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A Total Cost of Ownership model for the --Version 1-- and -- Version 2-- --Innovation-- system design

Master Internship – MSc Supply Chain Management

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Abstract:

In the internship period at --Company-- B.v., a Total Cost of Ownership (TCO) model was established for both system design that depicts a comprehensive overview of the total of costs incurred along the complete system life cycle. It was found that Procurement cost is a critical cost factor for both system design, while Installation cost reveals its criticality with regard to the --Version 1-- system as well. Besides, TCO per unit of volume and power capacity appear to be relatively large in comparison with competitor energy storage technologies. More accurate cost depictions may be obtained in a later stage of the commercial life of the system.

Confidentiality Notice:

This report is based on a real-world project conducted for an external company. To protect intellectual property and comply with confidentiality requirements, company names, product identifiers, and selected data points have been anonymized or adjusted. The analytical approach and conclusions remain representative.

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1. Introduction

First, a contextual analysis is provided for emphasizing the importance of carrying out the internship assignment provided by --Company-- B.v. This analysis is based on the current state of the electricity market and the importance of --Company--'s innovation within this context. Then, this innovation is discussed briefly and the conducted assignment with its corresponding importance for the future of the innovation is stated. Finally, a methodology for the manner in which the assignment was conducted is specified.

1.1 Context of the assignment

Since the rapid upscale in renewable energy technologies, a simultaneous rise in the need for energy flexibility has occurred. Energy flexibility can broadly be defined as ways and measures to properly balance supply and demand of energy systems. Peculiarly, it never used to be an issue of main concern. Power plants operators who controlled the supply of energy from e.g. coal-fired plants, natural gas plants, or nuclear plants had full control on deciding a fixed periodic amount of supply provided to the net. Hence, decades ago when these were the main options for providing energy as renewables had not been invented yet, it was a simple game of mind of deciding on a level of supply for meeting predicted demand. However, due to the variable nature of an ever increasing amount of supply produced by renewable energy technologies over time, it has become harder to match supply and demand at every point in time [43].

1.1.1 Types of energy flexibility

Accomplishing a desired level of flexibility within an energy system can be done in several ways. Broadly defined, it is done by using demand side management (DSM) and supply side flexibility. Furthermore, from the electricity system point of view, flexibility can be perceived as grid frequency and voltage control, delivery uncertainty and variability and power ramping rates. This suggests that a portfolio of solutions is necessary to tackle the short- and long-term balancing problems on the net.

The first branch of solutions is set for the demand side of the electricity market. Such end-use electricity consumption measures are typically price based and directly affect the loads of households and industries by certain price based programs. Examples are either programs

made for reducing (conservation and peak shaving), increasing (load growth and valley shifting) or rescheduling energy demand (load shifting) as seen in Figure 1. As can be observed, these programs differ by their impact on electricity consumption over time. Load shifting does however require some form of intermediate storage, as with for example battery storage, although it is met with no conversion losses [21] and allows for continuity of the process and quality of the final service offered. An example could be food supplies in a refrigerator acting as a cold storage [46]. So far, DSM has experienced a slow implementation rate as it has traditionally only been applied to cut peak power demand. Since only recently, its main focus lies more on the balancing of variable renewable production [29, 3].

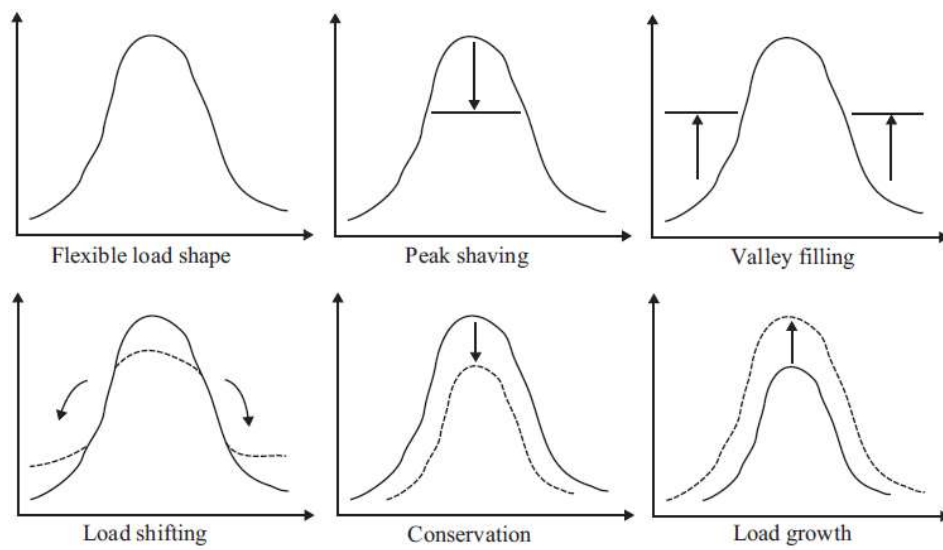


Figure 1: types of demand side management (DSM) [12].

The second branch of solutions comes from grid-related ancillary services and energy storage solutions. Ancillary services are performed by actors on the electricity grid to ensure a continuous and balanced flow of electricity, and can be characterized according to the time scale in which they are implemented. These time scales differ from a very short duration of seconds to minutes for power quality and regulation stemming from variations in network frequency and voltage of wind and solar generators' output, to days and even seasonal shifts to balance power consumption and generation.

Such ancillary services are provided with the help of energy storage solutions. Different types of these solutions are characterized by their differences in energy storage and power capacities. Hence, some are better suited to provide one type of capacity, while others can provide both storage and power capacities to some extent.

1.1.2 Energy storage solutions

Currently, popular solutions that have either been used extensively or show promising future efficacy are pumped hydro power energy storage (PHES), compressed air (CAES), hydrogen, batteries and flywheels.

Pumped hydro energy storage (PHES) is a technology where energy is generated by releasing water from a higher to a lower gravitational level through a hydro turbine. Before this happens, water is pumped upwards so that the higher reservoir becomes filled with water. A significant advantage of pumped hydro is the sustainable manner in which the energy is produced, and the fact that a plant can operate on different time scales from less than a minute [49], to seasonal cycles [14]. Lifetime expenses could however rise up to relatively large amounts, although this could be mitigated by using the ocean as the lower reservoir, such as on Okinawa island, Japan [30].

Moreover, compressed air energy storage (CAES) is another technology for storing energy which appears to be a cost-effective storage alternative to PHES due to its shorter construction time of 2-3 years and more flexibility when it comes to siting [51]. The functionality of the technology comes from pressurising air to higher pressure within for example salt caverns, steel pipes, or even under a sea bed [47]. When the time arrives to extract energy, the stored air is generally mixed with fuel, combusted and driven through a turbine or a handful of turbines. Eventually, the storage functionality stems from the fact that the compressor and expander operate independently at different points in time. So far, the economics of such a system have stopped it from expanding to a larger scale, though a higher natural gas prices and increased penetration of renewable sources should bring about change in this regard [52]. On top of this, a shorter construction time of two to three years and a better siting flexibility than pumped hydro, make for a cost-effective alternative to PHES.

Then, hydrogen comes into play as a third attractive way of storing energy. The technology functions by the combined function of its three main components: an electrolyzer that produces hydrogen from excess electricity, an electricity-producing fuel-cell that does the exact opposite, and a hydrogen container for storing the produced hydrogen. The storage technology can further be characterized by a high energy capacity, though a low volumetric energy capacity due to its low density. Surprisingly, the fact that these two can be separated brings about the advantage of long-term electrical storage. On top of that, the technology produces only water vapor as a side product, and therefore the technology can be characterized as environmentally friendly if clean sources of energy are utilized [44]

Furthermore, batteries have been a well-known form of energy storing functionality and are used in many applications. The technology functions thanks to two electrodes with different electron affinities. While discharging, electrons move downstream to the electrode with higher affinity in a spontaneous fashion. Contrarily, while charging, electrons are forced upstream to the electrode with lower affinity. This process eventually generates electricity. In practice, batteries are mainly used for short-term storage and corresponding short-term ancillary services due to near-instantaneous response times. Examples of this are short-term fluctuation reduction, power quality provision, or transmission deferral. [62, 36]. Many types of batteries exist that each come with their own advantages and disadvantages in terms of cost, efficiency, and energy and power densities.

Lastly, flywheels ought to be noticed due to their competing nature with batteries in the short-term market. This technology stores energy in the angular momentum of a fast rotating mass. It is connected to an electric generator and motor for electricity-kinetic energy-electricity conversion. Flywheels have a handful of precious advantages. The technology can be distinguished by its long life-span, high power and energy densities, a rapid response time, and virtually zero maintenance. On top of this, a high efficiency of around 90 percent is observed. On the other hand, a modest energy capacity, safety issues due to rapid-moving parts, and a self-discharge rate on the order of 0.5 percent of stored energy per hour, make for a combination of disadvantages. As noticed, the technology is very functional for the short-term electricity market by providing power quality control, stabilizing network voltage and frequency, and minimizing fluctuation of e.g. wind power.

1.2 The --Innovation-- technology

One can observe how each energy storage technology comes with a bundle of specific advantages and disadvantages. For this reason, it is impossible to generate one specific solution for providing energy flexibility on the supply side within each context. Moreover, when one takes this fact into consideration combined with the immaturity of the deployment of energy saving solutions, it can be stated that the energy storage market is in a very competitive and promising state with much to gain. This lays the ground for one of the fundamental reasons for the innovation of the --Innovation-- by --Company-- B.v.

1.2.1 Fundamentals of the innovation

The --Innovation-- is a relatively new system that brings about a similar functionality as Pumped Hydro Energy Storage, though on a smaller and more flexible scale. The system operates by a combination of two different reservoirs in between which a pump and a turbine is located. These pumps are driven by energy generated from offshore wind turbines and/or offshore solar parks, and pump water from the internal reservoir at atmospheric pressure into a flexible bladder that is exposed to the high hydrostatic pressure at the bottom of the sea. The filled-up bladder retains the stored energy for the time necessary. Eventually, whenever it is required, the energy is channelled through a hydro turbine under high pressure back to the internal reservoir.

Currently the main focus of implementation is within offshore wind farms. These type of renewable projects have only recently escaped the valley of death and are rapidly maturing and becoming commercially viable options that can be independent of subsidies. This implies the market is at the beginning of a probable massive growth, especially when taking into consideration EU goals and the corresponding Paris Climate Agreement. On top of this, it is very important for wind farms to become economically competitive with other sources of energy, and the --Innovation-- can significantly aid in this process. One figure of interest in regard to this is the Levelized Cost Of Energy (LCOE). It measures the average net present cost of electricity generation for a generating source over its entire lifetime. It is calculated by multiplying all costs incurred over the lifetime by the sum of electricity produced over the lifetime. Ultimately, the --Innovation-- would help to increase the total amount of electricity produced by providing electricity storage whenever necessary. This is done by preventing curtailment as excess energy could be stored to a certain level.

1.2.2 Comparison with competitors

As mentioned before, energy saving technology is not an entirely new concept and many different innovations, each with their unique characteristics, have already been made. For this reason, it is somewhat important for the --Innovation-- to retain a unique position within this field and thereby bring about a unique value concept. As one can observe from Figure 2, the --Innovation-- has a unique place within the value dimension of energy saving technologies, and can provide a specific type of customer value.

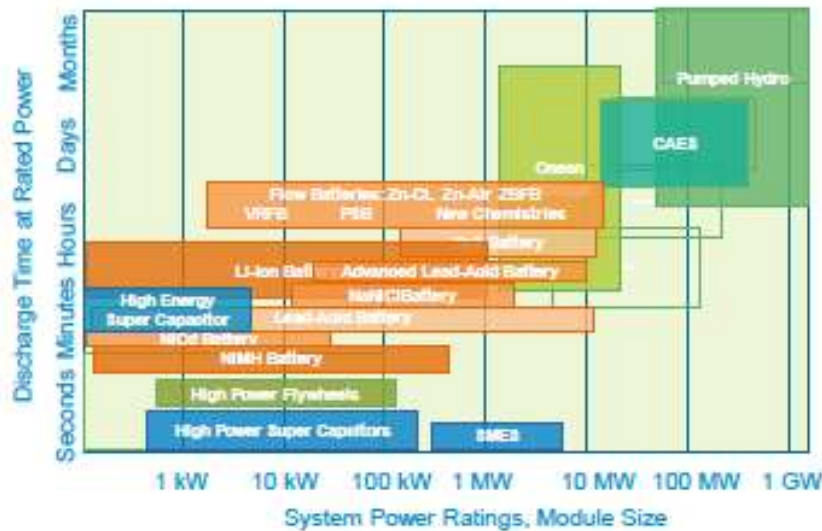


Figure 2: Position of the --Innovation-- within the dimension of energy saving characteristics

The main competition of the battery comes on the one hand from the technologies of Pumped Hydro Energy Storage (PHES) and Compressed Air Energy Storage (CAES), and on the other hand from electrochemical batteries, specifically VRFB and Li-on.

PHES and CAES could be considered genuine competitors due to their large storage volumes and large discharge time, making them perfectly suitable for the long-term energy market. Their main disadvantage compared to the --Innovation-- is the fact that they are dependent on topographical conditions. Specifically, large underground basins for CAES and mountainous regions for PHES. These are often found in remote regions and therefore the technology struggles in supporting peak load reduction and capacity management services. This is in contrast to the --Innovation--, which could be located directly next to the source.

On the other hand, electrochemical batteries face their own combination of struggles. First, the technology faces restrictions in scaling up the model sizes to larger amounts, thereby restricting the maximum storage volume. On the other hand, the technology also faces locational boundaries when considering offshore siting. Specifically, an offshore island would have to be created for the technology to function properly, pointing out an instant point of failure in this regard. On top of this, electrochemical batteries are known for wearing out after a certain amount of charge and discharge cycles, which implies a larger amount of replacement maintenance operations. Eventually, one ends up with a costly technology.

1.3 Total Cost of Ownership (TCO)

Total cost of Ownership (TCO) or Life Cycle Costing (LCC) is a popular cost modelling tool within the field of Supply Chain Management [33, 61]. It is mainly used as a strategic tool for lifecycle management of systems and products by taking into account all significant costs over the whole of the life cycle. Eventually, a complete and comprehensive model can assist in making important investment and operational decisions.

First, most TCO models are created for the vendor selection process, in which different asset scenarios supplied by different vendors are taken into consideration [53, 6]. Eventually after reviewing every scenario the optimal vendor is chosen. Second, some models are developed for considering an optimal asset configuration [38, 51, 32, 26], in which the performances and corresponding costs of different configuration scenarios are reviewed. Third, a handful of models is used in establishing valid and reasonable contract definitions with suppliers [4, 32]. Lastly, some contributions are composed for supporting asset operations decisions from the asset user's point of view. In this regard, one could think of operational decisions regarding utilization, maintenance, etc [35, 6, 59, 19].

In general, the method for calculating TCO can be distinguished in two main fashions: (i) ex-post calculation, and (ii) ex-ante calculation. Ex-post calculation is done using actual or historical data, and therefore relies on deterministic numbers which are ready to work with. For this reason, it is somewhat impossible to make an ex-post calculation for new types of solutions [9]. Moreover, if one uses ex-ante as the method of calculation, the approach is undertaken by stochastic/probabilistic methods such as a Monte Carlo Simulation [12]. In this manner, probability distributions for a select amount of input values are selected, and a gigantic amount of simulation runs are performed with random inputs from these distributions of stochastic input parameters. Eventually, one can observe intervals of the effect on output generated from each input distribution.

For this specific internship assignment, it is requested that a TCO model is created for the configuration of the --Innovation--. This is a somewhat unsurprising request if one considers previous research regarding TCO that has been conducted in the energy industry so far. Such research is mostly conducted to distinguish between the cost performance of a project or system over its entire life span. Therefore, it is of importance for the --Innovation-- to receive its own calculation and thereby assess its cost performance towards competitors.

1.3.1 Reference material

For a functional and proper TCO analysis for the --Innovation--, it is important to consider similar methodologies conducted in a similar context. After some research, offshore wind farms were found to contain well suited material for the eventual research approach. TCO modelling and analysis has already gained significant attention in the wind energy industry thanks to a surge in investments in wind projects [13]. Regarding research on the LCC of offshore wind farms, one can easily spot a slightly different manner in which all corresponding costs are analyzed and structured. It is however obvious that the main cost elements are always separated in a handful of main categories, specifically: Manufacturing and Acquisition, Installation, Operation and maintenance, and Dismantling and disposal.

Certain studies even take the carbon emission costs of offshore wind technologies and associated infrastructure into account [60]. Unfortunately, relative to other contexts and technologies, few works on the assessment of the LCC of offshore wind farms is available and most of these do not reveal in clear methodology in which all cost elements were calculated. On top of this, almost all of the material is conducted for offshore wind farms in shallow water areas, while the --Innovation-- also aims for serving deep water areas by its deep water battery design.

However, the use of previous offshore wind farms LCC calculations remains the top candidate for reference material, as both technologies are sited near to each other which brings about similar cost patterns as the --Innovation-- in terms of installation. Offshore wind turbines are distinguished from onshore wind turbines in this matter due to restricted access to the site caused by harsh weather condition, expensive grid installation costs and complex installation procedures. Eventually, this makes for a less economical case as different costs rise, and for this reason, offshore wind turbines contain a larger capacity than onshore wind turbines to bring about a more competitive LCOE.

Furthermore, varying works on the cost-competitiveness of a wide range of Electrical Energy Storage (EES) was also used as a second type of reference material for conducting the research.

1.4 Research Methodology

For the creation of a comprehensive model that captures all cost categories over the entire life cycle of the --Innovation-- and thereby generates a convincing final output for the total TCO, a combination of different information sources was considered. These are:

1. Academic literature & knowledge of study programme
2. Company documents
3. Company interviews
4. Expert opinions
5. Previous research conducted at --Company-- B.v.

These sources are furthermore utilized in their depicted order of importance. Hence, for a complete overview of every cost component the academic literature was taken into consideration first before any information from the company itself was looked at. Hereby, any previous material of the company was not directly copied unless the literature or followed university courses did not provide a reasonable figure or manner which could be used in a similar fashion. Eventually, for a handful of cost components either the literature/study programme or the company was unable to provide a clear indication of the cost, and hence experts on the subject were asked. In the final case in which it was either not possible to receive an expert's opinion on the point, previous research on the --Innovation-- was considered and their methodologies for certain cost components were taken into consideration.

1.4.1 Previous --Innovation-- TCO model

It should be noted that a previous LCC model was conducted at --Company--. This is a model constructed by P. Swaving Dijkstra [37] and contains an abstract overview of the eventual costs of the system. The model and corresponding LCC model established in this research distinguishes itself from the previous version by averting as much as possible assumptions of costs based on margins of other cost components. Furthermore, Dijkstra's model is limited in its input scope as the model only takes into account one configuration of the --Innovation--'s design. Hereby, the user is limited in its freedom in deciding on a certain combination of system requirements as these correspondingly impact the size of different system components. It can therefore be stated that, as a final configuration of the system size is still uncertain, the model created in this current state of the --Innovation--'s technological life adds proper value.

