpose, the environmental assessment results are also calculated using ReCiPe method to find out if similar pattern of impact can be observed and the quality of data employed in the assessment is also analyzed using data quality assessment.

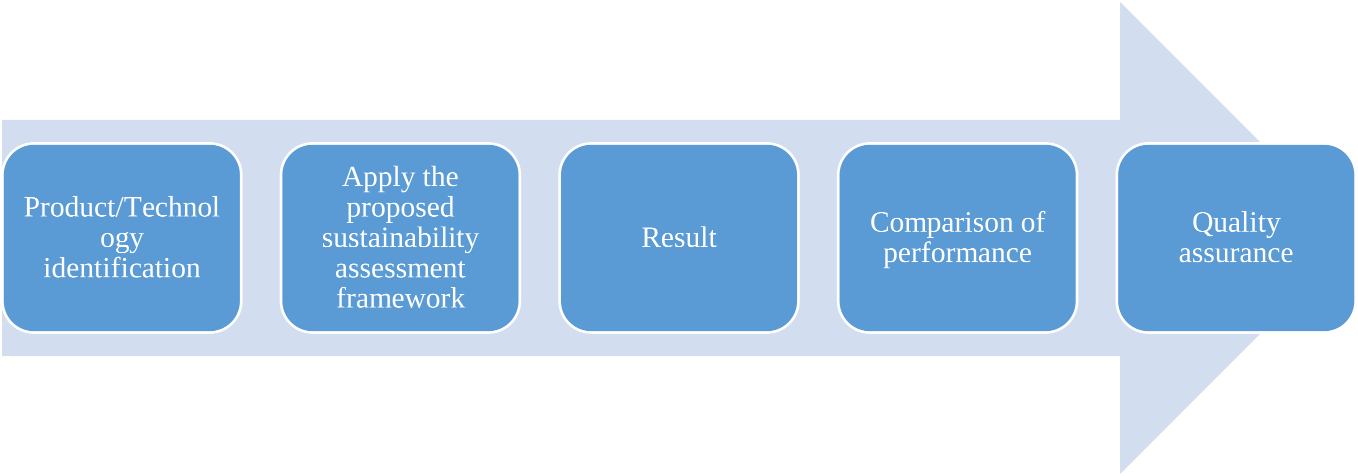


Figure 3.1 Application of sustainability assessment process

Sustainability issues		**Indicator**	**Unit**	**Life cycle stage considered**			
				Manufacture	Installation	Operation	End of life
Techno-economic Category	Reliability	Availability factor	%			x	
		Capacity factor	%			x	
		Dispatchability				x	
	Cost	Levelised cost	£/MWh	x	x	x	
	Financial feasibility	Payback period	years	x	x	x	
Environmental Category	Circularity	Material circularity	%	x	x	x	x
		Fuel circularity	%	x	x	x	x
	Energy Payback	Energy payback period	years	x	x	x	
	Acidification Potential (AP)			x	x	x	
	Eutrophication Potential (EP)			x	x	x	
	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)			x	x	x	
	Global Warming Potential (GWP 100 years)			x	x	x	
	Human Toxicity Potential (HTP inf.)			x	x	x	
	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)			x	x	x	
	Ozone Layer Depletion Potential (ODP, steady state)			x	x	x	
	Photochem. Ozone Creation Potential (POCP)			x	x	x	
	Terrestric Ecotoxicity Potential (TETP inf.)			x	x	x	
Social Category	Fuel poverty	Bill reduction rate	%	x	x	x	
	Employment provision	Employment provision	job/MW	x	x	x	

Table 3.3 Proposed sustainability assessment framework with indicators and life cycle stage considered

Chapter 4 Solar Photovoltaics

4.1Introduction

Solar PV is one of the fastest growing renewable energy technologies in the world (Branker et al., 2011), and the UK now has approximately 2% of the total global installations (BRE, 2018). Approximately 80%-90% of solar cells produced today are made from single- (or mono-) and poly-crystalline(Jungbluth *et al.*, 2012). Mono-crystalline silicon (also known as single-crystalline silicon, or s-Si) cells are made from silicon in the form of single crystal, and there are no boundaries between the silicon grains. This type of solar cell has high grade silicon material content and is known for its highest efficiencies (13%-18%) among all the commercialised solar cell types, and thus it is more costly compared to other types of solar cells. Poly-crystalline silicon (p-Si) cells are of relatively lower silicon content that the silicon is made from an agglomeration of crystals distributed in various orientations, which means electron-hole-recombination losses are unavoidable due to the boundaries between silicon grains. The p-Si cells has a lower efficiency compare to s-Si cells, and it is less costly.

Another type of solar cells is thin film solar cells, it is a less popular option for its lower efficiency compared to the silicon based solar cells. They are made of exceedingly thin layers of photovoltaic materials spread on glass or stainless steel, and sometimes plastic backings. Because of the reduced use of semiconductor materials, the efficiencies are lower for thin film solar cells and thus this type of cell is less costly in comparison to the previous two types. Cadmium telluride (CdTe) solar cells are the most common thin film solar cell; it is also the most controversial type of PV technology for its use of cadmium, which is a toxic and hazardous material. Although under normal circumstances the toxic substance is not released into the environment, in cases of fire, breakage and inappropriate recycle handling, currently-available CdTe can escape from the solar cells and contaminate the environment.

Almost all installed solar PV systems in the UK are connected to the existing electricity grid. A proportion of the power generated is consumed on site by the host, with any surplus power generated being exported to the distribution network for regional distribution.

In the North East region, 95% of installed solar PV systems are residential, grid connected systems (IEA-PVPS, 2016) at 4kW (nominal maximum) capacity, and include the solar modules themselves, inverters and mounting parts (also known as Balance of the System, BoS). This study is focused on solar PV technologies that are already installed in the North East England. Therefore a 4kWp residential roof-mounted grid-connected system is considered for this study. Solar cells of two types of silicon material as well as CdTe solar cells are selected to be representative of the existing installation type.

4.2 Assumptions

Four life cycle stages of solar PV are included in this study: manufacture of the equipment, installation, operation and end of life (Figure 4.1). The electrical grid connection is already in place prior to deployment of solar PV; therefore it is not included in the system boundary. A solar PV system includes the solar panel, the inverter and the mounting parts. The manufacturer-guaranteed lifetime of a solar PV system is 25-30 years, while the inverter needs to be changed every 10 years; after this period the energy system is still able to generate electricity at reduced efficiency, but to date there is no established data defining the drop-off time or efficiency reduction amounts. Therefore, a range of 25-30 years is considered to be the lifetime of a solar PV system.

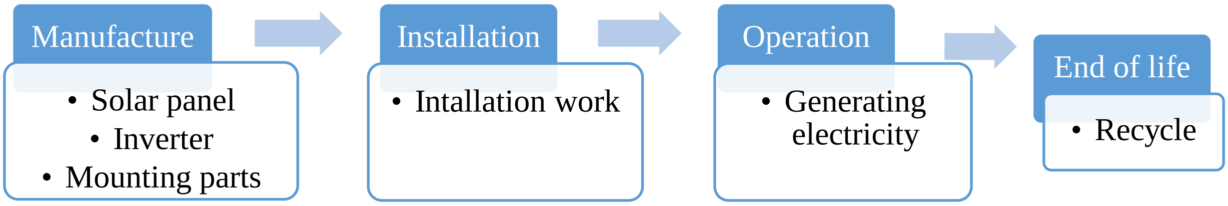


Figure 4.1 Lifecycle stages of solar PV

4.2.1 Key technical parameters

A list of key technical parameters is presented in Table 4.1. The efficiencies of the different types of solar PV modules are mentioned in the previous section. The cost of solar PV system varies depending on the manufacturer and equipment provider. A quotation provided by a local solar PV installer, Minel Energy, suggests that the cost of a 4kWp system alone varies from £3000 for the less popular CdTe cells to a maximum of £6000 for an s-Si system, with the installation cost ranging between £800 and £1000 for each system installed regardless of the panel material. Throughout their lifetime solar modules need to be cleaned to ensure optimum power output, and in some cases, the inverter needs to be replaced after 10 years. The majority of the solar installers offers a maintenance plan at the cost of £1200-£1500. A discount rate of 3.5% is applied according to the Green Book (Book, 2003). Lifetime energy consumption is estimated by Ecoinvent (EcoinventCentre, 2015), including the end of life treatment for both recoverable and unrecoverable waste, and is in line with existing literature (Peng *et al.*, 2013).

The average annual sunlight hours of the North East region is between 1230 and 1316 hours (MO, 2016). Annual energy yield is estimated based on the module efficiency rate and solar irradiation and ranges from 1600 kWh generated by CdTe at an efficiency of 6%, to 4800 kWh generated by the maximum possible efficiency of s-Si. A general annual efficiency degradation rate of 1% is applied to all solar PV systems (Zweibel *et al.*, 2008).

Income from a solar PV installation is generated through a Feed in Tariff (FiT) and the export of surplus electricity to the grid, in addition to bill reduction achieved by consuming the on-site generated electricity. The UK FiT currently offers a solar PV host 4.39 pence per kWh generation (DECC, 2015). PV systems in the UK are mostly currently installed without export meters and exported electricity is set to a deemed amount of 50% for such systems. System hosts receive a rate of 4.85p/kWh for the deemed 50% of electricity exported, which is thus irrespective of the actual surplus export amount. As mentioned in previous chapter, both FiT rate and export rate are discounted in the analysis by a Retail Price Index of 1.3%.

Parameters	**Types of material**					
	Silicon				**Thin film**	
	s-Si		**p-Si**		**CdTe**	
	Min	Max	Min	Max	Min	Max
Life-time (years)	25	30	25	30	25	30
Module Efficiency	16%	18%	15%	16%	6%	10%
System Cost (£/system)	5000	6000	4000	4500	3000	3500
Installation cost (£/system)	800-1000					
O&M cost (£/system life time)	1200-1500					
Discount rate	3.5%					
Annual Sunlight hours (hour)	1230-1316					
Annual energy yield per system (kWh)	4280	4800	4000	4280	1600	2680

Table 4.1 Key techno-economic parameters for solar PV

4.2.2 Environmental parameters

Material composition for solar PV system varies slightly depending on the model and manufacturer. Therefore an estimate of the total material consumption per system according to a European dataset provided by EcoinventCentre (2017a) is considered to be representative of the installed systems in the UK and is applied in this study. The total material consumption of solar PV systems is listed in Table 4.2. The dataset for s-Si and p-Si are identical in Ecoinvent 3.4. Hence a general estimation of the silicon-based system is used instead.

Recyclability is the percentage of material that can be reused after the product is recycled. In theory all metal, glass and silicon products have 100% recyclability; however in reality only a proportion of the material is sorted and recycled, the amount varying depending on the common recycling practice in the region. Table 4.3 shows the recoverable mass for the assessed CdTe and silicon solar PV.

Material use (kg/system)		Types of solar panel material	
		Silicon	**CdTe**
Input material	Aluminium	73.64	0.42
	Copper	6.16	14.56
	Board box	30.80	38.36
	Ethyvinylacetate	28.00	16.80
	Glass fibre reinforced plastic, polyamide	5.32	3.08
	Polyethylene terephthalate	10.44	0.00
	Silicon product	3.42	0.00
	Silica sand	0.00	1.40
	Glass	565.60	793.80
	Steel	0.00	6.50
	Sodium chloride	0.00	1.40
	Sodium hydroxide	0.00	1.40
Waste for treatment	Municipal solid waste	0.84	27.28
	Waste plastic mixture	47.32	19.88
	Waste polyvinyl fluoride	3.08	0.00

Table 4.2 Material consumption and waste for the treatment of solar PV system, data source: EcoinventCentre (2017a)

Material (kg/system)		Types of solar panel	
		Silicon	**CdTe**
Recoverable mass	Aluminium	70.69	0.4
	Copper	3.54	8.36
	Board box	26.64	33.18
	Glass fibre reinforced plastic, polyamide	0.53	0.31
	Polyethylene terephthalate	6.27	0
	Silicon product	2.9	0
	Glass	383.48	538.2
	Steel	0	3.38
	Waste plastic	12.3032	5.1688
	Material circularity	38%	35%

Table 4.3 Recoverable mass for the two assessed solar PV

4.2.3 Social Assumptions

The average UK domestic electricity bill is £578 per household in North East England based on an annual consumption of 3,800kWh in 2015 (Bradley *et al.*, 2013). Solar PV is able to achieve employment provision of 653 person-year/TWh (Stamford, 2012) regardless of the material used in the panel.

4.3. Results

This section presents the assessment results of solar PV systems. The techno-economic, environmental and social performances of the selected PV systems will be discussed separately, then a total ranking system will be applied to compare sustainability performances between the three selected types of PV systems.

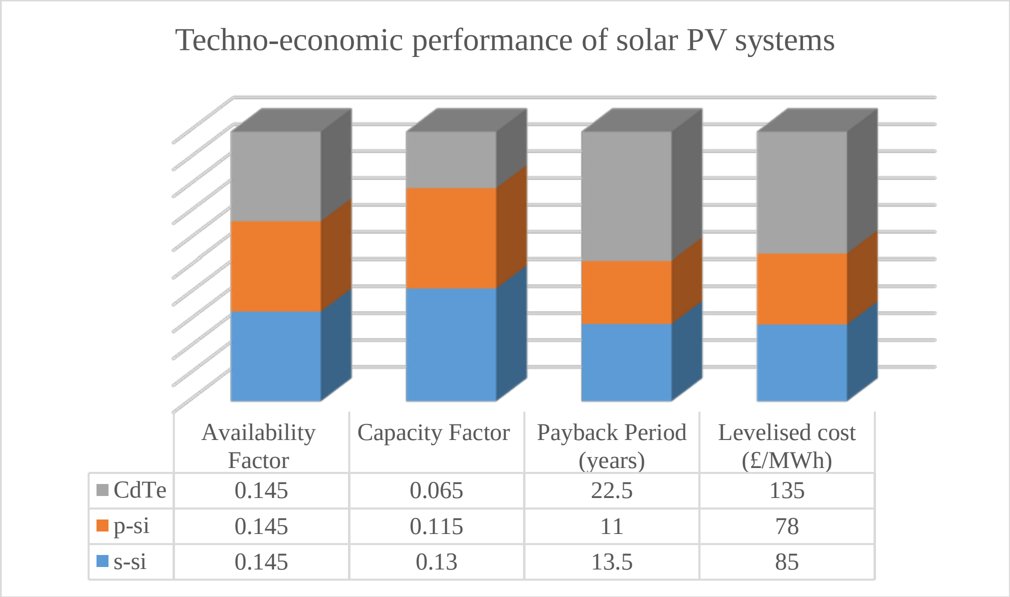
4.3.1 Techno-economic performance

The results for techno-economic performances are presented in Figure 4.2 using the average number obtained for each assessed model.

The levelised cost of electricity generation varies from £74/MWh to £169/MWh. The availability factor entirely depends on the regional sunlight duration; it is thus at the same level for all PV systems. Conversely, the difference between silicon and CdTe for the rest of the indicators are rather noticeable. Despite the low system cost, the payback period and levelised cost of CdTe systems are almost double that of silicon-based systems. The profitability factor of CdTe in particular reaches negative values, which indicates high investment risk. It can be concluded that the economic performance of CdTe systems is constrained by their low efficiency; the levelised cost is compromised by its low lifetime electricity output, which thus further compromises both the payback period and profitability.

Other than cost and materials, climate and geographical location are the other factors that constrain the return on investment (ROI) for solar PV systems. For instance, a silicon-based solar panel installed in California has a capacity factor of 20%, which brings the levelised generation cost to as low as $7/MWh (Reichelstein and Yorston, 2013); a horizontally-mounted silicon solar panel in Scandinavia has a capacity as low as 5.4% (Stamford and Azapagic, 2012) which is almost as low as the lowest estimation for the worst performing CdTe systems in this study.

The two selected silicon PV systems are both able to pay back the capital costs between 10-14 years, which is approximately within the first half of their generating lifetime (normally 25 years). The p-Si system can achieve break-even as early as four years ahead of s-Si systems. Due to its lower generation capacity, the CdTe system will not break even until possibly after manufacturer guaranteed lifetime has passed.



	Availability Factor	Capacity Factor	Payback Period (years)	Levelised cost (£/MWh)
⬜ CdTe	0.145	0.065	22.5	135
🟧 p-si	0.145	0.115	11	78
🟦 s-si	0.145	0.13	13.5	85

Figure 4.2 Techno-economic performance of solar PV systems

Based on present technology, solar PV is still considered to be not dispatchable therefore equal score is applied to all assessed panels. In summary, solar PV systems made of silicon materials perform better as a result of a higher yield of electricity, and also lower investment risk, in comparison to CdTe systems. The p-Si systems require the least capital investment and have the best performance among the three selected solar PV systems in the techno-economic category.

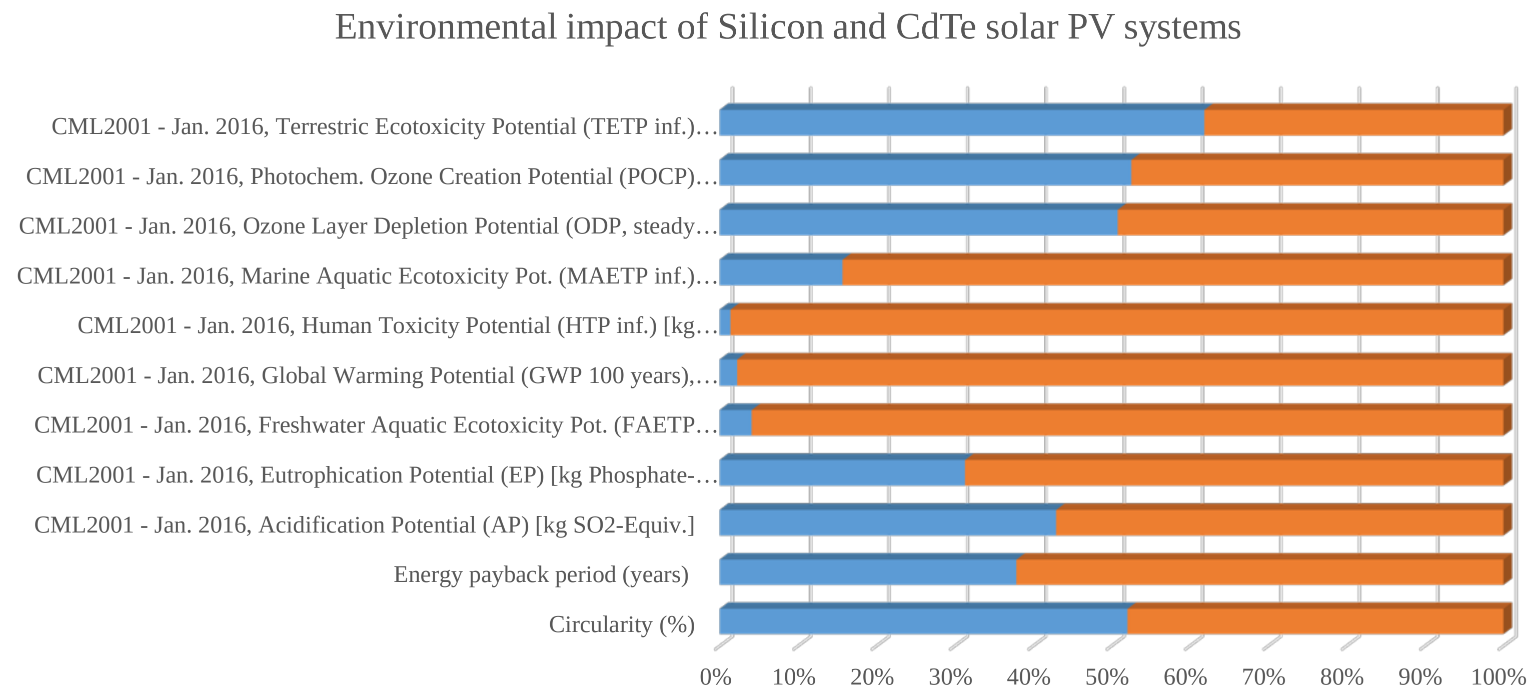
4.3.2 Environmental performance

Environmental performance of silicon and CdTe systems are illustrated in Figure 4.3. A generalized silicon-based PV system is used as a representative of both s-Si and p-Si systems.

The minor difference on material circularity can be found between the two compared systems, with the silicon-based system valued slightly higher than the CdTe system on this indicator. The circularity of both assessed systems is compromised by the current material recycling rate in the UK. In theory, silicon-based solar PV has a recycling rate of as high as 99.7% (Li *et al.*, 2016b); however result from this study conveys that less than half of the material consumed and waste produced is neither recycled nor recyclable. For example, as previously shown in table 4.2, the bulk of the mass for both PV systems is glass; in theory, the glass is 100% recyclable without loss in quality (Zapata and Hall, 2013), while compare to currently only 67.8% of the glass is recycled in the UK (DEFRA, 2015). The CdTe systems has higher toxicity related impacts compare to the silicon based system, this is because the use of cadmium material. Cadmium has high toxicity and it is largely soluble in water (Benavides *et al.*, 2005), incidents associated with cadmium poisoning can be found around the world(Järup, 2003). The use of cadmium is highly restricted, and Restriction of Hazardous Substances Directive (Directive, 2002) only permits its use in solar PV panels.

The total life time energy consumption for the silicon system is 11.25MWh and for the CdTe system is 8832kWh. In comparison with CdTe systems, the manufacturing process for silicon-based systems is more energy intensive, this can be explained by the difference in manufacture briefly illustrated in Figure 4.4. The process for producing each solar cell begins with quartz reduction; then metallurgical grade silicon is purified by a Siemens or modified Siemens process which requires high temperatures in order for trichlorosilane and hydrogen to react in the reactor chamber; this is then followed by the silicon crystallisation process. In the case of s-Si panels, the Czochralski process which involves gradually extracting the growing crystal from the melting pot is required to produce silicon of single form. These processes all requires a considerable amount of heat which therefore explains the high energy demand. In comparison, production of CdTe panels only involves applying a thin layer of semiconductor metal onto the glass backing, followed by a thermal treatment carried out with $CdCl_2$ (Kato *et al.*, 2001). Although CdTe consumes less energy than silicon based PV, but its energy payback period is let down by its lower conversion efficiency.

The silicon purification process and the significant proportion of aluminium (76.64kg) in the silicon-based system add to the system’s high acidification and eutrophication potential. The ozone depletion potential originates from the silicon solar PV manufacture process and can be traced to panel wafer production where 30% are generated by German production and 60% are emitted from Asian and US factories, where environmental legislation for the manufacturing process varies greatly from that in Europe. Silicon PV has higher impact in the category of terrestric toxicity potential, ozone layer depletion potential and photochemical ozone creation potential; this is caused by the heavy use of aluminium in the system.



	Circularity (%)	Energy payback period (years)	CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2-Equiv.]	CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2-Equiv.]	CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	CML2001 - Jan. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]
🟦 Silicon	0.38	2.5	50.3	29.2	1.32E+04	4.72E+03	2.36E+04	2.94E+07	0.000282	4.84	146
🟧 CdTe	0.35	4.1	66.8	64	3.10E+05	2.06E+05	1.67E+06	1.58E+08	0.000273	4.37	90

Figure 4.3 Environmental performance of Silicon and CdTe solar PV systems

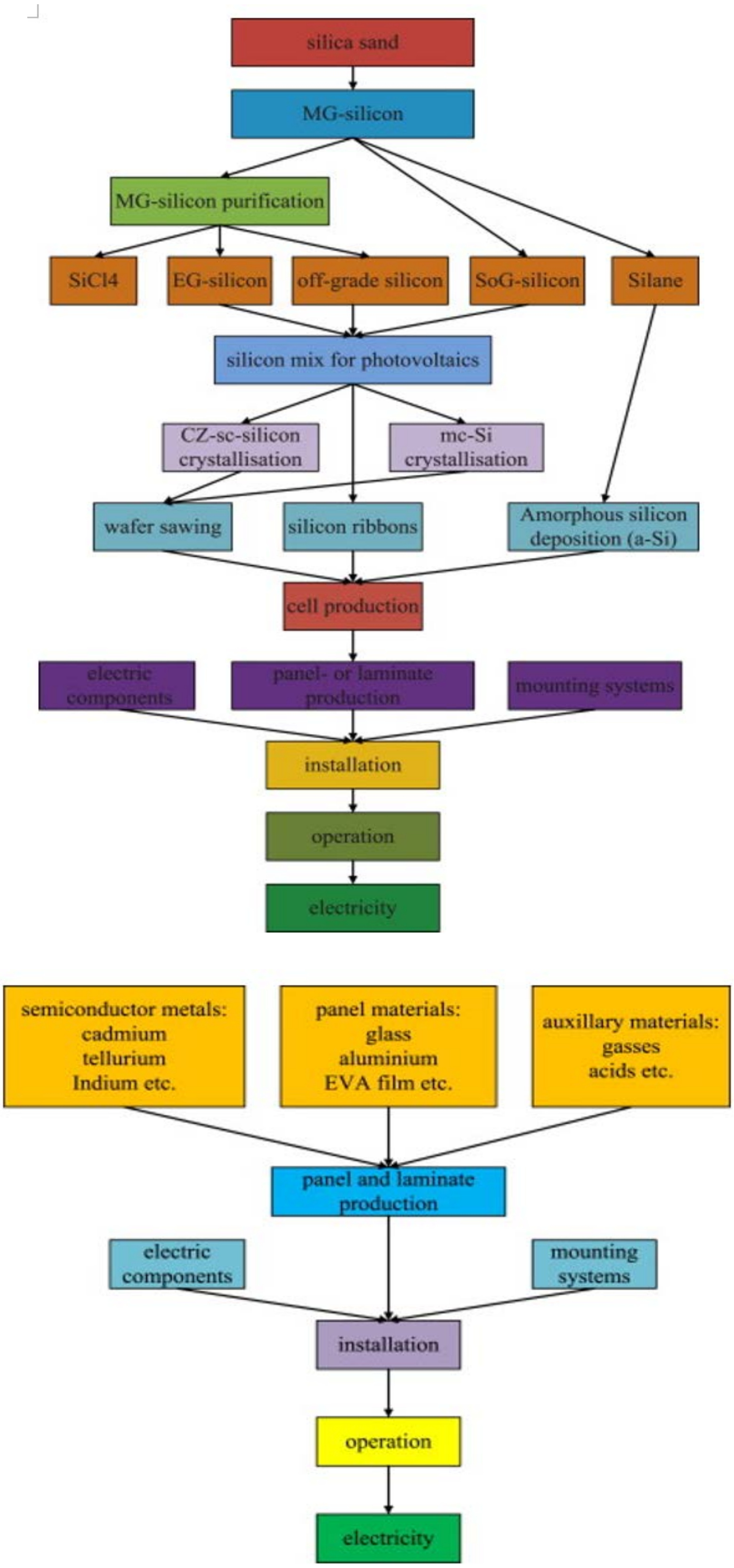


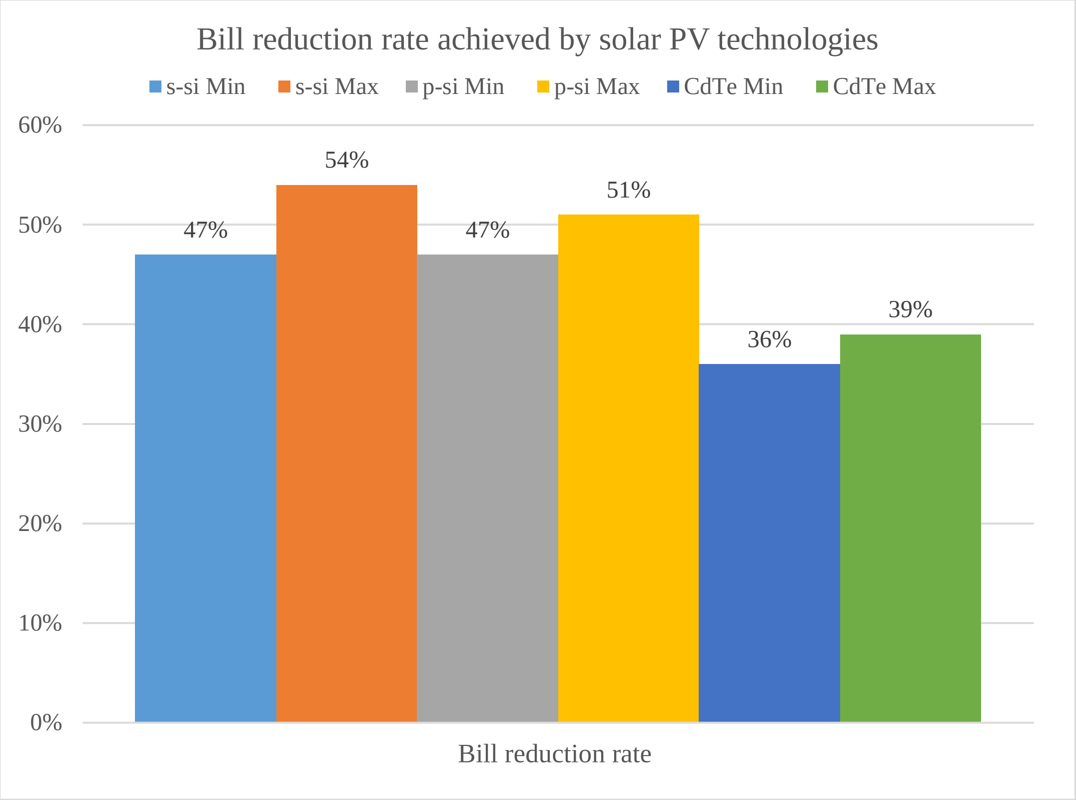
Figure 4.4 Manufacture process of silicon-based (top) and thin film (down) solar PV systems(Peng et al., 2013)

4.3.3 Social impacts

Existing data on employment creation through solar PV installation varies greatly. Cameron and van der Zwaan (2015) estimated an average of 11.2/MW of employment opportunities can be generated through installation of PV systems, survey undertook by Atherton and Rutovitz (2009) gives employment figure of 31.9person/MW installation, while a private sector study by Maia *et al.* (2011) conveys a total of 7 jobs can be created through 1 MW solar PV installation projects.

