Department of Mechanical and Aerospace Engineering

The Application of Techno-Economic Evaluation to Inform Policy Development

Author: William Gabriel Monteith

Supervisor: Cameron Johnstone

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Signed: *William Monteith* Date: 30/08/2021

Abstract

The CfD policy mechanism has been successful for the Offshore Wind Sector in accelerating the transition to Renewable Energy Sources (RES), by procuring large amounts of clean energy for the lowest cost to the consumer through an auction process. However, recent auction rounds have seen a decrease in local content for the UK turbine jacket manufacturing sector. Which has seen companies such as BiFab go into administration impacting the regenerational capabilities associated with renewable energy opportunities that the UK Governments Energy White Paper proposal seeks to maximise on. This has highlighted the issues surrounding the lowest cost mechanism and its impact on securing the economic benefits associated with primary, secondary and tertiary impacts of local content. The failure to predict this happening could be related to the lack of quantification surrounding secondary and tertiary impacts due to the absence of a global standardised framework for Techno-Economic analysis (TEA).

This research looks to quantify some of the primary, secondary and tertiary impacts associated with CfD bid prices and subsequent local content by using knowledge transfer of governmental reports and academic literature to create a modelling framework that enables the quantification of indirect impacts. By investigating the shortcomings of the CfD mechanism through hindcasting, this paper highlights the influence the application of techno-economic evaluation has on informing policy development.

The integration of the three pillars of sustainability to frame the parameters used in the model and the incorporation of circular principles, highlight how the economic benefits associated with awarding a fabrication contract for 4 turbine jackets to a local UK company, resulting in a 25% increase of the CfD strike price, far outweighs the benefits of the lower strike price agreed for the Seagreen windfarm project. This is modelled through a hindcasting process which uses information from the Scottish Governments BiFab Inquiry. The inquiry was conducted due to the failure of the local jacket fabrication company BiFab to be awarded a single contract for the Seagreen project resulting in the loss of £40 million of public money and the subsequent failure to secure any economic benefits from jacket fabrication.

The results of the modelling within this dissertation back the recent reports published by the Scottish Government and the Scottish Offshore Wind Energy Council regarding their acknowledgment of the UKs failure to secure anything close to the potential maximum amount of economic benefits associated with the OWS manufacturing supply chain.

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allocation of 42% of the overall total capacity as possible. For this instance, the hypothetical model windfarm was 1000MW only 75MW short of the aim for the capacity of the Seagreen development. Page **57**

List of Abbreviations

TEA – Techno Economic Analysis

EMF - Ellen Macarther Foundation

CfD – Contracts for Difference

MW – Megawatt

GW – Gigawatt

AU Gov – Australian Government

RES – Renewable Energy Sources

TRL – Technology Readiness Levels

TPL – Technology Performance Levels

HRES - Hybrid renewable energy system

EIA – Environmental Impact Assessment

IAIA - International Association for Impact Assessment

GVA – Gross Value Added

GDP – Gross Domestic Product

GHG – Green House Gasses

BEIS – Business Energy & Industrial Strategy

OWS – Offshore Wind Sector

SME – Small-to-Medium Enterprise

LCOE – Levelized Cost of Energy

ORE – Offshore Renewable Energy

EV – Electric Vehicle

EVOW - Economic Value of Wind

OWGP - Offshore Wind Growth Partnership

OWSD – Offshore Wind Sector Deal

CEWS – Circular Economy for Wind Sector

DCLG - Department for Communities and Local Government's

Chapter 1 – Introduction

The need to change our current energy systems has never been more significant due to the threat it poses to our climate, biodiversity and our health (Ellen Macarther Foundation (EMF), (EMF, 2020). The emerging climate crisis and the international targets set by the 2015 Paris accord has meant that a rapid transition away from a predominantly fossil fuel-based system must be prioritised. Governments across the globe aim to reduce carbon dioxide (CO_2) and greenhouse gas (GHG) emissions, as stated within the Paris accord, in order to limit temperature rises to 1.5°C of pre-industrial levels (Bauer & Menrad, 2019). The UK is looking to meet this commitment by creating a net-zero economy that reduces emissions whilst positively impacting jobs, economic growth and regional regeneration (ORE, 2020).

Innovative solutions that are sustainable and utilise renewable energy will need to be integrated into the energy system rapidly if the UK is to reach net-zero targets by 2050 (ORE, 2020). Key to the success of the transition will be the ability of SMEs creating sustainable innovative solutions that integrate into the energy system as seamlessly as possible (ORE Launch Academy, 2020). The need to accelerate the successful penetration of innovative solutions within the energy system has been realised by the UK government. As a result a number of policies, government agencies and organisations have been setup or implemented.

However, a delicate balance must be struck between the initial higher cost of integrating new technologies, processes and operations, and the initial increased cost to the consumer regarding the Levelized cost of energy (LCOE). Herein lies one of the many challenges governments face when committing to the necessary green targets, as political capital usually dictates the development of policies and which government stays in power within the four to five-year governmental cycle in the UK. A substantial rise in energy bills related to the initial adoption of renewable technologies could result in the popularity of a ruling party decreasing significantly along with their re-election chances.

The application of techno-economic analysis and evaluation is a significant tool that is used by governments and organisations to determine which renewable generating technologies will perform best both technically and economically whilst minimizing cost to the consumer (W. Ma et al, 2018). Subsequently, the application of Techno-Economic Analysis (TEA) is used to inform the development of governmental policy related to the energy system.

One of the Government's main mechanisms used to support low-carbon electricity generation is the contracts for difference (CfD) scheme. It's the UK Government's flagship scheme for procuring big volumes of clean power at lowest cost to bill payers, and is the delivery vehicle for the decarbonisation of the power sector and by extension, other sectors of the UK economy (Gov.UK-BEIS 2016). It works as an auction process with prospective bidders looking to secure contracts for renewable energy development projects. One of the main determining factors when awarding contracts to prospective bidders has been the lowest cost per MWh that a bid makes (R. Williams, 2019). This ensures that the LCOE for renewable projects remains as low as possible, however most recently the process for awarding contracts has come under scrutiny with short comings being identified.

In December 2020 the fabrication company Bifab, based on the south east coast of Fife went into administration. One of the main reasons for this was their inability to secure a manufacturing contract through the last CfD auction round for only 4 turbine jackets for the upcoming Seagreen Wind farm development project (BiFab Inquiry, 2021). BiFab's fabrication yard was only 60 miles from the proposed windfarm development site off the coast of Angus in the North Sea firth. The company had a previous track record of fabricating a significantly larger amount of turbine jackets. In 2017, they were fabricating 26 turbine jackets whilst employing 1400 people directly and indirectly (Rob McLaren, 2020). By heavily favouring the primary impact of cost when awarding contracts the CfD scheme has opened up the market to international state backed organisations that are able to undercut bids of local companies who are competing for the contracts (BiFab Inquiry, 2021). This has subsequently had an impact on the local supply chain within the UK regarding its growth within the renewable and sustainable sector which has resulted in companies such as BiFab going into administration and negatively impacting the regional economy and prospects of regeneration.

This paper will explore the potential for creating a model framework that attempts to quantify the primary (ie cost to the consumer), secondary (ie direct & indirect job creation) and tertiary (ie crime rate, health and social cost of carbon) impacts related to the local content of prospective CfD bids by incorporating circular principles where possible. Hindcasting, which is a way of testing a model by entering known or closely estimated inputs from past events to compare how well the output results perform against the actual result, will be conducted.

By using the process of hindcasting we will be able to robustness test the last CfD auction round and it's mechanism, based on qualitative and quantitative information from a suitable case study regarding its primary, secondary and tertiary impacts. After critiquing and identifying potential short comings in the model a supported decision-making framework, for potential use regarding techno-economic analysis of new and embryonic renewable technologies that enables more accurate economic quantification of the primary, secondary and tertiary impacts when considering lower costs for energy, will be developed.

1.1 - Background

Net-Zero

The UK government has recently set out a ten-point plan for a green industrial revolution along with publishing a White paper on “Powering our Net Zero Future” in response to the existential threat of climate change. In addition to this the government is having to navigate the impacts of the Covid-19 pandemic and Brexit. The white paper and Ten-point plan set out a vision of how the targets of net-zero will be met by 2050 in the UK. This includes how they will transition over from a predominantly fossil-fuel based energy system to a hybrid net-zero energy system, tackling energy generation, transport and heating. To enable this transition, significant investment and innovation by the public and private sectors will be needed in both existing and embryonic technologies that are renewable and sustainable (White Paper, 2020).

UK Offshore Wind Sector

The UK’s offshore wind capability consists of several windfarms located in selected areas of the ocean within UK waters. Windfarms consist of various number of wind turbines that harvest wind energy to create electricity that is transmitted through array and export cables, offshore substations, onshore substations and eventually to the national grid for consumption. Wind turbines can vary in the amount of power (typically in MW) they can generate which determines the windfarms overall rating in MW or GW. Most of the UK’s installed Offshore Wind turbines employ fixed-foundations, currently 90% use monopiles foundations whilst 10% use jacket foundations (ORE Catapult Foundations, 2020). The UK is looking to build floating offshore wind farms as part of their strategy going forward to secure the sectors future prosperity and increase its capability (SOWEC, 2021)

A further commitment to the offshore wind sector to increase its generating capabilities to 40 GW by 2030 (which should be enough energy to power every home in the UK) has been made (White Paper, 2020). In part, this is due to the Wind sector’s unprecedented success in scaling up and integrating wind turbine technology over the last ten years. Which has led to the cost per megawatt hour (MWh) of generated wind energy dropping significantly; as of

2019 the rough estimate was around £39.50 for offshore wind (Bifab Inquiry, 2021). Remarkably, five years previously, the cost for projects was priced at £114 per MWh (Bifab Inquiry, 2021). This has proven that accelerated adoption of renewable generation technologies is achievable with the necessary framework and governmental policies in place. However, there have been issues regarding governmental policies related to the awarding of lucrative contracts to companies who are outsourcing the manufacturing work to overseas organisations. This has impacted the effective development of low carbon electricity generation supply chains within the UK (Bifab Inquiry, 2021).

Energy System Challenges & Solutions proposed for the UK

For the transition to succeed, further penetration of innovative renewable technologies must be successfully integrated into the energy system if targets are to be met by 2050. Decarbonising heat and transport is proving more challenging than generating green energy. This is largely due to two factors, One: the current energy infrastructure system requires updated and upgraded with many parts of the system relying on old technology that cannot handle the increased loads from renewable energy sources without huge investment to support renewable heat and transport solutions (R. Bolton et al, 2015). Secondly: it is difficult to radically change the system quickly without adversely impacting many jobs and increasing prices for consumers for both the transport and heating systems as the renewable technologies that could provide solutions are relatively immature or at embryonic stages of technology readiness levels (TRL) meaning their price per MWh is not commercially favourable yet (AU Gov, 2014).

The two renewable solutions which the UK government currently favours for transport and heating challenges are hydrogen and electrification (White Paper, 2020). Both pose issues regarding technology performance and readiness levels as well as their sustainability credentials in particular electric vehicle (EV's) batteries (Dominish, E et al, 2019). These issues have a financial impact on the viability of proposed solutions which mean adoption of these technologies into the energy system now will result in an initial increase in cost to the consumer. How much of an increase is dependent on many variable factors within the private and public sector including, commercial readiness determined by the influence of market competition and governmental policies.

Tools Used to Analyse & Develop Commercialisation of RES

For organisations and governments to determine what innovative renewable technologies are potentially economically feasible solutions to the net-zero challenge, the proposed technologies economic performance must be analysed based on technical and financial input parameters. Therefore making, techno-economic analysis (TEA) of renewable technology solutions a powerful tool that is used to assess the economic viability of a solution whilst also providing direction to research, development, investment, and policy making (R.Muhmud et al, 2021). TEA integrates well in the initial process many private companies and R&D centres use for project development. Whilst undertaking techno-economic analysis, a key metric used by the UK and Australian governments to measure the technical readiness of renewable energy solutions is the technology readiness levels (TRL) index (Australian Gov, 2014). "The TRL index is a globally accepted benchmarking tool for tracking progress and supporting development of a specific technology through the early stages of the technology development chain", (Australian Gov, 2014). The TRL methodology was developed at NASA by Stan Sadin in 1974 and since it's inception the process has evolved and is implemented across a wide range of industries including renewable technologies (Australian Gov, 2014). It's currently used by government programs related to emerging renewable technologies to help applicants identify the stage of development of their innovation (Australian Gov, 2014). Another tool that can be used in conjunction with TRLs is the technology performance levels (TPL), by using both within a matrix the evaluation, comparison and discussion of different research technology development trajectories over the technology readiness and performance levels plane can be achieved (Weber, Jochem, 2012). The matrix of TRLs and TPLs can give valuable advice on the development strategy and tools required to achieve successful technology development outcomes at reduced development time, total development cost and encountered risk (Weber, Jochem, 2012). There are nine levels within both TRL & TPL indexes, quantifying both techno-economic functional and lifecycle performance of proposed technologies or services (Weber, Jochem, 2012).

UK Government Strategy: Policies & Agencies

The UK Government have setup various schemes and policies to enable innovation to grow and succeed within the UK. The Offshore Renewables industry has been identified as a high growth sector by the government with particular focus on how to accelerate innovation development (ORE Catapult). In 2013, the government setup nine publicly funded independent organisations called Catapults that are technology innovation and research centres. The catapult for Offshore Renewable Energy (ORE) is focused on accelerating innovation within the sector by helping small medium enterprises (SME) through the development phase of various TRLs for their innovative products, services and solutions (ORE Catapult). Various policies have been implemented by the UK government to help organisations through TRLs, such as: Grant funding, Programmes, Green Investment Banks and the Contracts for Difference scheme. Part of the Catapult's purpose is to advice and guide prospective SME's and large organisations about government policies that may have an impact on the industry or be of use to them throughout the development of innovative solutions. Part of the UK's government aim is to build a strong, competitive supply chain of businesses that provide the innovations, products and services needed to make the sector a global leader (ORE Catapult).

