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Simplified wind farm design as a serious game

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Abstract:
To maintain the current momentum of increasing interest and development in offshore wind energy, there is a need for novel training tools for engineers and researchers. Concurrently, additional educational outreach activities are required to inform the general public on the cost of energy from offshore wind and the research to improve it. A serious game may enable a new group of learners to explore the topic of offshore wind. The objective of this study is to develop a serious game for the design and management of offshore wind farms to be used for training and dissemination. The game's effectiveness is measured in terms of its simulations and its educational power. The study includes a literature review of serious game design and offshore wind energy followed by the development of game design and a functioning prototype using Python. This prototype was playtested and evaluated for educational impact and playability. The game design involves the joint tasks of building a game framework and developing a simplified offshore wind farm simulation. This simulation addresses weather prediction, offshore wind farm design, operation and maintenance, energy demand, climate change, finance, and stakeholder influence. The weather prediction model uses a Markov chain matrix to generate different sea states for every iteration of the game. The game is considered effective with respect to its simulation efficiency and its ability to produce realistic values for offshore wind energy. Playtesting demonstrated immersion and informed decision making among participants. Additional surveys revealed that the participants' knowledge on offshore wind had increased while playing the game. Key recommendations for future versions of this serious game about offshore wind energy are listed.

Keywords:

1. Offshore wind
2. Serious game
3. Weather forecasting
4. CoMEM

Esther R. Dornhelm

ERASMUS +: ERASMUS MUNDUS MOBILITY PROGRAMME

Master of Science in

COASTAL AND MARINE ENGINEERING AND MANAGEMENT

CoMEM

SIMPLIFIED WIND FARM DESIGN AS A SERIOUS GAME

Norwegian University of Science and Technology
July 11, 2018

Esther Dornhelm

The Erasmus+: Erasmus Mundus MSc in Coastal and Marine Engineering and Management is an integrated programme including mobility organized by five European partner institutions, coordinated by Norwegian University of Science and Technology (NTNU).

The joint study programme of 120 ECTS credits (two years full-time) has been obtained at two or three of the five CoMEM partner institutions:

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- Technische Universiteit (TU) Delft, The Netherlands
- Universitat Politècnica de Catalunya (UPC). BarcelonaTech. Barcelona, Spain
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During the first three semesters of the programme, students study at two or three different universities depending on their track of study. In the fourth and final semester an MSc project and thesis has to be completed. The two-year CoMEM programme leads to a multiple set of officially recognized MSc diploma certificates. These will be issued by the universities that have been attended by the student. The transcripts issued with the MSc Diploma Certificate of each university include grades/marks and credits for each subject.

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CoMEM Master Thesis

This thesis was completed by:
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Professor Michael Muskulus, Department of Civil and Environmental Engineering

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Preface

This master's thesis has been submitted in fulfilment of the requirements for the title of Master of Science (MSc) from the Erasmus Mundus Master in Coastal and Marine Engineering and Management (CoMEM). The study was completed at the Norwegian University of Science and Technology at the Department of Civil and Environmental Engineering. This work has been done under the supervision of Prof. Michael Muskulus and Helene Seyr, PhD candidate.

This work was conducted in an attempt to evaluate a new, alternative form of training and dissemination of scientific knowledge of offshore wind energy in the form of a serious game. The contribution of this study focuses on the simplification of offshore wind farm design, management, and lifetime costs in addition to evaluating the effectiveness of such a serious game. The concept is part of a proposal from the European Union's Advanced Wind Energy Systems Operation and Maintenance Expertise (AWESOME).

One innovative feature of this project is the placement of offshore wind energy in a new context. The dual purpose of the developed serious game, which is meant as a training tool for engineers and researchers as well as a dissemination instrument for the general public, makes it a unique and novel application in offshore wind energy. The future outlook of the study includes a strong potential to increase understanding and awareness about the challenges and opportunities of offshore wind energy as its full potential is realized in the future energy mix.

Summary

Offshore wind farm design and management is a complex endeavor. The relevance of cost and design drivers is difficult to assess even for experienced engineers. To maintain the current momentum of increasing investment, interest, and development in the field of wind energy, there is a need for the additional education of engineers, researchers and the general public. The engineering community would be best served by novel training tools and techniques to enhance recognition of design drivers, long term consequences of maintenance choices, and large-scale energy network potential. Concurrently, additional educational outreach activities are required to inform the general public on the price of energy from offshore wind and the costs of research to improve it. There is therefore also a need for educational outreach activities.

A modern approach to provide this education is to develop a serious game that teaches users important facts about offshore wind farm design and management and that is driven by an underlying, complex simulation. This study focuses on the simplification of offshore wind farm design, management, and lifetime costs in addition to evaluating alternative serious game approaches. The project goals are:

> *To develop a digital game for the design and the operational management of offshore wind farms to be used for training and dissemination; and*
>
> *To measure game effectiveness in terms of its simulations and educational power.*

The research starts with a familiarization of serious game design through the review of existing literature and digital and analog games. Literature is reviewed on the design of offshore wind farms, their operational management in practice and in research, and the identification of uncertainties with respect to future challenges. This review informs the game design process by defining the game framework and outlining the simulation of simplified offshore wind farm design and management. The final game design includes the construction and management of wind farms in a virtual sea to reach the preselected target within an allotted time and budget.

The offshore wind energy topics addressed in the game include weather prediction, offshore wind farm design, operation and maintenance (O&M), energy demand, climate change, finance, and stakeholder influence. The game uses procedural generation of weather and wind farm failures so that each run is unique. The weather prediction model uses Markov chain models to generate synthetic sea states during the game simulation. Results show that the model meets the stated requirements well when compared to similar studies.

The remaining offshore wind farm topics are integrated in varying degrees of detail to create the additional game rules and functions. Optimizer functions are programmed to give the user feedback on optimal substructure selection and O&M strategy. The game is completely defined and documented, and a playable prototype is programmed in Python using object-oriented programming. Several game run results using parameters identified in base case studies are compared to real offshore wind farm parameters. Game effectiveness in terms of simulation power was assessed through repeatedly running and evaluating the program. Results were typically accurate across the numerous parameters with minor exceptions regarding the under- or overestimation of costs. An analysis of simulation speed showed that the efficiency can be improved by reducing the number of random number generations per game loop.

The final game prototype was playtested in three segments, in order to assess its effectiveness in terms of educational power. A questionnaire distributed mid-study revealed specific areas of interest based on individual background. A playtesting session revealed that players were immersed in the game, made informed decisions while playing, and explored different features of the game. Surveys distributed before and after playtesting revealed that the participants' knowledge on offshore wind farm design had increased while playing the game. The most common new terminology expressed in post-game surveys include turbine and structural failures, electricity price, grid connections, O&M, and wind speed. The group discussions have highlighted the importance of improving game feedback. Specific points of interest are providing more direction on the long-term impact of choices and consolidating information in an improved interface.

This study documents the simplification process of offshore wind farm design. It outlines the necessary fundamental elements and provides an indication of where an increased level of detail may improve the accuracy of simulation results. Additionally, successful and unsuccessful playability factors regarding immersion, flow, and user experience are documented through the evaluation of a formal playtesting session. In doing so, this study provides a starting point to engage the public, game developers, professionals, and researchers to develop a new type of tool and understanding for offshore wind energy.

Acknowledgement

No academic work is ever achieved on one's own. It has taken the support, input, and expertise of several people to produce this work.

Firstly, I would like to thank Prof. Michael Muskulus for his continuous support through this thesis. Our meetings always brought new challenges to light and inspired me to expand upon the various facets of the thesis. His support challenged me to look deeper into unfamiliar subjects and to expand my programming capability.

Secondly, I would like to thank PhD Candidate Helene Seyr for providing frequent and valuable guidance. Her input always resulted in improvements to the final product in areas ranging from general concepts to minute details and creative features. She also reminded me to prioritize at times when the amount of work seemed overwhelming.

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Finally, I must express my profound gratitude to my parents, family, and friends for providing support and encouragement throughout my years of study and through the process of completing this thesis. Especially to all of my fellow CoMEM students, I am grateful for the experiences we've shared and accomplishments we've made together to complete this degree. This achievement would not have been possible without them. Thank you.

Esther Dornhelm
Trondheim, 2018

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1. Introduction

1.1 Background

International climate change policies have driven the renewable energy sector to immense investments in industry and research globally. The growing success of one such renewable resource, offshore wind energy, can be linked to the developments produced in research being quickly realized in the industry. New offshore wind installations saw a record year in 2017, growing 101% compared to 2016 with €7.5 billion of new investments announced to finance new farms (Wind Europe, 2017). Despite the growing success, there are still challenges to overcome before truly competitive costs of energy compared to other energy sources without sacrificing safety or productivity can be achieved.

To address these challenges, many studies are being conducted and field tested on cost reducing and production enhancing measures related to: innovative bottom fixed and floating support structures; improved wind speed and power forecasting methods; intelligent control systems; realistic grid integration sensitive to economic and political objectives; optimization of operation and maintenance (O&M) strategies under uncertainty; and much more.

Offshore wind farm design and operational management is a complex task as is demonstrated by the variety of approaches in practice and research. Even for experienced engineers it is sometimes difficult to correctly judge the relevance of different cost factors and design drivers in a multidisciplinary field. There is much that can be learned about how well-practiced and newly developed technologies and strategies affect offshore wind energy, and by extension the whole energy system. To maintain the current momentum of increasing investment, interest, and development in the field, there is a need for novel training tools and techniques for engineers and researchers that integrate the work of both industry and academia. Concurrently, the general public is concerned about the price of energy from offshore wind energy and the costs of research to improve it. There is therefore also a need for educational outreach activities.

A modern approach to provide this education is suggested by the European Union's Advanced Wind Energy Systems Operation and Maintenance Expertise (AWESOME): A serious game modelling stochastic wind park modelling and maintenance scheduling under uncertainty (UOL-FORWIND, NTNU, TUM, 2016). This study spearheads this concept through the development of a serious game that teaches users important facts and lessons about offshore wind energy. This approach offers the opportunity to integrate both existing and pioneering offshore wind practices in a tool that is as educational as it is entertaining. The game will be driven by an underlying, complex simulation based on engineering models, packaged in the form of an optimization challenge. Development of this simulation, optimization strategies, and game framework is the main scientific contribution of this project. The playability and engagement of the game drives how this otherwise non-unique simulation fits into an entirely new context.

