PivotBuoy

An Advanced System for Cost-effective and Reliable Mooring, Connection, Installation & Operation of Floating Wind

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D7.3: Socio-economic impact and LCA assessment

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EXECUTIVE SUMMARY

The PivotBuoy Project refers to an innovative offshore wind system that aims to reduce the costs of mooring systems and floating platforms, enable faster and cheaper installation and more reliable and sustainable operation. This report presents “Deliverable D7.3: Socio-economic impact and LCA assessment” with the purpose of evaluating the environmental and socio-economic aspects of the project from a life cycle perspective. It is conducted for a future commercial scenario consisting of 28 turbines of 15MW each, to be installed in the Canary Islands (Spain).

A conventional Life-Cycle Analysis (LCA) approach is used to compute energy and carbon flows, whilst regional and national Input-Output (IO) models are developed to assess the macroeconomic effects from the project’s deployment. This report details the methodology used for computing the LCA and IO models, whilst defining the parameters used in the analysis.

In terms of energy and carbon emissions, results from the LCA show that the mentioned wind farm holds much lower carbon intensity to produce the same amount of electricity than the Spanish grid using conventional forms of production, such as fossil fuels, and reasonable emission levels, when compared to other wind projects. It is noticed that the material intensity is the main driver of the emissions rates. The analysis was performed to two other locations, Viana do Castelo in Portugal and Golfe du Lion in France. Despite the reduction of transit distances, the project is shown to be more carbon intensive per energy unit, as a large amount of energy and carbon remains almost the same, since the contribution from the manufacturing phase is equally high, but energy production decreases due to lower local wind energy resource. Concerning end-of-life (EoL) management, recycling and reuse are shown to be a benefit to the project in terms of energy and carbon intensity, as this process has fewer impacts than the landfill waste scenario, besides the possibility of providing substitution of components instead of using virgin materials.

Detailed macro-economic analysis for the local and national locations highlights the large economic sector interdependency, showing that the proposed project stimulates output from all 27 aggregated sectors associated with the manufacture, construction, installation, operation, and decommissioning of the devices. Sectors directly related to manufacturing and transport are expectedly associated with the largest demand and output. The baseline case provides a peak of more than 20,000 jobs in the Canary Islands during the Operation and Maintenance phase over 20 total project lifetimes, and between approximately 7,000 and 9,000 nationally for the combined Manufacturing and Installation phases in Spain in one year, considering different local content capacities. This increase is due to a potential prospection on the Canarian participation in industrial activities. Other sectors indirectly linked to the project, such as accommodation and communications, will also experience benefits through the development of the economy.

While social factors are difficult to quantify, some behavioural patterns regarding the acceptance of renewable energy in the Canary Islands have been evaluated in a couple of studies, and despite some factors, mainly related to impacts on tourism activities and community well-being, in general a considerable level of social acceptance is expected due to the perceived benefits related to renewable energy in the region and a global climate change awareness.

The outputs from the model developed in this study highlight the wide-reaching macro-economic benefit of projects of this type, and when used in combination with environmental and techno-economic analysis will provide additional information to decision-makers.

It is important to mention, however, that the conclusions presented in this study are based on preliminary results for the baseline scenario (pilot project X30) and may differ for larger commercial scale projects, which may have different material lists and execution strategies.

LIST OF ACRONYMS

AHV	Anchor Handling Vessel
CAPEX	Capital Expenditure
CED	Cumulative Energy Demand
CLV	Cable laying vessel
CPT	Carbon Payback Time
CTV	Crew transfer vessel
DECEX	Decommissioning expenditure
EoL	End-of-Life
EPT	Energy Payback Time
EU	European Union
FTE	Full Time Equivalent
FOW	Floating offshore wind
FU	Function Unit
GHG	Greenhouse Gas
GVA	Gross Added Value
GWP	Global Warming Potential
HFC	Hydrofluorocarbons
ILCD	International Reference Life Cycle Data System
IO	Input-Output
ISO	International Standardization Organization
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
O&M	Operation and Maintenance
OPEX	Operational expenditure

PB	PivotBuoy
PFC	Perfluorocarbons
SPM	Single point mooring
SPMT	Self-propelled modular transport
TLP	Tension leg platform
TTP	Tow-to-Port
RES	Renewable energy source
RNA	Rotor-nacelle adaptor
ROV	Remotely Operated Vehicles

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1 INTRODUCTION

Floating offshore wind energy is one of the most promising emerging renewable energy technologies. Several types of technologies are being evaluated with the aim of obtaining more reliable and technologically and economically feasible systems. However, while capable of producing clean electricity, wind energy is not entirely environmentally friendly per se since energy is consumed and pollutants are emitted during the manufacturing, construction, operation, and decommissioning phases of wind turbines. Furthermore, the implementation of wind farms brings other effects to the region, such as environmental, economic, and social ones.

To understand the overall advantages of the large-scale deployment of the PivotBuoy (PB), it is necessary to go beyond device performance and techno-economics outputs. This deliverable aims to assess the socio-economic and environmental impacts of floating offshore wind farms in a future commercial scenario to be installed in the Canary Islands (Spain).

This report provides the results of a Life Cycle Assessment (LCA) which was developed to quantify the potential environmental impacts of the proposed system, and a socioeconomic impact analysis which assesses the potential economic impacts and job creation.

The comprehension of the embodied carbon and energy, as well as the macroeconomics aspects, allows for quantifying the regional benefits and concerns of the proposed floating offshore wind farm. The outcomes will help assess the wider impact of each of the analyses in conjunction with each other.

This report is structured as follows: after an introduction on the objective and scope of the present study (Chapter 1), a description of the PivotBuoy concept is presented (Chapter 2). Chapter 3 gives a comprehensive description of the methodological approach comprising the goal and scope of the LCA including functional unit, system boundaries, method of impact assessment applied, and the details of the Input-Output (IO) model including sectors aggregation, value chain and scenario definition. The approach undertaken for the social assessment is explained in sequence. Chapter 4 details the data collection carried out in each stage from manufacture to the device's disposal as the data used by the Input-Output (IO) model. A full analysis of the PivotBuoy is then carried out and the main results are shown in Chapter 5. The Life Cycle Impact Assessment (LCIA) includes calculations to achieve carbon and energy payback times as well as an analysis of a range of alternative scenarios regarding operation and recyclability. IO model results are shown in the sequence from a local and national perspective detailing the effects of the project's implementation on the Spanish economy. An additional qualitative study is included assessing likely social impacts and acceptance. Both numerical models are coupled to the techno-economic model detailed in [1], providing a comprehensive techno-economic—LCA—IO model able to assess a wide range of outputs for a variety of technologies and locations. A comparison of these reports' results with other wind offshore energy technologies is undergone under Chapter 6. Finally, conclusions are drawn in Chapter 7.

2 SYSTEM DESCRIPTION

2.1 General reference wind farm assumptions

2.1.1 Floating system design

The study reflects a floating offshore wind farm to be built in the future. Each device uses a full-scale PivotBuoy platform system developed by X1Wind, as a reference. This device is to accommodate a downwind version of the 15MW offshore reference turbine developed within [2]. A view of the whole assembly of the part-scale prototype X30 that serves as a reference for this study is presented in Figure 2.1.

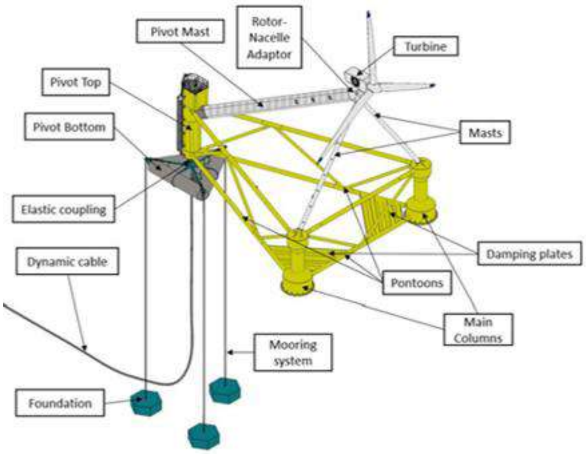

Figure 2.1. Final design and manufactured model of PivotBuoy.

The PivotBuoy is a novel subsystem that integrates the mooring system and the electric cable into a single point mooring (SPM). This combines the advantages of single point mooring systems with the stability and low weight of Tension Leg Platform (TLP) designs, reducing construction costs.

The platform structure itself is split into the TLP, which is installed independently and provides the station keeping and electrical connection, and the rest of the floating substructure structure. The floating substructure is comprised of two main columns and the PivotBuoy top column. The columns are connected by a twin pontoon with a jacket style bracing system. Heaving plates are installed in the two aft columns and in between the pontoons. The turbine nacelle is supported by three upper masts that connect to each column. A downwind turbine is installed, allowing the concept to weathervane freely around the mooring point and passively orient itself with the incoming wind. This removes the need for an active yaw system, reducing the mass located at hub height. Furthermore, there is no need for preconing and blade pre bending since the turbine blades will deflect away from the support masts while under load.

This concept merges a TLP mooring system, with the ease of installation of a semi-submersible, and the weather vanning capacity of single point mooring systems with a downwind turbine. The TLP mooring solution enables a low weight design of the platform, lowering construction costs. The stability during transit is provided by the three columns, which enables turbine integration at the port and facilitates the installation process, reducing costs. The ability to quickly disconnect the platform is designed for a tow-to-port strategy, which reduces operational costs.

PivotBuoy's modular design is comprised of two bodies, Pivot Bottom and Pivot Top, the lower body and upper body, respectively. The coupling system unites the pivot bottom to the TLP.

The floating structure consists of truss beams on whose top the turbine is to be assembled. It has 3 masts connecting the nacelle to each of the buoys, and 3 pontoons that connect the columns between themselves.

The turbine is composed of the nacelle, rotor, and blades. The RNA connects the turbine to the masts.

The mooring system consists of a TLP which is installed independently and provides the anchor point. The anchor is of a gravitational type and is made of reinforced concrete.

Electrical configuration: For the commercial scenario, with a total capacity of 420 MW, two export cables will be necessary, each with a 220kV capacity. All array cables were chosen as dynamic, due to the floating array, where the 66kV cables were considered for this study.

2.1.2 Farm Design

The farm is comprised of 28 x 15 MW wind turbine generators, for a total installed capacity of 420 MW and a project lifetime of 20 years. The key parameters of the reference scenario are summarized in Table 2.1.

Table 2.1 - Key Parameters of PivotBuoy.

Parameter	Value
Number of turbines	28
Nominal Capacity per device	15 MW
Total Rated Power	420 MW
Average Annual Energy Production per device	82 GW
Rotor diameter	240 m
Hub height	150 m
Operation Lifetime	20 years

For analysis purposes, a wind farm with 28 devices was considered as a baseline. To ensure consistency, the size of the system under analysis is the same for both assessments.

2.2 Location

The characteristics of the deployment area impact the LCA results, either due to the distance to be travelled for installation and O&M, in terms of fuel consumption and emissions, and to the length required by cables and mooring lines, which can vary according to water depth. It is also important to mention that different locations may present different wind profiles and consequently variations in energy production potential.

The location of the commercial scenario is assumed to be located in the Canary Islands (Spain), as shown in Figure 2.2. Table 2.2 shows the main site-specific distances.

Figure 2.2 - Location of the PivotBuoy installation area in the Gran Canary Islands (commercial scenario).

Table 2.2 – Site assumptions for the reference wind farm (baseline scenario).

Parameters	Baseline scenario (SP)
Location	Grand Canary Island, Spain
Long, Lat	27,77; -15,36
Distance from the nearest port to the site	45 km
Distance from site to shore	7,7 km
Distance from shore to substation/grid	9,6 km
Water depth at farm location	100 m

3 METHODOLOGY

3.1 Link between the assessments and the techno-economic model

Although the number of considerations, categories, and variables associated with the model makes integration with the LCA and the IO model more challenging, there was an effort to integrate both numerical models to maximize realism and ensure that consistent assumptions were applied throughout the PivotBuoy project, with an attempt to consider the same life cycle stages in both studies: Manufacturing, Assembly & Installation, O&M and Decommissioning & Disposal

The decision to create a coupled techno-economic—LCA—IO model requires all CAPEX and OPEX entries to be associated with their embodied energy and carbon, whilst also requiring detailed categorisation for IO assessment of macro-economic effects.

3.2 Life cycle assessment (LCA)

LCA is a method to assess the environmental aspects and potential cumulative impacts of a system over space and time throughout its life cycle from cradle to grave i.e., from the extraction of raw materials until its disposal [3]. This analysis has the purpose of analysing the components, materials, or stages of the life cycle with the most significant environmental burdens. LCAs can help engineers and designers in the decision-making process regarding product design.

Each stage of the life cycle is analysed in detail, and data on the energy, materials, emissions, and waste products associated are gathered. Justifiable assumptions are made when such information is not available. The results are then described as a set of identifiable consequences or impact categories. This methodology complies with international standards ISO 14040, which specifies the general framework, principles, and requirements for conducting and reporting this type of assessment [4]. This standard describes the LCA as comprising four main stages (Figure 3.1):

1) Goal and scope definition: Statement and definition of the intended purpose and boundaries of the analysis.
2) Inventory analysis: Definition and flow calculation of inputs and outputs to and from the defined system. In this case, the focus is on the net flow of equivalent carbon and energy.
3) Impact Assessment: Evaluation of the significance of the inventory analysis. Typically involves classification and characterisation of inventory analysis outputs and subsequent interpretation of results.
4) Interpretation.

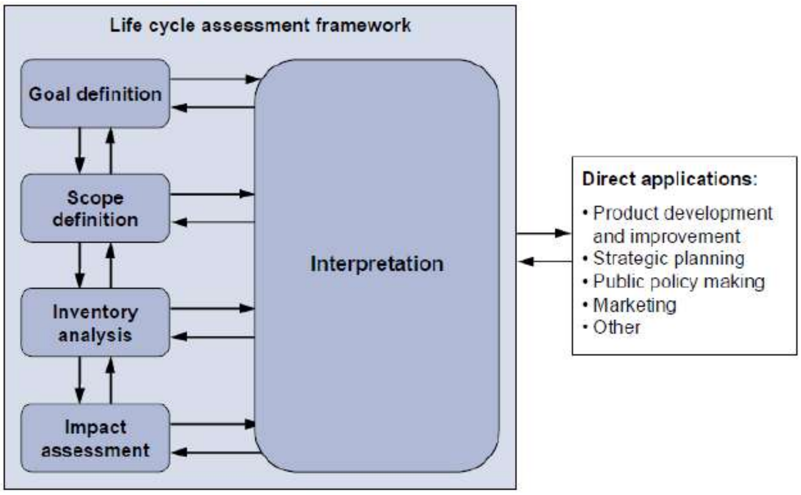

Figure 3.1 - Life Cycle Assessment framework; (ISO, 2006) modified.

3.2.1 Goal

The main purpose of the LCA is to assess the environmental impacts of a farm of floating offshore wind turbines in the commercial phase. The current study will help identify the most important life cycle stages of the device regarding the respective environmental impacts. Furthermore, a scenario analysis will support the identification of the alternatives with the least impact considering all life cycle stages.

Results will then be compared with other wind offshore technology, as well as with other type of marine energy sources and traditional means of electricity generation with the aim of identifying the benefits of using this type of configuration in comparison with other technologies. The LCA was conducted according to the International Reference Life Cycle Data (ILCD) System Handbook for LCA [3].

3.2.2 Scope

3.2.2.1 Functional Unit

The Functional Unit (FU) used is 1 kWh of electricity delivered to the Spanish electricity network from an offshore floating wind turbine. According to the studies carried out for this configuration, the wind farm, with 28 devices, is expected to produce 2426 GWh/year, along 20 years of lifespan.

3.2.2.2 System Boundaries

The system boundary encompasses all life cycle stages from "cradle to grave" as recommended by [5] taking into consideration the production of each part, their assembly and transport to the installation site, and O&M, as well as the process of decommissioning and disposal (Figure 3.2).

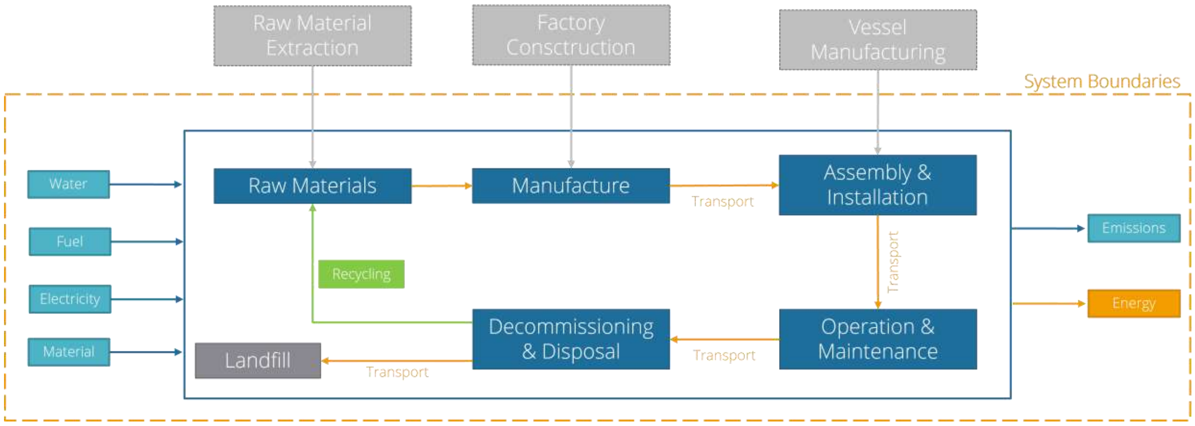

Figure 3.2 - System boundaries (built by the author).

Regarding the LCA physical boundaries, apart from the PivotBuoy itself, the analysis also covers the floating structure, the turbine, the mooring system, and the dynamic cable. The substation and all parts of the onshore electricity network and grid integration are outside the scope of this analysis. Since this is a descriptive study aiming at understanding the impact of a product and comparing it with other products with the same functional unit, the modelling principle for the Life Cycle Inventory (LCI) followed an attributional LCA approach [3].

All data regarding the extraction of raw materials, semi-finished products and components reflect the geographical region where the processes are assumed to take place. The methodology used to compute the flows for each stage is detailed in Section 4.