Circular Economy

With an increasing global demand the current energy system is not suitable for the needs of tomorrow due to the nature in which it extracts finite resources, is wasteful, polluting, and harms natural systems (EMF, 2020). Over the last century, the increasing economic activity consumption of raw material has led to material and energy import dependence (EEA, 2015). As such, integrating circular economic principles is a potential solution to the current model that will increase sustainability. The UK government has also made further commitments on moving towards a more circular economy, as stated in their Circular Economy Package policy statement published in 2020 (Gov.UK, 2020). This incorporation of circular economic principles will have an impact on a wide range of industries including the offshore renewable sector. As the 1st generation of offshore wind turbines near their end of lifecycle usage the opportunity to implement circular principles within decommissioning or extension of usage is possible (ORE Catapult, 2020). This could provide a solution to the disposal, decarbonisation and potential reuse of components. As an example, 80-85% of the weight of a wind turbine is recyclable (ORE Catapult, 2020). The incorporation of circular principles also creates the opportunity for the UK to develop supply chains that increase the security of supply for the materials needed to manufacture renewable technology products (Tihomir Tomić, Daniel Rolph Schneider, 2018). The "closing of the loop" approach used within circular principles effectively allows more sustainable resource management, whilst also potentially reducing the reliance on other nations for imported materials (Tihomir Tomić, Daniel Rolph Schneider, 2018).

The Three Pillars of Sustainability

Over the last twenty years sustainability has persistently been defined through three main pillars or principals, encompassing Society, Economy and Environment (B.Purvis et al, 2019). Contemporary literature acknowledges the explicitly embedded nature the three pillars have had in the formulation of the UN's diverse set of 17 sustainability development goals (SDG's), which were first introduced at the United Nations Conference on Sustainable Development in Rio de Janeiro in 2012 (UN, 2015). The SDG's have been adopted by the UN "as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity" (UN,2015). The three pillars of sustainability have been used by the UK Government and devolved administrations to underpin their sustainable development strategy making sure sustainable policy respects all three principals. The UK Government acknowledges that the three pillars are interconnected and that the long term economic growth is reliant on, protecting, and enhancing the environmental resources that underpin it, and paying due regard to social needs (GOV, SD).

This paper will use the three pillars to define the parameters used within the analysis modelling and evaluation. The model will attempt to incorporate the principles of sustainability as much as possible by attempting to frame the primary, secondary, and tertiary impacts in the context of the three main pillars. This will hopefully allow the interconnectivity and relationships between all three to be highlighted regarding their performance in relation to the various scenarios modelled.

1.2 - Aims & Motivations

With the UK Government recently publishing a number of policy proposals and route-map strategies for the transition over to a net-zero system and commitment to circular economic principals, analysis regarding the current governance and infrastructure is needed to ensure the promises of economic regeneration is met. Brexit and Covid-19 have had and will continue to have an impact on the UK economy. As such, "building back better" must also ensure that regional and local employment levels in areas that were previously targeted for regeneration are met through the creation of sustainable job opportunities related to the renewable sector. Or else, public opinion on the transition over to net-zero may sour impacting the amount of political capital the UK government has to deploy the necessary policies to reach emissions targets.

Even though commitments have been made to move away from a linear economic system towards a more circular one, certain policies related to the acceleration of innovative renewable solutions have not aligned with the commitments set out by the circular economy package. By highlighting the shortcomings of particular policies and re-examining specific parameters of the techno-economic analysis around certain renewable technologies, this paper will look to quantify the secondary and tertiary impacts related to policy development and deployment. The model will look to justify the re-examining of the initial cost impact related to MWh for renewable technologies and how giving greater considerations to the secondary and tertiary impacts could result in closer alignment with circular principles that benefit the development of local supply chains and regeneration for mature, new and innovative renewable technology solutions going forward.

Project Objectives

This study will analyse the current performance of the CfD scheme related to the transition of the energy system over to net-zero and evaluate the application of techno-economic analysis to inform policy development. The process will include:

- A review of literature to identify key parameters that affect TEA
- Examination of the complex nature of factors defining parameters and how they can potentially be quantified.
- Using Excel a Hindcasting model will be developed to help assess techno-economic scenarios related to Jacket manufacturing.
- A framework advising policy development regarding new and embryonic renewable technology deployment to achieve balance between cost to the consumer & GVA benefits (Gross Value Added).

1.3 - Scope

With the success the wind sector has had over the last 10 years and the commitment from the UK government to further invest into the offshore sector, evaluating the policies to determine any shortcomings is paramount when developing and modifying policies related to the integration of new innovative renewable solutions.

A particular policy that has helped keep consumer costs down and guaranteed investment security has been the CfD scheme. However, the mechanics of the scheme give overarching priority to the lowest cost per MWh. This has led to the UK manufacturing sector losing out on bids to companies based on the other side of the world for projects based in the UK. The difference between UK based company bids and other international organisation can be between 10-25% (BiFab Inquiry, 2021). This is based on the parameters associated with the initial cost impact and don't take into consideration the secondary and tertiary impacts that are harder to quantify but may have a significant impact on the UK's ability to acquire all the potential economic benefits related GVA from local content.

The model used to conduct hindcasting in this paper will attempt to quantify the secondary and tertiary impacts to help create a framework that incorporate certain circular principals to allow policy makers to find an equilibrium between low cost and wider societal and environmental value. Robustness testing will be used to evaluate the CfD scheme and its current form, the case study used for hindcasting will be the failed BiFab bid to manufacture turbine jackets for the Seagreen project based in close proximity to the fabrication yard in Fife.

Results of the robustness test and sensitivity analysis will be analysed, and potential shortcomings related to circular principles evaluated. An overview of how shortcomings in techno-economic evaluation and governmental policy development occurred will be attempted for the CfD mechanism.

1.4 - Methodology

The process of evaluating techno economic analysis and its application to inform policy development, will include:

- Reviewing Literature on techno-economic evaluation, Governmental strategy and policies aimed at the integration and acceleration of innovative renewable solutions.

- Identify parameters used within the techno-economic evaluation for the manufacturing of renewable technologies.
- Integrate key parameters into an Excel model to quantify the secondary and tertiary impacts to be able to compare their benefit valuation against CfD bids.
- Undertake sensitivity analysis to model various scenarios to gauge overall economic impact and decipher a balance between low cost and GVA.
- Based on literature and model results develop and demonstrate a framework to be used that incorporates more circular principles related to the awarding of manufacturing contracts for renewable technology solutions in the UK.

Chapter 2 - Literature Review

Intro: Following on from the information provided within the background section of this paper the Literature review will take a deeper look into the topics mentioned and introduce other factors that have shaped the aims and outcomes of this paper. The predominant focus will be on how TEA evaluation has impacted the development of government policy in relation to the integration and acceleration of innovative renewable technology.

2.1 Techno-economic Analysis Overview

TEA is a research agenda that is used in order to assess and evaluate the economic impact and consequences of innovative new technology. It examines technology development and research projects through the main parameters of costs, benefits, risks uncertainties and timeframes. This comes together as part of an extensive economic thought termed techno-economic paradigm (C. Perez, 2009)(C. Freeman, 1991).

Innovation based theory of economic growth and social development is fundamental to the techno-economic paradigm as conceived by Chris Freeman and Carlota Perez (inspired by the economists Schumpeter and Kondratieff). Both claim the most important factor in economic development is the role of technology, their focus is on the economic process of technological change. The fundamental concept is that technology and economy co-evolves (C. Freeman, 1991).

For TEA to evaluate the technical and economic feasibility of a process or technology a model needs to be created that integrates a wide variety of factors. The subsequent techno economic model is an integrated process and cost model which usually combines elements of process design, process modelling, equipment sizing, capital cost estimation, and operating cost estimation (C. Burk, 2018).

With the continued transition and acceleration towards a Hybrid renewable energy system (HRES) to reduce carbon emissions and ease energy consumption the need to identify the optimum mix of RES is paramount on a national, regional and building levels scale (W. Ma et al, 2018). As such, TEA of HRESs is vital to epitomise its supremacy and identify what kind of system and “corresponding considerations are needed for a certain situation”, (W. Ma et al, 2018).

The analysis process of TEA requires various steps to be undertaken such as: Scoping, Choosing Reference Designs, Selecting Scenarios, Developing Process Flows to Use for Analysis and Creating Cost Models (NREL, 2020).

- Scoping – essentially you are identifying the questions you are trying to answer. Depending on time and funding constraints you may have to prioritize some areas for high detail and rely on assumptions for others.
- Choosing Reference Designs - some device designs or aspects of devices in academic literature are not always reflective of what will be used if that technology were produced commercially.
- Selecting Scenarios – an example would be Modelling different manufacturing locations to reflect local differences in costs such as labor and electricity rates. By varying design parameters such as product size or material compositions, or process options such as deposition methods or automation.
- Developing Process Flows to Use for Analysis – as mentioned within the NREL tutorial of TEA, "there are other aspects of process flows that must be selected which vary significantly at different scales and stages of production, such as the through-put of production equipment, uptime, or yields."

2.2 - Cost Models

Creating Cost Models requires the input of various quantifiable parameters. A key metric of cost models is the minimum sustainable price (MSP), a price that provides the minimum rate of return necessary in a given industry to support a sustainable business over a long term (NREL, 2020). Specifically, MSP is influenced by a number of factors including manufacturing costs, overhead costs, and other financial considerations such as financing, discount rates, and tax incentives. Understanding manufacturing costs (also known as the cost of goods sold) are key to highlighting major cost drivers for particular innovative renewable technologies (NREL, 2020). These manufacturing costs can be broken down into materials, labour, electricity, maintenance, equipment costs, and facilities (NREL, 2020). This understanding of cost breakdown is critical to manufacturers who are trying to identify lower costs and calculate the MSP to be used to maximise growth and profit.

Other than Manufacturing costs the other set of costs that influence MSP are overhead costs. These include research and development costs, as well as sales, general, and administrative costs (NREL, 2020). According to the NREL “Overhead costs can vary significantly between companies, as well as over time within a given company. After summing up manufacturing and overhead costs, we then obtain the minimum sustainable price by assuming an operating margin, typically desired when pricing products within a given industry. An operating margin accounts for interest payments, profit, and the corporate tax rate. A sustainable operating margin can be estimated by interviewing industry members or by calculating the price needed for a business to break even over an assumed business lifespan, while adjusting for inflation and the cost of capital”. The technique of interviewing industry members is consistently used within other research papers, as well as governmental reports and inquiries associated with TEA and predicted future trends. As seen within papers such as E Uyarra et al, 2016 which examines the institutional and governance issues arising from the UK's support for innovation in low carbon manufacturing sectors.

2.2.1 - Cost Model Methodology Shortcomings

Focusing on the primary impact of MSP can lead to harder to quantify secondary and tertiary impacts being ignored that may indirectly have significant positive benefits to wider society. An example of this could be the focus on MSP within the UK government’s Contracts for Difference scheme that heavily focuses on lowering energy costs by awarding contracts to the lowest bidder. This has recently led to the content of UK based manufacturing companies reducing which has had a direct impact on the development of the UK’s renewable supply chain and resulted in job loss and redundancies (BiFab Inquiry 2021). The economic impact of the loss of jobs or failure to create and develop new jobs could be far greater than the benefits of awarding contracts for the lowest cost to reduce the LCOE.

The techno-economic paradigm shifts within each stage of industrial and technological advancement and evolution within our current economic system. This concept is discussed and covered within Perez’s 2009 paper on Technological revolutions and techno-economic paradigms, stated as follows: “A techno-economic paradigm is then the result of a complex collective learning process articulated in a dynamic mental model of the best economic, technological and organisational practice for the period in which a specific technological revolution is being adopted and assimilated by the economic and social system” (C.Perez, 2009). As such, the recent systematic transition of the energy system and subsequent focus on renewable technology within the UK has meant that we are in period of a complex learning.

This means that shortcomings regarding policy development will be exposed and hopefully amended.

2.3 – Techno-Economic Analysis Modelling Software

There is a need to evaluate the processes on how we deploy governmental policy that integrates and accelerates renewable energy sources (RES). TEA modelling is often deployed using computer software such as HOMER and EnergyPlan, however problems may occur in the process of designing and evaluating Hybrid Renewable Energy Systems (HRES) due to improper use of analysis methods or ignoring specific considerations (W. Ma et al, 2018). According to the Renewables 2017 Global Status Report over 164 countries have set renewable energy targets. This includes 48 developing countries whose leaders have committed to work towards installing a complete Renewable Energy scenario (REN21, 2017). As such each country has, their preferred TEA modelling method depending on countries various needs and situation. This can be seen when looking at what software tools are recommended when analysing at a national level. The top three tools that are most used and recommended for national application are EnergyPLAN, INFORSE and MARKAL/TIMES (W. Ma et al, 2018). Within the UK EnergyPLAN is the most used modelling tool integrating RE sources into the energy system regarding TEA evaluation, according to W. Ma et al, 2018. It is also used within other case studies associated with different countries and various energy sources such as Denmark with a flexible regulation system mix of CHP plants and Wind turbine's. These TEA studies look at the increased penetration of wind up to 100% and asses it's impact and timescale of deployment (H. Lund, 2005).

2.4 - Techno-Economic Analysis Modelling Outcomes

When looking at the UK on a national level the case studies undertaken and modelling done indicate that to obtain a technical and economic optimum various energy uses (thermal, mobility and electrical) need to be taken into account instead of only considering the electricity sector (N.A. Le, S.C. Bhattacharyya, 2011). Therefore, allowing RE penetration to be more sustainable. Subsequently, the use of the EnergyPLAn and other software tools have been used as a reference point to help shape the strategy and thinking behind harvesting more RES within the development of future energy integration policy and national energy planning (W. Ma et al, 2018). The evaluation of results from various case studies have indicated that the primary factor that TEA is predominantly concerned with is the energy systems ability with decentralized generation of RE to gain relatively more costs saving over the conventional current systems (Mason IG, et al, 2010). Further development regarding direct indicators such as the MREI (Maximum Renewable Energy Integration) have been proposed to asses the Maximum RE flexibility in absorbing renewable energy. As such, complicated techno-economic implications will have to be considered more closely when analysing energy system under higher levels of RE penetration (Zakeri B et al, 2015). However, results from Connolly et al suggest that a 100% RE system will be financial beneficial by 20 billion euros in 2050 compared to 2012. The same study (Connolly D, et al, 2016) measured and estimated the impacts of a 100% renewable energy scenario in Europe by 2050 would have on the economy (looking at total annual socio-economic cost), energy (primary energy supply) and environment (carbon dioxide emissions). It concluded that even though the cost of their smart energy scenario was 10–15% higher than our current system the economic benefit of ten million additional direct jobs within the EU, based on local investments, would provide a far greater overall economic benefit.

