Colorado State University
SYSE 695: Independent Study

Analyzing Lifecycle Requirements of Marine Hydrokinetic Energy Systems

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As a candidate for the Colorado State University Systems Engineering Master of Science Program (Plan B), I am producing this document as the fulfilment of the requirement to graduate as set by the Systems Engineer Department and the SYSE 695 Independent Study course.

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1 PROJECT ABSTRACT

The world today is striving towards green energy technologies and global access to affordable and clean energy is the 7th of 17 United Nations' Sustainable Development Goals. Demand for electricity is growing alongside the consequences posed by climate change and there is increasing need for systems that can generate electricity from renewable energy sources. We are therefore seeing a changeover from existing conventional energy sources to optimized and innovative cleaner sources. Ocean wave energy is one of the most promising sources of clean, and reliable energy, and it is estimated that there is a theoretical global wave energy potential of 32,000 TWh available per year (1). Moreover, with approximately 40% of the world's population residing in coastal areas, it provides opportunities for the deployment of Wave Energy Converters (WECs) for distributed generation.

For these reasons, marine hydrokinetic energy is a growing piece of the renewable energy sector that offers high predictability and additional energy sources for a diversified energy economy. The ocean covers approximately 70% of the earth's surface and contains an immense source of renewable energy from ocean waves. Wind and solar energy sources encounter challenges such as integration and predictability, which suggest a need for energy storage, as well as societal challenges such as competing for land use and environmental impact concerns. Marine hydrokinetic systems are located within water bodies, which can be forecast with greater accuracy and may not have the same challenges experienced by wind and solar. That said, wave energy technology is still an emerging form of renewable energy for which large-scale grid-connected project costs are currently poorly defined (2). Also, this resource is unevenly distributed throughout the world, and so converting waves into a useful form of energy will require the identification of potential Wave Energy Farm (WEF) locations. This should be undertaken in tandem with selecting an appropriate Wave Energy Converter (WEC), as the characteristics of these devices are critical in capturing the available wave power (1).

Hydrokinetic systems extract kinetic energy from moving water without the need for a dam, barrage, or penstock. These systems can generate power from low speed flowing water with limited environmental impact, over a much wider range of sites than those available for conventional hydropower generation. In this study, the hydrokinetic system has been selected instead of the traditional micro-hydropower. Its operation principle has many similarities to wind turbines. Knowing that water is approximately 800 times denser than air, the amount of energy produced by a hydrokinetic turbine is much greater than that produced by a wind turbine of equal diameter under equal water and wind speed. The other advantages of hydrokinetic

systems are that the water resource does not fluctuate unpredictably in a short period of time as the wind speed, and the flow of water is often more predictable than wind (3).

However, predictable energy production with a structurally more promising and economically competitive design is not the sole criterion for installing new power farms. There are other important life cycle analysis (LCA) issues like climate change, ozone layer depletion, and effects on surrounding environments (e.g., ecosystem quality, natural resources, and human health) that emerge as dominant factors from a green energy point of view (4). This project shall provide a comprehensive set of requirements applicable to Marine Hydrokinetic Energy Systems, together with the relevant justifications. The project intends to give a lifecycle approach to systems requirements from system conception, design & development, construction, distribution, operation, maintenance & support, to retirement/phase-out, and disposal considerations. The set of Requirements herewith described will be the baseline for considerations for realizing marine hydrokinetic energy technologies in oceans and other bodies of water. Further work may be required after the identification of a farm site since some requirements are specific to location.

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2 INTRODUCTION

In 2020, renewable energy sources (including wind, hydroelectric, solar, biomass, and geothermal energy) generated a record 834 billion kilowatt hours (kWh) of electricity, or about 21% of all the electricity generated in the United States (5). Most of the energy used today is from fossil fuels, which are limited and decreasing every day (6). A key concern today, is ensuring sustainable existence of natural life, and leaving a liveable and unpolluted environment for next generation. As such, reducing the use of the already diminishing reserves of fossil fuels seems an urgent necessity, and the concerned stakeholders are considering alternative energy sources. An ideal energy source (like marine hydrokinetic system) should be renewable and should have minimal environmental impact (7).

There are five main types of marine and hydrokinetic energy technologies: ocean wave, tidal stream, river, ocean current and ocean thermal (8). Flow is an essential concept of waterpower and there are mainly two methods of extracting energy from water. The classical method is to make a dam for creation of a static head. The other method is extracting energy from different water currents such as tidal, ocean, river, and irrigation canals. The latter (river and irrigation canals) need large flow openings to capture as much water as possible with low velocities and pressure. This makes the possibility of meeting our increasing energy demands with conventional hydropower seem very limited. That said, the energy in flowing water current still seems a good choice of renewables. Water provides the renewable energy option with a possibility of a continuous supply, and this kind of energy does not need storage. This shows a good application and possibility of using river and marine currents. Compared to other renewable energy sources, wave energy is more predictable, more constant, has a lower visual and environmental impact, and most significantly, a higher energy intensity. The kinetic energy of water current is converted to mechanical power which rotates a generator to produce the electricity. The working principle of hydrokinetic turbines from water currents is as shown in Figure 1 below.

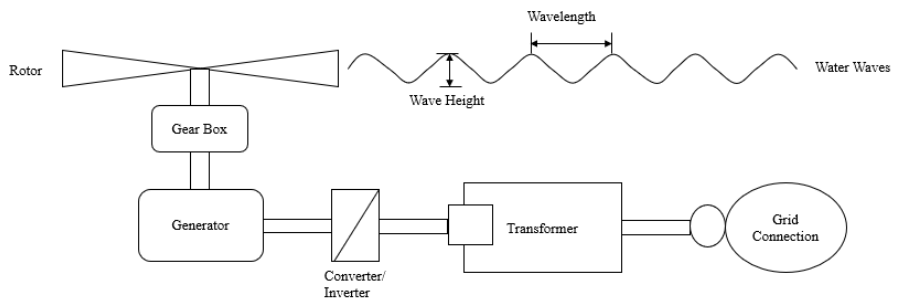
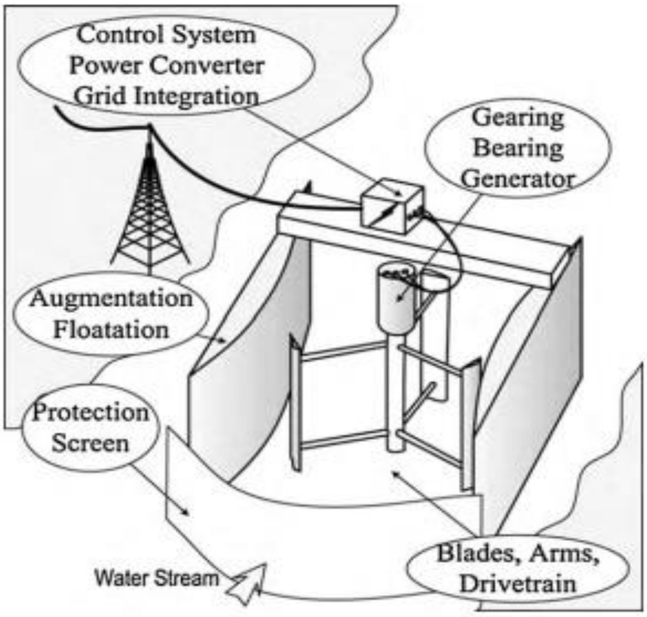


Figure 1: Working principle of hydrokinetic turbines

The working principle of a water current turbine is similar to that of a wind turbine. This concept is not new and has been investigated by many researchers since 1979 (9). The studies in the beginning phase were at a small scale. After 1990's, a new idea of utilizing water current turbine (WCT) for large scale systems emerged (10). Figure 2 below shows a hydrokinetic energy converter system that utilizes a water current turbine.



Source: M.J. Khan et al. / Applied Energy 86 (2009) 1823–1835

Figure 2: Hydrokinetic energy converter system

Wave energy technology development has not yet delivered the desired commercial maturity or, more importantly, the techno-economic performance needed to penetrate the electric utility marketplace. Both commercial readiness and market viability are required for successful entry and survival in the energy market (11). All interested parties agree that renewable energies can be used to cover the increasing energy needs and there is ongoing research on generating electricity from renewables. Challenges in developing commercial hydrokinetic systems include determining the technological, operational, and economic viability of hydrokinetic turbines, meeting permitting requirements, and gaining stakeholder acceptance. Hydrokinetic technology can be affected by debris, sediment, frazil, surface ice, and the interaction of turbine operations with fish and marine mammals in their habitat. There are hydrokinetic projects that are already in the pipeline around the world and the wave equation for power generation per meter of wavefront length is as follows.

$$P \approx \frac{\rho g^2}{64\pi} H^2 T$$

Where:

P = power per meter of wavefront length

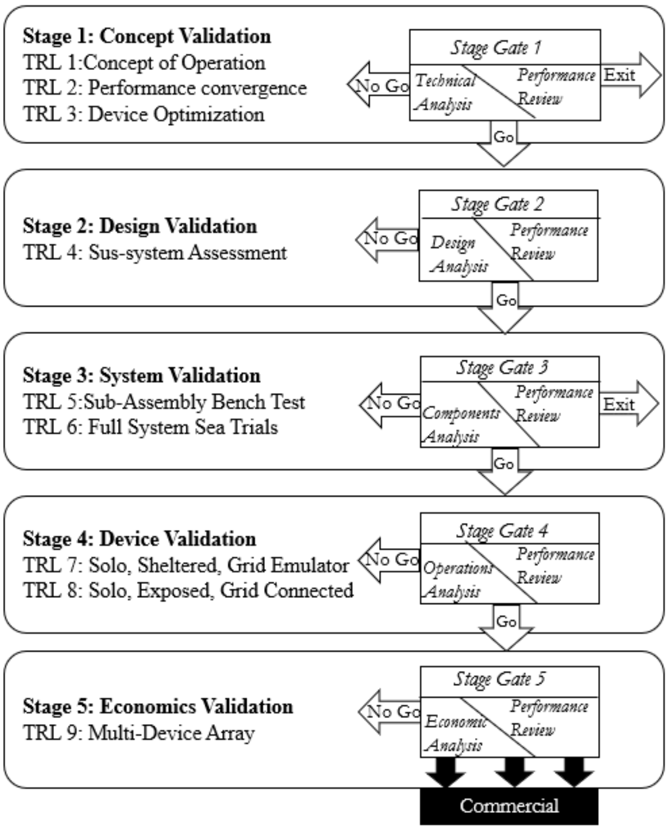
ρ = Wave Density

g = Acceleration due to Gravity

H = Wave Height

T = Wave Period

The question of how turbine operations impact the aquatic environment is one of the major issues that will determine stakeholder views and permitting agency approval of this new technology (12). Some prior research in this area experienced device failures and considerable investment losses over the years. To standardise the ad-hoc approach to WEC development that led to divergence in technology, slow rate of development as well as device failures and investment losses, an International Structured Development Plan was established by the International Energy Agency–Ocean Energy Systems (IEA–OES) group (13). This plan incorporates Technology Readiness Levels (TRLs) into a five-stage approach, which sets out the requirements for a WEC concept to achieve commercialisation. Figure 3 below shows the 5-stage approach.



Source: ESB and Vattenfall classification system

Figure 3: Technology Readiness Levels 5 step approach

These TRLs are internationally recognised and widely accepted as a benchmarking tool for tracking the advancement of emerging technologies and are commonly comprised of nine development levels with the ninth level representing the most mature technology. As shown in the Table 1 below, TRLs should not only be defined in terms of the technology's readiness to convert ocean wave energy and export it to the grid (functional readiness) but also address the project lifecycle requirements such as operational and supply chain readiness, and risk and cost reduction (lifecycle readiness) (14).

Table 1: TRLs Defined by Functional and Lifecycle Readiness

TRL	Functional Readiness	Lifecycle Readiness
1	Basic principles observed and reported	Potential uses of technology identified
2	Technology concept formulated	Market and purpose of technology identified
3	Analytical and experimental critical functions and/or characteristics proof of concept	Initial capital cost and power production estimates/targets established
4	WEC component and/or basic WEC subsystem validation in a lab environment	Preliminary lifecycle design: Targets for manufacturable, deployable, operable, and maintainable technology
5	WEC component and/or basic WEC subsystem validation in a relevant environment	Supply chain mobilization: Procurement of subsystem design, installation feasibility studies, cost estimates, etc.
6	WEC prototype demonstration in relevant environment	Customer Interaction: Consider customer requirements to inform the design. Inform customer of likely project site constraints
7	WEC prototype demonstration in operational environment	Ocean operational readiness: management of ocean risks, marine operations etc.
8	Actual full scale WEC completed and qualified through test and demonstration	Actual marine operations completed and qualified through test and demonstration
9	Operational performance and reliability demonstrated for an array of WECs	Fully de-risked business plan for utility scale deployment of arrays

2.1 System Perspective

There are 4 main perspectives that will be discussed further in this section: Engineering, Manufacturing/Construction, Operation & Maintenance, and finally Disposal. That said, system perspective also requires considerations in the 3 main stages defined below.

System identification: WEC development, classification schemes, and identification vary widely. Traditionally WECs are classified according to operating principle (overtopping device, oscillating water column, wave-activated bodies etc.), location (shoreline, nearshore and offshore; floating, submerged or bottom-standing), and Power Take-Off (PTO) systems (mechanical, hydraulic, pneumatic, and directly electrical) (1).

Site Selection: In the U.S., The Bureau of Ocean Energy Management (BOEM) partnering with National Oceanic and Atmospheric Administration (NOAA) have an open-source digital tool (Ocean Reports) that can be used to visualize coastal and ocean information, generate custom reports for all U.S. waters, and address location considerations for your intended site. Similarly, the European Union's WAVEPLAM (Wave Energy Planning and Marketing) project proposed using Multi-Criteria Analysis (MCA) within a Geographic Information System (GIS) framework to produce maps that depicted areas of varying suitability for a wave energy farm (1).

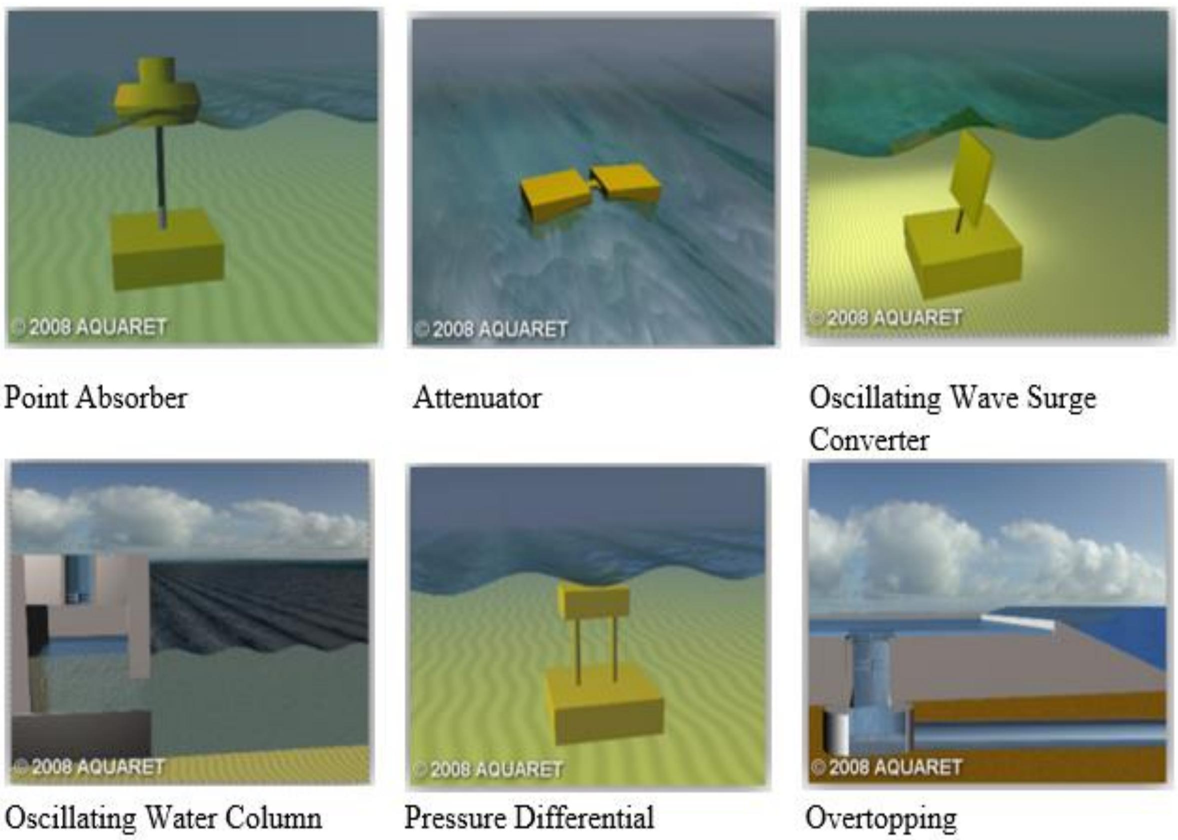
Site Matching: An important aspect to consider when selecting a suitable location for the deployment of a farm is determining which wave energy technology would be more appropriate for the particular conditions encountered at that site. There are three main methods for matching wave energy devices to potential marine energy sites: a) evaluating and comparing the performance of a single technology type at different locations; b) evaluating and comparing the performance of a range of technology types in a specific area; and c) evaluating and comparing the performance of different technology types at a range of sites (1).

2.1.1 Engineering

This is the first stage, and the objective is to design the wave energy farm. The process starts with stakeholders' wants and needs which are refined to generate the general system requirements. For engineering considerations, the system will leverage ocean current power which is created by wind and solar heating of the water, and variations in water density and salinity. Movement of water is quite natural for Earth, and the cause of this motion varies from wind, temperature difference, evaporation, etc. With water being approximately 800 times denser than water, there is continuous renewable high energy-dense power in this movement. The two main characteristics of quantifying these marine renewable resources are power density and the size of the recoverable resource. The power density is a good indicator of how cost-effective the power from a resource can be extracted (i.e., higher power densities yield lower costs of electricity); the recoverable resource size provides an understanding of the potential impact the resource can have on meeting future energy needs and is therefore important in determining if substantial investments into the sector are warranted (15). Ideally, the task of identifying and ranking viable wave energy sites would combine detailed cost data for a range of viable device designs with detailed site and market forecasts to quantify the economic value of potential projects. However,

a) The wave energy industry is still emerging, and most of the existing cost data are for prototypes, which has limitations for commercial scale relevance,
b) A device design—or type—that is economical in one location may not be so in another
c) Some devices are designed for deep water, others for shallow,
d) Different devices will have differing shipping costs or may be capable of being assembled with minimal infrastructure and installed from relatively small ships, and
e) Some devices may be designed for capturing energy from large and energetic waves, while others capture energy from smaller waves that exist more frequently (2).

Therefore, when looking at design, the stakeholder needs should determine the design of the wave farm and the choice of appropriate technology. There are several devices with a proven record of capturing energy from waves. Figure 4 below shows these types of devices, and a description of each device is given below.