This can be understood as the significant amount of job opportunities created through solar PV deployment are transferrable from other existing sectors such as construction and sales. In addition, there is a general lack of agreement on how job creation rate is recorded, which makes it difficult to form a complete picture on solar PV's ability to provide employment opportunities. Stamford (2012) estimated a job creation rate of 653 person-year/TWh for the UK. As informed by Minel Energy, the difference in types of solar PV technology and geographical location has little impact on the number of employment opportunities created for installing and maintain solar PV.

The North East of England suffers from the highest proportion of households in fuel poverty across England, with 11.1% of the households falling into fuel poverty(DBEIS, 2018a). It can be observed from Figure 4.5 that installation of a solar PV system can achieve a 36%-54% bill reduction rate, which can assist in alleviating fuel poverty within the region.



*F*igure 4.5 Bill reduction rate achieved by s-Si, p-Si and CdTe solar PV systems

Sustainability issues		Indicator	Type of solar photovoltaic systems					
			Silicon				**Thin Film**	
			s-Si		**p-Si**		**CdTe**	
			min	max	min	max	min	max
Techno-economic Category	Reliability	Availability factor	0.14-0.15					
		Capacity factor	12%	14%	11%	12%	5%	8%
	Cost	Levelised cost	74	96	68	88	101	169
	Dispatchability		24	24	24	24	24	24
	Financial feasibility	Payback period	13	14	10	12	13	26
		Profitability	0.84	2.12	0.65	2.12	-1.2	1.53
Environmental Category	Material circularity	Circularity	0.38				0.35	
	Energy Payback	Energy payback period	2.5				4.1	
	Global warming	Global warming potential	1.19E+04				2.06E+05	
	Acidification	Acidification potential	77.5				66.8	
	Eutrophication	Eutrophication potential	28.8				64	
	Ozone depletion	Ozone layer depletion potential	1.48E-03				2.73E-04	
Social Category	Fuel poverty	Bill reduction rate	47%	54%	47%	51%	36%	39%
	Employment provision	Employment provision	653					

Table 4.4 Sustainability assessment results for selected solar PV system

4.3.4 Summary of solar PV technology comparison

The assessment results are organized using a total ranking system to identify the strengths and shortcomings of each assessed technology, as displayed in Table 4.5. Assuming all indicators are equally important, a ranking score from 1 to 3 is assigned to each indicator based on the performance score of solar PV system at each category; where 1 represents the best performance and 3 accounts for the worst performance. The same ranking score is given to technologies that share the same performance within one category. All the scores are finally added to demonstrate the sustainability performance of each technology, where a lower score indicates better performance and a higher score worse performance.

Sustainability issues		**Indicator**	**Type of solar photovoltaic systems**		
			Silicon		**Thin Film**
			s-Si	**p-Si**	**CdTe**
Techno-economic Category	Reliability	Availability factor	1	1	1
		Capacity factor	2	1	3
	Cost	Levelised cost	2	1	3
	Dispatchability		1	1	1
	Financial feasibility	Payback period	2	1	3
		Profitability	1	2	3
	Sub-total		**9**	**7**	**14**
Environmental Category	Material circularity	Circularity	1	1	2
	Energy Payback	Energy payback period	1	1	2
	Global warming	Global warming potential	1	1	2
	Acidification	Acidification potential	2	2	1
	Eutrophication	Eutrophication potential	1	1	2
	Ozone depletion	Ozone layer depletion potential	1	1	2
	Sub-total		**7**	**7**	**11**
Social Category	Fuel poverty	Bill reduction rate	1	2	3
	Employment provision	Employment provision	1	1	1
	Sub-total		**2**	**3**	**4**
Grand Total			**18**	**17**	**29**

Table 4.5 Summarised sustainability ranking of solar PV systems

Examining the results listed in table 4.5, thin film solar PV system has the worst performance across all categories, and s-Si system ranks higher in the social impact category owing to its higher energy conversion efficiency. Overall, the p-Si system is the most sustainable option.

4.4. Discussion

This section discusses the results obtained from the sustainability assessment and other sustainability relevant issues associated with solar PV technology.

4.4.1 Economic assumptions

In the assessment carried out in this study, a standard real discount rate of 3.5% is applied to all solar PV systems in accordance to Social Time Preference Rate (STPR) published in the Green Book (Book, 2003). In practice, investors or decision makers may select a different discount rate to reflect their perception of financial risks, and thus discount rate varies from one case to another (IEA and NEA, 2015). Financial risks can be influenced by some factors such as maturity of the technology, the proportion of marginal cost, the lumpiness of investment, market incentives, and policy. For instance, as suggested by Oxera (2011, p. 11), when carrying out financial analysis, renewable energy technologies such as wind and solar PV should be given a discount rate of 6-9%, as these technologies possesses moderate financial risk for their low dependence on subsidies. Nevertheless, this discount rate was calculated in 2011, and so the most recent discount rate had been adjusted to 3.5% to reflect the recent reduction on FiT reduction and geopolitical changes (DECC, 2015; Dhingra *et al.*, 2016)

Finally, financial analysis carried out in this study does include the impact of administrative costs such as insurance cost and financing costs on the levelised cost of generation. These costs are influenced by the individual financing method and future technology learning, and these factors are not in the scope of this study. Nonetheless, these factors are recommended to be considered for future studies, particularly for the case of silicon-based solar PV modules, where the manufacturing cost of silicon wafers accounts for over 65% towards the total manufacturing cost of a solar cell and the majority of this cost occurs during the extraction and processing of silicon materials.

Recycling silicon PV is still unprofitable at present stage; with the positive role of learning economies and improved competitiveness of the recycled materials market, the system cost of solar PV systems can be expected to reduce in the future (D’Adamo *et al.*, 2017; Smith and Bogust, 2018).

4.5.2 Policy support

Economic barriers are both complex and significant when it comes to the deployment of renewable energy technologies (Allen *et al.*, 2008). Successful renewable energy diffusion with help from policy support are evident in many countries such as Japan (Yamada and Ikki, 2013), Germany (Network, 2014) and the US(Kann *et al.*, 2013). Strong policy support not only softens financial burdens but also encourages investor confidence which then subsequently advances R&D of the technology itself. Solar PV as an investment option requires a substantial proportion of capital investment which exceeds 60% of the total investment. Additionally, the economic feasibility of solar PV heavily relies on available financial incentives where FiT tariff accounts for 25%-60% of the total levelised cost (at 3.5% discount rate)(Oxera, 2011, p. 11; Dhingra *et al.*, 2016).

4.5.3 End of Life

As discussed in previous section, cadmium is a highly toxic substance, hence safe and efficient end of life treatment is required to ensure no harmful substance is leaked into the environmental. End of life scenario is carried out here to examine the potential environmental impact of the decommission process.

The UK is a relatively new market for PV; there have not been enough retired PV systems for the industry to establish a standard end of life treatment approach. So far, most of the UK's retired solar PV panels are processed as domestic waste, or occasionally transported to centralised European treatment facilities(Weckend *et al.*, 2016). Therefore assumptions about end of life treatment are made presuming the assessed PV panels are recycled to the maximum amount at current technology: silicon panels are dismantled, and components are recycled separately at the current material recycling rate. However, the case is different for CdTe systems because of the toxicity of the semiconductor material. Therefore the end of life solar panel scenario for CdTe system is assumed to follow the practice of the largest European-based manufacturer, First Solar's Frankfurt-Oder plant in Germany (as shown in Figure 4.6). The retired CdTe panels are treated through shredding, removal of the semiconductor film, solid-liquid separation, laminate foil-glass separation and rinsing, semiconductor precipitation, and dewatering. Eventually, the module is reduced to glass cullet and unrefined semiconductor material and recycled at their current material recycling rate. Due to lack of data for this practice, the environmental performance of the end of life treatment cannot be estimated in this study.

Furthermore, it should be noted that the end of life treatment technology for retired solar PV currently is still at development stage. Although recent technology enables a 60% recovery rate of silicon materials from retired PV panels (Kang *et al.*, 2012), this technology has yet to be commercialised. Considering the material recovering rate of solar panels has the potential to reach as high as 96-99.7% (Li *et al.*, 2016b), and the UK WEEE regulations have have created a separate category for retired PV panels and introduced a new requirement for PV installers to join a “distributor take-back scheme”. The scheme have been approved by the Department for Environment Food and Rural Affairs, and its implementation is currently under review(DEFRA, 2018a). Therefore the future for reduced environmental impact through improvement in both recycling practice and technology remains optimistic.

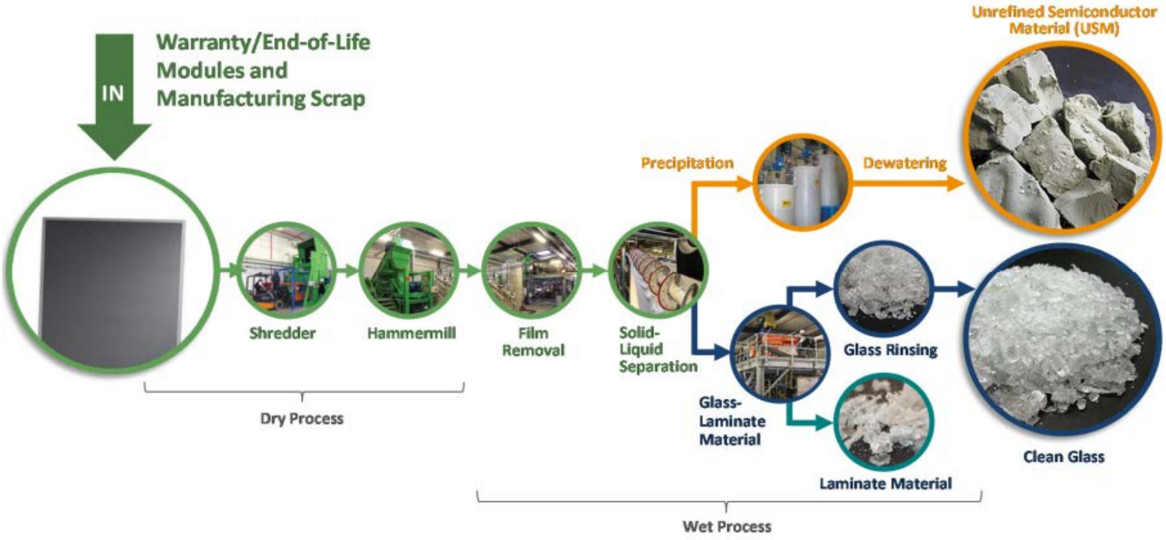


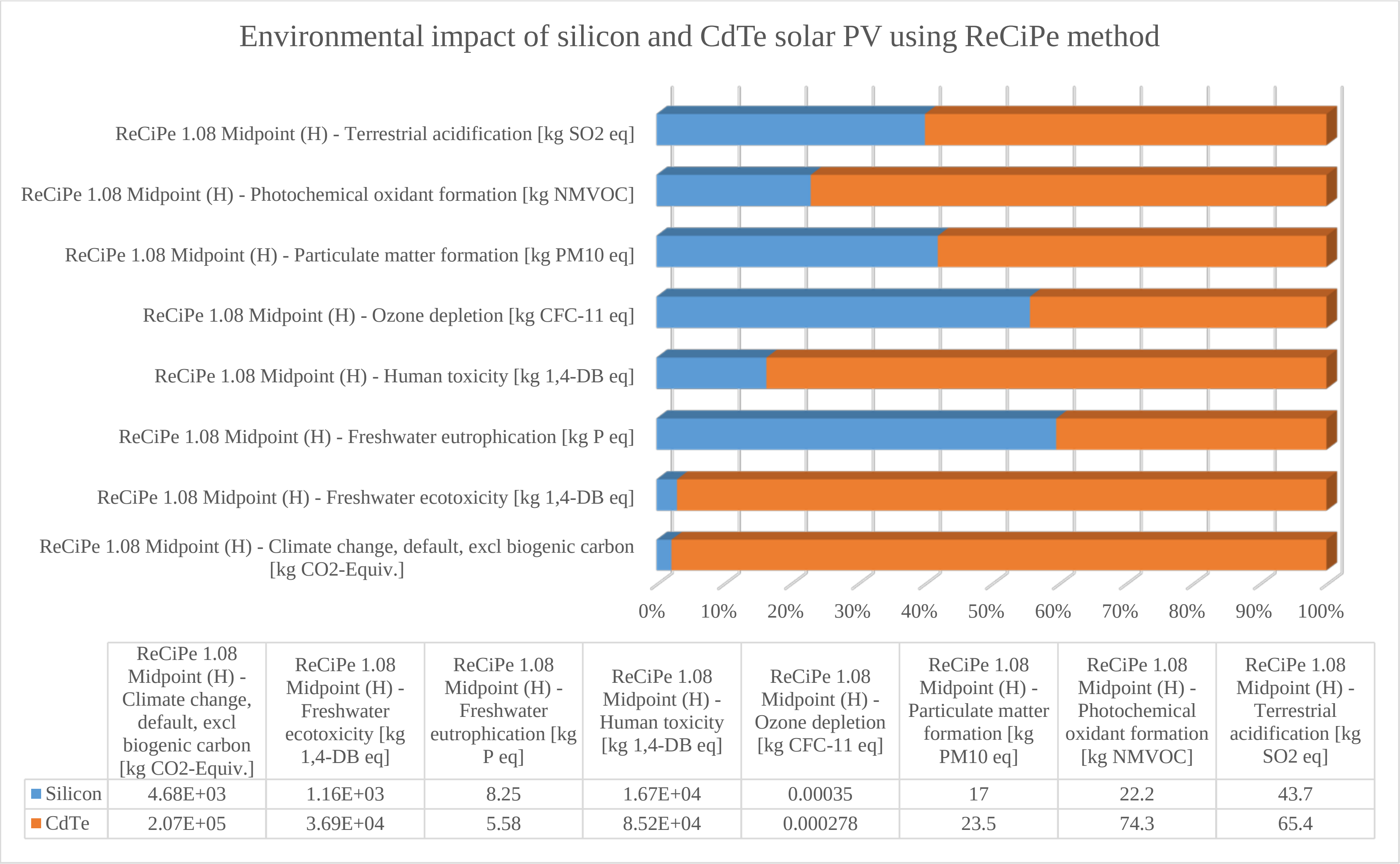
Figure 4.6 End of life treatment of retired CdTe solar PV panels (P. Sinha, 2012)

4.5.4. Sensitivity analysis

In compliance with LCA standard ISO 14044 (ISO, 2006b, p. 22), additional analysis has been carried out for data quality assurance purpose. Other than the CML method used in this study, ReCiPe is another both geographically valid and widely applied LCA method with thoroughly peer-reviewed impact categories (De Schryver *et al.*, 2009; Handbook, 2010). ReCiPe consists of both the mid-point and end-point method. For consistency purposes, only mid-point indicators that assess the same environmental impacts are included in this section. The results obtained from the ReCiPe method uses the same assumption, system boundary and process with that of the CML method.

Figures 4.7 show the environmental impact assessment result (apart from circularity and energy payback period as they were not assessed using CML method) for silicon and CdTe solar PV systems carried out using ReCiPe method. In the ReCiPe method, eutrophication potential is divided into freshwater and marine eutrophication potential, and acidification potential is defined as terrestrial acidification potential.

The environmental impact for both solar PV systems is almost identical using LCA methods, apart from the eutrophication potential. The difference is more prominent for silicon systems, where the eutrophication potential using the CML method amount to much higher value (28.73) than the value obtained using ReCiPe method (10.84). This difference originates from different eutrophication potential calculation algorithms between the CML and ReCiPe methods. The CML method calculates eutrophication potential based on LCA background research carried out in 1992 (Heijungs *et al.*, 1992), which assumes the worst case scenario by summing all nitrogen, potassium and organic matter emission in the phytoplankton molar element ratio of 106:16:1 for C:N:P, and no cause-effect mechanism is taken into consideration. On the other hand, the ReCiPe method is based on more recent research (Goedkoop *et al.*, 2009), and calculates eutrophication potential by categorising the receiving body where eutrophication substances are deposited which provides more precise modelling of environmental mechanisms with fewer substances covered (Bach and Finkbeiner, 2016). Considering the above circumstances, it is considered that eutrophication potential results obtained using the ReCiPe method provide more credible estimation compared to the results obtained using CML method.



	ReCiPe 1.08 Midpoint (H) - Climate change, default, excl biogenic carbon [kg CO2-Equiv.]	ReCiPe 1.08 Midpoint (H) - Freshwater ecotoxicity [kg 1,4-DB eq]	ReCiPe 1.08 Midpoint (H) - Freshwater eutrophication [kg P eq]	ReCiPe 1.08 Midpoint (H) - Human toxicity [kg 1,4-DB eq]	ReCiPe 1.08 Midpoint (H) - Ozone depletion [kg CFC-11 eq]	ReCiPe 1.08 Midpoint (H) - Particulate matter formation [kg PM10 eq]	ReCiPe 1.08 Midpoint (H) - Photochemical oxidant formation [kg NMVOC]	ReCiPe 1.08 Midpoint (H) - Terrestrial acidification [kg SO2 eq]
■ Silicon	4.68E+03	1.16E+03	8.25	1.67E+04	0.00035	17	22.2	43.7
■ CdTe	2.07E+05	3.69E+04	5.58	8.52E+04	0.000278	23.5	74.3	65.4

Figure 4.7 Environmental impact of silicon and CdTe solar PV using ReCiPe method

4.5.5 Sustainable supply chain

Solar PV is considered a “clean energy” by the general public, for the reason that it does not emit greenhouse gases during electricity generation. However, results from this study show that although solar PV technologies are emission-free during operation, the environmental impact derived from the manufacture and end of life treatment process are not negligible.

The economic globalisation and outsourcing of services has advanced the service of the supply chain, at the same time making it increasingly difficult for businesses and consumers to acknowledge and manage the impact of their decisions. Large companies have already started to demand more information from their suppliers and deploy LCA to track and optimise the sustainability performance of their products; and some companies have started to integrate LCSA in their sustainability strategy (Bonanni *et al.*, 2010; Herva *et al.*, 2011; Čuček *et al.*, 2012).

4.5.6 Data quality assessment

Table 4.6 below summaries the data quality analysis. The average score is 88%, slightly lower than that of onshore wind (90%) and higher than that of biomass CHP (82%). The weakest area is social indicators, where primary employment data was unable to obtain and literature sourced data was used to give an estimate. Overall, the quality of the data is considered to be good considering the goal and scope of this study. Recommendation for future work may include:

1. Improving the data quality by using primary data on employment provision and bill reduction achievements.
2. Explore hidden subsidies and incentives.
3. Including primary data on local material recycle practice to give a better estimate on circularity of solar PV.

Sustainability issues		**Indicator**	Normalised total
Techno-economic Category	Reliability	Availability factor	0.89
		Capacity factor	0.94
	Dispatchability		1.00
	Cost	Levelised cost	1.00
	Financial feasibility	Payback period	1.00
Environmental Category	Circularity	Material circularity	0.83
		Fuel circularity	1.00
	Energy Payback	Energy payback period	0.89
	Acidification Potential (AP)		0.83
	Eutrophication Potential (EP)		0.83
	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)		0.83
	Global Warming Potential (GWP 100 years)		0.83
	Human Toxicity Potential (HTP inf.)		0.83
	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)		0.83
	Ozone Layer Depletion Potential (ODP, steady state)		0.83
	Photochem. Ozone Creation Potential (POCP)		0.83
	Terrestric Ecotoxicity Potential (TETP inf.)		0.83
Social Category	Fuel poverty	Bill reduction rate	0.89
	Employment provision	Employment provision	0.78

Table 4.6 Data quality assessment result for solar PV

4.6 Summary

Three solar PV technologies that are widely deployed within the region were considered to be representative for existing solar PV deployment, and were selected for the assessment. Examining from the sustainability performance obtained from the assessment, it can be concluded that:

1. Although solar PV is commonly considered to be a “clean” energy option for its low emission during generation stage, the environmental impact caused during manufacturing stage is not negligible;
2. Solar PV installation in the Northeast region of England does not have excellent techno-economic performance, this is mainly due to the limited sunlight resource available within the region;
3. Fuel poverty can be effectively alleviated through bill reduction achieved by installation of solar PV;
4. The p-Si solar panel system is the most sustainable option among the solar PV systems

made of p-Si, s-Si and CdTe materials. The sustainability performance of solar PV systems can be improved with future technology advancement.

Chapter 5 Onshore wind

Wind energy had been widely implemented throughout Europe since1980s, fostered by the EU, as a renewable alternative to conventional energy technologies. By end of 2016 installed onshore wind capacity of the UK reaches 14,543MW, ranked the 3rd in the Europe (DECC, 2017). UK is one of the best locations for wind power in the world, and the wind resource of North of England is among the best across the Europe. (Rubert *et al.*, 2016). This chapter provides a sustainability assessment on the deployed onshore wind energy in the Northeast England. The chapter first introduces the design of wind turbines and explains the energy outlook within the region, then lays out the assumptions made for the assessment followed with the assessment results and discussion surrounding the sustainability issues of onshore wind technology.

5.1 Introduction

A wind turbine utilises the wind energy by converting the kinetic energy of wind into electrical energy. The world's wind energy system had been evolving gradually since the first electricity generation turbine was developed in the beginning of the 20th century. (Kumar *et al.*, 2016). One of the most important trend for onshore wind today is the expanded option of turbines offered by manufactures to meet wider range of site constraint and lower the levelised cost for developers. (IRENA, 2018a, p. 90) Wind turbine price is influenced by both demand-and-supply and commodity prices, such as the cost of copper, iron, steel and cement. The cost of turbines see a decrease since 2010 driven by the falling of commodity prices, increased supply chain competition and improvements in manufacturing process.

Another trend can observed in the wind industry over the past decade is the need for turbines with longer blades (proportionally larger rotors and higher hubs) which outputs greater energy, (Kumar *et al.*, 2016), and this trend demands lighter and slender turbine blades for the maximum energy yield. Traditionally, blades were made of glass fibre and polyester resin.(Serrano-González and Lacal-Arántegui, 2016), over the past few years manufactures started to integrate carbon fibres in the making of turbines to offer light, stiff and slender turbine blades that is required by the recent trend. The technology of carbon fibre blades is still in developing stage due to the high cost and difficulties in manufacturing process. (Serrano-González and Lacal-Arántegui, 2016). One of the reason for the shift towards larger turbines is because they liquidates project development cost over higher energy yield; however this sometimes contribute to higher economic cost (Fingersh *et al.*, 2006). In addition, the larger turbine blades is also a challenge for land transportation because of large turning radius. (Cotrell *et al.*, 2014)

Social barrier to onshore wind implementation not only within the UK had put constraint on the deployment of onshore wind technology. For example, Martindale wind farm (also known as high volts wind farm) constitutes of three wind turbines was put in place by EON energy, and this development had split the local community since 2003, with some accepting the turbines and others strongly opposing them. (BBC, 2014). One of the mitigation strategies offered by the wind farm hosts to soften the resistance is to set up community funds which can be used to support local community activities, such as replace roof of local churches and purchase of equipment for local football clubs etc.