2.5 - Limitations of Techno-Economic Analysis Modelling Results

The analysis within Connolly D, et al, is completed from a socio-economic perspective. Giving credence to the overall cost of energy, the type of resources used, the number of jobs created, and the balance of payment for the nation. The parameters stated within Connolly D, et al are credible examples of the key metrics which define a good or bad energy system from a society's perspective and conclude that: "future energy systems should be considered without imposing the limitations of existing institutions or regulations". However, Connelly D, et al does acknowledge some limitations regarding metrics within the model analysis conducted predominantly related to the exclusion of health costs. Which references M.A. Delucchi et al, 2011 and B.V. Mathiesen, et al, 2011 have highlighted the importance of other secondary and tertiary impacts related to TEA and the significance in terms of peoples well-being and the corresponding cost impact. Within both studies they reference the benefit of less pollution regarding the reduction of CO2 emissions for the general population's health. M.A. Delucchi et al, 2011 and B.V. Mathiesen, et al, 2011, also acknowledge that the increases in costs will occur regarding the transition to a HRES but the costs in the EU will potentially be counteracted by local job creation. The importance of the jobs created is considered, however the benefits of employment regarding its secondary and tertiary impacts on healthcare use and crime rates are not.

W. Ma et al concluded that the majority of countries that had started integrating RES or were modelling a scenario for RES on a large regional scale used different methods and software. Whilst Mijndertvan der Spek, et al 2020 agreed with the selection of a variety of methods they also added in the potential factor of TRL levels as being a factor when selecting an appropriate model. As such, this highlights that techno-economic analysis also requires different methods using different considerations and emphasises depending on a countries unique factors and technology capabilities. Thus, for HRES at national scale micrographic strategies instead of concrete system designing tend to be sought for by energy experts and policy makers (W. Ma et al, 2018).

2.6 - Issues with Techno-Economic Evaluation

An issue highlighted within W. Ma et al, was the use of previous techno-economic studies in Spain and Germany that were used to develop different RE incentive schemes across Europe (Punda. L, et al, 2017), to promote various technologies like PV (Dusonche L, Telaretti E. 2010),(Karakaya E, Sriwannawit P. 2015), wind power (Bean P, et al. 2016) or genetic policy options (UN Energy, 2007), to increase the share of renewables in a country. Due to this work being mainly focused on the initial technical primary impacts of wind energy integration, the socioeconomic and business-economic issues were ignored including the indirect (secondary and tertiary) impacts. These shortcomings were prevalent in a large volume of TEA evaluations constructed in the early 2010s, that commonly failed to include the secondary and tertiary impacts (W. Ma et al, 2018). It can be assumed that these studies may have had a direct impact on the policy development related to the acceleration of RES penetration. This thinking was also backed by E Uyarra et al, 2016 stating that “A number of analysts have pointed to an imbalance in the UK policy mix for low carbon innovation, with insufficient attention directed to-wards supply side instruments and the use of industrial policy to favour the domestic industry (Spencer and Arwas, 2013; Foxon et al., 2005)”. The impact of certain policies developed and implemented from 2010 to 2020 regarding the transition towards a Net-zero system have backed up E Uyarra’s statement. Proof of this can be found in regard to the decrease of local content within winning bids of the CfD scheme. Certain aspects of manufacturing contracts like turbine jackets only had 18% local UK content with the rest of the work being outsourced internationally (ORE Foundations, 2020). The estimated market value of the manufacturing of wind turbine jackets and piles for the UK is £1.6bn over the next ten years (ORE Foundations, 2020). Hence why increasing the local content within these areas of awarded contracts is essential to capitalise on the economic and regenerative benefits this amount of money can have.

2.7 - Factors Impacting the depth of Techno-Economic Analysis Evaluation & Solutions

Part of the reason why secondary and tertiary impacts have not been included in some of the early 2010s (W. Ma et al, 2018) TEA of HRES is because of the nature of complexity associated with the quantification of uncertainties related to indirect impacts and their potential lack of accuracy (Mijndertvan der Spek, et al 2020). However, the development of new uncertainty analysis methods and models if applied and understood can create enhanced complexity which would give additional valuable insight (Mijndertvan der Spek, et al 2020). Another reason could have been that the lack of maturity for the specific RE technologies evaluated within TEA, meaning access to data and knowledge would have been insufficient to derive probability distributions and undertake Monte-Carlo-Analysis (comprehensive uncertainty propagation method), (W. Zimmermann et al, 2020). Thus, knowledge on probability distribution functions of the variables would have been lacking, meaning quantification of the uncertainties related to secondary and tertiary impacts would have been difficult or inaccurate. However, a mitigating measure to this if faced when performing TEA on a new technology is a qualitative methods approach mentioned by Fernández-Dacosta et al, 2017.

A qualitative method can be useful, especially when using a pedigree matrix to establish confidence. Additionally, Multicriteria Decision Analysis (MCDA) may have been lacking or inadequately done in earlier TEAs that helped shape the policy development regarding decarbonisation of certain sectors within the UK. This assumption is based on the premise that MCDA if used correctly (which involves multiple dimensions, such as economic, social, and environmental criteria, and allows to evaluate trade-offs systematically (Wang et al., 2009)), can be helpful in covering all relevant criteria bringing together uncertainty and sensitivity analysis for decision making (W. Zimmermann et al, 2020). As such, the performance of certain Renewable Energy transition policies regarding social-economic and environmental impacts have not met their targets or are not likely too at their current rates (Josh Gabbatiss, 2021), with an attributing factor being the use of poorly implemented or selectively narrow TEA within policy development.

Mijndertvan der Spek, et al 2020, believes the reason for the lack of deployment of more complex analysis related to uncertainty or hard to quantify secondary and territory impacts within most current TEA evaluation is due to unawareness of uncertainty analysis options, as well as a lack of guidance on when and how to use such options. Another factor may be the lack of a global standard TEA framework however, there has been recent attempts to create and justify techno-economic assessment guidelines but they have been focused on particular technology fields such as Carbon Capture and Storage, as mentioned in A. W. Zimmermann et al, 2020. Until there is a global standard that can be adapted to all new innovative and existing RES there may be significant challenges to improving TEA studies in a structured inclusive way. Developing comparability of TEAs could lead to a more accurate analysis including secondary & tertiary impacts (indirect impacts). Additionally, improved comparability & clarity of TEA studies could lead to improved decision making and more efficient allocation of funds and time resources for the research, development, and deployment of renewable technologies as stated in A. W. Zimmermann et al, 2020 & Mijndertvan der Spek, et al 2020. EIA (Environmental Impact Assessment) is a good example of how to implement a global standardised framework that adapts to cover as many scenarios as possible along with considering primary, secondary, tertiary and cumulative impacts. This is due to EIA having an International Association for Impact Assessment. Which is an association of professionals globally involved with impact assessment, including both social impact assessment and environmental impact assessment (IAIA).

2.8 - Techno-Economic Analysis Frameworks

The implementation of framework and acknowledgement of secondary and tertiary impacts associated with social-economic and environmental factors has at least been acknowledged within the recent Scottish Government Offshore Wind to Green Hydrogen Opportunity Assessment Report (OWGHO, 2020). They have implemented a socio-economic framework in line with the Scottish Government’s National Performance Framework (NPF), which is used by policymakers and decision-making bodies to assess and monitor performance. The Socio-economic framework used within assessment of OWGHO report utilised a thorough list of social indicators/parameters to emphasize the indirect (Secondary & Tertiary) benefits of integrated and developing offshore wind and hydrogen in Scotland. The assessment also highlighted how demonstrating benefits according to indicators can highlight to what extent sector aims align with broader policy goals. However, none of the indirect secondary or tertiary impacts were quantified within the report. The government outsourced the cost modelling to a company called Xodus which used CAPEX and OPEX to calculate the Levelised Cost of Hydrogen. The fact there was no reference to potential ranges of quantified secondary or tertiary social-economic or environmental impacts alludes to a situation where there is little confidence in estimations based on the work done in this area for the offshore wind hydrogen sector or that the work to economically quantify these social secondary and tertiary impacts has not been done yet. This may also be due to the maturity of hydrogen technology and at which level the commercially proposed solutions are at within the TRL index. Hence why a more qualitative approach was taken which falls in line with what Fernández-Dacosta et al, 2017 stated regarding new technologies and approaches to quantify uncertainties related to secondary and tertiary impacts.

Table 1: Taken from the Scottish Government Offshore Wind to Green Hydrogen Opportunity Assessment Report (OWGHO, 2020), showing the socio-economic impact framework used in the report that closely aligns with indicators used in the Scottish Government's National Performance Framework (NPF).

	Social Indicator
Individual	Family, family life, and inter-generation issues
	Jobs, career, and employment
	Money and cost of living
Community	Local jobs, local industry, and community sustainability
	Transport connections and technology connections
	Education
	Shops and housing
	Socialising, recreation, parks, and leisure
	Friends, being involved, and supporting others
	Local identity, cultural heritage, and Gaelic
	Healthcare
	Connection to nature and landscape
	Local political and decision-making systems
Wider political and environmental context	Landscape, seascape, wildlife, and environmental change
	National and EU level political and decision-making systems.

2.9 - Estimated UK Gross Value Added from Innovative Offshore Renewable Energy Sources

Other reports published by Government backed entities such as ORE Catapult have attempted to quantify the potential GVA created through jobs within the supply chain of Wave & Tidal Stream development and integration of generating technologies. The report stated that by "2030 tidal stream could generate a net cumulative benefit to the UK of £1,400m, consisting of £1,600m GVA from domestic market, £1,100m GVA from exports, offset by £1,300m of revenue support". This is backed by the assumption that UK companies are expected to retain a majority of the domestic supply chain activity.

Table 2: Tidal stream annual UK GVA in 2030 and jobs supported by 2030 taken from the Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit report (ORE TSWE, 2018).

Component	UK Projects UK Content	UK Projects 2030 spend £m	UK GVA from UK projects in 2030 £m	Non UK Projects 2030 spend £m	UK GVA from Exports £m	Total UK GVA creation in 2030 £m	FTE supported by 2030 £m
Tidal Platform	65%	111	53	403	59	112	1,210
Foundations/ Moorings	80%	23	11	85	5	16	160
Electrical	70%	42	23	153	15	38	460
Installation	60%	21	12	78	7	19	450
Other Capex	72%	21	15	77	20	35	330
O&M [22]	75%	80	56	247	13	69	1,240
Development	75%	7	5	24	10	15	130
Total	70%	307	175	1,066	129	304	3,970

Table 3: Wave energy UK annual GVA in 2030 and jobs supported by 2040 taken from the Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit report (ORE TSWE, 2018).

Component	UK Projects UK Content	UK Projects 2040 spend £m	UK GVA from UK projects in 2040 £m	Non UK Projects 2040 spend £m	UK GVA from Exports £m	Total UK GVA creation in 2040 £m	FTE supported by 2040 £m
Wave energy converter	65%	101	48	1,549	226	275	2,970
Foundations/ Moorings	80%	21	10	327	19	30	280
Electrical	70%	38	21	587	58	79	940
Installation	60%	20	11	299	27	37	910
Other Capex	72%	19	14	297	76	89	830
O&M [23]	75%	73	51	773	42	93	1,820
Development	75%	6	5	92	37	42	380
Total	70%	280	159	3,924	486	645	8,140

However, the report concludes that policy support is needed to capitalise on the UK's current position as global leader within Wave & Tidal technology development. The technology itself is still within the early stages of development and potential developments within the technology need to be accelerated through the TRL index to achieve and prove commercial and financial viability. The requirement of a policy-driven route to market through CfD-type revenue support will most likely be needed for this to be achieved. The report calculated that the investment required through policy support is relatively modest and outweighed by the GVA generated from domestic and global markets for Wave & Tidal technology sector. It also alluded to the potential benefits of GVA being greater as indirect secondary and tertiary impacts had not been quantified within the reports model. The report was published in 2018 and identified the benefits of GVA related to supporting local supply chains and it's potential economic implications for regeneration, as a result none of the supporting policies like the CfD scheme where modified. This subsequently led to a reduction in local content within the 2019 CfD auction (ORE Foundations, 2020) and was a primary factor in certain manufacturing companies that had received millions of pounds of taxpayers money in investment support, going into administration resulting in redundancies (Bifab, Inquiry).

Offshore Wind & Hydrogen

The Offshore Wind & Hydrogen: Solving the Integration Challenge report came to similar conclusions regarding local content within supply chain development for hydrogen to ensure the UK maximises the economic, environmental and social benefits related to the opportunity of developing world leading capabilities. It stated that hydrogen generation projects can reach a cumulative GVA of up to £320bn, by 2050 and sustain 128,000 new jobs in the UK (OWH:SInC, 2020). It proposed continued use and to build upon the CfD mechanism as it had lowered costs significantly protecting consumers and targeting innovative technologies (OWH:SInC, 2020). However, it did not mention the CfD's failure to increase local content to at least 50% overall. Since the reports publication the UK government have actually looked to amend that percentage of local content within bids to at least 60% (CfD appraisal report 2021). The OWH:SInC, 2020 report doesn't specify the overall breakdown of thresholds for each sector involved within the overall bidding process. Previously this has led to certain industries like manufacturing suffering due to price competitiveness from state backed international companies winning bids and reducing local jacket manufacturing content to 18% within the last CfD auction (Bifab Inquiry, 2021). If the UK is to benefit from the opportunity of developing a global leading Offshore Wind & Hydrogen sector it will need to amend and develop policies taking into consideration the indirect impacts of prioritising the lowest cost per MWh has on local supply chains and the security of supply. The other issue regarding CfD's is associated with any bidding process in that the bidder/developer will underbid and be left unable to profitably develop the proposed project (Macauley,2008), (KEMA, 2006), (Wiser et al.,2005).