Source: Aqua-RET: Wave Technology Types http://www.aquaret.com/indexfca4.html

Figure 4: Types of Wave Energy Devices

1. **Point Absorber:** This is a floating structure which absorbs energy from all directions through its movements at or near the water surface. In principle, such a system consists of a damped oscillator which interacts with the wave. The net result is that energy is transferred from the wave to a load (16). A system can be called a 'point absorber' when its horizontal extent is much smaller than one wavelength, and a 'linear absorber' when the system is made as a straight construction, at least a few wavelengths long (17). A point absorber converts the motion of the buoyant top relative to the base into electrical power.
2. **Attenuator:** This is a floating device which operates parallel to the wave direction and effectively rides the waves. It captures energy from the relative motion of the two arms as the waves pass them.
3. **Oscillating Wave Surge Converter:** This device extracts energy from wave surges and the movement of water particles within them. This device consists of a surface-piercing buoyant flap oscillating as a pendulum around a hinge fixed to the sea bottom. The pitching motion of the WEC device combined with a hydraulic Power Take-Off (PTO), which connects the flap to its base, captures the energy from nearshore ocean surface waves (18).
4. **Oscillating Water Column:** This device consists of a partially submerged hollow structure with an air column. The waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. The device uses kinetic energy in the air caused by ocean waves to extract energy. This trapped air is allowed to flow to and from the atmosphere via the turbine.
5. **Pressure Differential:** This device uses the motion of waves to generate electricity. The wave motion causes the sea level to rise and fall above the device, inducing a pressure differential in the device. The alternating pressure pumps fluid through the system.
6. **Overtopping:** This device captures water as waves break into a storage reservoir. The reservoir creates a water level higher than that of the surrounding ocean surface. The water generates sufficient pressure necessary to turn a hydro turbine and is then returned to the sea through the bottom of the device.

2.1.2 Manufacturing/Construction

The perspective here is focused on the manufacturing and assembly of the wave energy farm. This requires confirming with the stakeholders that we are building the right system, and the process ends when the system is operational. Manufacturing/construction depends on the classification of the system. Wave energy converters can be classified in various ways. One way to do this would be classifying them as horizontal axis and vertical axis. The horizontal axis turbines can be separated into two groups: The rotational axis parallel to the water stream direction, and the rotational axis perpendicular to the water stream direction. Water wheels or crossflow turbines can be classified as perpendicular and horizontal axis turbines (3). Another popular classification is based on the working principle of the primary capture system and the secondary conversion system (the power take-off (PTO) system), as shown in Figure 5 below. All these considerations provide important information to be factored in construction. The specific type of system to be used in a powerplant is not selected until all operational studies and cost estimates are complete. The system selected depends largely on the site conditions. For example, if the farm site is prone to turbulence, a reaction turbine could be ideal (19). A reaction turbine has a horizontal or vertical wheel that runs with the wheel completely submerged. This feature helps to reduce effects of turbulence. In theory, the reaction turbine runs like a spinning lawn sprinkler - water at the center exerts pressure and escapes from the ends of the blades, causing rotation. Reaction turbines are the most commonly used turbines.

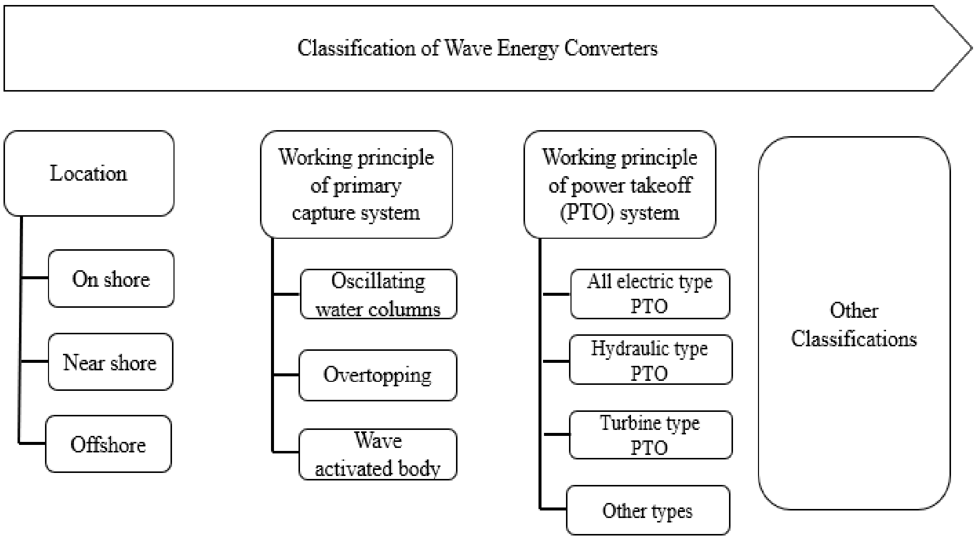


Figure 5: Classification of Wave Energy Converters

2.1.3 Operations and Maintenance

The objective at this stage is to safely operate the system and maximize revenue by producing and selling electricity. The electricity that is generated needs to be delivered to where it is needed: in homes, schools, offices, factories, etc. Marine systems are often in remote locations and the power produced must be transferred over some distance to its users. This means that the system of interest (SOI), though a system in its own right, will be considered a subsystem of the electricity grid, and the power generated will be connected to the grid for transportation and distribution to the end user. The Grid Connection will essentially be the interface between the system of interest and the system of systems. There is a vast networks of transmission lines and facilities already in place that are used to deliver electricity to the end users. These facilities have step-up transformers that raise the voltage so it can travel long distances through powerlines. At local substations, the facilities have step-down transformers that reduce the voltage so electricity can be divided up and directed to the end user. From an operations and maintenance lens, all this should be done while maintaining the farm's lifecycle requirements. For ease of operation, the system shall leverage on already existing networks to transmit electricity and the power generated shall be combined with power from other sources to meet the needs of the end user.

There are Monte Carlo models that can be used to repeatedly perform non-deterministic calculations to get the most probable operation and maintenance results for a given system, in a defined site. The tool uses this methodology and the related reliability data to perform energy and economic analysis of offshore farms, simulating the failures that limit their availability, and consequently, their productivity. Outputs are provided in the form of key performance indicators showing the various options in terms of reliability, availability, and maintainability of the farm (20). The working diagram of the model is schematically described in Figure 6 below.

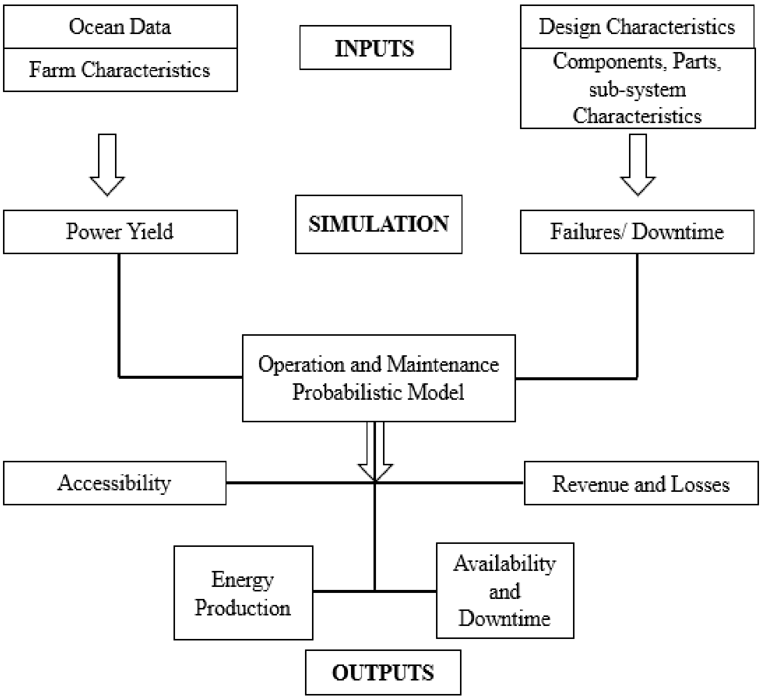


Figure 6: Workflow Diagram of the model

Operation and Maintenance includes energy and materials consumption, and component replacement. This includes the energy used within the operation and maintenance activities for the service life of the farm, and the transportation of replacement parts/materials (21).

2.1.4 Disposal

This stage includes replacing the farm or uninstalling and decommissioning the farm so that the deployment site is cleaned as required in permits and regulations. Disposal also looks at subsystems and parts that are no longer usable. The system is defined as the wave energy farm, up to the interconnection with the continental grid. This boundary includes all the materials and processes throughout the farm's lifecycle. This includes raw materials extraction & manufacturing, component manufacturing, module production, system assembly, installation, operation & maintenance, decommissioning, and recycling. Physically, the system boundary includes small components used for upstream module and system assembly as well as downstream maintenance (repairs and replacement), such as bolts, nuts, and studs, even though they account for a negligible portion of weight and minimal environmental impacts. The life cycle considerations are as shown in Figure 7 below.

Decommissioning and recycling considerations include energy and emissions related to the disassembly process as well as recycling or disposal of materials. Related transportation at the end of the life cycle is included as well. The end of life (EoL) includes materials to be recycled and reused to avoid raw materials extraction. Since there is no standardized practice of WEC system decommissioning and recycling or disposal, here it is assumed that majority of metals will be recycled; the gravity anchors and chains will remain in the seabed and reused for subsequent WEC anchoring; and other materials will be sent to either landfill or incineration (21).

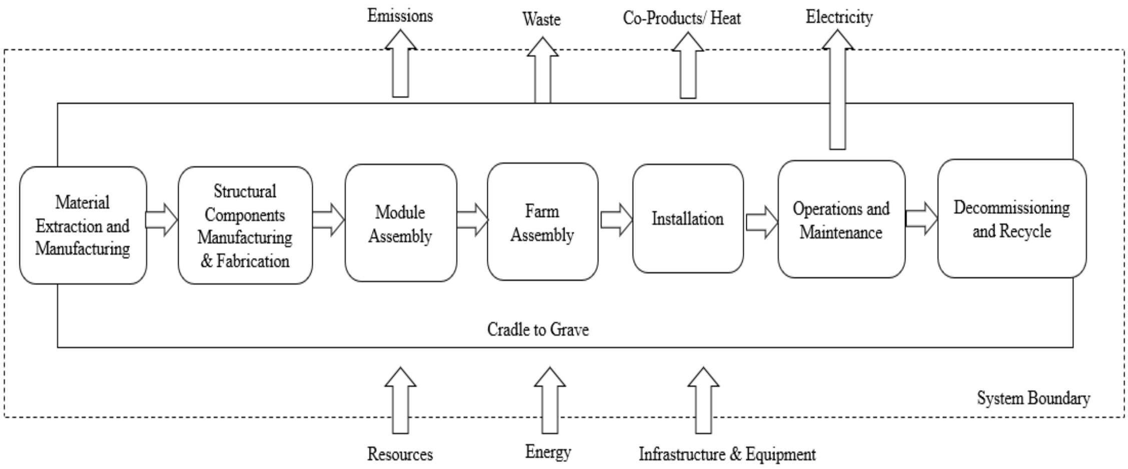


Figure 7: System Lifecycle and Boundaries

2.2 System Functions

Most of the technical issues, such as design and efficiency, could be met by focusing on intensive research and development. However, a great number of non-technical issues, such as policy frameworks and law enforcements, are so critical that they require much more attention in advancing such systems (22). Successful commercialization of wave energy technology inherently incorporates the concept of an array of wave energy converters (WECs). These devices, which constantly interact via hydrodynamic effects, require optimized control that can guarantee maximum energy extraction from incoming ocean waves while ensuring, at the same time, that any physical limitations associated with device and actuator systems are being consistently respected (23).

The system of interest (SoI) main function is to generate electricity from wave energy. For the system to achieve this function, it must be built first. Also, the farm shall not pollute the environment during construction, operation, or disposal, and the use of readily available and environmentally sound materials is desired. The entire system lifecycle should be considered from the beginning (system design), while performing this main function (operations), to the end (disposal). Other functions that are closely related to this main function are, grid connection and return on investment. This section uses use case diagrams to demonstrate the system functions. Figure 8 below is a use case diagram for system construction

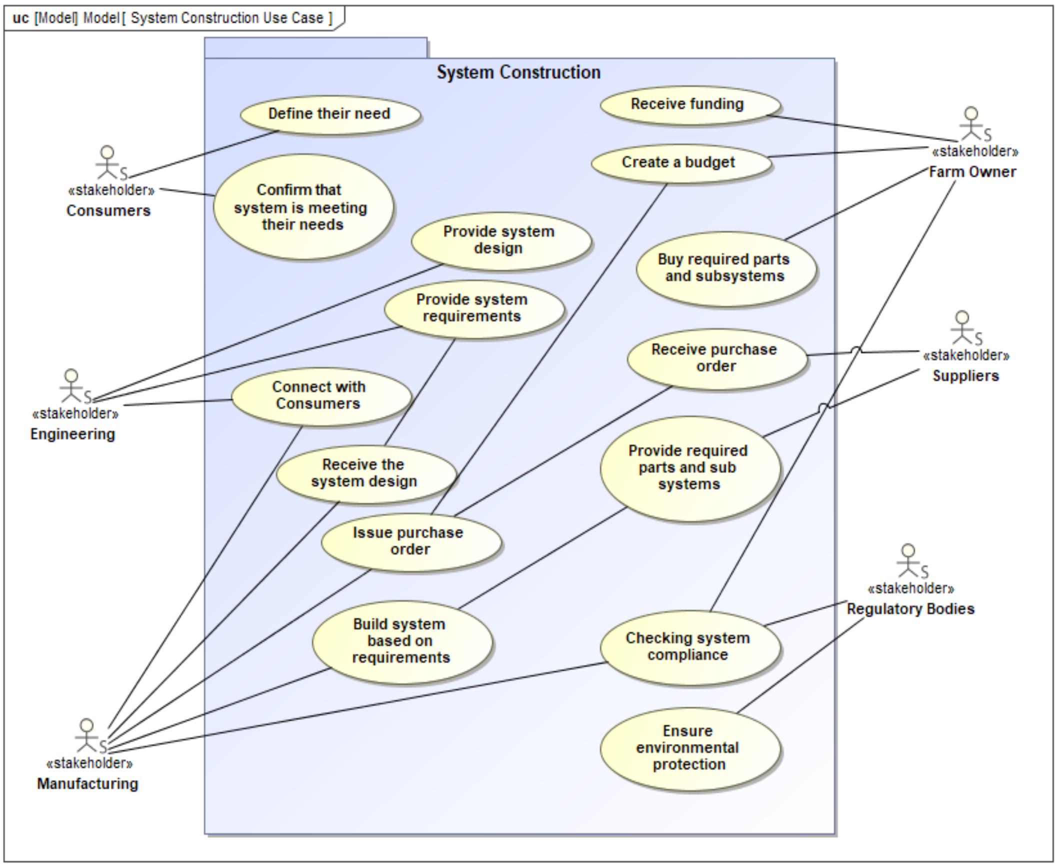


Figure 8: System Construction Use Case

The grid systems in North America are designed and operated to maintain an AC wave frequency of 60 hertz. This is the primary measure that system operators use to assess the real-time state of the interconnection. Deviations from 60 hertz (Hz) indicate instantaneous mismatches between electricity supply and demand. When the frequency is higher than 60 Hz, the system has more supply than demand. When the frequency is lower than 60 Hz, the system has more demand than the available supply. Deviations between electricity supply and demand outside a narrow frequency band can result in electric system failures (24). Figure 9 below shows the Grid connection use case.

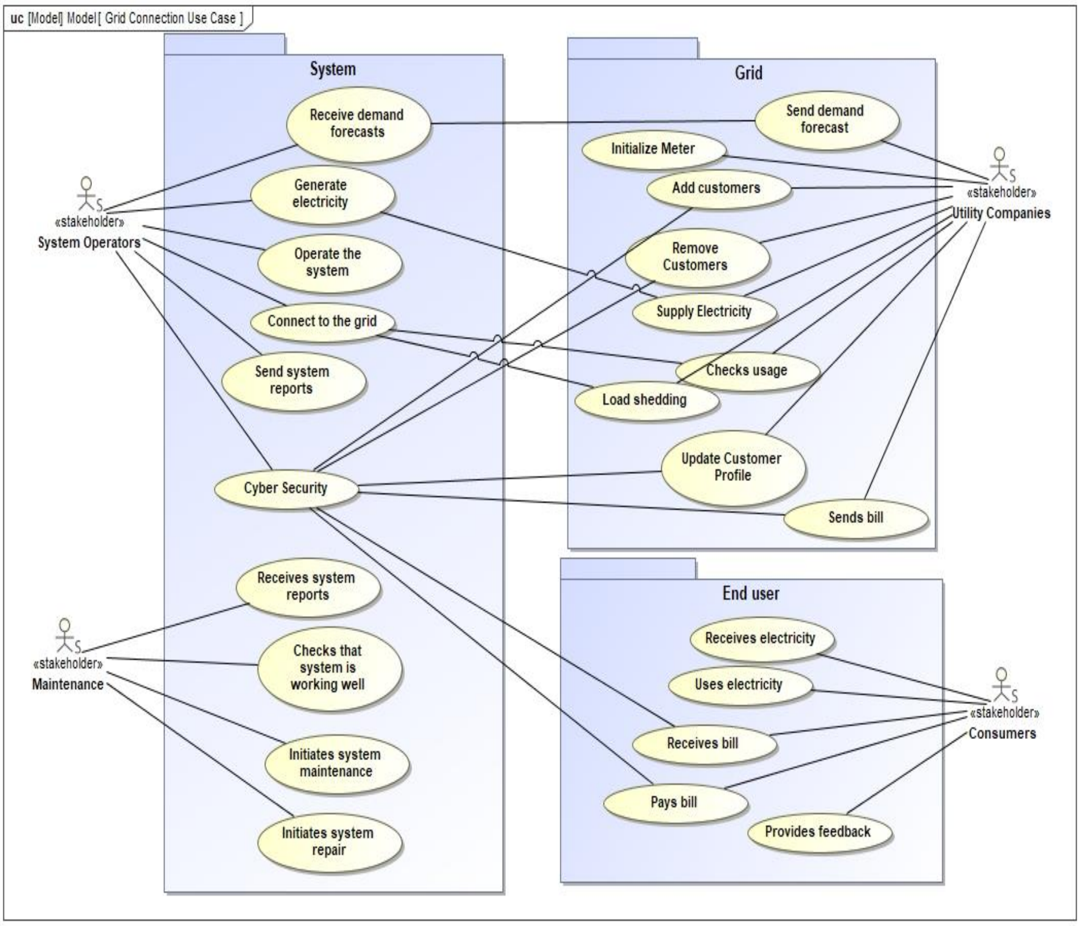


Figure 9: Grid Connection Use Case

To ensure a steady supply of electricity to consumers, operators of the electric power system, or grid, call on electric power plants to produce and place the right amount of electricity on the grid at every moment to instantaneously meet and balance electricity demand. In general, power plants do not generate electricity at their full capacities every hour of the day. There are three major types of generating units that vary by intended usage: **1) Base load generating units:** these normally supply all or part of the minimum, or base, demand (load) on the electric power grid. A base load generating unit runs continuously, producing electricity at a nearly constant rate throughout most of the day. **2) Peak load generating units:** these help to meet electricity demand when demand is at its highest, or peak, such as in late afternoon and when electricity use for air conditioning and heating increases during hot weather and cold weather, respectively. And **3) Intermediate load generating units:** these comprise the largest generating sector and provide load responsive operation between base load and peaking service. The demand profile varies over time and intermediate sources are in general technically and economically suited for following changes in load (25). Figure 10 below shows the demand and supply use case diagram based on intermediate load generating units.