There are approximately 270 wind farms installed in the UK. Factors such as regulatory restrictions on tip height, duration of the project and wind speeds are detrimental for selecting the suitable turbines for any location. Most of them are connected to the low voltage regional electricity networks as part of electricity distribution network (REF, 2015). Figure 5.1 below shows the location and installed capacity of wind farms throughout the region, using data extracted from UKWED (2018). Vast majority of the onshore wind installation in the Northeast region exists in forms of wind farms. The residential installations are not very common mainly due to the high investment and maintenance cost, difficulties with finding the ideal installation locations and limited wind resource in residential areas. Most of the turbines currently installed in the UK has rated power between 2-3MW. (WindEurope, 2018). This can be observed in table 5.1 where majority of the installations constitutes of turbines with rated power of 2MW and 2.05MW,the most popular models are Repower MM82, Vesta V80 and Sevenion MM92.There are only two wind farms opted for models with rated power less than 2MW, and one of them, high sharply wind farm is closed for retirement since December 2017 (Michaël.PIERROT, 2018)

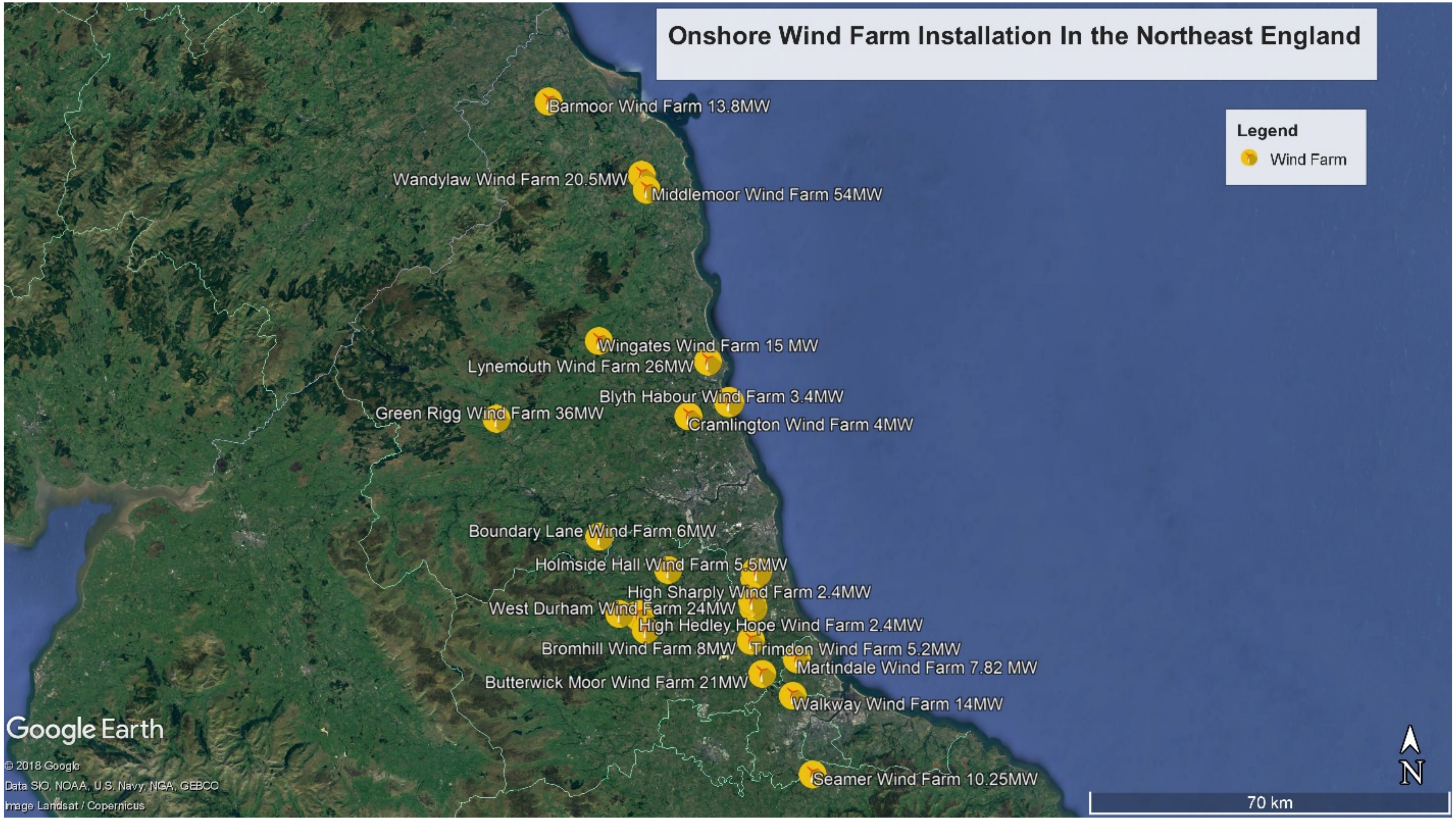


Figure 5.1 Map showing installation of wind farms within the Northeast region of England

Turbine Model	Installed Capacity	Installation Sites
Repower MM82	4*2MW	Broom Hill Wind Farm
	4*2MW	Langley Wind Farm
	5*2MW	Haswell Moor Wind Farm
	7*2 MW	Walkway Wind Farm
	4*2MW	Great Eppleton Wind Farm
	5*2MW	Seamer Wind Farm
	10*2 MW	Wandylaw Wind Farm
	12*2 MW	West Durham Wind Farm
Vesta V80	2*2MW	High Haswell Wind Farm
	2*2MW	Cramlington Wind Farm
	3*2MW	South Sharpley Wind Farm
	6*2MW	Barmoor Wind Farm
	18*2MW	Green Rigg Wind Farm
Gamesa G87	13*2MW	Lynemouth Wind Farm
Neg Micon NM80/2750	2*2.75MW	Holmside Hall Wind Farm
	3*2.75MW	Martindale Wind Farm
Nordex N90	6*2.5MW	Wingates Wind Farm
Vesta V90	18*3MW	Middlemoor Wind Farm
REpower M104	1*3.4MW	Blyth Harbour Wind Farm
Nordex N60/1300	2*1.3MW	High Sharpley Wind Farm
	4*1.3MW	Trimdon Wind Farm

Table 5.1 Installation of wind farms within the Northeast region of England

5.2 Assumption

Three wind turbine models are selected in this study: Repower MM82, Vesta V80, and Vesta V90; for that reason that MM82 and V80 are the most popular options within the region, and V90 is the model with rated power at 3MW with second highest installed capacity within the region. Figure 5.2 shows system boundary of the assessed technologies. Manufacture of a turbine including the production of the nacelle, tower and rotor; installation stage including construction of the foundation of the turbine, network connection and road building. Inventory data used for road buildings and grid connection for each assessed wind turbine model is scaled up of dataset provided by Garrett and Ronde (2011).Operation involves transportation to the site and the grease required for maintenance work. In the end of life stage all the materials constituted the turbine is assumed to be recycled at current recycling rate in the UK. The designed operational life-time of a turbine is assumed to be 20 years, this applies to all the parts and components of the plant. (IEC, 2005-08)

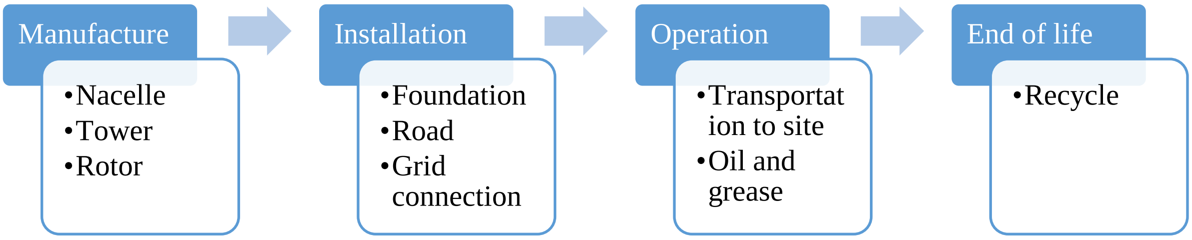


Figure 5.2 system boundaries of assessment on onshore wind turbines

5.2.1 Key techno-economic parameters

Table 5.2 displays key techno-economic parameters for wind technologies assessed in this study.

The availability factor, as defined by Vestas, is that “the percentage of a given period that a wind turbine is available for operation”(Conroy et al., 2011, p. 2969), the designed availability of a wind turbine is generally 98%; the operational availability is reduced by events such as scheduled and unscheduled maintenance, power system outages and control system faults.

Various tools for predicting a wind farm’s output had been developed (e.g. SCADA system, WaSP system are commonly used by renewable energy consultancies like Garrad Hassan), however data deployed in those analysis are not made publicly available. Therefore, in this study site specific data are used where possible to reveal the actual performance of wind energy within the region. Wind turbine performance data are obtained from Renewable Energy Foundation that is organised and corrected by G.Hughes (2012), as part his research on the wind turbine performance in the UK and Denmark. This dataset contains the actual output of each of the 282 recorded wind farms during the period of 2002-2012. Although not all wind farms are covered in the database, the data on following sites was able to be extracted for this study:

- High Haswell wind farm
- Haswell moor wind farm
- West Durham wind farm
- Langley wind farm
- Great Appleton wind farm

The performance data for Middlemoor wind farm is not available from this dataset, therefore the data for Aikengall wind farm is used instead, because these two wind farms are geographically adjacent to each other and shares similar wind resource. Capacity factors of each turbine model is then calculated from the dataset, which gives estimate to both annual and life-time electricity output.

Wind turbine investment cost can vary substantially, based on the turbine type, size of contract, location, region, commodity prices, demand and supply, as well as the level of subsidies (Blanco, 2009). Price of Vesta V80 and V90 are provided by the wind turbine manufacture Vesta, installation and operational costs are directly obtained as quota from local installation company the New Day Energy; the figures obtained are cross-checked to be in line with the onshore wind cost reviewed by (DECC, 2013) and FE (2013). Each wind farm can stay on the support of Renewable Obligation for 20 years, as mentioned in the methodology chapter the income generated through ROCs and exporting electricity to the amounts to £97.44/MWh.

	2MW Rated Power Turbines						3MW Rated Power Turbine		
	Vesta V80			Repower MM82			V90		
	Min	Average	Max	Min	Average	Max	Min	Average	Max
Hub Height (m)	60	63	77	59	63	80	65	78	85
Cut-in speed (m/s)	4			3.5			4		
Cut-out speed (m/s)	25			25			25		
Rated wind speed (m/s)	15			15			13		
Availability (%)	98%								
Capacity factor (%)	11%	26%	49%	9%	24%	47%	12%	33%	54%
Life time (years)	20								
Output per turbine per year(MWh)	1,927	4,555	8,585	1,577	4,205	8,234	2,102	5,782	9,461
Output per turbine lifetime (MWh)	38,544	91,104	171,696	31,536	84,096	164,688	42,048	115,632	189,216
Turbine cost (£/turbine)	2,000,000			/			3,000,000		
Installation cost(£/turbine)	500,000						725,000		
Annual O&M cost(£/turbine)	33,000						47,000		
Lifetime O&M cost(£/turbine)	660,000						940,000		
Levelised cost (£/MWh)	18	35	82				25	40	111

Table 5.2 Techno-economic parameters of assessed wind turbines

5.2.3 Environmental parameters

Table 5.3 shows the material consumptions for three assessed wind turbines, and table 5.4 shows the recoverable mass calculated based on the UK current material recycling rate. Despite turbine V90 has higher rated output power than MM82, it requires less material mass in total. Turbine MM82 has a heavier nacelle and rotor compare to the other Vesta models, and therefore it requires larger foundation proportionally, to support the machine weight.

Material use(t/system)			**Turbine models**		
			V80 (Hirschberg *et al.*, 2008)	**REpower MM82 (Guezuraga *et al.*, 2012)**	**V90 (Crawford, 2009)**
Manufacture	Rotor	Steel	11.0	20.0	19.9
		Glass fibre reinforced plastic	29.7	24.3	20.1
		Epoxy	0.0	1.8	8.0
	Nacelle	Steel	64.5	90.0	61.0
		Copper	1.0	2.4	4.0
		Aluminium	2.8	0.0	70.6
		Polyethylene	0.0	2.4	0.7
	Tower	Epoxy	0.6	8.1	0.0
		Steel	113.2	186.4	158.8
	sub-Total Mass		**182.0**	**335.4**	**343.1**
Installation	Foundation	Steel	80.0	80.0	36.0
		Concrete	1095.0	1164.0	1140.0
	Road	Gravel	147.0	147.0	147.0
		Sodium Chloride	2.3	2.3	2.3
	Network connection	Steel, low alloyed	8.8	8.8	9.2
		Copper	3.9	3.9	4.2
		Lead	7.6	7.6	8.0
		PVC	3.5	3.5	4.5
O&M	Lubricating oil	Lubricating oil	0.9	0.9	1.0
Total Mass			**1531.1**	**1753.5**	**1695.3**

Table 5.3 Material consumption for three assessed wind turbines

Recyclable material (t/system)		**Turbine models**		
		V80	**MM82**	**V90**
Rotor	Steel	5.70	10.42	10.36
	Glass fibre reinforced plastic	2.97	2.43	2.01
	Epoxy	0.00	0.00	0.00
Nacelle	Steel	33.52	46.80	31.72
	Copper	0.56	1.37	2.29
	Aluminium	2.73	0.00	67.80
	Polyethylene	0.00	0.00	0.00
Tower	Epoxy	0.00	0.00	0.00
	Steel	58.86	96.93	82.56
Material circularity (%)		**47%**	**47%**	**57%**

Table 5.4 Recoverable mass of three assessed wind turbines

5.2.4 Social parameters

Onshore wind has contributed 4.1% to the employment and 7.9% of the turnover of UK’s low carbon and renewable energy economy in 2016. (ONS, 2016) UK is one of the leading countries in the world in providing employment through wind energy, 40,000 employment opportunities was created in 2017 alone. (IRENA, 2018b)

In the year 2013, onshore wind contributed 700 employment to the Northeast region(DBEIS, 2015), and the total installed capacity for onshore wind in the region is 348.3MW (DBEIS, 2017b). The installation opportunity provided is 2 job/MW. Although there is no direct statistic data stating the O&M jobs created within the region through onshore wind projects, according to Cameron and van der Zwaan (2015) the O&M employment generated from onshore wind in the UK is 0.12 job/MW. Although majority of the manufacture job created is not located within the UK, it is 12.5 job/MW(Rutovitz and Atherton, 2009)

5.3 Result

The detailed assessment result is presented in table 5.8 in the end of the section; and the ranking of performances is listed in table 5.7.

5.3.1 Techno-economic performance

Capacity factor of three assessed turbines are shown in figure 5.3.Capacity factor and availability factor are closely linked; wind resource is abundant in the Northeast region of England where average wind speed (8-9m/s) already passed the cut-in speed for all turbines at just 45m above ground (DECC, 2012). The capacity factor is similar for all assessed turbines, where the average is 26% for the 2MW models and slightly higher at 33% for the 3MW model.

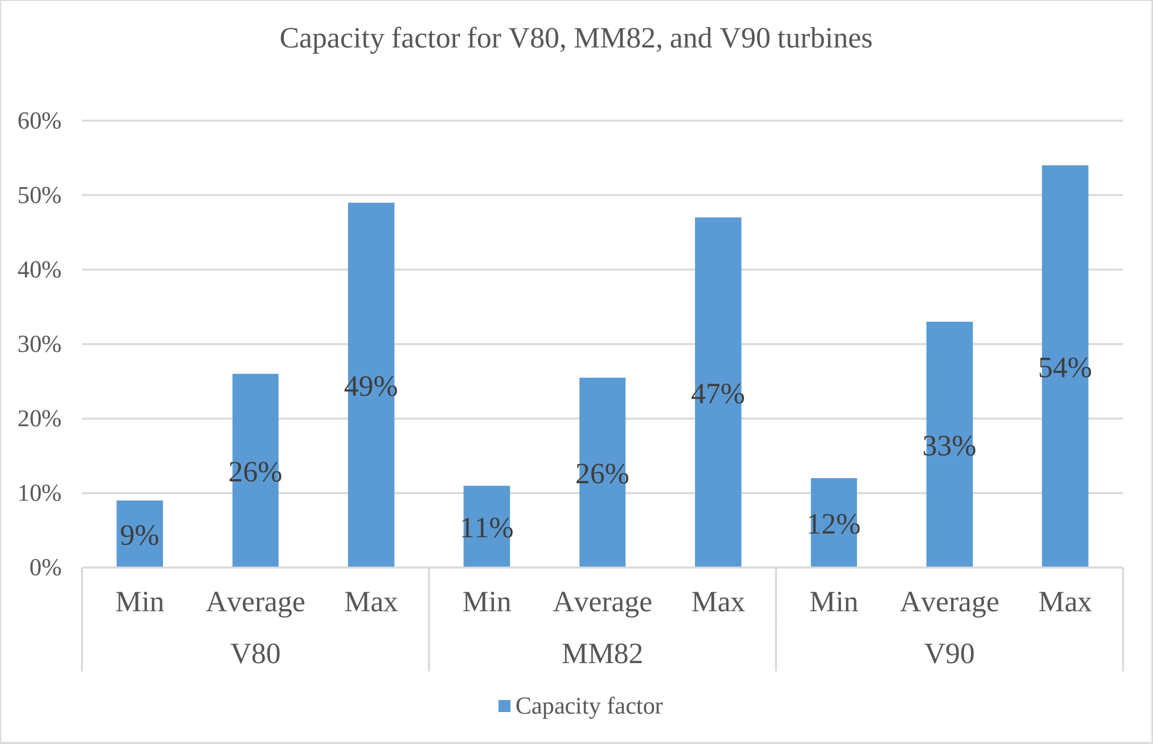


Figure 5.3 Capacity factor for three assessed wind turbines

Figure 5.4 shows the levelised cost for the three assessed wind turbines. Levelised cost for all assessed turbines range between £35-£40/MWh, is in line with data published by BEIS (2016). The levelised cost of V90 is only slightly higher than that of V80, the difference for average levelised cost is only £1/MWh.

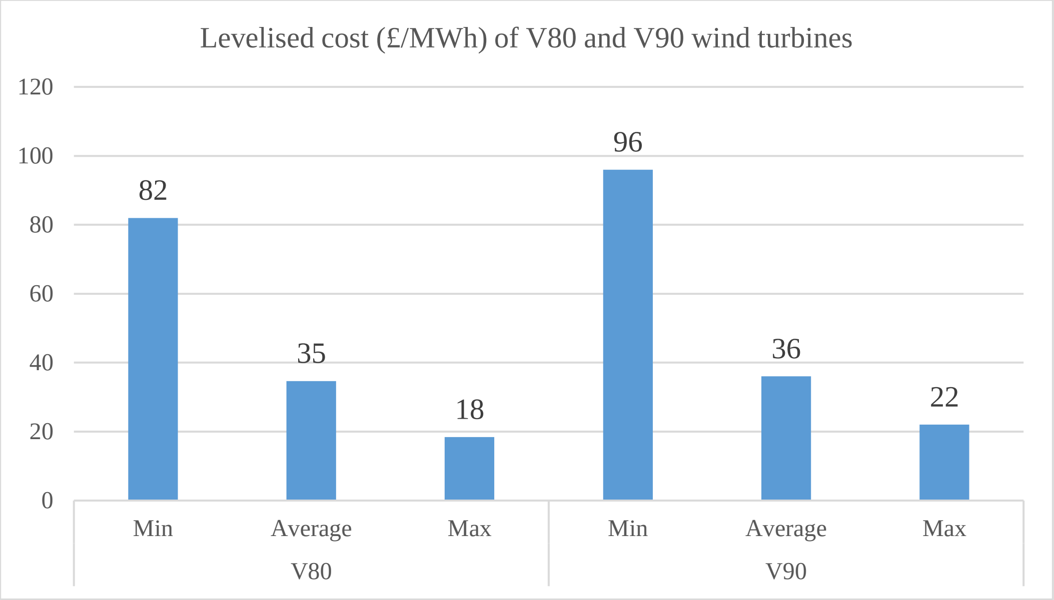


Figure 5.4 Levelised cost for three assessed wind turbines

5.3.2 Environmental performance

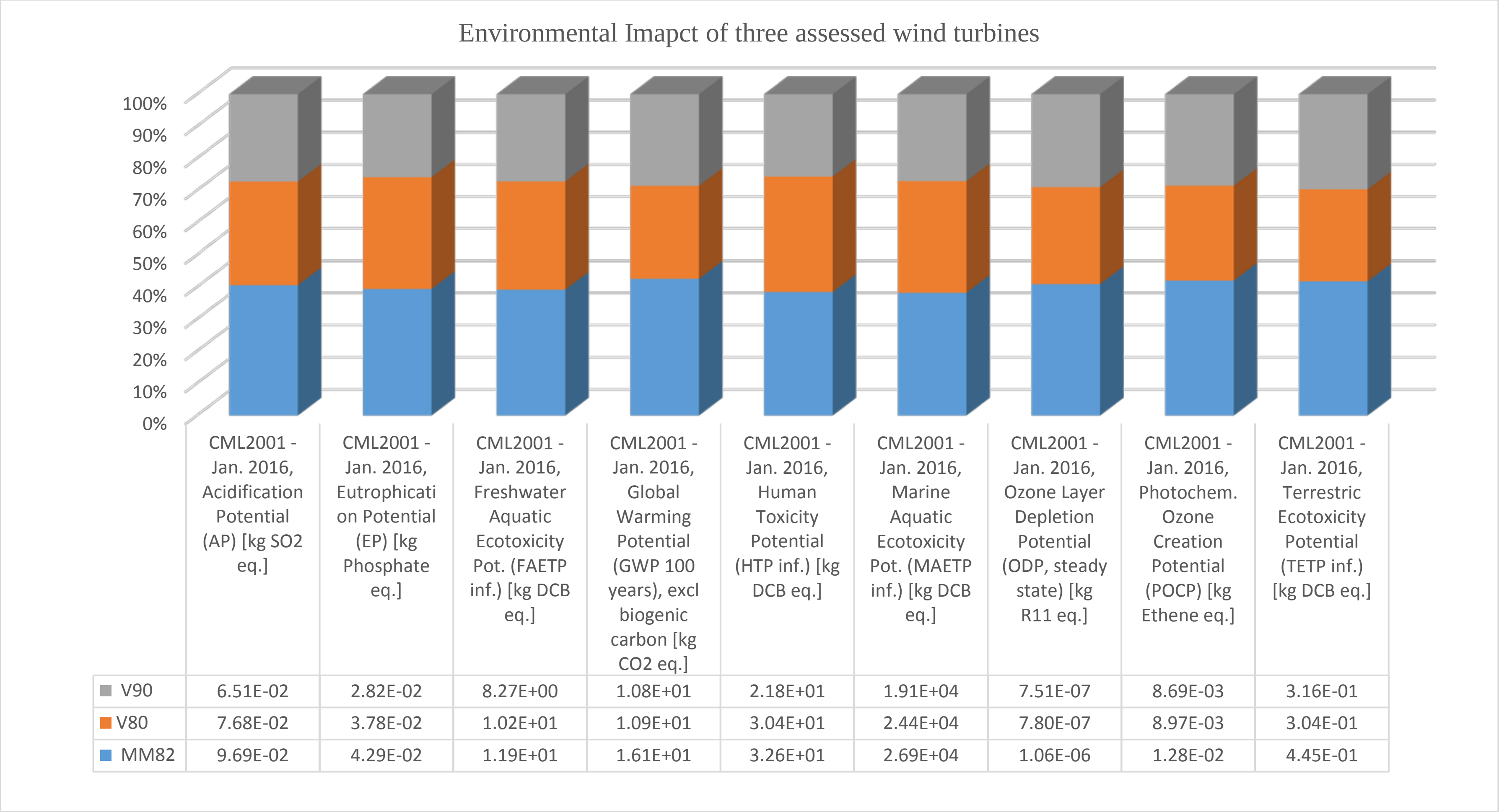
Figure5.5 shows the environmental impact of three assessed turbines, although the difference between different turbine models is not significant, turbine MM82 has the highest impact across almost all categories, this is due to the highest material consumption of this turbine (figure 5.6); and although model V90 consumes more material than V80, the total impact is discounted by highest energy yield. However, V90 has higher impact than MM82 in the terrestric ecotoxity potential, due to more copper used (figure 5.7-5.9).

Majority of the environmental impact occurred during manufacturing stage and installation stage (Figure 5.10-5.12), from the production of metal materials used in the turbine. Steel, the dominate metal used in wind turbines, has large environmental impacts, according to Allwood *et al.* (2012) 25% of the world's industrial CO_2 emission originates from steel production. Steel is generally extracted from iron ore and scrap electric steelmaking where raw materials are melted together then further purified through a refining vessel (Habashi, 1997; Norgate *et al.*, 2007). These manufacture processes requires large amount of heat which generally came from and the burning of fossil fuels releases greenhouse gases which then contributes to GWP. In addition, the metal production process also releases heavy metal and dust into the environmental, which then results in acidification, human, terrestric and freshwater toxicity. (Burchart-Korol, 2013)

Most of the wind farms locates in remote areas, therefore a combination of tarred roads and dirt roads need to be built to provide convenient access to the turbines. Observing figure5.13-5.15, the impact of road construction also plays significant part in the overall environmental performance. Table 5.6 shows the environmental impact of road construction. NMVOC in the table stands for non-methane volatile organic compounds, where the major source of this type of emission is use of solvent, combustion activities and production processes. (EEA, 2015) Non-biogenic NMVOCs contribute to the formation of tropospheric zone, altogether with the harmful chemical release into the water and soil causes damage to human and ecosystem health. (Marzouk *et al.*, 2017)

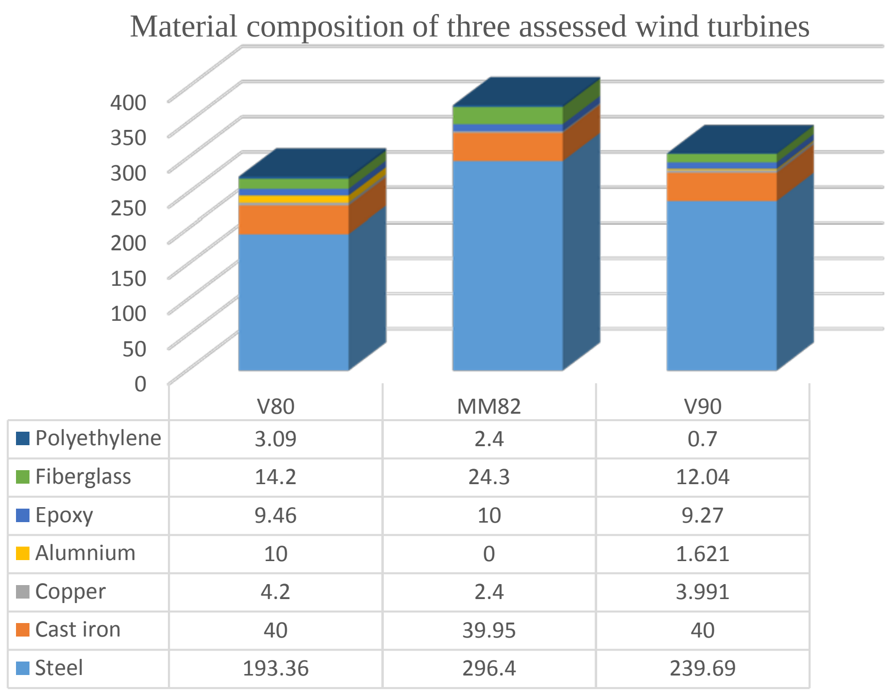
Blades of the turbine are mainly made of prepreg, a type of glass-fibre reinforced plastic where fabrics and fibres are pre-impregnated with epoxy resin and polyester thermosetting plastic under heat and pressure. (REpower, 2011; Vestas, 2013). Despite the lightweight of these materials, the energy consumed for producing these materials accounts for large proportion of the overall energy consumption.

There is no substantial difference between circularity of three assessed turbines, this can be explained by their similar material composition and same recycling rate applied for the materials. The average energy payback period for three turbines are all under one year, V90 has the best performance in this category due to its higher energy yield comparing to V80 and MM82. Under high wind condition, all turbines can break-even with the energy consumption within a quarter of the year.



	CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	CML2001 - Jan. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]
V90	6.51E-02	2.82E-02	8.27E+00	1.08E+01	2.18E+01	1.91E+04	7.51E-07	8.69E-03	3.16E-01
V80	7.68E-02	3.78E-02	1.02E+01	1.09E+01	3.04E+01	2.44E+04	7.80E-07	8.97E-03	3.04E-01
MM82	9.69E-02	4.29E-02	1.19E+01	1.61E+01	3.26E+01	2.69E+04	1.06E-06	1.28E-02	4.45E-01

Figure 5.5 Environmental impact assessment of three selected wind turbines



	V80	MM82	V90
Polyethylene	3.09	2.4	0.7
Fiberglass	14.2	24.3	12.04
Epoxy	9.46	10	9.27
Alumnium	10	0	1.621
Copper	4.2	2.4	3.991
Cast iron	40	39.95	40
Steel	193.36	296.4	239.69

Figure 5.6 Material composition of three selected wind turbines

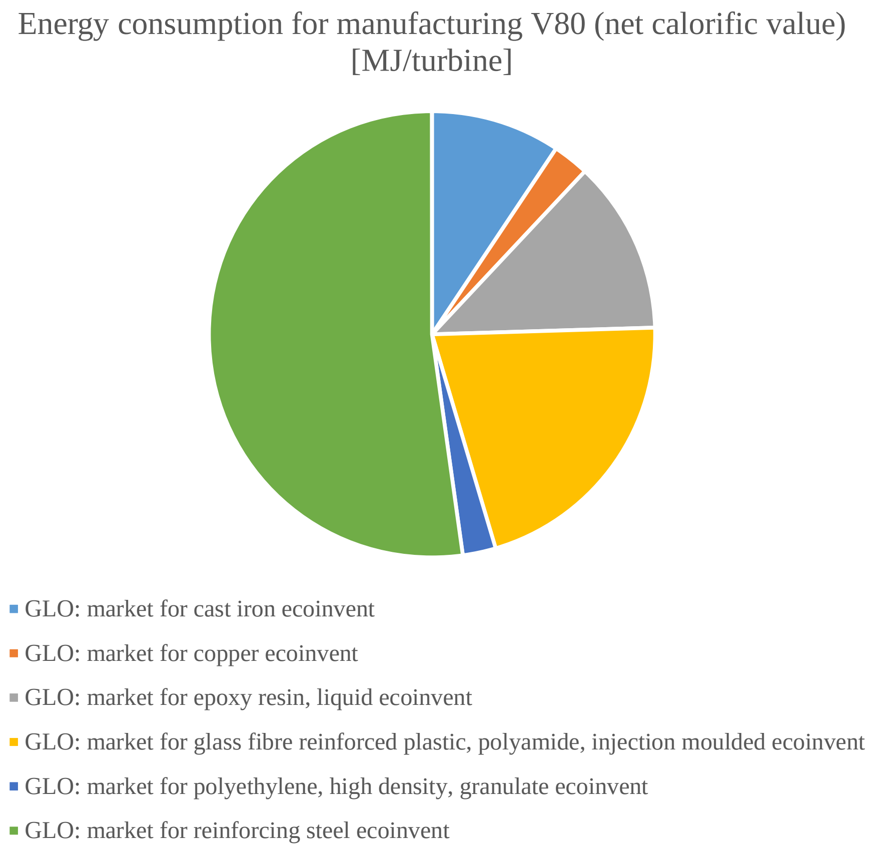


Figure 5.7 Energy consumption for manufacturing Vestas V80

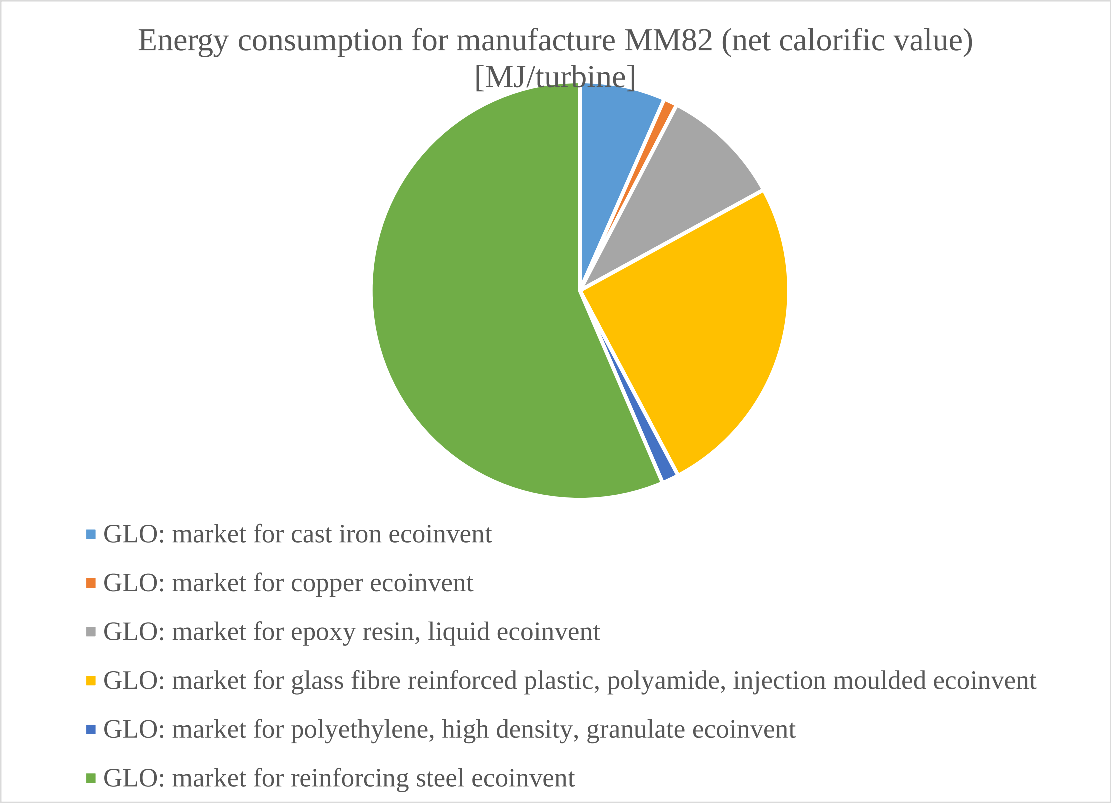


Figure 5.8 Energy consumption for manufacturing Repower MM82

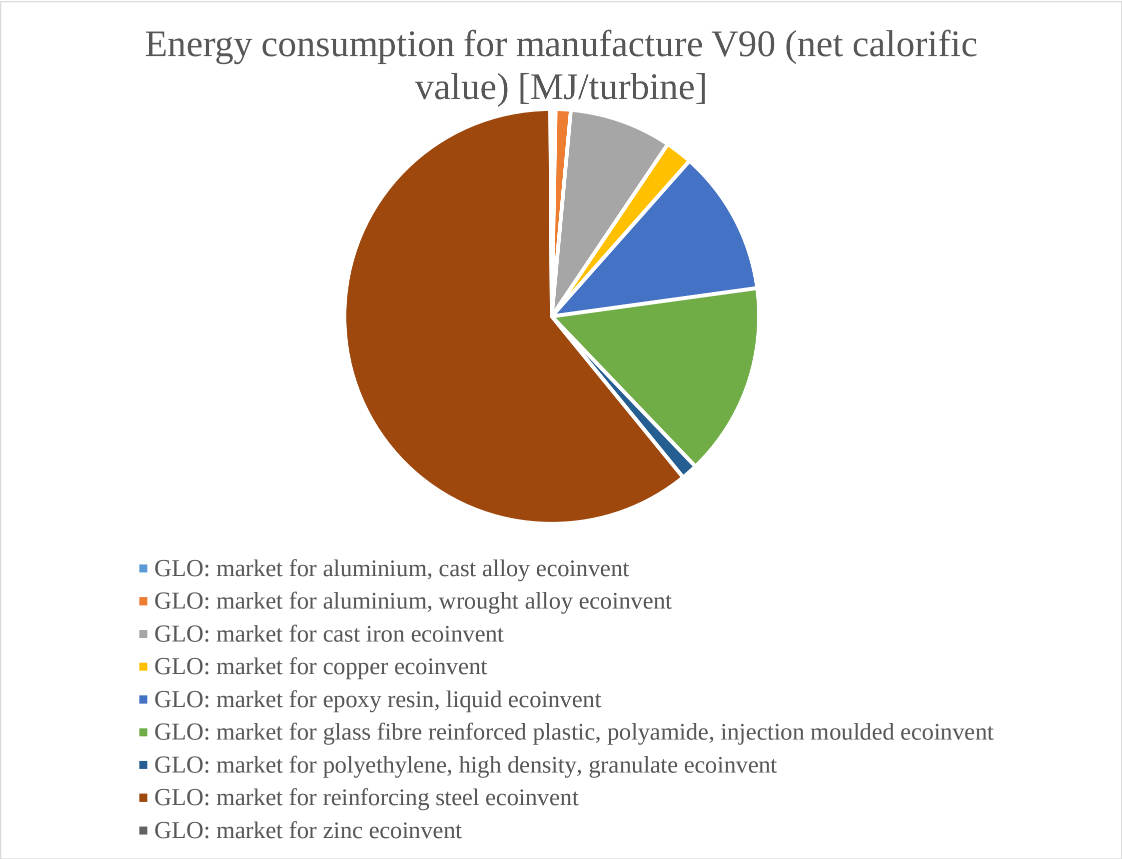
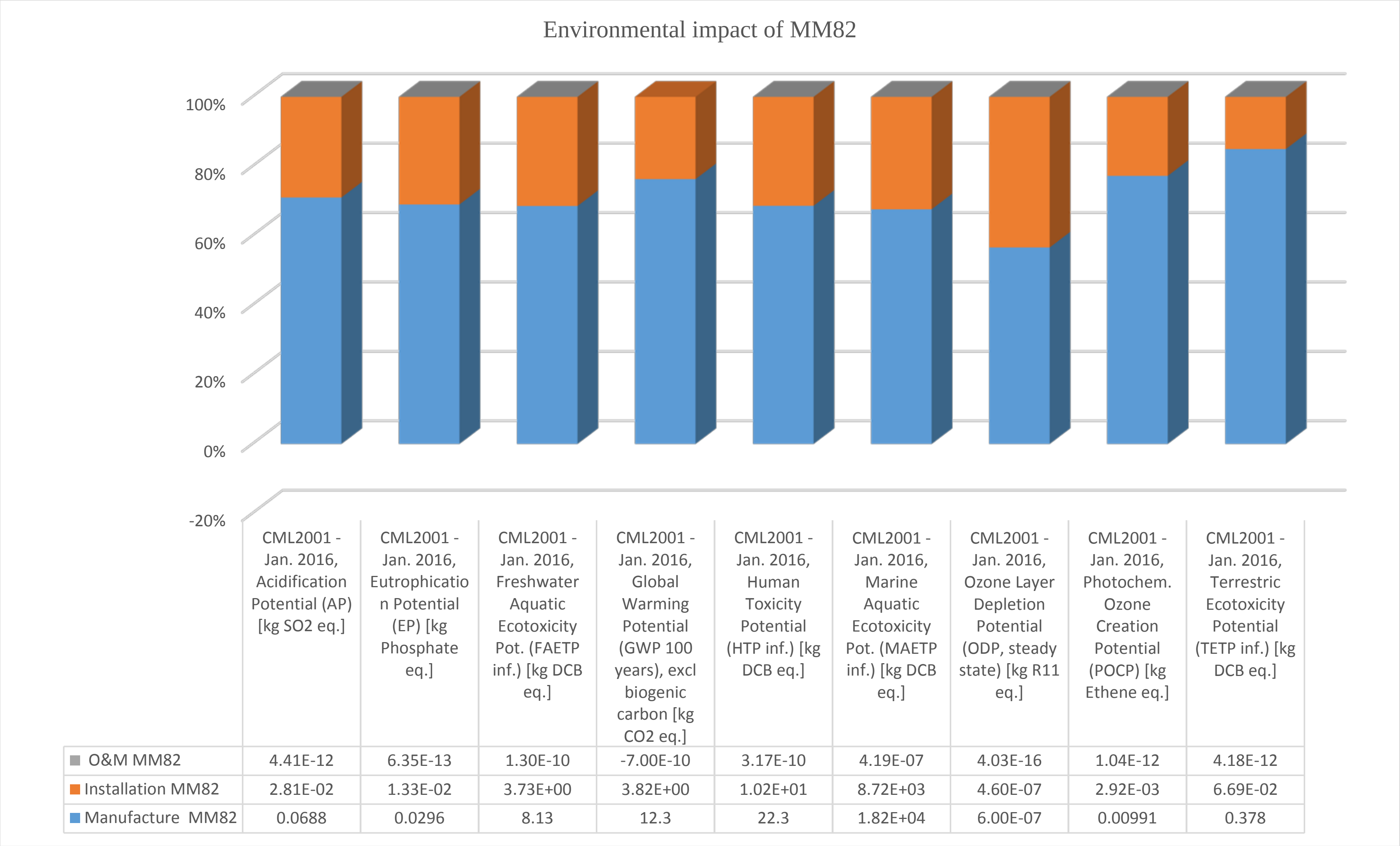
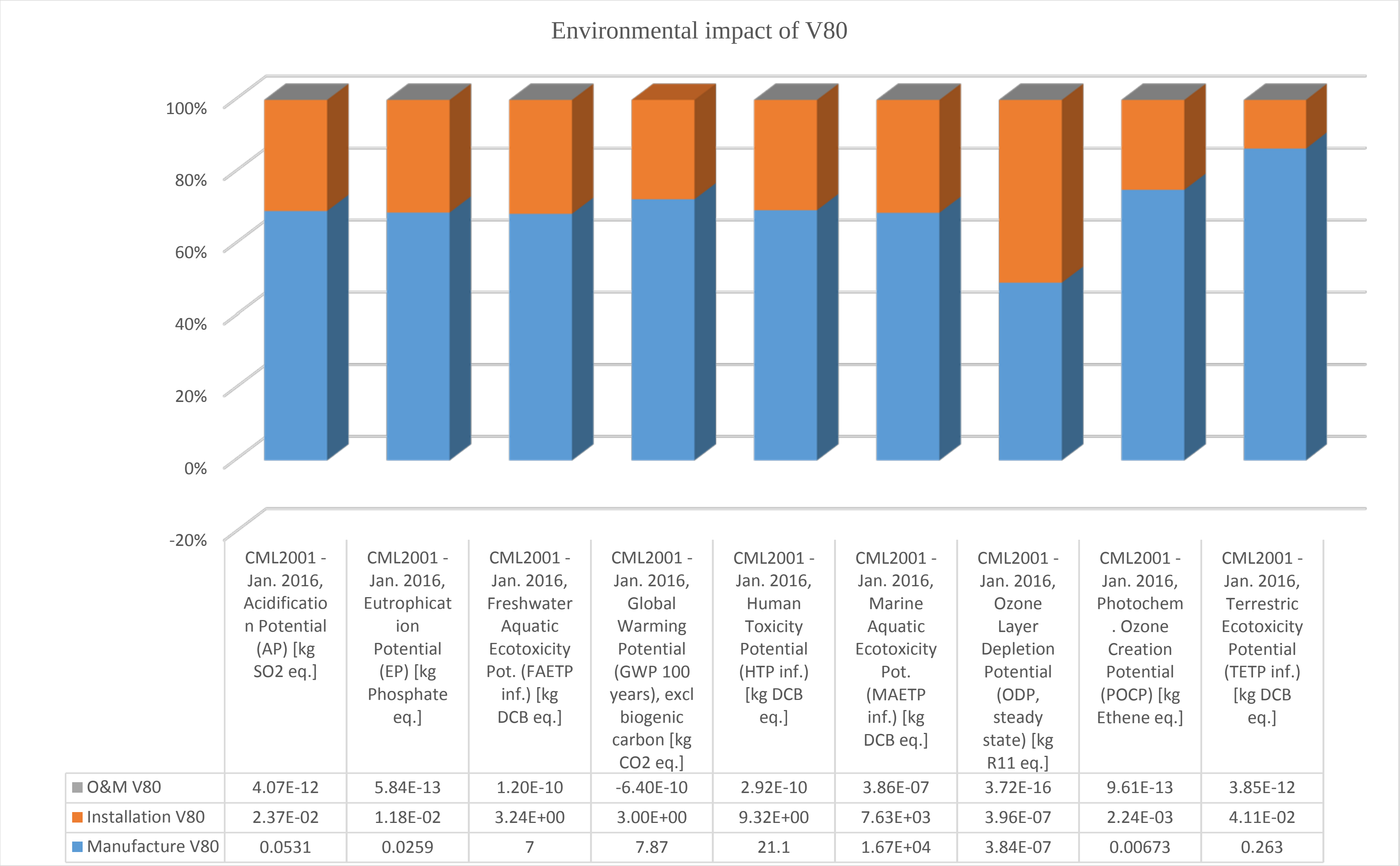


Figure 5.9 Energy consumption for manufacturing Vestas V90



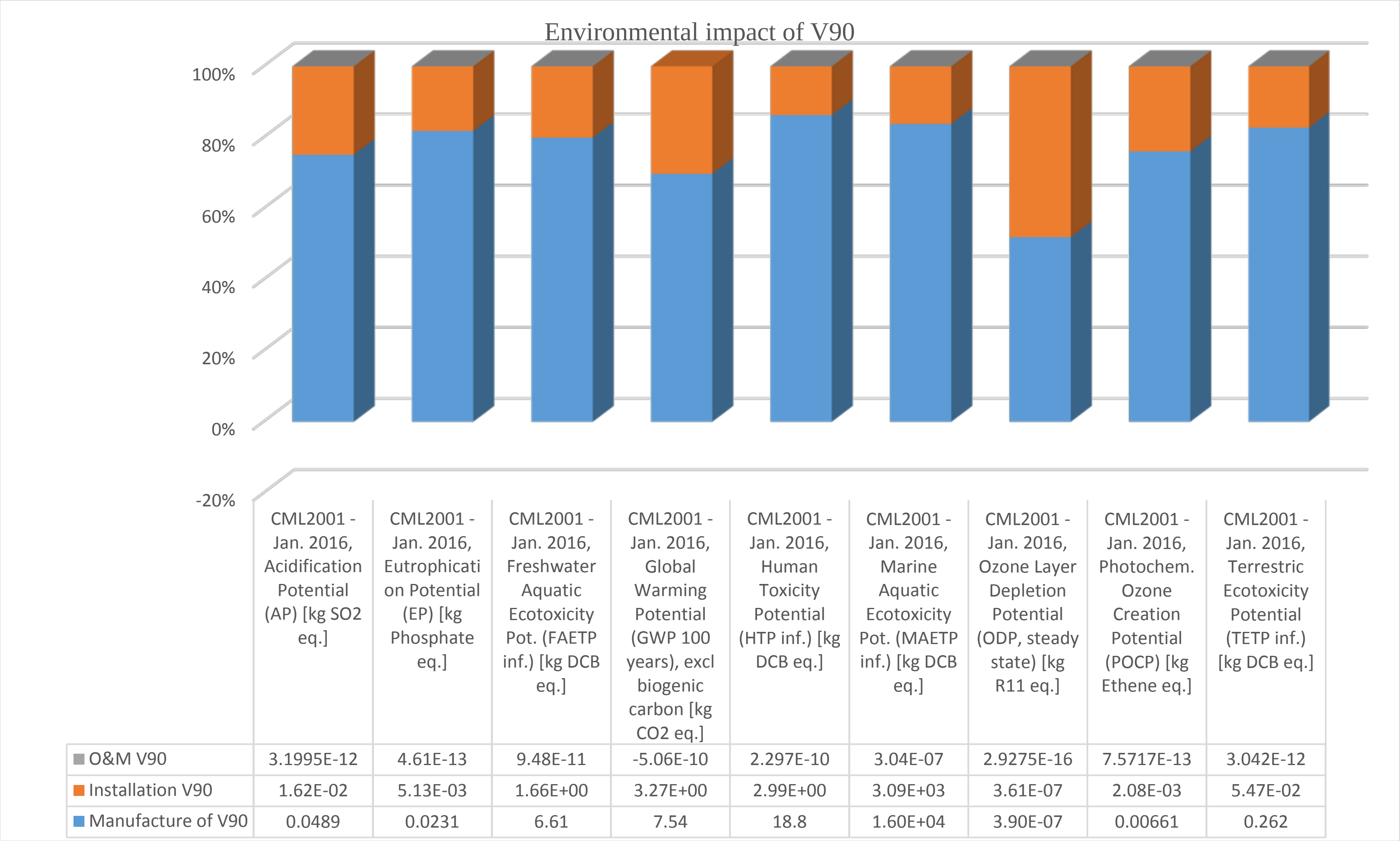
	CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	CML2001 - Jan. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]
■ O&M MM82	4.41E-12	6.35E-13	1.30E-10	-7.00E-10	3.17E-10	4.19E-07	4.03E-16	1.04E-12	4.18E-12
🟧 Installation MM82	2.81E-02	1.33E-02	3.73E+00	3.82E+00	1.02E+01	8.72E+03	4.60E-07	2.92E-03	6.69E-02
🟦 Manufacture MM82	0.0688	0.0296	8.13	12.3	22.3	1.82E+04	6.00E-07	0.00991	0.378

Figure 5.10 Environmental impact assessment of Repower MM82 at different life cycle stages



	CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	CML2001 - Jan. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]
■ O&M V80	4.07E-12	5.84E-13	1.20E-10	-6.40E-10	2.92E-10	3.86E-07	3.72E-16	9.61E-13	3.85E-12
■ Installation V80	2.37E-02	1.18E-02	3.24E+00	3.00E+00	9.32E+00	7.63E+03	3.96E-07	2.24E-03	4.11E-02
■ Manufacture V80	0.0531	0.0259	7	7.87	21.1	1.67E+04	3.84E-07	0.00673	0.263

Figure 5.11 Environmental impact assessment of Vestas V80 at different life cycle stages



	CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	CML2001 - Jan. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]
■ O&M V90	3.1995E-12	4.61E-13	9.48E-11	-5.06E-10	2.297E-10	3.04E-07	2.9275E-16	7.5717E-13	3.042E-12
■ Installation V90	1.62E-02	5.13E-03	1.66E+00	3.27E+00	2.99E+00	3.09E+03	3.61E-07	2.08E-03	5.47E-02
■ Manufacture of V90	0.0489	0.0231	6.61	7.54	18.8	1.60E+04	3.90E-07	0.00661	0.262

Figure 5.12 Environmental impact assessment of Vestas V90 at different life cycle stages

Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [Halogenated organic emissions to air]	3.05E-11
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Group PAH to air]	1.20E-07
Copper [Heavy metals to air]	2.50E-05
Chromium [Heavy metals to air]	1.85E-04
Lead [Heavy metals to air]	5.15E-04
Manganese [Heavy metals to air]	6.05E-04
Nitrogen oxides [Inorganic emissions to air]	1.25E-02
Dust (PM2.5) [Particles to air]	4.75E-02
Carbon monoxide [Inorganic emissions to air]	4.73E+00
Carbon dioxide [Inorganic emissions to air]	7.56E+01

Table 5.5 Emission per tonne of Steel production (kg/ton) (EcoinventCentre, 2017a)