The primary aim of this master thesis is to evaluate alternative forms of training and dissemination of scientific knowledge in the form of a game. A secondary aim is the integration of optimization strategies that solve the game either independently or as a response to user input, i.e., which can determine optimal playing strategies corresponding to optimal design or operational management of an offshore wind farm. Procedural generation will be used to capture uncertainties, so each run will present a different scenario to the user.

The project consists of the development a concept for a serious game in wind farm design and operational management. The game is completely defined and documented, and a playable prototype was programmed and evaluated in a playtesting session with voluntary participants.

1.2 Project goals

The overall goal is to evaluate a new, alternative form of training and dissemination of scientific knowledge of offshore wind energy in the form of a serious game. The contribution of this study focuses on the simplification of offshore wind farm design, management, and lifetime costs in addition to evaluating alternative serious game approaches. The project goals are to:

1. Develop a digital game for the design and the operational management of offshore wind farms to be used for two purposes:
   a. Training: The game should act as a novel training technique/tool by engineers and researchers to better understand cost and design drivers.
   b. Dissemination: The game should teach the public about important facts about offshore wind energy and serve as educational outreach.
2. Measure game effectiveness in terms of its simulations and educational power.

The educational goals of the game are different for the two project purposes of training and dissemination. Table 1.1 presents the educational goals for each purpose in terms of the desired change in knowledge and sentiment.

Table 1.1: Educational Goals

	Training	**Dissemination**
User	Engineers and researchers who want or need to improve their comprehension of offshore wind farm processes.	Young adults or adults without prior knowledge of offshore wind and are prompted or interested to gain knowledge on important facts or trends.
Desired knowledge	User should be able to describe: • Terminology • Major design drivers • Major cost drivers • Environmental parameters • Operational management dilemmas	User should be able to describe: • Challenges to building structures offshore • Opportunities of offshore wind when successful and progressive • Basic physical elements of offshore wind • Realistic costs of energy production
Desired change in sentiment	User should feel more confident and ready than before to begin or continue their work and research in the field	User should feel they are aware of the basic principles of offshore wind and feel a high appreciation for the topic.

1.3 Boundary conditions

The boundary conditions of this study are:

1. Relevant topics and the appropriate degree of simplification are identified in this study. The simulation behind the game includes simplified methods of wind farm design and management, with emphasis on future expandability.
2. Minimal effort shall be put into game production (making an attractive user experience). The game graphics were considered beyond the scope of this study.
3. Procedural generation is used to present a different scenario to the user for each run.
4. The prototype is implemented in Python.
5. The prototype is playtested once with voluntary participants.
6. It is assumed that the results of this work may be improved upon and utilized by game developers and producers in the future to create an attractive user experience.

1.4 Organization of research

This study covers three topics that are explored in conjunction with each other to accomplish the project goals. The three topics are offshore wind energy (design, operation, and economics), serious game design, and prototype development. The development of offshore wind farm models and investigation of serious games were done simultaneously during the development of the prototype. The organization of this report was constructed in a way to capture the justification behind every decision made to produce the resulting prototype as clearly as possible. The organization of the thesis is depicted in Figure 1.1. Following a literature review, the game objectives are established. The game framework, defined by dynamics and elements, are then outlined and used to create specific game rules and functions called game mechanics. Once implemented in a minimal prototype using Python, the game is tested and evaluated and refined until the final prototype is ready to be playtested.

One innovative feature of this project is the placement of offshore wind energy in a new context – a game rather than an engineering program (see section 2). For this reason, the aspects of serious games are always described first and the aspects regarding offshore wind are described second. This order does not represent priority of one topic over the other.

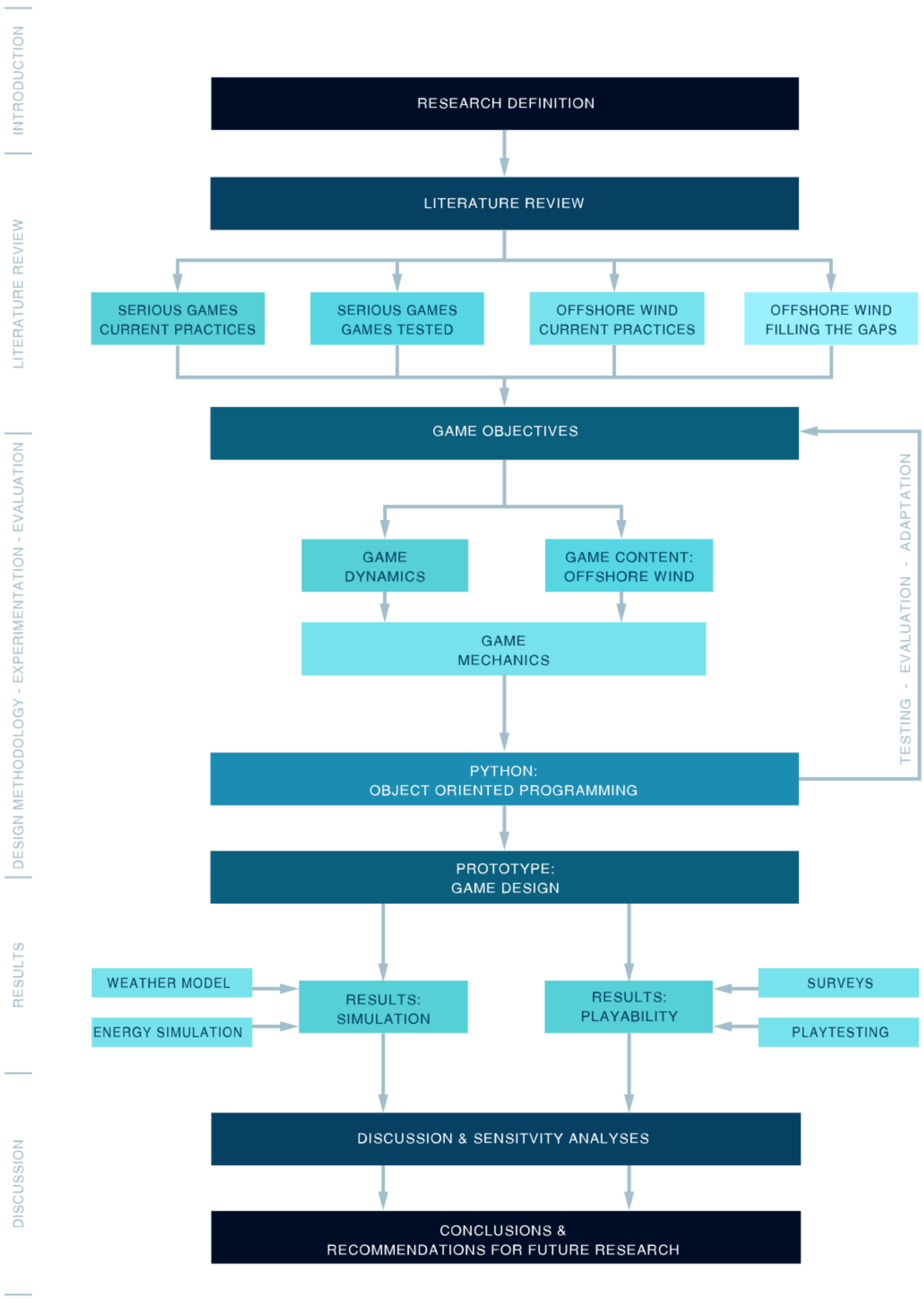

Figure 1.1: Organization of research

2. Literature Review

This section consists of a literature review on serious games, offshore wind practices, and offshore wind research, as well as the perceived knowledge gaps and misconceptions. It is predicted that the combination of these subjects is necessary to develop an effective serious game about offshore wind. First, literature is reviewed to evaluate the opportunities and limitations of serious games. Specifically, what has experience shown to be the essential elements of a learning game. Second, a literature review will be applied to playing actual games to document user interaction parameters. Third, the design and operational practices and research is explored to determine why further training in the field is important. Lastly, the outcome of the literature review includes the setting of boundary conditions necessary to design a serious game as well as the establishment of game objective(s).

2.1 Serious games

A great deal of practical work and research has been carried out in the field of serious games designed for medical purposes, history, social issues, engineering, and much more. *Serious Games Foundations*, *Concepts and Practice* by (Dörner, Göbel, Effelsberg, & Wiemeyer, 2016), consolidates the work of over 50 authors including researchers and professionals whose expertise or career lies in serious games. This source serves as a valuable resource throughout this thesis.

Dörner et al. (2016) define a serious game as a digital game intended to entertain and to achieve at least one additional goal known as a characterizing goal. The characterizing goals for this thesis application are different for the training and dissemination educational goals. The term serious game is itself an oxymoron. A game that is defined as serious may demotivate players simply because it is labelled as such. If the goal to entertain is neglected, the playing experience might be adverse, and result in a failure to achieve the characterizing goal. Serious game developers use various motivational tools to join fun and learning. Serious games can provide the extrinsic motivation to players who do not have the intrinsic motivation to engage with the subject matter otherwise. To properly integrate the subject matter (in this case, offshore wind energy) and enjoyment (fun and amusement), the collaboration between game designers, programmers, artists, and domain experts through the entire development is essential to create a successful serious game.

In the past, serious games drove the development of modern board games even before computers. The original patented version of *Monopoly*, *The Landlord's Game*, was designed in 1904 by Elizabeth Magie with the intension to demonstrate the consequences of an unrestrained capitalist economy. Video games were designed for serious purposes since the 1980s, although were often dismissed as constrained and thinly-disguised multiple-choice tests (there were exceptions, such as the infamous *Oregon Trail*.) Modern serious games are used in schools for many educational purposes. They integrate amusing gameplay closely tied to the subject matter, using the power of mechanics to teach principles and not just facts (Adams & Dormans, 2012).