To allow comparison with other marine renewable technologies and traditional means of electricity generation, carbon dioxide equivalent emissions per produced electricity (gCO_2eq/kWh) was the main unit defined for the study. This measure accounts for all six Kyoto GHG emissions: CO_2, Ch_4, N_2O, HFCs, PFCs and SF_6.

3.2.3 Tools and method of impact assessment

The SimaPro 8 was the LCA software used to model the system, with LCI data sourced from the Ecoinvent database (version 3.5). The impact assessment stage is achieved by translating the environmental loads from the inventory results into environmental impacts. A large number of inventory results is grouped into different impact categories through the characterization of the results that cause a specific impact e.g., emissions of CO_2, CH_4 and others contribute to the GHG effect with different weights defined according to their global warming potential. However different methods of impact assessment differ in the way each presents and weights the different impacts.

The midpoint impact assessment method is the most commonly adopted approach for LCA studies on ocean energy systems [6]. The Life Cycle Impact Assessment was carried out with the ReCiPe 2016 Midpoint method [7], one of the most widely used midpoint impact assessment methods. It calculates 18 midpoint indicators which focus on single environmental problems. Endpoint metrics present the environmental impact at three higher levels of aggregation. Converting midpoints to endpoints increases uncertainty in the results since some level of weighting is required, which leads to invalid results for comparison purposes. However, midpoint impact potentials are considered more abstract and difficult to interpret. CO_2 emissions and embodied energy are two examples as they do not provide information about the damaging effects of increased levels of GHGs or energy consumption. Furthermore, this aggregation simplifies the interpretation of the LCIA results, and the entire impact pathway is accounted for. Hence, the assessment at an endpoint level was also included (Figure 3.3). Although this LCA focuses on climate change, since the results are easier to communicate due to the current political focus on the field [8], an energy input assessment was carried out using Cumulative Energy Demand (CED) to calculate the total direct and indirect amount of energy consumed throughout the life cycle [9]. From the CED, the Energy Payback Time (EPT) of a wind farm can be estimated, representing the time needed for the farm to generate as much energy as the sum of the embodied energy of its whole lifespan. Similarly, it is possible to estimate the Carbon Payback Time (CPT), another important indicator, that measures the period required for the device to offset the carbon emissions generated throughout the device's life cycle.

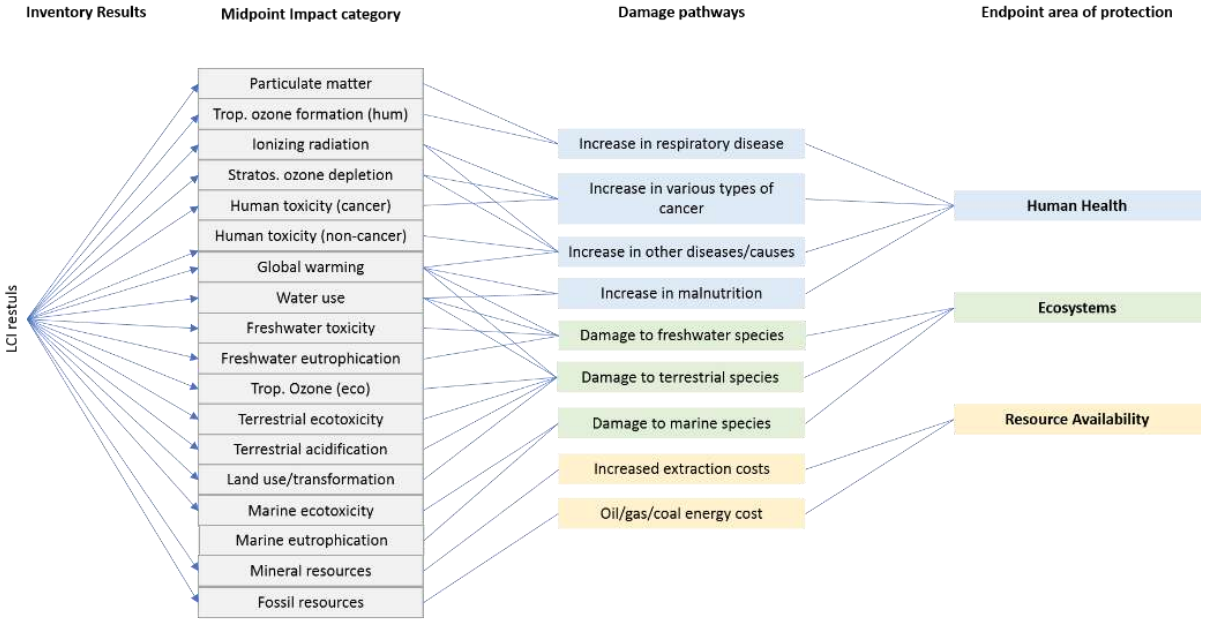

Figure 3.3 - Impact categories for characterization modelling at midpoint and endpoint levels (ReCiPe, 2016).

All processes from raw material extraction to disposal are covered by the LCA, as shown in the flowchart below (Figure 3.4). Each stage of the life cycle of the wind turbine is explained in more detail in this chapter. The manufacture of prefabricated components is not considered but the materials they are made of are.

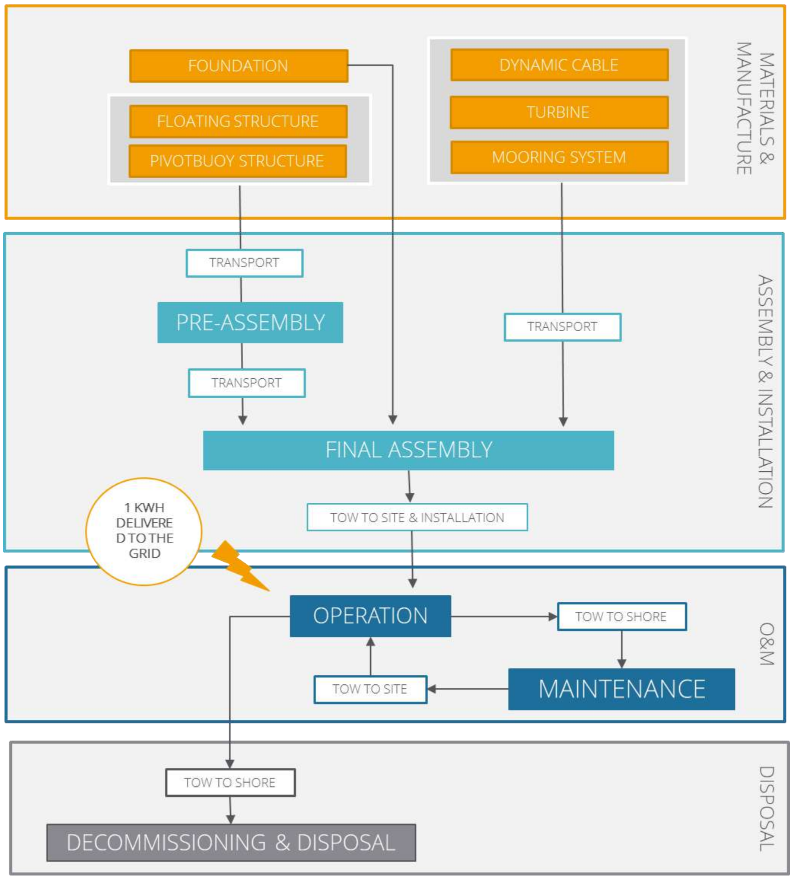

Figure 3.4 - Flowchart of the life cycle of the system.

3.3 Macro-economic analysis

Input–Output (IO) modelling is a quantitative method of macroeconomic analysis that relies on the interdependences between different sectors of the economy. This modelling approach enables to quantify the economic impact of a project in a specified region to be assessed, based on knowledge of direct and indirect sectoral spending that accounts for the inter-relationships between economic branches. Estimates are obtained for the number of created jobs and the total Gross Added Value (GVA) associated with the proposed project [10]. For this work, IO modelling is utilized to quantify and understand the effects of the instalment of the PivotBuoy on the economies of the Canary Islands, Spain, and the European Union (EU).

For this analysis a set of assumptions is considered:

- The general equilibrium is maintained at all times of the project's duration, i.e., demand, supply and price functions interact dynamically and result in a break-even point.
- The price of goods is assumed to be constant throughout the project's duration.
- The overall market status is assumed to be complete for the whole project's duration.

Different levels of economic interdependencies can be considered when applying IO modelling, which are classified into Type I and Type II effects, differing in their treatment of households' incomes and expenditures. The first type shows how much of each industry's output is needed, in terms of direct and indirect requirements to produce one unit of a given industry's output, considering the household sector as exogenous to the model, whilst Type II considers the direct, indirect, and induced effects resulting from household spending associated with the direct and indirect spend.

For this model Type II multiplier effects are considered as these values give a better indication of the total macroeconomic benefit of the proposed projects. The model is created in four stages, which are expanded further in the following sections:

1. Industrial sectors aggregation
2. Value-chain analysis
3. Scenario definition
4. Input-output model

3.3.1 Industrial sectors aggregation

The regional industrial classification covers an extensive range of sectors. Once the regional industrial sectors of interest have been identified through access to local economic data, an aggregation process can be undertaken to provide a clearer and easier understanding of the modelling outputs. For this work, regional classes have been aggregated into 27 classes (Table 3.1). This has been carried out by identifying common characteristics. These groups have been used for the creation of new industry by industry (I x I) matrices, describing the aggregated sector interdependencies.

Table 3.1 - Aggregated industry classes.

Grouped Sector Classification
1. Accommodation
2. Agriculture, forestry, and fishing
3. Chemical
4. Coal, oil, and gas extraction
5. Communication, finance, business
6. Construction
7. Distribution and other transport
8. Education, public, social, and other services
9. Electrical equipment
10. Electricity and gas
11. Engineering, research, and technical services
12. Food products; beverages; tobacco products
13. Health
14. Legal activities
15. Machinery and equipment
16. Metal and non-metal goods
17. Mining and quarrying
18. Motor vehicles
19. Other manufacturing
20. Other transport equipment
21. Recreation services
22. Rental and leasing services
23. Repair and maintenance
24. Textile
25. Tourism
26. Waste, remediation & management
27. Water

3.3.2 Value chain analysis

Analysis of the value-chain aims to identify the local and national sectors to deploy the project. It includes all stages considered in this study boundaries, namely Manufacturing, Assembly & Installation, O&M and Decommissioning & Disposal.

From the expertise acquired during the deployment of the X30 prototype, it was possible to estimate the CAPEX and OPEX, at a commercial level. Due to the ongoing stage of the project, it has not yet been possible to obtain more accurate data associated with OPEX, therefore the costs associated with O&M have been estimated based on the economic model developed for this project [1].

In order to implement the IO model, these entries need to be accordingly split into the key project's phases. In this way, each expenditure entry has been separated into the differing associated materials and services, and costs allocated to the most appropriate industrial classes.

While maintenance and decommissioning are assumed to be exclusive, the manufacturing and installation stages are modelled as overlapping. These phases are estimated to last 3, 2, 20 and 1 year respectively, with installation commencing after 1 year of manufacturing [10]. To simulate the time-series properly, the entries are divided by the respective number of years of each stage to calculate the annual direct output for the aggregated sector. The direct sectors will trigger the indirect and induced effects, according to their respective sectoral linkages.

The share of the expenditures and the main aggregated industrial sectors per project phase are detailed in Table 3.2. As mentioned, the cost distribution for the Manufacturing, Assembly & Installation, and Decommissioning & Disposal, were based on the data gathered from the prototype experience, scaled up to the commercial scenario, in terms of capacity and number of turbines, while the O&M cost relies on the figures found in the techno economic model.

Table 3.2 – Value-chain: Project phases and expenditure share.

Phase	Expenditure share	Aggregated industry classes
Manufacturing	49%	Metal and non-metal goods; Electrical equipment; Machinery and equipment; Construction; Engineering, research, and technical services; Legal activities
Assembly & Installation	15%	Other transport equipment; Distribution and other transport; Engineering, research, and technical services; Health
O&M	33%	Other transport equipment; Distribution and other transport; Repair and maintenance; Engineering, research, and technical services; Health; education, public, social, and other services
Decommissioning & Disposal	3%	Other transport equipment; Waste, remediation, and management; Distribution and other transport; Engineering, research, and technical services

3.3.3 Share of Investment

The scenarios undertaken were built by differentiating the share of the investment that could be satisfied by the Canarian, Spanish and foreign companies, during the four mentioned project phases.

In comparison to the national scenario, the Canary Islands holds a developed tertiary sector, but a still underdeveloped secondary sector. However, given the strategic ambition of the Canary Islands

Government to increase the share of renewable energy generation on the island, there is an interest in developing local infrastructure to support the offshore wind industry activities in the Gran Canaria region.

Given the uncertainty to attribute local industrial capacity, this study analyses three scenarios that are differentiated by the distribution of local content. The Case 1 reflects a more conservative approach and still considers a lower technological capacity in the Canary Islands, while the Case 2 focuses on a future prospection, where local content could potentially be increased given the investments foreseen for the development of local industry. Both scenarios are undertaken based on a study developed by [11]. Additionally, a third local content case is also considered, assuming a similar distribution as the one implemented within the X30 prototype, as displayed by X1Wind.

The distribution considered for the mentioned scenarios are presented in Table 3.3, Table 3.4 and Table 3.5 and represent the shares by project phase and region, i.e. Canary Island, Spain (Mainland), and EU and abroad.

Table 3.3 Share of investment by project phase - Local Content Case 1.

Phase	Canary Islands	Spain (Mainland)	EU and abroad
Manufacturing	2%	80%	18%
Assembly & Installation	55%	35%	10%
O&M	35%	34%	31%
Decommissioning & Disposal	100%	0%	0%

Table 3.4 – Share of investment by project phase - Local Content Case 2.

Phase	Canary Islands	Spain (Mainland)	EU and abroad
Manufacturing	5%	77%	18%
Assembly & Installation	77%	17%	5%
O&M	40%	29%	31%
Decommissioning & Disposal	100%	0%	0%

Table 3.5 - Share of investment by project phase - Local Content Case 3.

Phase	Canary Islands	Spain (Mainland)	EU and abroad
Manufacturing	4%	76%	20%
Assembly & Installation	73%	20%	7%
O&M	53%	19%	28%
Decommissioning & Disposal	100%	0%	0%

3.3.4 Input-output model

The methodology described in Sections 3.3.1 to 3.3.3 provides the final demand of the aggregated sector for the region of interest.

Mathematically, an IO model consists of a set of n linear equations with n unknown variables, which denotes the number of goods and services. As explained by [11], each of these goods (x_i) can be demanded as an intermediate demand (id_{ij}) of a good i from sector j (inter-industrial relationship) or as final demand (fd_i) of a good i. By dividing the intermediate sectorial demand by the sectorial production, it is possible to calculate the technical coefficients (a_{ij}). The technical coefficients capture the economic relationships between the sectors.

$$(a_{ij}) = \frac{(id_{ij})}{(x_i)} \quad (1)$$

In matrix notation, it can be represented by:

$$X = AX + D \quad (2)$$

Where X represents the production, A is the technical coefficient and D is the final demand. Thus, an IO model calculates the necessary output to satisfy the final demand assumed. This system traditionally can be solved according to the Leontief algorithm [12]:

$$X = (I - A)^{-1}D \quad (3)$$

Being I the respective identity matrix.

If assuming only the relationship among industrial branches by a matrix $[n \times n]$, it is possible to calculate the direct and indirect effects. However, this approach omits the role of salary's impact on the economy, the so-called induced effect. The induced effect can be easily included in an IO model by adding a new row and column representing the incomes (row) and household expenditures (column) of the determined economy, resulting in a matrix $[n + 1 \times n + 1]$.

The Leontief system calculates the necessary output to meet the demand required by the project. Nevertheless, the value-added generated (GVA) in the economy is represented by the difference between the total output and the intermediate demand:

$$GVA = va'(I - A^{-1})D \quad (4)$$

Where va' represents the value-added coefficients transposed and $(I - A^{-1})D$ the total output effect. The value-added coefficients can be estimated by diving the sectorial added value (VA_j) by the sectorial production (X_j).

$$va' = \frac{VA_j}{X_j} \quad (5)$$

Similarly, as shown in Equation (6) it is possible to estimate the employment effect (L), corresponding to the number of workers, and the relation with the employment coefficient transposed (l'), which is obtained by dividing the workers of each sector or the Full-Time Equivalent (FTE) (L_j) by the total sectorial production (X_j).

$$L = l'(I - A^{-1})D \quad (6)$$

$$l' = \frac{L_j}{X_j} \quad (7)$$

3.4 Qualitative Study on Social Impacts

Although GVA and employment statistics are important indicators, to evaluate the likely social impacts and uptake of the wind farms it is necessary to look beyond. An additional qualitative study is therefore conducted. The approach taken has been to review the literature on social impact studies focusing on wind technologies in analogous areas, as such Spanish islands. The output of this study is presented in Section 5.4.

4 DATA COLLECTION

Data collection has been conducted in close cooperation with the project partners involved in the design of PivotBuoy. However, due to the lack of information at the commercial scenario stage, some assumptions and approaches were therefore considered.

Foreground or primary data were collected from the project design team, material experts and engineers. All background or secondary data were ultimately derived from the Ecoinvent database and assumptions and approximations for non-available data. Since the Ecoinvent database does not contain all inventory information, some manufacture processes were modelled according to the energy consumed using data sourced elsewhere and new materials were created based on previous studies.

Most data in this database reflect the average European conditions. One exception is electricity production, for which data is provided by the country. This means that, for manufacturing processes assumed to take place e.g., in Spain (country code ES), the electricity mix used was changed to Finish electricity mix. For processes taking place in an unknown (European or global) location, the average European (code RER) or global (code GLO) electricity mix was used.

An offshore wind turbine consists of many components and sub-components of different natures and with several mechanical and electrical parts which mean it is difficult to gather information on all the parts from suppliers. This analysis focused therefore on the most important components. Given the expected small contribution of some electronic and electrical systems to the overall embodied carbon and considering their complexity, it was more appropriate to simplify this stage to avoid time consumption. Thus, a cut-off criterion of 1% was applied throughout the life cycle to exclude minor impacts and help set boundaries for the total system inventory [13]. As offshore wind devices only produce electricity and e.g., no heat, there is no need to allocate between more products, which simplifies the inventory.

4.1 Materials and Manufacture

The life cycle begins with the raw material extraction and processing followed by the manufacturing phase which comprises the moulding and shaping of the materials to form the device sub-components.