1.4.2 Overview of TCO model components and dynamics

In order for establishing a total cost configuration of all elements incurred over the complete life cycle of the --Innovation--, the total amount has to be separated into numerous sub-categories that each receive their separate calculation. Therefore, the final TCO model contains the follow cost categories:

- Pre-development & Consenting
- Procurement
- Assembly
- Installation & Commissioning
- Operation & Maintenance
- Decommissioning & Disposal

These calculations are independent of one another but receive similar input treatment to some extent. Specifically, each category contains its unique set of input parameters which are set according to the stakeholder's requirements. These affect the eventual output of that respective category, while simultaneously, part of that same output is affected by the basic input parameters. It should be noted that both the basic and the cost category-specific input parameters have to receive a certain value before any realistic output value for each cost category and TCO can be observed.

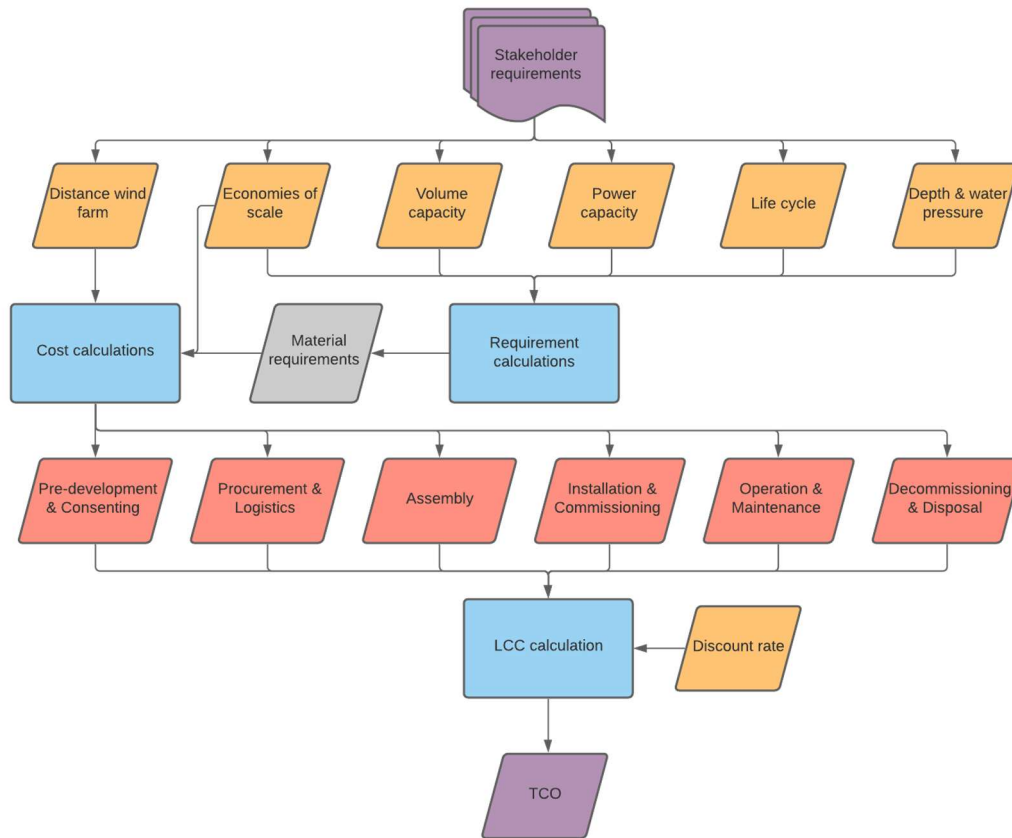


Figure 3: Step by step flowchart of the TCO model

Furthermore, as is observed from the step by step flowchart in Figure 3, amid the process of inputs and outputs a handful of processes take place. First, a complete set of requirements for each structure and component is calculated based on a specific stakeholder's requirements with regard to a filled out set of input parameters. The most important numbers in this step are the economies of scale, volume capacity, power capacity, life cycle, and depth & water pressure as observed in the flowchart. Other input parameters found in this part are e.g. different currency conversion rates, material densities, and a slider to choose between a cost-analysis for the --Version 1-- design or the --Version 2-- design.

The economies of scale variable is moreover a unique variable with regard to the complete set of input variables within the model. It explicitly takes into account the costs for multiple simultaneous units for each cost category. Hereby, cost benefits can be attained as the costs of certain components can be separated over multiple systems. In the current context, such benefits are especially valuable for the Installation & Commissioning, Operation & Maintenance, and Decommissioning & Disposal categories. Unfortunately, as the --Innovation-- still resides in an early stage of its development, many uncertainties were found

along the way concerning e.g. missing data or time constraints. These hampered the uptake of the economies of scale factor in a beneficial manner within the calculation of each of these respective cost categories. For this reason, the Installation & Commissioning, Operation & Maintenance, and Decommissioning & Disposal categories are the only two categories in which economies of scale results in cost benefits.

After all cost categories are separately calculated, the model moves to the final step of calculating the total TCO. This is done according to the sum of the Net Present Value (NPV) of all costs incurred over the complete life cycle of the --Innovation--. To calculate the NPV of a specific cost category, the following formula is used [37]:

$$NPV(d, N) = \sum_{t=0}^N \frac{C_t}{(1+d)^t}$$

In this formula C_t equals a specific cost incurred in year t . This cost is then divided by a factor of one plus the discount rate d , which is exponentialized by year t . This calculation is then performed for all number of year N in which the cost occurs. After summing all present values one obtains the final answer of the calculation and obtains a reasonable number for TCO in accordance with the set of input assumptions.

2. Prior research on --Innovation-- life cycle costs

As of the start of this research, prior cost analyses have been performed for the --Innovation-- system. These are the theses performed by T. Herwig [27] and Dijkstra on respectively the LCOE of the --Innovation-- 3 prototype and the TCO of the --Version 1-- --Innovation-- system. This chapter will provide an overview of the manner in which each cost category of the --Innovation-- system with its corresponding reasoning was analyzed in both theses. Hereby, a clear comparison between the constructed TCO model and older cost models is easier to reveal. It should be noted that Herwig's model was constructed for an older prototype of the --Innovation-- system, and thereby contains a slightly different combination of cost categories analyzed within his model. It is important though that a similar structure of cost categories between older models and the TCO model constructed in the current fashion is used to facilitate an easier comparison between old and new calculations. Therefore, the cost categories will be analyzed according to the set of cost categories which are discussed in the next chapter.

2.1 Previous research on pre-development & consenting

For the Pre-development & Consenting cost, Herwig calculates a handful of required costs as a percentage of the total procurement costs which he names “Other capital costs”. Data of offshore wind farms is used in principle, though those reference percentages are increased due to the novelty of the technology. An overview of these percentages and the corresponding subcategories of costs analyzed are depicted in table 1.

Requirement	Percentage of subsystem capital cost (%)	Normal percentage for the offshore wind industry (%)	Real value (M\$)
Contingencies	20%	8% - 11%	7.23
Environmental analyses	2%	1%	0.72%
Design and project management	10%	6%	3.62
Spare parts	2%	1%	0.72
Legal fees	2%	1%	0.72
Total	36%	17% - 20%	13.02

Table 1: Overview of pre-development & consenting created by Herwig

Dijkstra uses a similar method of using offshore wind percentages as a reference and doubles these for an accurate number that would suggest such costs for the --Innovation--.

Specifically, He considers reference offshore wind cost figures for development and project management costs (including environmental analyses), and insurance and contingencies at respectively five and nine percent of procurement costs, and thus subsequently doubles these number to 10 and 18 percent to arrive at the fractions used for this category of --Innovation-- cost calculations [58].

2.2 Previous research on Procurement costs

For a complete analysis on the different procurement costs of the --Company-- 3, Herwig uses a different set of costs compared to the set of costs incurred in the new designs of the --Innovation--. These cost categories are: Concrete superstructure, Bladders, Wind Turbine, Hydro Turbine, Scour protection and sea bed preparation, Floater-PTO, and the grid

connection. The addition of a wind turbine itself is caused by the fact that the --Innovation-- 3 design was composed as a combination of storage and floaters on a wind turbine system itself.

2.2.1 Rigid reservoir

First, regarding the concrete superstructure, Herwig used Solidworks to calculate alternative shapes and corresponding size and thickness for the superstructure. Eventually, a volume of material is provided as output, which constitutes the base for the total cost calculation of the structure in Herwig's model. Eventually, Herwig decided on one specific set of dimensions which is depicted in figure 4. Ultimately, one is able to decide on specific inputs regarding material price and density by themselves as these are left open as specific input parameters, and thereby calculate the volumetric cost and total cost of the design.

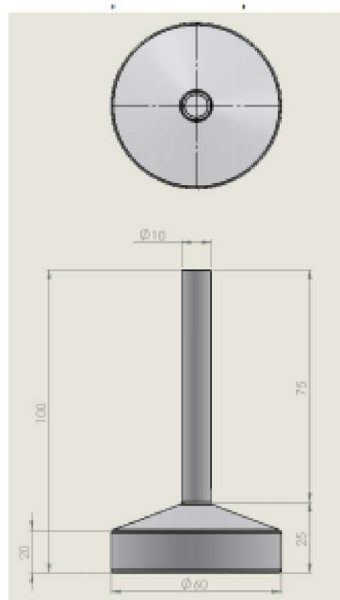


Figure 4: Dimensions of Herwig's calculated --Company-- 3 concrete structure

Contrary to this, Dijkstra leaves the option to the user of the model to decide on the specific set of input parameters for the concrete structure. In his model it is named the “Rigid Reservoir”, and all sorts of inputs have the option of alteration left open. Eventually, a volume of material is calculated which is then multiplied by a unit cost of concrete per cubic meter to end up at a final cost of the material.

Furthermore, he uses a set of standard inputs for the concrete reservoir to attain a rectangular shape and obtain a volumetric capacity of around 12,000 cubic meters. Hence, he assumes the dimensions of the --Version 1-- --Innovation-- system to be around 70x20x10 meters.

Ultimately, the basic starting point of the model is that the users can alter reservoir inputs until the desired volumetric capacity is reached. This is a stark contrast to the TCO model created in this research, as the user is able to set the power and volumetric capacity themselves in the basic set of inputs. Then, the model calculates the corresponding volumetric figures.

2.2.2 Flexible bladder

For the calculation of the total volume of the bladder material, Herwig applies the following formula:

$$Vol_{bm} = \left(\frac{4}{3} (r_{wf} + t_{bm})^3 * \pi \right) - Vol_{wf}$$

Here, r_{wf} is the radius of the working fluid present in one single bladder, t_{bm} is the thickness of the bladder material and Vol_{wf} is the total volume of the working fluid capacity of a single bladder. It is furthermore assumed that polyester with a density of 1500 kg/m³ and a cost of €2,000 per ton is used for the creation of the bladder, and that the thickness is between three and five centimeter.

Moreover, in Dijkstra's model, a volume of bladder material is calculated based on a handful of specific input parameters and the volumetric capacity of the rigid reservoir that accounts for the required volumetric capacity of the bladder. Again, polyester is opted for as the choice of material and it is assumed that the material is between three and five centimeters in thickness. This differs from the choice within the current established TCO model, as EPDM is used as the material for the --Version 2-- design, and PVC is used as the material for the --Version 1-- design.

2.2.3 Turbine system

For the calculation of the turbine system, Herwig first uses a tool provided by the University of Lancaster for the selection of the most suitable turbine. He eventually concluded that the use of a Francis or Pelton type turbine would be most suitable [34]. On top of this, the tool also proposed a formula for calculating the cost of a hydro turbine, which is as follows:

$$C_{Francis} = 282,000 * (QH^{0.05})^{0.11}$$

Where Q is the throughput in cubic meters per second, and H is the hydraulic head in meters. In order to arrive at a cost output in this regard, Herwig assumes the system to operate at 3MW power capacity.

Then, Dijkstra calculated the costs of the turbine system as a combination of engine room material cost and turbine costs. He makes the assumption that the engine room is fully constructed by concrete and uses placeholder values of 10x10x20 meters as assumed dimension. Ultimately, the user's freedom is brought about by changeable input parameters for the thickness of the roof, walls, and floor, as well as the diameter of the in- and outlets. As an initial estimation, he uses 0.5 meters as the thickness for the wall, roof, and floor, which calculates an eventual volumetric material of 371 cubic meters. This number is then multiplied by the unit cost of concrete to arrive at the cost of the engine room material.

For the turbine cost, Dijkstra opted for a different formula for estimating turbine costs instead than the one used by Herwig. His formula differs in the sense that it uses power capacity instead of volumetric throughput [66, 43, 39]. The eventual adopted formula is as follows:

$$C_{Francis} = 10513H^{-0.134}P^{-0.287}$$

Here, $C_{Francis}$ describes the cost per kW in dollars, H is the turbine head in meters, and P describes the turbine power capacity in kW. Eventually he arrives at a turbine cost of €2,138,609. He furthermore includes the cost of a pump for pumping the water from the rigid reservoir towards the flexible bladder. These are calculated by considering a cost of €290 per kW, which is based on a conventional pump in PHES systems [5, 10]. Eventually, he arrives at a total pump cost of €870,000.

2.2.4 Grid connection cost

In addition to all procurement costs which have been elaborated on so far, Herwig and Dijkstra both implement grid connection costs as an element of procurement costs. Due to complexity and uncertainty issues, Herwig has compared different types of transmission lines which translate to different cost patterns. Ultimately, he opts for a fraction of 12 percent of the total procurement costs to account for the total cost of the grid connection, which is assumed to be a reasonable estimate under his schematic setup of --Company-- 3 systems and corresponding transmission lines and transformers. This setup is furthermore depicted in figure 5. Dijkstra however, opts for an amount per MW installed power capacity, which he assumes to be €270,000 or 16 percent of the total investment costs. He derives these figures

from existing projects such as Danis wind farms Horns Rev and Nysted. By combining this cost with his assumed installed power capacity of 3MW, he calculates the total transmission cost to be €810,000.

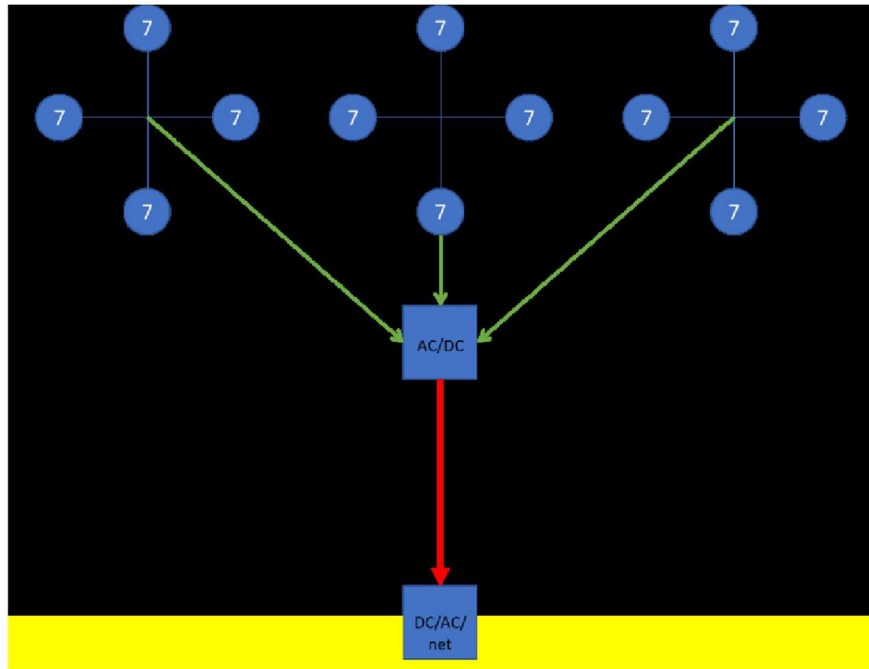


Figure 5: Herwig's schematic transmission setup for a combination of three systems

Eventually, it remains uncertain for one to assume the total grid costs to be a reasonable estimation of the actual grid connection costs. It is known that such costs remain project specific which makes it hard to derive an estimation that ends up to be close to the actual cost. For this reason, transmission costs are not included in the established TCO model of this research. Fortunately, a student named Emilija Lazdanaitė is performing research on the optimal grid configuration for the Innovation system. Her results may eventually be incorporated in the total procurement cost of the model itself.

2.3 Previous research on Assembly cost

Previous research on the assembly costs of the Innovation system was performed twice, although by a similar method. G. Di Donna [17] performed an in-depth analysis of total assembly costs for the older Company 3 design, and Dijkstra subsequently implemented this method with regard for the dimensions and characteristics of the Version 1 Innovation system.

For each cost component of the assembly costs, Di Donna combined a significant amount of input parameters with the specific --Company-- 3 dimensional specificities to derive an amount of working days necessary for successful completion of each of the steps in the complete set of necessary assembly operations. The complete set of operations for which a corresponding amount of days necessary for completion was calculated is as follows:

- Steel frame positioning
- Steel frame welding
- Rigid reservoir positioning
- Rigid reservoir assembly
- Rigid reservoir miscellaneous
- Engine room assembly
- Flexible bladder assembly

The complete set of working days required is eventually used in the calculation of the rental cost of the dock, forklift, and cranes. On top of this, the figure is also used in calculating lightning costs and salary cost of the assembly personnel.

Moreover, Dijkstra uses the same logic for the calculation of the --Version 1-- --Innovation-- system assembly cost, though the calculations of a handful of assembly operation days and cost parameters are altered. First, he scales the assembly days required for the rigid reservoir, engine room, and flexible bladder by a fraction of the --Version 1-- design specific weight of each of these components over the weight of that specific component in the --Company-- 3 design. In addition, the steel frame welding operational days is assumed to be zero, as this operation is non-existent in the assembly of the --Version 1-- --Innovation-- design. Finally, Dijkstra scales down the input rates of the electricity needed per hour (kW), the hourly forklift rate, and the hourly gantry crane rate by a volume factor that corresponds to the total volume of material of the --Version 1-- --Innovation-- system over the older volume of the --Company-- 3 system. In his calculation of the --Version 1-- --Innovation-- design volume, Dijkstra makes use of a safety factor that is added on top of the length, width and height of the system. These are assumed respectively to be five, three, and five meters. Eventually, a total assembly cost per system of €116,539 is established.

2.4 Previous research on Installation cost

For the total installation cost calculation, Dijkstra combines the cost of dredging, depositioning of the dredged hole, and transportation costs with regard to vessel rent for his calculation of total installation cost. The to be dredged hole receives a calculation based on a fixed dimension of 70x20x10 for the --Version 1-- --Innovation-- system design. This total dredging volume is then used in combination with cost factors that were received in talk between --Company-- B.v. and Dutch Dredging [18]. Eventually, Dijkstra established a required fraction for the number of days required for both dredging and depositioning and multiplies these by the daily rental rate of such a vessel. On top of this the fixed costs are added. Moreover, an assumed rate for the combined rental and operational expenses of cable placement and towing vessels is used. Dijkstra uses a value of €143,500 for this, and assumes one full day of rental for the complete installation of one system. By combining the dredging, depositioning, and vessel rate costs, Dijkstra arrives at a total installation cost of €446,165.