This study strives to communicate the training and dissemination of knowledge of offshore wind energy effectively and to encompass both learning facts and patterns. Therefore, it is important to choose a suitable medium. As Marshal McLuhan famously said, "the medium is the message". The game distinguishes itself from the direct presentation or broadcast of information (i.e. film) by creating an interactive communication between the designer, the player, and among the players. Furthermore, games use mechanics that accommodate different scenarios and different endings (Adams & Dormans, 2012). As offshore wind energy and farm design is a developing science containing numerous uncertainties, the serious game might offer a strong opportunity to convey substantial (and perhaps otherwise unreachable) messages for both training and dissemination.

Fu et al. (2007) measured the effectiveness of serious games and noted that whether a player enjoyed a game is a key factor in determining whether the player continues to learn from the game. In other words, the learner is prompted by self-motivation factors in the game and will choose to devote his or her time to playing the game. Utilization of the game offers an alternative to learning about the subject matter through literature or other methods. The EGameFlow scale was developed to test four serious games with research participants. The final version of the scale was broken into eight dimensions: concentration, goal clarity, feedback, challenge, control, immersion, social interaction, and knowledge improvement (Fu, Su, & Yu, 2007). The survey results using the scale are used as a reference for pedagogical design, and largely capture fundamental pedagogical principles present in similar research looked at in this literature review. This pedagogical design was also referenced while reviewing (and playing) existing serious games during this study.

One relevant example of a serious game is SimPort: a multiplayer management game framework as documented in (Warmerdam, Mayer, Bidarra, & Knepflé, 2006). SimPort is a multiplayer serious game where players learn about consequences of choices within long term strategies for port planning for educational and commercial organizations (Ludoscience, 2006). The game was developed in a collaboration between The University of Technology at Delft and Tygron Serious Gaming & Media. In SimPort's game framework evaluation, an important observation was noted: that the production of a serious game is typically shorter than of an entertainment game because the subject of the game is time limited. Such limitation could restrict the visual quality of a serious game compared to their entertainment counterparts. As a result, serious game developers will use an existing game framework, so they may maintain rapid production time and deliver a better than just decent looking game. Another observation in the paper, is that the developers considered the benefits of all-encompassing serious game engine to be preferable but more difficult to produce than a small number of specialized engines.

The task of interface development and final prototype development of the game would largely rely on work done by a game development team. The boundary conditions of this study focus on the engineering simulation and are outlined at the start of section 3.

2.2 Games tested

The importance of the game mechanics and engineering principles driving the simulation must not overtake the importance of designing an immersive, fun-to-play game. This distinguishes the product from an engineering simulation. It is therefore important to review literature as well as existing serious games to become familiar with recognizing game characteristics.

A common recommendation from professional game designers to become a better game designer is to play as many games as possible (Fullerton, 2014). This includes both playing and analyzing games and studying their history and development. In this study several games were played and analyzed to document the difference between games and more importantly, search for game features that may be relevant to a serious game about offshore wind.

The games that were played to contribute to the building of this serious game include Artemis, Funemployed, Save the World, 3M Wind Energy Virtual Lab, Farmville, and Windfall among many other digital and non-digital games. The review of game mechanics and playability of three specific games are documented to highlight the most significant takeaways.

2.2.1 3M Wind Energy Virtual Lab[1]

3M Wind Energy Virtual Lab claims to be an inquiry-based learning game designed to challenge children to find the best strategy to support 400 households with the lowest cost per year (Schaffhauser, 2014). After playing, the game seemed to be a one-sided promoter for 3M's products and did not help the user retain useful information about blade design other than what the options were, and how 3M's chemical coatings can improve the efficient of wind turbine blades. A crucial takeaway from this game is what to avoid in a serious game about wind energy. While the game goal was very clear, decision making felt uninformed, and there was little motivation to optimize playing strategy (Loh, Sheng, & Ifenthaler, 2015).

2.2.2 Farmville[2]

Farmville was the top game by active users on Facebook for over a year in 2010 (zynga, 2018). The game is a farming simulation where players learn about planting crops, raising animals, trading craft goods, and more through maintaining their virtual farms. The game has no time limit and many levels, making it as addicting as it is immersive. Players collect game currency to add value to their ecosystem as opposed to wanting to get richer for the sake of getting richer. By collecting more property and growing successful crops, the player's progress is met directly with leveling up and recognition. This leads to a keen desire to progress to achieve some end goal, measured by points and competitive ranks. The player is learning new terminology and strategies by trial and error without realizing he or she is learning. One noteworthy game dynamic is the collaboration with other players to earn rewards faster. The main takeaway from this game is how proper game immersion can result in effortless learning.

2.2.3 Windfall[3]

The most relevant game tested is Windfall by Persuasive Games. The goal is to fulfill a specific energy goal as quickly as possible by building turbines and power lines. The single player game offers three levels and the opportunity to save high scores. Gathering information about the game space was a notably relevant factor to learning about optimal strategies and inspired similar game features in this study. The game dynamic is a race to the finish style game with resource management. During the game, players realize how the happiness of other characters in the game (local residents) impacts the rate at which profit is received). Because the tools and instructions are simple, the player has a lot of freedom to focus on strategy by using different power line layouts and turbine size. This game served as a large inspiration for the thesis game. The main takeaway from this game is that a complex scientific field can be translated well into a serious game if presented clearly.

Snapshots of the three games discussed are presented in Figure 2.1, Figure 2.2, and Figure 2.3.

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[1] Available at www.youngscientistlab.com/sites/youngscientistlab.com/files/interactives/wind-energy
[2] Available at https://www.zynga.com/games/farmville
[3] Available at http://persuasivegames.com/game/windfall

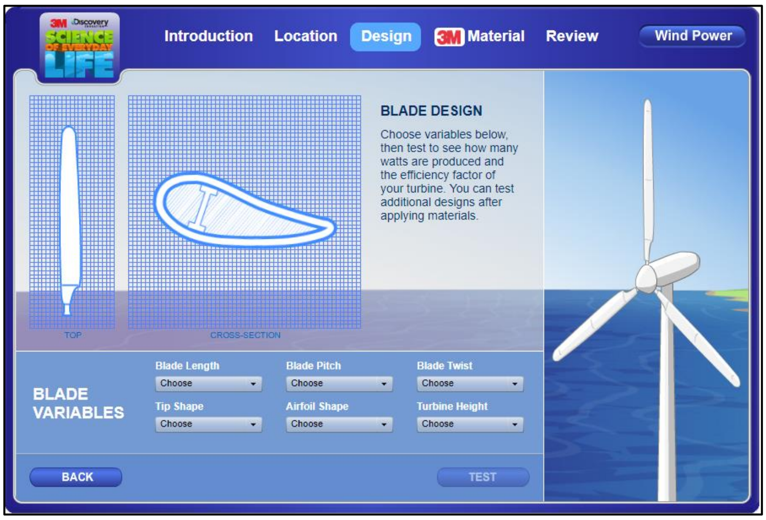


Figure 2.1: 3M Wind Energy Virtual Lab (3M, 2017)

Figure 2.2: Farmville (zynga, 2018)

Figure 2.3: Windfall, by Persuasive Games

2.3 Offshore wind: industry and research

To secure Europe's commitments to CO_2 emissions reductions and energy security, offshore wind has become a major contributor to the power mix. In 2016 the EU set a 2030 target to reduce emissions to 40% below 1990 levels with 27% renewable share for all of EU's energy usage (EY, 2015), which was increased to 32% in June 2018 (Europa, 2018). Striving to realize the full potential of offshore wind is critical because offshore wind may otherwise not be able to push Europe to meet its renewable energy targets and fulfill commitments to a low carbon economy, despite the tremendous success in industry and fossil fuel reduction (EY, 2015).

The last two decades have seen growth in investment, industry, and research and development (R&D) not only in offshore wind farms, but in the transformation of ports, power grids, and shipping sectors. The industry has seen the fastest growth rate of capacity installations of all renewables, with a 5-year compound annual growth rate of 31% in 2014. Furthermore, more than 1,250 scientific publications were published in Europe between 1994 and 2010 (an updated measure was not found but is expected to be much larger). Given the increasing scarcity of onshore sites, offshore wind is becoming increasingly attractive (EY, 2015). Investments in offshore wind energy were €18.2 bn in 2016 and €7.2 bn in 2017 (2.5 GW of new capacity financed). One explanation for this reduction in investments is that cost reductions have allowed investors to finance more capacity for less money (Wind Europe, 2017).

The offshore wind market in Europe has been successful in creating jobs and reducing fossil fuel imports and has seen growth opportunities in the global market. It is predicted to nearly triple its capacity from 8 GW today to 23.5 GW in 2020. Offshore wind power, however, is still relatively expensive. Its energy production costs must be reduced to remain a viable option in the long-term. In other words, the pace of growth in the industry must be matched by the pace of lowering costs (EY, 2015). Figure 2.4 presents the evolution of the levelized cost of energy (LCOE) desired according the cumulated offshore wind capacity through 2030. This demonstrates the magnitude of cost reductions in energy production necessary to achieve energy goals.