Chapter 3 - Development of Appraisal Methodology

In this chapter the paper will look to introduce and justify the structure, procedures adopted, and sequential process of evaluation being taken on. The identification of objectives/factors will enable the current performance, including capacity, targets, strategies and shortcomings, for the OWS regarding jacket manufacturing to be evaluated. Initially, looking at the OWS overall then focusing on the UK jacket manufacturing sector will enable a clearer picture to justify the related case study used for modelling and evaluation. This will also help refine and inform the structure, procedures adopted, and sequential process of evaluation undertaken including aims and justification.

3.1 - UK Offshore Wind Sector Overview

Current Capacity

As mentioned in the introduction section, the successful deployment of Offshore Wind (OSW) has been used by the government as an example of how to successfully integrate other RES. The current cumulative installed capacity of offshore wind in the United Kingdom is around 10GW (Statista, 2020), with the UK's target for operational OSW capacity increasing to 40GW by 2030 with the figure having being previously raised from 30GW set in 2019 (ORE:OSW-H2, 2020). The offshore wind sector currently supports an estimated 7,200 direct jobs as a whole (White Paper, 2020). In 2017 the gross value added (GVA) to the UK per GW of OSW installed, was £1.8bn. This was generated from the 32% of UK content within the winning CfD contract bids for the OSW sector auction (ORE: EVOW, 2017). Since 2017 the percentage of the overall UK content within OSW contracts has been quoted at 48% (Bifab, Inquiry).

Future Targets

With a target of 40 GW(upgraded from 30GW in 2020) to be reached by 2030 a subsequent offshore wind sector deal was signed in 2019. The deal set a target for 60% UK content along with the support of 27,000 jobs by 2030(ORE Foundations, 2020). Since then, the Prime Minister announced his Ten-point plan in November 2020, which sets out the details on how the government are laying the foundations for a green industrial revolution. It also includes plans for at least 1GW of floating wind capacity alongside the expansion of other “low-cost” renewable technologies to add to the energy source mix (White Paper, 2020). The Ten-point Plan was quickly followed up by the Energy White Paper in December 2020 which gave a more detailed insight into how the government is setting out to transition to our "Net Zero Future". These two publications by the government came as a reaction to the ongoing Covid-19 Pandemic and its subsequent impact on the UK economy along with Brexit. The energy white paper was also part of the UK government's agenda of "building back better" and "levelling up the country" regarding the economy and the regeneration of deprived areas within the UK.

Current Strategies

Part of the reason why the UK has been able to develop and deploy its OWS capacity from around 1GW in 2010 to currently 10GW is the implementation of supportive policies for the sector. In particular the CfD scheme, which is the UK's flagship scheme and main mechanism for supporting low-carbon electricity generation, has enabled investors to obtain a guarantee profitable strike price for the duration of the 15-year contract whilst ensuring that consumers get the lowest price per MWh for energy generated within the OWS (Gov.UK-BEIS, 2016). Over the course of the last 6 years the CfD auction has led to the significant lowering of price per MWh of energy generated from offshore Wind farms (Bifab Inquiry, 2021). The strike price per MWh generated for each of three auctions thus far have significantly reduced each time from £114 to £57 to then £41 in the last CfD auction round in 2019(Bifab, Inquiry 2021). This led to the procurement of 5.5GW of offshore wind and 275MW of remote island wind (White Paper, 2020). This has been hailed as a massive success and justification for the integration of RES and it's supporting policies by the UK government. It has also resulted in the LCOE reducing further for the OWS with predictions for projects commissioned in 2021 being between the values of £0.09 and 0.1/kWh (BVG Associates, March 2016). However, there was a lack of detailed information within the energy white paper about the UK content and its sectoral breakdown within the last bidding round.

<u>Future Strategies:</u>

CfD

Due to its success in deploying large scale clean energy at the lowest possible price to consumers, the CfD scheme will continue to be used as the main policy mechanism for the development and growth within the OWS & subsequent Green industrial revolution, as stated within the Ten-point Plan and Energy White paper. The strategies set out for the CfD include holding regular auction rounds every two years to accelerate development and diversity of low-cost renewable technologies (White Paper, 2020). The government has planned to hold the next auction in late 2021, which will also be open to solar photovoltaics, onshore wind and other established technologies which have been excluded from the auction scheme for the last 6 years (White Paper, 2020). The UK government have stated, that for future targets for the OWS to be achieved, it's vital that the CfD scheme offers value for money to consumers and continues to deliver low prices (White Paper, 2020). The wording within the white paper avoids the phrase "continues to offer" value for money to costumers. This may be due to the government making a number of technical changes to the auction process. One such change is the addition of more stringent requirements for the CfD supply chain plan process, which aims to ensure that the local content within bids makes up 60% in offshore wind projects by 2030. If future projects do not meet the expected target of local content then the contract could potentially be terminated (GOV CfD Changes, 2021). Following the publication of the energy white paper the UK government also asked for opinions on "how the CfD scheme could evolve beyond the 2021 auction", as well as looking at "how longer-term changes to the CfD or wider electricity market design can enable the effective integration of increasing renewables capacity" (GOV CfD Changes, 2021). Taking industrial views into consideration they have said they'll "seek a balance between options for further reform of the market with maintaining the success of the CfD in deploying low-cost renewables at scale," (White Paper, 2020).

Floating Offshore Wind: Innovation Funding

Along with CfD's, innovation funding support will be used to develop and deploy at least 1GW of floating offshore wind by 2030 (White Paper, 2020). The UK government is also planning to work more closely with devolved administrations, the crown estate and Crown Estate of Scotland to mitigate against issues related to the marine environment including seabed leasing to Wind farm developers. Whilst also ensuring the UK captures the economic benefits associated with the deployment of additional offshore wind technology (White Paper, 2020). The aim is to provide the foundation for a sustainable, competitive supply chain that enables offshore wind projects to scale up and subsequently accelerate cost reduction.

Offshore Wind Sector Deal – Manufacturing Supply Chain Support

Out with the CfD scheme the government signed an Offshore Wind Sector Deal in 2019 (as mentioned previously). Part of the deal is aimed at investing significant amounts of money into the UK's offshore wind manufacturing infrastructure, to grow and develop the local capabilities within the sector. This will hopefully create and secure jobs within the industry and provide opportunity in the local supply chain. Investment of up to £250m will be provided in order to build a stronger UK supply chain and in establishing the Offshore Wind Growth Partnership (OWGP) with the aim of supporting productivity and increasing competitiveness. The targets set by the deal for 2030 are as follows:

- Deliver 40 GW of installed capacity.
- Increase UK content from 48% in 2016 to 60% by 2030, including increases in the capital expenditure phase
- Support 27,000 jobs by 2030, with the majority of these in coastal communities
- Increase representation of women in the offshore wind workforce to at least a third.
- Increase exports fivefold to £2.6bn per year

£160 million of the announced funding will be part of the overall initiative to support the development of major portside infrastructure hubs, which will hopefully strengthen the UK offshore wind manufacturing sector. It is hoped that this will not only create more jobs but also raise the skills level across the country along with the regeneration of deprived coastal communities. Ideally, this will make UK manufacturing companies more competitive on a global scale, supporting overseas trade and creating investment opportunities for UK based companies (White Paper, 2020)(OWSD, 2019). The OWSD has recognised the need to develop the OWS manufacturing capacity to create a "competitive industrial base capable of servicing UK and international markets". The applicable direct actions stated within the OWSD, Energy White Paper and Ten-point plan will be addressed within the discussion section of this paper in more detail. If the target and commitments as stated within OWSD & White paper are met the OWS could generate £3 billion GVA a year by 2030, of which £1 billion could be export related. Hence why the investment from the OWSD alongside other offshore wind commitments are looking to make the most of this economic opportunity, as it would potentially provide support for up to "30,000 direct jobs and 30,000 indirect jobs in ports, factories and supply chains by 2030" (White Paper, 2020). Failure to maximise on this potential opportunity could risk security of supply regarding the access to future technological innovation products and also risk a public opinion backlash if employment opportunities are offshored and not forthcoming.

Issues Regarding the UK Offshore Wind Sector

Local Content

Even with the unprecedented success of the OWS development and deployment of wind turbine technology over the last decade certain issues have began to arise. The main one being the percentage of local UK content within successful CfD bids. As mentioned, the most recent auction round saw the strike price per MWh drop significantly to £41 per MWh which had not been predicted or anticipated by analysts (Bifab Inquiry, 2021). This was perceived as being great news for the consumer as lower costs per MWh means lower bills and more value for money. However, overall local content within the winning bids was only 48% (ORE, Manufacturing, 2020). Looking, at the breakdown per sector highlighted another more significant issue related to the UK manufacturing supply chain sector. The local content for the UK jacket manufacturing sector had reduced significantly from the previous auction round to only 18%(ORE, Manufacturing, 2020). The impact of this was felt within certain coastal communities were construction & fabrication ports were based, as a lack of pipeline work meant some companies like BiFab (based in Fife) went into administration leading to further redundancies (Bifab Inquiry, 2021). The immediate impact of a lack of UK content within winning bids translates to a missed opportunity regarding economic benefits. As uncertainty and a lack of jobs surrounding industries such as manufacturing lead to a drop in GDP of the surrounding area and increase in unemployment, whilst, the manufacturing work is outsourced at a cheaper rate to companies based abroad who obtain the additional direct and indirect benefits from the work. The secondary impact relates to the future capabilities of the offshore wind manufacturing sector, as a lack of contracts leads to a lack of investment and a lack of development of their facilities. This also means that locally based manufacturing companies are less likely to win future contracts as they don't have a recent proven track record of completing work to the required standard and are less likely to be equipped for the manufacturing of newer offshore wind technologies. A reduction in local content also reduces the effectiveness and value of the supportive policies put in place. As the money that is needed to invest and support the schemes and mechanisms to accelerate the transition towards renewable energy have a reduced outcome of GVA as the benefit cost ratio is negatively impacted.

Decommissioning

As the first generation of wind turbines nears their end of lifecycle usage the issue of decommissioning has become more apparent. The lack of planning for disposal, decarbonisation and potential reuse of components creates the question of what happens to the components and their associated environmental impact (ORE Catapult, CEWS, 2021). At least 80-85% (ORE Catapult, CEWS, 2021) of the weight of a wind turbine is recyclable however the necessary framework and best practice principles have not been fully developed. A potential solution to the decommissioning issue is the integration of circular economic principles. This has been acknowledged by ORE Catapult who are looking to address this industry issue by establishing the Circular Economy for the Wind Sector (CEWS) project to investigate new solutions for the bulk recycling of wind turbine blades and use of techno-economic analysis to assess their suitability for large-scale redeployment (ORE Catapult, CEWS, 2021). However, the project will have to setup a new circular economy supply chain for the OWS rapidly in the next couple of years and quantify its value for the circular solution to be established effectively as the first generation of wind turbines are coming to their end of lifecycle now.

Finite Resources

Security of supply of finite elements is also a growing issue as there is an over-reliance on rare earth magnets within turbine generators (Greenspur, 2021). The predicted global development and growth of the wind sector will put further pressure on the non-sustainable use of rare earth magnets (ORE Launch Academy, 2020). A possible eventuality is a shortage of the necessary turbine generators which leads to potential geo-political tensions rising from the security of supply for rare-earth elements. Incorporating circular principles by closing the loop regarding manufacturing and supply along with re-use as well as the integration of innovative sustainable solutions are the potential answer. However, both are still in their early stages of incorporation into the economic system and technical systems respectively and will require acceleration of scaling up to be adequately influential and successful within their respective systems.

3.2 - UK Jacket Manufacturing Sector

Figure 1: Wind Farm Jacket Foundations being transported by the Heavy Lift Vessel OHT Hawk (top right) from the Lamprell port based in the UAE heading to the North Sea. Image sourced from (Lamprell, 2021).

Market Value

By 2030 it is estimated that the value for the UK (uncontracted) offshore wind turbine foundations market will be around £5.5 billion (ORE Foundations, 2020). £1.6 billion of that will be for the manufacturing of jackets and piles, it is estimated that the cumulative UK market values between 2031 to 2050 for jackets and piles will be a further £1.5 billion. The value breakdown can be viewed as roughly 70% in the jackets and 30% in the piles and secondary steel (SS) (ORE Foundations, 2020). Which equates to around £1.1bn for jackets and £406m for piles and SS within the UK jacket market. With the increasing of the OWS targets to 40 GW the amount of turbines needed to reach the target is estimated at around 1,850 of that it is predicted roughly 350 of those turbines will need jacket foundations (ORE Foundations, 2020). To obtain the economic and social benefits associated with the estimated market value, the UK supply chain for jacket manufacturing will require local companies to be part of winning CfD bids.

Market Performance

Over the last few years, the UK windfarm jacket manufacturing sector has seen a significant reduction in the amount of contracts won through the CfD auction mechanism. The contracts are being awarded to companies based outside the UK with an increasing number of jackets being manufactured in the UAE and China (ORE Foundations, 2020).

In 2011 all 30 jackets for the Ormonde windfarm were fabricated in Scotland by BiFab (ORE Foundations, 2020). By 2018 jacket contracts for UK projects only had 50% of UK content with the rest going to companies based in Europe. Subsequently, only 18% of jackets for projects in 2019 to 2022 have been awarded to UK fabricator companies. In a push for further cost reductions related to enhancing the chances of successful bids for the CfD auction, a migration trend away from the UK to firstly Europe then more recently to the Middle East & Asia has occurred (Bifab Inquiry, 2021).

Typically, the cost difference between UK-fabricated transition pieces and jackets are 10-15% more expensive than the most competitive prices achievable in the market. This is further exasperated when looking at the breakdown of manufacturing costs compared to Asia and the Middle East were labour costs can be as low as £2.70 an hour (Bifab Inquiry, 2021). Even with cost reductions it is unlikely that UK fabricators will win more than a small share of contracts due to the premium of potentially 10–15% a buyer will incur on only a portion of the overall contract (ORE Foundations, 2020). In the last auction round for CfD it was estimated that one of the winning bids had undercut a UK fabrication companies cost by up to 25% for the manufacturing of turbine jackets (BiFab Inquiry, 2021). This ultimately led to the UK fabrication company going into administration even though it had previously received a significant amount of investment from the Scottish Government to enhance capabilities and competitiveness for auction tenders. This recent example highlights the disconnect between devolved governments and UK governmental policy, as not only did the UK lose out on potential economic benefits related to winning the contract but also millions of pounds of taxpayer’s money related to the potential return on investment put into the company.