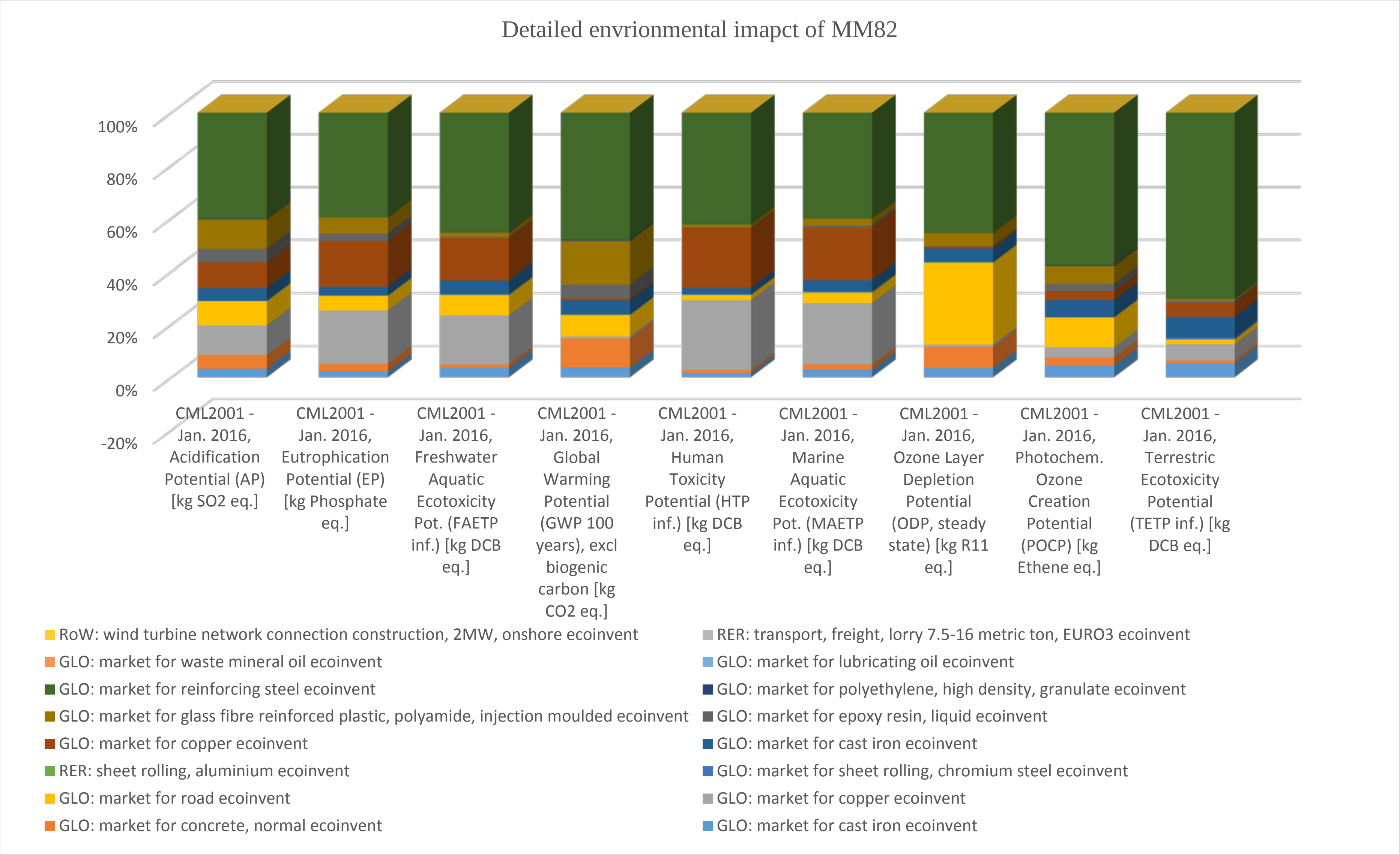


Figure 5.13 Environmental impact assessment of Repower MM82

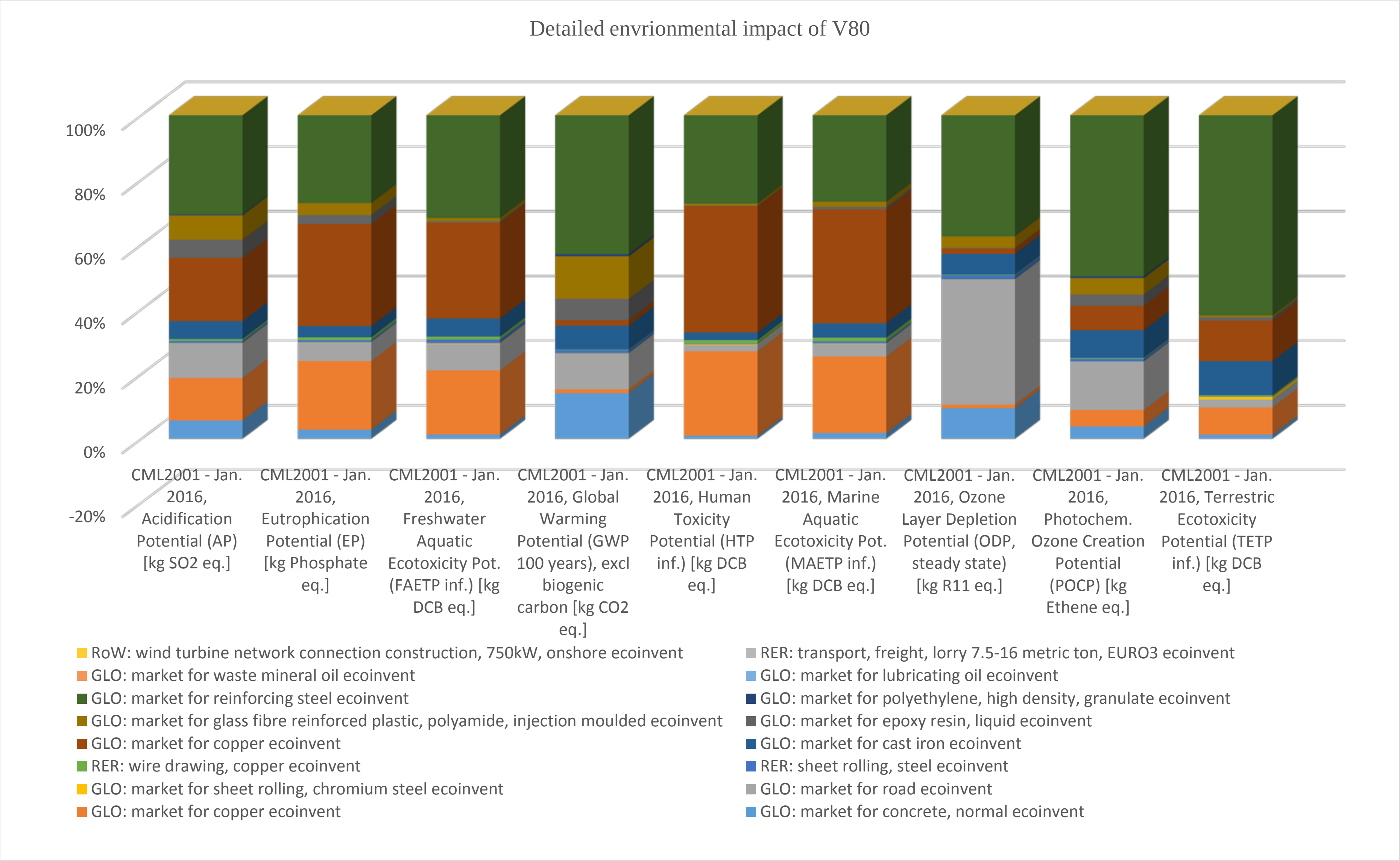


Figure 5.14 Environmental impact assessment of Vestas V80

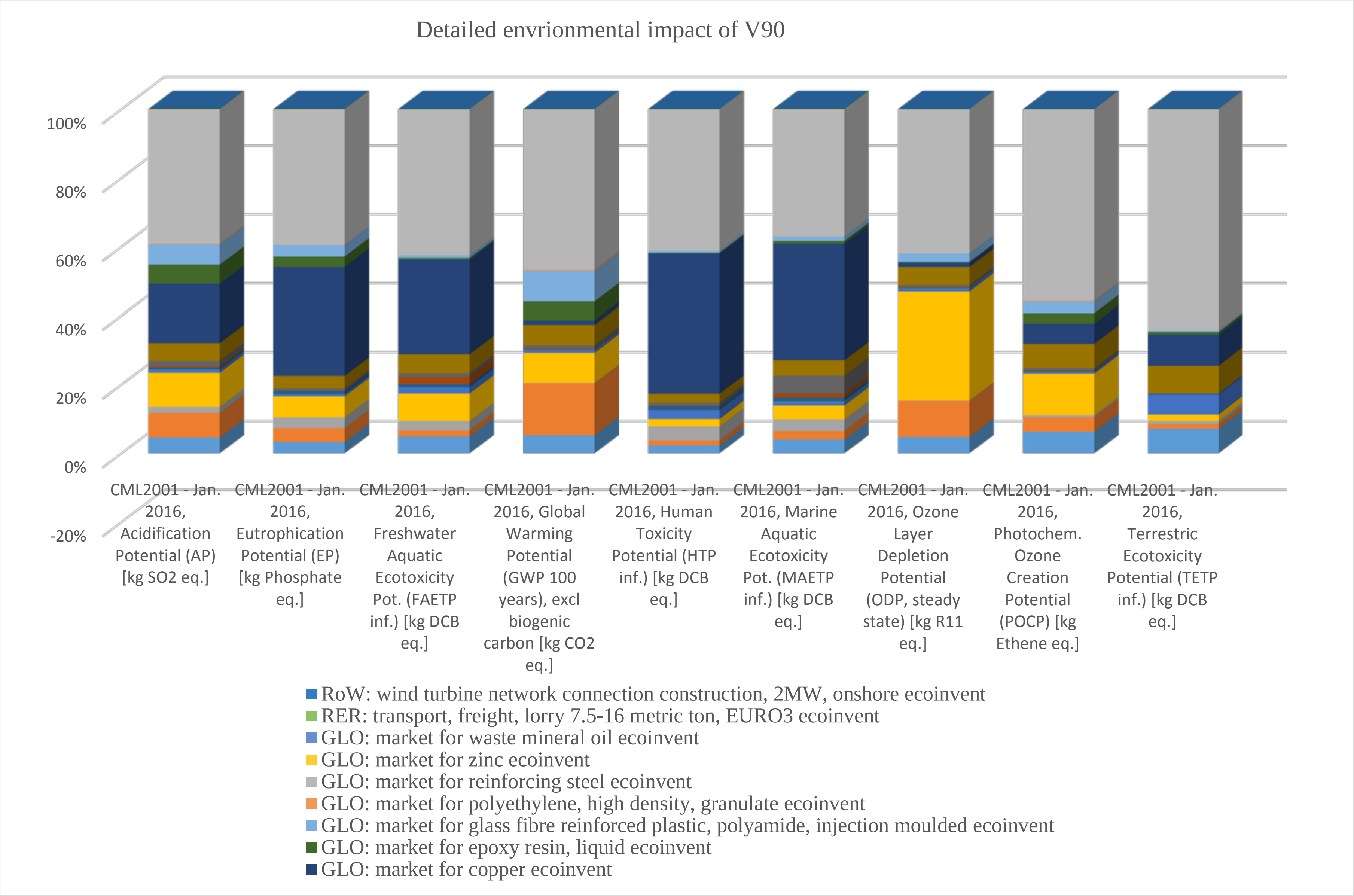


Figure 5.15 Environmental impact assessment of Vestas V90

1,1,1-Trichloroethane [Halogenated organic emissions to fresh water]	2.72E-18
1,1,1-Trichloroethane [Halogenated organic emissions to air]	4.37E-09
1-Butanol [Organic emissions to fresh water]	4.76E-08
1-Butanol [Group NMVOC to air]	2.52E-11
1-Pentanol [Organic emissions to fresh water]	5.58E-11
1-Pentanol [Group NMVOC to air]	2.32E-11
1-Pentene [Organic emissions to fresh water]	4.22E-11
1-Pentene [Group NMVOC to air]	7.29E-11
1-Propanol [Group NMVOC to air]	2.94E-10
2,4-Dichlorophenol [Halogenated organic emissions to air]	6.18E-11
2,4-Dichlorophenoxyacetic acid (2,4-D) [Pesticides to air]	4.27E-10
2,4-Dichlorophenoxyacetic acid (2,4-D) [Pesticides to agricultural soil]	1.43E-07
2-Aminopropanol [Organic emissions to fresh water]	2.35E-11
2-Aminopropanol [Group NMVOC to air]	9.76E-12
2-Chlorotoluene [Halogenated organic emissions to fresh water]	1.32E-10
2-Chlorotoluene [Halogenated organic emissions to air]	7.41E-11
2-Methyl-2-butene [Hydrocarbons to fresh water]	1.80E-11
2-Methyl-2-butene [Group NMVOC to air]	7.51E-12
2-Nitrobenzoic acid [Group NMVOC to air]	1.87E-11
3-Methylpentane [Group NMVOC to air]	5.21E-09
Acenaphthene [Hydrocarbons to sea water]	9.44E-11
Acenaphthene [Group NMVOC to air]	1.27E-10
Acenaphthene [Hydrocarbons to fresh water]	1.56E-09
Acenaphthylene [Hydrocarbons to sea water]	5.90E-12
Acenaphthylene [Group PAH to air]	1.12E-10
Acenaphthylene [Hydrocarbons to fresh water]	9.74E-11
Acephate [Pesticides to air]	4.54E-11
Acephate [Pesticides to agricultural soil]	3.13E-10
Acetaldehyde (Ethanal) [Organic emissions to fresh water]	1.64E-07
Acetaldehyde (Ethanal) [Group NMVOC to air]	2.50E-05
Acetamide [Pesticides to sea water]	1.12E-11

Table 5.6 Emission road construction (kg/meter annual) (EcoinventCentre, 2017a)

5.3.3 Social

Wind turbines do not directly contribute to bill reduction for the end consumers. A total of employment provision of 14.5job/MW can be achieved, where 0.12 job/MW is created at installation stage and majority 12.5job/MW is created during manufacture stage.

5.3.4 Summary of comparison

Table 4.7 below shows the performance ranking of three assessed wind turbines. It can be observed that turbine V90 has the best performance across all categories while V80 and MM82 shares the same score. V80 has slightly better performance in techno-economic category and MM82 better in environmental category. Although V90 is designed with higher output capacity, the levelised cost is slightly higher than that of V80, this is due to the higher cost associated with the V90 model, could also be explained by that since V90 is a newer model thus there is potential for the cost to be reduced further in the future.

			Assessed turbine models		
Sustainability issues		**Indicator**	**V80**	**MM82**	**V90**
Techno-economic Category	Reliability	Availability factor (%)	1	1	1
		Capacity factor (%)	3	2	1
	Cost	Levelised cost (£/MWh)	1	2	2
	Financial feasibility	Payback period	1	1	1
	Sub-total		**7**	**6**	**4**
Environmental Category	Material circularity	Circularity (%)	1	3	2
	Energy Payback	Energy payback period (years)	2	3	1
	Acidification Potential (AP)		2	3	1
	Eutrophication Potential (EP)		2	3	1
	Freshwater Aquatic Ecotoxity Pot. (FAETP inf.)		3	2	1
	Global Warming Potential (GWP 100 years)		2	3	1
	Human Toxicity Potential (HTP inf.)		3	2	1
	Marine Aquatic Ecotoxity Pot. (MAETP inf.)		3	2	1
	Ozone Layer Depletion Potential (ODP, steady state)		3	2	1
	Photochem. Ozone Creation Potential (POCP)		2	3	1
	Terrestric Ecotoxity Potential (TETP inf.)		3	1	2
	Sub-total		**26**	**27**	**13**
Social Category	Fuel poverty	Bill reduction rate	0	0	0
	Employment provision	Employment provision (job/MW)	1	1	1
	Sub-total		**1**	**1**	**1**
Grand Total			**34**	**34**	**18**

Table 5.7 Summarised sustainability ranking of assessed wind turbines

Sustainability issues		**Indicator**	**V80**			**MM82**			**V90**		
			Min	Average	Max	Min	Average	Max	Min	Average	Max
Techno-economic Category	Reliability	Availability factor (%)	98%								
		Capacity factor (%)	9%	26%	49%	11%	26%	47%	12%	33%	54%
	Dispatchability		24	24	24	24			24	24	24
	Cost	Levelised cost (£/MWh)	18	35	82				25	40	111
	Financial feasibility	Payback period	3	3.5	4	3	3.5	4	3	3.5	4
Environmental Category	Material circularity	Circularity (%)	62.6%			61.8%			62.1%		
	Energy Payback	Energy payback period (years)	0.31	0.58	1.37	0.46	0.89	2.38	0.33	0.54	1.48
	Acidification Potential (AP)		3.97E-02	7.49E-02	1.77E-01	4.05E-02	7.92E-02	2.11E-01	4.14E-02	6.77E-02	1.86E-01
	Eutrophication Potential (EP)		1.77E-02	3.33E-02	7.86E-02	1.82E-02	3.57E-02	9.51E-02	1.81E-02	2.96E-02	8.13E-02
	Freshwater Aquatic Ecotoxity Pot. (FAETP inf.)		7.10E+00	1.34E+01	3.16E+01	4.87E+00	9.54E+00	2.54E+01	5.09E+00	8.32E+00	2.29E+01
	Global Warming Potential (GWP 100 years)		6.46E+00	1.22E+01	2.88E+01	6.44E+00	1.26E+01	3.36E+01	6.93E+00	1.13E+01	3.12E+01
	Human Toxicity Potential (HTP inf.)		2.17E+01	4.09E+01	9.66E+01	1.38E+01	2.70E+01	7.21E+01	1.38E+01	2.26E+01	6.22E+01
	Marine Aquatic Ecotoxity Pot. (MAETP inf.)		1.40E+04	2.64E+04	6.23E+04	1.14E+04	2.23E+04	5.95E+04	1.15E+04	1.88E+04	5.18E+04
	Ozone Layer Depletion Potential (ODP, steady state)		4.66E-07	8.79E-07	2.08E-06	4.36E-07	8.53E-07	2.28E-06	4.65E-07	7.59E-07	2.09E-06
	Photochem. Ozone Creation Potential (POCP)		4.50E-03	8.49E-03	2.01E-02	4.90E-03	9.59E-03	2.56E-02	5.43E-03	8.88E-03	2.44E-02
	Terrestric Ecotoxity Potential (TETP inf.)		5.13E-01	9.67E-01	2.29E+00	1.59E-01	3.11E-01	8.28E-01	1.96E-01	3.20E-01	8.80E-01
Social Category	Fuel poverty	Bill reduction rate	n/a			n/a			n/a		
	Employment provision	Employment provision (job/MW)	14.62								

Table 5.8 Sustainability assessment results for three assessed wind turbines

5.4 Discussion

The assessed onshore wind technologies appeared well performed in all three categories. The availability factor is much higher than that of solar PV partially due to the advance of technology and also the abundant wind resource within the region. Capacity factor is less than 50% which is far from ideal. This means onshore wind can be considered as a suitable option for non-industrial areas or regions with high wind condition and low electricity demand, such as island of Orkney; it cannot offer sufficient supply for areas with high peak demand. The environmental impact is lower than that of solar PV, one of the reason being the impact is diluted by higher energy yield. Onshore wind is also more effective on employment provision compare to solar PV. Installation of onshore wind involves larger construction activities and the maintenance also requires workforce.

Although wind farm does not directly contribute to bill reduction, as stated in previous section, community funds are normally offered by the energy developers for spending on local projects. (Cowell et al., 2011) For example, a list of part of the community grants provided within the County Durham is shown in table 5.9. This provision of community benefits and payments to the communities as received attention from policy makers in recent years. The DECC (2014) published *Guidance on Community Benefits for Onshore Wind Developments: Best Practice Guidance for England*, which sets out the principles and best practice for designing and managing community benefits for wind developments in England. Disregard the argument that these community benefit flows constitute a compensation device for affected communities, (Armeni, 2016), it is evident that wind energy projects had presented additional opportunities to the local community(Munday *et al.*, 2011).

Name of grant	**Grant range**
High Hedley Hope II Wind Farm Community Benefits Fund	up to £1,000
Broom Hill Wind Farm Community Benefits Fund	up to £1,000
Langley Wind Farm Community Benefits Fund	up to £1,000
Boundary Lane Wind Farm Community Benefits Fund	up to £5,000
Trimdon Grange Wind Farm Community Benefits Fund	up to £2,000
Walkway Wind Farm Fund	up to £5,000
Butterwick Moor Wind Farm Community Benefits Fund	up to £5,000
West Durham Wind Farm Community Benefits Fund	up to £5,000

Table 5.9 A list of wind farm community fund within County Durham

5.4.1 Noise

Despite the benefit of wind energy had been well perceived and highly desired, large majority of the general public do not want have wind turbines locate near them, mainly for noise of operating turbines and their visual impact, as even as far as degrading the surrounding house price (Sims *et al.*, 2008; Kaldellis *et al.*, 2013; Mulvaney *et al.*, 2013; Tampakis *et al.*, 2013; Fokaides *et al.*, 2014), known as the “Not In My Backyard” (NIBY) syndrome. The general trend towards larger turbines is further stirring the public resistance of wind deployment(Lothian, 2008; Zografos and Martínez-Alier, 2009).

There are two types of noise generated by a turbine: mechanical noise, mainly from the gearbox and generator and aerodynamic noise; and aerodynamic noise, which mainly originates from the airflow around the turbine blade. (Pedersen and Persson Waye, 2004) Many claim that the aerodynamic noise is becoming a critical issue (Pedersen and Persson Waye, 2004; Bowdler and Leventhall, 2011) that the low frequency of this noise may cause annoyance to people who live nearby (Oerlemans *et al.*, 2007; Punch and Pabst, 2010) yet factual evidence is still lacking on this topic(Leung and Yang, 2012).

The noise level of a wind turbine normally ranges between 98-104Db(A) at wind speed of 8m/s; larger turbine such as V90 has noise level of 109Db (A) at 10m height(Vattenfall, 2013), which amount for approximately 40dB(A) for residence 500m away from the installations, and Waye and Öhrström (2002) argues that nose at such magnitude is equivalent to other source of community noise such as road traffic, which do not cause annoyance.(Pedersen *et al.*, 2010)

As a noise mitigation strategy, sometimes wind farm host will purchase properties near the wind farms and take them out of residential use except for short-term lets. (Vattenfall, 2013) In addition, noise reduction equipment had been made commercially available by companies such as Svenborg Brakes to reduce the noise impact.

5.4.2 Visual impact

Although a number of assessment method had been developed to examine the visual impact of wind turbines, such as Quechee Test(Owens, 2003), the Spanish Method (Tsoutsos et al., 2006), the Visualisation tool (Miller et al., 2005), perceptions modelling(Ladenburg, 2009) etc., the visual impact is difficult to measure, mainly because it is subject to personal perceptions(Bishop, 2002). Despite surveys convey that more than 70% in the UK do not opposite the installation of wind turbines for their visual impacts, some still believe that wind turbines can damage local tourism (Gourlay, 2008)

5.4.3Impact on wildlife

There had also been discussions surrounding the impact of wind turbines on wildlife, particularly bats (Barrios and Rodriguez, 2004; Bull et al., 2013; Premalatha et al., 2014); however these researches are also subject to uncertainties, e.g. whether the impact of scavenger removal is considered (Drewitt and Langston, 2006). Also, it is argued that the quantity of bird killed by predators than wind turbines; as suggested by MacKay (2008) there are more birds killed by cat than wind turbines. In mountainous regions, wind farms have been installed along mountain passes and other areas having high wind potential, and many of these locations also serve as key migratory routes for various species of birds. In some cases, collision-related mortality can result in population level effects on certain high-incidence bird species (Drewitt & Langston, 2008). Various site-specific mitigation and avoidance measures have been implemented, including modifications to turbine heights, spacing, and positioning. In the case of offshore wind power, interference with marine navigation, loss of benthic biota, and interference with cultural and visual resources (USACE, 2006) are further risks are implementation.

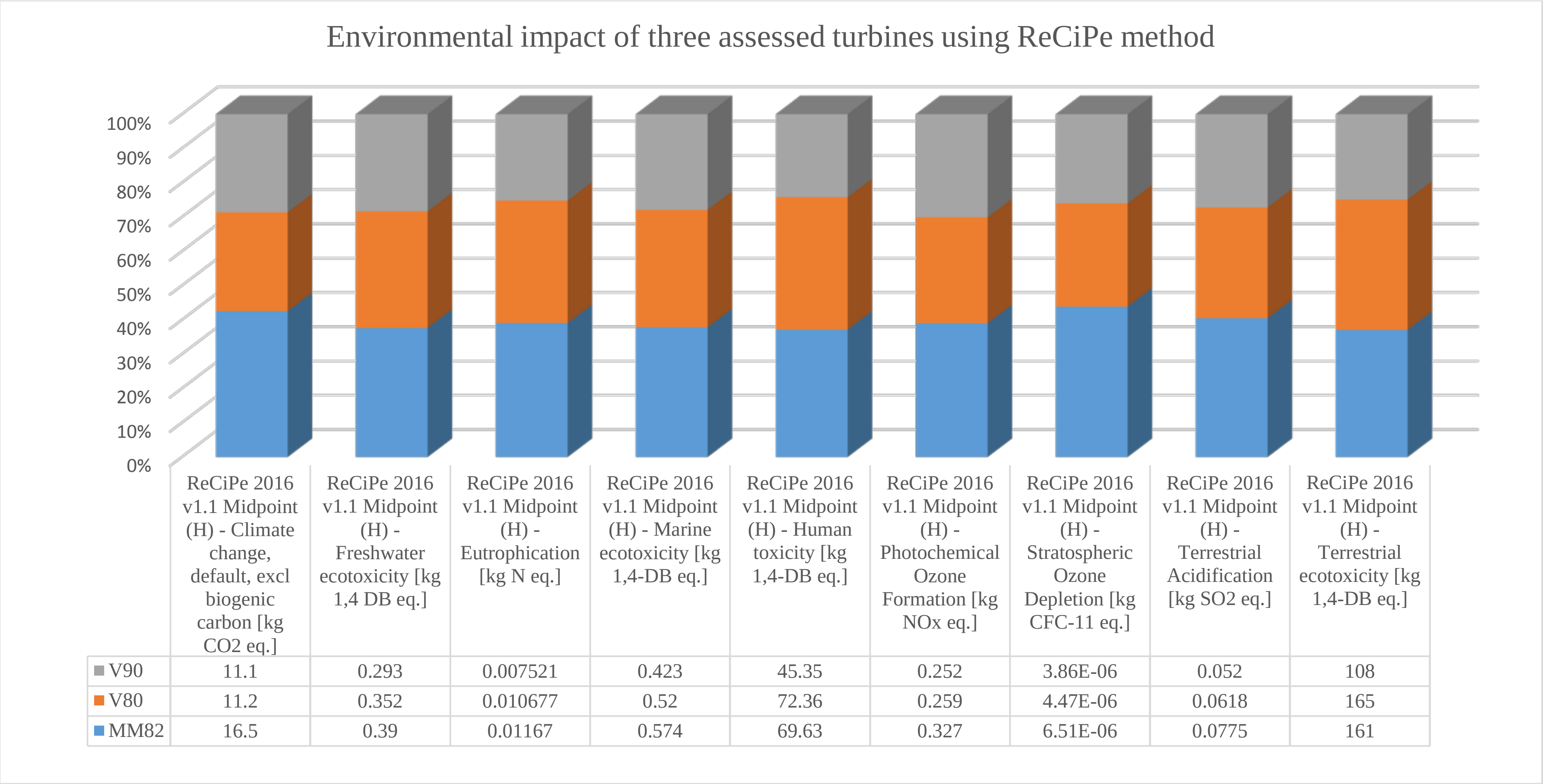
5.4.4 Radio interference

The operation of wind turbine causes electromagnetic interference which disturbs the transmission of radio when signals passing through the moving blades(Binopoulos and Haviaropoulos, 2006), the interference on air surveillance radar(Poupart, 2003; Tognolatti and Orlandi, 2008), weather radar(Vogt, 2011) and military radar(Kent *et al.*, 2008) had been investigated. Wind turbine manufactures had made effort to increase the use of synthetic materials and great deal of research had been done to look into the stealth turbine technology which applies radar cross section reduction techniques in designing the nacelle and blades to allow the co-existence of wind turbines and radars. For example, the QinetiQ used the Stealth Wind Turbine (SWT) technology in an EDF wind farm Perpignan, south France, had been proved to mitigate the impact on a nearby weather radar. However, the cost associated with the technologies is still high at the moment. (Kong *et al.*, 2013)

5.4.5 Sensitivity analysis

Figure 4.17 below demonstrates the environmental impact of three assessed turbines using ReCiPe method, the results is almost identical to that using the CML method, that V90 model has the lowest impact and MM82 has the highest impact across all categories; except in terrestric ecotoxiciy potential category, where V80 scores higher than MM82 using the ReCiPe method. Figure 5.16-5.18 below demonstrates the comparison of terrestric ecotoxity potential using both CML and ReCiPe methods for V80 and MM82 turbines. A noticeable difference can be spot in the impact of copper; where in ReCiPe method, the same mass of copper are given higher terrestrial ecotoxity character compare to the CML method; and since turbine V80 uses more copper than MM82 (figure material composition), the terrestrial ecotoxity potential for V80 became higher using ReCiPe method.

A new set of ranking scores is established using the result obtained from ReCiPe method as shown in table 5.10. It can be concluded that despite the difference in impact characterisation of copper, the total ranking for environmental impact remains the same using ReCiPe method.



	ReCiPe 2016 v1.1 Midpoint (H) - Climate change, default, excl biogenic carbon [kg CO2 eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Freshwater ecotoxicity [kg 1,4 DB eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Eutrophication [kg N eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Marine ecotoxicity [kg 1,4-DB eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Human toxicity [kg 1,4-DB eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Photochemical Ozone Formation [kg NOx eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Stratospheric Ozone Depletion [kg CFC-11 eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Terrestrial Acidification [kg SO2 eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Terrestrial ecotoxicity [kg 1,4-DB eq.]
■ V90	11.1	0.293	0.007521	0.423	45.35	0.252	3.86E-06	0.052	108
■ V80	11.2	0.352	0.010677	0.52	72.36	0.259	4.47E-06	0.0618	165
■ MM82	16.5	0.39	0.01167	0.574	69.63	0.327	6.51E-06	0.0775	161

Figure 5.16 Environmental impact of three assessed turbines using ReCiPe method

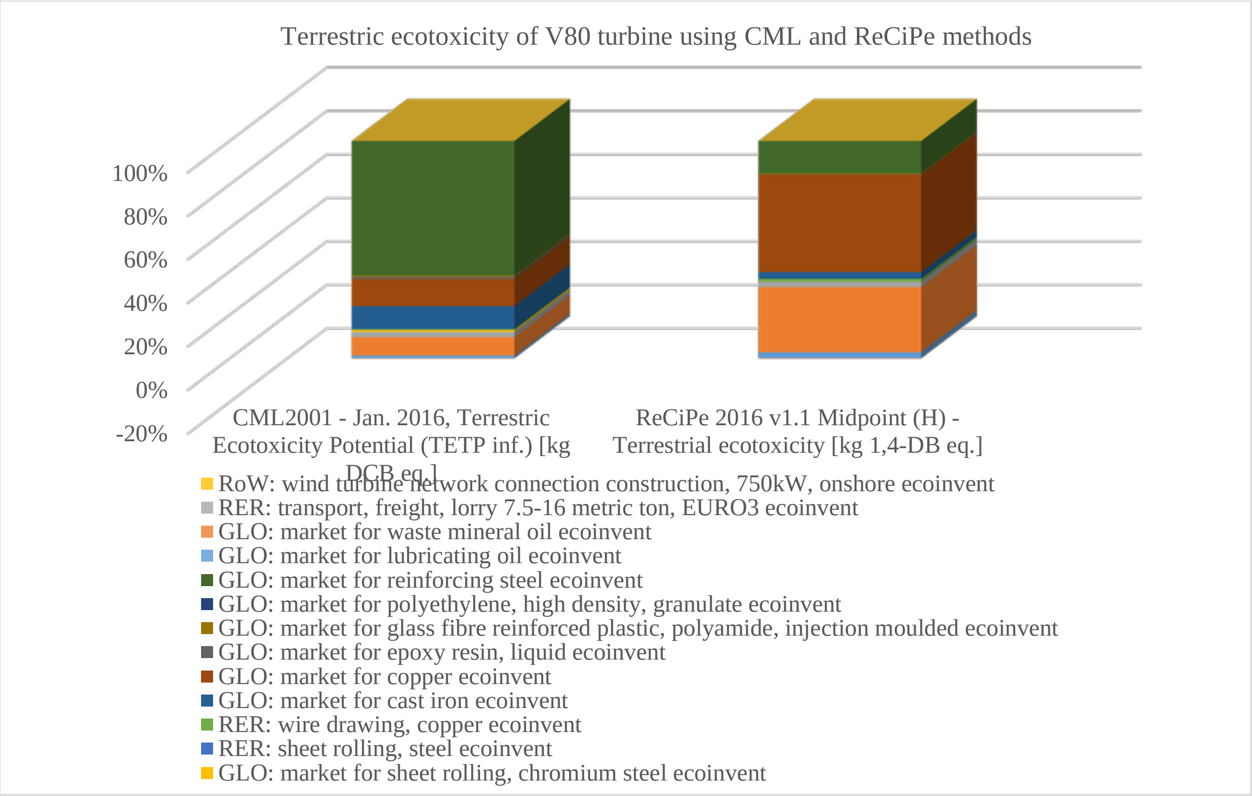


Figure 5.17 Comparison of terrestric ecotoxiciy of Vestas V80 turbine using CML and ReCiPe methods

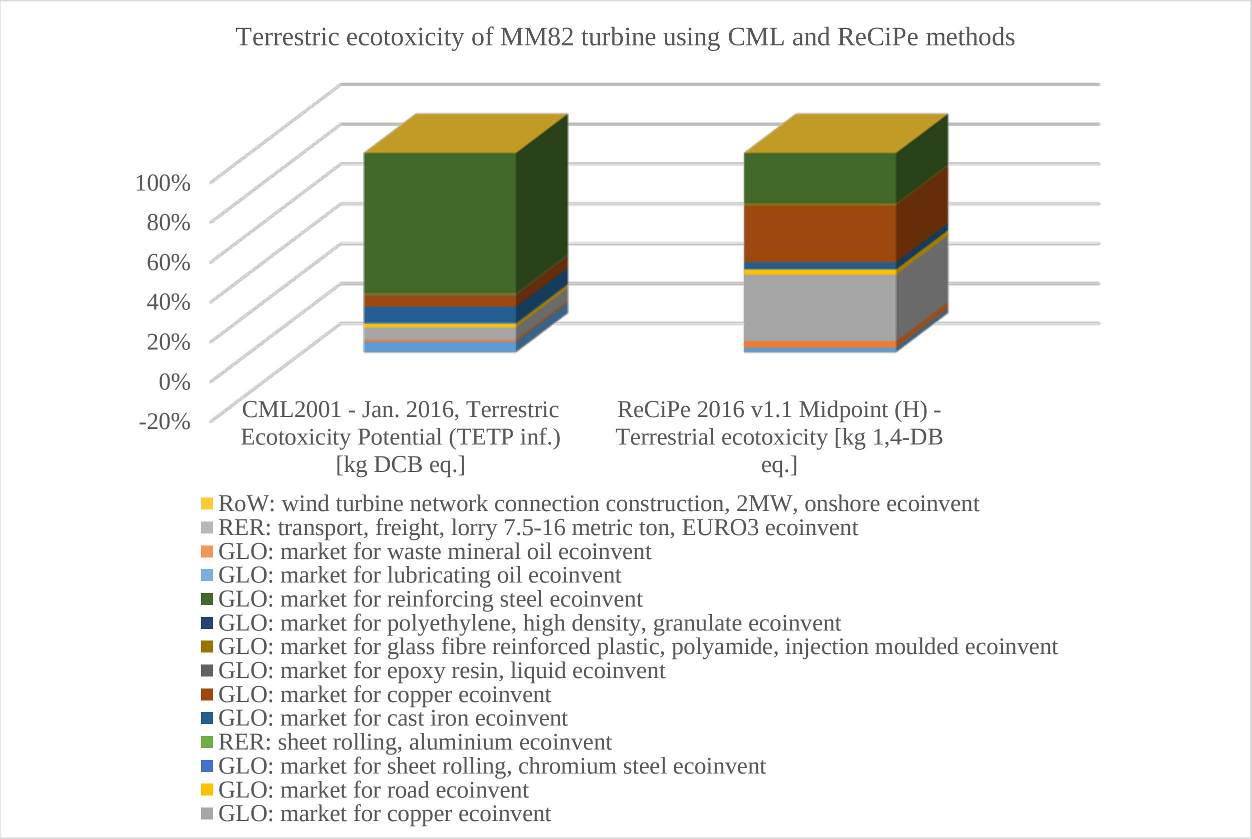


Figure 5.18 Comparison of terrestric ecotoxiciy of Repower MM82 turbine using CML and ReCiPe methods

`	**V80**	**MM82**	**V90**
Acidification Potential (AP)	2	3	1
Eutrophication Potential (EP)	2	3	1
Freshwater Aquatic Ecotoxity Pot. (FAETP inf.)	2	3	1
Global Warming Potential (GWP 100 years)	2	3	1
Human Toxicity Potential (HTP inf.)	3	2	1
Marine Aquatic Ecotoxity Pot. (MAETP inf.)	2	3	1
Ozone Layer Depletion Potential (ODP, steady state)	2	3	1
Photochem. Ozone Creation Potential (POCP)	2	3	1
Terrestric Ecotoxity Potential (TETP inf.)	3	2	1
Total score	**20**	**25**	**9**

Table 5.10 Ranking of environmental impacts of three assessed turbines using ReCiPe method

5.4.6 End of life

The large scale deployment of wind technology is still relatively new, only 12% of installed wind turbines in Europe reached 15 years of life time by 2016, 19 onshore wind farms within the UK had exceed 20 years of operational life, (Rubert *et al.*, 2016; Ziegler *et al.*, 2018) therefore no common practice have been established in this field and very little research have been carried out analysing the economics of end of life decision for wind turbines.(Ortegon *et al.*, 2013).