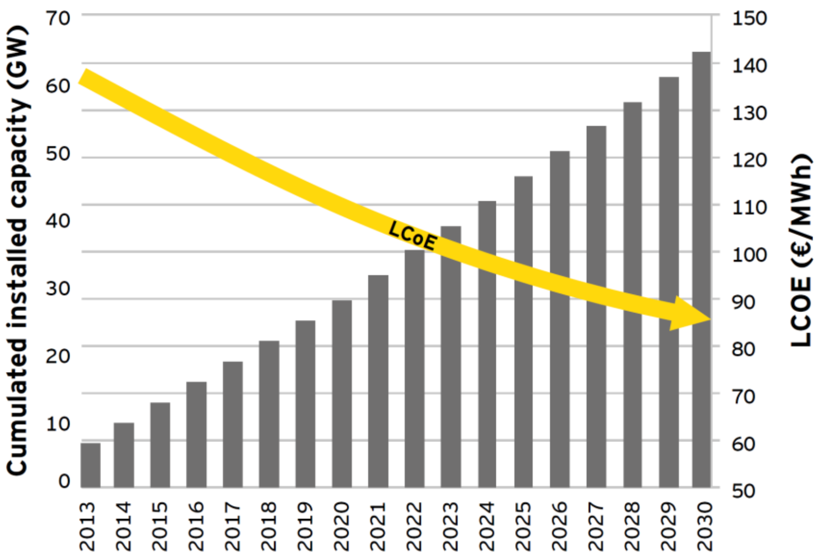


Figure 2.4: Evolution of LCOE with cumulated offshore wind capacity installed (EY, 2015)

With continued growth, improved technology and supply chain integration, the LCOE could go down to €90/MWh by 2030 given the combined effects of learning, specialization, investment, and scale. As the share of offshore wind increases, the transmission and interconnected infrastructure must follow suit in efficient integration and development. According to Ernst & Young (2015), the following measures must be prioritized to realize the full potential of offshore wind in Europe's future energy mix:

1. Cost-competitiveness in industry
    a. Reduce costs in magnitude and timeliness
    b. Achieve market competitiveness
    c. Secure acceptance by consumers, investors, and politicians in the long run
2. Stable regulatory framework
    a. Move away from largely policy-driven public support schemes
    b. Work with neighboring countries
3. Improved access to finance
    a. Facilitate development by reducing risk for investors
4. Cost- effective grid investment and connection
    a. Develop a fully integrated European electricity network to transmit large amount of power
    b. Perform network upgrades
5. Planning system issues addressed
    a. Simplify planning and permitting procedures to support timeliness
6. Overcoming supply and logistics challenges
    a. Upgrade and connect construction facilities and ports
    b. Increase number of installation vessels
7. Support of innovation and training and enhancement of synergies to reduce costs
    a. Promote partnerships, especially in research and development (R&D) and technological development and training
    b. Improve R&D efforts and workforce capacity

Cost cutting actions with respect to industry include the following:

1. Introduction of higher capacity turbines with better energy capture and reliability.
2. Continuous production of support structures.
3. Greater competition between industrial actors in key supply chain areas.
4. Greater supply chain optimization and logistical integration.

In addition to action in the policy and technology, improvements in the O&M of offshore wind farms can directly increase productivity. These include advanced control systems of individual turbines or long-term maintenance strategies. The uncertainties in weather prediction and accessibility to turbines are the main drivers behind the difficulty in optimizing such strategies.

The reduction of uncertainty in weather prediction may improve O&M by allowing for decisions to be more informed in efforts to reduce downtime. There is much literature on the various stochastic models for Metocean time series. Monbet el al. (2001) classify the models into: non-parametric models, models using Gaussian approximations, and other parametric models. They state that the choice of model for an application depends on the nature of the process being studied (univariate vs bivariate, intensity or direction). For efficient programming and reducing required computations, the finite state space Markov chain presents a parametric model known for its simplicity and success in application with fewer parameters to be estimated.

Various studies have reviewed the application of Markov weather models for the prediction of O&M availability at offshore wind farms (Scheu, Matha, & Muskulus, 2012; Hagen et al., 2013). These studies have documented success at replicating statistical parameters of sea state parameters and replicating weather window distributions in a simulation.

In addition to O&M availability, reliability figures have a significant impact on offshore wind farm availability. Reliability refers to the ability for the turbine to perform as intended under required conditions. Failures of turbine components reduce reliability (Scheu, Kolios, Fischer, & Brennan, 2017). There is some debate over the statistical distribution of turbine reliability over the turbine's lifecycle; however, a uniform distribution is commonly used both in practice and in research. Reliability of turbines, support structures, and subsea cables are explored individually in section 3.4.

A review of current offshore wind support structures and assessment of which are most likely to succeed in the future are documented in (Miñambres, 2012). The challenges and technological requirements to be faced in the offshore wind industry beyond the year 2020 are reviewed and prioritized through surveys completed by field experts. The most agreed upon factor that will affect the future of support structures in offshore wind is the industry moving towards deeper water. Given this trend, the next most agreed upon factor was whether new offshore wind support structure concepts will surpass existing ones in all water depths.

There is plenty of detailed information available for the improvement of the design and maintenance of offshore wind farms. The application of this information for a dissemination tool, however, greatly depends on the target audience age and background. Some starting points can be drawn from a list of "wind energy myths" compiled by the European Wind Energy Association (EWEA), which are listed hereafter:

1. Wind power is a niche-technology
2. Wind power is expensive
3. Wind power is unreliable
4. Wind power is bad for the environment
5. Wind power is bad for health

A broader survey of misconceptions and topics of interest from the public is required to improve the effect of the serious game. A brief survey was conducted to gather concerns and misconceptions about offshore wind power. This survey represents a small and non-diverse sample size. Notable concerns are listed hereafter:

- The effects of offshore wind farms on marine animals and birds are not entirely understood (AGI, 2018).
- Offshore wind farms built near the coastline may affect tourism and property values through visual and noise effects (AGI, 2018).
- Substantial amount of CO_2 is emitted during the production and installation of offshore wind turbines (Environment.co.za, 2013).

(Heier, 2014) addresses most of these myths by stating that wind power broadens the energy base and directly reduces environmental pollution. Furthermore, it is on its way to becoming economically competitive with conventional energy sources.

For this study, principles of offshore wind farm design regarding turbine technology, support structures, grid integration, environmental impact, energy demand, and climate change scenarios were collected and applied to the serious game. The results of this research are referenced throughout the report, particularly in section 3.4.

2.4 Filling the gaps

The literature review has illustrated the knowledge gaps with respect to reducing the cost of offshore wind design and maintenance in the next ten years. Furthermore, it has illustrated that an enhanced understanding of uncertainties for researchers and the public alike can directly contribute to reduced costs. Looking to learning methods to enhance this understanding, there is a multitude of various teaching and learning techniques. Some learners prefer to learn by reading a textbook, watching a documentary, studying in a group, or individually. The success of existing serious games indicates that some learners value alternative strategies. This does not imply superiority but rather that a greater number of learners can be reached by increasing the set of learning tools. Serious games provide one more way to explore the topic of offshore wind for a new group of learners (Dörner, Göbel, Effelsberg, & Wiemeyer, 2016).

The conclusions from the review of pertinent literature allow for further refining the boundary conditions. Firstly, the game scale will be set to a sea-wide network as opposed to farm-wide or structure-wide. Most studies indicate that international cooperation and energy sharing is a vital key to reaching the full potential of offshore wind. Furthermore, this scale provides the player with the possibility to simultaneously compare different wind farms. This may allow for learning of maintenance strategies with immediate feedback. Second, because of the large scope of offshore wind energy topics, certain principles will only be ‘stubbed out’ in the game design and prototype program but not fully integrated. The integration of the most fundamental topics allows for future developers and game experts to have a strong foundation and instruction of the serious game content. Third, after playing various serious games and reviewing pedagogical evidence, the game optimizer will be in the form of tips and tricks in this prototype, to encourage the application of new knowledge with immediate feedback. Finally, the author will take on the roles of game designer and subject matter expert. This integrated, balanced approach is expected to result in a more comprehensive outcome. A considerable effort is to be put into programming of the game prototype to best measure the integration of game design and subject matter, with minimal effort is to be put into graphic game user experience.

This thesis does not explore the impact of the benefits of improved awareness in society or specific improvements in research capabilities with improved training.

3. Methodology of designing Vindby

3.1 Terminology

The existing body of knowledge on how to design a serious game is extensive. While majority of the terminology and approaches align between the references, there are several differences. To maintain clarity and consistency, the guidelines in (Dörner, Göbel, Effelsberg, & Wiemeyer, 2016) are followed and will be supplemented when appropriate. Figure 3.1 presents an overview of the terminology defined in this section.

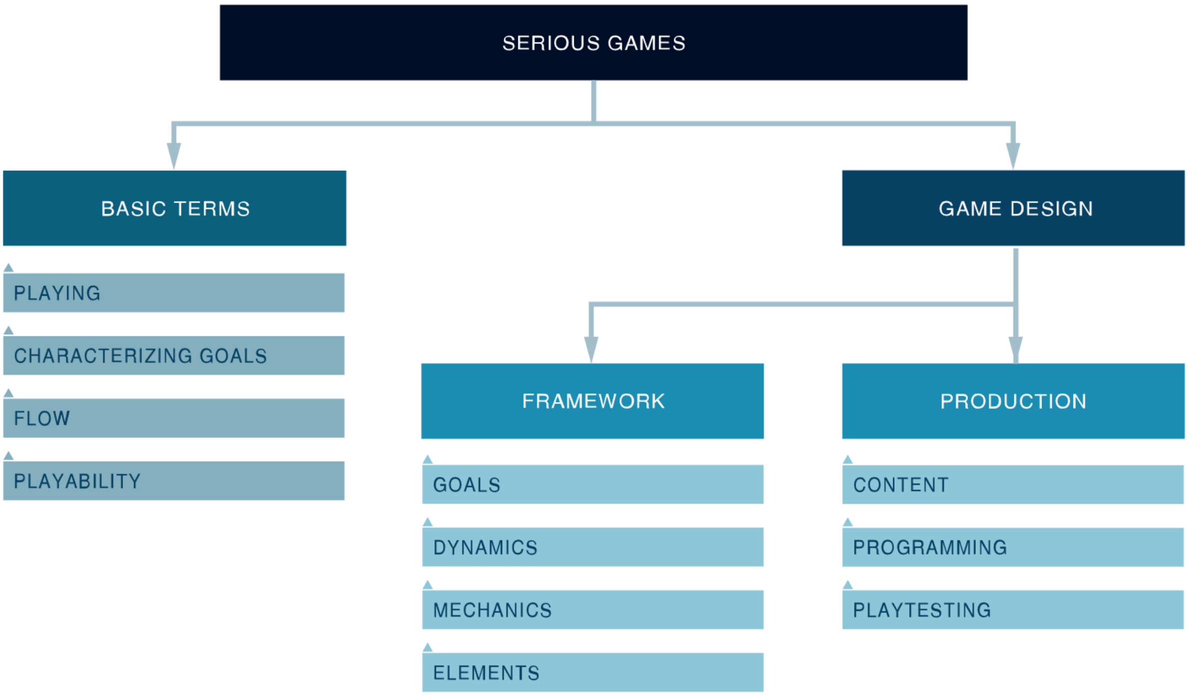


Figure 3.1: Terminology overview of serious games

Playing refers to a user engaging in the serious game for training or dissemination. This includes voluntary or required participation.