3.3 - Case Study – BiFab Inquiry 2021

Overview

Due to the situation that occurred after the last CfD auction round regarding jacket manufacturing contracts and the subsequent administration of the UK company Bifab, an Inquiry was set up by the Scottish Government. The findings and recommendations of the inquiry were published in the “BiFab, the offshore wind sector and Scottish supply chain” report which was made public in January 2021. A major reason why the inquiry was required was due to the £40 million (roughly) of public money that had been invested and spent on supporting Bifab since 2017 and its subsequent inability to secure a contract for the Seagreen & Neart na Gaoithe Windfarm Projects. As mentioned, this led to significant job losses within the local area of Fife were some of their fabrication yards are based. Impacting the regional and local economy that was already in need of regeneration support (BiFab Inquiry, 2021). As mentioned in the report, “when public money is involved, there must be transparency in decision making”, hence the need for the inquiry.

The inquiry covered; Policy Background, BiFabs Background and Timeline, Contracts for Difference, ScotWind Leases and Supply Chain Development Statements and Strategy. For the purposes of this dissertation we will focus predominantly on the issues raised in the report surrounding the contracts for difference mechanism. However, other topics such as supply chain development within the report are of interest when looking at the potential secondary and tertiary impacts related to developing local manufacturing content and its economic, social and environmental benefits.

Contracts for Difference Impact

As mentioned, Round 3 of the CfD auctions held in 2019 saw unprecedented low bid prices per MWh for contracts (£41 per MWh) related to offshore windfarm development projects. The £3 billion Seagreen joint venture project between SSE Renewables and Total Energies received bids from BiFab regarding the building of only 4 jackets. Their bid was unsuccessful even though their yard is only 50 miles away from the proposed site. SSE renewables awarded the engineering, procurement, construction and installation contract of the Seagreen foundations to Subsea 7, a company based out of Luxembourg. Subsea 7 then awarded the construction & fabrication contracts for 84 jackets to Chinese/US joint venture COOEC-Fluor Heavy Industries and the construction of the remaining 30 jackets to the UAE-based firm Lamprell. Within the inquiry it was revealed that the BiFab bid was competitive with most European based renewables fabricators. However, SSE Renewables suggested, without quoting exact bid figures, that there was a 10% difference between the BiFab bid and European companies and an additional 10-15% between BiFab and the middle east or Asia. The difference is predominantly due to low labour costs and the high capacities of fabrication ports related to economies of scale along with state backed funding in the Middle East and Asia which has led to OWS manufacturing contracts and work going there instead of the UK.

Contracts for Difference Shortcomings

The inquiry highlighted the tensions that can arise when the developers (SSE Renewables & Total) of Wind Farm Projects must balance between lowering costs to the consumer and ensuring local content targets are met. This becomes more difficult to financially justify for the developers in regard to subcontracting when they are having to pay a premium for a local service of up to 25% compared to companies based in the Middle-East and Asia. This is further exacerbated by the CfD mechanism which from current evidence gives additional weighting focus on the lowest price per bid (cost of supply) compared to other factors such as Quality of Supply, On-time Delivery, Warranties and Financial Strength, even though within the ORE Catapult Foundations Strategic Capability Assessment it states that “not always lowest bidder awarded contract”.

As alluded to previously, the UK Department for Business, Energy and Industrial Strategy (BEIS) greatly underestimated what offshore wind would currently cost (£47 per MWh). A large part of this is due to the perceived success of the CfD auctions in delivering large quantities of clean energy for the lowest price. However, this has led to a lack of money within the system according to the BiFab inquiry, which has led to the developers prioritising bringing down project costs and awarding contracts to organisations out of the UK. The report stated that the previous target of 50-55% local content within the Supply Chain Plan for the Seagreen development was only aspirational with commitments seemingly not always being met. This was primarily due to the fact that supply chain plans submitted to the BEIS for CfD applications were to encourage effective development but not necessarily be imposed. Effectively the BEIS could only assess and monitor the implementation but not actually enforce it.

Another factor that weakened the ability for local UK companies to be awarded contracts within the CfD mechanism was the leasing process. As confirmed by the crown estate within the report the "Leasing process does not impose any requirement on the level or location of supply chain impact". This was down to state aid rules and competition regulations, which mean "it would not be legal for the Crown Estate Scotland to require Scottish Content as a basis for leasing". The Crown Estate Scotland also confirmed that the information contained in the required presentation of the Supply Chain Development Statement, "will not form part of any scoring related to the selection of winning applications". This meant that applications from a developer were not negatively impacted by a lack of commitments to the Scottish Supply chain.

The factors mentioned above and within the BiFab Inquiry have directly attributed to issues surrounding UK content within CfD bids and subsequently impacted the UK's ability to make the most of economic, social and environmental opportunities associated with the development of a strong Offshore Wind manufacturing sector. The potential economic benefits and GVA missed out on within the last two CfD auction rounds have been acknowledged to some extent as seen within the new commitments to UK content and supply chain plans. However, with the economic impacts of the Coronavirus pandemic and Brexit yet to fully play out, certain coastal communities around the UK have been deprived of a potential economic boost at this current time which could have been supplied by more stringent commitments within the CfD mechanism to local manufacturing content and less priority given to lowest cost.

3.4 - Justification & Reasoning for Model

As mentioned above, the wind sector (including onshore & offshore) has to date been the most successfully integrated renewable energy source into the UK system regarding current capacity (Statista, 2021). The CfD scheme has been recognised by the UK government as having played a vital role in accelerating the scale and volume of clean wind power procured for the lowest price. Due to its success the government plan on continuing its use and expanding the range of renewable technologies eligible to bid within the scheme (White Paper, 2020), which will impact emerging and embryonic innovative RES technologies.

The UK government are making some adjustments to its processes regarding UK content and the development of UK supply chains to ensure a higher percentage of UK companies are involved in the winning bids (OWSD, 2019). This was partly due to the UK based manufacturing sector suffering a recent rapid decline in its involvement in successful bids. The last CfD auction saw the UK content for jacket manufacturing drop from around 50% to 18% (ORE Foundations, 2020). One of the main factors is the focus and priority given to the lowest cost within the CfD mechanism, which has seen UK manufacturing being priced out of the construction of Jackets for wind turbine foundations (BiFab, 2021).

To the authors knowledge there has been no academic research done regarding the quantification of indirect (secondary & tertiary) impacts related to the CfD mechanism regarding lowest cost/price. This along with the BiFab inquiry have influenced the motivations behind the model. Another factor influencing the justification of the model is the recent commitments to a circular economy and how the principals can potentially be incorporated into the CfD decision making process moving away from the current linear model. Thirdly and most importantly, the model will attempt to quantify the potential impact the CfD scheme has regarding its capabilities for the regeneration of deprived areas within the UK through the indirect benefits of manufacturing contracts. This will hopefully provide justification for the consistent inclusion of secondary and tertiary impacts within TEA evaluation and its overall significance when considering the lowest cost per CfD bid and the ramifications that may have on overall GVA potential. The model will look to quantify the reasoning behind selected bids that are significantly higher but achieve an optimum balance between lowest cost and highest GVA return to give the overall best value to consumers economically, socially and environmentally.

3.5 - Model Methodology

The model will look to create a framework that can be used to quantify or at least closely estimate specific secondary and tertiary impacts related to RES and local supply chain opportunities associated with the CfD mechanism. The purpose for this model will be to use current data for the UK offshore wind sector to estimate the cost to the consumer of the most recent CfD auction for the Seagreen development project. The results will then be used for a hindcasting process to conduct sensitivity analysis regarding the cost per MWh with assumed cost impact related to bids from Asia, the Middle East and the UK. The second part of the modelling framework process will look to quantify the primary direct impacts along with the indirect secondary and tertiary impacts related to the employment opportunities associated with the contracts for the number of jackets fabricated within the UK. Thirdly, the modelling framework will look to quantify the social carbon cost related to CO_2 emissions from heavy lift vessels that are used to transport turbine jackets from ports in China and the UAE. This will look to quantify the potential environmental benefit that may become available if circular principles are incorporated into the manufacturing sector to close the loop regarding its reliance on imported raw materials. For both the second and third parts of the modelling framework, sensitivity analysis will be conducted for the parameters regarding job creation related to number of manufactured jackets constructed and social carbon cost related to shipping routes from China and the UAE. These outputs will be analysed together to create a total benefit & loss figure related to the potential economic benefit of the direct and indirect impacts associated with the manufacturing of jackets within the UK. Finally, these estimated figures will be compared to the costs accrued for the UK consumer across a range of prices per MWh for the duration of the 15-year CfD lifecycle.

3.6 - Modelling Methodology Aim

The aim is to demonstrate that the modelling framework methodology used can provide enough adaptability to enable further secondary and tertiary impact parameters to be added that can be used within the TEA process and evaluation of other mature and innovative RES that are eligible for the CfD auction. It will hopefully demonstrate the limitations associated with the lowest cost mechanism within the CfD process and highlight the need for a more nuanced approach that enables the UK economy to make the most of the regenerative opportunity of the potential GVA whilst finding an equilibrium between reducing LCOE and wider economic benefit.

3.7 - Modelling Software

All calculations and modelling have been done on Microsoft excel due to its compatibility and ease of use regarding analysis and modification. Many governmental departments and international consultancies like PwC & Deloitte still use Microsoft excel for analytical modelling to create robust frameworks and reduce QA time for new users (BEIS, 2017). BEIS still use excel when doing quality assurance modelling for the energy sector (including RES technology evaluation) whilst using best practice methods (BEIS, 2017). The excel model has used the template provided by BEIS for modelling to ensure best practise methods are followed as closely as possible.

Chapter 4 - Application of the Appraisal Method

This Chapter will look to apply the methodology described in the previous chapter by firstly, defining the parameters for appraisal within the case study for use in the modelling and the hindcasting process. Secondly, through the application of the appraisal method, results will be produced that will be compared and discussed in the later chapters of this paper.

4.1 - Parameters Selected for Modelling

The parameters selected can be defined within the spectrum of the three pillars of sustainability. However, multiple parameters can intersect between two or all three pillars regarding their primary, secondary and tertiary impacts.

4.2 - Direct Cost to Consumer of Renewable Energy Sources through the CfD mechanism

For this direct impact parameter, information and data was collected on the cost breakdown of a typical offshore windfarm project and its potential net annual average energy production in MWh/MW. The main source used for this was the guide to an offshore wind farm published by ORE Catapult and BVG Associates. They estimated that a typical Windfarm project of 100 turbines at 10MW per turbine rating would generate a net annual average energy production of 4,471 MWh/year/MW. The lifecycle of the windfarm estimated was 27 years with a weighted average cost of capital (WACC) at 6%. The example used within the publication is a very close equivalent to the Seagreen project which will have 1,075MW capacity and up to 114 turbines (SSE Renewables, 2020). The typical example has similar dates regarding financial investment decision (FID) to proceed and first operation date along with the distance to the port at 60km (ORE BVG, 2019). For these reasons it was determined that the data selected and used from the ORE Catapult & BVG Associates resource would provide enough credibility and accuracy to be used within calculations to determine an estimation of cost to the consumer per annum and over the 15-year lifecycle regarding the CfD mechanism.

To calculate the typical costs per annum based on average estimated energy production the estimated figure of 4,471 MWh/year/MW was multiplied by £41. This was due to the lowest winning bid for the Seagreen project within the last CfD auction round in 2019 was £41 per MWh (BiFab Inquiry, 2021), (White Paper, 2020). This gave a total of £183,311 per annum and a total of £2,749,665 over the course of the 15-year CfD contract for 1000MW at a strike price of £41 per MWh. Sensitivity analysis was then done to establish the cost to the consumer annually and over a 15 years CfD lifecycle on increasing strike prices per MWh. The results of which can be seen below. For context, as mentioned in the BiFab inquiry, BiFabs bid was undercut by the winning bid at around 25%, which alludes to their impact on the potential figure rising to around £55 per MWh. Exact figures and details for the bids made within the CfD auction are not available due to commercial sensitivity.

Table 4: Showing the results of the sensitivity analysis done regarding increasing CfD bid pricing per MWh and it's consumer costs annually and over the 15 year CfD lifecycle.

CfD bid £/MWh	Average Cost to Consumer per annum (£)	Average Cost to Consumer per 15-year CfD (£)
£41.00	£183,311.00	£2,749,665.00
£43.00	£192,253.00	£2,883,795.00
£45.00	£201,195.00	£3,017,925.00
£47.00	£210,137.00	£3,152,055.00
£49.00	£219,079.00	£3,286,185.00
£51.00	£228,021.00	£3,420,315.00
£53.00	£236,963.00	£3,554,445.00
£55.00	£245,905.00	£3,688,575.00
£57.00	£254,847.00	£3,822,705.00
£59.00	£263,789.00	£3,956,835.00
£61.00	£272,731.00	£4,090,965.00

4.3 - Socio-economic Direct & Indirect Impacts of UK Employment

The process for individually quantifying the socio-economic direct and indirect impacts requires huge amounts of data and research to be done which takes a large multi-faceted research team a substantial length of time (DCLG, 2010). For the purpose of this paper the model will reference governmental, industrial and academic papers and reports to utilise the appropriate quantification methods used to determine figures related to the parameters chosen for direct & indirect impacts, as a result of time & resource constraints. The socio-economic parameters selected for this section were chosen from the 2010 DCLG report due to its relevance regarding the ability of regeneration direct and indirect impacts.

Direct Socio-economic Impacts

The direct socio-economic impacts selected for this particular model were unemployment cost savings per person and Value per net additional job. The data and figures referenced for use within the excel model come from the UK Governments, Department for Communities and Local Government's (DCLG) economic report into Valuing the benefits of Regeneration which was published in 2010. After a substantial time-consuming research process, it was determined that this was the most substantial and credible source of information to be used within this model. This was due to the reports use of best practise methods as well as having access to huge volumes of data and market information to validate the estimations and figure quoted within the report. It was also accredited by Cambridge Economic Associates along with eftec, CRESR, University of Warwick and Cambridge Econometrics.