2.5 Previous research on Operation & Maintenance cost

For the calculation of the total of Operation & Maintenance cost Herwig uses a combination of two methodologies which were used for an initial calculation by the --Company-- research group before. These are the methods of the research performed by De Vlucht [15] and the CTO of the company itself [48]. De Vlucht utilizes a fixed cost per kW of capacity which has a range of €130-290 kW/year, while the company CTO makes an estimation of a yearly percentage of procurement cost. Eventually, the estimates of both methods for a life cycle of 40 years fall respectively within the ranges of €36.4-€81.2 million and €22.06-€44.8 million. After combining both estimation, Herwig arrives at a lifetime Operation & Maintenance cost of €43.48 million, or €1.087 million per year.

Dijkstra furthermore opts for two Operation & Maintenance cost methods in which the second functions as an alternative to the first one. His first and main method, similarly to the manner on which Herwig based his cost calculation, is conducted by using the €130-290 kW/year range from the research of De Vlucht. He then calculates the total cost for the lower and upper bound over the complete lifetime of the --Innovation-- system, which is set to 20 years in his example. His total yearly energy production is furthermore calculated by taking the efficiencies of the system into account. Eventually, the average of the total lower and upper bound is taken to arrive at a total average Operation & Maintenance cost. Then, concerning

the alternative method, a rate of £76,000 MW/year is opted for, which is supported by additional literature on the cost build-up of offshore wind farms [58]. Ultimately, both methods end up with respectively an Operation & Maintenance cost of €9,757,125 and €4,060,823.

2.6 Previous research on Decommissioning & Disposal

As much was still unknown about the eventual --Innovation-- system Decommissioning & Disposal procedures before this specific research was conducted, both Herwig and Dijkstra use their own unique assumptions regarding the total cost of this unique cost category. After extensive literature search, little useful information was obtained apart from information provided through Shell on their exploration of decommissioning challenges and possibilities [55]. After eventually extrapolating this method towards the --Company-- 3 system, he arrives at a predicted Decommissioning cost of €14.7 million. Herwig considers this amount to be somewhat excessive and therefore does not think it would be representative enough for the --Company-- 3 system. Unfortunately, during his research little information on decommissioning was publicly available as decommissioning operations and corresponding knowledge and information have only now started to reveal themselves.

Then, Dijkstra used the same reference material from which the alternative Operation & Maintenance cost calculation was obtained, and considers their indications of costs of decommissioning for his eventual Decommissioning calculation alternatives. These indications are either 14 percent of the Procurement cost, or £330,000 per MW. It should be noted that again a consideration based on the costs of offshore wind farms was used, which therefore likely fosters incorrect estimates for both designs of the --Innovation-- system itself.

3. Excel tool setup explanation

In this section every tab of the model is elaborated upon in the time order in which the each tab is visited. For a comprehensive explanation, each section will contain an explanation of

the manner in which the costs add to the final TCO output, the calculations performed within each specific section, and the corresponding inputs used in performing the calculations. In the last sub-chapter, the eventual TCO build-up by its respective sub-components is discussed.

3.1 Basic inputs

The first tab that is visited after the introduction page is the one in which the most basic inputs that fundamentally pave the way for all subsequent calculations are set. These are separated in the following categories: locational parameters, system parameters, economic parameters, and material parameters.

The first set considers the locational parameters. These imply the set of parameters that affect the location at which the battery is installed. In essence, it summarizes the distance to the location and between specific battery installation sites, the depth of the water, and the density of the water. It should be noted that the distance between --Innovations-- within a specific location is calculated by a size assumption of the park. Specifically, if one assumes the total number of wind turbines and the total number of --Innovations-- within a wind farm to be spread out in a perfect square, one can estimate the distance between --Innovations-- by dividing the square root of the number of total wind farm turbines by the total number of wind farm batteries. Therefore, as a first assumption, the total number of turbines sited within wind farm Borselle 1, 2, 3, and 4 which totals 173 is taken. Then, this corresponds to a total of 29 --Innovations-- according to an estimate by H. Bijl of one battery per five turbines [2]. Finally, a distance of 3.44 km between --Innovations-- is calculated. This was calculated as the distance between batteries is useful in calculating economies of scale benefits within the different steps of the Installation costs. This will be elaborated on in that specific section of this report.

Moreover, a set of system parameters is found in which assumptions regarding the functionality of the system can be set. Important here is that a distinction between an analysis for the --Version 1-- design and the --Version 2-- design can be made. This subsequently affects the total of requirements and the TCO cost calculations. After this selection has been made, one can take a quick peak at the effective depth parameter in the set of locational parameters, as its calculation is affected by the choice of system design.

Then, a handful of economic parameters make their difference in the modelling calculations. Two of these are important here. Firstly, the economies of scale variable can be set. Its

relevance has been explained in the introduction, as it provides for economies of scale benefits in a handful of cost calculations. Under this number a check is placed on the maximum allowed economies of scale amount if the heavy transport vessel is opted for in the installation phase. Otherwise, this number can be ignored. Secondly, the discount factor can be set. This is an important consideration as it affects the present value of the complete set of costs incurred considerably.

Finally, a handful of density values for different raw materials can be set in the overview of material parameters.

3.1.1 Assumed set of Basic inputs for cost calculations

As the model is somewhat dynamic and thereby brings about many options for which a cost comparison can be established, a set of basic assumptions for both the --Version 1-- --Innovation-- and the --Version 2-- --Innovation-- system will be opted for. Hence, anytime the “current set of assumptions” is named, one should keep the assumptions of Table 2 for the --Version 1-- design and Table 3 for the --Version 2-- design in mind.

--Version 1-- design	Value	Unit
Water depth	38	Meter
Dredging depth	100	Meter
Effective depth	92.5	Meter
Density seawater	1,025	Kg/m3
Distance wind farm	20	Kilometer
Distance between --Innovations--	3.44	Kilometer
Life cycle	20	Years
Battery volume	6	MWh
Battery power	4	MW
Turbine efficiency	88.5%	Percent
Pump efficiency	87.5%	Percent

Table 2: Basic assumptions for the --Version 1-- --Innovation-- system cost calculations

--Version 2-- design	Value	Unit
Water depth	97.5	Meter
Dredging depth	0	Meter

Effective depth	92.5	Meter
Density seawater	1,025	Kg/m ³
Distance wind farm	20	Kilometer
Distance between --Innovations--	3.44	Kilometer
Life cycle	20	Years
Battery volume	6	MWh
Battery power	4	MW
Turbine efficiency	88.5%	Percent
Pump efficiency	87.5%	Percent

Table 3: Basic assumptions for the --Version 2-- --Innovation-- system cost calculations

3.2 Requirement calculations

After the set of basic inputs is set to their desired amount by the stakeholder, the requirement calculations tab can be observed for a complete calculation of all required materials in the creation of the system. Within this section, the calculations have been divided in calculations for the total of materials that constitute the rigid reservoir, the flexible bladder, and any other specificities. Additionally, the top bar that indicates for what specific component the calculation is performed, contains a specific color that depicts the applicability of the calculation with regard to one or both --Innovation-- systems. Hence, three different colors are observed for either an application to both systems, uniquely the --Version 2-- design, or uniquely the --Version 1-- design.

The complete set of calculation have been performed with the help of the Storage System Cost Comparison Tool, the Cost Assessment --Innovation-- (suction anchor design), and talks with the CTO and COO.

It should be noted that for the --Version 1-- design weight calculation of the metal base, supporting ribs, and compartment wall, a fraction of the weight of the --Version 2-- variant is taken for any specific set of basic assumptions. These fractions are in accordance with the system difference in total price of any of these components as set by the Storage System Cost Comparison Tool.

3.3 Total of requirements

In the total of requirements tab, the calculated requirements are summarized according to the choice of design. Here, the requirements with regard to the amount of valves, turbines, generators, and transformers are added, as these are not met with a complex calculation, but instead are added up based on the power output of the system and the economies of scale factor.

Furthermore, some of the requirements come with the same color coding as in the Requirement calculations tab. Hence, if for instance the --Version 2-- design is chosen as the choice of analysis, no value is shown for the requirements of manifold, geotextile, and ballast stones.

Ultimately, the specific requirements are used for the procurement calculations, and the total weight of the reservoir and bladder are depicted due to their functionality in the assembly cost calculations and in setting the maximum allowed economies of scale factor for installation by heavy transport vessel.

3.4 Pre-development and consenting

For offshore wind farms, the development usually starts around five years before the actual installation of the whole is executed. Specifically, it is very unusual to have an efficient short-duration switch from the idea to the start of the project. Much paperwork, feasibility studies, procedures etcetera ought to be undertaken before any other process may start. These costs are related to project management, legal authorization, surveys, engineering, and contingencies.

Project management usually includes all administrative tasks, pre-feasibility, tendering, financing, subcontractor negotiations, and internal controlling systems. Independently observed, these are small numbers in comparison to the total of other costs and simultaneously hard to calculate. For this reason, they receive a simple calculation based on a fraction of the Procurement costs, Assembly cost, and Installation & Commissioning cost (CAPEX). For the established model, this fraction will be based on that of offshore wind generation, and will take the value of 3% [42].

Then, for the successful deployment of an --Innovation--, legal authorization by local authorities is most likely required, just as in the case of offshore wind parks. This process may take up some time as approval is required before moving on to the next phase, and this

certainly takes into account a corresponding cost. For now, 0.13% of the procurement costs is used [58, 28].

Next up is the cost of surveys. These costs come into play while assessing the feasibility of an offshore project. The types of surveys conducted usually differ according to the type of information that is required for successful deployment. Regarding offshore wind projects, four different types of surveys are generally used. These are: environmental, coastal processes, and seabed and metocean conditions. As stated before, a lot is still uncertain about the eventual build-up of the different cost characteristics of the --Innovation--. For this reason, a fraction of 0.8% of the survey costs of a 500MW wind farm is used [40]. This percentage is established by considering the survey cost of one --Innovation-- system with a power capacity of 4MW. By dividing this number by the whole of 500MW, one obtains the percentage mentioned.

Moreover, engineering costs come into play into the design of structural choices of an offshore project. The activities undertaken in the matter are ones concerning design, the layout of the complete project, and the design of the grid connection and corresponding electrical systems. Again, a fraction of taken from the 500MW wind farm reference, but this time concerning the front-end engineering and design costs. This is a fraction of 0.8% as it is assumed that the pre-engineering of a 4MW --Innovation-- may be about half the cost of the pre-engineering of an 8MW wind turbine.

Lastly, contingencies exist for almost every project undertaken. These contingencies are unpredictable expenses that would annually occur. The contingency factor is normally considered a certain percentage of CAPEX, e.g. 10% in total [28]. As a total life span of 20 years is used within the mode, an annual contingency cost of $10\% / 20 = 0.5\%$ is used. These cost are eventually divided with the corresponding discount factor, and subsequently summed to obtain the NPV of contingency costs.

3.5 Procurement

After a successful pre-development stage, the first step in the chronological order of life cycle costs are the Procurement costs. These costs are compiled by combining the total of requirements with the purchasing price of the required materials, components and sub-systems of the complete --Innovation-- system itself. For a complete overview of the source of each price depicted within the Procurement tab of the Excel model, one is referred to Appendix A.

Moreover, an addition of a lower and upper bound per price figure can be found, as prices may likely fluctuate in the future, especially as the --Innovation-- is designed for a large part by commodities such as concrete, steel, and rubber. Hence, each fluctuation is calculated as a +/- five percent difference from the average fluctuation over the past four of five years, calculated for the given raw materials or as a weighted average of the given components composition of raw materials. For a clear calculation of all price fluctuations, one is referred to Appendix B in which a different document is embedded that directly leads to a document containing each calculation. It should be noted that for four of the five subsystem prices depicted at the bottom of the list of prices in the model, the exact material intensities were unclear. Therefore, a +/- five percent margin from zero percent average fluctuation was taken.

The eventual composition of the total costs are divided between cost components of the rigid reservoir, flexible bladder, shaft, pumping system, umbilical system, turbine system, --Version 1-- design extra's, and other costs. The values of these cost components is ultimately affected by the choice of the --Innovation-- system type for which these costs are calculated. Hence, the costs are calculated for either the --Version 1-- design or the --Version 2-- design. To be more specific in this regard, the next paragraph will outline the differences in more detail.

Firstly, for the total cost of the rigid reservoir, it is observed that the total amount is more than twice the size of that of the --Version 1-- design. This is largely brought about by the tenfold increase in costs of the steel components that support the concrete structure itself. Then,

Secondly, concerning the total flexible bladder costs, a fivefold increase in total costs is observed for the --Version 2-- design, which is caused by two specific reasons. First, due to differences in bladder volume between the different designs and the fact that the --Version 2-- bladder is constructed with EPDM instead of PVS which is larger in density and twice the price per kg, the total price of the bladder material is more than four times the price than that of the --Version 1-- design. On top of this, the --Version 2-- design comes with a handful of bladder connection materials which add additional costs.

Thirdly, a total cost for the shaft component is added to the overall depiction. This cost is calculated by multiplying the total weight of the shaft by the price of alloy steel. The weight is furthermore calculated by first deciding on the total height of shaft which is affected by the effective depth of the system and the additional height above the sea surface. This height is subsequently multiplied by the weight of the shaft per meter of height. For every centimeter

of wall thickness, one meter of shaft height contains a weight of 12.5 tons, as stated by the company's CTO. For the current version, the thickness is set at two centimeters, though the user is free to change this input value according to its wishes.

Then, pumping system costs are added for the --Version 2-- design which contains costs for pumps and pipes.

Furthermore, costs for the umbilical system are added as the exact same total number for both system designs, as both designs come with a fixed amount of air pipes, water pipes, and floaters.

Moreover, for the total costs of the turbine system, a similar amount for both design is established again. This is brought about by the fact that these costs are based on the total power capacity of the system, instead of the system design. Each turbine, generator, and transformer operates at a capacity of 500kW. Therefore, each time additional power capacity is added in the basic inputs up until an extra 500kW, one additional unit of each of these components is added and extra costs are incurred. For the total price of valves, the dynamics are slightly different. Specifically, the total butterfly valve cost, and thereby the corresponding number of valves is calculated by summing the total number of concrete reservoirs used for the set of basic input configurations and the total number of turbines used in a single --Innovation-- system, as each turbine system and reservoir will each receive their own valve.

Then, extra costs are incurred for specificities of the --Version 1-- design. These costs compose of costs for a manifold, geonet, and ballast stones. The manifold costs are calculated by multiplying the base case manifold costs by a fraction of the concrete reservoir volume over the base case concrete reservoir volume of 20,358 m². The base case can be found in the Storage System Cost Comparison Tool excel file. The geonet costs are calculated by multiplying the area of geonet required by the price of geonet per m². This required area is decided as the same required area space for the flexible bladder material. The ballast stone costs are calculated by multiplying the required amount of ballast stones in tons by the price of ballast stones per ton. It was decided by the CTO of the company that on each side of a flexible reservoir, 1,500 tons of ballast stones are placed. Therefore, in the requirement calculations the total rows of ballast stones are calculated based on the number of reservoirs used, and this number is subsequently multiplied by 1,500 tons of stone.

Finally, other costs are incurred for both systems which consists of the control system, steel components, and working fluid. For the --Version 1-- design, the calculation of these prices

works similarly to that of the manifold, by multiplying the --Version 1-- design base case cost by a fraction of the reservoir volume in the current settings over the reservoir volume of 20,358 m² in the base case. For the --Version 2-- design, the base case price is twofold as indicated in the Storage System Cost Comparison Tool of the company.

Eventually, by summing up all of these unique cost components, one arrives at the total procurement cost for the lower, middle, and upper bound of both --Innovation-- systems. For the middle bound in the current set of --Innovation-- system settings, it is established that the total procurement costs for the --Version 1-- design constitute €3,228,438, while this number ends up significantly higher for the --Version 2-- design at €6,889,501.

Calculations	Lower bound	Cost	Upper bound
Cost rigid reservoir	€ 270.278,38	€ 275.794,26	€ 297.857,80
Cost steel base	€ 167.002,77	€ 172.701,93	€ 185.309,17
Cost steel ribs	€ 151.110,94	€ 156.267,78	€ 167.675,33
Cost compartment wall	€ 6.306,32	€ 6.521,53	€ 6.997,61
Cost tension cable	€ 25.180,97	€ 26.230,18	€ 27.803,99
1. Total Cost rigid reservoir	€ 619.879,38	€ 637.515,69	€ 685.643,90
Cost bladder material	€ 44.939,95	€ 48.583,73	€ 52.227,50
Cost synthetic strip	€ 0,00	€ 0,00	€ 0,00
Cost steel strip	€ 0,00	€ 0,00	€ 0,00
Cost bolts	€ 0,00	€ 0,00	€ 0,00
Cost inserts	€ 0,00	€ 0,00	€ 0,00
2. Total cost flexible bladder	€ 44.939,95	€ 48.583,73	€ 52.227,50
3. Total cost shaft	€ 1.188.975,00	€ 1.235.345,03	€ 1.354.242,53
Cost pumps	€ 0,00	€ 0,00	€ 0,00
Cost pipes	€ 0,00	€ 0,00	€ 0,00
4. Total cost pumping system	€ 0,00	€ 0,00	€ 0,00
Cost water pipe	€ 28.290,00	€ 30.000,00	€ 31.710,00
Cost air pipe	€ 28.290,00	€ 30.000,00	€ 31.710,00
Cost floaters	€ 11.316,00	€ 12.000,00	€ 12.684,00
Cost electrical system	€ 30.786,83	€ 32.407,19	€ 34.027,55
5. Total cost umbilical system	€ 98.682,83	€ 104.407,19	€ 110.131,55
Cost butterfly valves	€ 17.406,00	€ 18.000,00	€ 19.314,00
Cost Francis turbine	€ 440.472,37	€ 455.504,00	€ 488.755,79
Cost generator	€ 146.453,96	€ 151.923,20	€ 157.392,44
Cost transformer	€ 11.985,20	€ 12.616,00	€ 13.246,80
6. Total cost turbine system	€ 616.317,53	€ 638.043,20	€ 678.709,03
Cost manifold	€ 61.573,66	€ 64.814,38	€ 68.055,10
Cost geonet	€ 4.946,63	€ 5.245,63	€ 5.544,64
Cost dumpstones	€ 115.710,00	€ 121.800,00	€ 127.890,00
7. Total cost buried design extra's	€ 182.230,29	€ 191.860,01	€ 201.489,73
Cost control system	€ 123.147,32	€ 129.628,76	€ 136.110,20
Cost steel components	€ 62.675,50	€ 64.814,38	€ 69.545,83
Cost working fluid	€ 46.180,25	€ 48.610,78	€ 51.041,32
Cost other	€ 123.147,32	€ 129.628,76	€ 136.110,20
8. Total other costs	€ 355.150,39	€ 372.682,68	€ 392.807,55
TOTAL PROCUREMENT COST	€ 3.106.175,38	€ 3.228.437,52	€ 3.475.251,78
TOTAL PROCUREMENT COST, SINGLE SYSTEM	€ 3.106.175,38	€ 3.228.437,52	€ 3.475.251,78