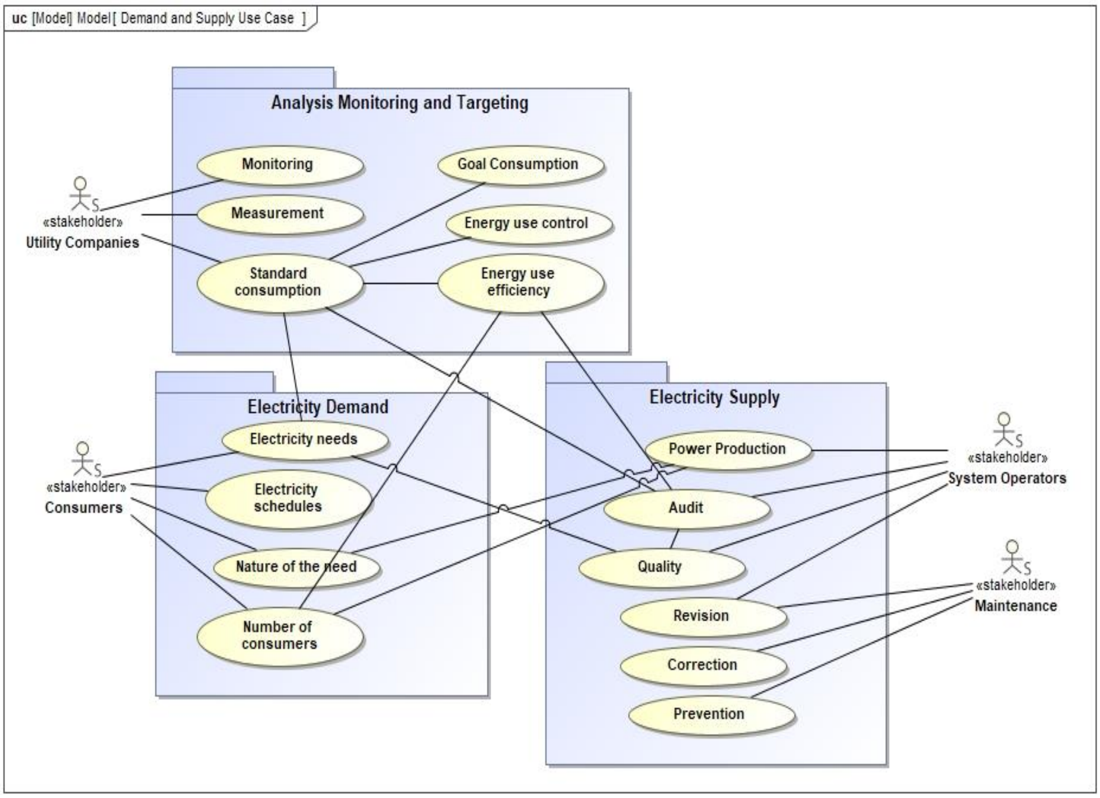
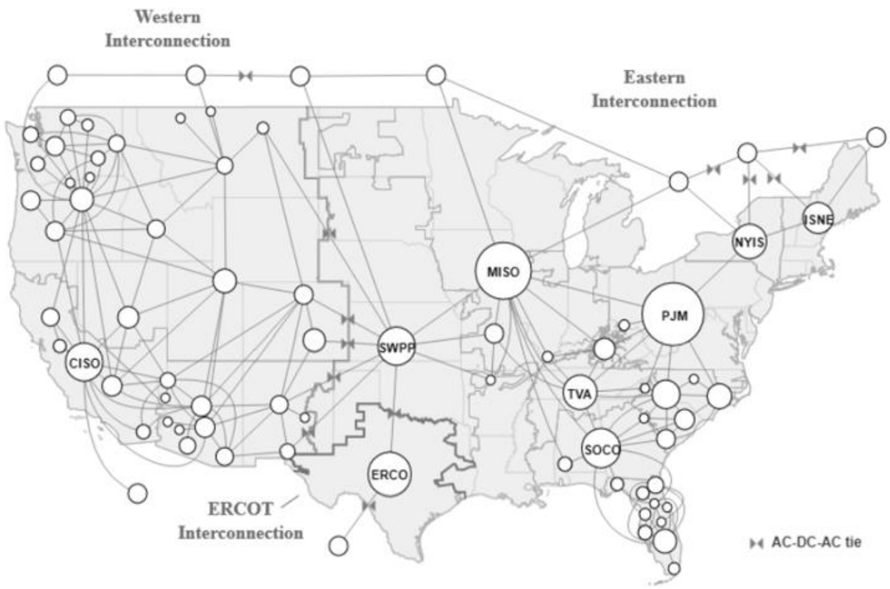


Figure 10: Demand and Supply Use Case

2.3 User Characteristics

This research is conducted in the United States of America, and the average user would have access to infrastructure, training materials, safety equipment, information for benchmarking, and required resources to safely use the system. Users in this context can be divided into two a) system user – responsible for daily production of electricity and b) Energy user – the customers that use electricity in their daily activities.

The system users are trained professionals with years of experience in both operations and maintenance. Since the system is designed to operate like other hydrokinetic systems, minimal user training/orientation will be needed. Training will however be made available for new users, and training manuals/user manuals will be made available to ensure safe diagnostics, operations, maintenance, or repairs. Since the system needs to connect to the grid, system users can be grouped based on the grid interconnections. The grid covering the continental United States is divided into three separate interconnections (Eastern Interconnection, Western Interconnection, and the Electric Reliability Council of Texas (ERCOT) Interconnection). Figure 11 below shows the 3 separate interconnections.



Source: US Energy Information Administration (EIA)

Figure 11: US Grid Interconnection

At a higher level, the balancing authority (BA), i.e., the authority responsible for maintaining the electricity balance within its region, will be communicating with system operators to ensure power demand is met. Demand forecast is a calculated value representing the amount of electricity load within the BA's electric system. A balancing authority derives a region's demand value by taking the total metered net electricity generation within its electric system and subtracting the total metered net electricity interchange occurring between the BA and its neighboring BAs. There are 66 balancing authorities in the US and each BA produces a day-ahead electricity demand forecast for every hour of the next day. These forecasts help BAs plan for and coordinate the reliable operation of their electric system (24). System users work closely with BA's and are trained and equipped to meet the energy demand for the region based on the BA's forecasts.

The renewable energy users across the country are generally concerned with climate change and the effects of generating electricity from fossil fuels. These may be individuals or organizations concerned with reducing greenhouse gas emissions from fossil fuels and reducing air pollution. In the US, growth in renewable energy production and use is widespread but different for each state. Figure 12 below shows the 2019 breakdown of each state measured by proportion of electricity generated and used from renewable sources

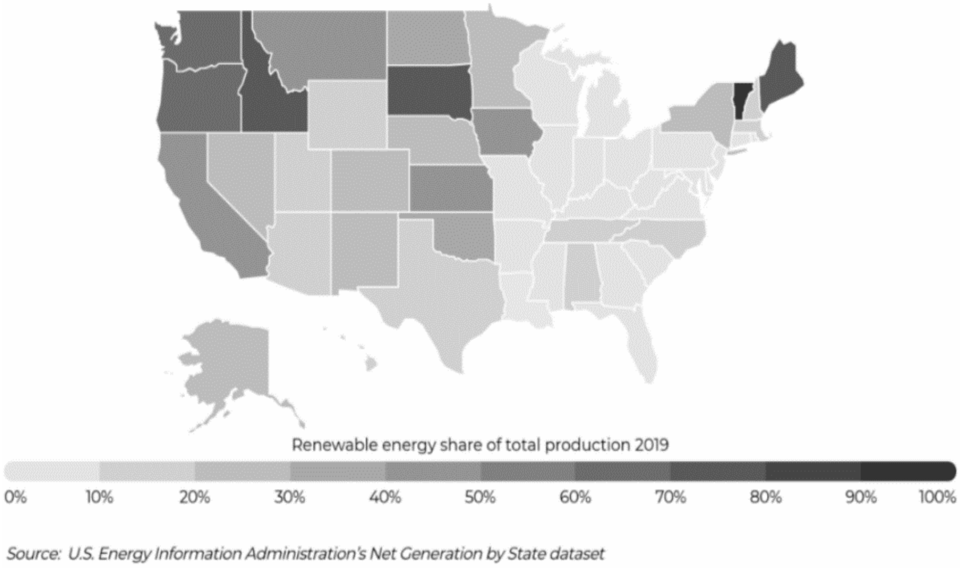


Figure 12: Renewable Energy Share of Total Production

2.4 Assumptions and Dependencies

There is completed and ongoing research that addresses hydrokinetic systems capabilities and threshold levels. Some of the completed research can help direct important system decisions such as **farm size (**farm size can be determined by population of area – population determines energy needed from a site and this can help determine the size), and a**ppropriate materials** (this can be determined by location and some of the design considerations are informed by temperature of the site, water speed, water strength, approval process etc).

There are also considerations that are specific to location. For example, for some parts of the US, wholesale electricity markets are traditionally regulated, meaning that vertically integrated utilities are responsible for the entire flow of electricity to consumers. They own the generation, transmission and distribution systems used to serve electricity consumers. Other parts of the country (the Northeast, Midwest, Texas, and California) have a restructured competitive market. These markets are run by independent system operators (ISOs) (ISOs includes both regional transmission organizations [RTOs] and ISOs). ISOs use competitive market mechanisms that allow independent power producers and non-utility generators to trade power. In a restructured competitive market, utilities are commonly responsible for retailing the electricity service to customers and are less likely to own generation and transmission resources (26).

Depending on the chosen site, the project will most likely need both political goodwill and support from the residents and other key stakeholders. There are other users of the area and aquatic animals that inhabit the location (where the plant would be built) and so goodwill is vital for the success of the project. This paper will focus on more high-level requirements while acknowledging that there is need for further work to address the specific needs and considerations that are associated with the site of the farm.

2.5 Context

There are thriving research and development communities and device developers around the world undertaking both fundamental, applied research, and technology development of both wave and marine current energy conversion (27). However, due to the harsh marine environment (such as saline water, strong winds, and waves), wave energy-conversion devices are vulnerable to seawater corrosion and wind wave damage. This implies a high cost of research, development, and operations, which to some extent, restricts further development of these systems. The costs associated with ocean tests are high and thus, most of the research in this area is based on simulations and mathematical models which have limitations (28). These are issues that will need to be addressed for successful wave energy-conversion systems.

Common environmental concerns associated with marine energy include,

a) The effects of electromagnetic fields and underwater noise,
b) Physical presence's potential to alter the behaviour of marine mammals, fish, and seabirds with attraction, avoidance, entanglement,
c) Potential effect on marine processes such as sediment transport and water quality,
d) Foundation/mooring systems can affect benthic organisms via entanglement/ entrapment,
e) Electromotive force effects produced from subsea power cables,
f) Minor collision risk,
g) Artificial reef accumulation near fixed installations, and
h) Potential disruption to roosting sites (29).

A complex wave energy system can be decomposed into subsystems, those subsystems into sub-subsystems, and so forth. The functional requirements can then be flowed down to each component of the system, and rigorous tracing of allocations can be applied to ensure component traceability to the functional requirements. Figure 13 below shows a sample system definition and decomposition for a WEC farm (30).

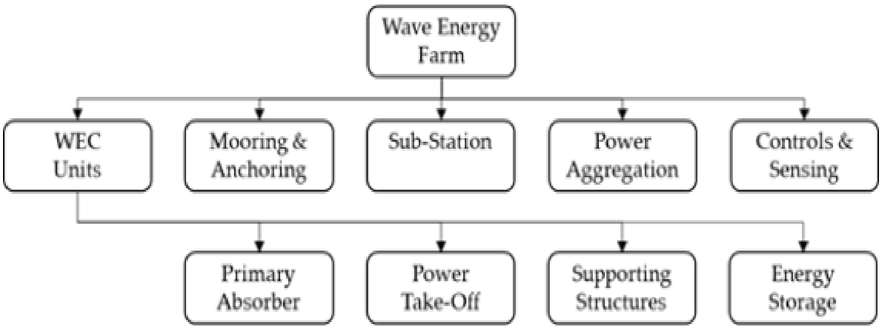


Figure 13: System definition and decomposition

For any technology, it is vitally important to collaborate with the wide variety of stakeholders involved and invested in the product. Each stakeholder will have different needs and values, and some will have greater importance or relevance to the technology than others. Generally, stakeholders in the energy sector have identified seven capabilities for grid connection. These are

a) Have a market-competitive cost of energy
b) Provide a secure investment opportunity
c) Be reliable (for grid operations)
d) Benefit society
e) Be acceptable for permitting and certification
f) Be safe
g) Be deployable globally (30).

These general capabilities will be discussed further in subsequent sections.

3 STAKEHOLDERS

3.1 Definition and Viewpoints

INCOSE defines stakeholders as an individual or organization having a right, share, claim, or interest in a system or in its possession of characteristics that meet their needs and expectations; therefore, stakeholders include but are not limited to, end users, end user organizations, supporters, developers, producers, trainers, maintainers, disposers, acquirers, customers, operators, supplier organizations, and regulatory bodies (31). Based on this, each stakeholder would have a specific interest to the system, but different stakeholders may have an overlap in interest. The following is a list of the stakeholders, their definition, and interests:

1. Consumer: This refers to individuals, companies, or organizations that the system is designed for – they use electricity in their daily activities. The end users of electricity can be grouped into four main categories: transportation, industry, residential and commercial. Residential, commercial, and industrial customers each account for roughly one-third of the nation's electricity use. The transportation sector accounts for a small fraction of electricity use, though this fraction could increase as electric vehicles become more widespread (32). Figure 14 below shows the customers' viewpoints.

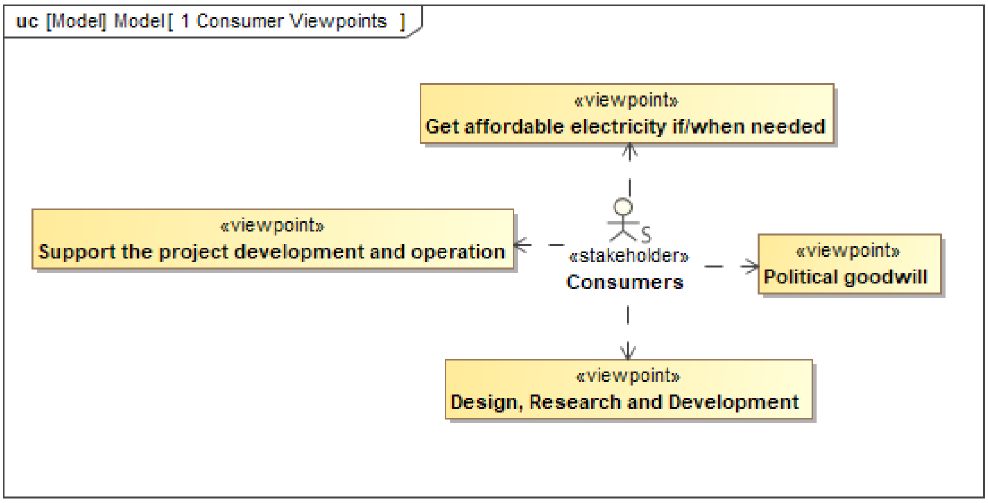


Figure 14: Customer Viewpoints

2. Farm Owner: This could be an individual, groups of individuals, or organization that owns the energy farm. In the US, private equity firms own 683 utility-scale electric power plants with 150,225 MW of capacity, including: 217 natural gas plants with 97,385 MW; 15 coal plants with 18,009 MW; 23 oil plants with 4,158 MW; 186 solar plants with 4,259 MW; and 147 wind power facilities with 17,622 MW. A small share of private equity owned power generation capacity comes from hydroelectric, geothermal, biomass, or nuclear power plants

(0.8 percent, 0.5 percent, 0.3 percent, and 1.7 percent, respectively) (33). Figure 15 Below shows the farm owner's viewpoints.

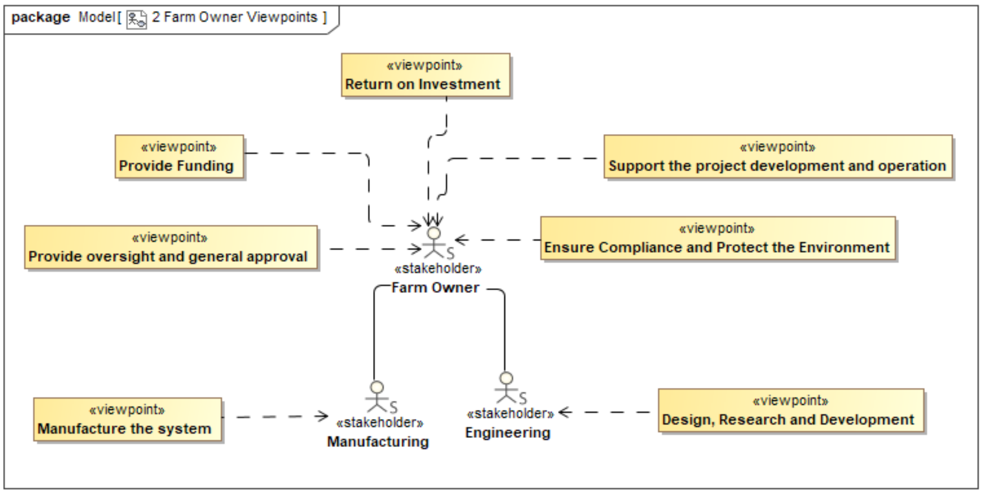


Figure 15: Farm Owner Viewpoints

3. Engineering and Manufacturing: For this paper, engineering includes everyone involved in the design of the system while manufacturing includes everyone involved in the building and setup of the system. Both groups work closely with the stakeholder to ensure they are designing and building the right system as expressed by stakeholder needs. As such, they manage changes within the project and look at issues like solving technical problems, safety, quality standards, compliance with code etc. Figure 16 below shows the Engineering and Manufacturing viewpoints.

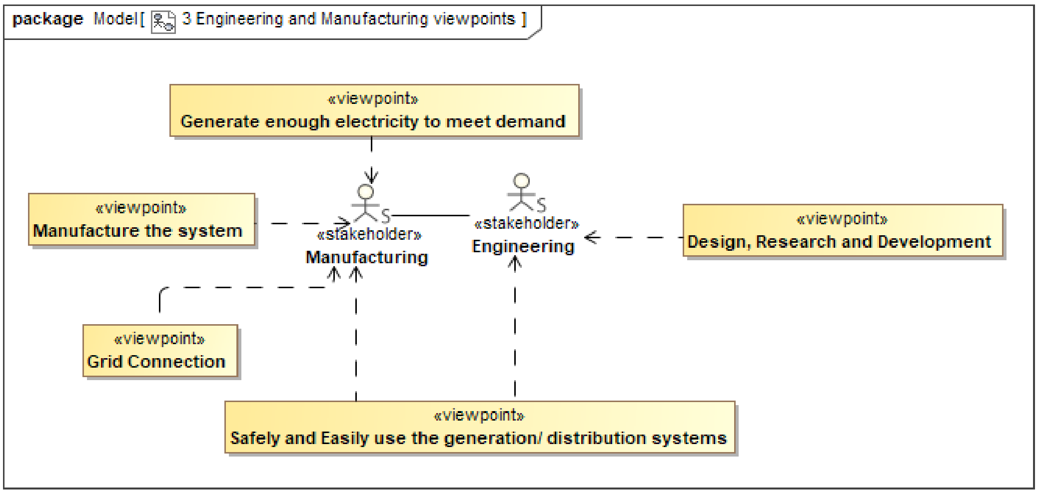


Figure 16: Engineering and Manufacturing Viewpoints

4. Operation and Maintenance: Operation includes anyone involved with the activities required to generate electricity - activities for daily running of the farm (this may include security, control, principles, procedures, and quality) while maintenance includes anyone concerned with keeping the system running in order. Figure 17 below shows the Operations and Maintenance viewpoints.