Unemployment Cost Saving/Benefit per Person

By taking figures quoted for earnings generated by a beneficiary who has moved from worklessness into employment the direct value for unemployment cost savings per person can be estimated. The report used evidence from the Department for Work and Pensions for the earnings of an average Jobseeker's allowance claimant moving from worklessness into work which was £11,779 per annum for 2009 (DCLG, 2010). For use within the model the rate of inflation had to be considered in terms of what the value of that figure would be in 2020. To calculate this the Bank of England's Inflation calculator was used (BoE, 2021), which gave the figure £16,158. It was noted within the DCLG report that the persistence of these benefits may only last for a year.

Value per net Additional Job

Similarly, the figure for the value per net additional job was derived from the DCLG governmental report on regeneration for the reasons explained above regarding credibility and access to data analysed. The report estimated the Gross Value added per employee regarding net additional job by applying market data and translating it into values. The data was drawn from the Annual Business Inquiry and the Office for National Statistics. The report was able to use these sources to derive GVA in a number of ways which allowed for fined grained analysis in spatial terms i.e., regional levels as well as sectoral analysis (DCLG, 2010). As mentioned within the report there is significant geographical variation regarding the average GVA added per employee. The figure estimated for the North of England was used within the model due to its economic and social similarities to the East coast of Fife (ONS GDP, 2019), (ONS GVA, 2019). This estimated average figure was £34,000 GVA added per employee for 2007 and with the inflation calculated for up to 2021 the figure used within the model was £48,240. The DCLG paper also suggested that the benefits may last up to three years.

Indirect (secondary & tertiary) Socio-economic Impacts

As with the direct impacts, the DCLG 2010 report on regeneration and its direct and indirect impacts is used as a basis for the estimation of the value per each secondary and tertiary impact parameter within this model. As explained above the best in practice framework and methodology used within the report and access to vast amounts of data and market information make it, to the authors knowledge, the most credible source to use for the scope and indirect parameters of this model. Even though they were published ten years apart, the DCLG's report focus on regeneration aligns with the Energy White papers aim of regenerating deprived areas through the transition over to renewable energy technologies.

Health - NHS Cost saving per individual in Employment

The paper stated that in relation to health, the Department for Work and Pensions work estimates that getting a person into work will reduce annual NHS costs by £508 (in 2008 prices). A higher cost-saving emerges for those with disabilities (£1016) (DCLG, 2010). In applying the evidence, the report took a cautious approach by applying the lowest figure and inflating it to 2009 price value. Which resulted in the annual benefit per net positive outcome into employment being £513. Additional for the purpose of the model the figure was inflated to 2020 prices which was £700 per person moving from worklessness into employment.

Crime rate Cost Saving per Individual Employed

For this parameter the figure estimated was £2087 including inflation. This was based on the work done within the DCLG 2010 report which used research from the Department for Work and Pensions drawing the Home Office's data to estimate the cost of crime associated with the employment programmes. The estimated figure chosen was the lowest value given of £1522.

Housing Stock - private betterment minus disamenity - value per net additional dwelling improved

Refurbishment activity through employment may be assumed to lead to some improvement in asset value within the DCLG report. In order to place a preliminary, indicative value on this strand of activity the report estimated that 10 per cent of the illustrative benefit of new build housing (£29,159) might be ascribed to housing improvements, leading to a per unit value of private consumption benefit of £2,916 or £3823.63 considering inflation till 2020.

Housing Stock - Society benefit, security, safety and warmth value per net additional dwelling improved

The report noted how various Decent Homes Health Impact Assessments had estimated the wider benefits to society arising from refurbishment activity. The DCLG applied the results from the Ealing Decent Homes Health Impact Assessment which generated an indicative Benefit Cost Ratio of 1.8 in total (based on benefits occurring over a 30 year period), most of it through the benefits of enhanced security. An estimated figure of £1,065 was used for the base figure before calculating the figure related to inflation up to 2020 which was £1,396.

Table 5: Listing the Direct primary (yellow) and Indirect (green) (secondary and tertiary) socio-economic parameters and their associated values inflated to 2020 prices.

Direct	**Indirect**	**Indirect**	
North East unemployment cost saving (inflation 2.9% average a year from 2009)	NHS Cost saving per individual in work (inflation 2.6% average a year from 2008)	Crime rate cost saving per individual in work (inflation 2.9% average a year from 2009)	**Total** benefit/saving
£16,158.05	**£699.98**	**£2,087.83**	**£18,945.86**
North East value per net additional job (inflation 2.7% average a year from 2007)	Housing Stock - private betterment minnus disamenity - value per net additional dwelling improved (inflation 2.7% average a year from 2010)	Housing Stock - Society benefit, security, safety and warmth value per net additional dwelling improved (inflation 2.7% average a year from 2010)	**Total** benefit/saving
£48,240.00	**£3,823.63**	**£1,396.49**	**£53,460**

4.4 - Environmental Direct Impacts

Annual Average CO_2 Emitted per Journey

This parameter was selected on the assumption that if circular principles are properly incorporated into the energy system including manufacturing the UK will be less reliant on imported raw materials by transitioning the supply chain towards a loop model rather than the current linear one. This would have a direct positive impact on the environment through reduced CO_2 emissions from Heavy Lift Vessels transporting fabricated turbine jackets along with raw materials from ports in China and the UAE.

To quantify this impact the social cost of carbon which gives a monetary value of $51 USD per tonne of CO_2 emitted was used within the calculation to estimate the impact of this parameter (Jean Chemnick, 2021).

The vessels typically used to ship turbine jackets across from the UAE and Chinese ports to the UK Offshore Windfarm sites are Heavy Lift Vessels. The Hawk heavy lift vessel from OHT is regularly used by sub-contractors to ship Jackets to Wind Farm development sites in the UK such as the Moray East offshore wind farm (Adrijana Buljan, 2020). However, data regarding the vessels emissions calculation were not available due to the ship not being registered on the EU database as required by Article 21 of Regulation (EU) 2015/757 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport (EMSA, 2021). Instead, the model used a similar sized vessel to the OHT Hawk called the Blue Marlin which can also be used for jacket transportation (Boskalis, 2019). By using the annual average CO_2 emissions per distance [kg CO_2 / n mile] for 2018 & 2019 calculated by the EMSA EU database for the blue marlin and shipping route distance in nautical miles from the Lamprell Sharjah port in the UAE and the COOEC-Fluor Heavy Industries Gaolan Port in China to the east coast of Fife in Scotland (Ports.com, 2021), an estimation of average CO2 can be calculated for a single trip for jacket transportation from the two ports that will be used for the Seagreen windfarm development project. These figures are multiplied by the social cost of carbon within the model to give an estimation of the economic cost of emissions from the shipping routes associated with the transportation of jackets for the Seagreen project.

Table 6: Parameters used for calculation of social carbon cost of transporting turbine jackets from fabrication ports awarded CfD contracts in 2019.

Average of 2018 & 2019 emissions per distance [kg CO_2 / n mile]	**Social Cost of Carbon per Ton ($51)**	**Nautical miles between BiFab harbour & Port Khalid, Lamprell Sharjah, UAE**	**Nautical miles between BiFab harbour & COOEC-Fluor Heavy Industries Co., Ltd, Gaolan Port China**
855.6	£36.71	(-50 n mile) = 7273	(-50 n mile) = 11,343
	Exchange rate at the time of calculation **0.719**	Total Social Carbon Cost for one Journey = **£228,438.21**	Total Social Carbon Cost for one Journey = **£356,273.15**

4.5 - Number of Jobs Directly/Indirectly created & Number of Jackets

These two parameters are used within the model to calculate potential economic benefit within sensitivity analysis and what the economic impact would be if UK content for the manufacturing of jackets hypothetically reached 60%, as stated within the Energy White Paper. By using references from local papers and the BiFab enquiry regarding the creation of direct and indirect jobs and the number of jackets manufactured in BiFab's fabrication yards across 2020, 2019 and 2017 it was possible to estimate an average of jobs per jacket. This linear model used the most conservative figures from news outlets and reports. The relationship represents the social and economic impacts directly related to the CfD's mechanism that has enabled the acceleration of outsourcing of manufacturing contracts over the last 6 years.

Table 7: Showing linear relationship of average number of jobs per turbine and the references used.

Average Number of jobs per one turbine jacket roughly	Number of Jobs Directly & Indirectly Created	Number of Subsea Turbine Jackets Contracted	Reference	Average Number Jobs for Jackets
2020	290	8	(SCN, 2021)	36.25
2019	145	4	(BiFab Inquiry, 2021)	36.25
2017	1400	26	(Rob McLaren, 2020)	53.85
				Overall Average = 42.12

Chapter 5 - Comparison and Discussion of Outputs & Results

This Chapter will look to define the outputs and results of the modelling conducted whilst also comparing and discussing them. Through comparison and discussion, the formulation of outcomes related to the results will be defined.

5.1 - Model Results

After combining all the estimated values for the direct and indirect impacts associated with economic, social and environmental factors and performing sensitivity analysis regarding number of jackets contracted for fabrication, a comparison could be made against the cost to the consumer for a variety of strike prices in regards to the CfD contracts over the 15 year cycle, as seen in table…. below.

The results highlight how the UK economy is missing out on a significant amount of potential economic benefit that could have a transformative impact on the regeneration of deprived coastal communities. Through Hindcasting (Table…) the model demonstrates that if the BiFab contract had been awarded at the strike price of £55 MWh (roughly the cost of the bid that would have occurred) the cost to the consumer over the 15 years would have been £1,549,201.50. However, by winning the contract for the fabrication of 4 jackets the potential economic benefit generated could potentially reach a total between £10,498,867 and £7,751,717.40 roughly over the course of only a year. The minimum estimated economic benefit potential of around £7,751,717.40 over the course of only a year still represents a massive potential net benefit of around £6,202,515.90 to the UK economy taking into consideration the cost to the consumer over the 15-year CfD strike price of £55 per MWh. By outsourcing the majority of jacket manufacturing contracts through the CfD mechanism the cost benefit ratio is hugely reduced as potential GVA generated from the primary, secondary and tertiary impacts does not occur.

Table 8: The table displays all the results from hindcasting model and sensitivity analysis (darker shaded colours) done regarding primary, secondary and tertiary impacts related to jacket manufacturing within the UK and CfD cost to the consumer through increasing strike prices for a typical windfarm project with 1000 MW capacity and 100 turbines producing a Net annual average of 4,471MWh/year/MW. The colouring represents the different parameters used related to the socio-economic context.

CfD bid £/MWh	Average Cost to Consumer per 15 year CfD (£)	Number of Jobs Directly/Indirectly created	Number of Jackets	Total Worklesness Benefits/savings impact (£) per annum	Total Net Job Benefits/savings including social carbon impact (£) per annum (china)	Total Net Job Benefits/savings including social carbon impact (£) per annum (UAE)
£41.00	£2,749,665.00	290	8	£5,494,299.40	£16,215,981.10	£15,960,311.22
£43.00	£2,883,795.00	145	4	£2,747,149.70	£8,107,990.55	£7,980,155.61
£45.00	£3,017,925.00	1400	26	£26,524,204.00	£76,625,533.75	£75,986,359.05
£47.00	£3,152,055.00	500	12	£9,472,930.00	£27,442,606.30	£27,186,936.42
£49.00	£3,286,185.00	1264	30	£23,939,988.70	£69,333,573.38	£68,694,398.68
£51.00	£3,420,315.00	2527	60	£47,879,977.39	£138,667,146.76	£137,388,797.36
£53.00	£3,554,445.00	1853	44	£35,111,983.42	£101,926,756.39	£100,904,076.87
£55.00	£3,688,575.00	2190	52	£41,495,980.41	£120,296,951.58	£119,146,437.12
£57.00	£3,822,705.00	2948	70	£55,859,973.62	£161,897,095.61	£160,363,076.33
£59.00	£3,956,835.00	1601	38	£30,323,985.68	£88,060,041.72	£87,165,197.14
£61.00	£4,090,965.00	3285	78	£62,243,970.61	£180,267,290.79	£178,605,436.57

Hindcast Model Result

Table 9: Results of hindcasting, comparing the cost to the consumer and the related secondary and tertiary impacts regarding economic benefit of the winning £41 per MWh bid that occurred and the potential scenario outcome of the BiFab bid if it had won the contract at £55 per MWh. The parameters of the hindcast were set as close to the Seagreen CfD project allocation of 42% of the overall total capacity as possible. For this instance, the hypothetical model windfarm was 1000MW only 75MW short of the aim for the capacity of the Seagreen development.