Table 4: Procurement costs --Version 1-- design (4MW power capacity, 6MWh volume capacity)

<i>Calculations</i>	<i>Lower bound</i>	<i>Cost</i>	<i>Upper bound</i>
Cost rigid reservoir	€ 239.092,41	€ 243.971,85	€ 263.489,59
Cost steel base	€ 1.670.027,67	€ 1.727.019,31	€ 1.853.091,72
Cost steel ribs	€ 1.511.109,42	€ 1.562.677,78	€ 1.676.753,26
Cost compartment wall	€ 63.063,24	€ 65.215,34	€ 69.976,06
Cost tension cable	€ 50.361,95	€ 52.460,36	€ 55.607,98
1. Total Cost rigid reservoir	€ 3.533.654,68	€ 3.651.344,64	€ 3.918.918,62
Cost bladder material	€ 194.631,98	€ 204.875,77	€ 215.119,56
Cost synthetic strip	€ 23.620,24	€ 25.047,98	€ 26.475,71
Cost steel strip	€ 15.182,07	€ 15.700,18	€ 16.846,29
Cost bolts	€ 3.191,10	€ 3.300,00	€ 3.540,90
Cost inserts	€ 31.911,00	€ 33.000,00	€ 35.409,00
2. Total cost flexible bladder	€ 268.536,40	€ 281.923,92	€ 297.391,46
3. Total cost shaft	€ 1.188.975,00	€ 1.235.345,03	€ 1.354.242,53
Cost pumps	€ 193.400,00	€ 200.000,00	€ 214.600,00
Cost pipes	€ 626,15	€ 664,00	€ 701,85
4. Total cost pumping system	€ 194.026,15	€ 200.664,00	€ 215.301,85
Cost water pipe	€ 28.290,00	€ 30.000,00	€ 31.710,00
Cost air pipe	€ 28.290,00	€ 30.000,00	€ 31.710,00
Cost floaters	€ 11.316,00	€ 12.000,00	€ 12.684,00
Cost electrical system	€ 61.573,66	€ 64.814,38	€ 68.055,10
5. Total cost umbilical system	€ 129.469,66	€ 136.814,38	€ 144.159,10
Cost butterfly valves	€ 17.406,00	€ 18.000,00	€ 19.314,00
Cost Francis turbine	€ 440.472,37	€ 455.504,00	€ 488.755,79
Cost generator	€ 146.453,96	€ 151.923,20	€ 157.392,44
Cost transformer	€ 11.985,20	€ 12.616,00	€ 13.246,80
6. Total cost turbine system	€ 616.317,53	€ 638.043,20	€ 678.709,03
Cost manifold	€ 0,00	€ 0,00	€ 0,00
Cost geonet	€ 0,00	€ 0,00	€ 0,00
Cost dumpstones	€ 0,00	€ 0,00	€ 0,00
7. Total cost buried design extra's	€ 0,00	€ 0,00	€ 0,00
Cost control system	€ 246.294,64	€ 259.257,52	€ 272.220,39
Cost steel components	€ 125.351,01	€ 129.628,76	€ 139.091,66
Cost working fluid	€ 92.360,49	€ 97.221,57	€ 102.082,65
Cost other	€ 246.294,64	€ 259.257,52	€ 272.220,39
8. Total other costs	€ 710.300,79	€ 745.365,36	€ 785.615,09
TOTAL PROCUREMENT COST	€ 6.641.280,21	€ 6.889.500,54	€ 7.394.337,67
TOTAL PROCUREMENT COST, SINGLE SYSTEM	€ 6.641.280,21	€ 6.889.500,54	€ 7.394.337,67

Table 5: Total procurement cost --Version 2-- design (4MW power capacity, 6MWh volume capacity)

3.6 Assembly

Assembly costs are the costs of assembling the system from its bundle of materials and components. They occur after the Procurement operations are fully complete and all

components have been delivered to a respective port of installation. It is known from previous research on the --Innovation-- that a dry-dock is the preferred method of installation due to the massive size and weight of the complete system. Di donna and Dijkstra have both performed their separate analyses on the most suitable dry dock for the assembly of the --Innovation--. This was performed for the structural size of the --Company-- 3 prototype by Di Donna and for the --Version 1-- design by Dijkstra. The importance for such an analyses stems from the importance of economies of scale in attaining cost benefits over the life cycle operations of the innovation. A larger dry dock would result in more opportunities for economies of scale benefits, and therefore makes such a location a more attractive option.

Table 6 presents partly the full analysis on dry docks performed by Dijkstra. For the full set of options analyzed, the Appendix of Dijkstra's research can be consulted. Besides economies of scale benefits, his analysis also considered dry-dock locations with respect to the North Sea and European Union membership to rule out regulation uncertainties. After observing the outcomes of the analysis, it can be concluded that the Verolme yard in the harbor of Rotterdam is the most promising option when taking into account the three main criteria. Moreover, this yard has recently been acquired by the Damen group [11]. They constitute a ship builder who is able to host large repair and maintenance operations involving heavy marine structures. While utilizing the Verolme yard, they would also be able to host larger repair and maintenance operations due to their portfolio of other dry docks.

Yard	City	L (m)	B (m)	D (m)	No. Of -- Innovatio ns--
Port autonome du Havre / Soreni	Le Havre (FR)	319	38	17.5	4
Damen Shiprepair Brest	Brest (FR)	420	80	10.4	10
Blohm + Voss repair	Hamburg (DE)	288	44.2	10.2	3
Blohm + Voss repair	Hamburg (DE)	321	52	10.8	4
Lloyd Werft Bremerhaven	Bremerhaven (DE)	335	35	11.5	4
Meyer Werft	Papenburg (DE)	482	45	10	6
Damen Verolme	Rotterdam (NL)	275	40.4	10.3	3
Damen Verolme	Rotterdam (NL)	405	90	11.1	15

Table 6: Suitable dry dock options

Hence, the Rotterdam harbor is opted for the port of assembly and installation within the constructed model. This is a somewhat important consideration as it affects the distance from port to installation site, which plays an important consideration in the make-up of Installation costs. This will be elaborated further upon in the subsequent Installation and Commissioning subchapter.

Furthermore, for a further analysis on the calculated assembly costs of the TCO model, a similar approach as initiated by Di Donna and scaled towards the --Version 1-- --Innovation-- design by Dijkstra is opted for. This method is based on the amount of labor days required for every assembly operation and corresponding cost factors that are affected by these labor day requirements.

First, the user fills in a handful of input parameters for the eventual cost calculations to be performed within this section. The input requirements range from rent rates of different dock facilities towards a handful of requirements in terms of lightning hours, electricity, and cranes for the assembly of one system.

Another important calculation which is already performed at this moment is the total amount of days required for the assembly operations. These calculations are based on the amount of assembly days required for one OG3 --Innovation-- system calculated by Di Donna and use a similar method for scaling these numbers to the newer versions of the --Innovation-- as done by Dijkstra. A sharp contrast in this matter is the fact that the weight factor may change according to the set of basic inputs that affect the weight dimensions of the system itself. This slightly changes the dynamics of the calculations. Specifically, for the calculations in which a weight factor is not used according to Dijkstra's method, the same type of calculation applies. On the other hand, for the calculations in which a weight factor does get used according to Dijkstra's method, the same method applies by multiplying Di Donna's number times the weight factor, though this weight factor is variable instead of constant and differs according to the set of input parameters and the type of battery for which the TCO calculation is performed (--Version 2-- or --Version 1--)

An exception to both of these methods is the assembly days requirement calculation for the engine room. So far, past research at --Company-- B.v. has assumed engine room costs to be based on a total tonnage of steel, making Dijkstra's weight scaling method somewhat easy to execute for this calculation. The TCO model created in this case however, uses a handful of different components which each have their own material intensities for the set-up of engine

room costs. For this reason, Dijkstra's engine room weight factor based on a --Version 1-- design with a power capacity of 3MW is scaled towards the power capacity of the current model which is set at 4MW. Eventually, Di Donna's day's requirement for one OG3 unit is multiplied by this new weight factor, which is subsequently multiplied by the economies of scale factor.

Finally, the combination of assembly input parameters and the total amount of assembly days will bring about the eventual output numbers for the different assembly cost components. For the current set of input parameters, corresponding cost figures are depicted in Table 7. It is observed how the total assembly cost for one --Version 1-- design system is estimated at €121,183 while for the --Version 2-- design this output number becomes more than doubled with a value of €242,170. This difference can essentially be explained by the larger weight of the rigid and flexible reservoir of the --Version 2-- design, plus the fact that the --Version 2-- design receives extra assembly days due to the welding of the steel frame, as this process is not undertaken for the --Version 1-- design. Hereby, the total assembly days required surges from 5.61 to 10.11 days. To summarize the complete process of steps undertaken within the assembly costs calculation a flowchart is provided in figure 6.

ASSEMBLY COST COMPARISON	--Version 1-- design	--Version 2-- design
Total dock cost	€94,595	€170,564
Total lighting cost	€7,772	€14,014
Total forklift cost	€4,391	€7,917
Total cranes cost	€13,561	€48,117
Total salary cost	€864	€1,557
Total assembly cost	€121,183	€242,170

Table 7: Assembly costs comparison between both --Innovation-- system types

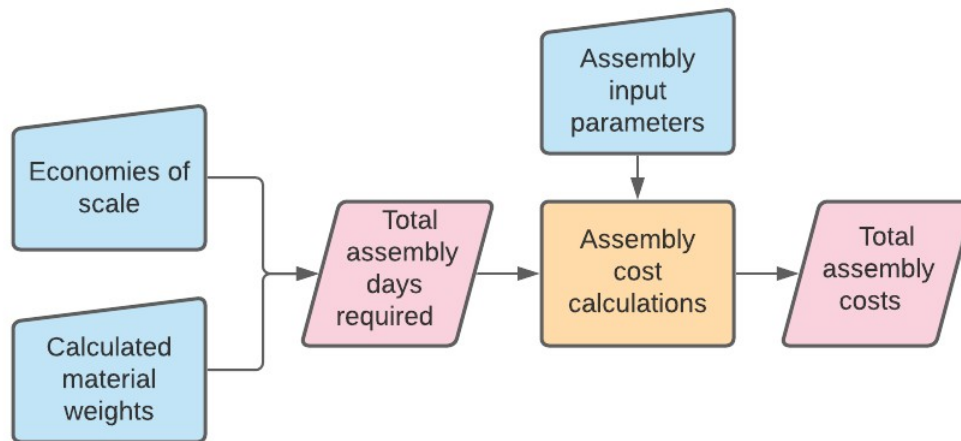


Figure 6: flowchart of the steps undertaken to obtain the total assembly costs

3.7 Installation & Commissioning

The next category of costs from a chronological point of view are the Installation & Commissioning costs. These costs are incurred during the process in which the assembled system is transported to its specific site of operation, and during any additional marine operations for ensuring that the system is ready to function according to its necessities for proper functionality. The commissioning costs furthermore differ from the installation part in the fact that commissioning activities involve those costs outside of the necessary marine operations in which the installed system is tested on achieving the prospected functionality. On top of this, the model also provides the option to include insurance costs incurred during this process.

3.7.1 Installation expenses

The installation process involves different steps in which marine operations are undertaken which are necessary for the successful installation of the --Innovation-- system. For the --Version 1-- --Innovation-- design, these steps are chronologically:

1. Dredging and seabed preparation
2. Concrete structure installation
3. Pouring
4. Flexible bladder installation
5. Ballast stone placement

For the --Version 2-- design however, only two of these steps are necessary however, as the --Version 2-- design is designed as a single unit system which contains all components and necessary reservoirs. Hereby, the first two steps remain. It should be noted though, that the seabed preparation is the only part of the --Version 2-- design installation necessary from step one, and step two is renamed as the complete system is installed instead of just the concrete reservoir. Hence, the chronological order of steps becomes:

1. Seabed preparation
2. --Innovation-- system installation

In the following subsections, all steps are discussed, for if necessary both --Innovation-- design types.

3.7.1.1 Dredging and seabed preparation

In the first step of the installation process, costs are incurred for the dredging of the seabed and corresponding seabed preparation if the --Version 1-- design is opted for in the basic inputs, or costs for just the seabed preparation if the --Version 2-- design is opted for.

Concerning the costs of dredging, a calculation is performed based on the size of the to be dredged hole divided by the dredging capacity of a dredging vessel per hour, which provides the total number of hours necessary for dredging the desired hole. These number of hours are converted to days and rounded up to a whole number of days for which the vessel ought to be hired. Ultimately, this number is multiplied by the cost of the dredging vessel per day, and summed by the fixed cost of hiring the vessel. These input costs are respectively €100,000 and €200,000 in the current set of settings. If the --Version 1-- design is chosen in the basic inputs, a total number of two dredging days is calculated, and thereby a total cost of dredging of €400,000 is calculated.

It should be noted that this is the first part of the TCO model in which economies of scale benefits are attainable. This is the case as the time spent for reaching the location and returning to port, and the fixed cost of hiring the vessel are spread over multiple --Innovation-- systems. On top of this, the number of days on which the vessel is rented is always rounded up as it seems unlikely that a vessel is hired for a fraction of a day. Therefore, economies of scale benefits will also be attained if more operations are performed for each single day of paid vessel day rent.

Then, the cost of flattening the seabed and cost of surveys are added to produce the final number of dredging costs. These costs are fixed at respectively €30,000 and €8,000 and were obtained from the Storage System Cost Comparison Tool model.

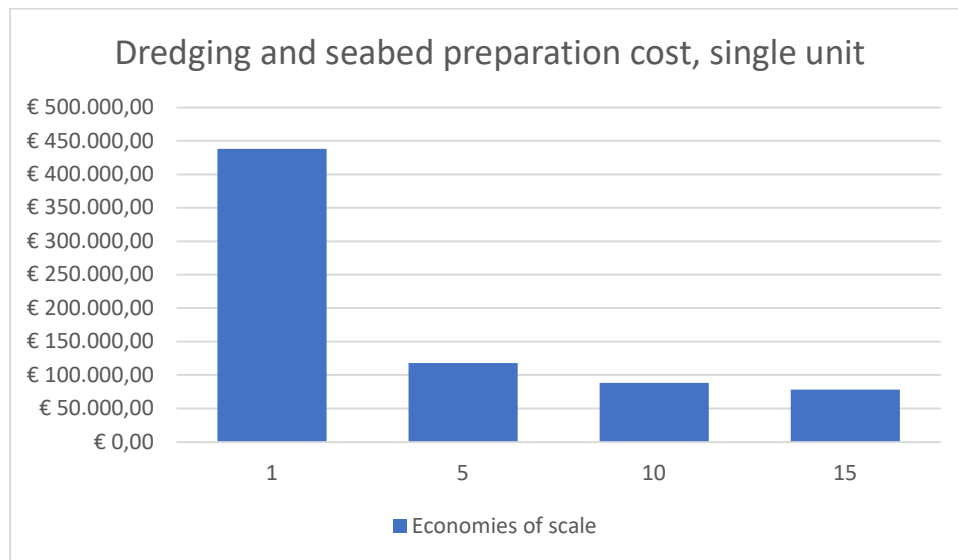


Figure 7: Economies of scale benefits for --Version 1-- version dredging and seabed preparation

3.7.1.2 Concrete structure installation / --Innovation-- system installation

In the second part of the of the installation process, either the concrete reservoir is installed in the dredged hole if the --Version 1-- design is opted for, or the complete --Innovation-- system is installed on the sea bottom if the --Version 2-- design is opted for. A first interesting sight of this step in the cost calculation process is the slider for the choice of installation vessel. This slider can be used to pick for what choice of vessel the cost calculations will be performed.

Then, regarding the cost calculation of this step, the costs are calculated by summing the costs for loading the barge and the costs of hiring the selected vessel(s) itself. Concerning the costs of renting the vessel, costs are incurred for the total number of vessel days for which a rental price is eventually paid. This number of vessel days is established by the time spent at sea, and if the tug vessel option is chosen, for the number of tug vessels used in the marine operation. In an interview with an employee of Boskalis, it was established that for an --Innovation-- system this operation can be performed by four tug vessel with 75 ton bollard pull with an average speed of 7.41 km/h (Boskalis, interview, 3th of June 2021).

Again, economies of scale benefits are achievable. For the tug vessels option these are most significant, as for the current settings it takes approximately eight hours to install one system, while for two systems only an extra of approximately two and a half hours will be added due to the distance to the next system taking approximately half an hour and the deployment time on-site being only two hours. For the heavy transport option, the same logic applies, though for each unit of increase in economies of scale an extra day of renting the vessel is added for loading, thereby cancelling out a significant portion of the relative economies of scales cost benefit. The benefits of both options are displayed in Figures 8 and 9.

For the loading cost component, costs are calculated based on a cost indication provided by Mammoet for renting a load-in load-out vessel to load a single --Innovation-- system on a heavy transport vessel. This cost figure is set at €450,000, which was obtained from a phone call with an employee of Mammoet. This operation may take a couple of days as the --Innovation-- system is slowly moved towards the sea shore, which brings about an extra day of renting a heavy transport vessel as the vessel ought to be in place for the --Innovation-- system to get loaded on.

Ultimately, for the current --Innovation-- system settings, the time that the installation vessel is rented is set at 2 days and 1 day for the heavy transport vessel and tug vessels respectively. Thereby, the total installation step costs incurred by using a heavy transport vessel comes at €590,000 and the total installation step costs incurred by using the tug vessels comes at €50,000.

3.7.1.3 Pouring

Then, the next step in the order of installation is pouring. As mentioned, this step is only incurred for the --Version 1-- design option. The methodology in which these costs are calculated is similar to that of the dredging process. Hence, a number of vessel days is required for which the pouring vessel is hired, and the number is rounded up to a whole number of vessel days.

Again, economies of scale benefits apply. In this regard, the logic is the same as for the dredging part of the total calculation. These benefits are depicted in Figure 10.

For the current settings of the --Innovation-- and an economies of scale set at one, a total of two pouring days is calculated, thereby reaching a total cost of pouring of €240,000.