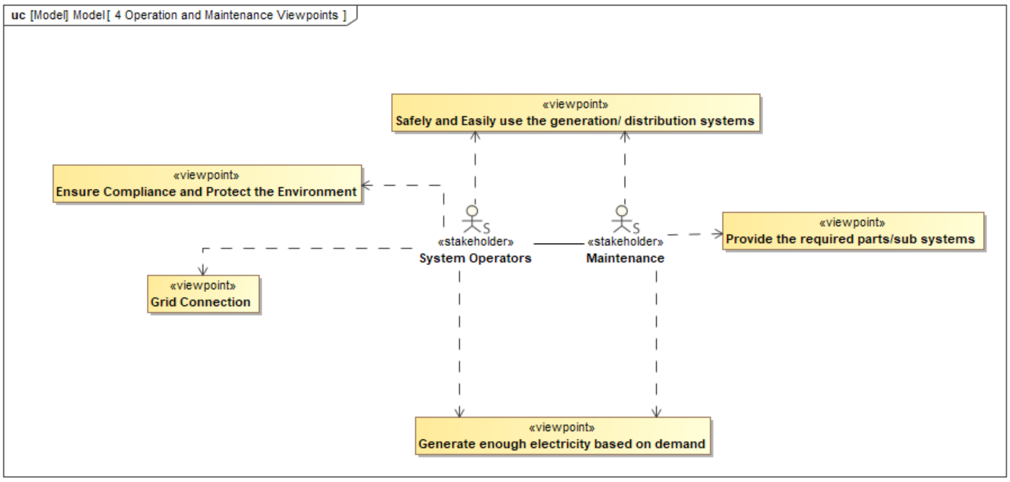


Figure 17: Operations and Maintenance Viewpoints

5. Financiers: This refers to individuals or groups or organizations that provide funding for the project. Public-private partnerships (PPPs) can play an important role in financing infrastructure projects. Combining private and public funding streams can enable stakeholders to raise more capital than would otherwise be possible. Some benefits of PPPs are that they: decrease the stress on public funds, expedite implementation timeframes, leverage private sector specialty expertise, decrease the risk for the public entity, and have quicker payback times (34). Figure 18 below shows the Financiers' viewpoints.

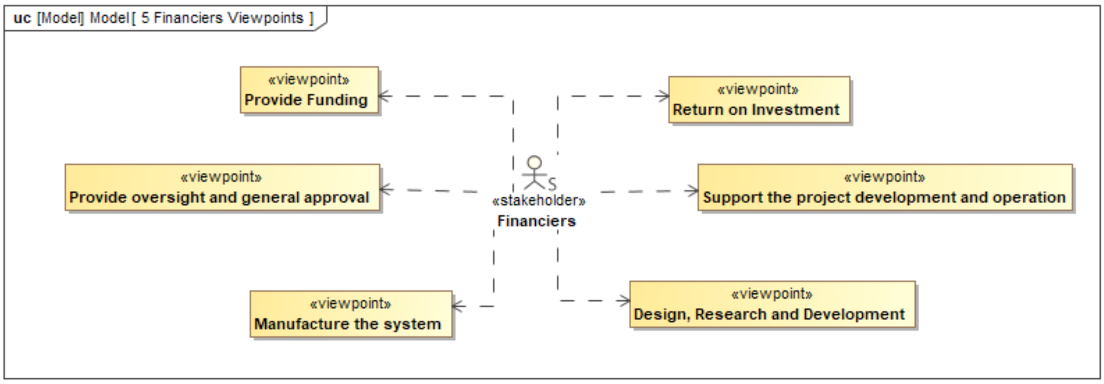


Figure 18: Financiers Viewpoints

6. Suppliers: These can be divided into two 1) First Tier Supplier – they provide the main parts, subsystems and systems that will make up the system of interest. 2) Second Tier Suppliers – they supply COTS, land storage, ocean storage, and transportation. Figure 19 below shows the Suppliers viewpoints

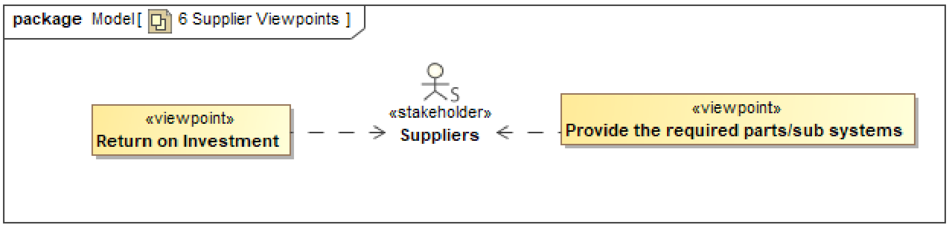


Figure 19: Suppliers Viewpoints

7. Government: The government has always been—and always will be—a player in energy markets. For example, the federal government has made investments in energy for years by granting access to resources on public lands, helping build railroads and waterways to transport fuels, building dams to provide electricity, subsidizing exploration and extraction of fossil fuels, providing financing to electrify rural America, taking on risk in nuclear power, and conducting research and development in virtually all energy sources. The federal government has a suite of tools at its disposal to make investments, including cash grants, regulatory incentives, tax expenditures, and financing supports. When properly designed and targeted, each of these tools plays an important role (35). Figure 20 below shows the Government's viewpoints.

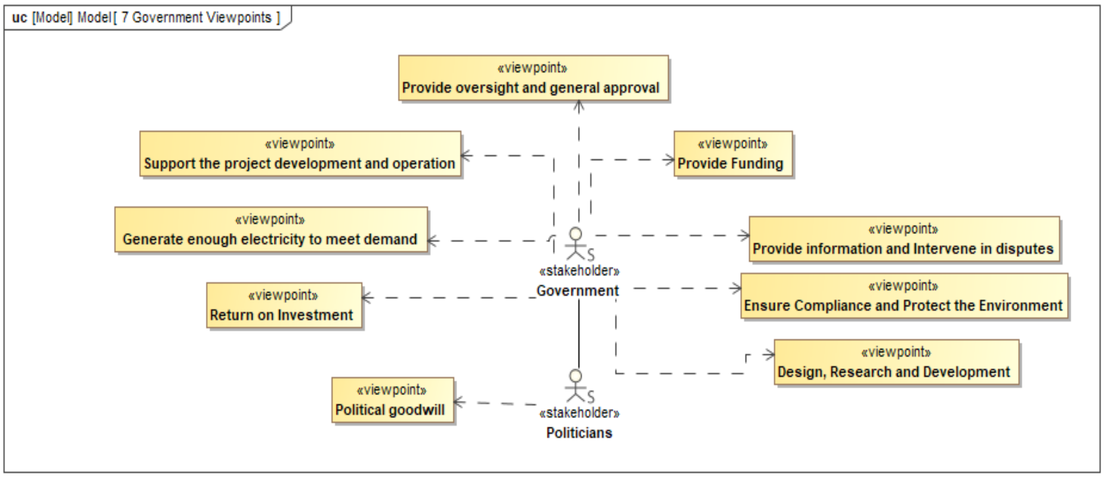


Figure 20: Government Viewpoints

8. Politicians: Politics has always been intertwined with issues like cost of energy, environmental issues, and climate change. As such, based on political affiliations, not all politicians embrace renewable energy – some have shared ill-informed opinions to score political points from their supporters. The political influence on the energy sector can be easily misunderstood. Because sustainable energy transitions take place over decades, no single government can launch and sustain a system. Politicians therefore must consider various electoral scenarios over long periods of time. The problem is further complicated by technological change and the effects of energy policy on electoral outcomes. In such a dynamic environment, political parties must adopt strategies that consider the implications of their policies over long periods of time (36). Figure 21 below shows the Politicians' viewpoints.

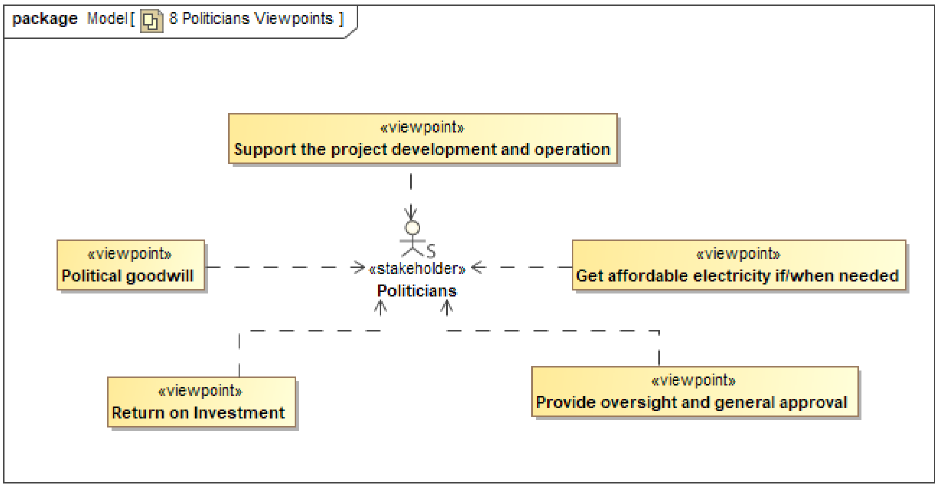


Figure 21: Politicians Viewpoints

9. Energy Distributors: There are many definitions of an energy distributor. Some of these include, 1) A licensed operator of the distribution system through which electricity is supplied. 2) The electricity distribution network service provider in whose network area the electricity works are or will be located. 3) A person who holds a utility service license to distribute electricity. And 4) A person who is authorised by a distribution license to distribute electricity except where he is acting otherwise than for purposes connected with the carrying on of activities authorised by the licence (37). This paper will not distinguish the differences and will generalize their viewpoints as shown in Figure 22 below.

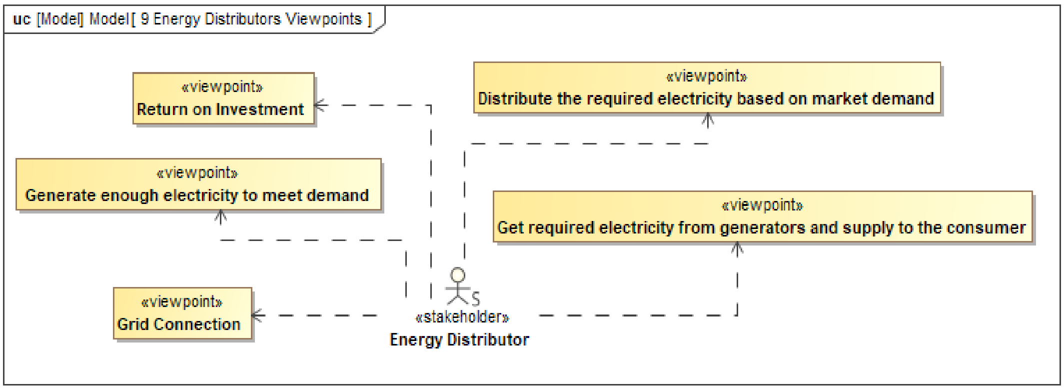


Figure 22: Energy Distributors Viewpoints

10. Utility Companies: This means all persons, firms, or corporations engaged in the business of providing electric, gas, or natural gas service to consumer. For example, in Colorado, utility companies provide electricity at the retail and wholesale levels. Retail electric utilities provide electricity to power homes and businesses in Colorado, while wholesale electric utilities generate electricity and provide power for other utilities. Depending on where retail customers are located within the state, customers may be served by an investor-owned utility, a cooperative utility, or a municipal utility. Investor-owned utilities are for-profit corporations that are regulated by the Colorado Public Utilities Commission (PUC). Colorado has two investor-owned electric utilities - Black Hills Energy and Public Service Company of Colorado, known as Xcel Energy. Coloradans are also served by 29 municipal utilities and 22 rural electric cooperatives. Since municipal and cooperative utilities are not operated as for-profit corporations, they are not regulated by the PUC (38). Figure 23 below shows the Utility Companies' viewpoints.

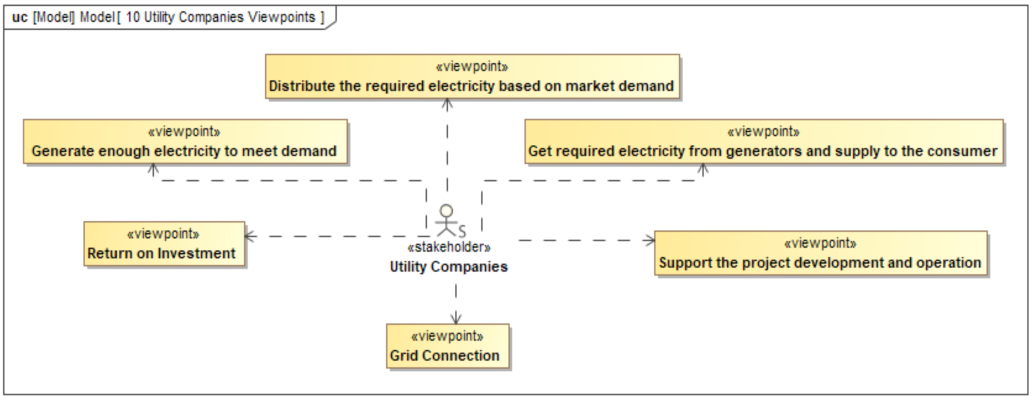


Figure 23: Utility Companies' Viewpoints

11. Consultants: Renewable energy consultants carry out energy surveys and audits to advise their clients. They draw on their technical expertise to help companies and individuals explore, understand, and install renewable energy systems. They may work as consultants with state Departments of Energy, or with global corporations and private engineering firms that promote sustainability. Their goal is to facilitate smooth communication, integrate work activities, and ensure the successful delivery of the system (39). As such, any stakeholder can hire their own consultant in their quest to get reliable information that can help shape their opinions and decisions. In cases where the project team is providing subjective information, consultants can be hired to provide unbiased data, and ethical issues (if any) can be brought to light from this information. This makes their roles important as they can be considered subject matter experts.

12. Mediators: A mediator is an impartial and objective facilitator attempting to assist the parties in creating a solution to their dispute outside of the litigation process. Mediators do not act as judges or arbitrators; a mediator does not impose a solution upon the parties. Rather, the mediator will facilitate the parties themselves reaching their own solution through the guided use of problem-solving analysis and techniques. A skilled neutral mediator often gives the parties the opportunity to tell their side of the issue and then work constructively to resolve it, even if the parties have not been able to resolve the issue in the past (40). Some potential stakeholders that may have disputes include associations, companies, finance institutions, inventors, service providers etc. and areas of dispute may include materials used, technologies used, breach of confidentiality, design, infrastructure, software, and research & development. All these may require mediation and Figure 24 below shows the Mediators and Consultants viewpoints

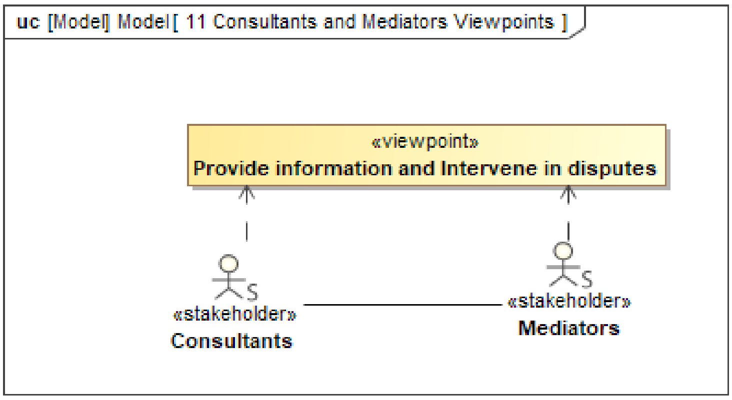


Figure 24: Mediators and Consultants Viewpoints

13. Other users of the area: U.S. coast and ocean governance is diverse and multifaceted, with literally dozens of legally relevant agencies, Native American tribal nations, and private stakeholders all interacting within the legal framework established by a diverse body of laws passed by state legislatures and the U.S. Congress. Further complicating matters, jurisdiction over ocean spaces, subsea lands, and living and marine resources is divided between federal, state, and tribal governments, across a multitude of political boundaries. Due to these diverse governmental authorities, U.S. Ocean governance is often characterized by tension and careful negotiation among multiple parties (41). Figure 25 below shows other users of the area viewpoints.

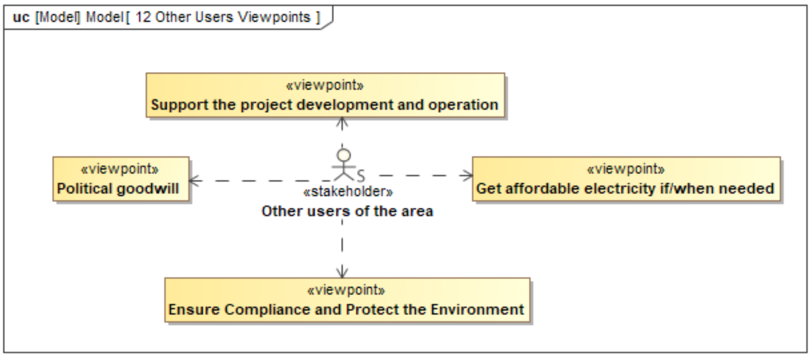


Figure 25: Other Users Viewpoints

14. Water Rights: There are 12 types of water rights a) Riparian b) non-Riparian c) Prior appropriation d) Hybrid water rights e) Absolute dominion f) Correlative g) Community water rights h) Littoral rights i) Navigable servitude j) Overlying rights k) Public trust and l) Right to clean water. In the United States, the western states have historically followed prior appropriation, which grants the right to divert water to the first person who started using the water. Most eastern states follow the riparian rights, which limits water use to the owner of the land adjacent to the water. The commerce clause gives the Congress the authority to allocate interstate waters to serve the national interest—even if doing so means overriding state law.

15. Land Rights: Through the common law, state law, and the Constitution, the rights of people to acquire, use, and dispose of property freely are protected. The federal government however retains the right and obligation to manage federal lands under the Constitution. This right and obligation includes the authority to both reserve water rights and mitigate against the impacts of the exercise of privately held water rights on public lands. Congress, on the other hand, is charged with directing the Executive Branch's implementation of those rights and obligations.

16. Regulatory bodies: Under the Federal Power Act (FPA), Federal Energy Regulatory Commission (FERC) has jurisdiction over any project in navigable waters that uses water to generate electricity. With this jurisdiction, FERC has authority over the siting and licensing of hydrokinetic facilities, as well as the siting and licensing of the primary transmission line from the project to the point that it is connected to a line carrying electricity from other sources. FERC is an independent agency that regulates the interstate transmission of electricity, natural gas, and oil. Within FERC, the Office of Energy Projects (OEP) is responsible for the approval and oversight of hydroelectric projects. OEP focuses on a). Project siting and development; b). Balancing environmental and other concerns; c). Ensuring compliance; and d). Safeguarding the public (42). For this paper, regulatory bodies include water rights and land rights, and Figure 26 below shows the Regulatory Bodies viewpoints.