CfD bid £/MWh	Average Cost to Consumer per annum (£)	Average Cost to Consumer per 15 year CfD (£)	Number of Jobs Directly/Indirectly created	Number of Jackets	Total Worklesness Benefits/savings impact (£) per annum	Total Net Job Benefits/saving Impact (£) per annum
£55.00	£103,280.10	£1,549,201.50	145	4	£2,747,149.70	£7,751,717.40
£41.61	£78,136.10	£1,172,041.36	0	0	0	0

Sensitivity Analysis

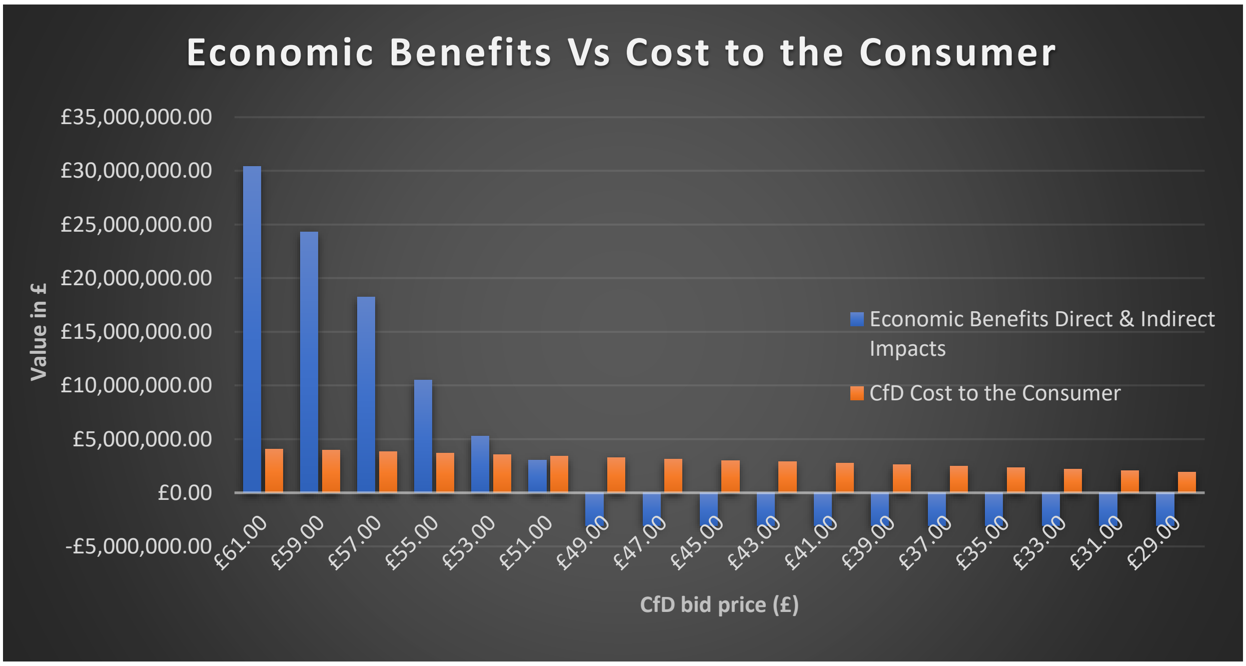

Figure 2: Highlights the CfD bid cost to the consumer over 15-year lifecycle and compares this to economic benefits of jacket manufacturing contracts and the hypothetical bids that may be put in based on the BiFab Inquiry and other sources varying the number of jackets fabricated and associated jobs based on decreasing local content regarding lower CfD bids.

5.2 - Discussion

Application of Literature for TEA Evaluation

As stated within the Introduction section, this model has highlighted the need to re-examine the CfD mechanism to find an equilibrium between cost to the consumer and economic benefit generated from increased local content. Although this paper only looks at the quantification of the direct, secondary and tertiary impacts related to the fabrication contracts for turbine jackets, it can be assumed that the evaluation of TEA (if conducted) within the initial development of the CfD policy mechanism did not foresee the issues that have developed regarding local content within this sector and its impact on securing economic benefit.

The focus on lowering costs may have attributed to the direct, indirect secondary and tertiary impacts being underestimated or overlooked for a number of reasons alluded to in the literature review including:

- Indirect secondary and tertiary impacts are difficult to accurately quantify (DCLG, 2010). They can require vast amounts of data along with complex quantative and qualitative approaches to decipher as close to approximate values as possible as mentioned within Mijndertvan der Spek, et al.
- The immaturity of the OWS at the stage of CfD mechanism development may have meant that there was insufficient data creating further difficulties in accurately quantifying secondary and tertiary impacts within TEA evaluation alluded to in W. Zimmerman et al.
- The lack of a global standardised Framework for TEA would have impacted the ability to clearly compare with other TEA evaluations due to inconsistent parameters and factors being evaluated within different analysis's (W. Zimmermann et al, 2020).

However, knowledge of these shortcomings regarding TEA have been known throughout the last decade as mentioned in Spencer and Arwas, 2013; Foxon et al., 2005, E Uyarra et al, 2016 and W. Ma et al, 2018.

The fact that the government published a paper on valuing the benefits of regeneration and acknowledged the issue of quantifying indirect secondary and tertiary impacts back in 2010 (which was forwarded by Grant Shapps the current Secretary of state for transport) highlights a disconnect within government between departments and agencies related to this area of research and of governmental publications and policy development.

The topic of regeneration focuses on the process of reversing economic, social and physical decay in areas where it has reached a stage when market forces alone will not suffice (DCLG, 2010). Regeneration has been at the heart of certain UK policy ideologies over the last decade such as the "Big Society" and more recently "Levelling Up" & "Building Back Better". However, the potential for regeneration of coastal communities through renewable energy policies has not materialised even though part of the government's aim regarding the OWS was to develop local supply chains within the renewables sector. Thus, re-emphasizing a disconnect between aims, actions and outcomes of the CfD mechanism and its potential impact on the regeneration within local communities.

This is backed by the model's hindcasting results, which uses parameters from the DCLG report from 2010, alluding to missed opportunities in the last auction round of 2019 regarding potential economic benefit generation that could have had significant regenerative impacts within coastal communities, like the ones in Fife. It could potentially be argued that the CfD mechanism may have attributed to the further demise of coastal communities that relied on fabrication yards to provide a source of employment for the surrounding area, as lower bids priced out UK manufacturing companies from winning contracts through the mechanisms focus on favouring the lowest bids, facilitating a "race to the bottom" (BiFab Inquiry, 2021). Further research would need to be conducted to accurately determine potential negative impacts the CfD mechanism has had within local communities across the UK.

A further disconnect also appears to be prevalent within the Scottish government regarding the impacts of the CfD mechanism and investment of public money into manufacturing companies working within the OWS. The loss of £40 million of public money (invested by the Scottish Government) after BiFab went into administration doesn't quantify the additional loss of economic benefits and the additional health and crime costs associated with a rise in unemployment. The minimum GVA reduction for the initial year after BiFab's administration would be around £7 million if the job losses didn't result in anyone claiming employment benefits by finding employment quickly. The disappearance of future economic benefits for the local region in Fife associated with the closer of the fabrication yard has a far larger national impact. It not only hampers Scotland's ability to maintain a healthy jacket manufacturing supply chain but reduces the GVA benefit for the UK and potentially impacts public opinion on the transition to a net-zero economy if unemployment levels rise. More importantly it negatively impacts the UK OWS's ability to build a strong and globally competitive future offshore wind supply chain sector and secure the associated economic benefits.

The lack of inclusion or importance given to secondary and tertiary impacts within initial TEA evaluation may have played a part in the disconnect between UK government departments and devolved administration regarding the policy development of the CfD mechanism. As it has proved unfit to secure the indirect economic benefits associated with the manufacturing supply chain of turbine jacket foundations. The amendments made by the UK government to the CfD scheme regarding an increase of UK content to 60% will hopefully reverse the trend seen within the jacket manufacturing sector. To ensure UK content aims are met the termination of contracts could/will occur if supply chain targets are not adhered too (GOV CfD Changes, 2021). However, this may potentially lead to further project delays and cancelations which have already hampered the expected development of the Scottish Offshore wind sector as described within the Strategic Investment Assessment (SIA) Report published in August 2021, even with the Supply Chain Plan being moved to one month of the contract Milestone Delivery Date (MDD). As mentioned in the report, collaboration is needed between all Governmental parties involved including the UK Government and the devolved administrations, along with private sector organisations involved in the development of offshore projects and their tiered suppliers to ensure the UK secures the economic benefits associated with developing a strong supply chain infrastructure for future prosperity.

The CfD policy has been so successful at procuring large volumes of green energy for the lowest price that bidding prices are now below wholesale reference price levels (J. Brabben, 2019). So therefore, a legitimate question to ask is, why does the budget-based approach to CfD auctions still have to remain?

Further reductions in the price per MWh of bids could potentially jeopardise offshore wind project developments due to winning bids potentially struggling to meet local content targets around the supply chain plan process due to cost factors and initial adaption to the changes made. The labour costs within the UK manufacturing sector are significantly higher than the equivalent £2.70 per hour quoted within the BiFab Inquiry regarding the hourly rate for labour within fabrication yards based in the UAE and China. Therefore, the increase in labour costs associated with manufacturing work done in the UK could lead to pinch points regarding contract terminations due to challenges related to increasing local content, which would result in further delays or cancelations of developments.

Hindcasting Implications

The result from the hindcasting process shows that there was no additional economic, social or environmental benefit other than a lower cost per MWh for the consumer regarding the awarding of the contract to COOEC-Fluor Heavy Industries & Lamprell. If the Bifab bid had won, the contract for the fabrication of only 4 jackets the price to the consumer would have increased by an estimated total of £377,160 over the 15-year lifecycle of the CfD. However, the benefits within only the first year could have been £7,751,717.40 assuming all 145 jobs were ongoing through the year. The figure doesn't consider the additional economic benefits associated with reduced worklessness and the indirect impacts of health and crime, which reduces cost and strain on the NHS and the prison service of the local area. With the additional economic benefits and savings included for worklessness the figure could rise to £10,498,867 assuming that all 145 employees would have claimed Jobseekers allowance if unemployed. Even with a hypothetical worst-case scenario of only securing the economic benefits associated with a reduction in worklessness and it's direct, secondary and tertiary impacts the value of benefits is estimated to be around £2,747,149.70. This figure equates to over £1 million in net benefits/savings accrued from awarding the fabrication contract of only 4 jackets to BiFab at a CfD bid price of £55 per MWh.

The estimated economic benefits associated with the fabrication contract for only 4 jackets highlights the need to increase the percentage of local content for jacket manufacturing within the upcoming CfD auction rounds or miss out on millions of pounds worth of economic benefits that would potential regenerate deprived coastal communities and enable the development of capabilities to ensure the future prosperity of the UK manufacturing OWS.

Modelling limitations

As mentioned within the "parameter selected for modelling" section, the model used estimations from various sources including governmental reports, publications, academic papers and articles for the quantification of certain parameters. As stated, this was mainly due to time and resource constraints. Pulling together credible accurate references to use within the model framework and the hindcasting process proved time consuming and challenging.

The limited academic research on the topic of secondary and tertiary impacts of the CfD mechanism added to this issue. This also meant that values used from various papers for the quantification of parameters may be subject to further scrutiny. However, value transfer is common practice in the appraisal of impacts by using monetary valuation evidence from existing studies (eftec, 2009).

A primary source for a number of economic values associated with the social-economic direct and indirect impacts within the model was the DCLG report. The report itself acknowledges its own limitations at the time including the difficulty of quantifying certain secondary and tertiary impacts if there wasn't a market valuation due to the absence of market data. However, the majority of the estimated figures used in the model did have sound market valuation through market data from the time which was in line with treasury guidance. The figures used within this papers model tended to be on the conservative side if there was a range to choose from so that the potential inflation of economic benefits was minimised to reduce the chances of over-estimation.

The impact parameters within the model that contributed the most to the potential GVA (dependant on CfD jacket contracts) were the unemployment cost saving/benefit and the Value per net additional job. In all parameter values referenced from the DCLG report the use of market data was recognised as legitimate by departments such as the Department for Work and Pensions, the Department for Business, Innovation and Skills and HM Treasury. However, the limitations arose regarding lack of robust information related to cumulative benefit after the initial year the benefit occurred on. Additionally, the report acknowledged that the figures were initial estimates that need to be supplemented through further evidence. The DCLG's approach did provide a practical framework for valuation and a useful starting point in terms of the available evidence, but also highlighted the need for continuing research on all of the areas referenced.

Some of the valuations calculated using figures from the DCLG report that was published in 2010 may not be as accurate as hoped even after inflation calculations for their value within the present day, due to the length of time between the estimations of the figures within the report and the conducting of the model based on the CfD scenario from 2019/20. An example of this being the impacts of governmental policy on Job seekers allowance which was frozen from 2015 till 2020 (BBC, 2019). Thus, calculating inflation regarding the unemployment cost saving/benefit may be up for further scrutiny. However, the former Chancellor Phillip

Hammond said “that increase in benefits will resume in line with [the CPI rate of inflation] in the normal way from 2020” (BBC, 2019).

As mentioned within the environmental direct impact section, the calculations were based on data accessible to the author. This meant that a number of limitations arose from the use of the data selected which could impact the calculations and result for CO_2 emitted, including:

- Different Vessels might have been used varying in size, load and efficiency for the transportation of jackets.
- Different shipping routes might have been taken depending on shipping traffic and weather conditions
- The average figure was taken from one ship similar in size to others used for turbine jacket installation over the course of the years 2018 & 2019. These two years could be the exception, to gain more accuracy a wider range of vessels should be taken into consideration along with a longer time period to look at the average annual CO_2 emitted per nautical mile in tons.

Sensitivity Analysis

The sensitivity analysis conducted estimates the cost to the consumer per annum and over the 15-year lifecycle of the various bid prices per MWh within the CfD auction process. This enables a comparison to be made between the potential benefits related to the GVA of jackets manufactured within the hindcast scenario for the BiFab bid and its potential cost to the consumer through its estimated CfD price of £55MWh. Hypothetically the valuations calculated within the sensitivity analysis could be used to determine an optimised value creating an equilibrium between cost to the consumer and GVA generated through local content related to the fabrication of turbine jackets. This in turn should highlight the shortcomings of the CfD mechanism within the context of lowest price not giving the most value to the UK economy.

The relationship between the amount of jobs per turbine jacket is represented in a linear way within the sensitivity analysis. The author acknowledges that in reality this is not the case and that the number of jobs per turbine jacket would exponential increase rather than linearly i.e., winning a contract that doubles the number of jackets being manufactured wouldn’t necessarily mean that the amount of people employed doubles. However, figures taken from references regarding employment and number of jackets manufactured at BiFab were taken from the 2017, 2019 and 2020 to give an average regarding number of jobs per jacket. With the data available to the author this was the most accurate methodology to use for this parameter. Further research would be required to determine an accurate exponential factor related to number of jobs per jacket manufactured.

The model described in this paper provides a practical framework and a good starting point for the valuation of secondary and tertiary impacts related to manufacturing and supply chain growth within the CfD mechanism. Further research into additional parameters and scenarios will enable the model to tackle some of its current limitations and increase its complexity to enhance accuracy. The strength of the framework lies within its adaptability regarding its potential use within evaluating different scenarios and renewable technologies that are eligible for the CfD scheme. Credible data and values are key to the accuracy within the model; therefore the continuation of best practice methods must be used going forward.