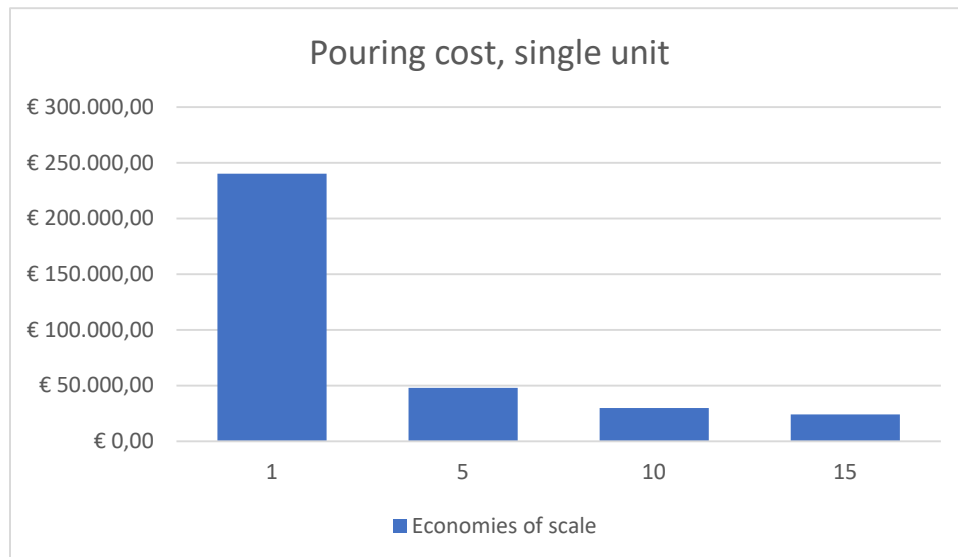


Figure 10: Economies of scale benefits for pouring

3.7.1.4 Flexible bladder installation

As the dredged hole is filled thanks to the work of the pouring marine operation, the next step in line is the installation of the flexible bladder. As the --Version 2-- design only requires one marine operation for the on-site placement, this step is only incurred when opting for the --Version 1-- design. As in the second step of the complete installation process, again a choice can be made in the model by a slider on what type of vessel is chosen for this part of the installation, specifically tug vessels or dive support vessels. In the same interview with the employee of Boskalis, it was mentioned that this operation can be performed by either two dive support vessels or four tug vessels (Boskalis, interview, 3th of June 2021).

Concerning the calculation methodology, the same logic applies as with the installation in step two for the option of tug vessels. Hence, the total number of rounded up vessel days required is calculated first as the time spent travelling back and forth from the site and the time for deployment on-site, which is then multiplied by the amount of vessels required for the installation of a single system. On top of this, the same economies of scale logic as in step two also applies, due to the addition of just the travelling time to the next location and the additional deployment time on-site if an extra system is installed simultaneously. The effects of this are revealed in Figure 11 for the tug vessels option, and Figure 12 for the dive support vessels option.

For the current settings of the --Innovation-- and an economies of scale set at one, a total of one vessel day is calculated for both types of installation vessels, hereby bringing the costs of this step in the installation process to €40,000 and €35,000 for respectively the tug vessels and dive support vessels options.

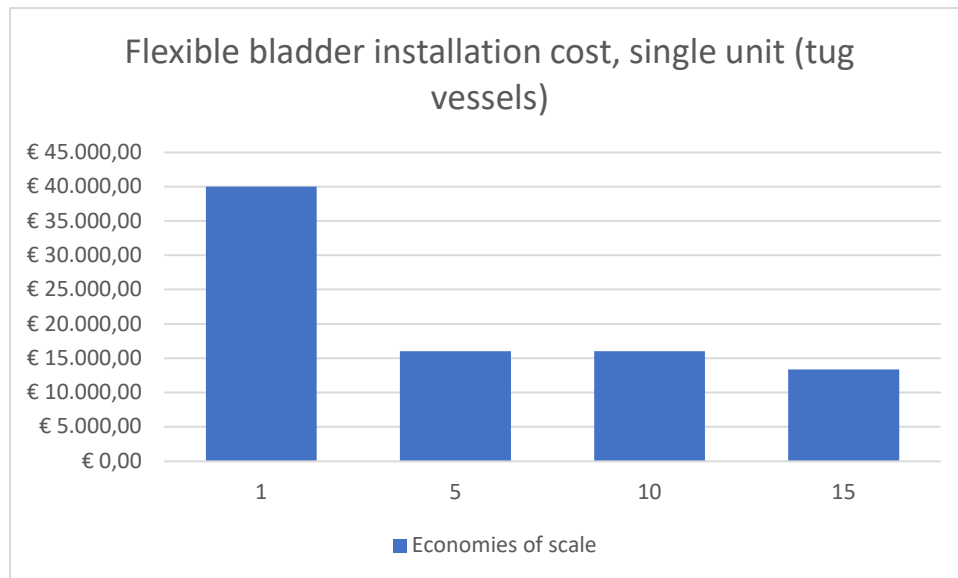


Figure 11: Economies of scale benefits flexible bladder installation by tug vessels

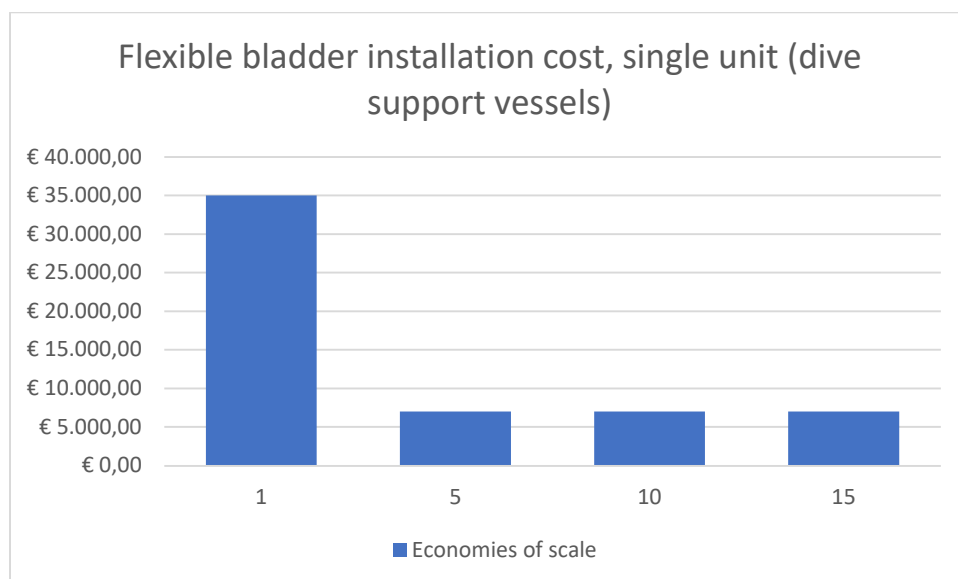


Figure 12: Economies of scale benefits flexible bladder installation by dive support vessels

3.7.1.5 Ballast stone placement

The last step of the installation process is the step in which ballast stones are placed for scour protection of the --Version 1-- --Innovation-- system. This is done by the help of a fallpipe vessel, and in this case the Boskalis Rockpiper is selected as reference material. This vessel can carry approximately 24,000 tons of dumpstones per marine operation, which is enough for a handful of simultaneous --Innovation-- systems per operation. In the talks with the employee of Boskalis, it was mentioned that the Rockpiper ought to get loaded before every operation in a port in Norway, thereby taking up two vessel days in transportation time before reaching the North Sea (Boskalis, interview, 3th of June 2021). On top of that, the loading process could take up a single day. Hence, a total of five vessel days are already required per marine operation, without the addition of the time spent-on site per --Innovation-- system.

Hence, for the total ballast stone placement cost calculation, the amount of rounded up vessel days is calculated first as a combination of loading time, transportation time to and from the site, the transportation time between --Innovation-- system if economies of scale is applied, and the single operation time on-site per --Innovation-- system. This number is then multiplied by the daily rental cost of a fallpipe vessel.

Then, with regard to economies of scales, the dynamics are slightly different compared to the other marine operations. As was mentioned, this Boskalis Rockpiper can only carry 24,000 tons of ballast stone on one marine operations. Therefore, the loading and transportation costs are added for every addition of economies of scales that passes the “maximum amount of ballast stone operations per trip” figure in the model. This figure is calculated by dividing the capacity of the fallpipe vessel by the required amount of ballast stones per --Innovation-- system, which is subsequently rounded down. Hence, ballast stone placement costs are minimized if the maximum capacity of each fallpipe vessel trip is fully used. The effects of this for the current --Innovation-- system settings is depicted in Figure 13. It can be observed that an input of 16 provides the lowest costs in this example. This is justifiable as the maximum number of ballast stone operations per trip is eight, which implies that the maximum fallpipe vessel capacity is reached in both trips.

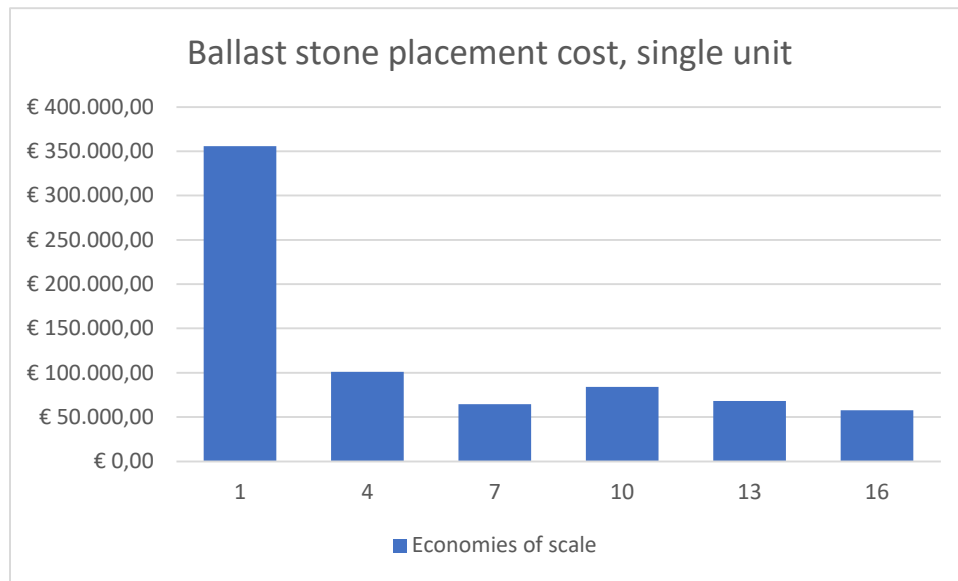


Figure 13: Economies of scale benefits Ballast stone placement

3.7.2 Commissioning and insurance expenses

After all installation steps are successfully undertaken, the system ought to be tested for possible early failures and to increase the reliability of the system. After talks with the COO of the company, an indication of the commissioning expenses was provided. Specifically, in the model it is assumed that four employees will work two work-days for the system to be successfully commissioned. Hereby, a total commissioning cost of €1,800 is calculated if we assume a normal work day to be nine hours.

Additionally, the options are left open to include a yearly performance monitoring and warranty cost and set the amount of years for which this cost ought to be incurred, and to include a yearly P&I and Hull and Machinery insurance cost with a corresponding amount of years for which this cost ought to be incurred.

3.8 Operation & Maintenance

For the successful exploitation of a large amount of assets, Operation & Maintenance activities are common recurring cost components for the entire life span of the asset. For the -- Innovation--, this is therefore not a surprising addition to the overall picture of life cycle costs. Concerning operational expenses, the yearly amount is generated based on the power and volume capacity of the battery system, while the maintenance expenses are mostly affected by the configuration of components and corresponding failure rates.

3.8.1 Operational expenses

The operational expenses can be separated in three main cost components, these are specifically:

- Cost of seabed rental
- Insurance cost
- Periodic connection tariff

For the cost of seabed rental the Central Government Real Estate Agency has calculated the cost of seabed rental to be approximately €0,98 for every MWh of output produced if the distance of the wind farm from the coast is lower than 12 nautical miles. Therefore, the amount of cycles per year is calculated based on the difference between the volume and output capacity, and a factor to account for the fact that only a fraction of these maximum cycles will probably be achieved. For the current configuration of 6 MWh battery volume and 4 MW battery power, an estimation of 1825 cycles per year was found. Eventually, an estimate for the yearly cost of seabed rental of €10,731 was established.

Then, the possibility for the stakeholder is left open to fill in a yearly insurance cost. Due to the novelty of the innovation, and the fact that not a single --Innovation-- has been fully operational so far, it is hard to estimate a correct number for this cost component. Therefore, it is not wise to make a wild guess which resulted in the decision to leave this option open.

Finally, a periodic connection tariff makes up the last part of the operational expenditures. Compared to the insurance cost, a first estimate of this cost component has been established based on the periodic connection tariff of Liander for 2MVA – 5MVA users and generators which is €660 per month, ending up at a yearly tariff of €7,920. Fortunately, --Company-- will most likely avoid yearly transmission costs as Liander clearly states that such costs are only incurred for electricity users instead of also producers.

3.8.2 Maintenance expenses

Maintenance expense are the second category of expenses which the --Innovation-- will face during its entire life span. They can be characterized as periodic expenses that occur after a certain interval when the system is does not function according to a desired level of performance anymore. Generally, there are four types of maintenance activities which each

have their own cost patterns. These are: corrective maintenance, preventive maintenance, predictive maintenance, and revision maintenance [45]. It has been determined that from these four types the revision maintenance strategy will be used for the maintenance operations of the --Innovation--. This is a maintenance strategy which performs periodic long-term maintenance operations for the most important equipment. The choice for this type of strategy instead of for instance a predictive or preventive maintenance strategy stems from the fact that the system will not be met with strict policies for the continuous running of equipment, as in the case with large power plants that ought to function uninterruptedly. After talks with the CTO of the company, it was established that every five years a revision maintenance for the turbine, generator, transformer, and valve will be undertaken.

Therefore, revision maintenance data was obtained from a system of five 200MW PHES units working simultaneously at the same location [45]. The calculation for the total cost is scaled down and corrected for the --Innovation--'s system and maintenance operations specificities when calculations are performed for acquiring the total maintenance cost as a TCO cost characteristic. On top of this, costs are added for hiring a maintenance vessel (in this case a dive support vessel) as one marine operations is necessary for each --Innovation-- system with regard to maintenance.

The total maintenance cost for a life cycle of 20 years can hence be calculated according to the following formula:

$$T = \{5, 10, 15, 20\}, C_{\text{maintenance}} = \sum_{t=T} C_{\text{labor},t} + C_{\text{material},t} + C_{\text{generation loss},t} + C_{\text{marine operation}}$$

As the cost data is obtained for a revision maintenance of five 200MW PHES units, some changes were made to the manner in which the costs were calculated. First, concerning the labor costs, the amount of hours and people required for the revision maintenance per component of one --Innovation-- system were scaled down from the total of five 200MW PHES units towards one single 200MW PHES unit. The reasoning for this stems from the fact that 200MW and 4MW equipment can both be characterized as being large in size, therefore making it unreasonable to scale the labor hours further down towards 4MW.

Next, the material cost were scaled down from the provided data of material cost per 200MW PHES unit towards the 4MW --Innovation-- system. This proved to be justifiable as the cost of such electrical and mechanical components tends to increase linearly with the increasing power capacity.

Lastly, the alteration to the generation loss costs was made for an assumption of two hours of on-site revision maintenance per --Innovation-- system. It is observed in the model that the provided generation loss cost data for the five 200MW PHES units is relatively high. This is caused by the fact that a lot of hours are put into the maintenance of the PHES components, while the system is unable to generate electricity during these hours. For the --Innovation-- system however, the current planned fashion in which maintenance operations will be undertaken is a rapid switch of machine room components by replacing them with fully functional ones, and transporting the components that require revision back to the shore where they will receive their respective maintenance. Hence, this requires considerably less time on-site, and therefore a smaller generation loss cost. The costs are eventually calculated by first scaling down the generation loss cost figure from the total of one 200MW PHES unit towards the 4MW --Innovation--. Then, this number is divided by the required number of hours of revision maintenance of the corresponding components of the complete 1000MW PHES installation, and finally this number is multiplied by the “revision time on-site” input variable, which is two hours as assumed.

The total maintenance cost of each subcomponent in the current --Innovation-- system settings is depicted in Figure 14. Due to limits of space within the figure, each sub component has been assigned a number. These are:

1. Generator maintenance cost
2. Warning transformer maintenance cost
3. Current transformer maintenance cost
4. Voltage transformer maintenance cost
5. Main power transformer maintenance cost
6. Internal transformer maintenance cost
7. Butterfly valve maintenance cost
8. Turbine maintenance cost

Peculiarly, a relatively large maintenance cost is observed for the generator compared to the other machine room components. This is most likely brought about by a significantly larger amount of labor hours required for the successful revision of the generator component.

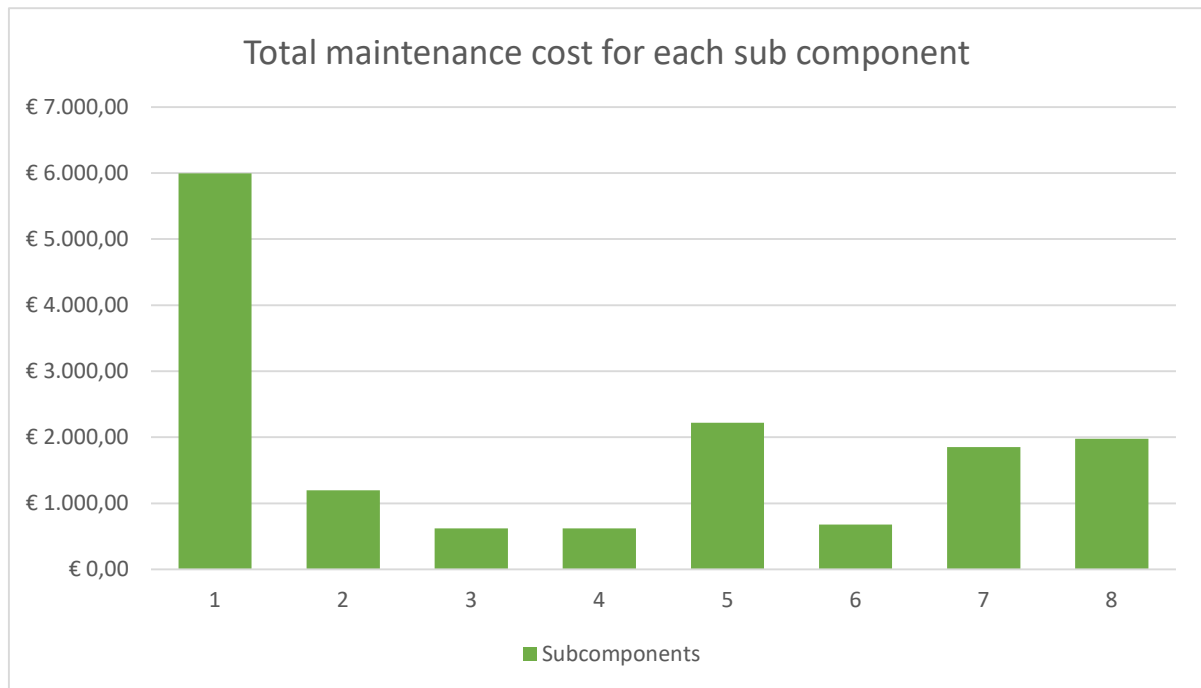


Figure 14: Maintenance cost for each sub-component

Finally, transportation costs are added based on the daily vessel rate of a dive support vessel, as it was concluded by the COO of the company that such a vessel is best suited for this type of operation. As in the case of the installation costs, this cost factor makes use economies of scale benefits if more systems are visited during the same day of vessel rent.