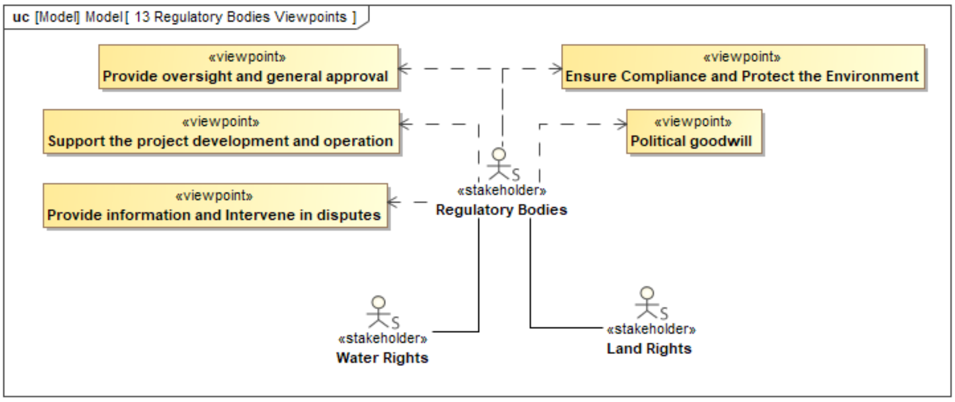


Figure 26: Regulatory Bodies Viewpoints

Table 2 below is a summary of the federal authorization required before construction begins. The column of Other Agencies refers to agencies that are likely to be involved in project evaluation for a particular authorization or environmental review. Based on the farm location, some of the agencies listed may not be involved and other agencies may be involved even though they are not listed here.

Table 2: Regulatory Bodies and Federal Authorization

Permit/Approval	Primary Legal Authority	Lead Agency	Other Agencies	Anticipated Process Time
Federal Hydroelectric License	Federal Power Act, Energy Policy Act of 2005	FERC	COE, BOEM, FWS, NOAA, USCG, BIA, EPA, NPS, USFS, ACHP, USGS, BLM; tribal governments; other relevant federal, state, and/or local agencies	2-6 years
Preliminary Permit				At least 60 days
Nationwide Permit 52	Rivers and Harbors Act; Clean Water Act	COE	FWS, NOAA, NPS, ACHP, tribal governments; other relevant federal, state, and/or local agencies	Varies; at least 40 days
Commercial Renewable Energy Lease	Outer Continental Shelf Lands Act, Energy Policy Act of 2005	BOEM	COE, FERC, FWS, NOAA, USCG, BIA, EPA, NPS, USFS, ACHP, USGS, BLM; tribal governments; other relevant federal, state, and/or local agencies	6-8 years if competitively issued; 3+ years if no competitive interest
CWA 404 Permit	404 Clean Water Act	COE	EPA, FWS, NMFS	60-120 days, more if EIS needed
COE 10 Permit	10 Rivers & Harbors Act	COE	FWS, NMFS	60-120 days, more if EIS needed
Private Aids to Navigation Permit	Coast Guard Regulations	USCG	COE, state resource agencies	3 months+
NEPA Analysis (ROD, FONSI, Categorical Exclusion)	National Environmental Policy Act	FERC	EPA, NOAA, other relevant federal and state agencies	2-6 months for an EA; 12-24 months for an EIS7
7 ESA Consultation	Endangered Species Act	NMFS, FWS	FERC, COE, USCG	4-6 months
Marine Mammal Consultation	Marine Mammal Protection Act	NMFS, FWS	None specified	4-24 months
Essential Fish Habitat Assessment	Magnuson-Stevens Act	NMFS	Regional Fisheries Management Council, FERC, BOEM, COE	30-60 days

Permit/Approval	Primary Legal Authority	Lead Agency	Other Agencies	Anticipated Process Time
Fish and Wildlife Coordination Act Consultation	Fish and Wildlife Coordination Act	FWS	FERC, NMFS	Varies
Migratory Bird Consultation	Migratory Bird Treaty Act	FWS	FERC, COE, state resource agencies	Varies
106 NHPA Consultation	National Historic Preservation Act	Advisory Council on Historic Preservation	FERC, BOEM, COE, state resource agencies	2-6 months
CZMA Federal Consistency Determination	307 Coastal Zone Management Act	Designated State Agency	Relevant federal and state agencies	6 months
Water Quality Certification	401 Clean Water Act	Designated State Agency	Relevant federal and state agencies	Up to 1 year

3.2 Stakeholder Needs

The matrix in Table 3 below can be used to demonstrate the stakeholder viewpoints that were discussed above. This shows the interrelationships and interconnects of their viewpoints which shall be used to identify needs. As shown, each stakeholder has a viewpoint or interest to the project, but there is an overlap of viewpoints for multiple stakeholders. Stakeholders begin with desires, and expectations that may contain vague, ambiguous statements that are difficult to use for systems engineering activities. Care must be taken to ensure that those desires and expectations are combined into a set of clear and concise need statements that are useful as a starting point for system definition. These need statements will then be further clarified and translated into a more engineering-oriented language in a set of stakeholder requirements to enable proper architecture definition and requirement activities. Stakeholder requirements play major roles in systems engineering, as they form the basis of system requirements activities, form the basis of system validation and stakeholder acceptance, act as a reference for integration and verification activities, and serve as means of communication between the technical staff, management, finance department, and the stakeholder community (43).

Table 3: Stakeholder Needs Matrix

Legend
- Association (Direct and Implied)
- Dependency (Direct and Implied)

Model		Consultants	Consumers	Electricity Generators	Energy Distributor	Engineering	Farm Owner	Financiers	Government	Land Rights	Maintenance	Manufacturing	Mediators	Other users of the area	Politicians	Regulatory Bodies	Suppliers	System Operators	Utility Companies	Water Rights
Model		1	2	1	4	3	8	4		5	4	5	1	2	8	5	4	3	3	4
Design, Research and Development	3					A, D		A												
Distribute the required electricity based on market demand	2			A	A															
Ensure Compliance and Protect the Environment	5						D							A		A, D		A		
Generate enough electricity to meet demand	6				A		A				A	D						A	A	
Get affordable electricity if/when needed	2		A												D					
Get required electricity from generators and supply to the consumer	2				A														A	
Grid Connection	3				A							D							A	
Manufacture the system	3							A				A, D								
Political goodwill	5									A				A	A, D					A
Provide Funding	2						D	A												
Provide information and Intervene in disputes	5	A								A			A			A				A
Provide oversight and general approval	4						D			D					D	D				
Provide the required parts/sub systems	3										A						A, D			
Return on Investment	8						A, D	A			A				A, D		A, D			
Safely and Easily use the generation/ distribution systems	4					D					A	D						A		
Support the project development and operation	10		A				A, D			A, D					A, D	A				A, D

From the stakeholders' viewpoints defined above, their needs are grouped as shown in Table 4 below. This list is not conclusive - a project team intending to build a wave energy farm will need to engage with their stakeholder to get a conclusive list.

Table 4: Stakeholder Needs

ID	Stakeholder Need	Source
SN-0100	Stakeholders have the need to generate power from wave energy	Farm owner
SN-0200	Stakeholders have the need to distribute the generated power through already existing systems	Distributor
SN-0300	Stakeholders have the need for market competitive cost of energy	Consumer
SN-0400	Stakeholders have the need to design a system that meets their customer requirements	Engineering
SN-0500	Stakeholders have the need to build a system that meets their customer requirements	Manufacturing
SN-0600	Stakeholders have the need to protect the environment	Regulatory bodies
SN-0700	Stakeholders have the need to ensure system support	Government
SN-0800	Stakeholders have the need for return on investment with minimal project risk	Financiers
SN-0900	Stakeholders have the need to ensure regulatory requirements are met and system complies with code	Regulatory bodies

ID	Stakeholder Need	Source
SN-1000	Stakeholders have the need to operate a system that is safe	System Operators
SN-1100	Stakeholders have the need for a system that is easy to maintain	Maintenance
SN-1200	Stakeholders have the need for easily accessible parts and sub systems	Maintenance
SN-1300	Stakeholders have the need to match demand and supply of electricity	Utility Company
SN-1400	Stakeholders have the need to garner public support and political goodwill	Politicians
SN-1500	Stakeholders have the need to reduce dependency on fossil fuels	Government
SN-1600	Stakeholders have the need to reduce cost of energy	Farm owner
SN-1700	Stakeholders have the need to get reliable electricity	Customer
SN-1800	Stakeholders have the need to provide oversight for water rights	Water rights actors
SN-1900	Stakeholders have the need to provide oversight for land rights	Land rights actors
SN-2000	Stakeholders have a need to create a system that is safe to dispose after use	Manufacturing

The definition of stakeholders' needs and requirements involves the activities necessary to elicit and prioritize these needs, and transform them into a set of defined stakeholder requirements. Defining the problem or the issue to be solved and identifying the opportunity for developing a new solution (or improving a system-of-interest), must begin prior to starting the activities necessary to define stakeholder needs and requirements (44). Figure 27 below is a diagrammatic representation of the interconnects in stakeholders needs and will be the basis for defining system requirements.

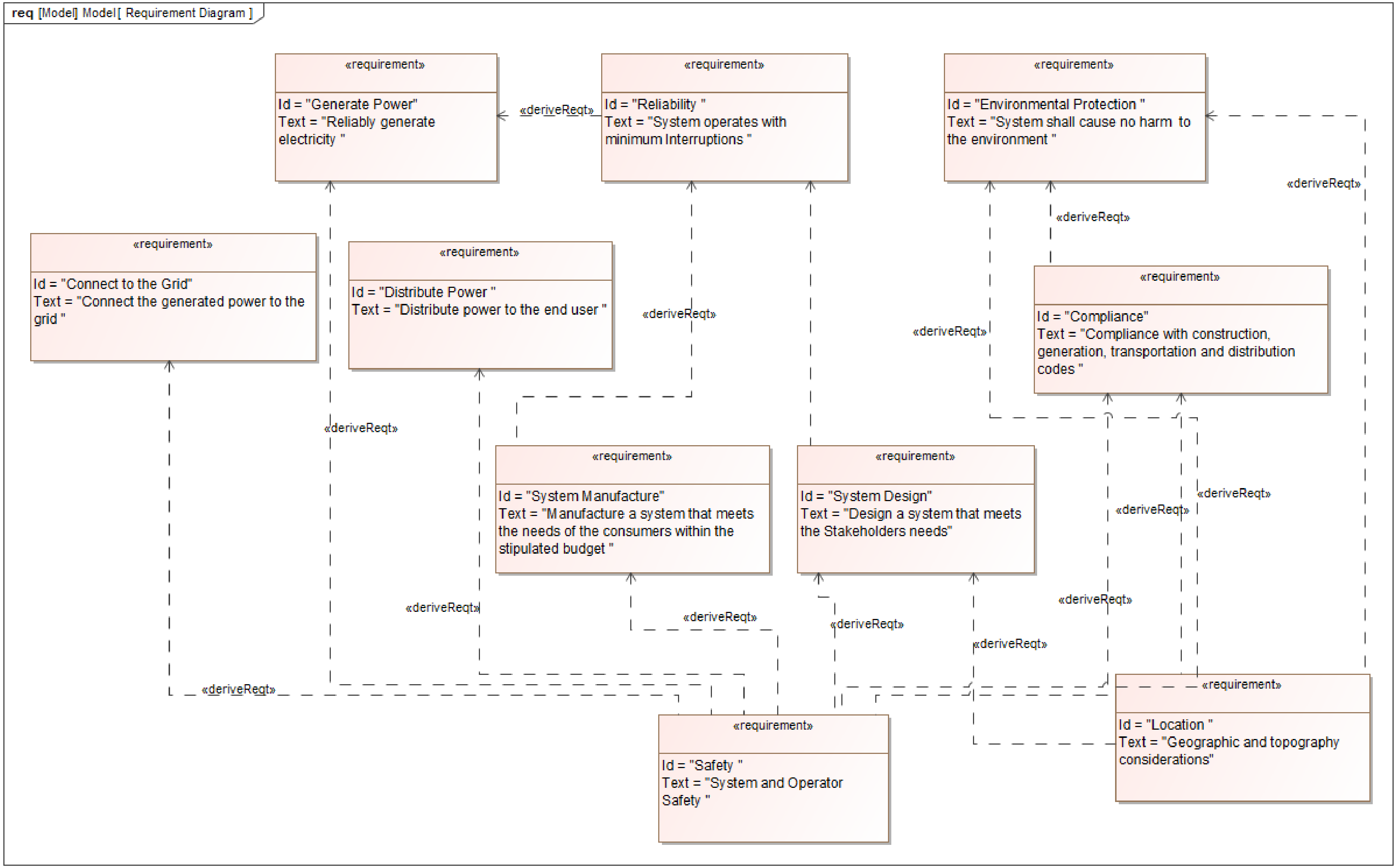


Figure 27: Interconnects in Stakeholder needs expressed as requirements

4 SYSTEM REQUIREMENTS

System Requirements are derived from Stakeholder needs. An important parameter for determining the requirements of a hydrokinetic energy farm is the regulatory framework that governs these systems. Long time frames to achieve regulatory approvals can result in a lack of investment in hydrokinetic systems with consequent retardation of needed technology development. The Federal Energy Regulatory Commission (FERC) has a leading role in regulating hydrokinetic (and other) energy through the Federal Power Act (FPA) authorization. Permits from the FERC give an individual firm the exclusive right to study and eventually utilize the hydrokinetic potential of a reach of river or marine region for which the permit applies (45). In addition to the FERC's regulatory role, other federal and state agencies provide input and their own regulatory function, depending on a particular project's proposed location. Table 5 below shows the relevant regulatory functions.

Table 5: Relevant regulatory functions

Permitting and leasing oversight agencies	
Agency	**Regulatory Authority**
Federal Energy Regulatory Commission (FERC)	In-water electric power generation (federal & state waters)
U.S. Army Corps of Engineers (USACE)	Land use and navigable waterways (federal & state waters)
U.S. Fish and Wildlife Service	Fish and habitat (state waters)
US Department of Natural Resources	Land use (state lands)
NOAA National Marine Fisheries Service (NMFSF)	Fish, marine mammal, and habitat conservation (federal waters)
U.S. Dept. of the Interior Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE)	Regulation and leasing (federal waters)

For projects located in ocean waters beyond the three-mile limit that defines state coastal waters, a project may require approvals from several federal agencies to meet regulatory requirements.

4.1 Considerations

Funding – Such projects are labour intensive and require a lot of money for design, development, operation, and maintenance. Funding considerations looks at the cost of materials, cost of construction labour, cost of operations, cost of maintenance, and cost of disposal. There are other factors that can affect funding like political goodwill and support from other stakeholders.

Return on investments: This is a key component for the plant owners, the financiers, and suppliers. The required ROI for any project is generally stipulated by the concerned stakeholders and can be negotiated prior to the start of the project, or at other stages that are agreed upon. There are other reasons why a project may be approved, but ROI plays a key role to the financiers.

4.2 Design Requirements

Design Requirements are closely linked to location (which provides the system context). System design starts with developing stakeholder expectations (their needs, goals, wants, objectives, constraints, and success criteria), and then developing the technical requirements (which incorporate functional requirements, performance requirements, interface requirements, operational requirements, safety requirements, and the "illities"). All these need to be validated based on the stakeholder needs. The Bureau of Ocean Energy Management (BOEM) partnering with National Oceanic and Atmospheric Administration (NOAA) have an open-source digital tool (Ocean Reports) that can be used to visualize coastal and ocean information, generate custom reports for all U.S. waters, and address design considerations depending on your intended site. For example, if you are intending to build your farm in Oregon State Waters, you can find information on the geographic area, depth and elevation, populated spaces, Federal, State and County Jurisdictions, Congressional and Legislative Districts, Federal Statutes, and Indian Land Areas.

Figure 28 below is a sample Oregon Waters report that can be generated by the tool. This open-source tool can help address key issues like a) Who are the key stakeholders? b) What is the market size? c) What is the appropriate farm size for this market? d) What are the Federal Statutes for the site? e) What are the legal restrictions for the site? f) What are the permitting requirements for the site? g) Does the design and construction meet the stakeholders' needs? g) What is the construction cost for this site? h) What are the depth considerations? etc.

The ability to generate steady sales is important for farm owner, financiers, suppliers, local & regional agencies, and policy makers. Having a sustainable business is pertinent to addressing legal restrictions and permitting requirements. Figure 29 below shows the design requirements which looks at system design in relation to site of the farm. The main constraints here are shallow water/ deep water constraints, topography, budget, safety, environment protection, and distance from the shore.