This stage includes the manufacturing of components for each main system for the farm scenario under analysis. To ease the model development, the system has been divided into 5 main systems: PivotBuoy Structure, Turbine, Foundation and Others. The approximate mass breakdown for each system and sub-component is shown in Figure 4.1.

The "PivotBuoy Structure" comprises the Pivot Top, Pivot Bottom, Pivot Mast, Pontoons, PS & SB Columns, PS & SB Masts, Damping Plates, Coupling system and Rotor-nacelle adaptor (RNA). The system "Turbine" represents the turbine itself with its main components, while the "Foundation" represents the 3 concrete anchors. The dynamic cables and mooring system are indicated in the system "Others".

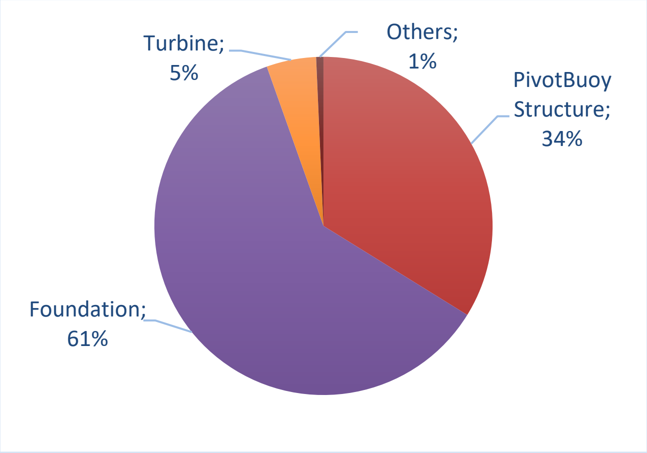

Figure 4.1 - Systems– approximate mass breakdown

The steel mass of the main structures is based on the 1:3 scale prototype values provided by [14]. Given the non-availability of information regarding the commercial scale design, this has been considered as an estimate, although the increase to a 15MW turbine may not necessarily mean a linear variation. The foundation comprises a gravity base system, where its mass is based on the volume of 3 concrete blocks (2700kg/m^3 of density) with an internal steel structure (8050 kg/m^3 of density), estimated at about 7% of the total volume of each block.

Turbine characteristics are based on IEA's 15 MW reference turbine [2] as highlighted in the [15]. The composition of the different types of materials of a turbine was calculated based on [16], being approximately 68% steel, 14% fibreglass, 14% cast iron, 2% copper and 2% aluminium.

The dynamic cable is assumed to have around 19 kg/m with a share of 19% copper, 20% polyethylene and 60% steel. The length of dynamic array cables was calculated as the same approach as PivotBuoy Deliverable D7.1.

The mass of the prefabricated devices was assumed from similar manufacturers' information, however, only the impact of material extraction was considered in this model, neglecting the energy expended in the manufacturing processes.

PivotBuoy is largely constructed from steel and concrete. The steel is cut and welded to shape before being painted with corrosion-resistant paint. The energy consumption for the machining and painting processes was based on [17] assuming an average consumption of 1.65 MJ/kg and 55MJ/m^2, respectively. Calculations for the welding process were undergone assuming the need for 4,35 kg of welded steel per meter [18].

Manufacture of the main parts, such as the Pivot and Floating Structure, is assumed to take place in mainland Spain. The turbine, the majority of the mooring system and the coupling system are expected to be acquired from abroad (EU), while the prefabricated dynamic cables are considered to originate externally to EU.

Reiteratively, given that the information about the commercial scale project is not available at this moment, it is important to mention that the execution strategy described in this section was based on the prototype and taken as assumptions for the purpose of this assessment.

A mass-based analysis was carried out with a breakdown of the most significant quantities of incoming materials for the wind turbine including the prefabricated components, as shown in Figure 4.2. As can be noticed, the concrete represents the most significant share of PivotBuoy. It is attributable to the choice of anchor selection at the design phase (concrete gravity anchor), which may vary depending on the site location.

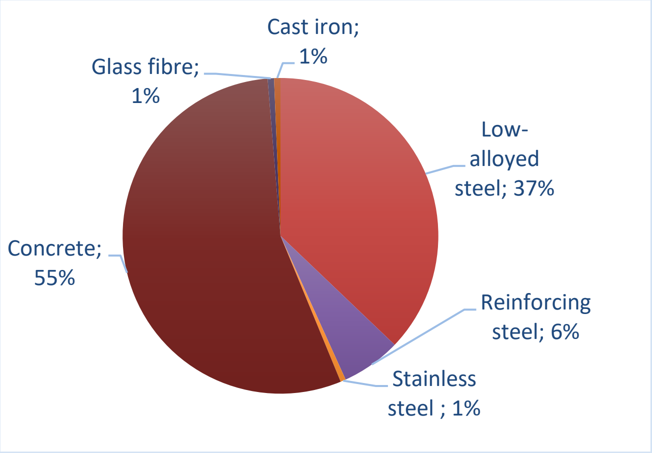

Figure 4.2 - Material breakdown.

4.2 Assembly and Installation

This stage encompasses pre-assembly and final assembly stages, which include crane work and welding work as well as road and sea transport of components to the final installation site. Components manufactured at Spain (Mainland) will be sent to a Spanish port for pre-assembly. The Pivot Bottom and the Pontoons will be shipped by vessel, while PS & SB Masts, Pivot Mast, Pivot Top, PS & SB Columns, RNA, and Damping Plates by road. The foundation’s manufacturing takes place at the final assembly site (Canary Islands), all components will be also assembled before installation.

The structural components will be shipped from the mainland to the island by cargo vessel. Other components, such as the mooring system, turbine and dynamic cables are supposed to be sent by road to the south of mainland Spain where they took a ferry to the Canary Islands.

The functional unit of transportation is the payload distance measured in ‘tkm’ and represents the transport of 1000 kg of goods over 1 km. It is calculated by multiplying the travelled distance (km) by the device mass (kg).

A crane was considered for the pre-assembly and final assembly phases. Since no data from the manufacturer was available and the impacts of final assembly are expected to be relatively small, a rough estimate for consumption, taken from [19]was used. The time spent for each operation of assembly and installation was based on the techno-economic model.

After final assembly, specialist sea vessels are required to install moorings, prepare the seabed, tow and install the device. The processes to prepare the site installation was not taken into consideration in this analysis, considering that its impact is relatively small on the results.

The transport of each system to the installation site is performed by tugboats from the harbour to site deployment and it is given in terms of payload, given by the distance and mass of the component.

In the installation approach, the time and vessels/equipment required to carry out the tasks of turbine integration, load out, transportation, installation and inspection were estimated based on the techno-economic model developed in a previous stage.

By scaling Ecoinvent data for a freight ship to match the fuel consumption of each type of vessel, as suggested by [20], it is possible to achieve the correspondent payload of each operation, where 1 tkm corresponds to 0,0028 litres of fuel.

Table 4.1 - Vessel and equipment consumption during Assembly & Installation phase.

Vessel	Consumption (l/h, *kWh/h)	Reference
Crane	18*	[19]
SPMT	47	[21]
ROV	50	[22]
AHV	120	[23]
Tugboat	150	[20]
CLV	150	[20]

4.3 Operation and Maintenance

The PivotBuoy system enables a so-called Tow-to-Port (TTP) maintenance approach, where the large repairs can be carried out at the port, avoiding the use of large offshore vessels, which can be an advantage and a significant driver to reducing the O&M time, emissions, costs, and ultimately the LCOE, as stated by [15].

To represent the O&M phase, the assumptions made for the techno-economic model described in PivotBuoy Deliverable D7.1 are used. For the preventive campaign, minor repairs are supposed to occur annually while major maintenance is assumed to be undergone every 5 years. The corrective actions are based on failure rates, which determine the type of vessels required, as well as the total use and fuel consumption.

The TTP actions are assumed to occur in a Canarian port. The total use of the vessels considers the preventive and corrective maintenance, throughout the project lifetime, to guarantee the long-term operationality of the whole installation. The vessels used at this phase are presented in Table 4.2.

Table 4.2 - Vessel and fuel consumption during the O&M phase.

Sea Vessel	Fuel consumption (l/h)	Reference
CTV	130	[23]
ROV	50	[22]
AHV	120	[23]
Tugboat	150	[20]
CLV	150	[20]

Change of oil, lubrication, and transport to and from the turbines are included in the stage of O&M. A conservative estimate includes that the generators, mooring lines, and blades are to be renewed once over the lifetime of the project so that the additional material and transport for this task must be considered. Transport on shore is done by truck, and it is considered as being 900/km per year throughout the lifetime of the project [24].

4.4 Decommissioning and Disposal

This phase represents an important part of the LCA, encompassing the End-of-Life (EoL) of the project and exploring how it will be managed. The defined approach could contribute to an improvement in the overall environmental impact by giving credit to the emissions released in the other stages.

Decommissioning of PivotBuoy includes cranage and transport from the operational site to the final disposal. The disassembly is assumed to be equivalent to a reversed installation process, and so it is considered through the same amount of fuel consumption. The disposal scenario considers two different EoL routes based on the literature review – recycling and landfilling (Table 4.3).

Table 4.3 - Assumptions for EoL scenarios.

Material	Type of disposal and ratios
Low alloyed and Stainless Steel	Recycle 85%, Waste treatment 15%
Cast Iron	Recycle 85%, Waste treatment 15%

At the EoL of the device, following similar assumptions made in other studies, metal components are assumed to be transported to a recycling centre and the concrete blocks are re-crushed and reused. Recycling leads to a reduction of the net energy and carbon flows into the system boundaries. Transport to the final disposal site was considered negligible compared to other life cycle stages and thus is excluded from the analysis.

4.5 Macroeconomic data

The sectorial data and IO tables were obtained from the Canarian and Spanish Statical Institutes, [25] and [26] respectively. These are normalised to compute the multiplier effect from the known interdependencies. To compute macroeconomic effects, it is therefore required to have up-to-date IxI matrices, and to allocate all project spend to aggregated classes. The latest information provided is in reference to 2005 and 2015, correspondingly. However, although there may be economic impacts from the Covid-19 pandemic, as well as from the Russia-Ukraine conflict and energy crisis that is currently crossing the European continent, for this study, these factors are considered to be beyond the normal economic patterns. Thus, considering the evolution of the Spanish economic sectors, with a production chain without major variations over these last years, the statistical parameters provided can be considered with a certain level of reliability.

5 RESULTS

5.1 Life Cycle Impact Assessment (LCIA)

The LCI produced a list of around 1700 substances consumed or emitted throughout the life cycle. Table 5.1 shows the total life cycle emissions of the six Kyoto GHG for the analysed wind farm. Although further calculations are required, it is already visible that CO_2 emissions are significant, and that it mostly arises during steel manufacture.

The ReCiPe impact assessment method was applied to characterize the results of the LCI and the environmental impacts. A cut-off criterion of 1% was applied to visualize the most relevant contributors. Since ocean energy is broadly considered a technology that will contribute to a low-carbon energy system, special attention was given to the LCA results on the global warming potential (GWP), which for this model results in 11.24 g CO2 eq. Nevertheless, an overview of all 18 impacts from both ReCiPe and CED impact assessment methods is summarized in Table 5.2.

Table 5.1 - Emissions of the Kyoto Protocol GHGs.

Gas		Emissions (g/kWh)	GWP (g CO_2 eq/kWh)
Carbon Dioxide	CO2	11,00	11,00
Methane	CH4	0,03	1,06
Nitrous Oxide	N2O	5,41E-04	0,16
Sulphur Hexafluoride	SF6	5,45E-07	1,42E-02
Hydrofluorocarbons	HFC	1,46E-07	5,66E-04
Perfluorocarbons	PFC	3,78E-06	0,01

Table 5.2 - Results of LCIA and CED calculation with acronyms.

Impact Category	Emissions	Unit/kWh
Global warming (GWP)	11,24	g CO2 eq
Stratospheric ozone depletion (SOD)	6,73E-06	g CFC11 eq
Ionizing radiation (IR)	5,99E-02	Bq Co-60 eq
Ozone formation. Human health (OF Hum)	3,41E-02	g NOx eq
Fine particulate matter formation (FPMF)	2,82E-02	g PM2.5 eq
Ozone formation. Terrestrial ecosystems (OF Eco)	3,57E-02	g NOx eq
Terrestrial acidification (TA)	4,37E-02	g SO2 eq
Freshwater eutrophication (F Eut)	6,18E-04	g P eq
Marine eutrophication (M Eut)	3,54E-04	g N eq
Terrestrial ecotoxicity (T Etox)	1,29E+02	g 1.4-DCB
Freshwater ecotoxicity (F Etox)	3,46E-02	g 1.4-DCB
Marine ecotoxicity (M Etox)	1,08E-01	g 1.4-DCB
Human carcinogenic toxicity (HT car)	1,85E+00	g 1.4-DCB
Human non-carcinogenic toxicity (HT noncar)	7,60E+00	g 1.4-DCB
Land use (LU)	2,57E-01	m2a crop eq
Mineral resource scarcity (MRS)	5,53E-01	g Cu eq
Fossil resource scarcity (FRS)	2,73E+00	g oil eq
Water consumption (WC)	7,63E-05	m3
Cumulative Energy Demand (CED)	149,00	kJ

Figure 5.1 illustrates the contribution of the life cycle stages to each impact category. The level of contribution depends on the impact category that is being valued but some trends can be observed. The manufacture of each system is displayed separately. As shown in the graph, for almost all impact categories, manufacturing contributes to the most environmental impacts, particularly the foundation and floating system, which have as main material concrete and steel, respectively. Assembly processes and transport of the subcomponents to the port for final assembly as well as the transport of the device

to the installation site and maintenance tasks are included in the Assembly & Installation and O&M, respectively.

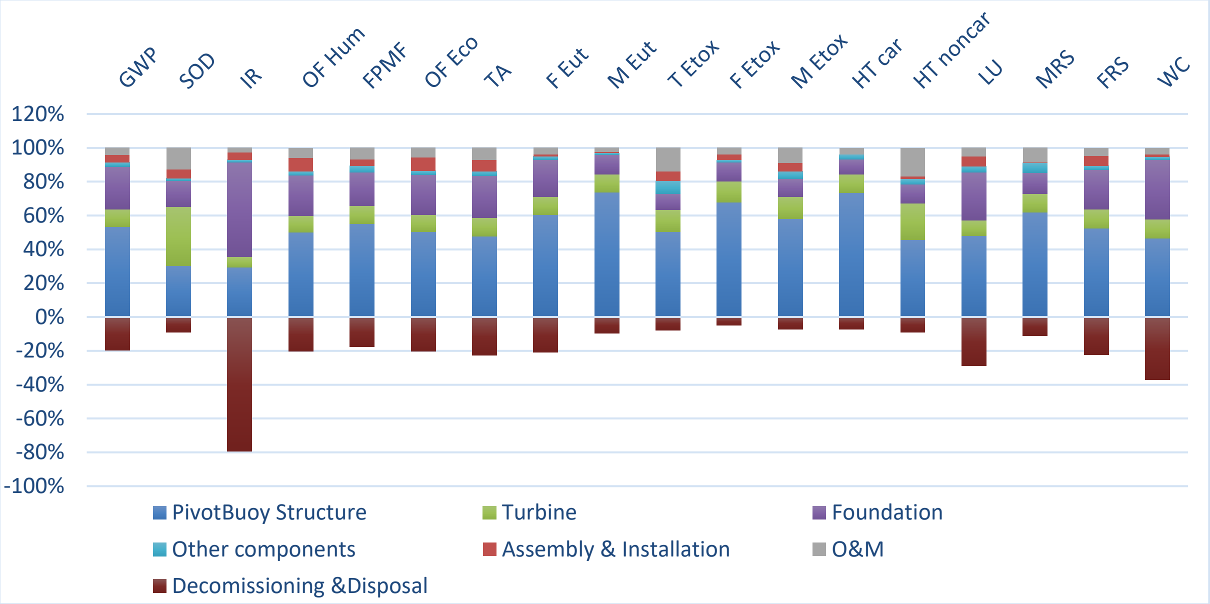

Figure 5.1 - Breakdown of impacts by life cycle stage for each impact category.

The results for the impact category GWP are shown in Figure 5.2 in g CO_2 eq/kWh. Impacts related to Assembly & Installation and O&M represent 4% for each phase, indicating a small impact on the overall results whereas the manufacturing stage has the biggest impact of all life cycle stages. Sea and road transport, and processes, such as crane operations, are considered in these stages, as materials used in the replacements of spare parts, as mentioned in Section 4.3.

Manufacturing contributes with approximately 12 g CO_2 eq/kWh to the overall GWP results during this stage, corresponding to 89% (before applying credits for recycling). The manufacture of the foundation accounts for 27% (approx. 3 g CO_2 eq/kWh) and the manufacture of the floating system for 34% (approx. 4 g CO_2 eq/kWh) of the impacts during this stage. These impacts are large because cement and low-alloyed steel production are very energy-intensive, and thus contribute to substantial GHG emissions.

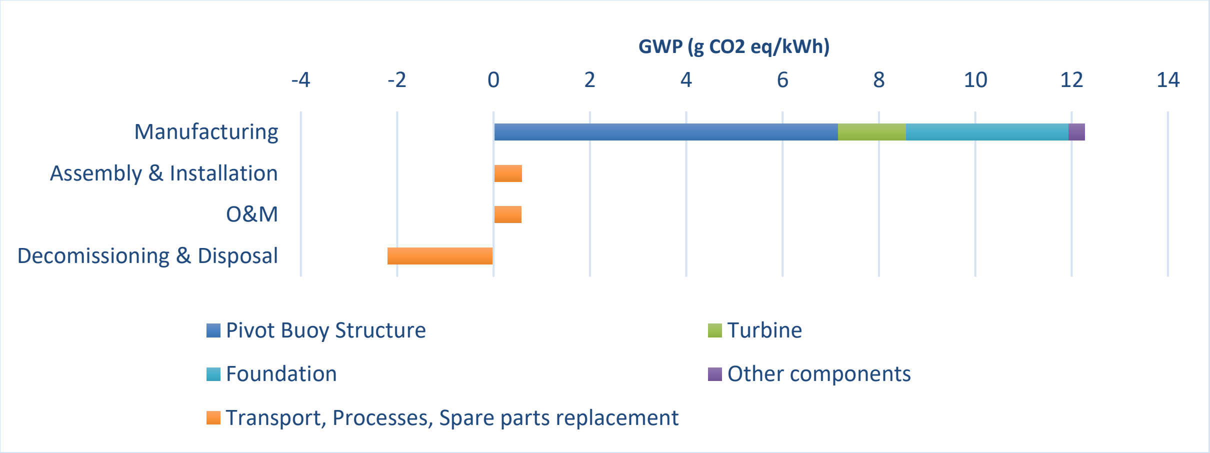

Figure 5.2 - Global Warming Potential.