Characterizing goals refer to the additional purpose of a serious game other than entertainment. The characterizing goal for training is to improve technical judgement of the user. The characterizing goal for dissemination is to enhance the sentiment of the user towards offshore wind energy and introduce basic terminology. These goals are refined throughout the report and summarized in the conclusion.

Flow is the experience while playing characterized by exclusive concentration on the game, feeling immersed, feeling in control, facing clear goals, and receiving immediate and consistent feedback. Flow is one of several psychological models of player experience and it will drive various decisions in the game design process. It should encompass motivation to play, appeal to a spectrum of end users, removing factors that demotivate, and creating meaningful hints with feedback (Dörner, Göbel, Effelsberg, & Wiemeyer, 2016) (Schell, 2015).

Playability is the term used when referring to game usability, player experience, and the inclination for continued play. For the sake of simplicity playability will almost always be referred to as a composite measure throughout the methodology.

Content refers to domain-specific knowledge. In this study this pertains to simplified offshore wind farm design. This includes the engineering models, weather simulation, values, and formulas used to build the game.

Programming refers to the relevant algorithms and programming concepts used in the hardware and software arrangements on which the game is played. One of the challenges of programming is to ensure the game runs at a desired speed on different computers throughout the game. In this study, the serious game is expected to be programmed in Python with standard computer hardware and is expected to run adequately on any platform that supports Python.

Playtesting is the process of testing the prototype of a game by individuals not involved in the study. Feedback from players after playtesting is used to improve the prototype.

Game design is broken down into two concepts: framework (goals, dynamics, mechanics, and elements) and production (content and programming). Determining the ideal mechanics and elements is an iterative process and relies heavily on playtesting. In the next sections, game design concepts are defined in general and established in detail for this thesis.

Game objectives or game goals are what the player must achieve to win (not to be confused with the characterizing goals). The game goal includes a specific target to reach by playing.

Game dynamics are the means by which players achieve the goal and can include one or many different dynamics.

Game elements are features of the game that keep players engaged. Games use one or more elements (Knowledge Guru, 2013).

This chapter describes the process of establishing the game framework, programming the framework, and the game content. The end of the section summarizes this work in the final game design describing how the serious game looks and works. Following the design and finalization of the prototype, section 4.3 reports how well the game functions by measuring computational efficiency and how well it represents the game content by comparing the output to existing offshore wind farms.

The game is called Vindby and will be referred to as such. Vindby is chosen as the name of the game both as an ode to the world's first offshore wind park in 1991 in Denmark and as a translation in Norwegian to "wind city".

3.2 Game framework

The serious game must have one or more game goals and a framework to support the players to achieve these goals. The framework for Vindby is established alongside development of serious content and game development/programming to ensure proper integration of the two aspects following (Dörner, Göbel, Effelsberg, & Wiemeyer, 2016). In this section, the final game framework is described in addition to the alternatives considered.

3.2.1 Game objectives

The following three game goal alternatives were considered for Vindby:

- Design an offshore wind farm for a random set of environmental conditions, one at a time. This goal is rejected because it does not allow for learning about farm interconnectedness.
- Create a network with multiple players. This goal is inspired by economy building games like *the Sims*, *Farmville*, and *Civilization*. It is rejected because at this stage, programming efforts to create saveable, multiplayer systems may negatively impact the quality of programming the game itself. Additionally, goals in such games tend to be loosely defined, and players often set their own intermediate goals (Adams & Dormans, 2012).
- Reach a certain target in time by building wind farms in a virtual sea. This goal is selected for Vindby. In the future, this may be translated to an economy building style game.

The goal utilizing multiple wind farms is selected to encourage players to test alternative solutions in one game. One of the valuable attributes of playing games is that the player 'learns by doing' without negative consequences in the real world, which can be practiced by testing alternative solutions with the goal of learning about what does and doesn't work for use in future alternatives (Dieleman & Huisingh, 2006).

Five specific game goals were created on this basis using different targets. This allows for one game to be tested for different durations and targets of interest to different players. The player can select from the following game goals:

1. PROFIT: Invest all the initial investment (€1 bn) in capital costs and break overall profit by 2025.
2. COMPETE: Keep playing until 2030 and achieve an overall score higher than another player.
3. DOMINATE: Achieve 10% share of all energy supply can be provided by offshore wind by 2050.
4. SAVE THE PLANET: Prevent the global temperature from increasing by 2 degrees by 2100.
5. FREE4ALL: Free play without time limits.

3.2.2 Game dynamics

Common dynamics include: Race to the finish, collection, territory acquisition, solve, rescue, escape, alignment, construct, and capture (Knowledge Guru, 2013). The main game dynamic of Vindby is design and build. Additional game dynamics were formulated considering the game goals and game mechanics through iteration. The final game dynamics includes construction and management of wind farms in a virtual sea to reach the selected target within an allotted time and budget.

The pace of the game is adjusted to match the game content and framework. For content requiring reflective thinking such as Vindby, a slow-paced game is more appropriate than a fast-paced game, which is for when fast reactions matter (Dörner, Göbel, Effelsberg, & Wiemeyer, 2016). While the game does impose a time limit to reinforce real life constraints on renewable energy, it is relatively slow paced and does not require quick reactions. Additionally, the player may pause the game at any moment. Figure 3.2 presents the game dynamics and basic game mechanic introduced in later sections.

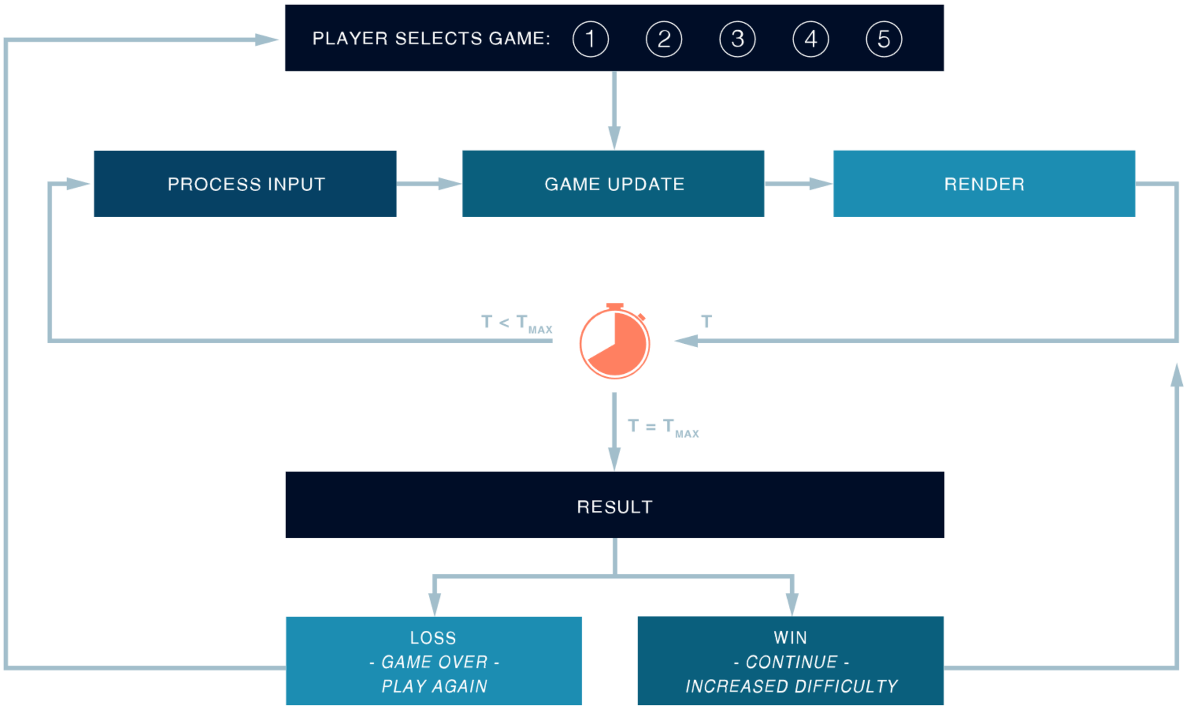


Figure 3.2: Game dynamics

In this study, game dynamics are illustrated using standard flow charts as opposed to intricate machination diagrams. Whereas these diagrams are useful to simulate game dynamics without writing code, more attention was spent on programming the prototype.

3.2.3 Game elements

Some elements used in Vindby include: rewards, resources, scoring, story, chance, and strategy. These elements are selected because of their relevance to the actual game content and are referenced in section 3.4.

Studies in neuronal sciences indicate the importance of emotional engagement for learning efforts. Immersion helps achieve the goals of serious games as well as provides motivation to the player to continue playing. (Dörner, Göbel, Effelsberg, & Wiemeyer, 2016)

Rewards are used throughout the game to encourage and build self-esteem for the player, which is often recognized as large contributing factor to game immersion. Resources are limited and displayed with transparency to aid in decision making. One of the main attractions of digital games is the clarity of increasing skill level (Merrill, 2002). Scoring indicates progress on a variety of measures as opposed to the main game goal. Scoring is not a crucial part of Vindby but may be developed further following playtesting. The story of Vindby takes place in a virtual sea with varying conditions throughout the sea. The story extends onshore, where there is a growing energy demand and growing climate change effects. The player is the main character, builder, designer, and operator. Other stakeholder characters include the government, the public, and shareholders to further demonstrate consequences of player decisions. Details of the story are introduced in section 3.4.

To maintain player engagement, their decisions must be impactful and not tangential to the game goal. Therefore, the types of decisions made must be revisited and checked whether they are hollow, obvious, or uninformed so as not to cause disinterest in the player. If they are, such choices should be redesigned. Fullerton (2014) listed the following preferred decisions:

- Informed decision; where the player has ample information
- Dramatic decision; taps into a player's emotional state
- Weighted decision; a balanced decision with consequences on both sides
- Immediate decision; has an immediate impact
- Long-term decision; whose impact will be felt down the road

In general, there is a place in games where decisions are placed simply for creativity or exploration. Finding a balance between the types of decisions that contribute to game flow that keeps players interested is more important than relying on one or more specific types of decision categories (Fullerton, 2014).