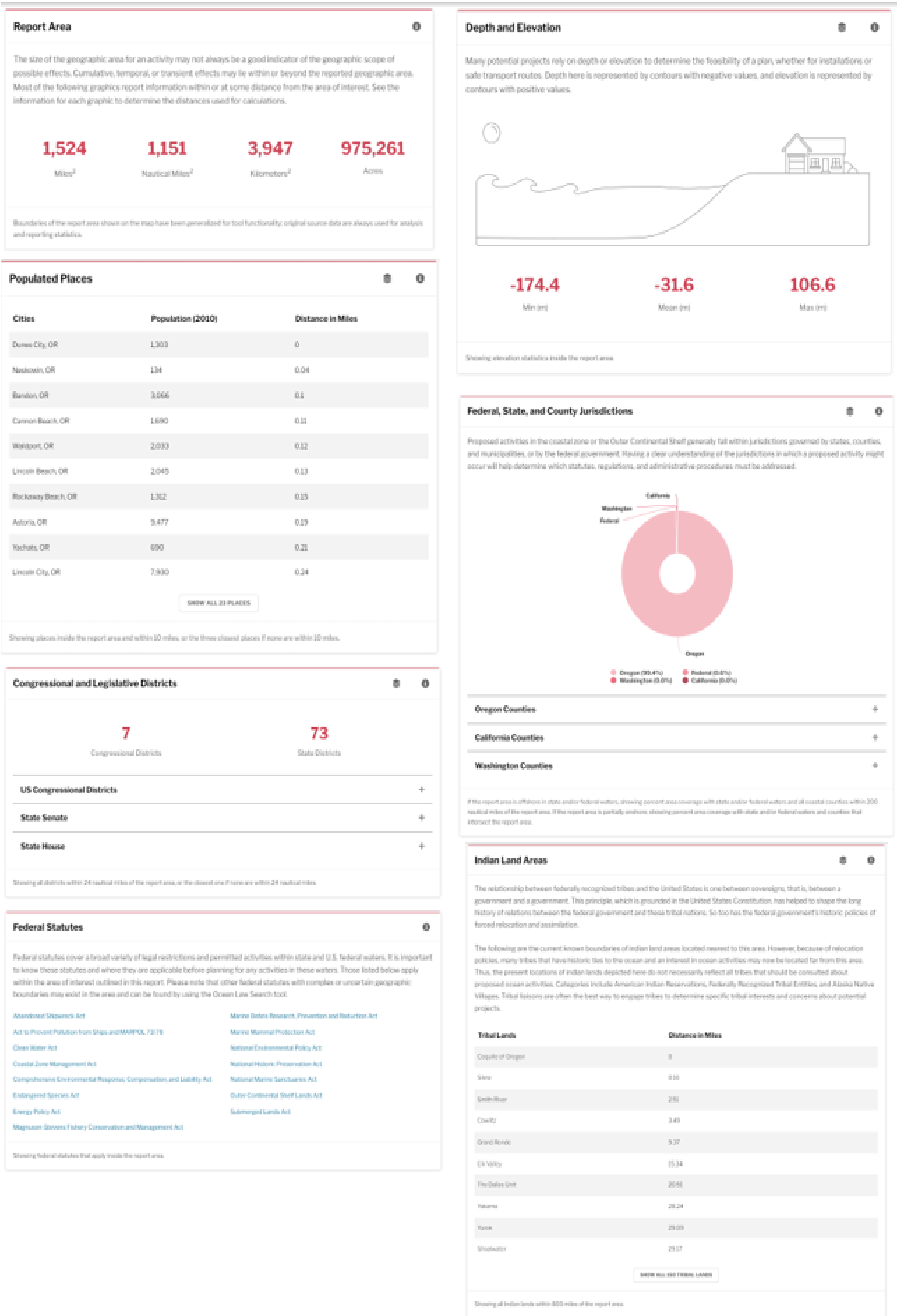


Figure 28: Oregon Waters Ocean Report

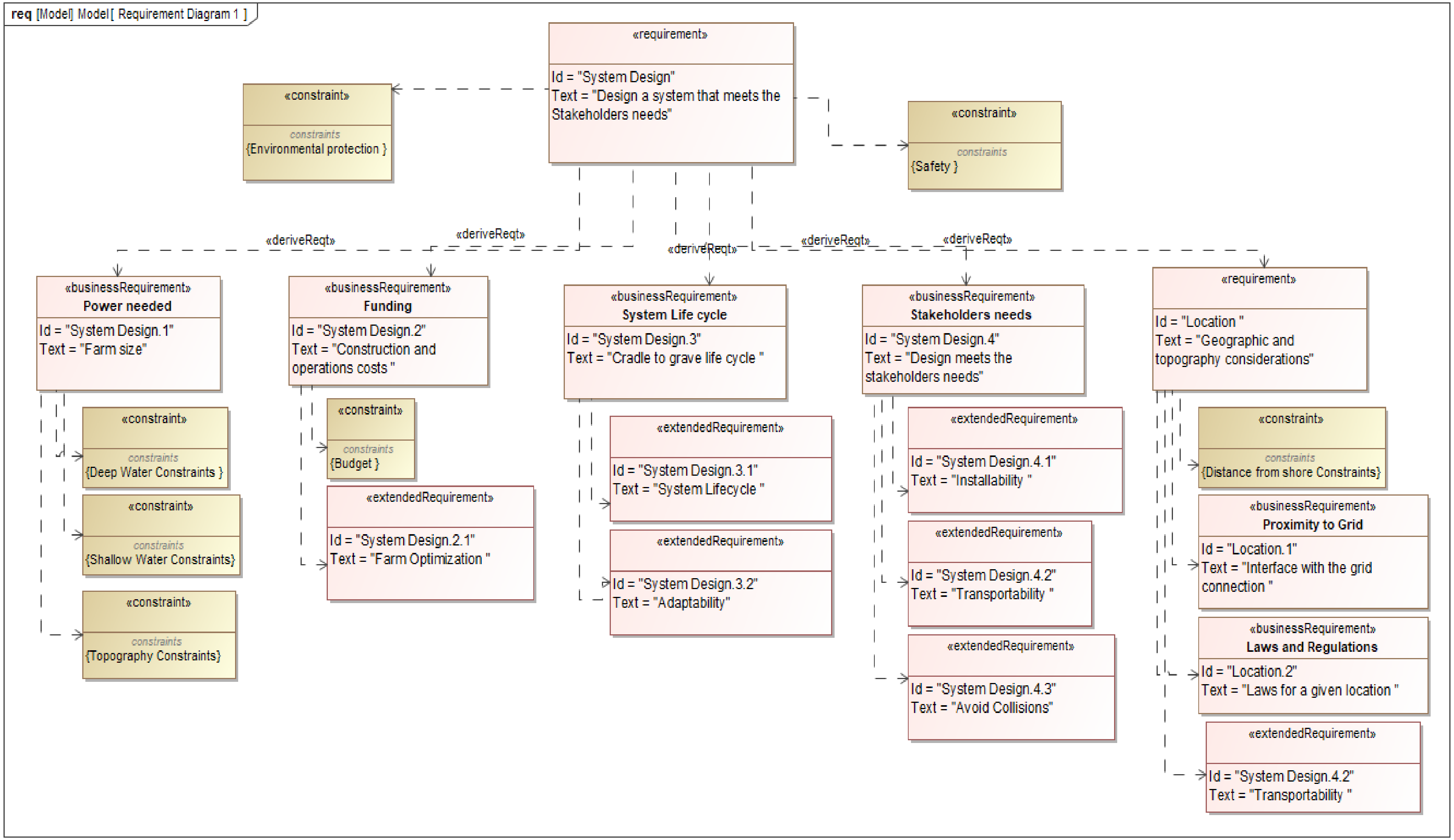


Figure 29: Design Requirements Diagram

4.3 Manufacture/Construction Requirements

There is a Wave Energy Converter Simulator (WEC-Sim), developed by NREL and Sandia National Laboratories, that simulates how wave energy technology designs might perform once deployed. The open-source WEC-Sim tool was developed in MATLAB/ SIMULINK and can model devices of almost any shape and size and provide precise data on how each technological component will function in waves of various heights and forces. That includes the machine's body, joints and constraints, power take-off systems (which convert wave energy into electricity), and the mooring systems that keep devices tethered in place. A generalized workflow diagram is as shown in Figure 30. Working from left to right, this diagram illustrates the major steps in determining characteristic loads for a WEC. This characteristic load, which may be the maximum mooring tension or equivalent fatigue load in a structural member, can be evaluated against structural capacities (46).

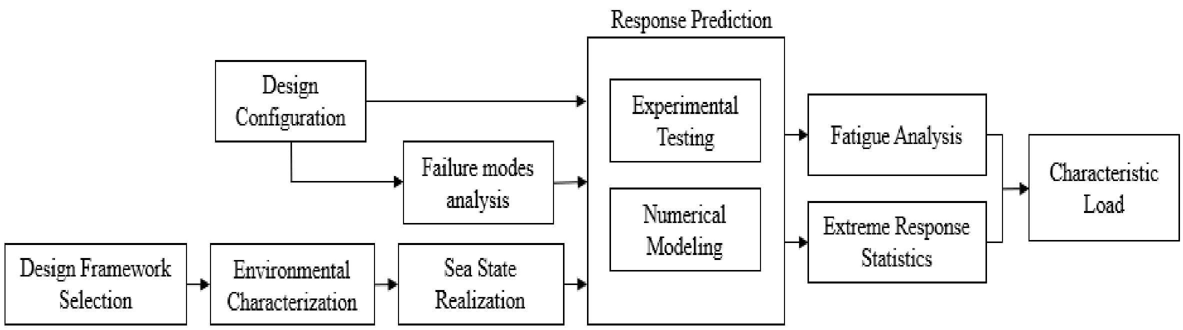
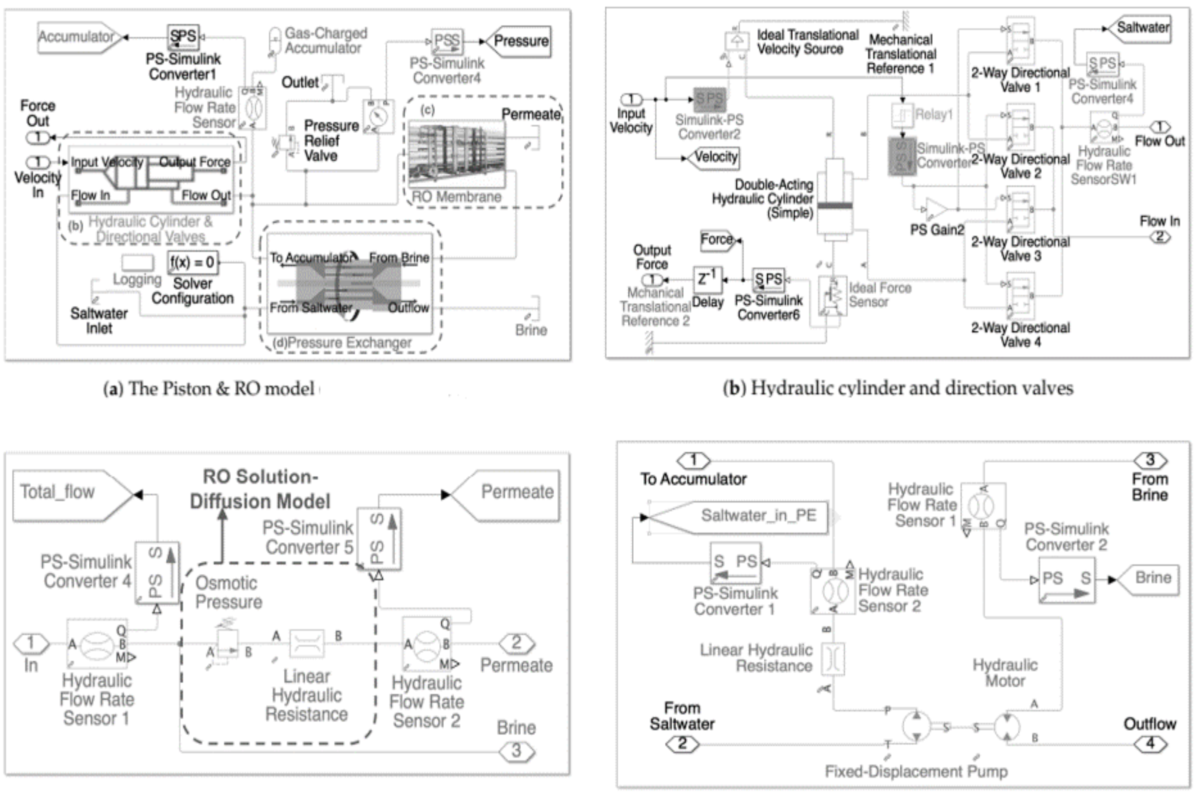


Figure 30: General WEC design workflow with component processes

WEC-Sim's comprehensive analyses can save the wave energy community time, money, and effort by exploring new designs in a low-risk, virtual environment—well before expensive, high-risk physical modelling campaigns and ocean trials. The software enables technology developers to improve their wave energy converters during the design process, potentially speeding up development. And WEC-Sim can simulate far more than wave energy technology. When paired with other modelling tools, it can analyse almost any ocean-bound device (47). For example, Figure 31 below shows the WEC-Sim model of a hydraulic component inside the Piston and RO block. The hydraulic system consists of a set of subsystems, including a dual-acting hydraulic cylinder, a set of directional valves, a gas-pressure accumulator, a pressure-relief valve, sets of RO membranes and a pressure exchanger (48).



(a) The Piston & RO model

(b) Hydraulic cylinder and direction valves

(c) RO model

(d) Pressure exchanger

Source: Journal of Marine Science Engineering

Figure 31: WEC-Sim model of hydraulic components

As such, hydrokinetic energy systems characteristic loads and threshold levels are well understood and built into the system considerations, and so the paper will not address threshold levels. There are also coastal engineering design codes and manuals that provide design philosophies, procedures, and formulae for the design, recommend suitable return periods (and methods to determine the wave climate for design), and provide recommendations for design wave height and period conditions. Figure 32 below shows the construction requirements for a wave energy farm. The system needs to be constructed before it can generate electricity. To do this, the primary considerations are, system design, structural and operation integrity, design configurations, and system budget. There are several constraints associated with manufacturing/construction, but the main constraint is compliance. The system will need to meet or exceed all construction regulatory requirements before operations can begin. The system will also need to meet regulatory and compliance requirements in daily operations and maintenance activities.

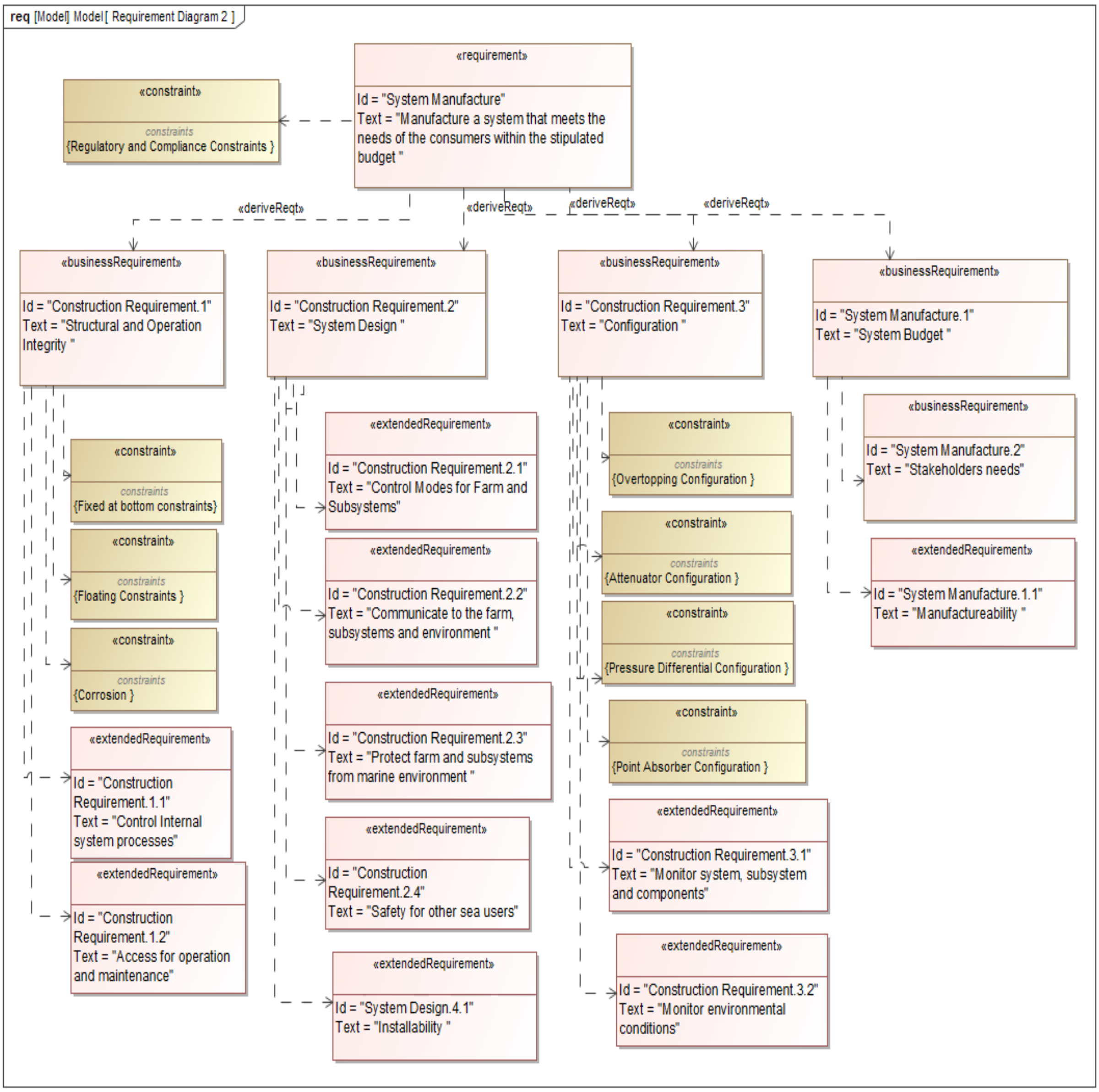


Figure 32: Construction Requirements Diagram

4.4 Functional and Operational Requirements

The overall functional and operational analysis integrates three elements (functional requirements, function allocation, and task analysis) to establish requirements for the farm design. System functional and operational analysis addresses operational aspects of the plant by systematically defining equipment, software, personnel, and procedural data requirements that meet all functional objectives of the farm. This also includes operation centers, the control room, and its operating crew. Functional requirements assist in determining the design of the farm and the design of the interface- particularly the control room interface and the fail-safe for safe plant shutdown outside the control room (49). Figure 33 shows the functional and operational requirements for a marine energy farm.

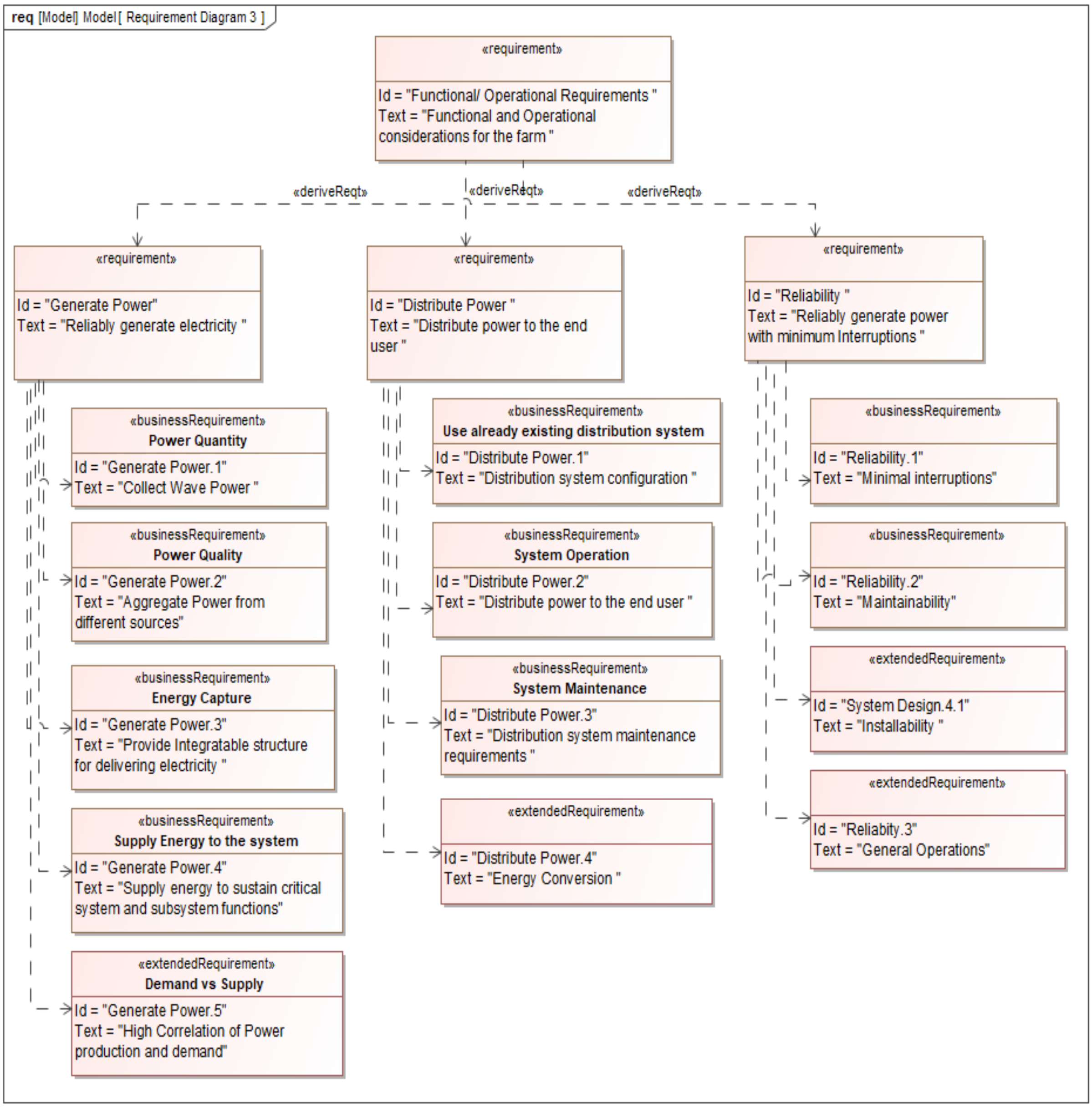


Figure 33: Functional and Operational Requirements

4.5 Interface Requirements

The grid is an external system to the farm and grid failure will limit project success. The wave energy farm should be designed to connect to the grid and the interface requirements and considerations are critical to the success of the project. Because of the stochastic nature of the marine environment, weather conditions or operational conditions may lead to extreme loads and responses that exceed fatigue limit. The probabilities of such events and their financial consequences (repair costs, loss of assets, or loss of production) need to be understood, and the relevant, possible cascade failures need to be considered (11). At the interface, the two main functions are to connect to the grid and distribute the power to the end user. Figure 34 shows the interface requirements for the farm.