The results of the impact assessment at end-point level are shown in Figure 5.3, where emissions are related to their damage to the three areas of protection: ecosystem quality, human health, and natural resources. The contribution of each life cycle stage is fairly even across the three areas.

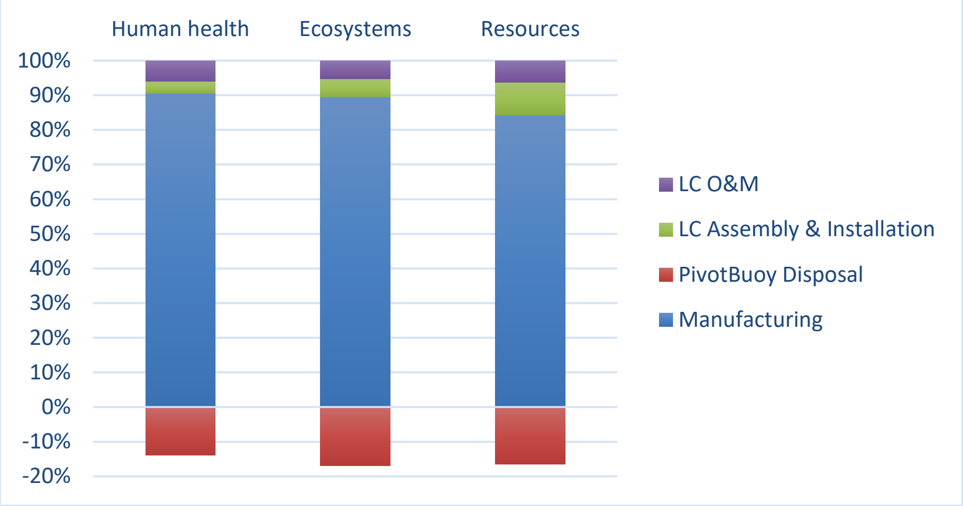

Figure 5.3 - Results of ReCiPe impact assessment method applied at the endpoint level.

The annual energy production of the whole wind farm is estimated to be around 2426 GWh, which results in an energy intensity of 149 kJ/kWh, as previously illustrated in Table 5.2. The CED is estimated for five classes of primary energy carriers: fossil, nuclear, hydro, biomass, and others (wind, solar and geothermal). Differences in different types of cumulative energy demands are mainly due to the consideration of location-specific electricity mixes. The preponderance of non-renewable energies, especially energy from fossil fuels, is observable (Figure 5.4), where for each kWh of electricity, 125 kJ of fossil energy is used i.e., 84% of the total energy demand comes from fossil fuels.

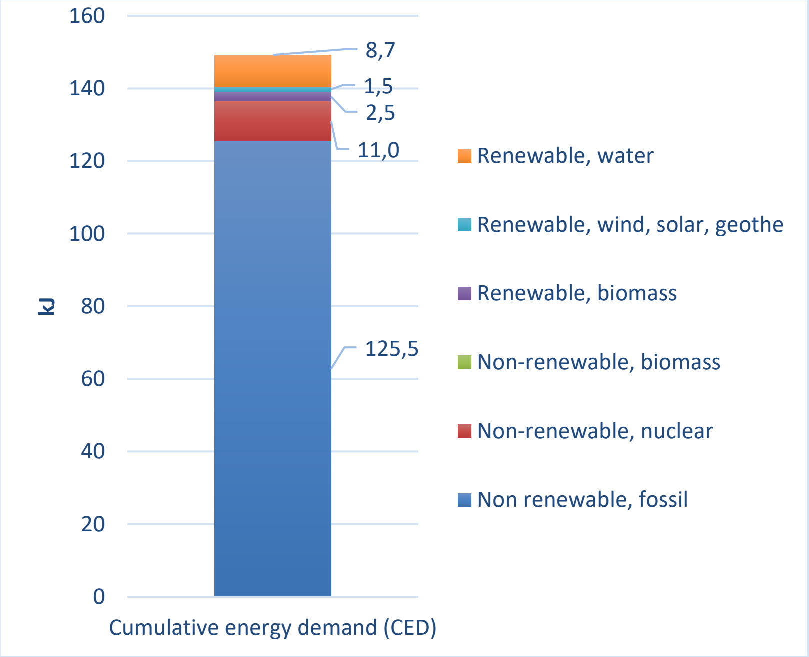

Figure 5.4 - CED Results.

This project has received funding from the European Union's Horizon H2020 research and innovation programme under grant agreement No 815159

5.2 Energy and Carbon Payback Times

Energy and Carbon payback time (EPT and CPT, respectively) are important indicators for renewable resources. CPT measures the period (months) required for the device to offset the carbon emissions generated throughout the device's life cycle process and is calculated according to Equation (7). The energy payback time represents the amount of time that the system needs to run in order to produce the amount of energy equivalent to the primary energy consumed throughout its lifetime and is calculated according to Equation (8).

$$CO_2eq\ payback\ (CPT) = \frac{Total\ CO_2eq\ emissions\ throughout\ life\ cycle\ (gCO_2eq)}{Annual\ CO_2eq\ avoided} \quad (7)$$

$$Energy\ payback\ time\ (EPT) = \frac{Life\ Cycle\ Embodied\ Energy}{Energy\ produced\ (EP)_{year}} \quad (8)$$

The carbon avoided by the device relies on the type of generation and is location dependent. However, it is the accepted practice to assume that the electricity offset by the device will be the average of the Spanish grid. According to the Ecoinvent database, the emissions for medium voltage electricity in Spain have CO_2 intensity of 0,32 kg CO_2/kWh. The GWP and CED were found in Section 5.1 to be 11,49 g CO_2 eq/kWh and 149 kJ/kWh, respectively. These values correspond to a CPT of 8,6 months and an EPT of 9,9 months.

5.3 Alternative scenario analysis

There are several potential sources of uncertainty in this study arising from some approximations and assumptions made in this early stage of PivotBuoy. A range of three scenarios was drawn to assess that uncertainty and, consequently, to model potential improvements in the life cycle environmental impact. Results presented in this section are indicative and interpretation needs further study regarding the sensitivity of each parameter variation.

5.3.1 Site Deployment

Given the larger distance from the manufacturing site in the Canary Islands, an analyse was conducted considering two different sites, namely, Viana do Castelo (Portugal) and Golfe du Lion (France), as described in Table 5.3.

Table 5.3 - Parameters of site deployment analysis.

Parameters	Baseline scenario	Alternative scenario 1	Alternative scenario 2
Location	The Canary Islands, Spain	Viana do Castelo, Portugal	Golfe du Lion, France
Long, Lat	27,77; -15,36	41,72; -8,96	42,84; 3,24
Distance from the nearest port to the site	45 km	17 km	17 km
Distance from site to shore	7,7 km	17 km	17,5 km
Distance from shore to substation/grid	9,6 km	21,3 km	21,9 km
Water depth at farm location	100 m	100 m	75 m
Annual energy production	2426 GWh	1513 GWh	1906 GWh

This project has received funding from the European Union's Horizon H2020 research and innovation programme under grant agreement No 815159

For this approach, the same assumptions of manufacturing (material, process, and location) are considered, although different sites for the Assembly & Installation, O&M and Decommissioning & Disposal phases. The main differences between these sites are the distance to the port and to shore, water depth and wind profile. Despite the shortest distances from the port and manufacturing site, the results show a higher GWG impact for both alternative scenarios. The carbon emissions for the Portuguese site are around 17,8 g CO_2 eq/kWh and 14,5 g CO_2 eq/kWh for the site located in France, as presented in Figure 5.5.

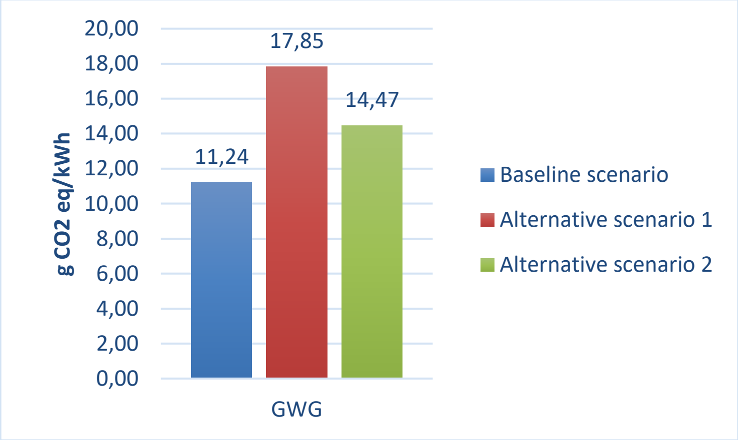

Figure 5.5 - GWG results for different scenarios.

As the Assembly & Installation and O&M phases present a small share of total carbon intensity, the impact caused by the distances travelled during these actions is not so substantial overall. Furthermore, with manufacturing playing the main role in the final impact, for regions with different wind profiles and lower energy production, the g CO2/kW ratios tend to be higher, as the same material intensity is used to produce less energy, i.e., the same amount of material is spread over fewer kWh delivered to the grid.

5.3.2 Recycling

Decommissioning should be carried out in a sustainable manner by recycling and reuse methods. At this stage, an analysis is made to verify the impact of not recycling and reusing materials, as was done in the baseline model.

Table 5.4 – Parameters of site recycling analysis.

Parameters	Baseline scenario	Alternative scenario 3
Waste Scenario	Recycling rate 85%	No recycling and reuse

Considering the disposal assumption, the GWP of the baseline scenario was found to be 11.24 g CO_2 eq/kWh. This value rises 56% if the disposal scenario is excluded, highlighting the important role this stage plays in the overall life cycle. It is important to mention that in this model, the metals that will be recycled do not count as avoided material (reuse), but as avoided emissions in the process of waste treatment (landfill).

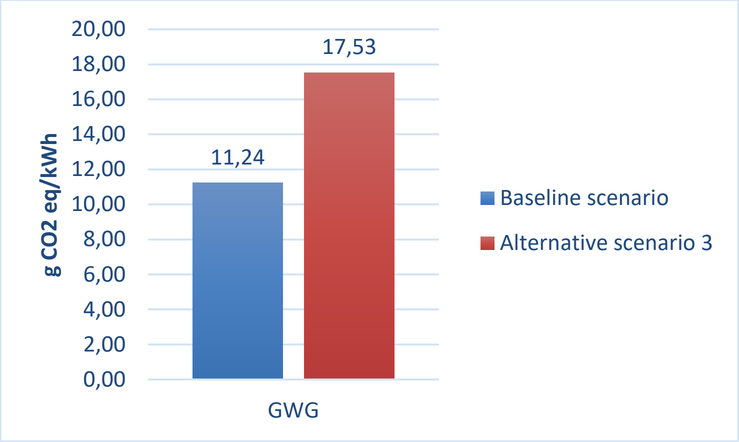

Figure 5.6 GWG results for no recycling scenario.

5.4 Input-Output Model

Due to the highly location-dependent nature of macro-economic studies, the IO results are presented locally (Canary Islands) and from the national (Spain) perspective, separately.

5.4.1 Direct, Indirect and Induced Outputs

The direct outputs for each of the 27 aggregated sectors, each project stage, and each local content caseare presented in Figure 5.7, Figure 5.8 and Figure 5.9 for the Canary Islands, while the figures representing the mainland are indicated in Figure 5.10, Figure 5.11 and Figure 5.12 . These values are shown per annum of the project stage in question, and as such to obtain total values it is required to consider the number of years of each project phase, detailed in Section 3.3.2. As these represent the direct outputs, these are essentially the industries that are being directly impacted by the development of the baseline wind farm.

As indicated in Table 3.3, Table 3.4 and Table 3.5, the Assembly and Installation phase holds the most meaningful portion of activities in the Canary Islands, being “Distribution and other transport” and “Engineering, research and technical services” the most significant investments for this stage. However, given the location-based character of the tasks to be carried out and the larger contribution of the investments in the manufacturing stage the “Metal and non-metal goods” also indicates a significant part in investments in the region, ranging from 3 M€ to 8 M€ for cases of lower and higher local content, respectively.

In counterpart, as expected, the impacts on the Spanish economy related to the fabrication phase are more prominent as many activities are considered to be undertaken at the national level, which holds a large share of total inputs. The industrial manufacturing sectors in Spain are most directly influenced at the manufacturing phase, whilst transport and technical services dominate the expenditure for installation and maintenance, although represent minor allocation.

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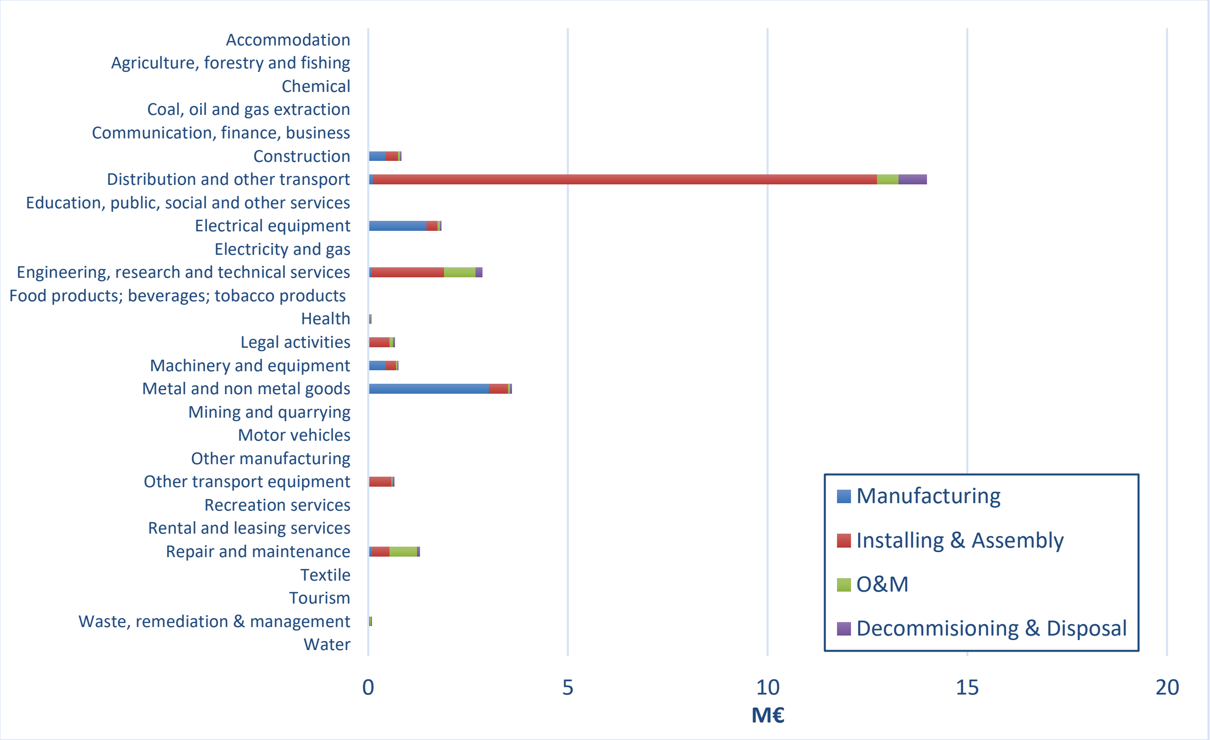

Figure 5.7 - Direct Output per industry and annum (Canary Islands) - Local Content Case 1.

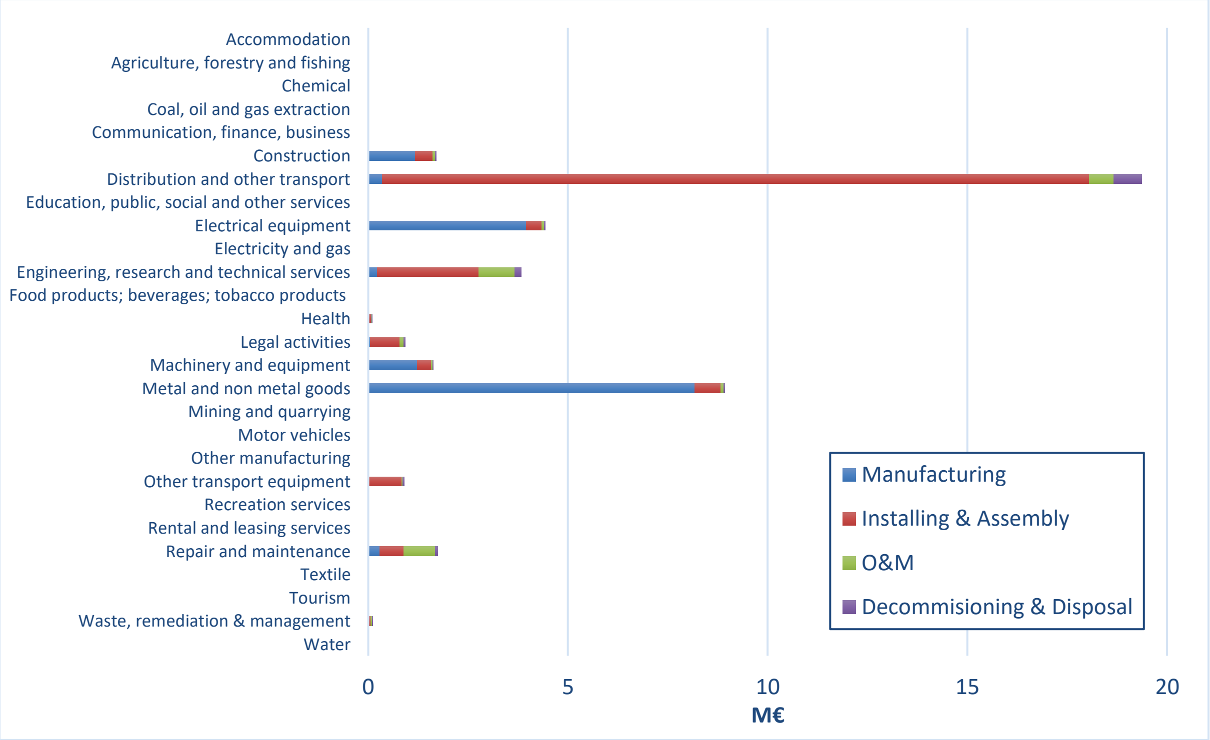

Figure 5.8 - Direct Output per industry and annum (Canary Islands) - Local Content Case 2.