A frequently admired game element present in digital games is an Easter egg, i.e. a hidden feature of the game that does not necessarily contribute to overall game mechanics. Vindby uses a couple of Easter eggs to encourage excitement. One such Easter egg involves naming wind farm after existing offshore wind farms (worldwide). This action accelerates the farm's construction phase, so the farm can immediately proceed to operation.

3.2.4 Game mechanics

Game mechanics control the way players interact with the game. It includes rules and procedures that guide the player and internal structure of the game defined by game dynamics. The mechanics of a serious game can be intrinsic or extrinsic, which affect how the serious content is revealed (Figure 3.3). An example of an intrinsic game is a flight simulator that is used to train pilots. An example of an extrinsic game would involve answering questions about a serious topic to defeat an enemy. (Dörner, Göbel, Effelsberg, & Wiemeyer, 2016). Vindby is mostly intrinsic because of the breadth of content that is to be covered for the training characterizing goal. As the figure displays, additional game mechanics are used to supplement serious content to enhanced playability.

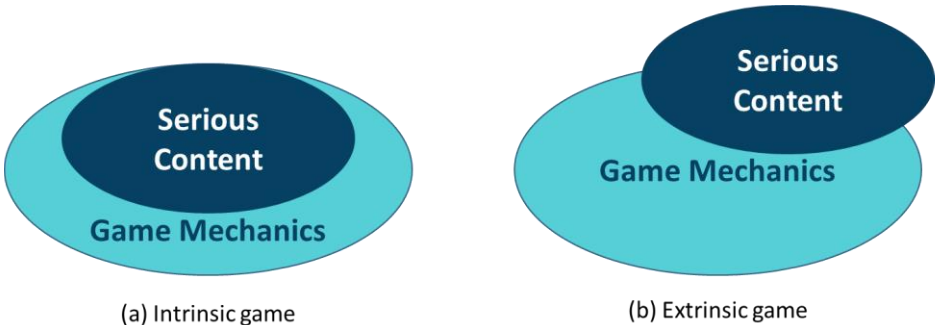


Figure 3.3: Integration strategies, adapted from (Dörner, Göbel, Effelsberg, & Wiemeyer, 2016)

As Vindby is an intrinsic game, game mechanics heavily rely on the serious content to determine specific rules and processes. Game mechanics are defined using rules and processes for game space, time, objects, actions, and rules (Schell, 2015). The game space is a virtual sea (referred to as the "sea grid") divided into 100 unique cells (Figure 3.4). The top of the figure shows the location of the shoreline and the only existing onshore substation. Game time is measured in calendar dates to give real context to offshore wind timelines. Objects, actions, and rules and their relevant game mechanics are explored in section 3.4.

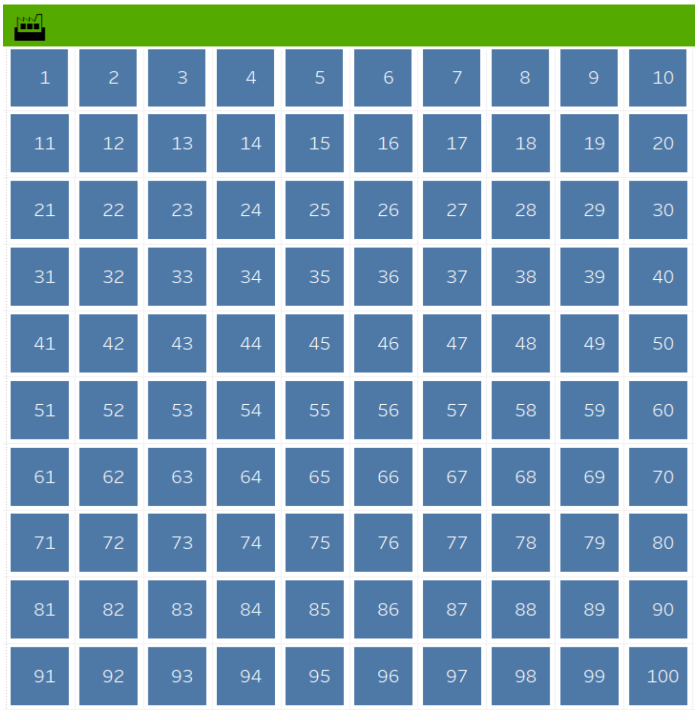


Figure 3.4: Vindby virtual sea grid

A few game mechanics defined early in the game design are:

- The player is given an initial investment at the start of the game to pay for activities, i.e. building and maintaining wind farms
- The player must not run out of money
- The game is won if the player reached the target of the selected goal
- Various bonuses, penalties, and special features are revealed throughout playing

For the characterizing goal of training, the game mechanics must employ a simulation that is a simplified yet accurate representation of all included topics. For the characterizing goal of dissemination, the game mechanics must be relatable, engaging, and fun.

3.3 Programming

The Vindby prototype was coded using Python (3.6) and Object-oriented programming (OOP) and did not use Pygame. Python is known to be relatively easy to learn and extremely powerful. It has "*efficient high-level data structures and a simple but effective approach to object-oriented programming*" (Swaroop, 2018). For preliminary game development, the prototype is minimal and enough to test game mechanics and generate random values. OOP is a programming style used to organize code by creating objects, which can be easily understood and extended. Additionally, OOP is known to translate code well from real-world objects and interactions. Pygame is a Python package frequently used to construct games; however, it is largely used for creating visual components, which was considered beyond the scope of this study.

Within OOP, a common game-specific programming pattern is a game loop. Almost all games have a game loop and very few programs other than games used them (Nystrom, 2014). A simple game loop is represented in the game dynamics figure in Figure 3.2. The game continuously loops through process input, update game, render, and a time delay. Each update advances the game time by a specified amount and it takes a certain amount of real time to process the updates. To deal with variable game speed (it is assumed the user must have the ability to speed up or slow down time), and variable machine capabilities, a catch-up method is used by applying a fixed time step with synchronization. The game runs at a fixed speed but with addition of a delay to keep the game from running too fast. This delay is dynamic and allows for consistent speed. The various terms used to reference game speed and loop intervals are defined as follows:

Game time: The time in the game simulation measured in minutes but displayed as calendar dates. Increases in intervals equal to the game speed times 1 second.

Game speed: The game time interval per real time second as chosen by the user. Slow speed runs at 1 hour per second, normal speed runs at 1 week per second, and fast speed runs at 1 month per second.

Wind time: The game time that is increased in intervals equal to the wind interval.

Wind interval: The game time interval at which the main simulation runs regardless of game speed. This is equal to 1 hour in the current version of Vindby.

In section 3.4, references are made to objects in the prototype program. To highlight these occurrences, the objects are displayed in the format below, using the central game object and supporting objects as examples. A list of all objects, their properties, and their methods are summarized in Appendix B .

Game: *Includes the game loop and all properties of the game.*

Interaction: *Handles most functions related to retrieving user input for various functions such as wind farm design.*

gameTools: *Includes functions used by all objects in the game such as updating scores, checking rewards, end of game procedures, time and date conversions, and Easter egg handling.*

App: *Contains the graphical user interface that runs alongside the game (in a thread).*

3.4 Game content

The game content includes the design and maintenance of offshore wind farms. There is a high upper limit for how detailed the content can be in a serious game because it is packaged in a simulation. Scientific simulations focus on accuracy, while ordinary game simulations focus on entertainment. Game designer Chris Crawford observed in his 1984 book *The Art of Computer Game Design*:

> *Accuracy is the sine qua non of simulations; clarity the sine qua non of games. A simulation bears the same relationship to a game that a technical drawing bears to a painting. A game is not merely a small simulation lacking the degree of detail that a simulation possesses; a game deliberately suppresses detail to accentuate the broader message that the designer wishes to present. Where a simulation is detailed a game is stylized.* (Crawford, 1984)

The simulation of a serious game falls between an entertainment and scientific simulation depending on the characterizing goals. A training game such as Vindby is expected to represent the subject matter correctly, like a flight simulator. While an entertainment game eliminates details that are not fun, a serious game relies on details to educate users about the subject. A simulation is always an abstraction of the system it represents. Abstraction of the system can be done by eliminating factors that have little effect, or by simplifying features that contribute to the overall mechanics, but whose inner workings don't significantly change the outcome (Adams & Dormans, 2012).

The topics that were selected to be integrating to Vindby are listed hereafter. These topics were identified through many iterations of game mechanics, review of offshore wind current practices, review of ongoing research, and discussions with colleagues.

- Weather prediction
- Wind farm design, construction, and decommissioning
- O&M strategies
- Energy demand and climate change
- Finance
- Stakeholder influence

The scale and economy of the game content is almost entirely based on European practices due to the level of experience and technology present. The following topics are identified as subjects valuable to Vindby and are stubbed out in the prototype. These topics were beyond the scope of the study and prototype but there is an indication in line of where the additional code would be used (also referred to as "stubbed out" code).

- Investments in renewable energies and R&D
- Turbine control systems
- Wind direction
- Energy sharing between regions
- Inter-turbine and inter-farm wake effects
- Comparison to onshore wind

The following sections describe the content of Vindby in detail with respect to weather prediction, wind farm design, operation and maintenance, energy demand/climate change, finance/costs, stakeholders, and optimization functions.

3.4.1 Weather prediction

Accurate weather prediction is valuable to two characterizing goals of Vindby: first, improved weather modelling improves the user's understanding of expected energy production and weather windows for safe operation, maintenance, and construction, and: second, recognition that the wind speed varies greatly, but that wind offshore offers tremendous benefits in terms of magnitude and variability compared to onshore. This topic is the game content topic with the highest degree of detail. It is meant to illustrate the game's potential use as an advanced training tool and serve as an example for the other game content topics to be explored in further detail.

Various stochastic models for wind and sea state time series indicate that the direction of the wind is seemingly less important in wind energy than the magnitude. This is likely due to the turbine blades being self-seeking for optimal wind direction (Anuradha, Keshavan, Ramu, & Sankar, 2016). Therefore, the wind speed magnitude is modelled probabilistically and distinctly for each cell in Vindby's sea grid.