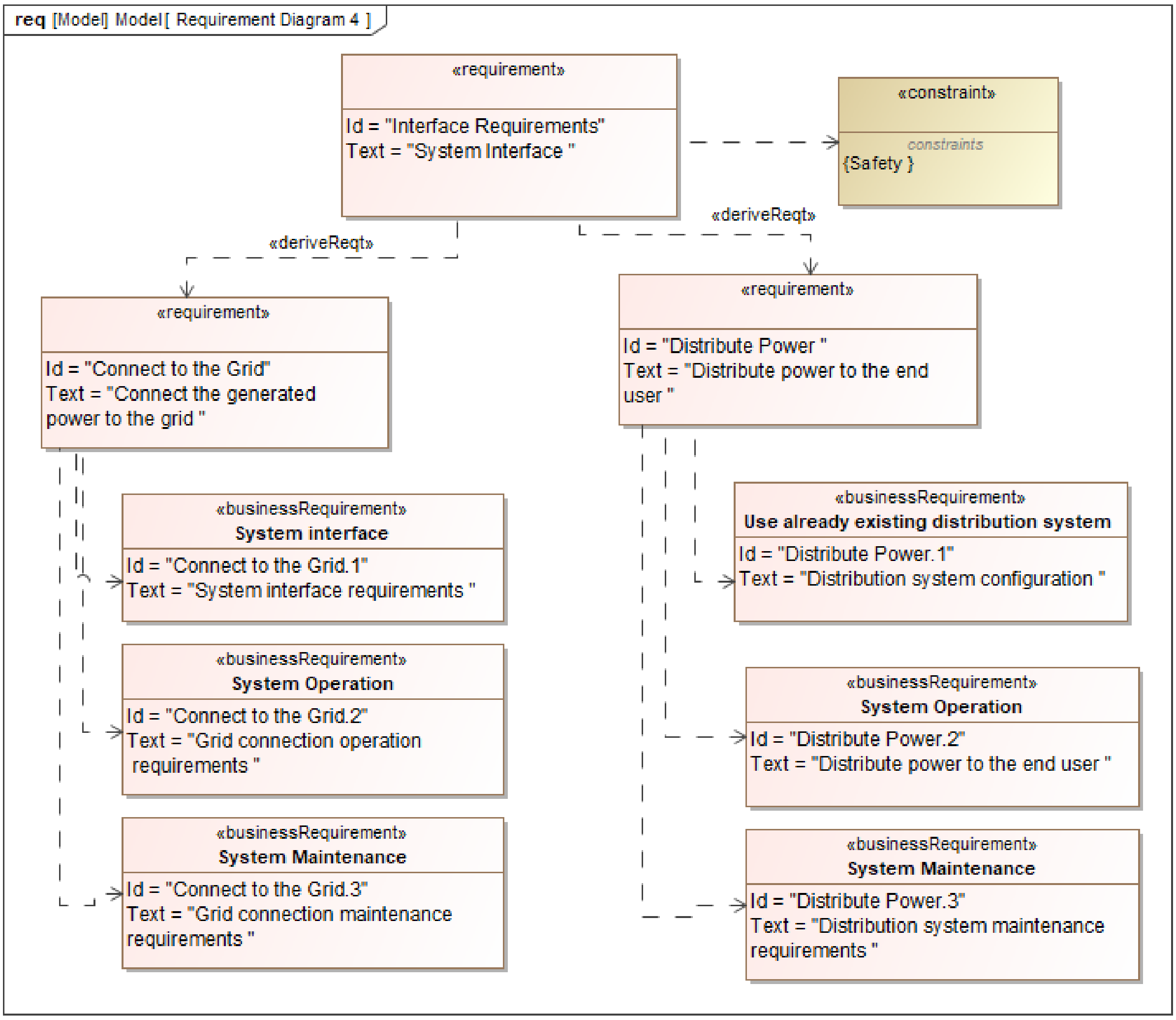


Figure 34: Interface Requirements Diagram

The interface requirements include:

1) The farm's ability to provide reliable energy production forecasts – this is required for 20-minute and 24-hour horizon. The forecasts are needed if the power generated is to be sold to utility companies or sold through a power purchase agreement (PPA). Intermittent power is challenging for grid operators when working on grid stability or load balancing, and this may limit the ability of the wave farm to sell the power they are generating. The farm should therefore have a high-capacity factor and produce electricity during periods of higher electricity demand.
2) Low uncertainty of operations and production – uncertainties may be due to reliability and durability of the subsystem or the system-of-interest. For example, if unplanned

maintenance requests are more than expected, there is a higher uncertainty in the system's reliability, and this may affect the farm's ability to meet the interface requirements.

4.6 Safety Requirements

Safety is a critical concern when human beings are involved, particularly at sea. This looks at the safety of everyone involved in the design, manufacture, and operation/maintenance of the farm. It also looks at the safety of marine/aquatic animals and the final consumer. The farm must consider the entire system lifecycle (from cradle to grave) and incorporate all safety measures bearing in mind that human beings (and other living creatures) can be unpredictable. Safety requirements address issues such as:

1) The farm's ability to avoid and survive collisions with other marine users, ships, and aquatic animals. They may collide with one or several parts/subsystems of the farm, and such collisions could cascade into system failures.
2) Farm's ability to survive grid failures, grid losses, or grid interruptions. What are the fail-safe mechanisms that the farm can use in such circumstances considering the grid is an external (enabling system)? The system should be protected from technical repercussions of failures in other systems that are outside the system of interest, and the financial repercussions should be minimal.
3) Farm ability to meet grid compliance requirements – this is the ability to deliver power that meets the power quality, voltage, frequency, and flicker requirements.

Safety is closely related to compliance, and some of the compliance requirements are enforced for safety reasons. The farm needs to meet all the environmental regulations for it to be environmentally acceptable. For example, The Fish and Wildlife Coordination Act directs the Service to investigate and report on proposed Federal actions that affect any stream or other body of water and to provide recommendations to minimize impacts on fish and wildlife resources. Figure 35 shows the safety requirements for the farm.

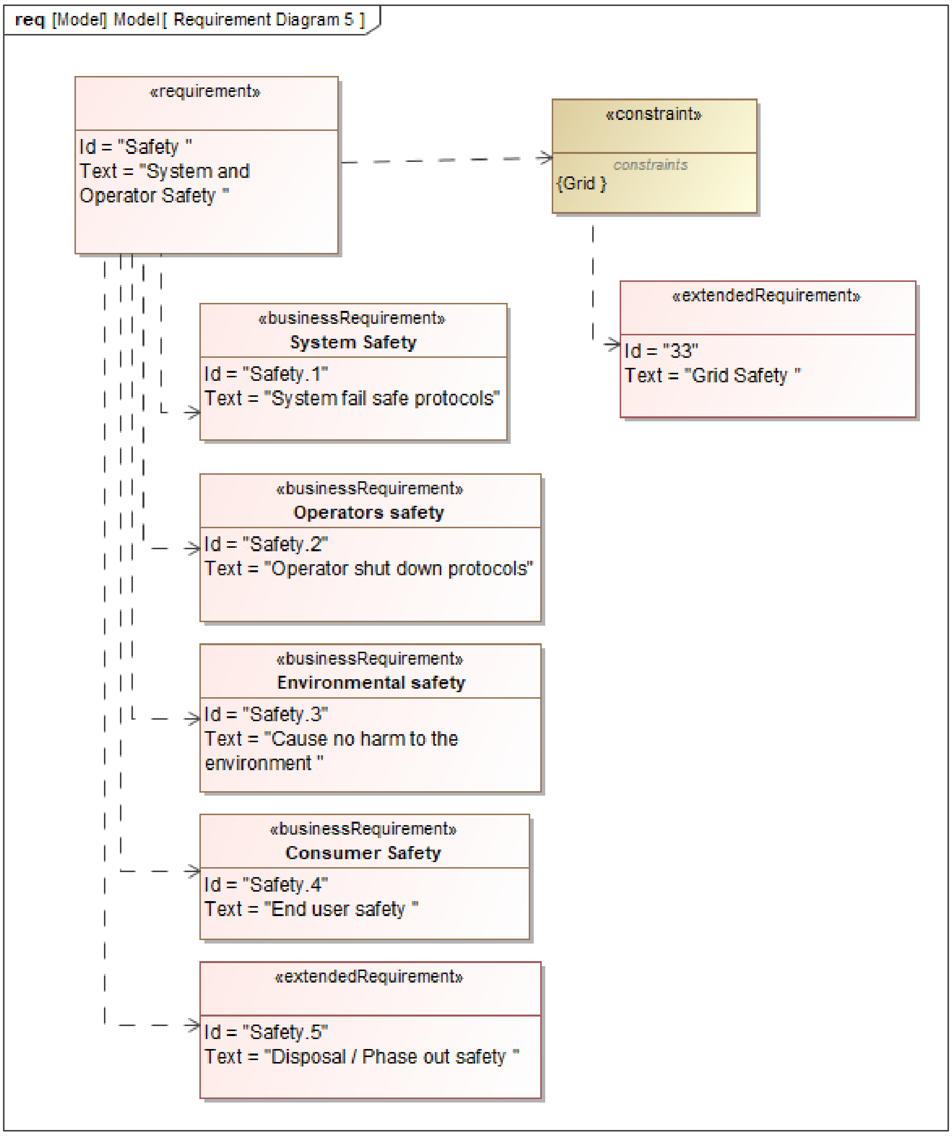


Figure 35: Safety Requirements Diagram

4.7 Reliability Requirements

Reliability looks at the probability that the system will perform its intended function, under the stated conditions, for the required period, without failure. System reliability can address the following issues:

1) How well can the system generate electricity from wave energy? Can it generate large amounts of electricity? A highly reliable farm can help avoid costly planned and unplanned maintenance costs, and the amount of electricity generated is essential to valuing the farm.
2) What is the system's durability over the lifetime of the plant? This will reduce the costs of maintenance and planned interruptions. If the wave farm is made of highly durable

components, the number of parts and components that are subject to wear and abrasion will be small.

3) Can the system absorb large amounts of wave energy? This implies the system can adjust to a wide range of frequencies, heights, and wave directions, and that it would be minimally affected by tides, currents, and wind.
4) Does the system have a high conversion efficiency of the extracted energy to electrical energy? This can be achieved by having a small number of conversion steps for the electrical system with each step designed to be highly efficient.

Reliability is attained by proven high-quality components, by reducing the number of parts or components depending on their known failure modes (looking at fatigue, wear, abrasion, corrosion, chemical attack, thermal overload, clogging, and photolysis), and by circumventing impulsive loads (things like end-stops, shock loading, and snap loads). For a system to be reliable the cost of repair for parts/subsystems that are likely to require frequent unplanned maintenance should be low. Costs in this context include replacement parts, transportation to and from the site of repair, fees incurred because of wait times for weather windows, and fees for trained workers. Reliability is coupled with environmental protection. It is not enough to simply build a system that can perform its intended function; it should do this without causing harm to the environment. This is a key parameter to the stakeholders and will be discussed further in the regulatory requirements section. Figure 36 shows the reliability requirements for the system.

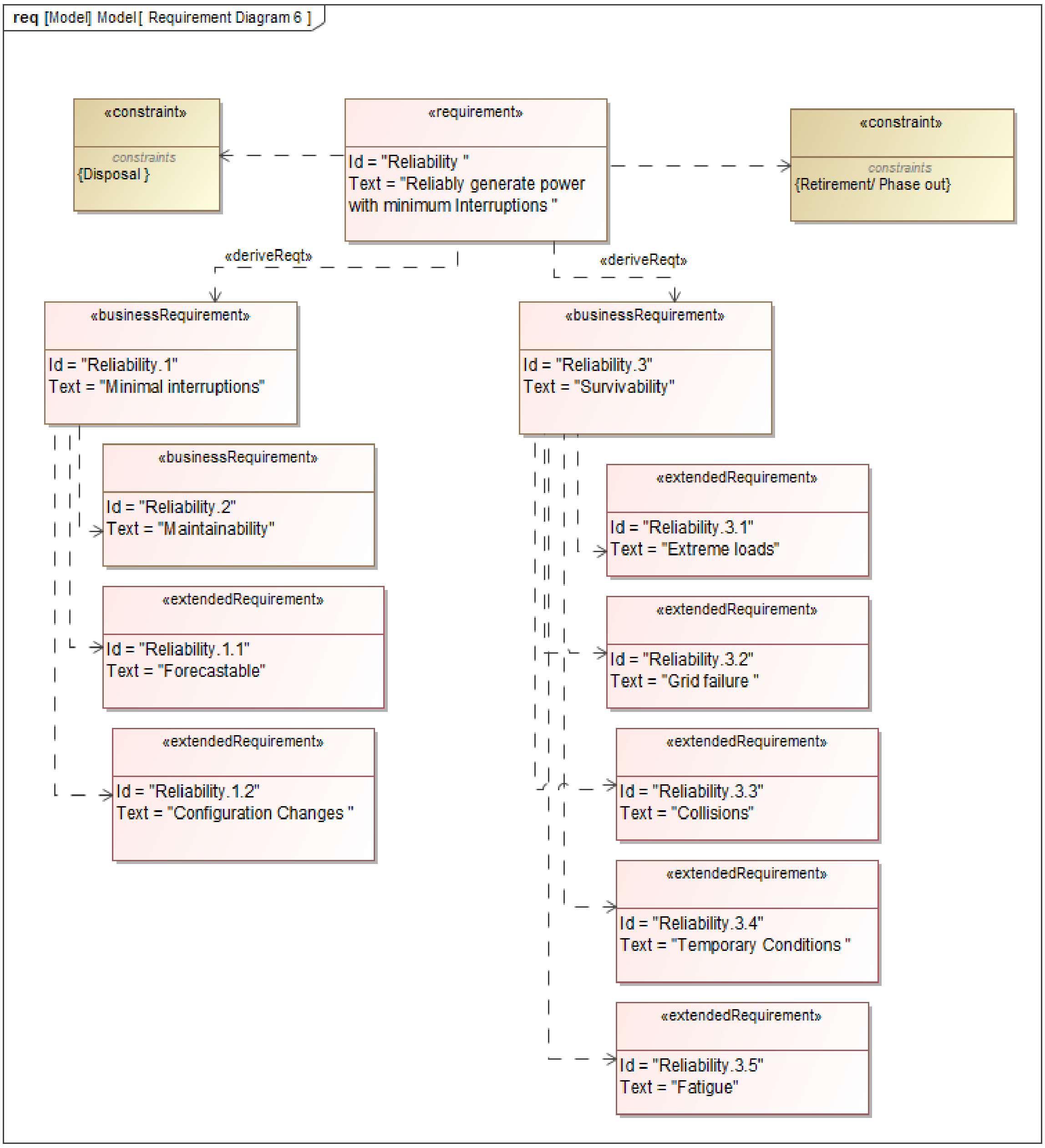


Figure 36: Reliability Requirements

4.8 Regulatory Requirements

Some requirements are implemented through site-specific binding regulatory compliance documents, such as federal facility agreements, consent decrees, and other legal arrangements, which may contain enforceable milestones for specific clean-up actions. The US Department of Energy signed many of the federal facility agreements with the Environmental Protection Agency (EPA) and state regulatory agencies in the early 1990s. The milestones in some of the documents were designed to be updated as conditions evolved. In addition, sites may apply for permits to conduct certain work, such as RCRA permits for the management of hazardous waste (50). On the other hand, The Federal Energy Regulatory Commission (FERC), is an independent agency that regulates the interstate transmission of electricity, natural gas, and oil. FERC also reviews proposals to build liquefied natural gas (LNG) terminals and interstate natural gas pipelines as well as licensing hydropower projects. The Energy Policy Act of 2005 gave FERC additional responsibilities as outlined and updated in their strategic plan. Regulatory and compliance requirements are heavily dependent on the location of the farm. Figure 37 below shows the general regulatory requirements for a wave energy farm.

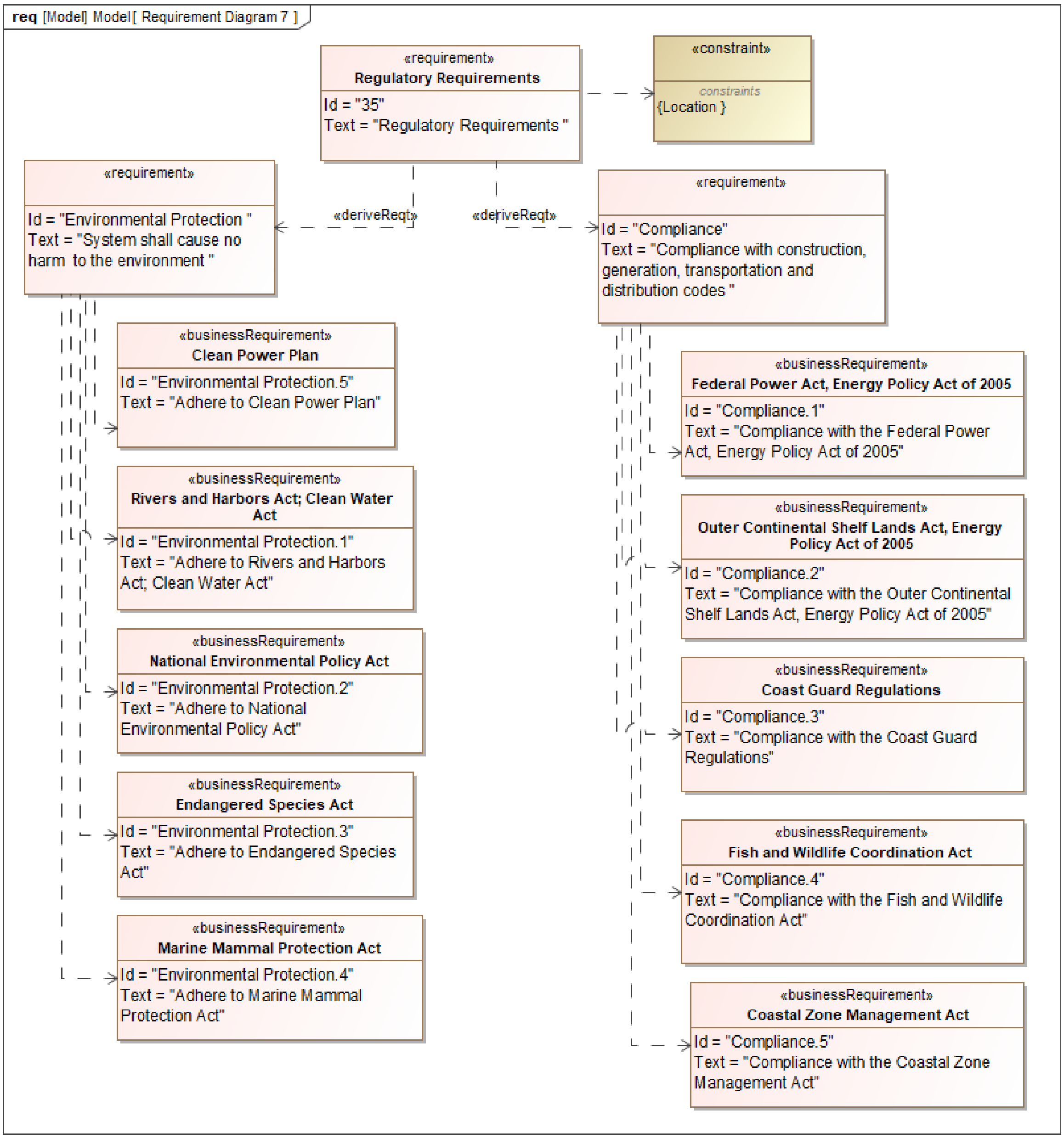


Figure 37: Regulatory Requirements

4.9 Investment Requirements

Investments in clean energy infrastructure needs to be scaled up significantly in the coming years to support the broader development, economic and climate agenda. Given strains on public finances, engaging private sector capital will be key. Several obstacles, resulting from market and government failures – including fossil-fuel subsidies, the lack of supportive policies as well as outstanding barriers to international trade and investment – still hamper investment in renewable energy. A key challenge for stakeholders to catalyse investment flows in clean energy is to design and implement clear and predictable policy frameworks. OECD has a Policy Guidance for Investment in Clean Energy Infrastructure that aims to assist governments in identifying ways to engage private enterprises in financing and developing clean energy infrastructure. It thus provides policymakers with a list of issues to consider for enhancing private investment in clean energy infrastructure, particularly in the following areas: investment policy; investment promotion and facilitation; competition; financial markets; and public governance. It also addresses other policy areas and cross-cutting issues (e.g., regional co-operation for promoting clean energy infrastructure) (51). Figure 38 below shows the investment requirements.