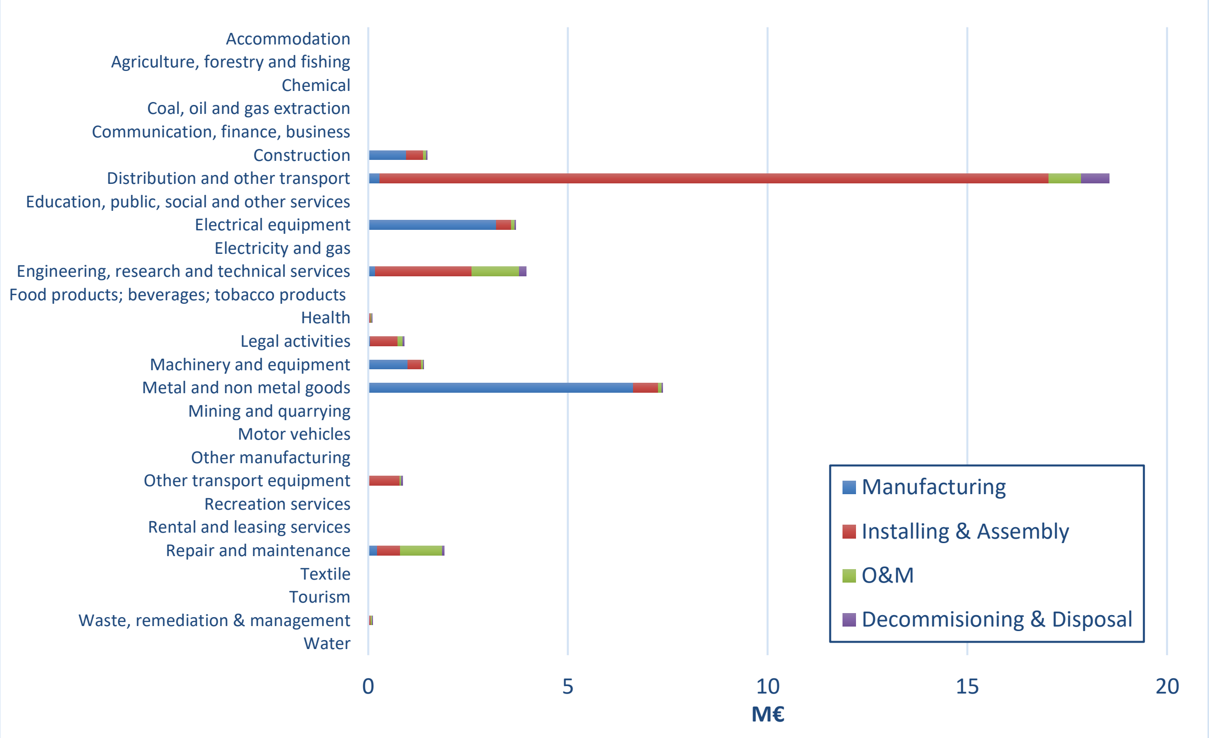

Figure 5.9 - Direct Output per industry and annum (Canary Islands) - Local Content Case 3.

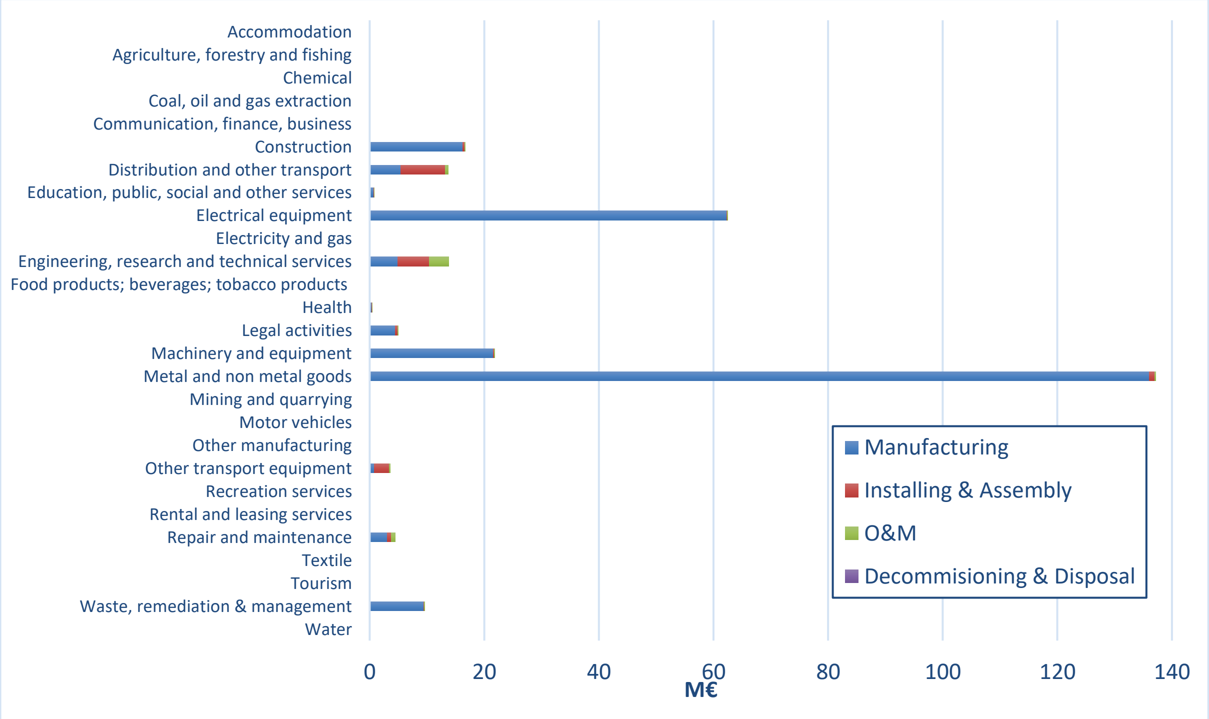

Figure 5.10 - Direct Output per industry and annum (Spain) - Local Content Case 1.

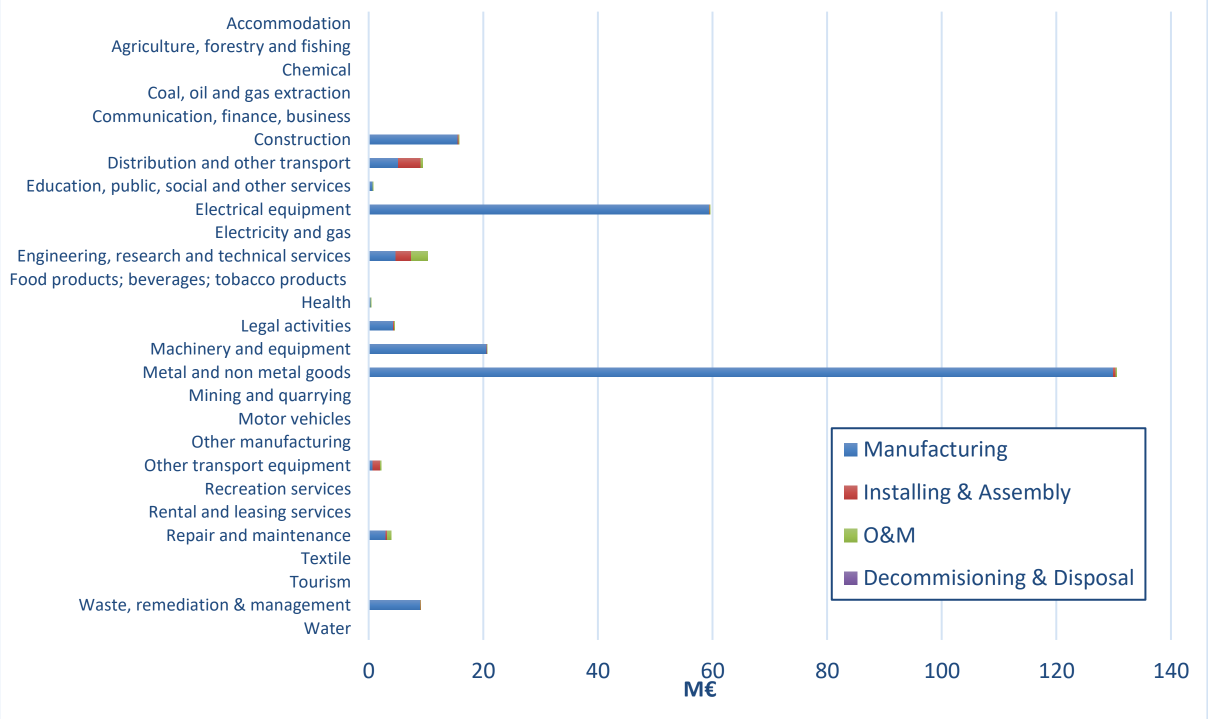

Figure 5.11 - Direct Output per industry and annum (Spain) - Local Content Case 2.

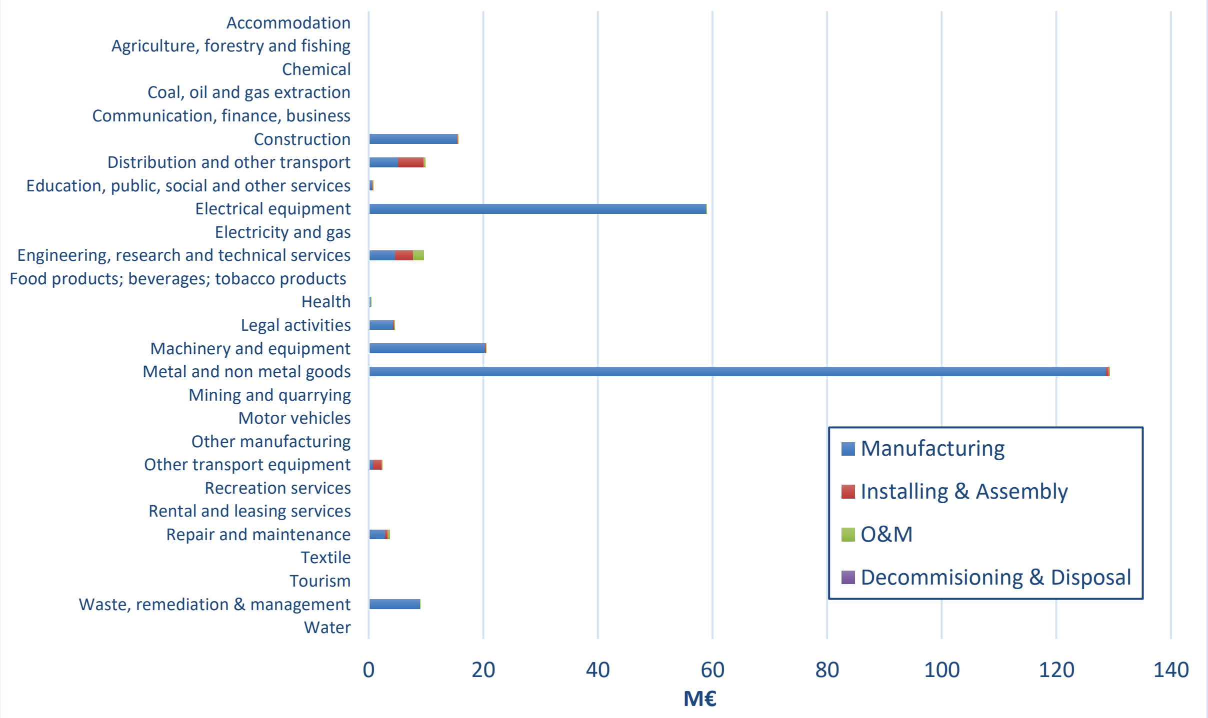

Figure 5.12 - Direct Output per industry and annum (Spain) - Local Content Case 3.

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The Type II outputs are presented in Figure 5.13, Figure 5.14 and Figure 5.15 for the Canary Islands and in Figure 5.16, Figure 5.17 and Figure 5.18 for the mainland As these include the direct, indirect, and induced effects of the project, all aggregate sectors have some associated output, and an increase is observed in these directly affected sectors due to interdependence-based multiplier effects. It is interesting to observe how some sectors that are not directly affected have high production expectations connected to PivotBuoy when considering Type II effects.

Observing the two regions it is evident that the “Accommodation” sector is substantially impacted by indirectly related factors. This clearly demonstrates the significant and wide-reaching indirect effects resulting from project development.

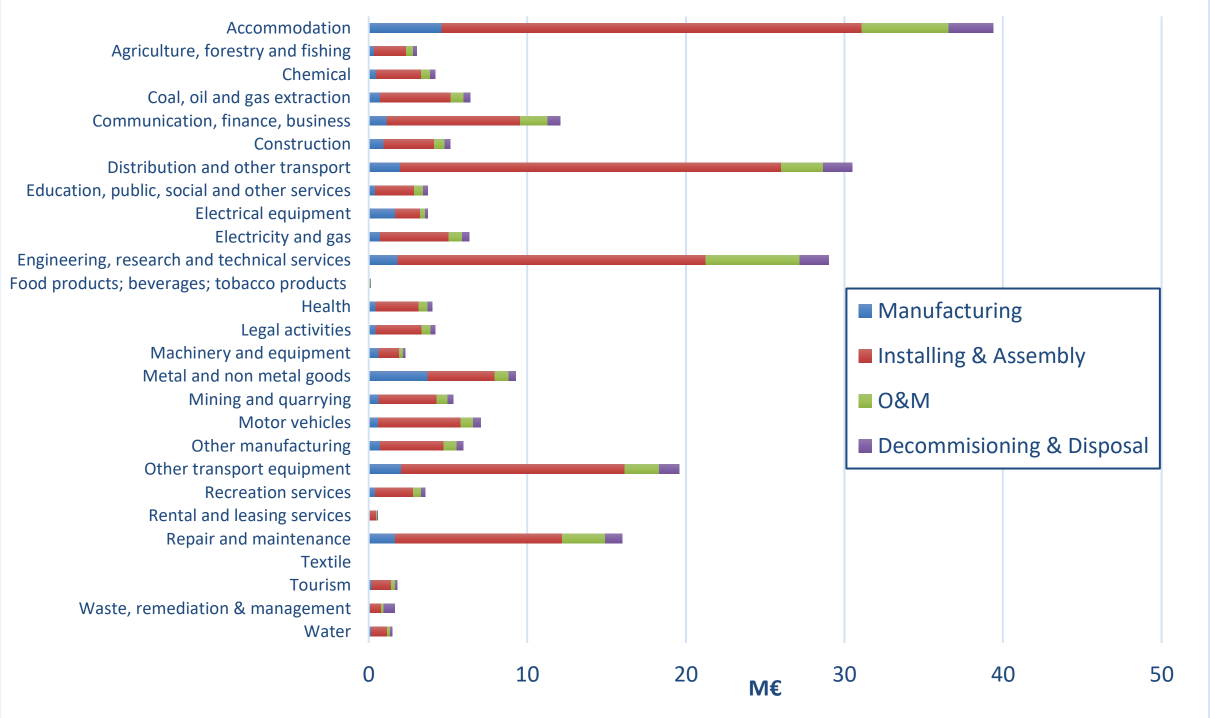

Figure 5.13 - Direct, Indirect and Induced Output per industry and annum (Canary Islands) - Local Content Case 1.

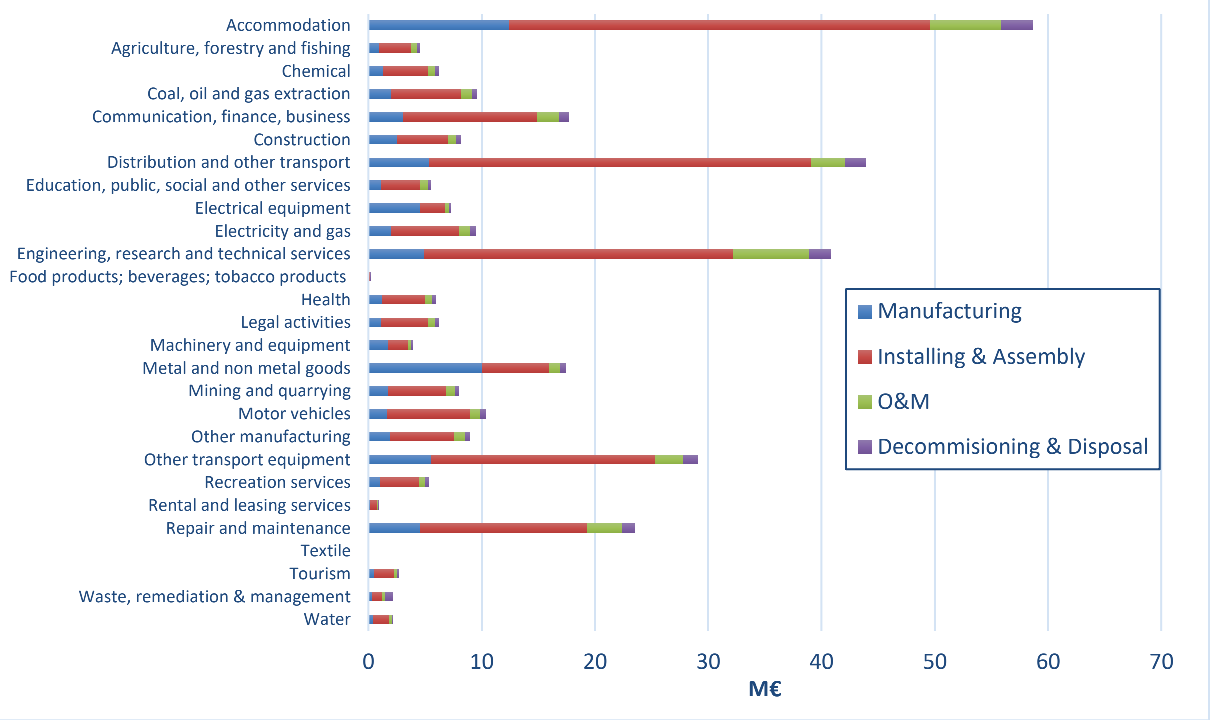

Figure 5.14 - Direct, Indirect and Induced Output per industry and annum (Canary Islands) - Local Content Case 2.