At present, the most common practice are repower and decommission. For repowering, a series of test will be carried out and the turbines of little repower value or ability will be removed and replaced with upgraded turbine, the wind farm will continue its service. Repowering offers advantages of higher efficiency, potential reduction in the number of turbines and lower operational cost. For decommissioning option, all the structures both above and underneath the ground will be completely removed, the topsoil of the land will be replaced and the area will be revegetated, then another two-years of remediation and monitoring programme will be carried out in the area till the land is recovered to its original state. (MDEP, 2010)

The retired turbines in most cases will be either remanufactured or recycled. Remanufacture is a process that a turbine will be refurbished and recovered to the performance of the original equipment manufacturer specifications. Although remanufacture and refurbish wind turbines are less than prevalent in the UK, it had been a growing business across the world over the past few years. (CRR, 2017). The original equipment manufacturers had been keen to remanufacture their products not only motivated by the profit this process brought, also because of high demand for spare parts during the warranty period, the brand and technology protection from independent operators.(Seitz, 2007). In addition, many retired turbines were had very little tear and wear; for example in the case of Germany, under the encouragement of government energy policy, many turbines were installed in the past decade regardless of wind resource of the installed location; as a result, many turbines that were installed in low wind areas hadn't been through intensive wear and tear and those can be sold as second hand turbine straight away without having to be refurbished. For example, as quoted by energy service company Solvento[11], a Vestas V80 made in 2002 located in the Northern Germany can be sold for £230,000; and a Vestas V90 first installed in 2008 has resale value of £650,000.

Moreover, lately there had been discussion on lifetime extension of the turbines where the turbines structural life will be examined and maintained to extend its service life to a longer period (DNV.GL, 2016; MEGAVIND, 2016; Ziegler *et al.*, 2018). In cases where a turbine has sufficient life to serve without compromising its safety level, extend an aging turbine may translate into higher maintenance costs.

Other than the technical and economic aspects, legal aspect is also detrimental for end of life decisions. For example, changes in legislation may outlaw the possibilities of having wind turbines installed within a given region; also since the contract and land lease expiries too, whether the end of life option is lifetime extension or repowering, it can only be made possible if the land owner agrees to further contract.

Finally, recycle provides a least economically attractive but feasible end of life solution for wind turbines; the global demand of metal materials such as steel, aluminium, iron keeps recycling as the last resort for turbine end of life options (Vestas, 2012)

5.4.7 Data quality assessment

Table 5.11 shows the results of data quality assessment for onshore wind technology. The overall score is 91%, higher than that of solar PV (88%), indicating that although uncertainties can be introduced by the 13% loss of data quality, yet it is considered to be good for the purpose of this study. The weakest area is once again the social category. The employment data was generic statistic data provided in existing literature, which although is sufficient for the purpose but the accuracy can be improved by adoption of field collected data. The techno economic category has the best data quality due to the results were obtained using actual performance data. Overall, the data quality used for assessing the sustainability of onshore

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[11] Solvento energy consulting gmbh, An Austria based energy consulting company specialise in onshore wind energy.

wind is considered to be good, recommendation for future work can include:

1. Adoption of primary data on employment provision;
2. Further information on funding and grants received for the onshore wind projects to increase the accuracy of cost estimation;
3. Including data on new built wind farms to have an updated view on the performance of onshore wind technology.

Sustainability issues		**Indicator**	Normalised total
Techno-economic Category	Reliability	Availability factor	1.00
		Capacity factor	1.00
	Dispatchability		1.00
	Cost	Levelised cost	0.94
	Financial feasibility	Payback period	0.94
Environmental Category	Circularity	Material circularity	0.78
		Fuel circularity	1.00
	Energy Payback	Energy payback period	0.78
	Acidification Potential (AP)		0.89
	Eutrophication Potential (EP)		0.89
	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)		0.89
	Global Warming Potential (GWP 100 years)		0.89
	Human Toxicity Potential (HTP inf.)		0.89
	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)		0.89
	Ozone Layer Depletion Potential (ODP, steady state)		0.89
	Photochem. Ozone Creation Potential (POCP)		0.89
	Terrestric Ecotoxicity Potential (TETP inf.)		0.89
Social Category	Fuel poverty	Bill reduction rate	1
	Employment provision	Employment provision	0.83

Table 5.11 Data quality assessment result for onshore wind

5.5 Summary

The sustainability results from onshore wind technology in this chapter can be summarised as follows:

1. There are difference of sustainability performance between turbines of different rated power, but differences are not significant.
2. Capacity factor of onshore wind technologies (average 26%-33%) is significantly higher than that of sola PV (average 6%-13%), the levelised cost is almost half of solar PV (£96-101/MWh), all these results in shorter financially payback period and energy payback period.

3. Material circularity for wind turbines are higher than that of solar PV, because of larger proportion of metal composition in the machine.
4. Onshore wind projects do not directly contribute to reduce fuel poverty; however, the local investment provided by developers do bring economic opportunities to the local community.

Chapter 6 Biomass CHP

This chapter assess the sustainability of biomass CHP deployed within the Northeast region. The chapter starts with introducing the outlook of the assessed technology followed with overview of the case study in which the assessed investigates; then results obtained from the assessment is explained and discussed.

6.1 Introduction

Biomass is the organic material derived from plant that may be converted into other forms of energy. It is the only combustible renewable source for electricity generation. It had been a favoured energy source in human history for a long time because it is easily produced in almost any environment and regenerates quickly.(Evans *et al.*, 2010) There are many types of biomass available for electricity generation e.g. bagasse, agriculture residuals, dedicated energy crops etc. UK has large quantities of agricultural and forestry residues currently go to waste. Utilising these biomass represent an important opportunity to improve the management of UK’s rural areas and to reduce waste. (Parliament, 2004)

Observing from figure 6.1-6.2, Northeast region of England has abundant biomass resource particularly along the coast line and the Tyne River. The most dominate type of biomass within the region is willow with some miscanthus towards north of the region.

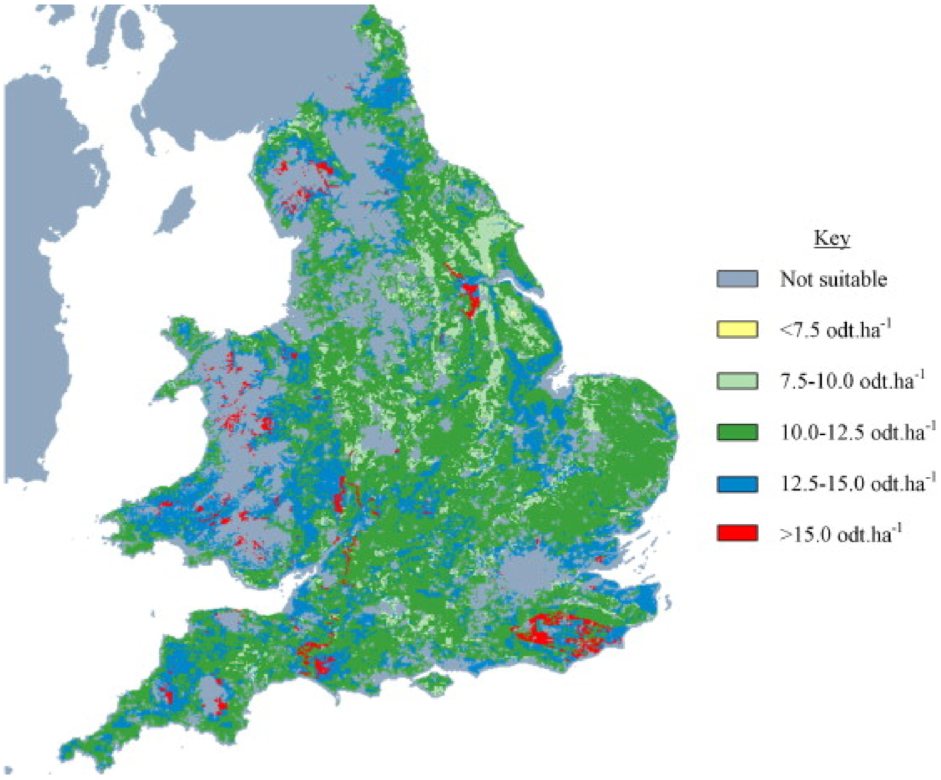

Figure 6.1 Map showing maximum energy crop yield in the England and Wales (Bauen *et al.*, 2010)

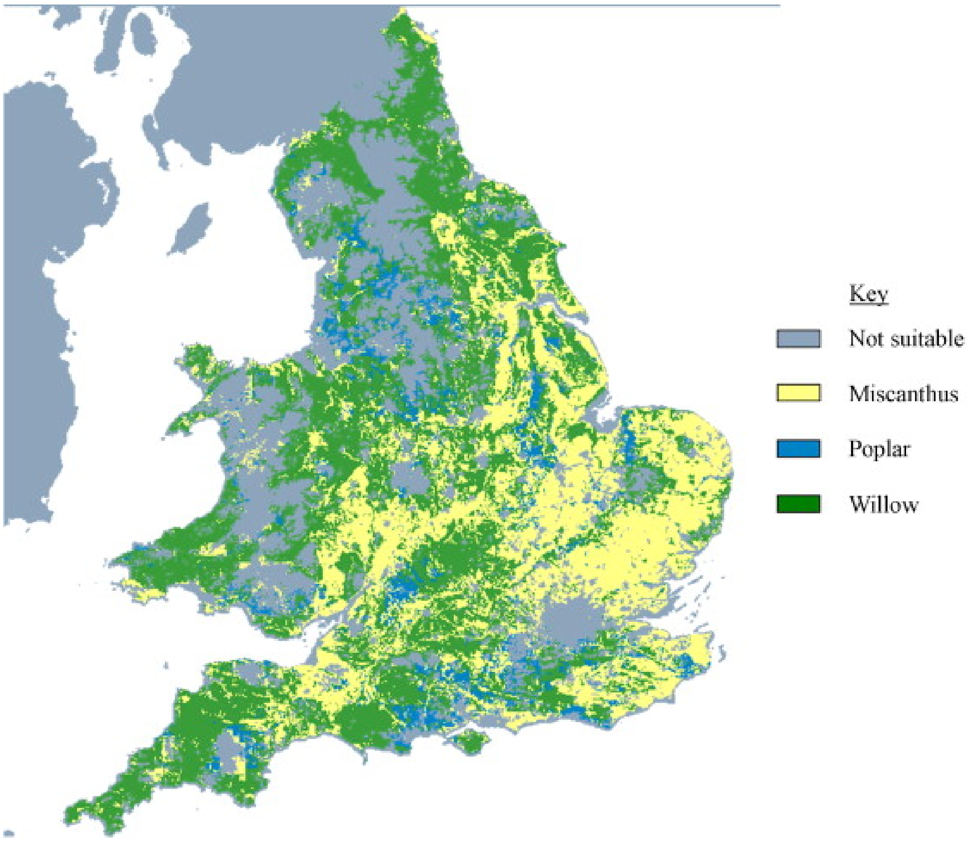

Figure 6.2 Map showing maximum yielding biomass type in the England and Wales (Bauen *et al.*, 2010)

Currently there are three primary technologies that for combustion based biomass-to-energy conversion: pyrolysis, gasification and direction combustion. Direct combustion is the simplest and oldest technology among the three; where pyrolysis and gasification involves firstly modifying property of the biomass fuel to transform it into combustible gases as well as condensable vapours in case of pyrolysis (Bain *et al.*, 1997; Tabberer and Tabberer, 1998; Ganesh and Banerjee, 2001), then these gases with high calorific values are then combusted in a gas turbine to convert into energy. Pyrolysis and gasification has higher efficiency than direct combustion, but they are more costly options; especially in the case of gasification, normally only clean fuel source such as wood pellets and wood chips can be used since the gas combusted in the engine has to be clean.

When converting the energy embedded within the biomass to electricity using these technologies, heat in form of steam is also generated alongside the process. “Cogeneration”, also known as Combined Heat and Power generation harvests both forms of energy, thereby significantly increase the utilization of fuel. The main components of a CHP system consist of prime mover, generator, and heat recovery equipment. The prime mover, sometimes also known as the heat engine is the centre of the overall CHP system; for biomass CHP systems, steam turbine and Stirling engine are the two typically known prime movers. Stirling engine has a much smaller output (≤ 2kw), so far had been only limited for commercial introduction and demonstration purpose; steam turbines had been in use for over 100 years, is the most widely used prime mover for CHP applications. In a typical steam turbine driven biomass CHP, steam is produced in a biomass steam boiler, then drives the turbine which generates electricity, and the remaining heat is also harvested.

6.1.1 Wilton 10 power plant

Northeast region of England has the largest gas and steam turbine CHP electrical capacity across the UK, and 77% of the market for CHP is dominated large scale plant(>10MWe). (DBEIS, 2017a)The case study selected for the biomass CHP technology is Wilton 10 power station (referred as Wilton10 from this point). Wilton 10 locates in the southbound of the Northeast region of England (figure 6.3-6.4), is the largest biomass project in the UK. The power plant owned by a Singapore company SembCorp Utilities, was in built since 2005 and officially opened on 12 Nov 2007. The plant has a total installed capacity of 38MW with heat to electrical ratio 4:15, was built to power the entire Wilton industrial estate (equivalent to powering 30,000 homes) (DUKES, 2018).

A total of 300,000 tons of wood is consumed at the plant every year. Feedstock comes from four sources: 40% is recycled wood supplied by company UKWR[12], 20% is supplied from surrounding recycling sites as offcuts from sawmills; 20% of feedstocks is collected, with help from the Forestry Commission, from local forests in form of small round wood logs after routine tree felling operations with help from; 20% comprises short rotation coppice willow, a type of specially grown energy crops collected from farmers within 50 miles radius of Wilton10, and it is supplied by local company Greenery. It is claimed that feedstock demand of the biomass plant promoted the growth of approximately 7,500 acres of coppices in the region which had created havens for local wildlife (McIlveen-Wright *et al.*, 2013; Utilities, 2015).

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[12] UK Wood Recycling Ltd (UKWR) was launched in 2006 next to Wilton 10 support the plant by supplying 80,000 tonnes of wood chips per year WRAP (2017) *Regional Market Assessment for Wood Waste for North East England*..

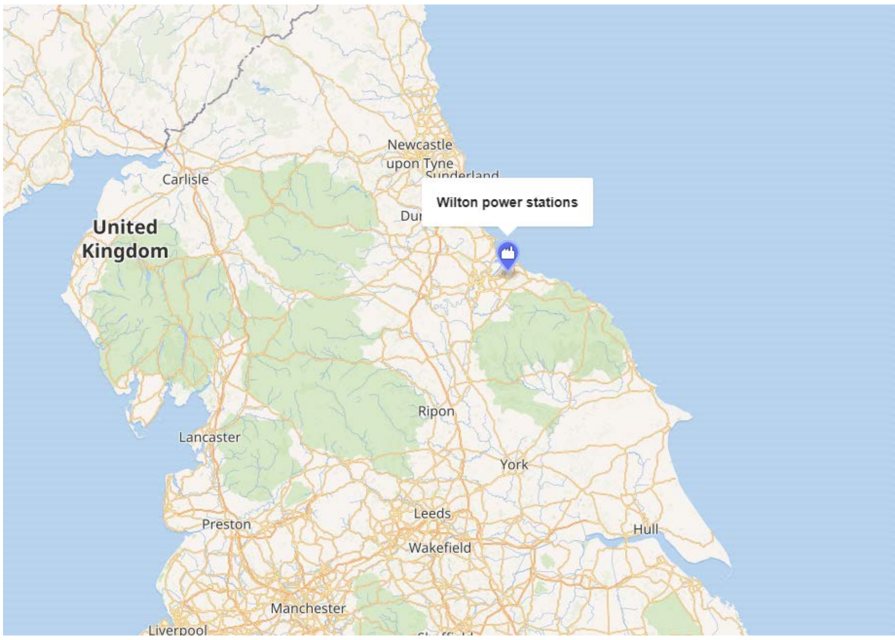


Figure 6.3 Location of Wilton 10 power station

Figure 6.4 Photo of Wilton 10 power station

McIlveen-Wright et al. (2013) investigated the techno-environmental performance of the Wilton 10 plant along with another two biomass plant in the UK using ECLIPSE modelling approach; the author also provided a schematic graph of Wilton 10, which is illustrated in figure 6.5 below. The primary mover used in Wilton is SST 400 steam turbine supplied by Siemens, includes a condenser, fender gearbox, oil system, and PCS7 system. (SIEMENS, 2003) The bubbling fluidized-bed boiler is provided by Foster Wheeler under $53 million contract including design, build and commission the complete boiler island. The boiler included the fuel handling system, biomass fuelled boiler and flue gas treatment system. Fluidized bed combustion is the best technology to process fuel with low quality and high ash content(Saidur et al., 2011), which is the case for the fuel processed at Wilton 10.This particular boiler is ideal for handling biofuels with high moisture content and difficult ash characteristics at low level of emission. (Wheeler, 2008).The feedstock are processed and mixed before being fed into the boiler.

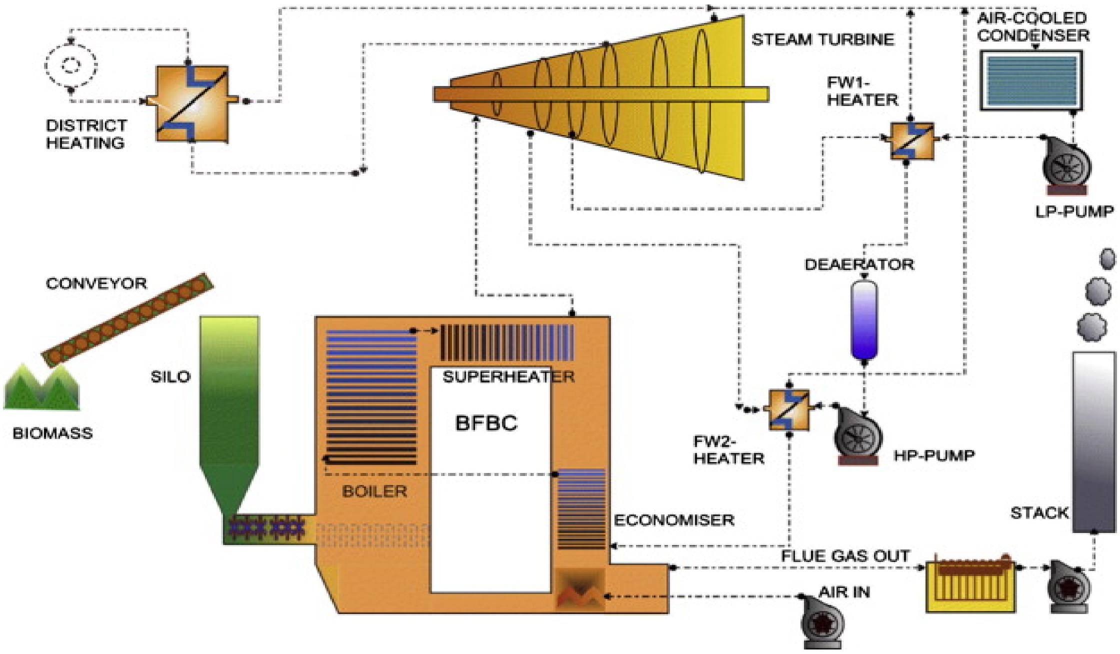


Figure 6.5 Schematic of Wilton 10. (McIlveen-Wright *et al.*, 2013)

6.2 Assumption

This section provides the assumptions made for sustainability assessment on the case study Wilton 10.

6.2.1 System boundary

The guaranteed operational life time for the system is 20 years. The system boundary of the assessment is illustrated in figure 6.6 below. Manufacture stage includes production all the main components of the system, the steam turbine, the boiler and the pump and installation stage includes construction of the plant. For operation stage, fuel combusted in the plant and oil required for occasional maintenance are accounted for. The transport range for the biomass is within 20miles. Life time of the plant is assumed to be 40 years according to the industrial standard; the plant may be given life time extension post the designed lifetime.

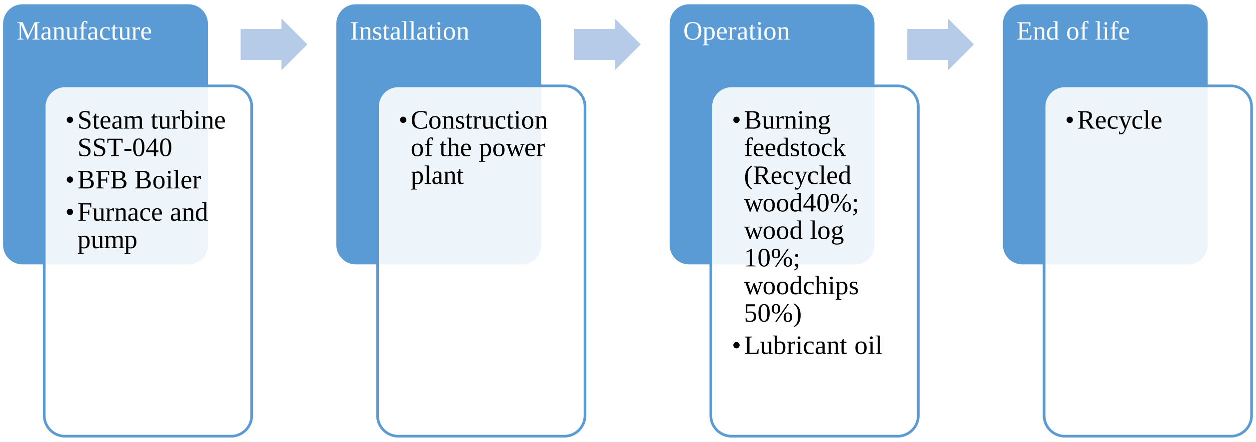


Figure 6.6 System boundary for Wilton 10

6.2.2 Product impact allocation

Each CHP system produces two products, heat and electricity. For systems with multiple products, the ISO standard (ISO, 2006a) recommends a hierarchy for decisions on allocating the impacts between products: 1. System expansion, that the system boundary to include the impacts of all products(Ekvall and Finnveden, 2001) and hence allocation can be avoided; 2. Allocation based on the physical, economic, social and biological causality caused by final products(Rebitzer *et al.*, 2004); 3. When causality cannot be determined, allocation should be made based on the other output-input relationships, such as economic value, product mass, volume etc. (Svanes *et al.*, 2011). The principle of product impact allocation is to reflects the underlying physical relationships between the products(ISO, 2006a), i.e. " the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system"(EEA, 1998). Since the goal of this study is defined as investigate the impact of solely electricity production, therefore the impact allocation cannot be avoided. In this study, a gross energy allocation approach is applied, that impact of the heat and electricity in the category of levelised cost and environmental impact categories are allocated based on their output ratio.

6.2.3 Carbon neutrality

There's been discussion surrounding the carbon emission of biomass combustion. Bioenergy is thought a carbon neutral energy option, since it can be used to avoid greenhouse gas emissions from fossil fuels (Nakicenovic *et al.*, 2000). Some argues that Forests acts as a carbon sink, and combustion can release the carbon to the atmosphere(Kelsey *et al.*, 2014);using bioenergy instead of fossil fuels does not alter combustion emission, because the amount of CO_2 released is roughly the same per unit of energy regardless of the source. (Searchinger *et al.*, 2009). In the domain of carbon foot printing, prominent guidance such as European Union Emissions Trading Scheme(EC, 2007) and UK Standard Assessment Procedure for Energy Rating of Dwellings(DBEIS, 2008) defines biomass a carbon neutral energy fuel; organisations such as World Business Council for Sustainable and World Resources (2001) considers the carbon neutrality of biomass to be problematic, yet still considers the carbon emission from combustion of biomass should be excluded from carbon footprint.

Emission of biomass energy can be classified as product chain emission and resource emission. The former is the emission associate with produce, transport and convert the fuel; and the later means the emission released when the biomass is burnt. (Zanchi *et al.*, 2012). In this study, emission from biomass combustion is considered to be carbon neutral, because the biomass combusted in the study are mainly recycled woods and co-products from sawmill, they will forest will eventually decay and decompose which eventually release the carbon back to the atmosphere; in addition, the database applied in this study Ecoinvent(Werner *et al.*, 2007) also offsets carbon emission from biomass combustion with a sequestration credit which is equal to the combustion emission, which leads to zero carbon emission footprint.

6.2.4 Techno-economic assumptions

Table 6.1 shows the key techno-economic assumption made for Wilton 10. The capacity factor is calculated using actual generation data from 2007-2018 (DECC, 2018). The availability of the system is determined in two folds, the feedstock availability and the system operational availability. Typically, a well-designed biomass CHP system has an average availability factor of 92%-98%, the only downtime is due to scheduled maintenance and occasional incidents. (USEPA, 2007, p. 37) In case of Wilton 10, there had been records of down time due to feedstock, therefore the availability factor is assumed to be between 92% and 98%. Capacity factor of Wilton 10 is between 55% and 70% at most of the time and sometimes reaches as high as 100%.

Since the detailed cost information for Wilton10 is not made available to the public, the costs used in the assumptions are derived from UK specific biomass CHP associated costs from BEIS (2016). The data presented by BEIS (2016) is considered to be accurate and up to date.

	Min	Ave	Max
Capacity factor (%)	24%	62%	80%
Availability (%)	92%		98%
Life time (years)	40		
Output per year(MWh)	62,321	162,852	209,964
Output lifetime (MWh)	1,558,025	4,713,987	8,398,560
Capital cost (£/MWh)	5.3	6.1	7.0
Construction cost (£/MWh)	69.8	76.4	83.0
Fuel cost(£/MWh)	26.2	31.1	36.0
O&M (£/MWh)	35.0	38.0	41.0
Levelised cost (£/MWh)	136	152	167

Table 6.1 Key techno-economic parameters for Wilton 10

6.2.3Environmental assumptions

Table 6.2 shows the material composition of Wilton 10, and table 6.3 shows the material use during installation stage. Since the boiler equipment's are bespoke designed for Wilton 10, the data on material use is restricted to public access. The data for boiler material use is scaled up from Kelly *et al.* (2014), and the material use for pump production is scaled up from material use for 1MW capacity pump using data from EcoinventCentre (2017b). The steam turbine data is directly obtained from Siemens brochures (SIEMENS, 2003; SIEMENS, 2013). No site specific data available for installation activities, Ecoinvent data set for constructing 1MW co-generation unit is scaled up and used (EcoinventCentre, 2010), other than all the necessary construction material needed the dataset also include transport activities ($1.5*10^3$km of transport by car per unit construction)

Only material used for the equipment are considered for recycling process. The dataset based on a wood combustion CHP generation dataset (EcoinventCentre, 2017c) is used to estimate the impact of the combustion process; activities including combustion, emissions to air, disposal of ashes and all substances needed for the operation (e.g. lubricating oil, organic chemicals, sodium chloride, chlorine etc.) Feedstock is wood chips with moisture level of 30%, 529kg (dry mass) of feedstock is consumed to produce 1MWhe. (McIlveen-Wright *et al.*, 2013).