3.9 Decommissioning & Disposal

The final cost category that ought to be calculated to obtain a reasonable value for the TCO are the costs for decommissioning and salvage value for disposal. Both of these categories are incurred at the final phase of the life cycle of the --Innovation--. Decommissioning costs are those costs incurred during the operation in which the system is removed from its location after its successful useful life time. Interestingly, the process of disposal is the only category in which revenue is collected instead of the payment of costs. These revenues are obtained due to the salvage value of the decommissioned components and materials.

3.9.1 Decommissioning costs

First, the structure ought to be decommissioned after its final operational year has expired. This constitutes a single marine operation in which a single dive support vessel will venture out to the destined location, and remove the components of the machine room and the first

two meters of shaft that resides below the sea surface level. This exact number of two meters was suggested by the COO of the company itself. Besides, it is assumed that two hours are need for a single decommissioning operation on-site.

For the cost calculation of the decommissioning operation, economies of scale benefits ought to be obtained, just as in the case of the marine operations performed within the installation phase. Hence, the model takes this into account by rounding up the fraction of days calculated to a whole number of days, as it seems rational that vessels are hired according to a vessel day rate. Hereby, *ceteris paribus* economies of scale benefits can be achieved for up until 10 simultaneous unit.

3.9.2 Disposal revenues

As discussed in the introduction of this subchapter, during the decommissioning part the structure is removed as it does not provide the required functional capacity anymore. After discussing this operation with the CEO and COO of the company, it was concluded that the components in the machine room and the first two meters of the shaft above the water surface ought to be removed due to obligations by corresponding decommissioning legislation. These can fortunately all be salvaged independently. It should be noted that for the calculation of the salvage values revenue parameters per kg of respective material were obtained from KH-metals [31].

Moreover, it was concluded by the CTO of the company that the total weight of the shaft that ought to be removed is constructed with approximately 125 tons of steel. In talk with the CTO it was concluded that all shaft material until two meters below sea surface should be removed. This corresponded to a total shaft length of five meters as a total of three meters will reside above surface. In the model, the total length above the water can be altered within the total of requirements tab. The eventual salvage value of this steel was calculated to be €27,500 based on the value of scrap steel per kilogram.

Then, after extensive research, it was established that a large portion of the materials used in the components of the machine room have their specific salvage value. For the salvage value of a worn-out Francis turbine of 4 MW, a salvage value of €21,754 was calculated. This value is based on the salvage value of 9,888 kilograms of stainless steel for a 2MW Francis turbine [64], multiplied by a scaling factor towards the --Innovation--'s power output.

Then, for the salvage value of the generator, copper values of a permanent magnet generator were used as reference material. The choice for the adoption of this type of generator stems from its popular use in offshore wind turbine applications. This is mainly thanks to a reduction in size as the incorporation of a gearbox is eliminated, thereby decreasing the generator's weight [50, 24, 65]. On top of this, they use a more reliable and simpler design that allows them to be more efficient, operate at lower speeds, and require less maintenance [41]. Furthermore, Table 8 reveals material intensities of a 1MW permanent magnet generator [25]. Reviewing the list, it may seem unreasonable at first to only consider the copper's salvage value. Neodymium and dysprosium are however rare earth materials, and it is known that less than one percent of rare earth material is recycled [1]. Besides, iron is considered a ferrous metal, which is not worth enough per kg for salvage values to make an effective difference on the total amount salvaged. Therefore, the eventual salvage value of the permanent magnet generator in the model obtains a value of €116,560, and is calculated by multiplying the salvage value of 4,700 kilograms of copper by a scaling factor towards the power capacity of the --Innovation--.

Material	Intensity (kg)
Neodymium	200
Dysprosium	13.33
Iron	76,600
Copper	4,700

Table 8: 1MW permanent magnet generator material intensities

Finally, the salvage value for the transformer was established with the help of additional reference literature on the material intensities of the different components of a 1.25MW generating capacity wind turbine [8]. It was established that 3,600 kg scrap steel and 1,600 kg copper can be salvaged for a transformer operating at this capacity. Hence, for the total salvage value of the --Innovation-- transformer, these values have been scaled down towards the power capacity of the --Innovation-- system, and subsequently multiplied by the salvage value per kg of both materials. Eventually, a total salvage value of €34,278 was obtained. It is concluded in the current stings that therefore the total salvage value of the --Innovation-- system is €200,092. This value will eventually be discounted with a discount factor corresponding to the final operational year of the battery, and subtracted from the final TCO costs.

3.10 Total cost of Ownership (TCO)

After each cost component has successfully been calculated, one can observe the final outcome of the model in terms of the Total Cost of Ownership. The incurred costs are categorized according to the type of cost and the time period in which the cost occurs. The time period is set according to the life cycle parameter in the Basic Inputs tab, and thereby changes the manner in which some costs are incurred. Specifically, if the life cycle is set to 30 instead of 20 years, the total decommissioning and disposal costs that always occur in the final year, will be discounted by a larger discount factor. On top of this, one can use the slider in the top left to choose between a depiction of the lower bound, middle bound, or upper bound costs for the pre-development & Consenting and procurement costs.

For the calculation of the Total cost of Ownership, the incurred costs for every time period are summed up first and subsequently discounted by the corresponding discount factor of that time period. For the calculation of the discount factor of each specific time period, the following formula is used:

$$\text{Discount factor } t = (1 + d)^t$$

Here, d corresponds to the general discount factor with no additional time period calculation which one assumes to be a certain percentage in the basic input parameters tab.

Furthermore, two cost depictions require extra elaboration on their specific depiction within the overview. First, the maintenance costs are depicted according to the specified revision maintenance interval parameter that one can change in the Operation & Maintenance tab and takes a value between three and seven years. Hereby, the maintenance cost occur every X years for the remainder of the amount of time periods t . Moreover, the disposal revenue numbers are depicted in green color, denoting the opposite of costs. Hence, they are subtracted from the total costs of that specific time period.

To summarize the TCO per category, one is referred to Figure 15-18 and Table 9. These represent the absolute discounted cost per cost category, the relative discounted costs per cost category, and a legend for explaining the color differences. Most noticeable is the fact that the Procurement cost category is the highest for both --Innovation-- system types by a large margin. As mentioned in the paragraph discussing Procurement, this is caused largely by the high costs for the different steel components and the steel shaft. Moreover, for the --Version 1-- --Innovation-- design, the installation costs make up for a significant relative margin of the total cost by 21 percent, even though it still seems far away from the total Procurement cost.

This is for the cheap option in which tug vessels are chosen for the step in which the concrete reservoir is installed, hence the total cost could end up higher if the company does decide to opt for the heavy transport vessel here. Furthermore, total discounted Pre-development & Consenting cost comes at respectively 14 and 11 percent of the total TCO for the --Version 1-- --Innovation-- system and the --Version 2-- --Innovation-- system, and may therefore be seen as another cost component that affects the TCO in a significant way. Interestingly, the total discounted Assembly and Operation & Maintenance cost are relatively small.

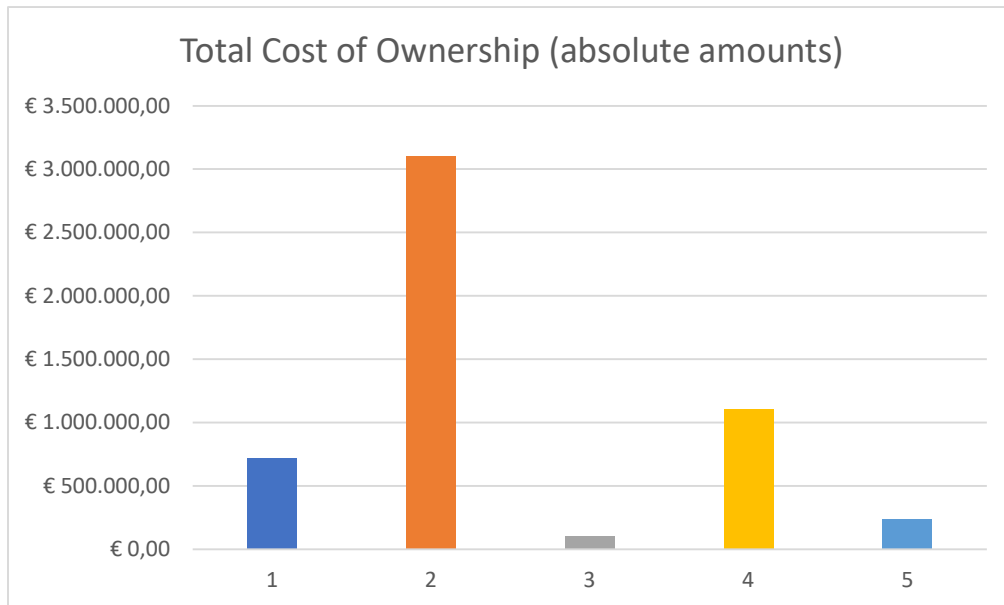


Figure 15: Total absolute discounted cost per cost category for the --Version 1-- --Innovation-- system

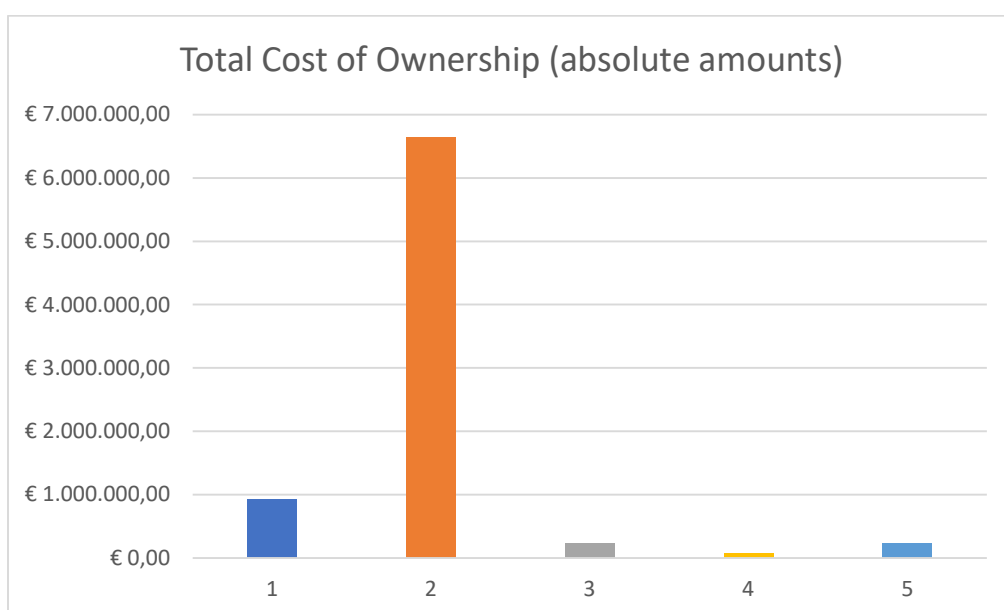


Figure 16: Total absolute discounted cost per cost category for the --Version 2-- --Innovation-- system

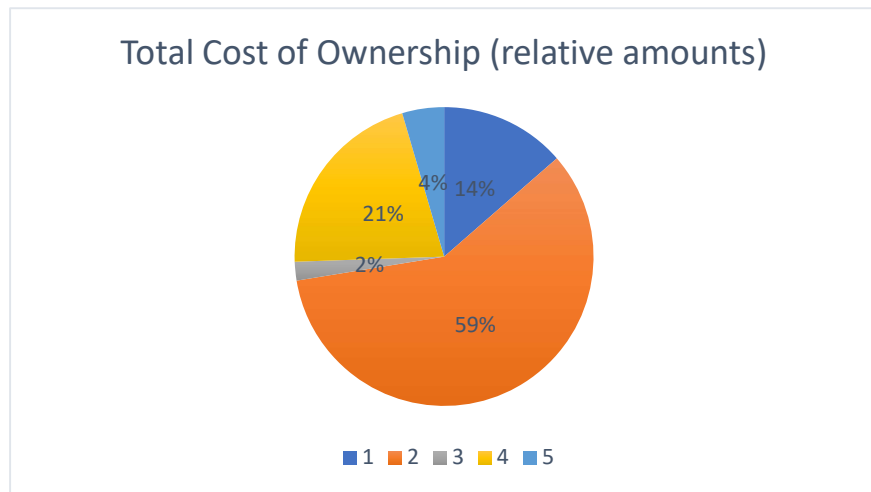


Figure 17: Total relative discounted cost per cost category for the --Version 2-- --Innovation-- system

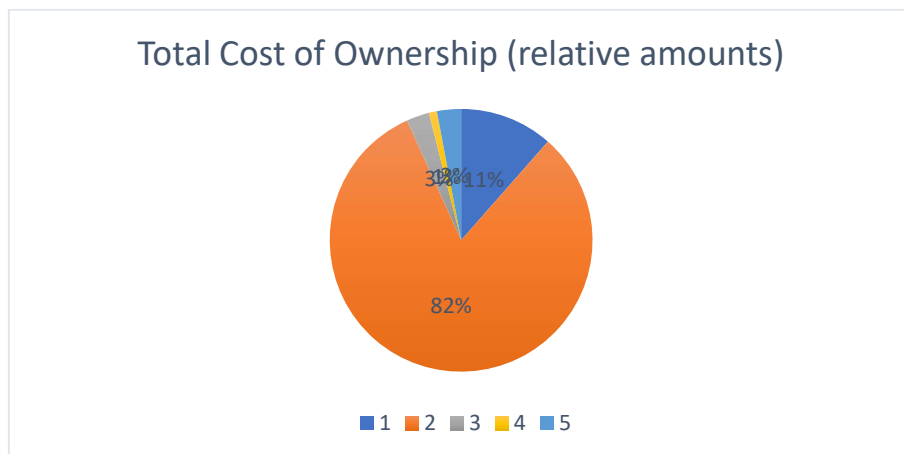


Figure 18: Total relative discounted cost per cost category for the --Version 2-- --Innovation-- system

Legend:		
1	=	Pre-development & Consenting
2	=	Procurement
3	=	Assembly
4	=	Installation & Commissioning
5	=	Operation & Maintenance

Table 9: Legend for Figures 12-15

4. Sensitivity analysis

As noticed so far, the TCO model is established for a comprehensive analysis of the eventual TCO output for a given set of input parameters. Therefore, an easy comparison between criticality of these different parameters is one of the main functionalities of the model. To provide a set of insights in this regard, the following chapter provides three sets of sensitivity matrices for a given combination of changing input parameters, applied to both --Innovation-- system types. These combinations are opted for as due to their dynamic impact on the eventual TCO output. Hence, the following combinations are elaborated upon in the following subchapters:

- Power capacity [MW] & Volume capacity [MWh] □ Total Cost of Ownership (TCO)
- Distance wind farm [km] & Economies of scale [#] □ Total Cost of Ownership (TCO), single unit
- Life cycle [years] & Revision maintenance interval [years] □ Total Cost of Ownership (TCO)

4.1 Power Capacity (MW) & Volume Capacity (MWh)

The first two input parameters that receive a combined sensitivity analysis is the combination of Power Capacity (MW) and Volume Capacity (MWh). The combination of these is opted for due to their combined effect on the functionality of the system, and thereby the material dimensions for it to function as required. This directly affects the first three chronological cost categories in the cost calculation of the eventual TCO value, and hence has considerable criticality on the eventual output value. In Table 10, the sensitivity for both of these parameters on the change in the corresponding TCO is observed. From a glance one already observes considerably large variance in output cost value. For the --Version 1-- --Innovation-- system, the top horizontal row experiences a total change in output value of 32.4 percent, while the most left vertical column experiences this in an even greater fashion by a total shift of 73.3 percent. On top of this, if one considers the total diagonal change from the top left until the bottom right of the matrix, a total change of 104.2 percent is experienced. On the other hand, an even greater effect can be observed with regard to the impact on the changing TCO values for the --Version 2-- design as observed in Table 11. Here, the total change in the top row corresponds to 26.4 percent, while a somewhat gigantic effect is observed for the most left column and the total diagonal change with respectively 240.6 and 270.6 percent. This difference is as expected, as larger material volumes are taken into account for each value of volume input for the --Version 2-- design, which directly affects the largest TCO cost

category: Procurement. From this, it can be concluded that these input parameters can be considered critical with regard to their impact on the eventual TCO value, and therefore ought to receive significant consideration in setting their required value, especially for the total Volume Capacity.

<i>--Version 1-- --Innovation-- system</i>								
Total Cost of Ownership (TCO)		Power Capacity (MW)						
		1	2	3	4	5	6	7
Volume Capacity (MWh)	2	€3,610,220	€3,805,456	€4,000,692	€4,195,929	€4,391,165	€4,586,401	€4,781,637
	4	€4,007,976	€4,203,212	€4,398,448	€4,593,685	€4,788,921	€4,984,157	€5,179,393
	6	€4,559,022	€4,768,503	€4,956,628	€5,144,754	€5,354,235	€5,542,360	€5,730,486
	8	€4,937,793	€5,133,037	€5,328,281	€5,523,525	€5,718,769	€5,914,013	€6,109,257
	10	€5,502,730	€5,705,093	€5,871,864	€6,074,226	€6,276,588	€6,478,951	€6,681,313
	12	€5,816,262	€5,983,041	€6,192,530	€6,402,018	€6,568,797	€6,778,286	€6,987,774
	14	€6,221,262	€6,388,041	€6,604,648	€6,771,427	€6,988,034	€7,154,813	€7,371,420

Table 10: Power capacity [MW] & Volume Capacity [MWh] sensitivity analysis – --Version 1-- --Innovation-- system

<i>--Version 2-- --Innovation-- system</i>								
Total Cost of Ownership (TCO)		Power Capacity (MW)						
		1	2	3	4	5	6	7
Volume Capacity (MWh)	2	€4,430,278	€4,625,514	€4,820,750	€5,015,986	€5,211,222	€5,406,458	€5,601,694
	4	€6,232,008	€6,427,245	€6,662,481	€6,817,717	€7,012,953	€7,208,189	€7,403,425
	6	€8,027,376	€8,236,856	€8,424,982	€8,613,108	€8,822,588	€9,010,714	€9,198,840
	8	€9,838,473	€10,033,717	€10,228,961	€10,424,205	€10,619,449	€10,814,693	€11,009,937
	10	€11,647,408	€11,849,770	€12,016,541	€12,218,903	€12,421,266	€12,623,628	€12,825,990
	12	€13,459,517	€13,626,296	€13,835,784	€14,045,273	€14,212,052	€14,421,540	€14,631,029
	14	€15,268,538	€15,435,316	€15,651,923	€15,818,702	€16,035,309	€16,202,087	€16,418,695

Table 11: Power capacity [MW] & Volume Capacity [MWh] sensitivity analysis – --Version 2-- --Innovation-- system

4.2 Distance Wind Farm [km] & Economies of scale [#]

The second set of input parameters that receive their unique set of sensitivity analyses, is the combination of Distance to the wind farm [km] and Economies of Scale [#]. Much has been discussed on the significance of the Economies of Scales parameter so far, and therefore it is vital to opt for this parameter in testing its criticality. This is done in combination with the distance to the wind farm as both parameters bring about their effect in the Installation part of the cost analysis. It would therefore be interesting to reveal their dynamic interplay and evaluate the insights from this. Hence, Table 12 and Table 13 depict this again for both the --Version 1-- and --Version 2-- --Innovation-- system. A first peculiarity that is notices, is the fact that TCO is the highest if the lowest distance of 20 km is opted for in all cases of given Economies of Scale values. After inferring the reasoning for this, it was found that this is caused by the hard border of 12 nautical miles in paying yearly cost of seabed rental. Hence, the depicted 20 km values for the distance from shore to the wind farm, are the only ones in the given matrix in which yearly cost of seabed rental is not paid. Hereby, the shortest specified distance is the one in which the highest TCO values are observed for all values of Economies of Scale in both the --Version 1-- and --Version 2-- example. Though, it should be noted that the parameter in essence has no significant absolute or relative impact on the overall TCO value. Moreover, large decreasing TCO values are observed for changes in the Economies of Scale parameter from 1 to 20 for both the --Version 1-- and --Version 2-- design. These are respectively decreasing values of around 50 and 20 percent. The difference between these numbers is brought about by the impact the parameter has on the cost of installation, which was a considerable factor in the total TCO build-up of the --Version 1-- --Innovation-- system due to its larger amount of required marine operations. Finally, although the Distance to the wind farm parameter is met with little unique impact on TCO itself, its impact does become larger for larger values of the Economies of scale parameter. Specifically, while for an Economies of Scale set at a value of 1, the distance parameter only increases TCO by 0.8 percent if distance is increased from 40 to 140 km. This impact rises to 2.5 percent for the same distance increase if an Economies of scale value of 20 is opted for.