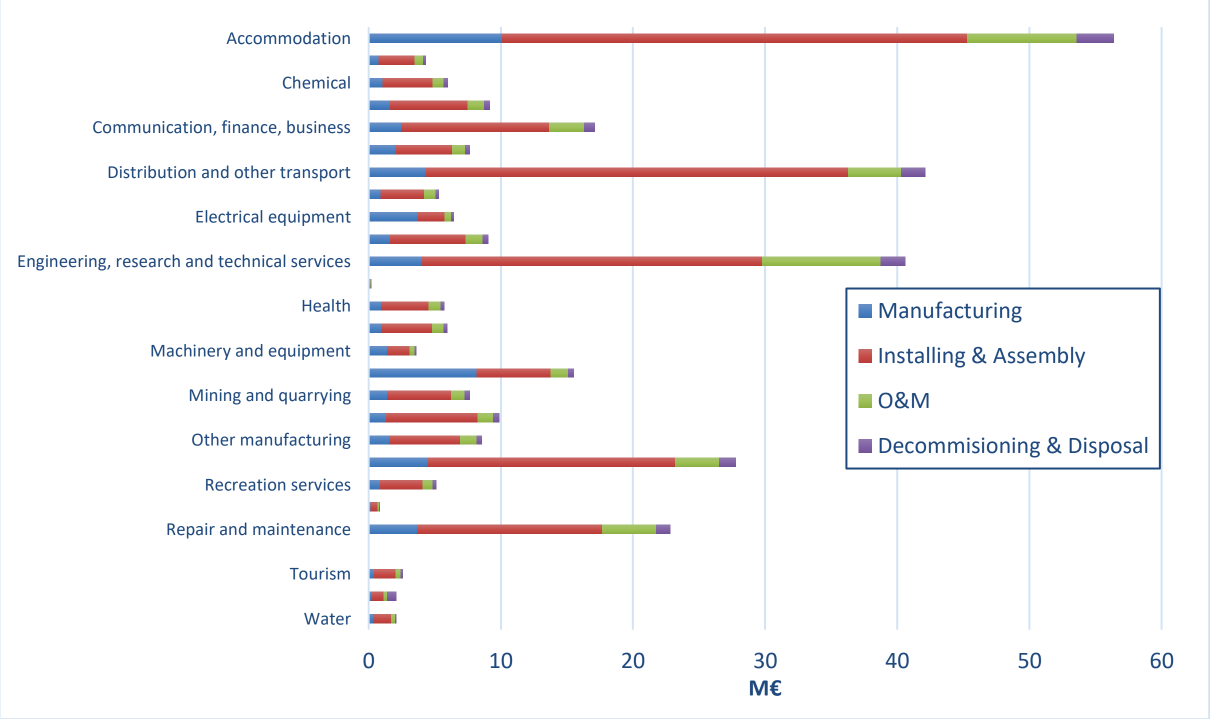

Figure 5.15 - Direct, Indirect and Induced Output per industry and annum (Canary Islands) - Local Content Case 3.

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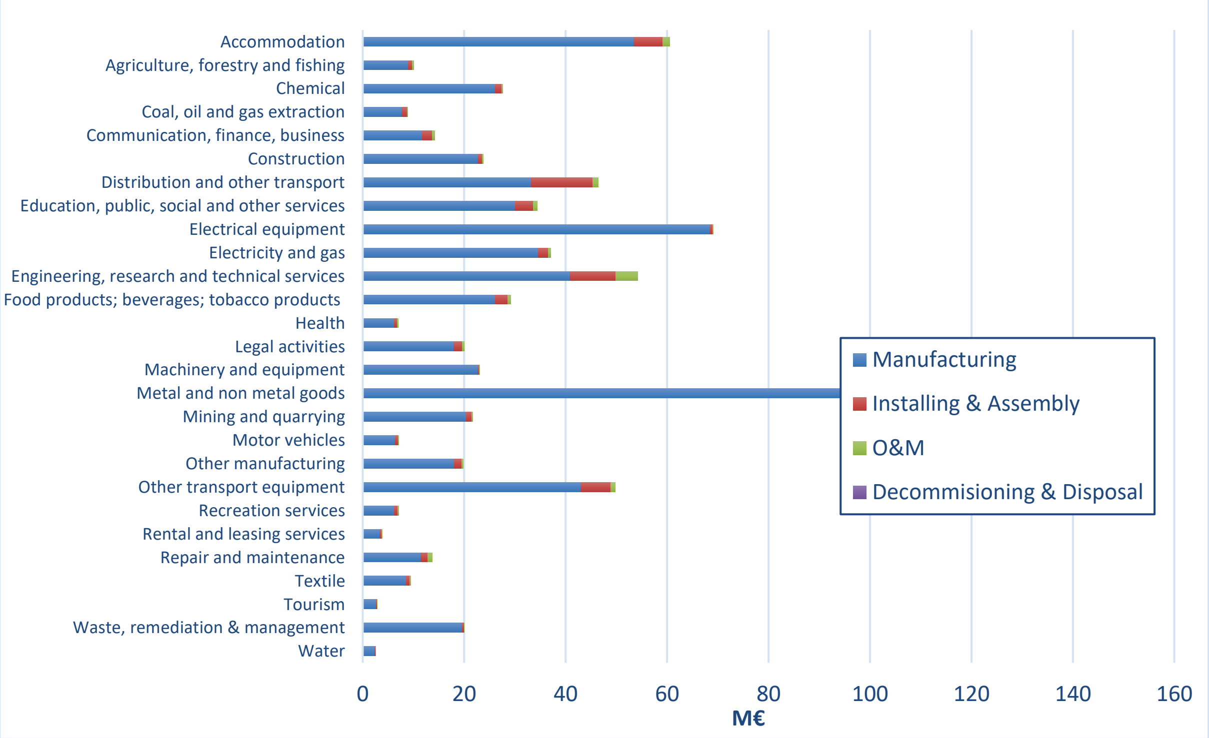

Figure 5.16 - Direct, Indirect and Induced Output per industry and annum (Spain) - Local Content Case 1.

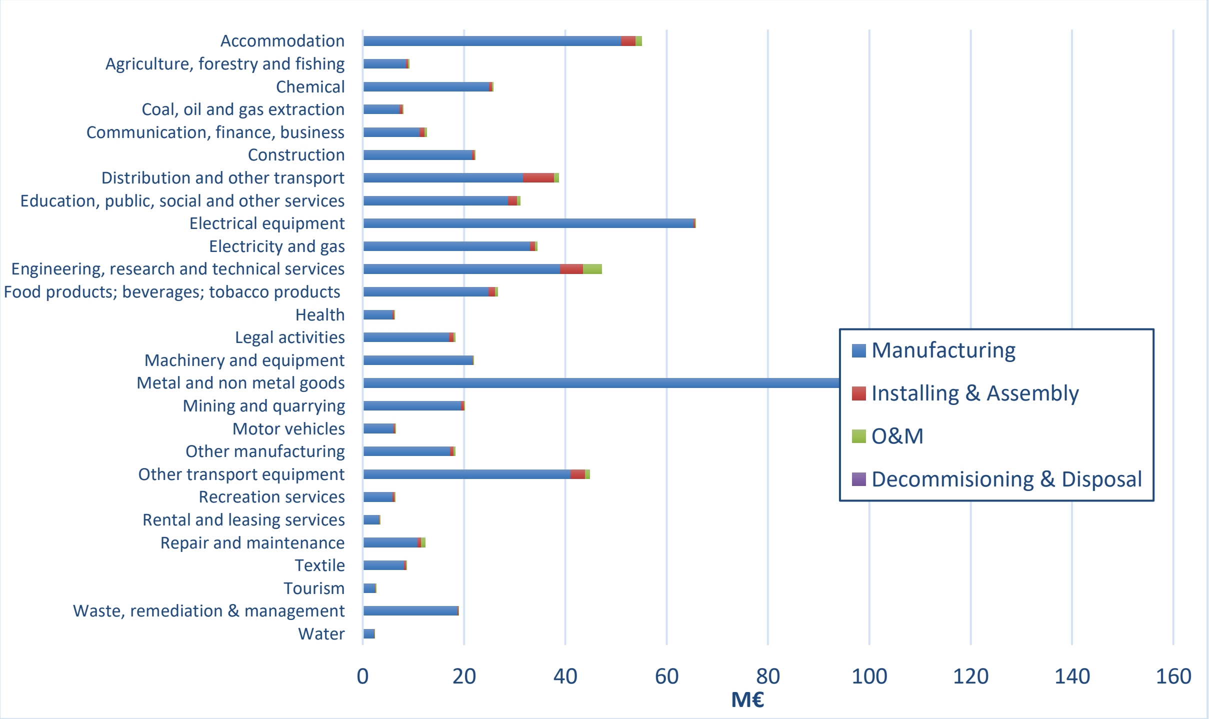

Figure 5.17 - Direct, Indirect and Induced Output per industry and annum (Spain) - Local Content Case 2.

This project has received funding from the European Union's Horizon H2020 research and innovation programme under grant agreement No 815159

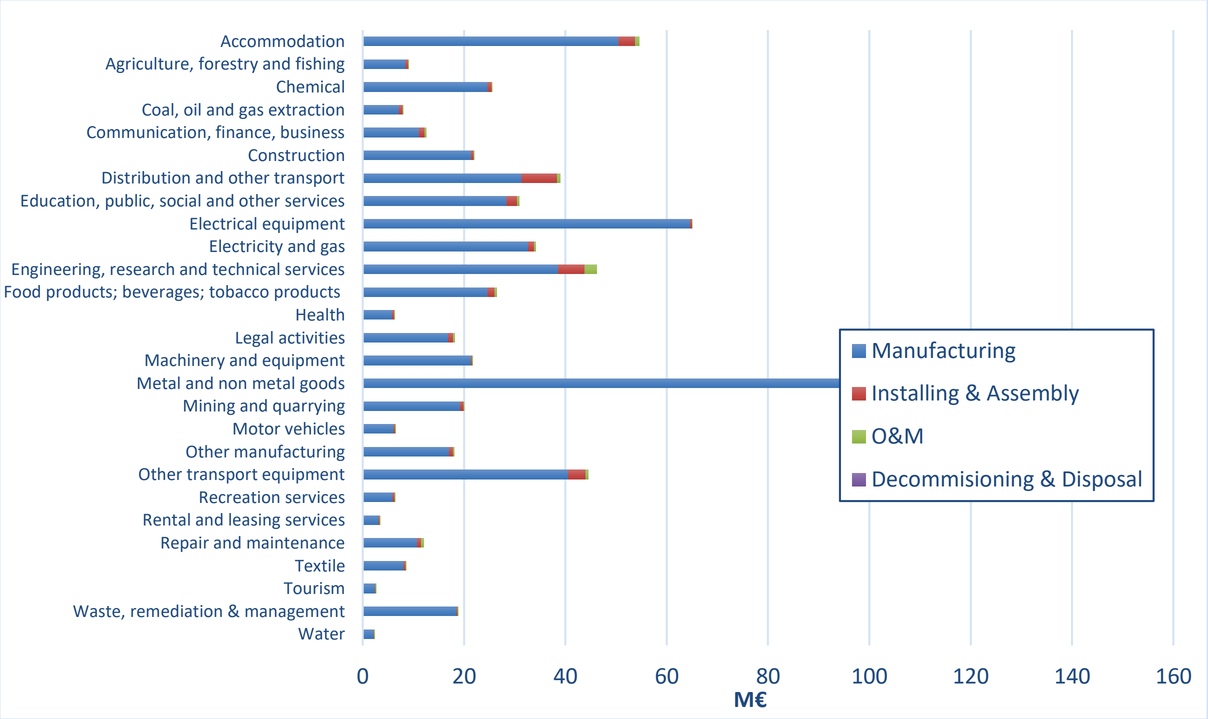

Figure 5.18 - Direct, Indirect and Induced Output per industry and annum (Spain) - Local Content Case 3.

5.4.2 Employment effects

Given the methodology detailed in Section 3.3.4, it is possible to estimate the total Type II jobs attributed to each of the sectors associated with the project demand. This includes indirect and induced jobs supported in interlinked sectors resulting from the project expenditure. Summing these and assessing over the project lifecycle yields the graph presented from Figure 5.19 to Figure 5.24, which represents the resulting jobs across the Canarian and Spanish sectors in that year of operation and for the total lifespan of the project, for each local content approach.

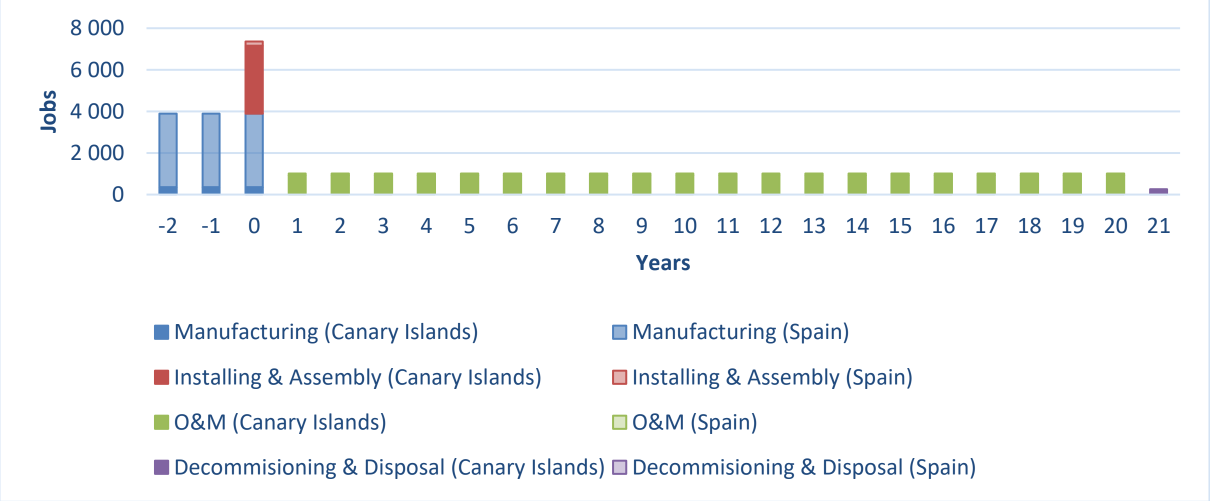

Figure 5.19 - Type II jobs as a function of project year (Canary Islands and Spain) - Local Content Case 1.

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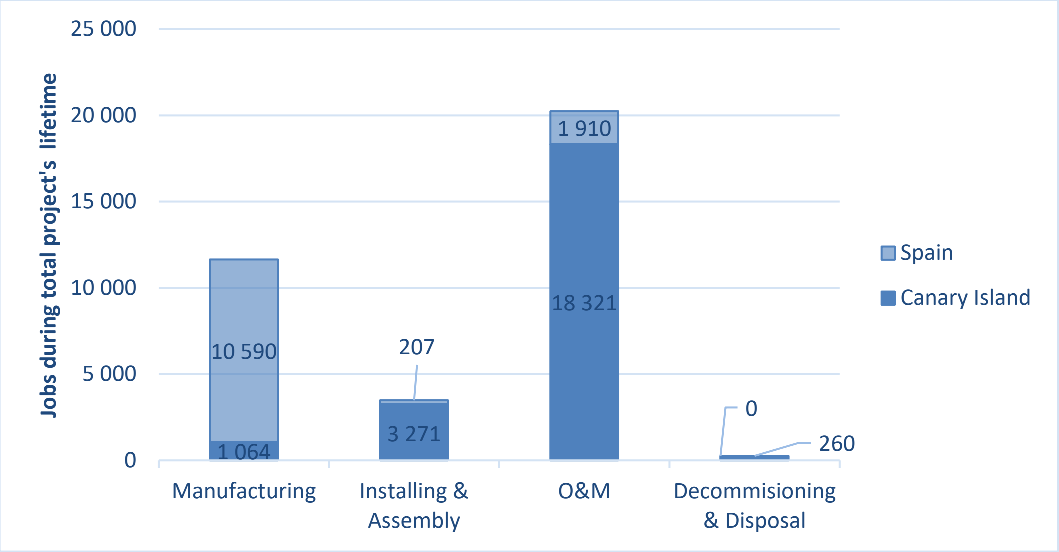

Figure 5.20 - Type II jobs as a function of project's lifetime (Canary Island and Spain) - Local Content Case 1.

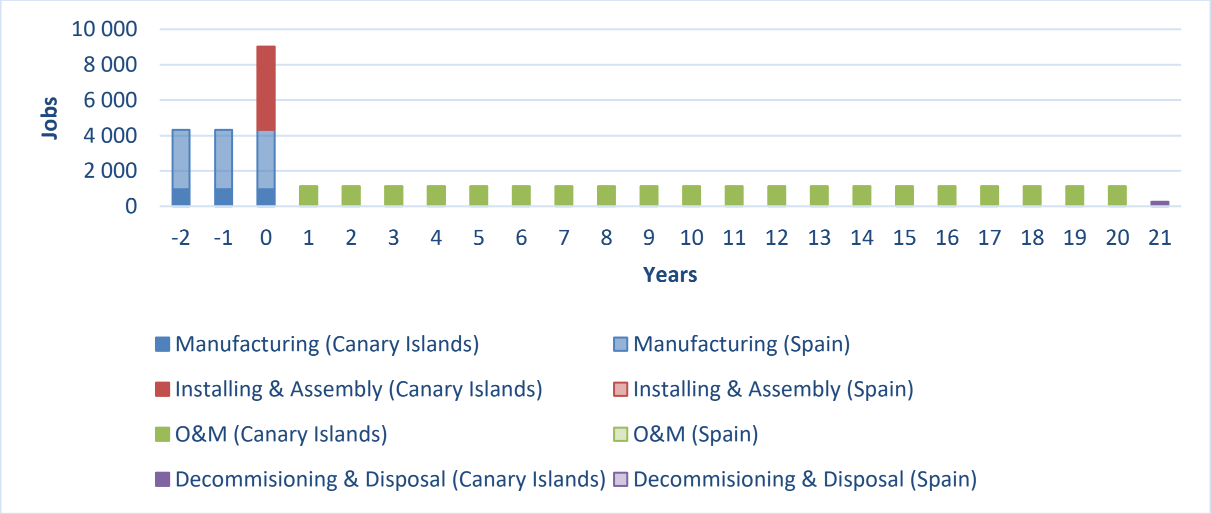

Figure 5.21 -Type II jobs as a function of project year (Canary Islands and Spain) - Local Content Case 2.