The two sea state parameters used in Vindby are significant wave height and mean wind speed. Wind speed is used to generate production, and both parameters are used to determine persistence of weather windows. Weather windows indicate the availability of a turbine to be repaired and relies on meeting a threshold for wind speed and wave height remaining for the time duration of a repair or during construction. The development of weather conditions is described by stochastic transitions (Hagen, Simonsen, Hofmann, & Muskulus, 2013) and opposed to random sampling.

Theoretically, any period may be used for wind speed averaging. Shorter periods will have larger variance and a better representation of productivity due to turbulence (WMO, 2008), but will require more computations and slow down the simulation. Power spectral analysis shows the wind speed variation periods containing the most energy and can be used to determine the adequate time resolution. The Vindby weather simulation uses 10-minute intervals, as this interval is used throughout the wind industry to measure turbulence and determine reliability of larger wind turbine drive trains (Figure 3.5) (Tavner, 2012).

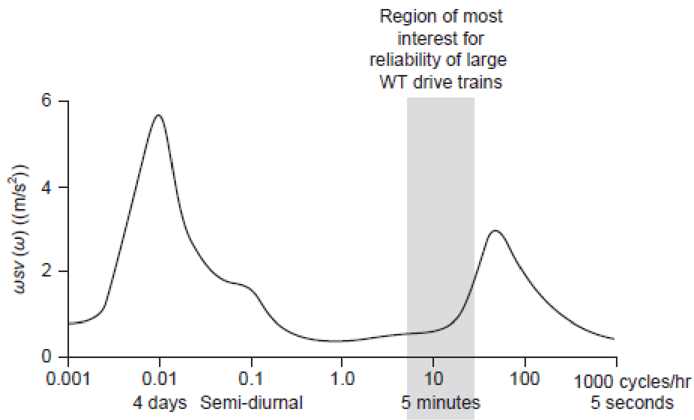


Figure 3.5: Van der Hoeven power spectrum of horizontal wind speeds (Tavner, 2012)

Generating sea states

According to (Monbet & Marteau, 2001), the three main categories of generating realistic sea states are: simulation based on Gaussian statistics, ARMA processes, and stochastic processes assuming the Markov property. Various studies including (Scheu, Matha, & Muskulus, 2012) and (Hagen, Simonsen, Hofmann, & Muskulus, 2013) have shown that Markov models accurately reproduce statistical parameters of an original dataset, especially for measuring weather windows.

A Markov chain model is selected for wind time series generation in Vindby. A Markov model is a discrete stochastic process. It is a simple and efficient method that assumes the future weather only depends on the current weather state. The development of current to future weather state is described by stochastic transitions. The transitions are established using an existing dataset. The transition probabilities are estimated by discretizing the average frequencies of transitions observed in the data and can be presented in matrix form as described by (Scheu, Matha, & Muskulus, 2012) as follows:

$$M : \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1s} \\ p_{21} & p_{22} & \cdots & p_{2s} \\ \cdots & \cdots & \cdots & \cdots \\ p_{s1} & p_{s2} & \cdots & p_{ss} \end{bmatrix}$$

Year-round seasonality was accounted for by developing different matrices for each month. When predicting sea states the first time each month, it is possible that the previous wind bin has a zero probability of occurrence in the next month based on observed data. In these rare, but possible scenarios, the closest non-zero bin (smallest absolute value of the distance between bins) is used to continue the Markov chain.

In wind energy applications, wind speed is typically modelled, and wave heights are derived from the wind. The literature reviewed on Markov processes use modelled wave height and derived wind speed because the focus is on weather windows, which depend more on wave heights. Both methods ('wave to wind' and 'wind to wave') were explored to choose which results in a better simulation of production variation and weather windows in terms of computation efficiency and statistical accuracy.

The wave and wind data used is from FINO1[4], which is a research platform in the German North Sea near the wind farm Alpha Ventus, 45 km from shore. This dataset is selected because it is the dataset used in (Dinwoodie, Endrerud, Hofmann, Martin, & Sperstad, 2014), which includes reference cases for verification of O&M simulation models for offshore wind farms. Specifically, the wave buoy data and wind data at 90m height are used. The reference case, which is used for comparison in section 4.2, uses the time series for weather data instead of a synthetic weather time series. The years of data chosen are 2007-2012 to capture severe storms that occurred in 2008. Five years of data is used to enhance the impact of the storm conditions in Vindby, provided that the space is virtual and not meant to represent a specific place.

Challenge: wind and wave resolutions

One challenge while using conditional probabilities between wind and wave data is that the original datasets are at different resolutions. Wave data resolution varies with a mean and standard deviation of 53 and 12 minutes, respectively, and wind speed resolution is uniformly 10 minutes (excluding large gaps.) One-hour wave Markov matrices may only accurately predict one-hour wind speeds, and likewise ten-minute wind speeds cannot predict ten-minute wave heights. To address the former, the wind dataset was transformed to one-hour averages to create the 'wind to wave' and 'wave to wind' conditional probability matrices. Six ten-minute wind speeds were derived from the hourly wind sample using one of the following two methods:

1. Markov matrices: use of Markov matrix created from the ten-minute data starting with the hourly sample.
2. Gaussian distribution: use of a standard deviation to sample around the hourly sample, treated as the hourly mean.

The second of these approaches was introduced after evaluating the distributions of ten-minute wind speeds around hourly means divided into wind bins. When looking at the distribution of

[4] Provided by the Bundesministerium fuer Wirtschaft und Energie (BMWi), Federal Ministry for Economic Affairs and Energy and the Projekttraeger Juelich, project executing organization (PTJ). Downloaded from http://fino.bsh.de/index.cgi?seite=plot_formular

ten-minute wind speeds with the same hourly mean wind bin, the distribution appeared consistently Gaussian for hourly means less than 25 m/s. Figure 3.6 presents the distribution of ten-minute wind speeds by the hourly mean bin for all the data. Data for different hourly bins are distinguished by color. Given that turbulence is defined by standard deviation over mean, the standard deviation is chosen as a useful parameter in predicting ten-minute wind speeds. The distribution was further refined by separating the standard deviations by month as well. Figure 3.7 presents the value of standard deviations for three different months to illustrate the seasonal variations. The distributions for hourly mean wind speeds greater than approximately 25 m/s are not as smooth as for lower hourly mean wind speeds due to a lower number of observation points (381 instances out of 248,072 total).

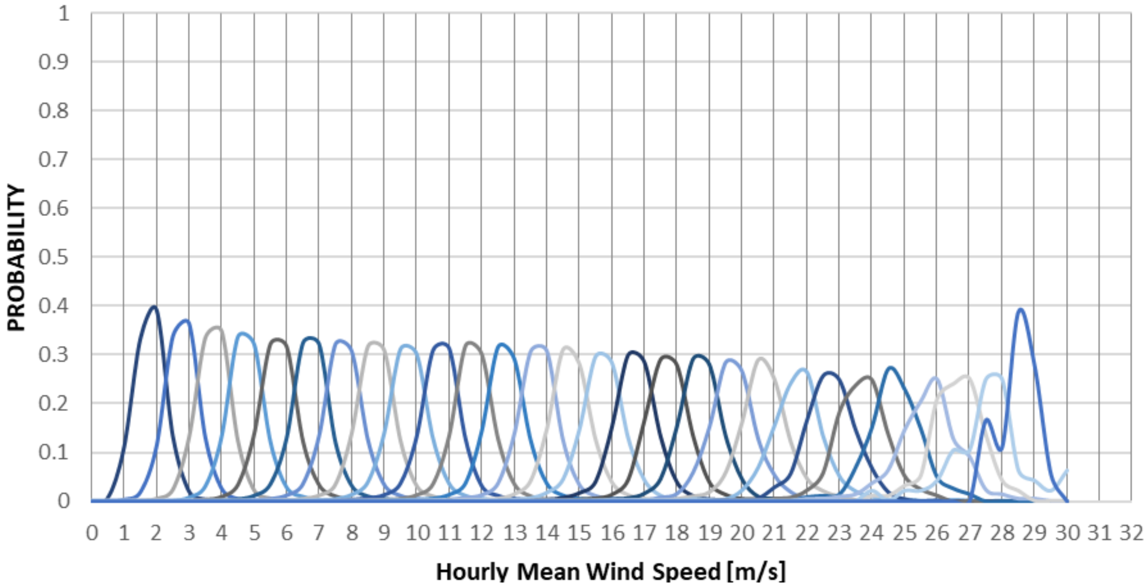


Figure 3.6: Probability distribution for 10-minute wind speeds for 1-hour bins

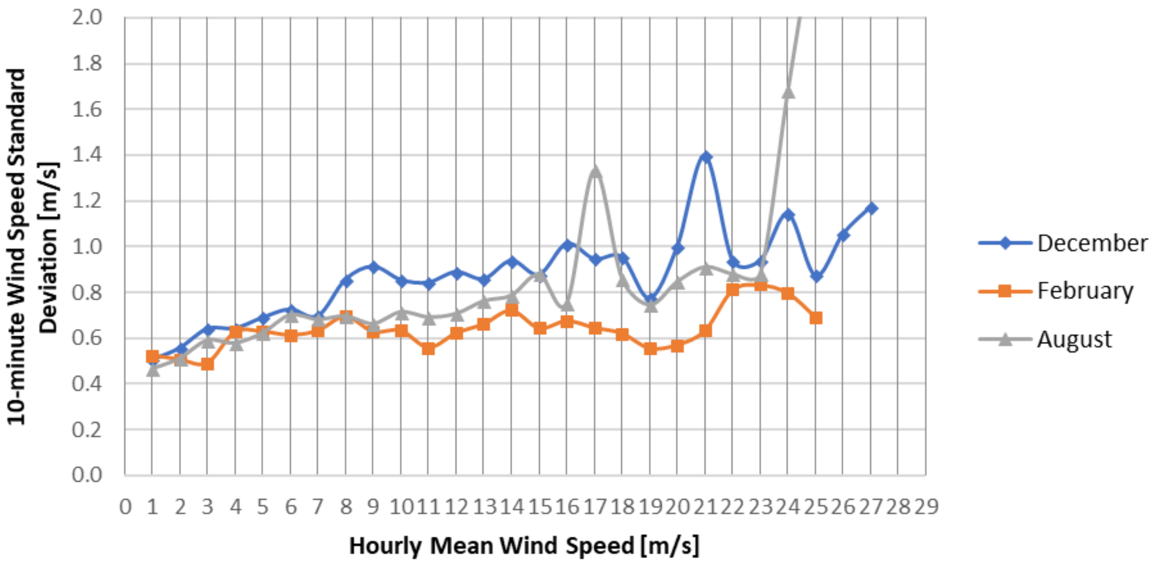


Figure 3.7: Standard deviation of 10-minute wind speed for 1- hour bins for three months