--Version 1-- --Innovation-- system								
Total Cost of Ownership (TCO), single unit		Distance wind farm [km]						
		20	40	60	80	100	120	140
Economies of scale [#]	1	€5,144,754	€5,037,979	€5,037,979	€5,037,979	€5,077,979	€5,077,979	€5,077,979
	4	€3,036,122	€2,939,348	€2,958,098	€2,958,098	€2,968,098	€2,986,848	€2,996,848
	7	€2,740,856	€2,662,653	€2,679,082	€2,684,796	€2,701,225	€2,717,296	€2,728,010
	10	€2,669,923	€2,577,898	€2,585,898	€2,597,398	€2,612,898	€2,624,398	€2,632,398
	14	€2,580,021	€2,484,317	€2,495,389	€2,517,889	€2,528,960	€2,542,889	€2,553,960
	17	€2,567,674	€2,472,370	€2,483,546	€2,495,107	€2,506,487	€2,517,958	€2,531,340
	20	€2,536,122	€2,439,097	€2,452,472	€2,463,972	€2,475,722	€2,487,222	€2,498,972

Table 12: Distance wind farm [km] & Economies of Scale [#] sensitivity analysis – --Version 1-- --Innovation-- system

--Version 2-- --Innovation-- system								
Total Cost of Ownership (TCO), single unit		Distance wind farm [km]						
		20	40	60	80	100	120	140
Economies of scale [#]	1	€8,613,108	€8,506,333	€8,506,333	€8,506,333	€8,546,333	€8,546,333	€8,546,333
	4	€7,264,129	€7,167,355	€7,177,355	€7,177,355	€7,187,355	€7,197,355	€7,207,355
	7	€7,073,277	€6,972,217	€6,983,645	€6,989,359	€7,000,788	€7,016,859	€7,022,574
	10	€6,998,237	€6,902,713	€6,910,713	€6,918,713	€6,930,713	€6,938,713	€6,946,713
	14	€6,951,753	€6,853,549	€6,862,121	€6,870,692	€6,879,264	€6,890,692	€6,899,264
	17	€6,930,971	€6,833,608	€6,840,667	€6,850,079	€6,859,490	€6,868,902	€6,880,225
	20	€6,917,074	€6,818,300	€6,829,924	€6,837,924	€6,847,924	€6,855,924	€6,865,924

Table 13: Distance wind farm [km] & Economies of Scale [#] sensitivity analysis – --Version 2-- --Innovation-- system

4.3 Life cycle [years] & Discount rate [%]

The last set of input parameters that receive a sensitivity treatment is the combination of Life Cycle [years] and Discount rate [%]. The combination was opted for as the discount rate affects the incurred cost in each year, while this amount of years is set according to the amount of predicted life cycle years, and the results can be observed in Table 14 and Table 15. Peculiarly, as the amount of life cycle years increases the TCO value reaches a higher value in the --Version 1-- design example as expected, while a lower value is reached in the --Version 2-- example. This is brought about by the contingencies costs in the Pre-Development & Consenting cost part. This figure is a percentage of the procurement cost that is shared in equal amounts over the amount of life cycle years chosen. This implies that the present value of the total contingency costs is lowered for each added extra life cycle year. Hence, the present value of contingency costs is lowered by a larger absolute amount for the --Version 2-- Design for every year in life cycle added as procurement costs are significantly higher for this design type. Simultaneously, the rise due to extra life cycle years in Operation & Maintenance and Decommissioning & Disposal cost is similar for both designs and equals an amount larger than the present value of contingency costs for the --Version 1-- design, while a smaller amount is reached for the --Version 2-- Design. Hence the differing pattern in TCO for the specified sensitivity matrices. Ultimately, it is concluded from the graphs that both the amount of life cycle years and discount rate have little impact on the eventual TCO value as the --Version 1-- design reveals a diagonal decline of 0.9 percent, while the --Version 2-- design reveals a decline of 1.5 percent.

<i>--Version 1-- --Innovation-- system</i>							
Total Cost of Ownership (TCO)		Life cycle [years]					
		20	22	24	26	28	30
Discount rate [%]	8%	€5,180,266	€5,184,956	€5,193,388	€5,195,868	€5,201,158	€5,202,128
	8.5%	€5,169,735	€5,173,476	€5,180,526	€5,182,192	€5,186,312	€5,186,608
	9%	€5,159,665	€5,162,537	€5,168,338	€5,169,275	€5,172,361	€5,172,068
	9.5%	€1,150,033	€5,152,107	€5,156,784	€5,157,067	€5,159,242	€5,158,433
	10%	€5,140,816	€5,142,160	€5,145,822	€5,145,522	€5,146,892	€5,145,636
	10.5%	€5,131,992	€5,132,669	€5,135,416	€5,134,596	€5,135,258	€5,133,612

Table 14: Life cycle [years] & Discount rate [%] – --Version 1-- --Innovation-- system

<i>--Version 2-- --Innovation-- system</i>							
Total Cost of Ownership (TCO)		Life cycle [years]					
		20	22	24	26	28	30
Discount rate [%]	8%	€8,661,852	€8,654,629	€8,652,138	€8,644,589	€8,640,656	€8,633,131
	8.5%	€8,644,520	€8,636,280	€8,632,390	€8,624,051	€8,619,003	€8,610,886
	9%	€8,628,019	€8,618,872	€8,613,744	€8,604,772	€8,598,717	€8,590,109
	9.5%	€8,612,301	€8,602,346	€8,596,125	€8,586,517	€8,579,692	€8,570,680
	10%	€8,597,319	€8,586,648	€8,579,465	€8,569,356	€8,561,831	€8,552,490
	10.5%	€8,583,033	€8,571,728	€8,563,700	€8,553,164	€8,545,045	€8,535,442

Table 15: Life cycle [years] & Discount rate [%] – --Version 2-- --Innovation-- system

5. Fluctuation analysis

For a more in-depth look at the critical elements of the constructed model, a fluctuation analysis was conducted on the Procurement cost of the different components of both --Innovation-- system designs, as it was shown that Procurement is highly critical in the sensitivity analysis. The fluctuation analysis takes into account a lower and upper bound of each component cost based on a fluctuation in price, as calculated for all raw materials in Appendix B, and a cost fluctuation due to changes in component dimensions. Specifically, for both --Innovation-- system designs, a dimensional cost fluctuation was calculated for the eight components that reveal the largest criticality in terms of price. For the --Version 1-- --Innovation-- system design, these are the following from highest to lowest price criticality:

1. Shaft
2. Rigid reservoir
3. Francis Turbine
4. Steel ribs
5. Steel base
6. Dumpstones
7. Generator
8. Bladder material

Furthermore, the --Version 2-- design is met with the following eight components cost for which a dimensional cost fluctuation was calculated:

1. Steel ribs
2. Shaft
3. Steel base
4. Rigid reservoir
5. Francis Turbine
6. Bladder material
7. Pumps
8. Generator

For the dimensional cost fluctuations, each component receives a treatment in which one component dimension is changed in size on the order of $\pm 50\%$. These are specifically depicted in Table 16 and the results on the absolute fluctuation of these given cost components is depicted in Figure 19 and Figure 20 for respectively the --Version 1-- and --Version 2-- --Innovation-- systems.

Cost category	Dimensional fluctuation treatment
Shaft	$\pm 1\text{cm}$ thickness Shaft
Rigid reservoir	± 1 unit safety thickness
Francis Turbine	$\pm 2\text{MW}$ power capacity
Generator	$\pm 2\text{MW}$ power capacity
Steel ribs	$\pm 0.01\text{m}$ thickness ribs
Steel base	$\pm 0.015\text{m}$ thickness skirt and plate
Dumpstones	± 750 tons dumpstones per row
Bladder material	$\pm 0.005\text{m}$ thickness rubber
Pumps	± 5 pieces

Table 16: Treatment overview dimensional fluctuations

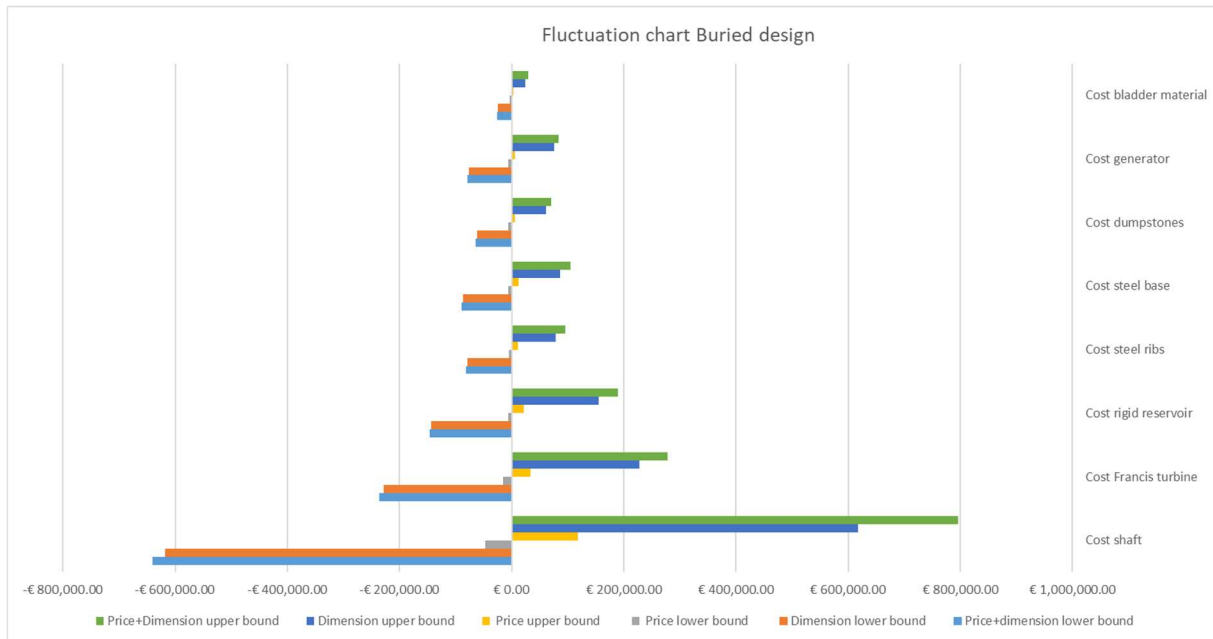


Figure 19: Fluctuation analysis --Version 1-- --Innovation-- design

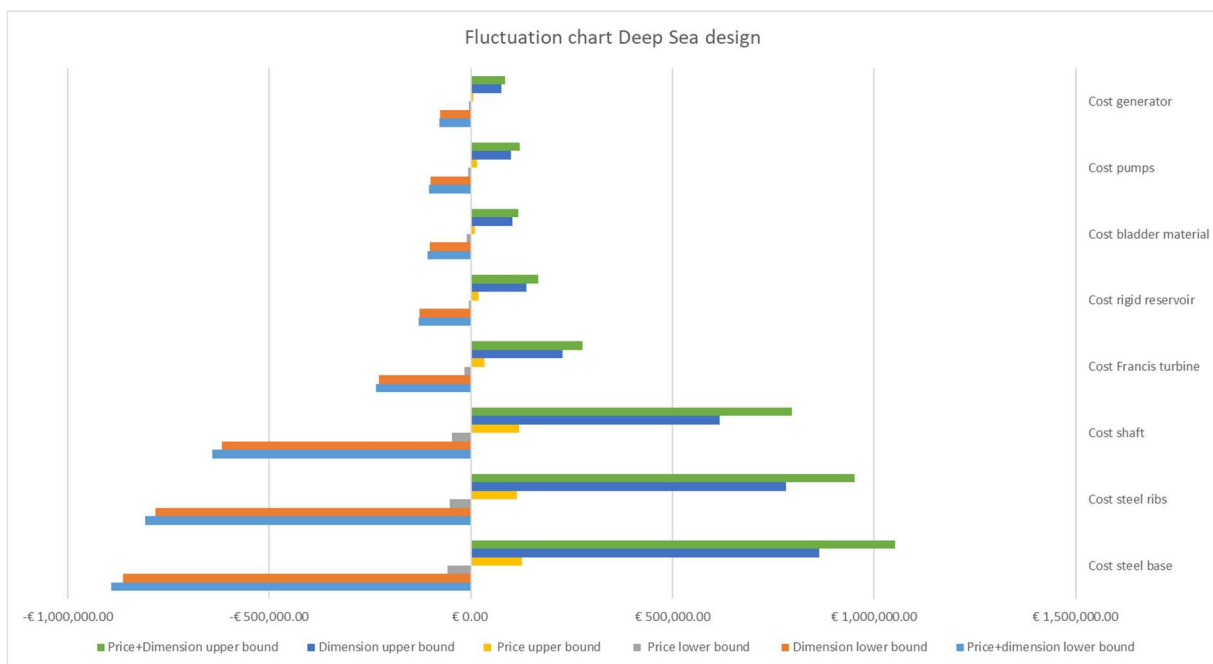


Figure 20: Fluctuation analysis --Version 2-- --Innovation-- design

By observing the figures, different fluctuations depicted by different colors are observed. From the largest negative fluctuation to the highest positive fluctuation, these depict fluctuations in which only the price specific, only the dimensional, or price specific and dimensional simultaneously play a role. Hence, a total of six fluctuation bars per subcomponent are observed.

From the overview of --Version 1-- design fluctuations, it is found that the shaft plays a critical role in its criticality with regard to cost fluctuation. If a change towards a lower bound price and a decrease of 1cm thickness occur simultaneously, one observes a decrease in total shaft cost of more than €600,000, while this number corresponds to an increase in the price of around €800,000 if these forces work the other way around. Hence, for the --Version 1-- --Innovation-- design, this component can be regarded as critical.

Furthermore, with regard to the --Version 2-- --Innovation-- system, the steel base and ribs can also be regarded as critical cost components. As discussed in the Procurement section, these costs are tenfold for the --Version 2-- design, hence this gigantic increase is not left out in the part of cost fluctuation. Hence, for the steel base, steel ribs, and shaft a lower bound cost decrease of respectively €900,000, €800,000, and €650,000 is observed, while a total upper bound increase of respectively €1,050,000, €950,000, and €800,000 is observed.

6. Discussion

The TCO model was established to obtain a comprehensive analysis of all costs incurred over the entire lifetime of the --Innovation-- system. This was undertaken with the goal of depicting the cost-competitiveness of both systems in mind, so that a clear comparison with competitors would be possible. Therefore, with the best of available methodologies and insights, an attempt was made to obtain clear indications of the different cost categories, while staying away from estimations based on percentages of other cost categories as much as possible. This was for instance the case in the work of Dijkstra, in which percentages of the Procurement costs were utilized for obtaining Maintenance and Decommissioning estimates. The tool created in this research however, only used percentages of other cost in estimations of the incurred costs in the Pre-Development & Consenting phase. Besides, Dijkstra also suggested the consolidation of different marine operations within the installation phase as an opportunity for future work, and the established model within this research takes that into account by adding the option to model economies of scale benefits within especially the Installation cost category.

From the depiction of results for both the --Version 1-- --Innovation-- system and the --Version 2-- --Innovation-- system, it was observed how Procurement costs brings about the largest portion of TCO costs with respectively 59 and 82 percent for the --Version 1-- and --Version 2-- --Innovation-- system design. This is mainly caused by the material costs of the

rigid reservoir, as it is planned to use steel for the shaft, and stainless steel for a handful of other subcomponents of the reservoir itself. This again was revealed in the sensitivity analysis, in which a changing value of the volume capacity output that directly affects the rigid reservoir dimensions, had the largest criticality with regard to the rising TCO output value. On top of this, the steel components also revealed the largest criticality in the fluctuation analyses for both the --Version 1-- and --Version 2-- --Innovation-- systems.

Moreover, in an attempt to strike a comparison to competitive technologies, Table 17 provides reference material table that provides a percentage figure of the yearly Operation & Maintenance cost as a percentage of CAPEX for each specific technology. For the --Version 1-- and --Version 2-- --Innovation-- systems, these are as discounted values respectively 0.28% and 0.17% of the cost. In comparison with competing bulk technologies, the percentages are significantly lower which should come as good news, though higher percentages are met if the --Innovation--'s Operation & Maintenance cost not discounted. Furthermore, it would be wise to perform simulation study research to retrieve a more accurate picture and optimize the maintenance cost of each specific --Innovation-- system design type in a later stage of their commercial life. Such analyses have been performed for instance in the offshore wind energy industry [16, 53].