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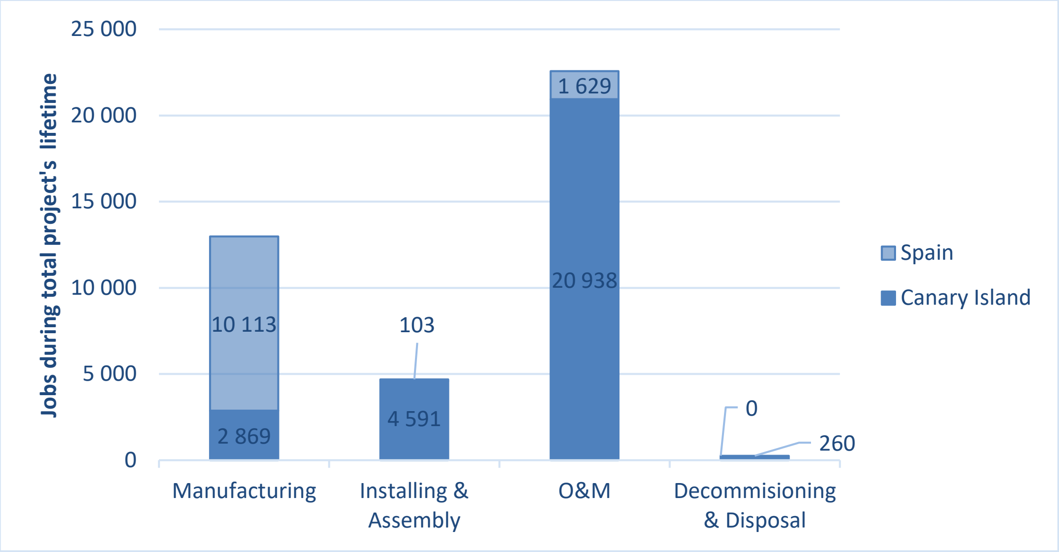

Figure 5.22 -Type II jobs as a function of project's lifetime (Canary Island and Spain) - Local Content Case 2.

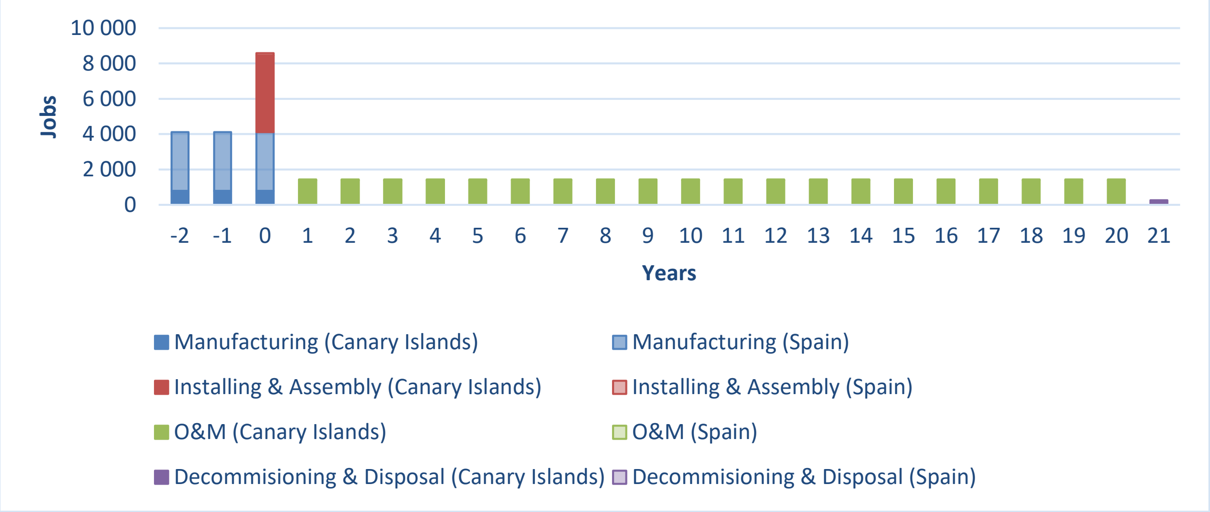

Figure 5.23 -Type II jobs as a function of project year (Canary Islands and Spain) - Local Content Case 3.

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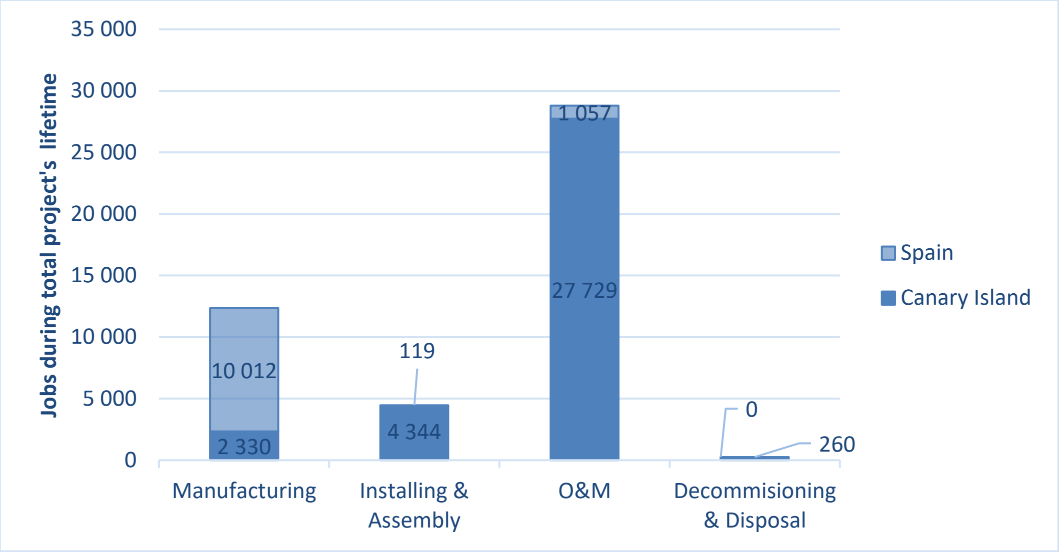

Figure 5.24 -Type II jobs as a function of project's lifetime (Canary Island and Spain) - Local Content Case 3.

The local character of the Canary Islands, as a less industrialised region, means higher employment needs to produce 1M€ of investment, compared to the Spanish industrial chain among the different local content variation. The O&M holds the most significant participation in the long-term, estimated at 355, 956 and 777 direct, indirect, and induced jobs per year during the total period of PivotBuoy operation, for each local content framework analysed, respectively Looking at Spain as a whole, as expected, during the joint fabrication and installation phase there is a peak, corresponding to 7362, 9021 and 8577 jobs supported by the project and connected with all sectors for cases 1, 2 and 3, correspondingly.

It is worth mentioning that employment results indicate the necessary additional amount to support the final demand. However, since it is calculated based on FTE, instead of new hires, some companies may choose to operate using their current labour force satisfying this demand increase, by assuming the possibility to increase the number of working hours of the current employees, reassign employees to the new project or to invest in new labour-saving technologies.

5.4.3 GVA effects

The GVA equivalent indicated in the Section 5.4.2 are presented from Figure 5.25 to Figure 5.30, using the GVA effects calculated for the aggregated Canarian and Spanish sectors. Since jobs and GVA are heavily correlated to total expenditure an analogous trend with the project stage is observed. For the Canary Islands scenario, peak GVA for each local content case is estimated at 114, 174 and 160 M€ at year 0, during the Manufacturing and Installation & Assembly phases, while for the total Spanish perspective it corresponds to 310, 356 and 342 M€ during this year. In the long term, the O&M phase represents the most meaningful impact during total project's lifetime, varying in a range of about 570 and 860 M€

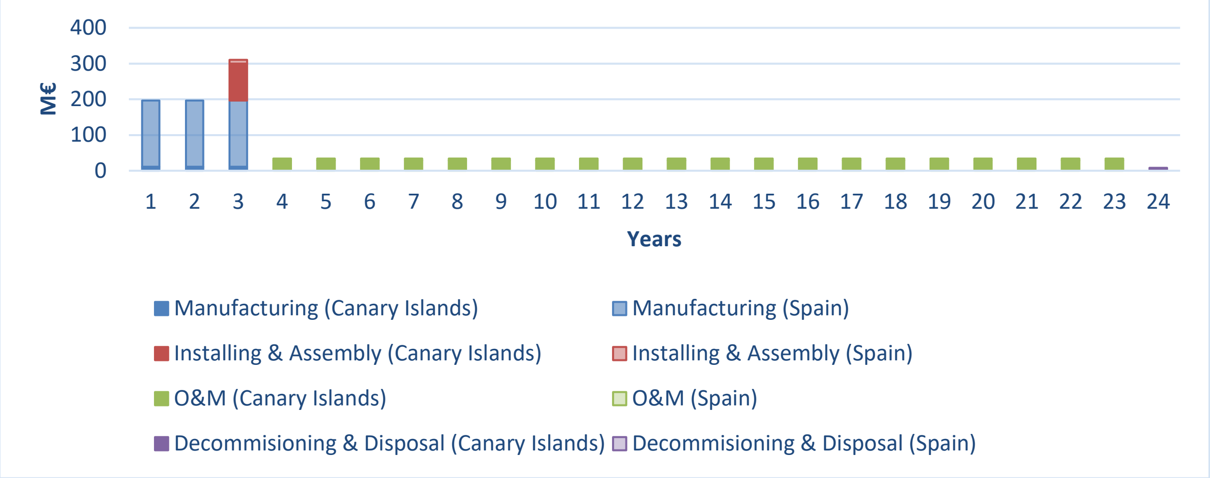

Figure 5.25 - Type II GVA as a function of project year (Canary Islands and Spain) - Local Content Case 1.

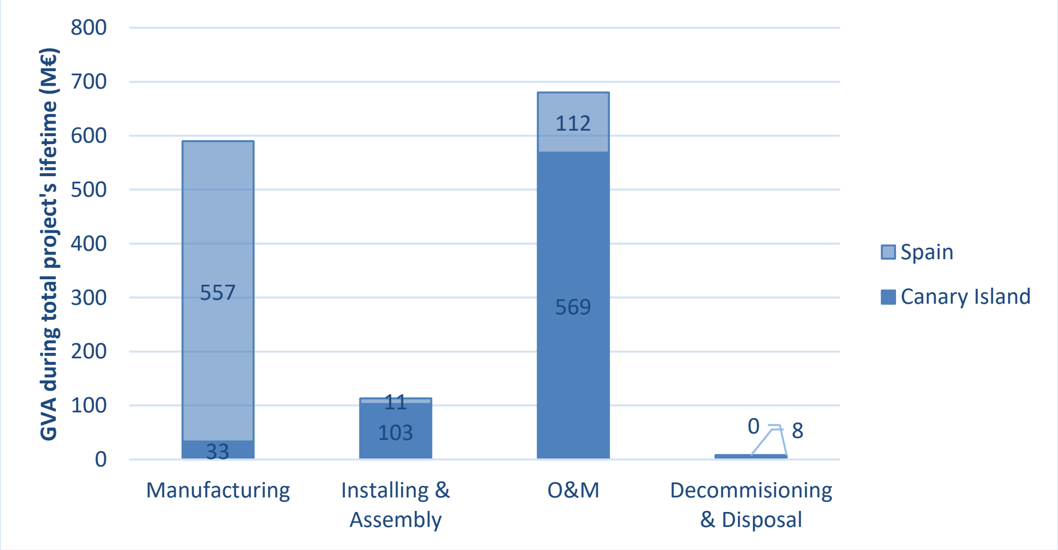

Figure 5.26 - Type II GVA as a function of project's lifetime year (Canary Island and Spain) - Local Content Case 1.

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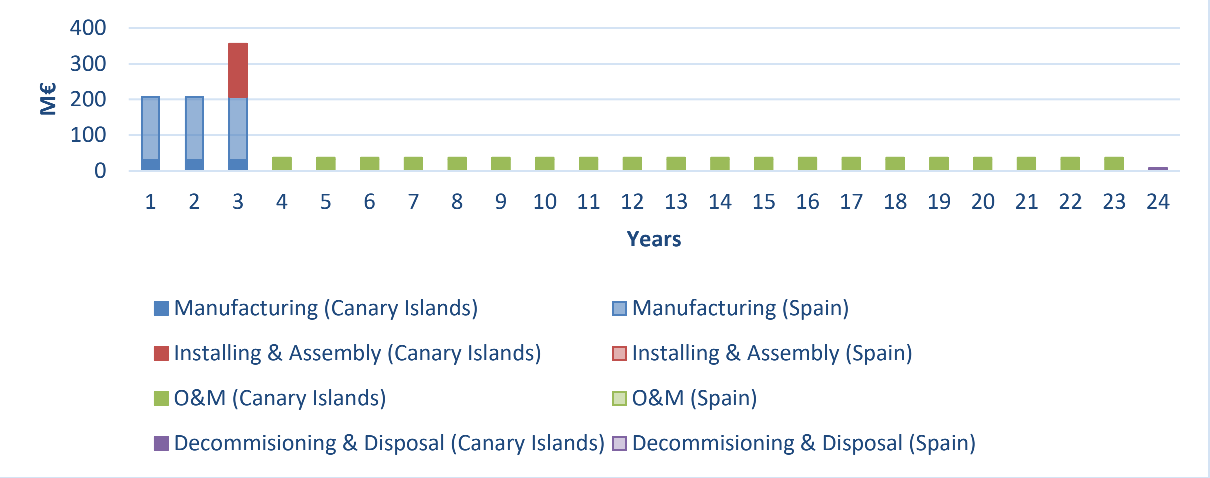

Figure 5.27 - Type II GVA as a function of project year (Canary Islands and Spain) - Local Content Case 2.

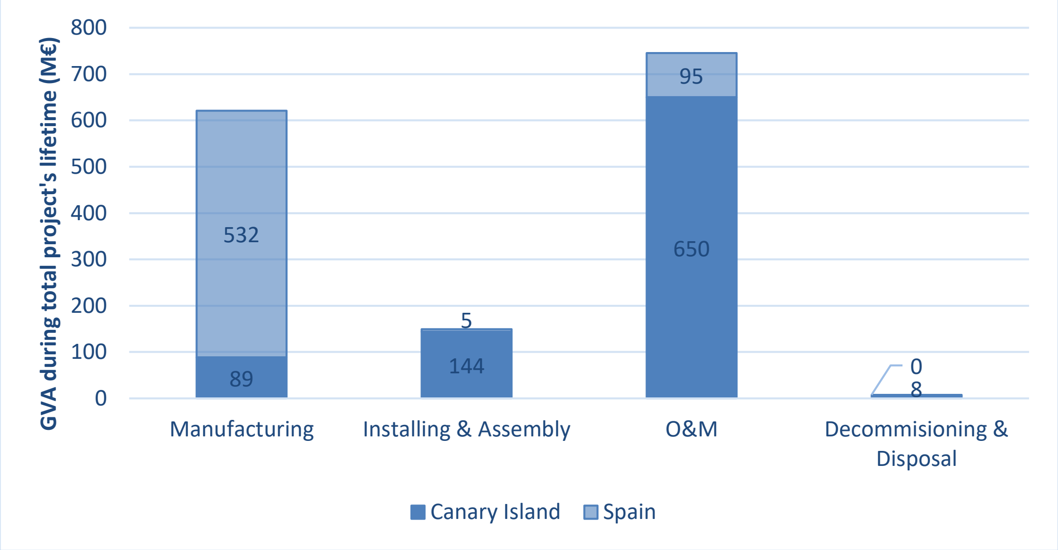

Figure 5.28 - Type II GVA as a function of project's lifetime year (Canary Island and Spain) - Local Content Case 2.

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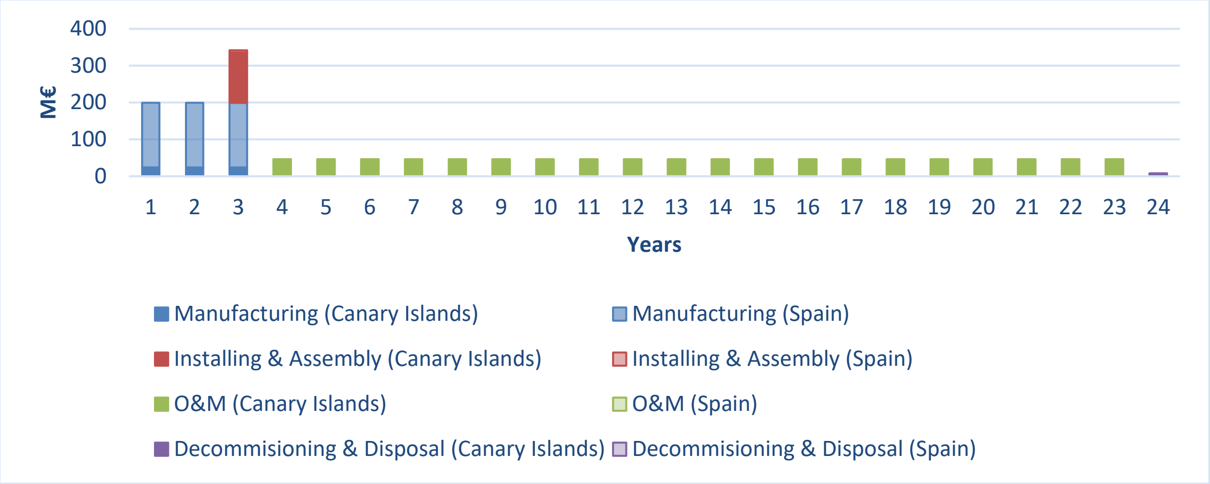

Figure 5.29 - Type II GVA as a function of project year (Canary Islands and Spain) - Local Content Case 3.