According to EcoinventCentre (2017c), 5.29kg wood ash mixture is created as waste for each 1MWhe electricity generated. There is currently no process in Wilton power plant to process this ash. Although there had been recent studies looking into utilization of the ash, for example to recycle it back to the ground of forest; however the argument surrounding the unburnt carbon content and heavy metal contamination of the ash, this recycling options had not been made widely available. (Neves *et al.*, 2011; James *et al.*, 2012)

Main components	**Material**	**Consumption mass**	**Recoverable mass**
Steam turbine SST-040 and Silo	Non-alloy steel	342.97	178.34
	Cast iron	79.15	41.16
	Low alloy steel	395.73	205.78
	High alloy steel	61.56	32.01
	sub-total mass	**879.4**	**457.3**
Boiler	Steel	778.30	404.72
	Copper	57.89	33.00
	Cast iron	38.34	19.94
	Glass wool	7.48	0.00
	Glass fiber	2.88	0.29
	Aluminum	5.75	5.52
	Nylon	0.58	0.00
	sub-total mass	**891.21**	**463.46**
Pump	Reinforcing steel	147.50	76.70
	Low-alloyed steel	147.50	76.70
	sub-total mass	295.00	153.40
Total		**2065.61**	**1074.15**
Total Recyclability		**52%**	

Table 6.2 Material composition and recyclability of Wilton 10 (t/system)

	Components	**Material**	**Mass (t/system)**	**Recoverable mass (t/system)**
Input material	Valves	brass and polyvinylchloride	6.33	3.61
	Hydraulic fittings	brass	3.45	1.97
	Expansion vase	steel	11.50	5.98
	Tubes	copper	2.11	1.20
	Packaging	cardboard	2.49	2.16
Waste material	Packaging	plastic	0.38	0.10
		cardboard	2.11	1.82
		wood	84.35	50.61
	Material circularity		**59.8%**	

Table 6.3 Materia composition and recyclability of Wilton 10 during installation stage

6.2.4 Social parameters

Wilton 10 is directly supplying for the Wilton estate, no bill reduction for local communities. According to Sembsolutions (2017), 400 employment opportunities were created during construction of the plant and a further 15 permanent employment is required directly at the operation stage; this gives an estimate of 10.92 job/MWe. Thornley *et al.* (2008) thoroughly studied quantification of employment for biomass plants, including two short rotation coppice biomass CHP facilities in the UK with capacity of 2MWe and 25 MWe; concluded that the larger the plant is the more job opportunities it offers. The 25MWe plant included in the referenced study created 160 full time positions over the lifetime of the plant,36 jobs are directly created at the at the operation phase,124 are created during construction phase, which gives an estimate of 6.4job/MWe. Therefore assumption can be made that 6.4-10.92 jobs can be created throughout the construction and O&M phase.

6.3 Results

The final assessment result of Wilton 10 is present in table 6.4; and the performances are discussed in categories below.

6.3.1 Techno-economic performances

Biomass CHP proven to be a reliable yet expensive energy supply; where both the capacity (41%-100%) and levelised costs (£136-167/MWh) are higher than that of onshore wind (capacity factor 9-54%, levelised cost £35-111/MWh). Although the payback period is much longer than that of the onshore wind (0.3-1.5 years), plant can break-even towards the end of its first quarter life-time. Components of the levelised cost is demonstrated in figure 6.7. Different from onshore wind and solar PV, the capital cost for biomass power plant only makes up to 4% of the total levelised cost, while on the other hand, construction cost makes up the largest segment in levelised cost, the second come in place is the fuel cost. Although biomass is considered to be renewable energy, but costs associated with the fuel plays a continuous role throughout the plant’s life time.

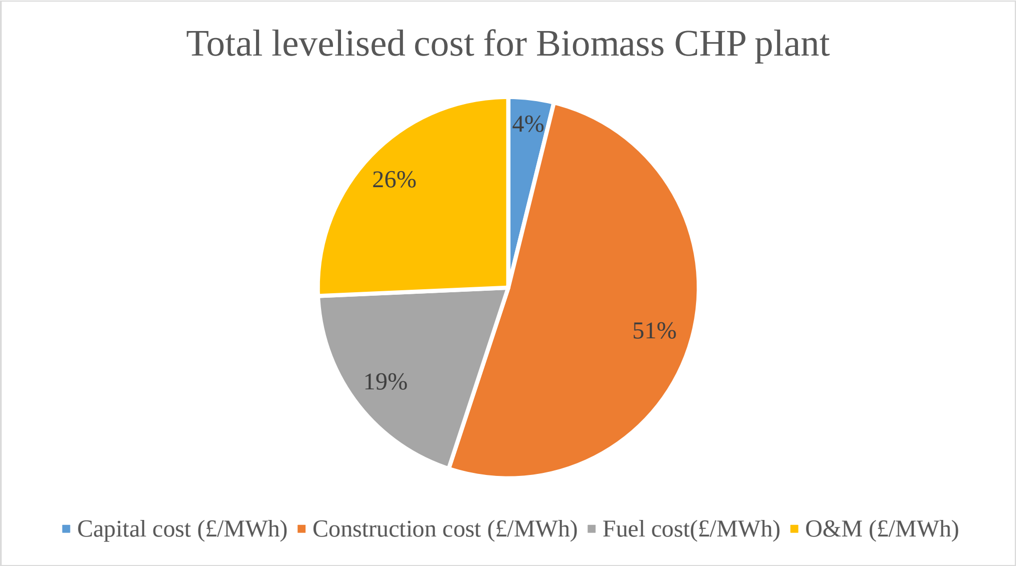


Figure 6.7 Composition of total levelised cost for biomass CHP plant

6.3.2 Environmental performances

Figure 6.8 below shows the overall environmental impact of Wilton 10 at each life cycle stages. In contrary to common belief, the combustion of the biomass outweighs the impact of rest of the activities; while on the other hand, impact of the plant make presence in ecotoxiciy to marine and freshwater systems, which is largely caused by the use of electricity and use of plywood, as well as other construction materials such as concrete and steel; and the impact of plywood originates from the transportation of the material from suppliers to the final user.

Intensive construction work is involved in installation stage of the assessed CHP plant as displayed in figure 6.9; and the environmental impact of transportation is the most noticeable in the construction of CHP plant than onshore wind projects. The fossil fuel required for the transportation activities had contributed to all impact categories, particularly in the impact category of ODP, where the transport impact surpassed the impact of steel. In summary, the impact of installation is caused by the consumption of fossil fuel for the electricity needed and transportation activities.

Figure 6.10 shows the impact occurred during manufacture stage. Like the case of onshore wind, majority of the impact derived from the use of metal material, mainly copper, steel and aluminium. Electricity consumed to produce this equipment also has noticeable impact, particularly in the category of ozone depletion and global warming.

Payback period for the assessed system is between 0.5-1.24 years. This value is significantly lower than the result of the same power plant presented by McIlveen-Wright et al.

(2013),which is 13-19 years; however, the methodology of McIlveen-Wright et al. (2013) is not clearly explained, therefore a comparison cannot be made.

The assumptions used to estimate the energy consumption is detrimental to the payback period; some studies considers the biomass embodied energy to be part of the energy consumed, which leads to longer payback periods, between nine to ten years (Proka et al., 2014; Odavić et al., 2017); some argues that the biomass energy is converted to the form of electricity and heat, and therefore it should be not be considered to be part of energy consumption(Mann and Spath, 2001), which applies to the case of this study and explains the shorter payback period.

Circularity of the CHP is divided into material circularity and fuel circularity. The overall material circularity of the CHP plant (52%) is lower than that of onshore wind (62%) and higher than that of solar PV (35%-38%).

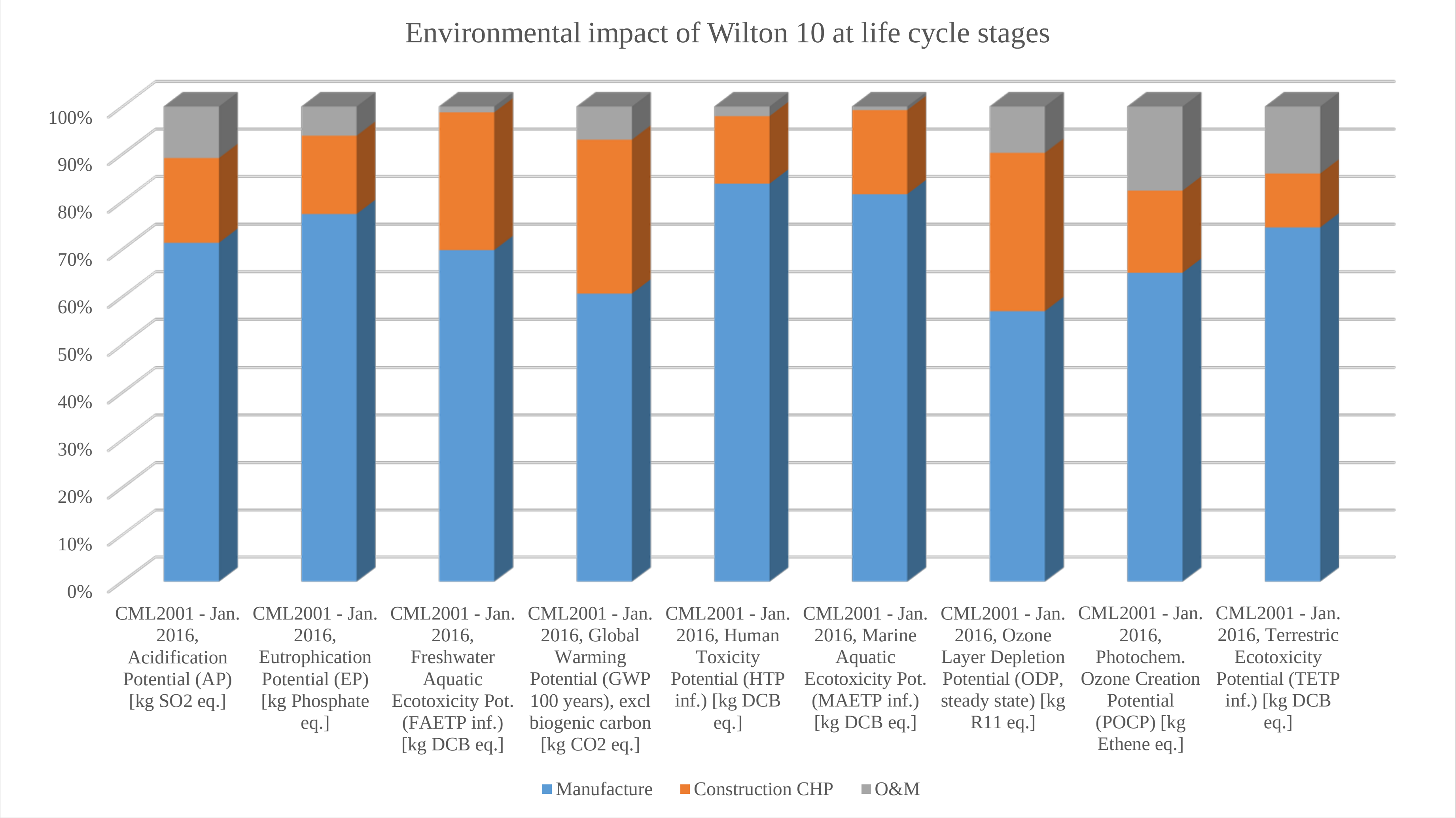


Figure 6.8 Environmental impact of Wilton 10 at life cycle stages

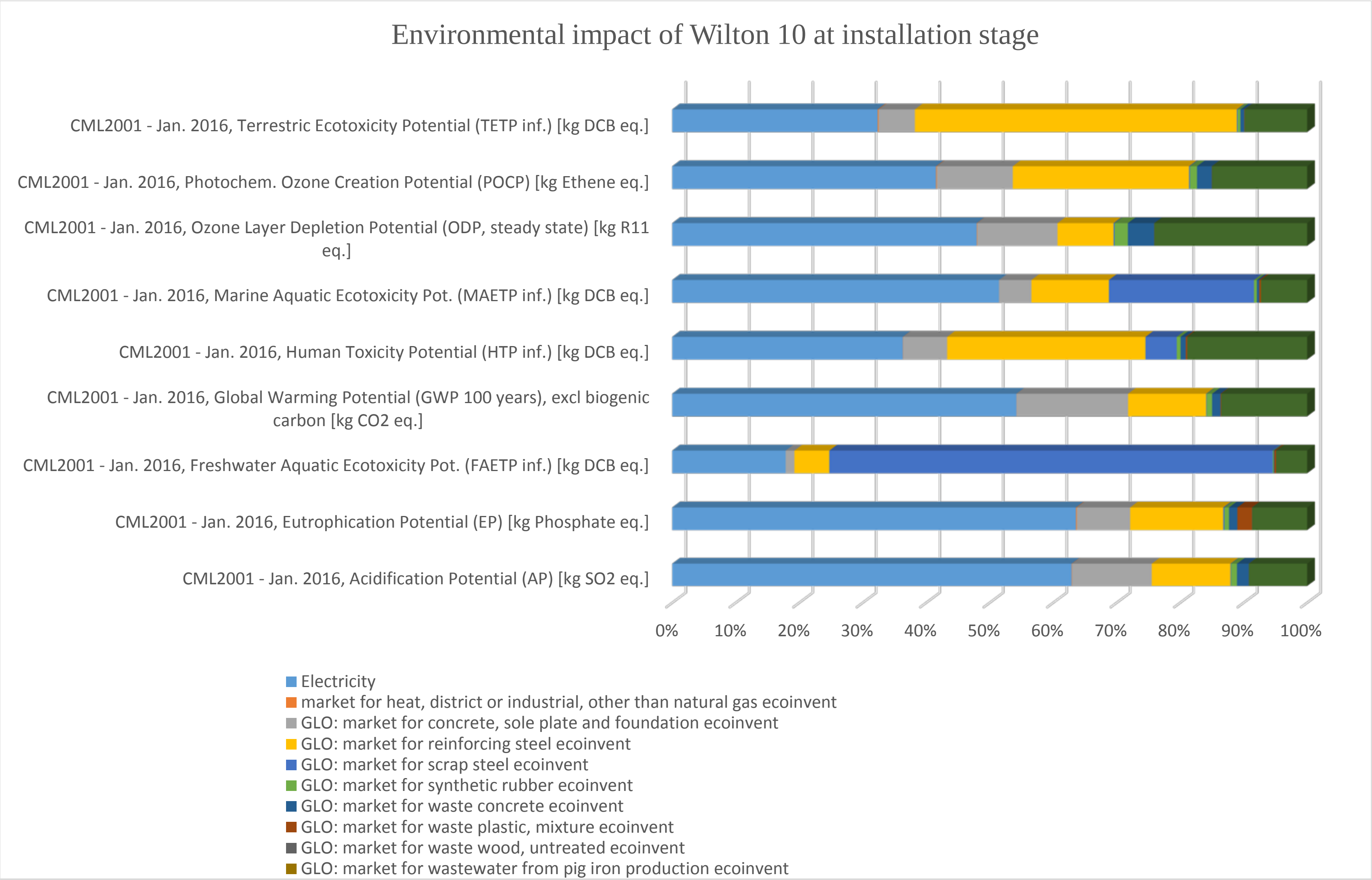


Figure 6.9 Environmental impact of Wilton 10 at installation stage

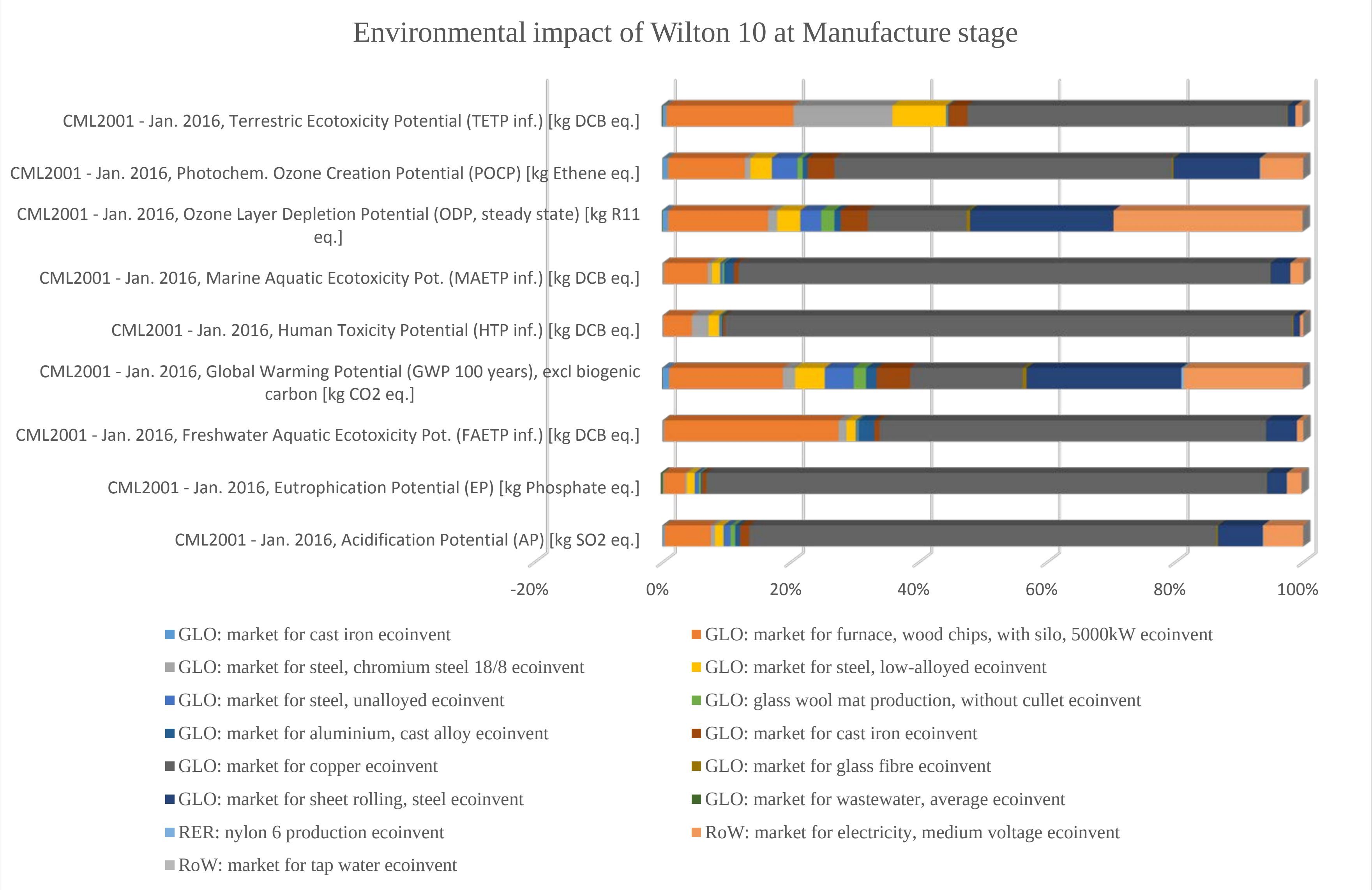


Figure 6.10 Environmental impact of Wilton 10 at manufacture stage

6.3.2 Social performances

Like vast majority of the industrial CHP systems, Wilton 10 was built to support its industrial state and hence do not assist local residence in energy bill reduction.

Most jobs are created during construction of the plant, but they are not long-term employment opportunities; on the other hand, less jobs are created at the operational stage, but these employment opportunities has a longer term impact on the local community. Despite the large scale of construction, Wilton 10 appear to create less employment opportunities compare to onshore wind.

Sustainability issues		**Indicator**	**Wilton 10**		
			Min.	**Ave.**	**Max.**
Techno-economic Category	Reliability	Availability factor	92%	95%	98%
		Capacity factor	41%	80%	100%
	Cost	Levelised cost	136	152	167
	Financial feasibility	Payback period	13	16	19
Environmental Category	Circularity	Material Circularity	56%		
		Fuel circularity	0%		
	Energy Payback	Energy payback period	4	8.5	13
	Acidification Potential (AP)		8.35E-04	7.68E-03	8.52E-01
	Eutrophication Potential (EP)		2.89E-04	4.66E-03	2.99E-01
	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)		1.54E-02	1.19E+00	1.83E+01
	Global Warming Potential (GWP 100 years)		5.73E-02	4.66E-01	5.83E+01
	Human Toxicity Potential (HTP inf.)		8.84E-02	4.24E+00	9.87E+01
	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)		2.63E+01	3.20E+03	3.41E+04
	Ozone Layer Depletion Potential (ODP, steady state)		3.77E-09	3.85E-08	3.85E-06
	Photochem. Ozone Creation Potential (POCP)		9.29E-05	5.24E-04	9.40E-02
	Terrestric Ecotoxicity Potential (TETP inf.)		3.87E-03	2.73E-02	3.92E+00
Social Category	Fuel poverty	Bill reduction rate	n/a		
	Employment provision	Employment provision	6.4	8.7	10.92

Table 6.4 Sustainability assessment results of Wilton 10

6.4 Discussion

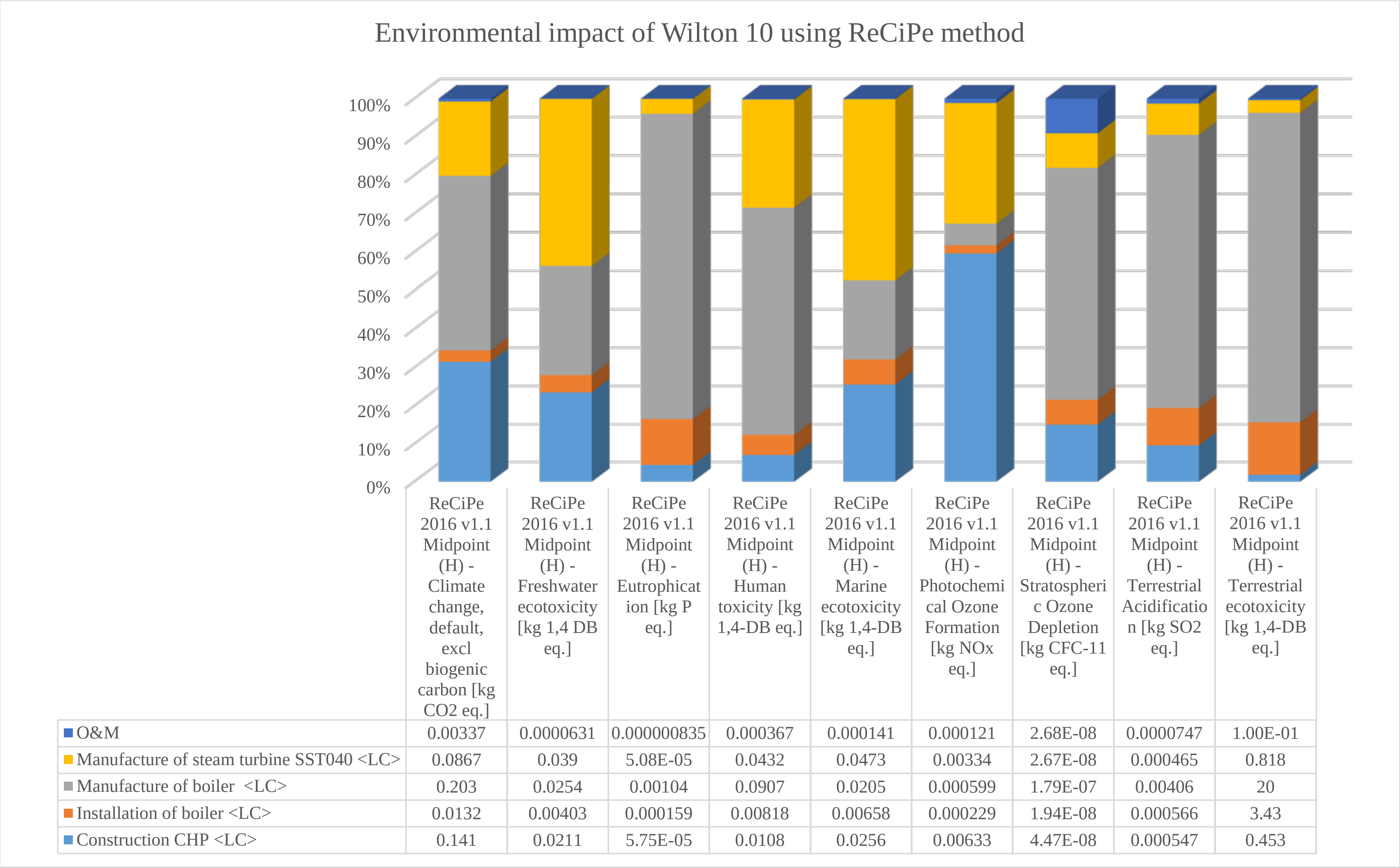
CHP systems are often located onsite, in case of this study, Wilton 10 is used to supply energy for the entire Wilton industrial estate, not only this reduces the energy lost in transmission and distribution, it also make the industrial estate less reliant on the electrical grid and has less chance of losing power. In addition, Wilton 10 provides heat and electricity to the estate on a continuous basis, this is particularly financially beneficial when the electricity price is high.

6.4.1 Uncertainty in results

This assessment involves collation of data (e.g. assumptions for environmental impact of CHP installation is the scaled-up value of a 1MW CHP system), although these assumptions are made within reasonable range, but they do present source of uncertainty. The uncertainties limit the predictive capacity of the study, but does neither diminish its ability to be representative for the technology assessed nor lessen its usefulness in carrying out comparison with the other two assessed technologies, solar PV and onshore wind.

6.4.2 Sensitivity analysis

Figure 6.11-6.13 shows the environmental impact of Wilton10 calculated using ReCiPe method, the pattern of share of impact during each life cycle stage resemble great similarity to the results obtained using CML method; where combustion of biomass dominates the impact across all categories and installation stage has the smallest share of impact. There is noticeable impact of manufacture at eutrophication and water body ecotoxiciy. Copper has overall large impact at all categories throughout the manufacture stage; the proportion of copper’s impact in terrestrial ecotoxiciy using ReCiPe method is higher than that using the CML method; as explained in previous chapter, this is due to the higher characterisation factor given to copper in ReCiPe methodology. Another difference is that the impact of insulation material used in boiler, glass wool does not show any impact using the ReCiPe method; while showing impact in ODP and GWP categories using the CML method. The impact of electricity used in installation stage appears to take up smaller proportion in ReCiPe method; while the impact of transport and metal materials remain prominent in the overall impact.