Input Data		Gravity Storage	Pumped hydro	Compr. air	Lithium-ion	Sodium-sulfur
System size: 1 GWh / 0.125 GW						
Capex - energy	\$/kWh	337	220	15	278	298
Capex - power	\$/kW	692	1,349	896	282	454
System size: 2 GWh / 0.250 GW						
Capex - energy	\$/kWh	229	178	14	263	298
Capex - power	\$/kW	609	1,267	729	250	426
System size: 5 GWh / 0.625 GW						
Capex - energy	\$/kWh	139	134	12	245	298
Capex - power	\$/kW	547	1,166	554	213	392
System size: 10 GWh / 1.250 GW						
Capex - energy	\$/kWh	96	109	11	232	298
Capex - power	\$/kW	523	1,094	451	189	368
O&M cost	%	0.30%	0.31%	0.36%	1.38%	0.88%
Replacement cost	\$/kW	25	112	90	-	-
EoL cost	\$/kWh	-	-	-	-	-
Discharge duration	hours	8	8	8	8	8
Depth of discharge	%	100%	100%	100%	80%	80%
Cycle life	#	19,800	21,900	14,600	3,500	5,500
Shelf life	years	60	60	40	10	15
Round-trip efficiency	%	80%	80%	42%	81%	75%
Degradation	% pa	0%	0%	0%	-3%	-2%
Construction time	years	3.5	5	5	1	2
Replacement interval	years	10	20	4	-	-

Note: Capex represents specific energy and power cost, not total cost in energy / power terms.

Table 17: Technology parameters of competing storage technologies

Lastly, for a clear legitimization of the obtained results a waterfall chart was created to compare the cost build-up of Procurement towards that of older cost models. This was done for both --Innovation-- system designs and the results are depicted in Figures 21 and 22.

In both charts, a handful of large differences in cost-build up are observed. For the --Version 1-- --Innovation-- design, one observes a drop at the part in which costs of the hydro turbine system are compared. This is brought about by the fact that older cost models used a prediction per MW of production, while the current model uses actual online price figures of the different turbine system components, and sums these up to obtain a better grounded estimate. Ultimately, this cost difference is largely offset by the addition of Shaft costs in the current cost-build up, which is an element that was left out in older models.

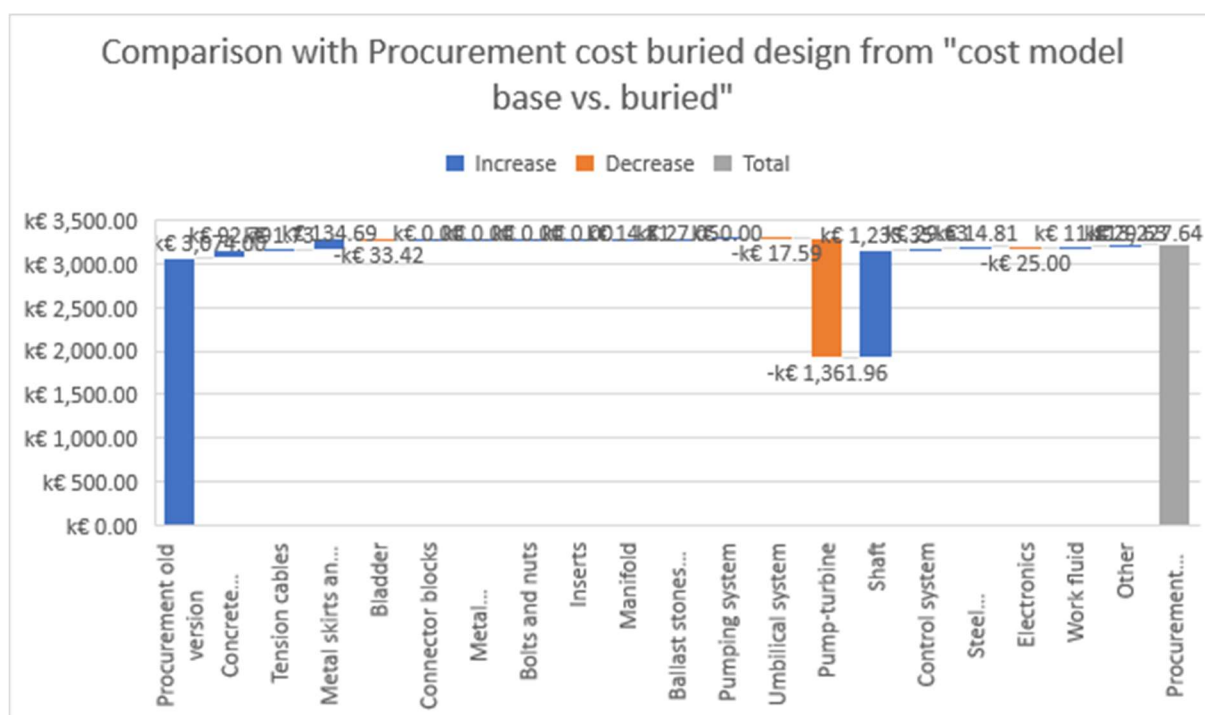


Figure 21: Difference in --Version 1-- design cost build up between the current model and the old model

Then, for the --Version 2-- version of the diagram, a different pattern of peculiar cost differences are observed. First, the cost of metal skirts and suction anchors is higher in absolute terms in the current model. This is for the largest part caused by a larger updated price of stainless steel, but also by larger material requirements over which this price is calculated. These larger requirements are subsequently brought about by a larger rigid reservoir volume as the basic volume and power capacity, and the effective depth are set to larger amounts in the current model. Moreover, the cost difference in the turbine system and shaft follow the same reasoning as in the --Version 1-- --Innovation-- system design, though the older cost model doubles the estimated turbine cost for the --Version 2-- version, though

this estimation was later found to be incorrect. Hence the larger difference. It should be noted that the --Version 2-- design will likely obtain a different configuration to its design than the attachment of a shaft for maintenance operations to become possible. Though shaft costs have been added as the shaft substitute will most likely bring about a large cost factor.

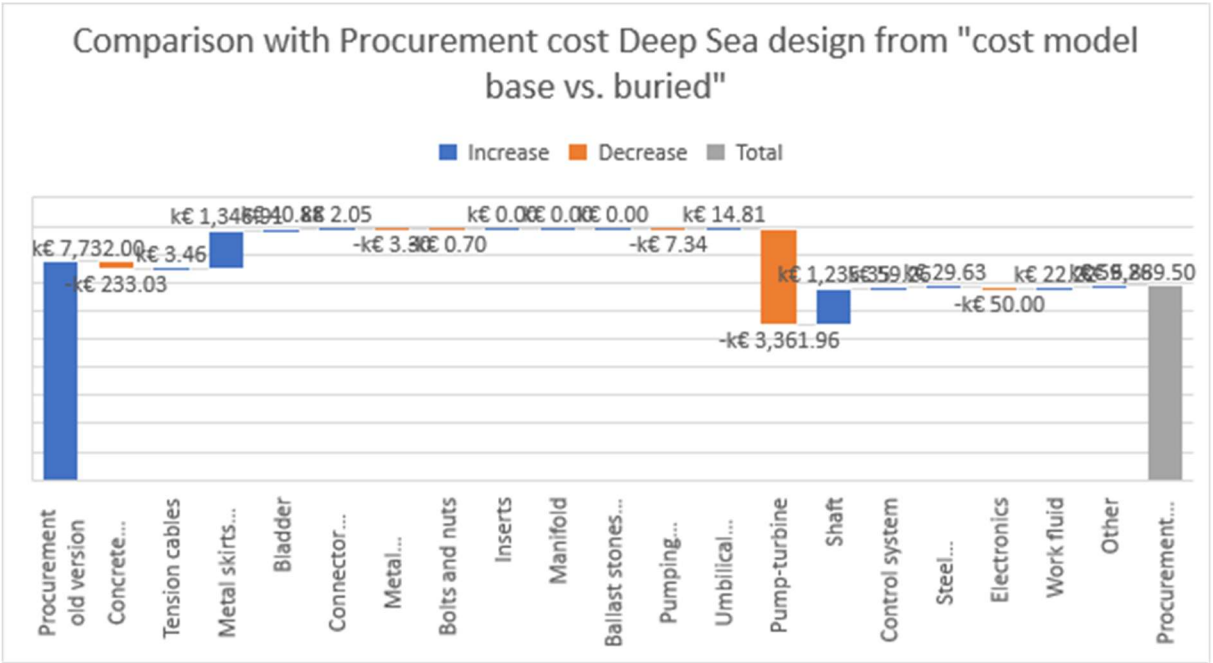


Figure 22: Difference in --Version 2-- design cost build up between the current model and the old model

Ultimately, it is also imperative to provide a similar chart and compare the eventual TCO cost build-up to the model created by Dijkstra. Therefore, Figure 23 provides this for all cost categories incurred over the complete life cycle. First, it is observed how Procurement costs were found to be more than €3 million higher in the current model. This is explained by three specific reasons. Specifically, the fact that Dijkstra implements manufacturing costs, pump costs, and grid connection costs of respectively €1,158,1921, €870,000, and €810,000. Manufacturing costs are first not included as the prices specified in the Procurement tab are based on real-time online prices for specific materials and components, hence manufacturing costs are already included within them. Pump costs are not included as Francis turbines can function as both a hydraulic pump and hydraulic turbine, and a price figure for a Francis turbine is already depicted. Lastly, grid connection costs are not included as there is still too much uncertainty about its tailor made construction for --Innovation-- systems, and therefore pose too much of an uncertainty if included as a cost.

Also, Procurement cost is significantly lower in the current model and Assembly and Installation & Commissioning cost remain relatively unchanged, it is logical to observe a smaller Pre-Development & Consenting cost for the current model as well.

Then, a gigantic difference of more than €9 million is observed in the comparison of Operation & Maintenance costs between both models. Hereby, it seems as if the current cost build-up within this model is unreasonable. This however is not the case. Dijkstra bases his OPEX estimation on that of offshore wind turbines which are met with a larger amount of expensive marine operations, and much larger generation loss cost as turbines could not be running for weeks or months if for instance a transformer needs revision maintenance [22]. Moreover, the current figure has already obtained enough legitimization after it was compared with the OPEX figures of other storage technologies in Table 17, to which the calculated -- Innovation-- value came close to that of its competitors.

Lastly, Dijkstra arrives at a larger Decommissioning & Disposal value. This is caused by his use of a CAPEX fraction in estimating this amount, without paying attention to any possible salvage revenues. It is known that the current model calculates decommissioning costs based on one marine operation, and does take disposal revenues into account. Hence, the difference in estimations.

Finally, external costs are not included in the current cost setup as it is recommended for the company to perform a separate Life Cycle Assessment for this.

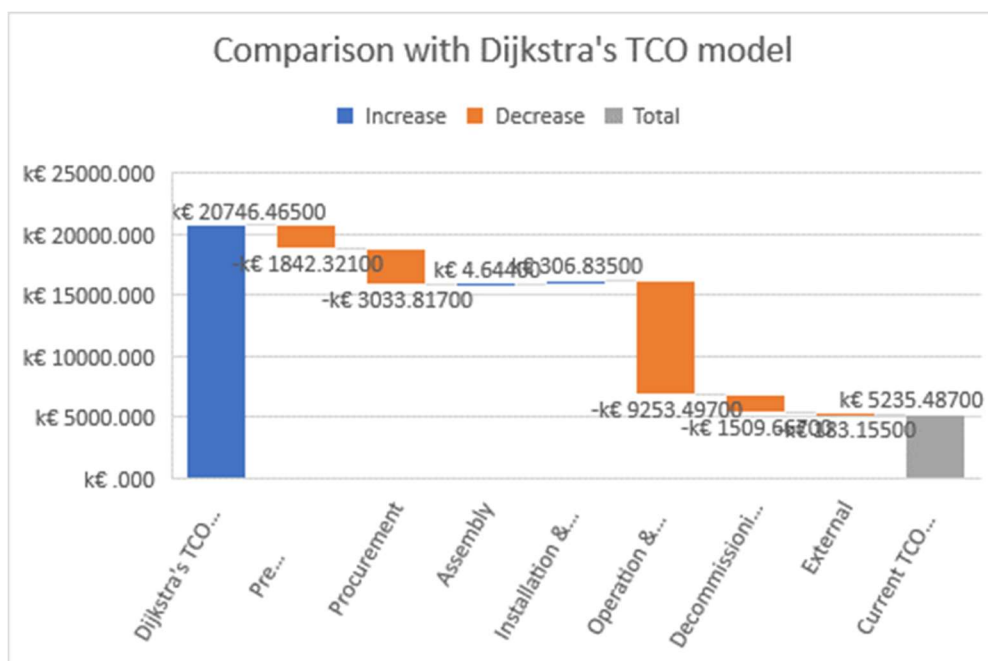


Figure 23: TCO comparison between Dijkstra's model and the current one

7. Conclusion

For the Internship time followed at the company, the requirement was provided for the creation of a Total Cost of Ownership model, in which important changing input parameters would provide an accurate cost prediction of discounted values of the corresponding categories that make up the Total Cost of Ownership (TCO) of the --Innovation--. This was done according to a stepwise approach in which methodologies and insights were gathered for each separate cost category separately, which afterwards were used with the required modelling skills for a comprehensive overview of the incurred cost.

Specifically, during the first step of the process information was gathered on the specificities of the Total Cost of Ownership and its usefulness in different contexts and settings. This information was then taken into account in the second step in which company material, company research, academic literature, and an interview were simultaneously considered for a reasonable manner in which all incurred costs could be computed. Afterwards, the complete collection of insights provided the fruits for enough knowledge from which a cost setup could be established, and the modelling of the tool was undertaken.

It could be concluded that both --Innovation-- system designs provide their unique cost structures that each accompanies a handful of advantages and disadvantages. For the --Version 1-- --Innovation-- design, the overall TCO value is the lower one with a value of around €5.2 million. This seems therefore the better option at first hand, though this ought to be taken with a grain of salt as the calculated installation costs play a reasonable part in the eventual cost make-up. On top of that, during the interview with Boskalis it was emphasized that the estimates of the installation cost category could prove to be incorrect due to several contingencies that may spike the cost. These contingencies are caused by the bigger amount of marine operations for the --Version 1-- --Innovation-- to be successfully installed.

Then, for the --Version 2-- --Innovation-- system, the TCO value is somewhat higher with a value of around €8.1 million. As discussed, these costs are mainly brought about by the excessive capital expenditures which are caused by the extra use of stainless steel in the concrete structure itself. On the other hand, costs incurred in every other step of the Life Cycle are considerably lower which could be seen as an advantage of this system choice.

It should be noted that the creation of the model has not come without its hurdles. It could definitely be stated that better methods apply for the estimation of the different cost categories, though these require the systems to be commercially and use and come with

corresponding data on for instance supplier selection, lot sizes, maintenance strategies, components failure rates etcetera. If such data is available, more extensive research on each type of cost incurred over the complete life cycle can be conducted, and thereby more accurate results can be estimated. An example of this is the management of spare parts and corresponding costs incurred for this [56].

Finally, the research of Emilija Lazdanaitė on the grid composition of the --Innovation-- system could be taken into account for establishing a reasonable cost estimate for such an eventual composition.

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9. Appendix

Appendix A: Source of prices used in Procurement

Name of price parameter	Source
Stainless steel	https://www.alibaba.com/product-detail/TISCO-321-304l-stainless-steel-sheet_60518790192.html?spm=a2700.7724857.normalList.13.6c6561247LKfYg&s=p

Alloy steel	https://www.alibaba.com/product-detail/Alloy-Steel-The-Global-High-Quality_1600210063061.html?spm=a2700.7724857.normal_offer.d_title.3d1f3e9cmhHnd1&s=p
Concrete	Price excel model cost --Version 2-- design
Tension cables	https://www.alibaba.com/product-detail/dyneema-fiber-high-strength-UHMWPE-ROPE_60852339237.html?spm=a2700.7724857.normalList.103.7059611enUqfJI
EPDM	https://www.alibaba.com/product-detail/factory-1-50mm-epdm-rubber-price_60185094591.html?spm=a2700.7724857.normalList.95.290c55f46yNTmb
PVC	https://www.statista.com/statistics/1171131/price-polyvinyl-chloride-forecast-globally/
Synthetic strip	Price excel model cost --Version 2-- design
Bolts	Price excel model cost --Version 2-- design
Inserts	Price excel model cost --Version 2-- design
Pump	Price excel model cost --Version 2-- design
Valve	https://www.alibaba.com/product-detail/Butterfly-Valve-Best-selling-Manual-Nodular_1600234914280.html?spm=a2700.galleryofferlist.normal_offer.d_title.60461e388PZp1s&s=p
Pipe	https://www.alibaba.com/product-detail/Factory-direct-price-20mm-to-1000mm_60820992532.html?spm=a2700.7724838.2017115.1.1bca45152KbYhu
Francis turbine	https://dutch.alibaba.com/product-detail/100kw-500kw-hydroelectric-francis-generator-turbine-for-hydro-power-plant-1600091754770.html?spm=a2700.8699010.29.17.760b454aW83Xrj
Generator	https://www.alibaba.com/product-detail/50kw-500kw-Permanent-Magnet-Generator-5KW_1600219309373.html?spm=a2700.7724857.topad_classic.d_title.675635dcxZkSZw
Transformer	https://www.alibaba.com/product-detail/500kw-Transformer-Outdoor-23KV-3-Phase_1600190796477.html?spm=a2700.7724857.normal_offer.d_title.4b3f351bXeVkyE&s=p
Air pipe	Cost excel model --Version 2-- design
Water pipe	Cost excel model --Version 2-- design

Floater	https://www.alibaba.com/product-detail/Dredge-Floats-HDPE-Pipe-Floater-for_62423191997.html?spm=a2700.galleryofferlist.normal_offer.d_title.7ec3db2bRxAYAH&s=p
Manifold	Cost excel model --Version 2-- design
Geotextile	https://www.alibaba.com/product-detail/HDPE-Geonet-5mm-From-China-Professional_1600251874777.html?spm=a2700.7724857.normal_offer.d_title.66b35daaOhcWBU&s=p
Ballast stones	https://www.aggregatessupplier.com/product/rail-ballast/

Appendix B: Procurement price fluctuations calculation (Double click to open)

Gevoeligheidsanalyse – Ocean battery material costs

De waarschijnlijke prijsfluctuaties van de inkoop materialen is geanalyseerd en berekend op basis van historische data. De variabelen in deze gevoeligheidsanalyse zijn beton, staal, polyethyleen plaat (kunststof), Roestvrije stalen plaat, rubber, dyneema-vezel, HDPE holle buizen, koper en graniet.

Wordt gerekend met 5% verschil van het gemiddelde (-5 en +5)

Beton (concrete)

Wordt berekend over een tijdsspan van 4 jaar

2017: 2.87%

2018: 3.64%

2019: 3.02%

2020: 2.47%

$(2.87 + 3.64 + 3.02 + 2.47) : 4 = 3\%$ stijging gemiddeld (-2% en 8%)

Wapening (reinforcement)

2017: 2.72%

2018: 7.87%

2019: -1.06%

2020: 0.24%

$(2.72 + 7.87 + 0.24 - 1.06) : 4 = 2.44\%$ stijging gemiddeld (-3.44% en 7.44%)

Staal (steel)

2017: 0.75%

2018: 27.22%

2019: 7.6%

2020: 0.22%

$(0.75 + 27.22 + 7.6 + 0.22) : 4 = 8.9\%$ stijging gemiddeld (3.9% en 13.9%)

Polyethyleen plaat kunststof (plastic polyethylene)

2017: 5.9%

2018: 3.8%

2019: 4.27%