Circular Principles

The model's incorporation of circular principles was based on a hypothetical scenario of the UK manufacturing sector closing the loop regarding the import supply of the raw materials needed for the fabrication of turbine jackets. The recent policy package by the Scottish government regarding circular principles shows that the future supply chain for jacket manufacturing may also incorporate circular economic principles. If this scenario comes to fruition then the point made by SSE within the BiFab inquiry that CO2 emitted by transporting jackets across the world is roughly the same as the amount emitted for the transportation of the raw materials needed for jacket fabrication to Scotland, is completely mitigated against. The result from the model highlights the social carbon cost of the journeys of Heavy-lift vessels that transport jackets fabricated in the UAE and China to Scotland. The quantification and estimated cost enables the model to incorporate a relationship to circular principals in regards to the social, environmental and economic benefit savings attributed to reducing CO2 emissions of the current overall fabrication process.

Further research needs to be done to define a strategic road map regarding assimilation of circular principals within the decommissioning of the 1st generation of offshore wind turbines. This could potentially enable the UK to develop the first offshore wind circular supply chain that would increase security of supply, sustainability and local content which could enable the UK to maximise and secure the economic benefits associated with the primary, secondary and tertiary impacts. However, collaboration between Governments and the private sector will be needed to push this agenda forward.

Chapter 6 – Closing Remarks

6.1 Conclusion

The hindcasting model results of this study focus on the loss of potential economic benefit related to outsourcing the fabrication of turbine jackets for UK windfarm projects. It highlights how the economic benefits associated with awarding just a small number of jacket contracts to local UK firms can potential out-weigh the higher CfD strike price per MWh by millions of pounds, when the quantification of primary, secondary and tertiary impacts is incorporated into aspects of TEA modelling & evaluation.

Through the sensitivity analysis conducted the model estimates the potential economic benefits on offer if the fabrication of jackets for a typical UK offshore windfarm project increased its local content up to 60% and further. These estimated figures were compared to a number of CfD strike price bids to understand what the cost to the consumer would potentially be then compared it to the estimated economic benefits accrued from various amounts of UK content. The estimated values further backed the assumptions raised from the hindcasting process that increasing local content can potentially create a substantial economic benefit that far outweighs the benefits of lowering costs per MWh that has led to a decrease in local content within the jacket manufacturing sector.

These results highlighted the potential need to further scrutinise the CfD mechanism regarding its impact on the UK's manufacturing supply chain industry of the OWS and its inability to secure the economic benefits associated with winning contracts. This inability to be part of winning CfD bids is a significant problem for the UK & Scottish Governments as the loss of potential benefits can negatively impact coastal communities with fabrication yards and hamper regeneration of the subsequent deprived areas. This ultimately impacts the public opinion on green policy initiatives and reduces the political capital of governing parties to implement more ambitious green targets that are needed to prevent a climate catastrophe. The lack of CfD contracts for the UK manufacturing sector also has a cumulative impact on the ability of the sector to win further work and develop capabilities to manufacture future technologies such as, floating offshore wind platforms. Which could have negative implications for the prosperity of the UK manufacturing sector and reduce its ability to secure the potential economic benefits associated with a strong local supply chain infrastructure that reduces its reliance on imports and exports its expertise and products globally.

The recent actions by the UK government regarding the increase of UK content within the CfD mechanism through more stringent requirements for the supply chain plan process and the announcement of the 160-million-pound scheme to support the development of offshore wind manufacturing infrastructure, shows that they are aware of the significant loss of economic benefit that has occurred and are looking to amend this to secure future prosperity. However, the budget-based approach to CfD auctions still remains even though bidding prices are now below wholesale reference price levels. This could potentially jeopardise offshore wind project developments as winning bids may struggle to meet local content targets due to the increase in labour costs associated with manufacturing work done in the UK, which would lead to contract terminations and further delays or cancelations of developments. As such, the authors recommendation based on the results from the model and research conducted within this paper would be to incorporate a modelling framework into the bidding process that allows the decision maker to award the contract to the CfD bid that has the optimum balance between low-cost per MWh and generation of economic benefits provided through UK content. This may create a longer process for the CfD with additional complexity and criteria that could have side effects this paper has not considered. However, the benefits of implementing a framework that creates an equilibrium between low cost and economic benefit is worth exploring for future prosperity regarding its regeneration potential.

At the initial inception the modelling framework should incorporate the primary, secondary and tertiary impacts along with the parameters alluded to in this papers model along with many others more typically associated with TEA. It should be adaptable to changing scenarios and different renewable energy technologies including mature, new and embryonic innovative solutions. It should always attempt to quantify as accurately as possible secondary and tertiary impacts based on the social, economic and environmental pillars referenced within this paper and incorporate circular principles were possible. The approach should be adapted into a global TEA standardised framework to allow legitimate, accurate and fair comparisons to be made when evaluating renewable energy technologies and subsequent policy development. A global standardised framework could have the same impact on TEA evaluation as the IAIA has had on EIA, which would allow governments to collaborate more efficiently and make better informed robust decisions regarding policies to sustainably and successfully tackle the transition to net-zero based energy systems.

As for this research project, the model and the outcomes of the study demonstrate:

- The importance of using TEA to inform policy development especially around best value criteria rather than lowest cost.
- A need to put greater emphasis on holistic approaches to gain a greater overall understanding of potential impacts and associated benefits.
- The best value for consumers is making sure local content is prioritised. This should be used as a primary driver for developing a circular economy and to inform future policy.

The research on this dissertation also indicates that further work is needed regarding collaboration between all parties involved within policy development and the application of techno-economic evaluation. Governments need to better understand and predict the impacts of energy policies regarding job opportunities and their associated primary, secondary and tertiary impacts or risk jeopardising future economic benefits and public opinion associated with transitioning to Net-zero.

6.2 - Future Work

As mentioned, the academic research on the topic of the CfD mechanism and the quantification of its secondary and tertiary impacts is lacking. To the authors knowledge this is the first paper to attempt to combine elements of TEA related to the quantification of primary, secondary and tertiary impacts and relate it to the CfD mechanism considering social economic and environmental parameters through hindcasting. As a result, there are a number of areas that would require further research to validate some of the assumptions made based on the research and results regarding this paper and its model. Due to the many topics and factors that have been mentioned it would be best to continuously monitor and research all aspects of the paper due to the additional depth of detail that could be achieved with further analysis that is not confined by time constraints and limited resource.

Firstly, further research is required to accurately estimate the longevity of potential secondary and tertiary benefit impacts and their accumulating potential over a number of years, as alluded to in the DCLG report. The addition of further parameters is needed to further establish the relationship between offshore wind and regeneration of coastal communities within the UK.

To increase accuracy for the estimated primary, secondary and tertiary impacts up to date market data and information will be needed for all parameters mentioned within the paper and for any future additional ones. As this papers modelling used the valuations from the DCLG report that was based primarily upon Market data and information from around its publication in 2010.

Further research on the impacts the CfD mechanism has had on other sectors within the OWS regarding the secondary and tertiary impacts to develop a clearer overall picture. This reflects that this paper's modelling only focused on the jacket manufacturing sector which is only part of one type of foundation for offshore wind turbines but suffered one of the largest decreases in local content percentages in the last auction round.

Quantifying more parameters looking at the relationship between Offshore Wind Development and Regeneration.

Understanding how to incorporate circular principles further within current government policy mechanisms to continue to develop renewable energy generating capacity is a topic that has been touched on within this paper but would need further research to establish potential best practice approaches. Along with further detailed analysis of how this would work strategically for the UK's offshore wind manufacturing sector and supply chain.

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Appendices

1 - Model Screen-shots:

Summary

Name	Hindcast Quantification of Primary Secondary and Tertiary Impacts related to local content and CfD bids for Turbine Jacket Manufacturing
Description/Purpose	To Qauntify Primary, Secondary and Tertiary Impacts related to social, economic and environmental parameters related to local content and compare the benefit values to the cost to the consumer of the strike price of CfD bids for Jacket fabrication contracts. Demonstarte the added value of increasing local content by considering the indirect impacts that are rarily quatified within TEA, Reports and Anlysis used by Government departments.
Creation date	Jul-21
Owner / Contact	William Monteith, william.monteith.2020@uni.strath.ac.uk
Version number	1
Link to model's assumptions log	N/A (as the log is within the main model file)

Note	Unless there is a valid reason otherwise, all models will be open sourced within the department when complete.

Figure 3: Showing the summary of the models introduction page.

Direct & Indirect Parameters/Impacts Related to Bussiness Development and Support along with the Indirect impacts of Housing Improvement	Value per net additional job	Housing Stock - private betterment minnus disamenity - value per net additional dwelling improved	Housing Stock - Society benefit, security, safety and warmth value per net additional dwelling improved
Estimated Average Number of jobs per one turbine jacket	Number of Subsea Turbine Jackets Contracted	Number of Jobs Directly & Indirectly Created (referenced)	Average Number Jobs per Jacket

Evironmental Parameters	**Direct**			**Indirect**
CO2 emmions regarding Heavy Lift Vessels used for Jacket Transportation	Annual average CO_2 emissions per distance [kg CO_2 / n mile]	Nautical miles between bifab harbour & Port Khalid, Lamprell Sharjah, UAE	Nautical miles between bifab harbour & COOEC-Fluor Heavy Industries Co., Ltd, Gaolan Port China	Social Cost of Carbon per Tonne

Techno-Economic Parameters

Renewable Energy Technology: Parameters Selected for a Typical UK Offshore Windfram	Net annual average energy production MWh/year/MW	Wind farm rating (MW)	Wind turbine rating (MW)	Distance to shore, grid, port (km)	Number of turbines
Policy Mechanism: CfD Paremeters Selected	CfD bid strike price £/MWh	Average Cost to Consumer per annum (£)	Average Cost to Consumer per 15 year CfD (£)		

Logs | Units | Scenarios >> | Inputs>> | Calculations >> | Outputs >>

Figure 4: Showing the tab sheet storing model parameters for Framework regarding quantification of Direct (primary) & Indirect (Secondary & Tertiary) Impacts

Figures referenced from the DCLG Report on Regeneration, 2010	£34,000	£2,916	£1,065		
Estimated Average Number of jobs per one turbine jacket	Number of Subsea Turbine Jackets Contracted	Number of Jobs Directly & Indirectly Created (referenced)	Average Number Jobs per Jacket		
Scottish Construction Now, 2021: Figures for 2021	8	290	36.25		
BiFab Inquiry, 2021: Figures for 2019	4	145	36.25		
Rob McLaren, 2020: Figures for 2017	26	1400	53.85		
			Overall Average = **42.12**		
Evironmental Parameters	Direct			Indirect	
CO2 emmions regarding Heavy Lift Vessels used for Jacket Transportation	Annual average CO_2 emissions per distance [kg CO_2 / n mile]	Nautical miles between bifab harbour & Port Khalid, Lamprell Sharjah, UAE	Nautical miles between bifab harbour & COOEC-Fluor Heavy Industries Co., Ltd, Gaolan Port China	Social Cost of Carbon per Tonne	
Reference's for estimated figures	EMSA Europa, Emmision Report Database for Blue Marlin Heavy Lift Vessel	Ports.com shipping route	Ports.com shipping route	Jean Chemnick, 2021	

Logs | Units | Scenarios >> | Inputs>> | Calculations >> | Outpu

Figure 5: Showing the Inputs tab sheet for storing data from external sources, reference tables and assumptions.

Socio-Economic Parameters	**Inflation Calculations Used within Bank of England Inflation Calculater:** https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator
Calculating costs between years. The inflation calculator works for amounts between £1 and £1,000,000,000,000 (£1 trillion).	Cost in 2020 = Cost in 2007 × (2020 price index ÷ 2007 price index)
Average Inflation, The inflation calculator also tells you the average yearly inflation rate between two years	Average Inflation = (((2020 price index ÷ 2010 price Index)0.1)×100
Jobs per Jacket	Number of Jobs Directly & Indirectly Created ÷ Number of Jackets contracted
Estimated Average Number of Jobs per Jacket	Jobs per Jacket for (2021 + 2019 + 2017) ÷ Number of years of input Data (ie, 3)
Calculating Total Direct and Indirect (Secondary & Tertiary) Benefits	

Logs | Units | Scenarios >> | Inputs>> | Calculations >> | Outputs >>

Figure 6: Showing Tab Sheet containing formulae/calculations.

Hindcast Modelling Outputs

42% capacity of Seagreen project awarded CfD contract

CfD bid £/MWh	Average Cost to Consumer per annum (£)	Average Cost to Consumer per 15 year CfD (£)	Number of Jackets	Number of Jobs Directly/Indirectly created	Total Worklesness Benefits/savings impact (£) per annum	Total Value per net additional job Benefits/savings - direct & indirect (£) per annum	Total Direct & Indirect socio-economic benefits (£) per annum
£55.00	£103,280.10	£1,549,201.50	4	145	£2,747,149.70	£7,751,717.40	£10,498,867.10
£41.61	£78,136.10	£1,172,041.36	0	0	0	0	0

Sensitivety Analysis

CfD bid £/MWh	Average Cost to Consumer per 15 year CfD (£)	jobs	jackets	Total Value per net additional job Benefits/savings - direct & indirect (£) per annum	Total Direct & Indirect socio-economic benefits (£) per annum
£61.00	£4,090,965.00	420	10	£22,453,250.40	£30,410,511.60
£59.00	£3,956,835.00	336	8	£17,962,600.32	£24,328,409.28
£57.00	£3,822,705.00	252	6	£13,471,950.24	£18,246,306.96
£55.00	£3,688,575.00	145	4	£7,751,717.40	£10,498,867.10

Total benefit/saving - Direct & Inderect Unemployment cost saving per person	Number of Jobs Directly/Indirectly created	Number of Jackets	Total Benefits/savings (£) per annum
£18,945.86	290	8	£5,494,299.40
£18,945.86	145	4	£2,747,149.70
£18,945.86	1400	26	£26,524,204.00
£18,945.86	500	12	£9,472,930.00

Figure 7: Showing Sheet Containing Model Outputs.

2 – ShareDrive Link

Share drive link to model below:

https://strath-my.sharepoint.com/:x:/g/personal/william_monteith_2020_uni_strath_ac_uk/EfJiQddFUcBAmB3oWJYhBg0BDHbfAHhkKc7DWEm98sxwZQ?e=By0Hyg

Student No.