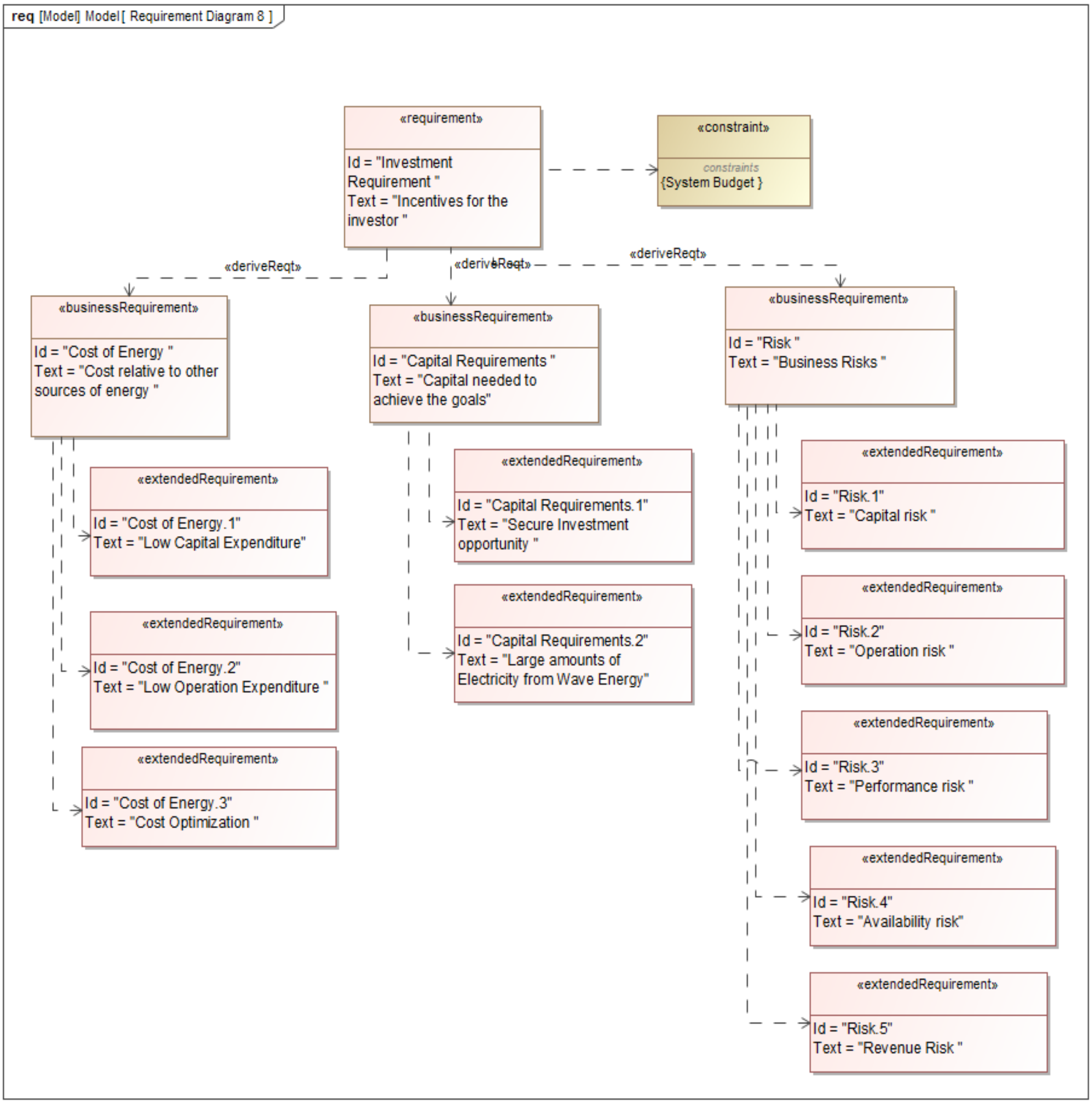


Figure 38: Investment Requirements

5 VIEWS

Knowledge integration and collaboration with external partners is a valuable step in the design process due to the increasing scale and complexity of the design problems. It becomes important for system engineers to be in close contact with stakeholders, (this includes the people, communities, and organizations who are affecting, or being affected by, the problem or the solution) from the early stages of the design process. Most of the methods utilized in this paper are user-focused, aiming at understanding the users and designing for the user experience (52). A project team using a similar approach would have a higher chance of success since the system needs to be useful and acceptable to the stakeholders.

The purpose of this section is to match stakeholders' needs with systems requirements. The System requirements are defined by The INCOSE Guide for Writing Requirements (2019) (53) and listed in a row of the table as presented in Table 6 below. These requirements are tracked down to stakeholders' needs that were defined in the earlier section. The priority levels were arbitrarily picked and can be rearranged to meet the stakeholders needs and requirements.

Table 6: Systems Requirement Description

ID	System Requirement	Priority	Description	Stakeholder Need/ Requirements
SR-DD-0100	Design and development	High	System shall generate power from wave energy	SN-0100
SR-DD-0200	Design and development	High	System shall meet the required energy needs for its location	SN-1300 and SN-0400
SR-DD-0300	Design and development	High	System construction shall meet all required codes	SN-0900 and SN-0500
SR-Q-0100	Quality	High	System operation and maintenance shall meet all required codes	SN-0900
SR-Q-0200	Quality	High	System shall meet all required permitting and inspection codes	SN-0900
SR-MS-0100	Maintenance and support	Medium	System disposal shall meet all required codes	SN-2000
SR-I-0100	Interface	Medium	System shall connect to the already existing grid	SN-0200
SR-I-0200	Interface	Medium	System shall distribute the generated power	SN-0200
SR-F-0100	Functional	High	System shall continuously operate with minimal interruptions	SN-1700
SR-MS-0200	Maintenance and support	Medium	System maintenance shall not require shut down	SN-1100

ID	System Requirement	Priority	Description	Stakeholder Need/ Requirements
SR-SR-0100	Safety and Reliability	High	The system shall adhere to the power industry required safety protocols	SN-1000
SR-MS-0300	Maintenance and Support	Medium	The system shall use standard parts/subsystems for ease of maintenance	SN-1200
SR-F-0200	Functional	Medium	The system shall reduce GHG emissions caused by power generation	SN-0600 and SN-1500
SR-F-0300	Functional	Medium	The system shall provide affordable power through wave energy	SN-0300 and SN-1600
SR-SR-0200	Safety and Reliability	High	System construction shall protect the environment	SN-0600
SR-SR-0300	Safety and Reliability	High	System operation and maintenance shall protect the environment	SN-0600
SR-RD-0100	Retirement and Disposal	Medium	System disposal shall cause no harm to the environment	SN-0600
SR-SR-0400	Safety and Reliability	High	The System shall comply with Grid performance Code requirements	SN-0900
SR-SR-0500	Safety and Reliability	High	The System Shall comply with the Electricity Distribution Code.	SN-0900
SR-Q-0300	Quality	High	System shall comply with water and land rights	SN-1800 and SN-1900
SR-F-0600	Functional	Medium	System shall provide the agreed upon return on investment	SN-0800
SR-MS-0400	Maintenance and Support	Medium	System shall be easy to operate and maintain	SN-1100
SR-F-0700	Functional	Medium	System shall garner support from all required stakeholders	SN-0700 and SN-1400

System requirements are all of the requirements at the system level that describe the functions which the system as a whole should fulfil, to satisfy the stakeholder needs and requirements. These are expressed in an appropriate combination of textual statements, views, and non-functional requirements; the latter expressing the levels of safety, security, reliability, etc., that will be necessary. System requirements play major roles in systems engineering, as they: a) Form the basis of system architecture and design activities. b) Form the basis of system integration and verification activities. c) Act as a reference for validation and stakeholder acceptance. d) Provide a means of communication between the various technical staff that interact throughout the project (54).

6 CONCLUSION

This paper addresses system requirements for a hydrokinetic power system. Generally, renewable energy technologies are seen as some of the most important solutions for the future, and they need to be further developed to take over most of the energy needs. Many emerging technologies exist, and they have different levels of maturity. The scale of implementation is not the same either. For marine hydrokinetic systems, there is still a need for more research to ensure the convergence of ideas and a well-thought-out implementation strategy. It is likely that future research and development in marine hydrokinetic energy will focus on the development of hardware for harsh ocean environments. Other research concepts will focus on lowering the capital and Operations & Maintenance costs. Eventually, there will be a convergence of ideas and concepts will emerge with mature technologies that are economically viable for massive commercial deployment (55).

Ocean wave energy is one of the most promising sources of clean, reliable, and renewable energy, and it is estimated that there is a theoretical global wave energy potential of 32,000 TWh available per year. Moreover, with approximately 40% of the world's population residing in coastal areas, it provides opportunities for the deployment of Wave Energy Converters (WECs) for distributed generation. Hydrokinetic systems provide the solution to the demand for electricity without the consequences posed by climate change. There is an increasing need for systems that can generate electricity from renewable energy sources. Based on what this paper covers, an area that would need further examination is research that would facilitate convergence of ideas and designs. We acknowledge that there is no one size fits all design or idea, but a convergence of ideas would enhance synergy and enhance investment in the industry. Also, since water as a resource is unevenly distributed throughout the world, converting waves into a useful form of energy will require the identification of potential Wave Energy Farm (WEF) locations. This should be undertaken in tandem with selecting an appropriate Wave Energy Converter (WEC), as the characteristics of these devices are critical in capturing the available wave power.

The paper looked at high level system requirements while acknowledging that there is need for further work to address the specific needs and considerations that are associated with the site of the farm. It does not get to the level of granularity required to have a complete set of system requirements. As discussed, most of the system requirements are dependent on the Wave Energy Farm (WEF) site, therefore more research is required to get a complete set. Ideally, the process should start with identification of a site before identifying all the stakeholders and collecting their needs/wants. Also, Technology Readiness Level (TRL) varies for each location and a complete set of design & construction requirements needs to start with the site. Outside this research, areas for future study include:

1. **System cost analysis and cost optimization:** As shown in the five-stage approach for Technology Readiness Levels (TRLs), a wave farm needs to achieve commercialization. This requires further cost analysis and cost optimization research. The TRLs are a great benchmarking tool for analysing how far we are from commercialization of the technology.
2. **System Verification and Validation**: There are a lot of pilot projects throughout the world. These projects were conducted independently and there is still need to have convergence of ideas and processes. Since the costs associated with ocean tests are high, most of the research in this area is based on simulations and mathematical models which have limitations. Research would focus on standardization and for system verification and validation. The verification methods that are appropriate for these systems are:

   Inspection (**I**) – Verification by inspection consists of visual determination of physical characteristics. Visual inspection of either graphical interface, textual results, Stakeholder manual, or equipment manufacturer specifications. Provide documentation and/or visual inspection, providing evidence of the correct implementation that satisfy the requirement by means of screenshot, extraction of sections from operational manuals, etc.

   Analysis (**A**) – Verification by analysis is done when other methods are not appropriate or too cumbersome to perform a verification by test. It is usually done by collecting data like test results related to some part of the system, and then, knowing the system design, an engineering-based judgement is performed to infer whether the verification was successful or not.

   Demonstration (**D**) – Verification by demonstration is done when verifying the behaviour of the system, either once or more than once, without special test equipment or instrumentation. Demonstration can be documented in different ways, such as with pictures or screen captures.

   Test (**T**) - Verification tests consist of measuring product performance and functions under representative environment

7 APPENDIX

7.1 Glossary

This glossary is created as a supplement for the CAMEO Model to provide insights on applicable terminology and how to use the model. Its aim is to facilitate consistency in describing system requirements of a hydrokinetic system. The model is publicly available in Github through the link: https://github.com/ColoradoOmbogo/SysML-Hydrokinetic-Systems-Requirements and users are encouraged to customize the model to make it a conclusive and useful tool. Use of the tool is intuitive and there are two main sections in the model.

Section 1: Looks at the stakeholders and their viewpoints. This is a general list of stakeholders, and the system can be customized to either add more stakeholders (if they are not represented in the classifications above), delete stakeholders (if they are not relevant to the intended farm site), or separate stakeholders (if there is need to divide one stakeholder further) to ensure all their needs are met.

Section 2: Looks at the requirements for system design, system manufacture, safety, functional/operational, interface, reliability, regulatory, and investment. Though these are the categories that were picked, the model is customizable and different classifications can be used based on stakeholder needs.

Other diagrams in the model are looking at interconnects and dependencies among the requirements and the stakeholder viewpoints. Figure 39 below shows the sections available through the model .

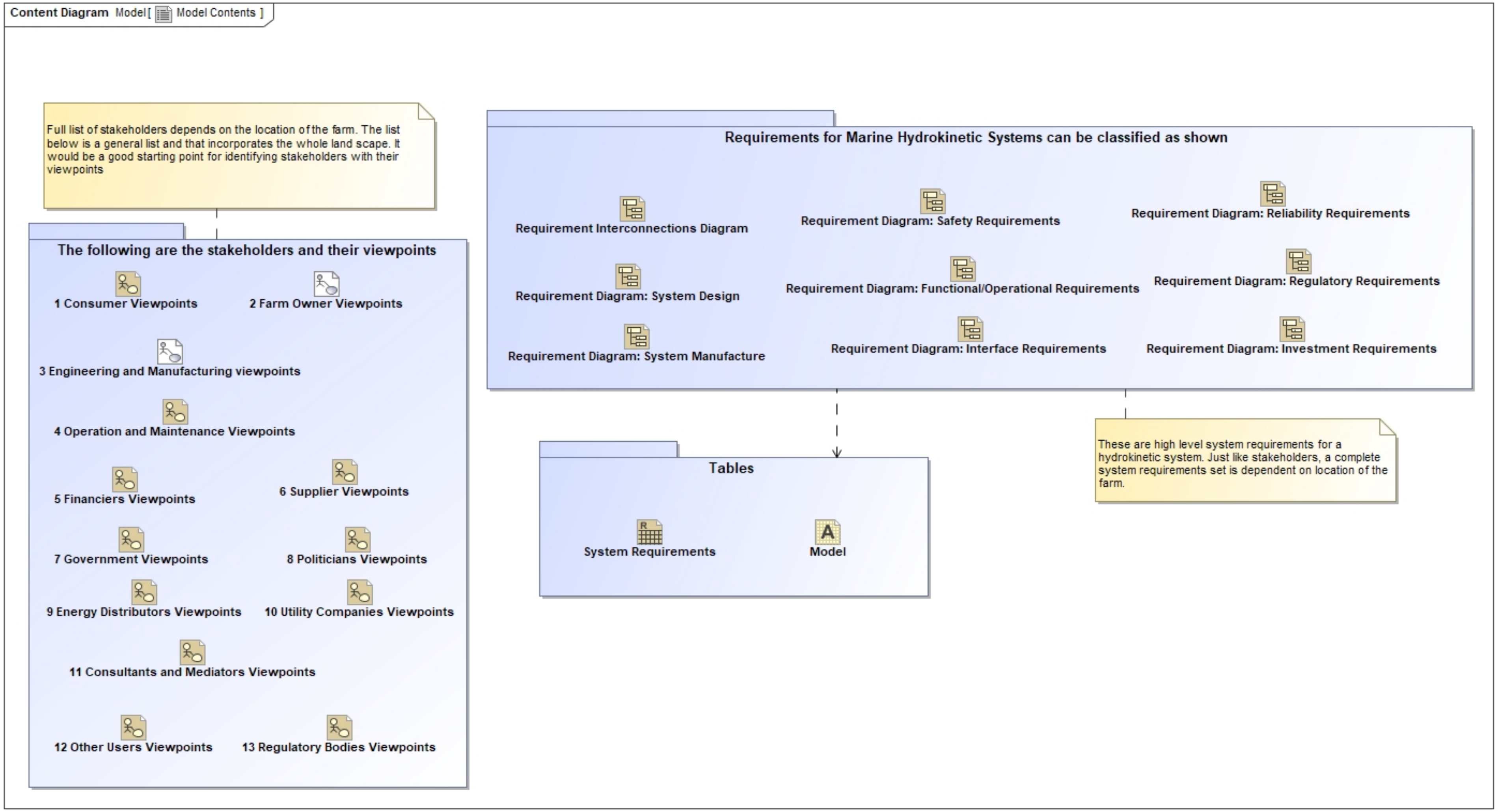


Figure 39: Glossary of Marine Hydrokinetic System Requirements

7.2 Acronyms

The project shall use the following labelling convention to associate unique identifiers and acronyms.

Table 7: List of Acronyms

Tag	Description
ACHP	Advisory Council on Historic Preservation
BIA	Bureau of Indian Affairs
BOEM	Bureau of Ocean Energy Management
BLM	Bureau of Land Management
CC	Control Centre
COE	US Army Corps of Engineers
CWA	Clean Water Act
CZMA	Coastal Zone Management Act
DPS	Distributed Power Systems
EPA	Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
FONSI	Finding of No Significant Impact
FPA	Federal Power Act
FR	Functional Requirements
FWS	US Fish and Wildlife Service
GHG	Greenhouse Gas Emission
HEE	Hydrokinetic Energy Extraction
KWh	Kilowatt Hour
MW	Mega Watt
NHPA	National Historic Preservation Act
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
LCA	Life Cycle Analysis
RD	Requirements Document
RES	Renewable Energy Sources
ROD	Record of Decision
RR	Reliability Requirements
SR	System Requirements
SRD	System Requirements Document
SOI	System of Interest
TPL	Technology Performance Level
USCG	US Coast Guard
USFS	US Forest Service
USGS	US Geological Survey
WEC	Wave Energy Converter
SN	Stakeholder Needs
SG	Stakeholder Goals
QR	Quality Requirements

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