	ReCiPe 2016 v1.1 Midpoint (H) - Climate change, default, excl biogenic carbon [kg CO2 eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Freshwater ecotoxicity [kg 1,4 DB eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Eutrophication [kg P eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Human toxicity [kg 1,4-DB eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Marine ecotoxicity [kg 1,4-DB eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Photochemical Ozone Formation [kg NOx eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Stratospheric Ozone Depletion [kg CFC-11 eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Terrestrial Acidification [kg SO2 eq.]	ReCiPe 2016 v1.1 Midpoint (H) - Terrestrial ecotoxicity [kg 1,4-DB eq.]
■ O&M	0.00337	0.0000631	0.000000835	0.000367	0.000141	0.000121	2.68E-08	0.0000747	1.00E-01
■ Manufacture of steam turbine SST040 <LC>	0.0867	0.039	5.08E-05	0.0432	0.0473	0.00334	2.67E-08	0.000465	0.818
■ Manufacture of boiler <LC>	0.203	0.0254	0.00104	0.0907	0.0205	0.000599	1.79E-07	0.00406	20
■ Installation of boiler <LC>	0.0132	0.00403	0.000159	0.00818	0.00658	0.000229	1.94E-08	0.000566	3.43
■ Construction CHP <LC>	0.141	0.0211	5.75E-05	0.0108	0.0256	0.00633	4.47E-08	0.000547	0.453

Figure 6.11 Environmental imapct of Wilton 10 using ReCiPe method

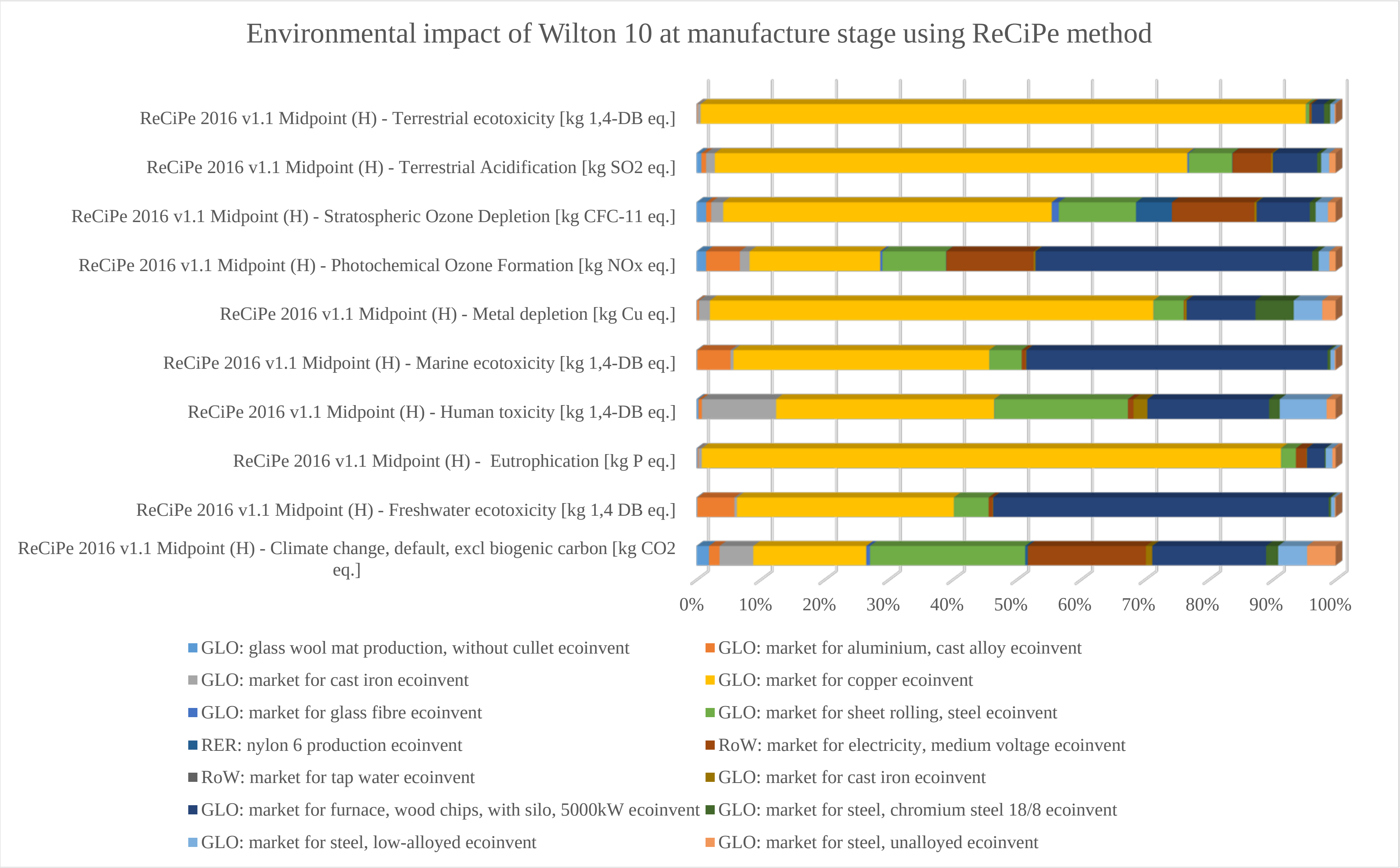


Figure 6.12 Environmental impact of Wilton 10 at manufacture stage using ReCiPe method

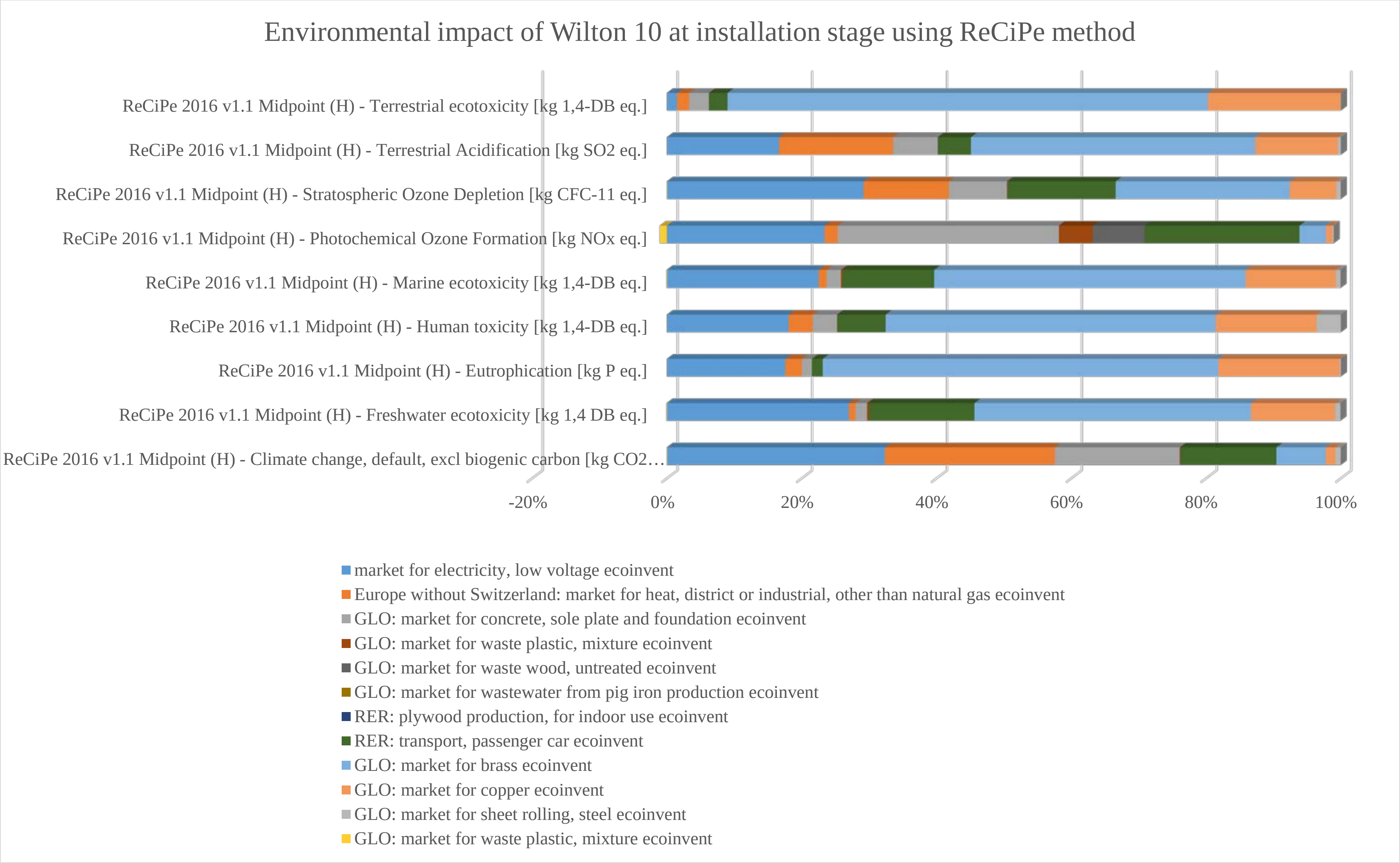


Figure 6.13 Environmental impact of Wilton 10 at installation stage using ReCiPe method

6.4.3 Domestic installation

In addition to large scale biomass CHP plants, some micro-generation biomass CHP plants have been installed at domestic dwellings, community estates etc. These micro CHP plants are not made widely available partially due to their low cost-effectiveness unless heavy subsidy is offered, also because of its high capital cost which makes it inaccessible for low-income owners. (Walker, 2008) With the current subsidy scheme, for example Low Carbon Buildings Programme, 70% of the system and installation cost still need to be paid upfront by the CHP hosts.

There are CHP systems set up by social housing and housing associations for their low-income tenants, but the actual impact are often hard to examine, sometimes due to poor management. For example Byker Community trust installed one CHP plant aim to assist its tenant with energy costs, but the assistance it offered to relive fuel poverty, as disclosed by the trust, that due to the “complexity of the system”, it is not possible to quantity the exact level of savings can be delivered. (BCT, 2016)

Project financing is usual tied to biomass fuel availability and investors seem only willing to embark upon investment if 10 or 15 years supply contracts are in place; and such contracts are not currently often offered by biomass fuel suppliers. In the case of Wilton10, to ensure a stable supply chain, as stated previously UKWR Company was established on the fuel supply; however many other smaller projects such as local schools do not have the ability to establish such facility are facing difficulties with financing the project.

6.4.4 Supply chain

A typical biomass supply chain is comprised of several discrete processes. These processes may include ground preparation and planting, cultivation, harvesting, handling, storage, in-field/forest transportation, road transportation and utilization of the fuel at the power station.

Although biomass is considered to be a ‘carbon neutral’ fuel source, since using it for energy generation emits the same amount of carbon that the plants have absorbed while growing, there are processes required that use conventional fuel sources (e.g. logistics of biomass, pelleting) or require the use of other resources that might have an adverse impact on the environment and human health (pesticides, fertilisers etc.). Furthermore, biomass production and use could potentially have positive or negative social effects when performed in large scale, such as employment levels, health effects, noise from transportation, visual impact, loss of biodiversity etc. Therefore, the sustainability of using biomass for energy generation purposes cannot be considered as a given

A reliable and financially efficient supply chain is crucial to the success of a CHP plant. The forestry biomass resource, especially forestry biomass is abundant in the UK thanks to the mild winters, plentiful rainfall, fertile soil and hill sheltered topography. UK forestry is well regulated and majority of the wood demand s associated with biomass electricity projects, and so far very few of these projects have reached beyond the drawing board. (S.Cirell, 2018) However, for other type of resources such as agriculture biomass, the supply is seasonal. As indicated in the result section, fuel cost makes up to 42% of the total operational costs, therefore the seasonal change in supply-demand leads to significant increase in the cost of the fuel; or sometimes storage space would be required to balance the cost. Although the case of Wilton 10, the fuel stock is available all year round, and the fuel price does not subject to seasonal fluctuation; but CHP systems with this function is still rare in practice (Rentizelas, 2014).

According to Caputo *et al.* (2005), 56–76% of the fuel cost are due to the biomass logistics. The typical transportation mode for biomass in the UK is road; ship and train are also considered when long distance transport is required (Hamelinck *et al.*, 2004). Although biomass is considered to be a ‘carbon neutral’ fuel source, results obtained in this study conveyed that transportation of biomass has unneglectable environmental impact. The key issue that biomass transportation faces is that biomass is low-density, and it leads to increased cost of collection, handling, transport and storage of the supply chain. (Rentizelas, 2014)

In addition, it had been argued that removal of forest residues may result in a decrease of the carbon pool within the litter on the forest floor. This may affect the interaction between the litter pool and top layer of soil, which could manifest itself as a reduction in soil carbon in the long term. This could reduce soil fertility and impact on the greenhouse gas balance. However, there are studies suggests that the loss of soil fertility is minimal (James and Harrison, 2016). Further investigation is evidently needed to clarify the extent of the impact.

6.4.5 Data quality assessment

Table 6.5 below shows data quality assessment for sustainability assessment on the selected biomass CHP technology. The average score is 88%, much lower than that of the other two assessed technologies (solar PV88% and onshore wind 91%). The weakness lies on the techno-economic data. Due to the reason that the cost related data are not made available for public, generic data obtained from literature are used in this study. Although the employed data are selected to be geographically and technologically representative, but adoption of primary data can largely improve accuracy of this study. On the other hand, the employment data shows to have higher quality than the data used in solar PV assessment.

Overall, the data quality of biomass CHP case study is considered to be sufficient for purpose of this study, future work can improve in the following areas:

1. Obtaining primary cost data on the power plant, including the hidden incentives and subsidies
2. Investigate relevant pollution control measures that are already installed in the plant, as well as collect actual operational data, to thus increase the accuracy of the assessment results.

Sustainability issues		**Indicator**	Normalised total
Techno-economic Category	Reliability	Availability factor	0.83
		Capacity factor	0.83
	Cost	Levelised cost	0.83
	Financial feasibility	Payback period	0.83
Environmental Category	Circularity	Material circularity	0.89
		Fuel circularity	0.83
	Energy Payback	Energy payback period	0.89
	Acidification Potential (AP)		0.89
	Eutrophication Potential (EP)		0.89
	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)		0.89
	Global Warming Potential (GWP 100 years)		0.89
	Human Toxicity Potential (HTP inf.)		0.89
	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)		0.89
	Ozone Layer Depletion Potential (ODP, steady state)		0.89
	Photochem. Ozone Creation Potential (POCP)		0.89
	Terrestric Ecotoxicity Potential (TETP inf.)		0.89
Social Category	Fuel poverty	Bill reduction rate	1.00
	Employment provision	Employment provision	0.83

Table 6.5 Data quality assessment result for biomass CHP

6.5 Summary

The outcome of the assessment can be concluded as follows:

1. Biomass CHP is a dispatchable energy supply, with high capacity factor means the technology is capable to meet peak demand; however scheduled or non-scheduled downtime means biomass CHP cannot be the solo energy source and it needed to be paired with other energy technology to ensure a stable supply.
2. The impact of biomass used for this technology needs to be investigated further.
3. The recyclability of the burnt ash can be further explored to increase fuel circularity

Chapter 7 Discussion

Following on from sustainability assessment of the three energy technologies, this chapter first compares the sustainability performance of three assessed technologies, then demonstrates how the designed framework can be applied to assessing the sustainability of electricity mixes through scenario analysis.

7.1 Comparison of three assessed technologies

The sustainability performance of solar PV, onshore wind and biomass CHP has been discussed in chapter 4-6, this section provides summary of direct comparison of these three technologies. Table 7.1 compares the sustainability performance of the assessed technologies using the average value obtained as result for each indicator; and table 7.2 presents the ranking of each technology.

Observe from the ranking, onshore wind has the best overall performance and followed with biomass CHP. The performance of solar PV is not ideal. The worst performing category for solar PV is its environmental performance which is mainly let down by the low reliability of the technology. A solar PV system installed in the Northeast region is only able to perform at 10% of its design capacity; which means 90% more installation would be required to achieve the designed maximum electricity supply. The general capacity factor of solar PV is only 16%-22% (Besarati *et al.*, 2013; Chandel *et al.*, 2014), but to a large extend the low performance of solar PV is related to the limited solar irradiation within the Northeast region, and this can be seen from the low availability factor at 15%. On the other hand, solar PV systems installed in the southwest coast of the country, such as Cornwall where solar irradiation is almost 50% more than the Northeast region of England would score higher in the reliability category and reduce the overall environmental impact. The same can be said for onshore wind, which has the best performance across all categories largely due to the high wind speed in the Northeast region which enables the turbines to operate at 98% of the time. This reflects the importance of regional based sustainability assessment that renewable energy perform differently throughout different regions in the country.

Although solar PV is not the best performing technology supply, and even in country like Germany where the deployment of solar PV is high, the amount of electricity generated through solar PV in the past ten years is between 0.8% and 6% of the total electricity generation (EuroStat, 2018). However, observing from the overall performance of solar PV, the merit of the energy is the ability to reduce fuel poverty. System cost for solar PV is the most accessible energy option among the three, it has low system cost and short installation time; and with financial assistance it can be installed at point where fuel poverty is a concerning issue. Although it does not have high energy yield, but a 4KWp system can offer substantial electricity to a household need.

Onshore wind is known as an intermittent energy source because it is not available to generate at all times; however, the results conveys the otherwise: the availability factor of the assessed wind energy is even higher than the CHP plant. Present day's wind turbines are designed to suit most wind conditions, given the location of installation is carefully selected, most of the time the turbine will be able to operate. In comparison, the CHP appeared to offer less stability in terms of continuous energy supply. That the onshore wind technology can be deployed as a standalone source of energy supply for areas with low energy demand in general, while on the other hand CHP needs to be paired with other energy technology to ensure a stable supply over the time. The merit of CHP lies in its high dispatchability and capacity. As mentioned, that onshore wind cannot be regarded as a suitable standalone option for areas with high peak demand because its energy output cannot be ramped up or ramped down in response to demand curve.

One reason for the slower deployment rate of CHP can be observed here, that the lower price offered by solar PV and onshore wind took over the market share of CHP technology. The fuel cost is a continuous investment that needs to be secured throughout the entire operational life of the technology, and the cost can be substantial as the size of installed capacity increases.

Decommission procedures is not well established for all the assessed energy technologies. The end of life stage is assessed in this study through material circularity, and the possible decommission options for solar PV and onshore wind are discussed in previous chapters. Partially due to the reason that renewable energy is still "young" and the standard decommission practice had not formed; but from what have discussed in the study can conclude that the impacts are not negligible. For example, for construction projects such as onshore wind and biomass power station, decommission of the plant would involve use of explosive materials to break down the structure, which may lead to pollution and degradation of environment. The real-life decommission practice also affect the circularity of these technologies. For example if the windfarm is decommissioned using explosives, then most of the materials will be regarded as construction and demolition waste, and a different recycling rate shall be applied to the circularity indicator(DEFRA, 2018b).

Sustainability issues		Indicator	Solar PV	Onshore wind	Biomass CHP
Techno-economic Category	Reliability	Availability factor	15%	98%	95%
		Capacity factor	10%	30%	80%
	Dispatchability		8	8	4
	Cost	Levelised cost	99	52	152
	Financial feasibility	Payback period	9	4	10.5
Environmental Category	Circularity	Material circularity	56%	62%	56%
		Fuel circularity	0%	0%	0%
	Energy Payback	Energy payback period	3.3	1	0.87
	Acidification Potential (AP)		5.26E+01	1.02E-01	8.42E-01
	Eutrophication Potential (EP)		8.08E+04	4.53E-02	2.93E-01
	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)		1.33E+05	1.42E+01	1.65E+01
	Global Warming Potential (GWP 100 years)		4.76E+05	1.66E+01	5.77E+01
	Human Toxicity Potential (HTP inf.)		4.73E+07	4.12E+01	9.25E+01
	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)		4.69E+07	3.09E+04	2.94E+04
	Ozone Layer Depletion Potential (ODP, steady state)		2.30E+00	1.15E-06	3.80E-06
	Photochemical. Ozone Creation Potential (POCP)		6.13E+01	1.24E-02	9.33E-02
	Terrestric Ecotoxicity Potential (TETP inf.)		1.18E+02	7.18E-01	3.89E+00
Social Category	Fuel poverty	Bill reduction rate	54%	n/a	n/a
	Employment provision	Employment provision	0.65	14.62	8.7

Table 7.1 Sustainability performance of three assessed technologies: solar PV, onshore wind and biomass CHP

Sustainability issues		**Indicator**	**Solar PV**	**Onshore wind**	**Biomass CHP**
Techno-economic Category	Reliability	Availability factor	3	1	2
		Capacity factor	3	2	1
	Dispatchability		2	2	1
	Cost	Levelised cost	2	1	3
	Financial feasibility	Payback period	2	1	3
Subtotal			**10**	**5**	**9**
Environmental Category	Circularity	Material circularity	1	2	1
		Fuel circularity	0	0	0
	Energy Payback	Energy payback period	3	2	1
	Acidification Potential (AP)		3	1	2
	Eutrophication Potential (EP)		3	1	2
	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)		3	1	2
	Global Warming Potential (GWP 100 years)		3	1	2
	Human Toxicity Potential (HTP inf.)		3	1	2
	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)		3	2	1
	Ozone Layer Depletion Potential (ODP, steady state)		3	1	0
	Photochem. Ozone Creation Potential (POCP)		3	0	0
	Terrestric Ecotoxicity Potential (TETP inf.)		3	1	2
Subtotal			**31**	**13**	**15**
Social Category	Fuel poverty	Bill reduction rate	1	2	2
	Employment provision	Employment provision	3	1	2
Subtotal			**4**	**3**	**4**
Grand Total			**44**	**21**	**27**

Table 7.2 Sustainability performance ranking of three assessed technologies: solar PV, onshore wind and biomass CHP

7.2 Energy mix scenarios

Three fictional scenarios of energy mix using existing decentralised energy technology within the Northeast region are analysed in this section. Purpose of carrying out this scenarios analysis are in two folds: firstly, is to demonstrate how the designed mode can be applied to examine energy mix scenarios and assists with decision making and energy planning; secondly, it aims to explore the implication of potential future regional electricity mix scenarios in the Northeast region of UK.

Presume the annual electricity demand is equivalent to assumption of the Northeast region of England at 1,162,200 MWh (DBEIS, 2017c), and this demand is to be supplied by solar PV, onshore wind and biomass CHP; the three analysed scenarios are:

1) Base case scenario. This scenario is based on the ratio of biomass, onshore Wind and Solar PV in the present day electricity mix (DBEIS, 2018b). The energy mix is made of solar PV 12%, onshore wind 55% and biomass CHP 33%.

2) Low carbon scenario. This scenario is established based on energy mix achieving 25% carbon emission reduction in comparison to the base case scenario, the carbon emission is computerized using CO_2 equivalent emission. The energy mix is made up with 9% solar PV, 60% onshore wind and 31% biomass CHP.

3) High demand scenario. This scenario is driven by the goal of achieving 64% of average operational capacity; therefore it is assumed that biomass CHP is the baseload technology and supplies 90% of the energy requirement, and solar with the lowest score in the techno-economic performance will share 3% of total energy load and onshore wind will share 7% of the total demand.

Based on the annual energy demand, and assumed energy mix, the required installed capacity for each technology is listed in table 7.3 below.

Base scenario	**Energy technology**	Solar PV	Onshore Wind	Biomass CHP
	Energy mix (%)	**12%**	**55%**	**33%**
	Required installed capacity (MW)	15	24	5
Low Carbon scenario	**Energy technology**	Solar PV	Onshore Wind	Biomass CHP
	Energy mix (%)	**9%**	**60%**	**31%**
	Required installed capacity (MW)	12	27	5
High Demand scenario	**Energy technology**	Solar PV	Onshore Wind	Biomass CHP
	Energy mix (%)	**3%**	**7%**	**90%**
	Required installed capacity (MW)	3	3	15

Table 7.3 Summary of scenarios considered

5

Results for these scenarios are illustrated in table 7.4, and ranking of scores is shown in table 7.5 below. The high demand scenario has the best performance among all, particular in environmental category which is unexpected; but it scores the lowest in the social category for its limited ability to alleviate fuel poverty and employment provision; in addition, the energy cost per unit is also much higher than the other two scenarios and this also result in longer payback period. This scenario may favour stakeholders with higher energy demand and flexible budgets, and also interest in improving environmental impacts from energy consumption.

Interestingly the Low carbon scenario does not have the best environmental performance among all categories despite the effort of achieving over 25% carbon reduction, this is predominately caused by higher proportion of solar PV involvement in the energy mix; it also has the lowest energy cost but also the lowest dispatchability due to smaller proportion of biomass CHP included in the energy mix. The positive side is that the levelised energy cost is low, therefore this may favour stakeholders with aim to achieve carbon reductions within limited budget. The low carbon scenario also scores higher in employment provision and energy period; but the difference is less than 5% in both indicators means unless large scale of installation is involved otherwise this character will not be very prominent.

The base scenario scores the lowest in overall performance, but it offers the highest bill reduction rate; therefore this may be suitable for stakeholders with tackling fuel poverty as key goal in mind.

		Scenarios		
Sustainability issues	**Indicator**	**Base scenario**	**Low carbon**	**High demand**
Techno-economic Category	Availability factor (%)	86.99%	89.56%	92.65%
	Capacity factor (%)	31.00%	43.73%	64.40%
	Dispatchability	8	12	4
	Levelised cost (£/MWh)	90.64	87.23	142.42
	Payback period (year/MWh)	6.745	6.465	9.91
Environmental Category	Material circularity (%)	59.26%	59.56%	55.77%
	Fuel circularity (%)	0%	0%	0%
	Energy payback period (year/MWh)	1.23	1.1667	0.919
	Acidification Potential (AP) [kg SO2 eq.]	6.64E+00	5.05E+00	1.82E+00
	Eutrophication Potential (EP) [kg Phosphate eq.]	9.70E+03	7.27E+03	1.62E+03
	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	1.60E+04	1.20E+04	2.69E+03
	Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	5.72E+04	4.29E+04	9.57E+03
	Human Toxicity Potential (HTP inf.) [kg DCB eq.]	5.67E+06	4.25E+06	9.46E+05
	Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	5.65E+06	4.24E+06	9.66E+05
	Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	2.76E-01	2.07E-01	4.61E-02
	Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	7.39E+00	5.55E+00	1.31E+00
	Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	1.58E+01	1.23E+01	1.47E+01
Social Category	Bill reduction rate (%)	6.48%	4.86%	5.40%
	Employment provision (job/MW)	10.99	11.53	9.08

Table 7.4 Sustainability performance results of three assessed scenarios

		Scenarios		
Sustainability issues	**Indicator**	**Base scenario**	**Low carbon**	**High demand**
Techno-economic Category	Availability factor (%)	3	2	1
	Dispatchability	2	3	1
	Capacity factor (%)	3	2	1
	Levelised cost (£/MWh)	2	1	3
	Payback period (year/MWh)	2	1	3
sub-total		**13**	**8**	**9**
Environmental Category	Material circularity (%)	2	3	1
	Fuel circularity (%)	0	0	0
	Energy payback period (year/MWh)	3	2	1
	Acidification Potential (AP) [kg SO2 eq.]	3	2	1
	Eutrophication Potential (EP) [kg Phosphate eq.]	3	2	1
	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	3	2	1
	Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	3	2	1
	Human Toxicity Potential (HTP inf.) [kg DCB eq.]	3	2	1
	Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	3	2	1
	Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	3	2	1
	Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	3	2	1
	Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	3	1	2
sub-total		**32**	**22**	**12**
Social Category	Bill reduction rate (%)	1	3	2
	Employment provision (job/MW)	2	1	3
sub-total		**3**	**4**	**5**
Grand total		**46**	**35**	**26**

Table 7.5 Ranking of sustainability performance for three assessed scenarios

7.3 Summary

The outcomes of this chapter can be summarised as follows:

1. In terms of sustainability performance, no technology is superior to another; and definition of sustainability needs to be addressed in the context of regional development target and resource profile.
2. Wind is commonly categorized as intermittent energy source, and thus onshore wind is often associated with unstable electricity supply; however, due to the ideal wind condition of Northeast region, the availability of installed wind turbines appear to exceed that of the other two assessed technologies. This conveys the importance of considering regional characteristics for energy planning.
3. Solar PV is widely considered to be “green energy” technology to the general publics, this is due to the low emission during electricity generation stage. The research discovered that the negative impact of solar PV is mainly occurred during manufacture the system components. This ascertains the necessity of life cycle study when examining sustainability of technologies.
4. Biomass CHP is a stable supply; when supply chain can be sustainably managed, it can be a reliable and dispatchable energy supply with low environmental impacts.
5. Energy sustainability is complex, and energy decision making cannot be single-goal oriented; instead an integrated assessment needs to be conducted in order to achieve the best solution. Although the low carbon scenario satisfies the goal of reducing the carbon emission by 25% in comparison to the base scenario, it does effectively reduce the overall environmental impact; on the other hand, the high demand scenario not only offers the most stable energy supply, it can achieve better environmental performance comparing to the other two scenarios, with the higher electricity cost as the downside.

Chapter 8 Summary

This research developed a regional life cycle sustainability assessment framework combines the triple bottom line principle and life cycle approach, and this framework was applied to three dominate decentralised renewable energy options in the Northeast region of UK, they are: solar PV, onshore wind and biomass CHP. The objectives of this research have been met as follows:

1. Existing sustainability assessment framework and indicators have been reviewed in chapter 2

2. A regional life cycle sustainability assessment framework have been established and presented in chapter 3

3. The framework is then applied to assess sustainability of solar PV (chapter 4), onshore wind (chapter5) and biomass CHP (chapter 6)

4. The sustainability performance of the assessed electricity options are then compared. Moreover, the application of the designed framework is demonstrated by applying on three energy mix scenarios (chapter 7)

Assessment on the energy mix scenarios (chapter 7) demonstrated the complexity of energy decision making, and also the effectiveness of the proposed framework in assist sustainable energy decision making process. Before exploring the "most sustainable" energy technology, the definition of sustainability needs to be established in accordance with the regional development strategy and resource profile. And since achieving sustainability is a dynamic process, the energy planning requires constant adjusting. Based on the findings of this study, policy recommendations can be made in the following section.

8.1 Policy recommendations

Based on the findings of this study, policy recommendations can be made as follows:

1. A working definition of sustainability is required in order to establish what energy options are sustainable;
2. There is no "one-fits-all" energy solutions, due to regional social, economic and environmental characteristic, and therefore energy planning is more effective to be carried out on a regional scale;

3. Understanding the impact of a product throughout its entire life cycle is crucial to ensure that decision made in one place does not place burden on the development of another;
4. with many of the installed renewable energy systems soon approaching end of their life time, guidelines and codes of best practice on energy decommission practice needs to be integrated into national legislation to make clean energy technologies really “clean”;

8.2 Recommendation for future work

1. Collation of data is involved and assumptions are made in this research where primary data is not available. Although data sourced and assumptions made were considered to be reliable and representative but they do introduce certainties to the result. The application of assumption and secondary data does not diminish the representativeness and validity of the research, but it does limit the predictive capacity for particular applications. Future study shall include the missing information; for example the hidden subsidies, actual cost information on power plants and employment number etc.
2. Other currently operating grid-connected technologies in the region (such as offshore wind, natural gas CHP, natural gas with CCS etc.) may be included in future studies, to allow a more comprehensive comparison.
3. Decommission practice of energy technologies shall be further investigated.

For future application to cases involving different policymaking processes and market mechanisms, the assessment indicators can be modified to cater to the particulars of the application. The indicator selection process should follow the guidelines provided in this study, and the structure of the proposed framework should remain unchanged.

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