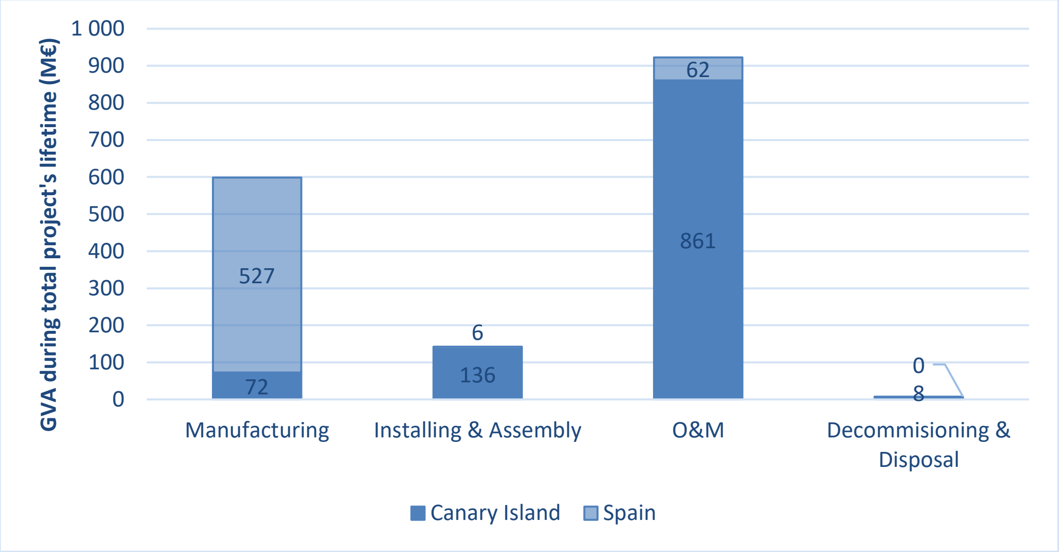

Figure 5.30 - Type II GVA as a function of project's lifetime year (Canary Island and Spain) - Local Content Case 3.

5.5 Social Impact Assessment

As offshore renewable energy generation schemes become increasingly prevalent throughout Europe and the UK alike, social acceptance of such projects plays an important role in their future development and expansion. It is, therefore, necessary to develop a thorough understanding of the effects a given project might have on society and how it might respond to it.

5.5.1 Overview of Social Impacts

When considering any industrial development, it is necessary to consider the positive and negative effects induced by the prospective project, which may be related to the technical characteristics of wind energy projects, environmental impacts, economic impacts, social impacts, contextual factors and individual characteristics. Plentiful literature exists on the potential impacts of offshore wind developments on local society [27]. Key critical drivers of social acceptance are highlighted as follow:

Negative

- Noise generated during material transportation, construction, and operation.
- Limiting navigation of commercial, recreational, and military vessels.
- Changes and obstructions to the seascape.
- Possible damage to beaches, local ecology, and geographical heritage.
- A decrease in tourism as a result of environmental changes.
- Risks to commercial and recreational fishing due to changes in local fish populations.
- Socio-cultural values and place attachment.

Positive

- Decreased reliance on fossil fuels at the economic, and strategic levels
- Potential for GHG decrease.
- Deployment of the energy transition.
- Reduction of wildlife and landscape impacts caused by other types of electricity generation.
- Potential for development of multi-purpose technologies to use the environment in a sustainable way.
- Governance and regulatory frameworks for implementation of renewable projects.
- Financial support schemes.
- Benefits to local infrastructure through building new roads and upgrading existing ones for material transport.
- Increased employment associated with the project.
- Indirect increase in salaries/employment due to economic growth in the region.
- Development of sectors beyond tourism, which is the predominant one.

The use of wind energy has grown rapidly in the past few years, where it has been supported by many countries eager to promote cleaner alternative energy sources and reduce dependence on fossil fuels on environmental and strategic levels. This leads to a potential for environmental and socio-economic development, especially for regions with certain resource, economic or spatial constraints, which could be the case for islands. In this case, the strategic assessment of these environmental and economic impacts, both positive and negative, and the development of ways to mitigate these negative impacts are prior operations to be carried out in the overall development of wind energy, socio-economically and ecologically, so that renewable projects can have a net positive effect compared to fossil fuel-based scenarios.

Some technical aspects can be more easily measured. However, socio-acceptance is an intrinsic human aspect that is evaluated in a qualitative way and is intimately associated with the information that society gets from these types of technologies.

[28] developed a model to assess the psychosocial functioning of the acceptance of the various energy sources, as such, wind offshore, in the Canary Islands. The study was carried out through a set of variables, namely information and utility (normative motives), perceived risk and benefits (gain motives), and negative and positive emotions (hedonic motives), where acceptance refers to a favourable response related to a fact that is manifested in the form of opinion or consent.

Normative motives can impact the acceptance of energy sources in many ways. The utility is associated with the evaluation of the perceived value of gains or losses from a given performance. On the other hand, information can have positive or negative effects on acceptance, depending on the type of power considered. However, it has proven to be a key element in the acceptance of energy sources, where people on this subject tend to accept this type of energy to a greater extent and are willing to pay for it. Gain motives or perceived risk can be evaluated from a negative perspective, such as financial, safety, health, or environmental risks.

However, perceived benefits can be positively associated with the acceptance of different technologies for cost savings, job creation, energy efficiency or environmental friendliness. Hedonic motives are associated with emotions that are generated by any stimulus or situation that the individual faces. Emotions may indicate a moral connotation associated with the perception of risks and benefits.

The study states that when simultaneously evaluating RES (Renewable energy source) it holds a preference in comparison to non-renewable energies. By analysing wind energy acceptance, utility, perceived benefits, and positive emotions were the factors that had the most involvement in acceptance, although information also showed to have a positive aspect. Perceived risks had the most negative impact, followed by negative emotions.

The prevailing trade winds in the Canary Islands may be influencing the perception of the greater utility of wind energy. In counterpart, the Canary Islands show a tertiary sector with a high level of development, characterising a typical tourism-led economy, which leads to the negative evaluation of acceptance, given the perceived impacts of the dissemination of projects of this magnitude.

A study carried out by [27] for some European regions, indicates that in general, several factors related to the technical characteristics of projects and the environmental impacts are considered critical barriers, in the sense that the factors, on average, have high impact frequency. Specifically for the Balearic Islands in Spain, the societal impacts on health and well-being and quality of life are considered barriers to social acceptance.

Both studies, however, show that information and transparency are important drivers for local community acceptance. Information is essential to build trust and promote a positive attitude in the population toward renewable energies.

Social factors are difficult to quantify. Thus, it is a more common practice to study patterns of behaviour qualitatively for acceptance of specific wind energy projects at a local level by community members. In general, the focus would be on strengthening existing drivers and reducing existing barriers involving all relevant stakeholders equally and sharing relevant project information to improve perceived participation in decision-making and establishing a benefit-sharing scheme.

6 DISCUSSION

6.1 Comparison with other systems

6.1.1 Environmental outputs

Considering different types and configurations of wind turbines, the LCA results present consistency in comparison to the range of some devices analysed in the literature reviewed, as presented in Table 6.1 regarding GWG (10,9 – 23,0 g CO2 eq). Despite being the same type of energy production, the indicated analyses cover different types of technologies and configurations and considering the eventual variations in the methodology and assumptions taken in these different assessments, it can be expected that this may justify the variation in the results obtained.

Due to the tow-to-port strategy, a reduction on the time required for tasks and consequently the emissions along the project lifespan can be expected. Most of the carbon intensity is derived from the manufacturer phase, due to the high amount of material, mainly steel and concrete.

In comparison to the devices indicated in Table 6.1, PivotBuoy holds a larger rated capacity and consequently a higher energy production potential. Thus, even being a larger-scale turbine, the amount of emissions, mainly due to raw material extraction and manufacturing phases, is spread over the total amount of kWh delivered to the grid, leading to a lower carbon intensity.

The opposite can be noticed for the barge-type floating wind turbine platform. As stated by [29], one of the most important factors for its high carbon intensity is the high amount of concrete and steel, where only the structure counts to 95% of the total mass. Being a turbine with 2MW, a large ratio between material and energy produced is expected, being the total emissions presented as around 18 g CO2 eq.

The FOW project is the closest to PivotBuoy in terms of rated power. However, according to [30], the mass per device is around 30% higher and water depth is more than double in comparison to the values considered in this study case, implying higher material impact. The configuration of the device, comprising a concrete structure combined with foam for buoyancy, the mooring system, and some associated uncertainties at this level of the analysis regarding the design, could also contribute to the indicated mass difference. However, it is important to mention that for the FOW analysis no recycling is considered. Concrete and sand used in this configuration is considered to be left in the site, however without resulting in any environmental penalty or credit, differently from what occurs in the Pivot Buoy analysis, where the disposal phase represents a portion to be subtracted in the total result, thus decreasing the impact, highlighting once again the significant role of recycling.

Table 6.1 - Total global warming potential for different types of wind turbines.

Turbine type	Turbine rating (MW)	Emissions (g CO2 eq/kWh)	Reference
PivotBuoy	15	11,2	Current analysis
FOW	12	23,0	[30]
Sway	5	11,5	[29]
Barge	2	18,6	[29]
Monopile	6	10.9	[8]

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Comparing with other marine renewable energies, according to a literature review conducted by [22] wave energy converters may hold a carbon intensity around 13 – 126 g CO2 eq/kWh, presenting a wide range depending on the technologies and material adopted. In comparison to tidal energy converters, the carbon emission can be around 8.6 – 23.8 g CO2 eq/kWh. However, due to a lower level of technological maturity of these two mentioned technologies, some uncertainties should also be considered, showing that the PivotBuoy as a device for wind energy production, is likely to present positive benefits in terms of carbon footprint.

Regarding other electricity sources, based on data provided by [31] and [32] PivotBuoy shows to be a low-carbon alternative, mainly when in comparison to conventional power generation. Figure 6.1 summarises the carbon footprint caused by the production of 1 kWh of electricity by a range of other means of production.

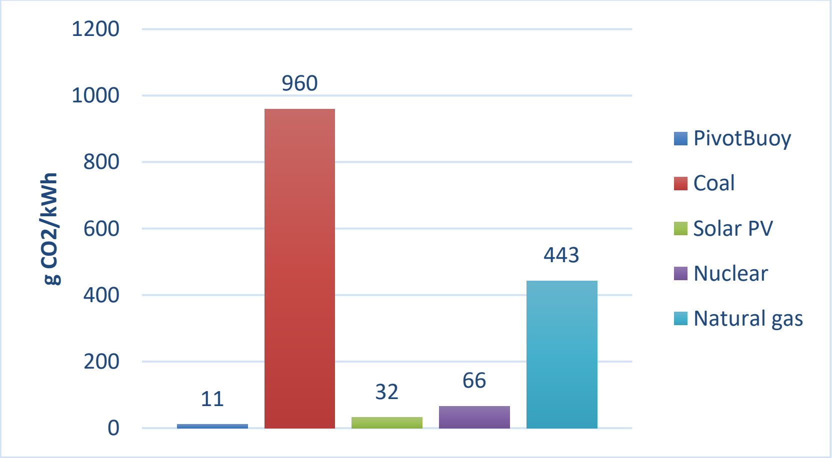

Figure 6.1 - Comparison of impacts of PivotBuoy with other forms of energy production.

The impact on material choices play an important role in the final results of design, performance and environmental analyses. Components made by steel tend to be heavier than the ones manufactured from composite materials. However, according to [31] composite material cannot be recycled, and the disposal phase comprises landfill or incineration processes, which may cause greenhouse emissions around 80% greater, and human and ecosystem health risks. Alternatives to non-recyclable composite materials need further study in order to analyse the environmental impacts, through, for example, resin and fibre separation processes to enable reuse and recycling, as well as the energy and carbon footprint involved in these actions.

6.1.2 Socio-economic outputs

The results indicated in Figure 5.19, Figure 5.21 and Figure 5.23 can be translated into yearly employment rates during Manufacturing, Assembly and Installation, O&M and Decommissioning & Disposal, in terms of jobs/MW, under the national level (the Canary Islands plus Mainland), impacted by the direct, indirect and induced effects, as shown in Table 6.2.

Table 6.2 - Yearly employment rate (jobs/MW) by each phase and local content case.

Employment rate [jobs/MW] per local content case	Manufacturing	Assembly & Installation	O&M	Decommissioning & Disposal
Case 1	9,2	8,3	2,4	0,6
Case 2	10,3	11,2	2,7	0,6
Case 3	9,8	10,6	3,4	0,6

Due to the high dependence of macroeconomic factors on the location of the studies, as well as the participation of the supply chain and different types of technology it is difficult to state the impact of a project on the local economy.

A study conducted by [33] referenced a rate of 13 jobs/MW for manufacturing and construction phases and 0,2 jobs/MW for O&M for the wind industry in Asturias, both only under direct effects.

Another research, carried out by [11] for a 200 MW floating wind farm in Gran Canaria, reported a rate of 6,23 jobs/MW under the Manufacturing and Assembly & Installation phases, and 0,91 jobs/MW during the O&M stage, considering the sum of impacts in the Canary Islands and Spanish Mainland.

A similar analysis by [34], however, for a bottom-fixed offshore wind farm located in Brittany (France), indicates that the yearly employment rates during the CAPEX phase would be equivalent to 6,03 jobs/MW.

These figures show that, even though they are obtained using an I-O model, they cannot be directly compared with the results using the Spanish I-O model developed in this report due to the intrinsic characteristics of the project as well as different study approaches. However, given the order of magnitude observed and considering the uncertainties on both sides, it can be considered that the results presented in this study can be used as a credible indication. Furthermore, the premises considered in these analyses point to a possible development of the Canarian supply chain and maximisation of the island's local resources, thus increasing the possibility of development of the region in terms of investment, employment and opportunities.

Being the GVA effect strongly related to the employment effect, as can be seen in the trend graphs, it can be deemed that the results presented in Section 5.4.3 are also in line with the model.

6.2 Integration of Analysis

Techno-economic models can be used to assess the LCOE of a given project, and the potential cost reduction of a given technology, to aid in the design process of technology and for preliminary feasibility studies for a project. By coupling a techno-economic model with a macro-economic and environmental model, the benefits and impacts can be assessed at the same time, providing support in the decision-making process. It is to be highlighted that the overall benefit cannot be analysed from one point of view exclusively and must allow the contributions to be assessed from the perspectives of various stakeholders to incorporate the success and profitability of the project into the overall macroeconomic and environmental benefit.

This study presented an attempt at a combined approach of analysis between the techno-economic model [1] and the energy and carbon flows, and the macroeconomic and social impacts of the

PivotBuoy project. However, the partial limitation of the techno-economic model is the fact that the investment is assessed in its particular context, not considering all the affected industries, leading to the wider effects being ignored.

Design decisions are driven by technical and techno-economic performance, with energy and carbon flows as a consequence of these decisions. However, certain design decisions aimed at cost reduction can result in a large increase in embodied energy and carbon, such as the use of concrete, typically used to reduce structural cost, but which consequently incurs a significant reduction in energy and carbon performance.

The most desirable outcome of the coupled analysis would depend on the perspective of the individual evaluator. For example, project developers may prioritise the reduction of LCOE and have the number of jobs and GVA for this project only consequently, while government bodies may prioritise the jobs created associated with the project that provides an LCOE value at a satisfactory threshold. However, if these projects are incentivised with the aim of reducing carbon emissions, then the performance relative to the global warming potential and energy-associated renewable energy projects should clearly be considered to assess the projects with the greatest overall benefit.

For assessing wind farm projects, macroeconomic methods may be particularly favourable as the total environmental and economic benefits can be used to inform decision-making. This may be particularly relevant for policymakers when deciding the appropriate level of subsidy to stimulate the sector.

7 CONCLUSIONS

This report addresses the environmental and socio-economic impacts of the PivotBuoy deployment in the Canary Islands, from a future commercial scenario perspective, from a life cycle assessment.

The LCA was conducted to quantify the embodied carbon and energy of the proposed project and to understand the main drivers affecting the potential emissions, considering the energy intensity and materials used in all stages of the full-scale project, from raw material extraction to materials processing, manufacturing, transportation, assembly and installation, operation and maintenance, and decommissioning and disposal. This LCA could provide hints on how to further reduce costs, with material and process flow characterisation.

The resulting carbon intensity of 11,24 gCO2 eq/kWh and energy intensity of 149 kJ/kWh is generally comparable with earlier studies for wind energy technologies and is very low compared to current forms of power generation. This LCA is aligned with previous studies on wind energy technologies in concluding the main environmental impacts are due to materials use and Manufacturing processes, while Assembly & Installation and O&M do not show significant impacts. High GWP and CED levels during manufacture are due to high amounts of material used, particularly steel and concrete. Results are based on a high rate of recycling of steel and concrete being achieved. Regarding alternative materials, further studies need to be conducted to analyse the impact on design, performance and environmental impacts. Globally, both preliminary energy and carbon payback times were found to be slightly below 1 year emphasizing once again the capability of renewable energy sources of paying back the energy and GHG emissions embedded in their life cycle.

The scenario analysis showed that reducing the distances to be travelled during the installation and maintenance phases does not significantly impact the carbon impact, as the impact of the manufacturing phase, which is highly meaningful, remains almost the same for all scenarios (Canary Island in Spain, Viana do Castelo in Portugal, and Gulf of Lion in France). In fact, the perceived impact was just the opposite, where analysing locations with lower wind generation potential, an increase in emissions impact was observed.

This report corroborated with previous studies proving the importance of the EoL scenario for the overall environmental performance and highlighted that a significant positive effect can be achieved if virgin materials can be substituted by recycled materials.

Regarding the macroeconomic evaluation, an input-output model is applied to assess the potential economic impacts and job creation, through an attempted approach coupled to the techno-economic model developed previously and under the same perspective as the scenario considered for the LCA.

The analysis indicates that the project will directly stimulate various sectors associated with the manufacture, construction, installation, and operation of the devices, along with those associated with insurance and financial sectors, project management and specialised services. Other sectors indirectly linked to the project, such as accommodation and communications, will also experience benefits through the development of the economy. The current economic characteristics of the Canary Islands region is mainly supported by the tertiary sector, more specifically tourism, with small participation in the secondary sector. However, the potential for developing opportunities in the Canary Islands' value chain is remarkable when considering the untapped capacity at the local level.

The outputs from the model developed in this study highlight the wide-reaching macro-economic benefit of projects of this type, and when used in combination with environmental and techno-economic analysis will provide additional information to decision-makers.

Despite some community concerns, in general, a reasonable level of social acceptance is expected due to the information and perceived benefits in relation to renewable energies in the region, at an economic and environmental aspects

The quality of the data in this preliminary study was constrained by the lack of input data, mostly not yet available during the conceptual design phase of the device. Some assumptions were made from previously published studies and these secondary data estimates can lead to errors that propagate through the literature undetected. In addition, some data from the statistical bodies may be a little outdated, which may lead to some deviation from the current economic scenario.

The conclusions indicated in this analysis were based on the design and the construction, installation and operation strategies for the prototype and show preliminary results that may vary when scaled up to a commercial project, which may present different types of materials and execution strategies.

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