Challenge: sea-wide weather variation

Another challenge is generating sea-wide weather variation. To demonstrate variations of weather in the offshore environment, Vindby's virtual sea is divided into 100 cells, each with distinct environmental characteristics. All cells use the same Markov matrix to save setup time. Each occupied cell then runs its own weather simulation (unoccupied cells are excluded to minimize computing time.) Cells must have distinct mean wind speeds to demonstrate variation offshore. This is achieved is by using a wind speed factor to increase or decrease the simulated mean wind speed and wave height magnitudes while maintaining their distributions. On 4C Offshore's online public database of offshore wind farms, the global wind speed rankings range from 5.5 m/s (Golfo di Trieste in the Adriatic Sea) to 12.12 m/s (Fujian Putian City Flat Bay in the Taiwan Strait) (4Coffshore, 2018). As the mean wind speed of the entire FINO1 dataset is 9.4 m/s, wind speed factors of 0.5 to 1.3 are used to achieve a range of 4.7 to 12.2 m/s. Because Vindby's sea is fictitious, wind speed factors are assigned randomly to different cells with generally increasing mean wind speed farther from shore. A future version of Vindby should present different parameters each time it is played to ensure that players play a new game every time (discourage the re-playing of the game until the perfect "solution" is found).

Resolutions of 0.4m for significant wave heights and 1 m/s for wind speed result in stable transition probability estimates according to (Scheu, Matha, & Muskulus, 2012). These values are held constant because the analysis was developed to focus on overall approach to predicting ten-minute wind speed variability, weather windows, and wind speed factors.

Testing the model

Before implementing the weather prediction model into Vindby, different simulation methods are each run 10 times (based on time limitations as each run took about half a day to complete) for 10 years each to establish the effects of wind speed factor, 10-minute data sampling method (Markov vs Gaussian), and using a 'wave to wind' vs 'wind to wave' Markov approach. Wave height boundaries of 1.5m and 2m and wind speed boundaries of 15 m/s and 20 m/s are used to test persistence. A 10-year simulation is chosen after a quick analysis of the stability of mean wind speeds after 1, 5, 10, 15, and 20 years simulations. After at least 10 years of simulation, the change in mean wind speeds did not vary more than 1%.

The complete results are presented in section 4.1. For the purposes of game design, the following game mechanics are applied to Vindby:

1. The game loop runs at a game speed interval of one hour.
2. In the game hour, one wave height and six wind speeds are generated.
3. The wave height is used to determine if vessels can access the farm.
4. The wind speed is used to determine total production for the hour.

The Vindby objects used for weather generation are as follows:

Markov: *Generates Markov matrices once during game setup to be used by each weather model.*

Weather: *Generates weather conditions for one cell. Output includes one wave height and six wind speeds per hour.*

Wind speed variation is presented to the player in the form a varying production and availability to perform O&M as is described in following sections.

3.4.2 Offshore wind farm design

Intelligent wind farm design is one of the most fundamental activities in Vindby. This section presents how wind farm design translates into game mechanics.

WindFarm: *Represents one wind farm.*

Site Selection

One characterizing dissemination goal is for the player to gain an appreciation for the short-listing process of informing and selecting an adequate construction site. The characterizing training goal is for the player to learn about various offshore parameters and the consequences of neglecting them. The site selection process is applied to the sea grid object, which consists of 100 cell objects.

SeaGrid: *Represents the sea grid*

Cell: *Represents one cell in the sea grid with unique environmental properties*

To develop an appreciation of site selection, players are given minimal information to start. The player can then spend money to do site investigations to gather more site information. For simplicity, all properties kept homogenous across one sea grid cell (a site). The site selection information includes:

1. Mean wind speed (requires investigation)

   Mean wind speed offshore influences the expected power output of an offshore wind farm. The mean wind speed for a given cell is determined from the cell's weather model and wind speed wind speed factor.
2. Water depth

   Water depth influences the size of support structure required and the general construction feasibility. The water depth is determined by assigning categories of very shallow (5-15m), shallow (15-30m), medium (30-50m), deep (50-70m), and very deep (70-200m). The different cells are assigned deeper categories at increasing distances from the shore, while integrating some randomness to reflect reality. Uniformly distributed random values are selected for each cell based on the category. While water depth requires timely investigation, Vindby offers it 'for free' to help get players started on building.
3. Soil quality (requires investigation)

   Soil properties influence the design of structure foundations. Vindby only distinguishes between good, medium, and poor-quality soil, assigned randomly to cells with some continuity in regions. More detailed parameters could be integrated in future versions of Vindby to further explore design drivers.
4. Distance to shore

   The distance to shore influences the design (cable lengths, water depths, visual impact, and energy conversion) and maintenance (accessibility and repair times) of offshore wind farms. The sea grid consists of a 100 km by 100 km square sea, where each cells distance to shore is measured from its centroid. This is not the distance to the onshore substation, which is located next to cell 1. The sea grid does not aim to represent existing seas or countries. In other words, future versions of Vindby may include models of the North Sea, Sea of Japan, North East coast of the USA, etc.

5. Environmental restrictions (requires investigation)

   Safety of personnel and the public and environmental protection cut across all criteria and strategies, in terms of priority (EWEA, 2007). Benthic activity, marine animal habitats, and fisheries are ecosystem components that result in offshore areas requiring mitigation or being protected and off limits (Ellis, Clark, Rouse, & Lamarche, 2017). Vindby assigns sensitive or protected statuses to certain cells. During design, the player can incorporate mitigation measures to avoid adverse effects and fines.

6. Vessel route (requires investigation)

   The existence of a vessel route is intended to represent the risk of vessel collision. Studying ship traffic distribution is the critical step in quantifying ship collision risk (Christensen, Andersen, & Pedersen, 2000). In Vindby, the risk of ship collision does not exist; however, building within an existing route will prompt the payment for risk reducing measures such as markings or guard vessels.

7. Status

   For simplicity, one wind farm can occupy one cell at a time, regardless of the number of turbines in the farm for simplicity. If a farm has been decommissioned, the player can build another farm in its place. In future versions of Vindby, this may be updated to better reflect reality.

In a future version of Vindby, it is recommended to offer different scales of site investigation such as a desktop study or full investigation with consequences of different reliability of data. Specifically, choosing a full investigation would be more expensive and provide exact values of environmental parameters. A desktop study would be less expensive and provide data that is sampled from a probabilistic distribution with a mean equal to the exact value.

Vindby currently uses a preloaded dataset of the cell properties listed above. In future versions, the cell characteristics may be randomly generated following certain guidelines during game setup to ensure that no two games are the same. The current prototype cell characteristics are presented in Figure 3.8, Figure 3.9, and Figure 3.10.

Figure 3.8: Vindby sea grid wind speed factor

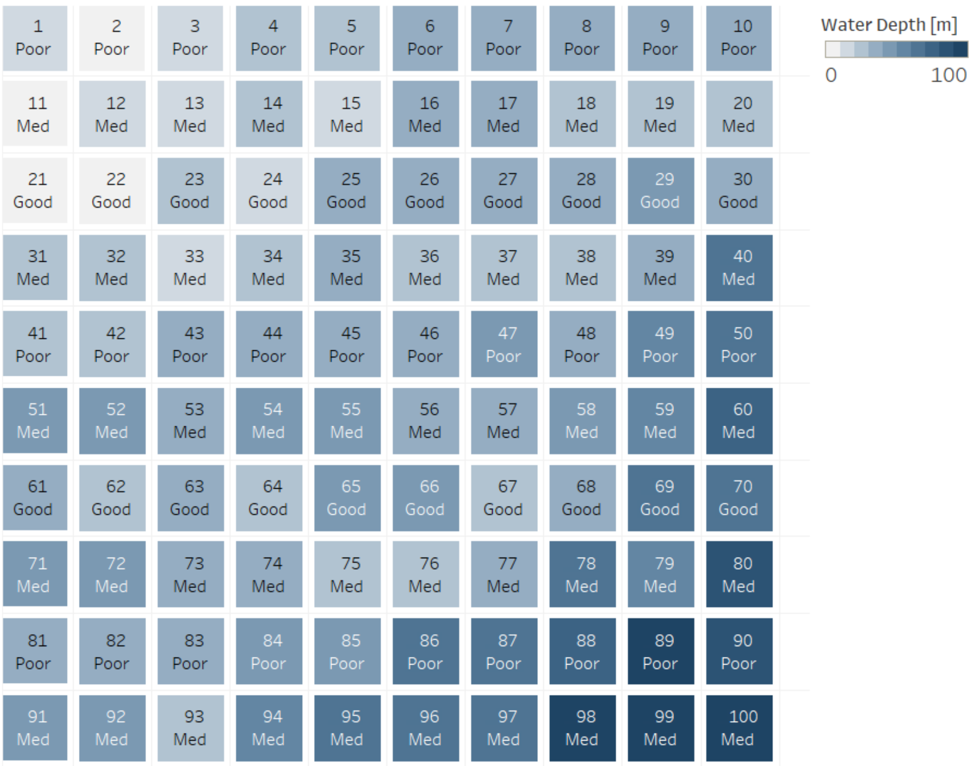


Figure 3.9: Vindby sea grid water depth and soil quality

Figure 3.10: Vindby sea grid environmental and navigational constraints

Turbine Technology

The building blocks of the offshore wind structures are represented in Figure 3.11. There are four objects utilized to construct turbines in Vindby.

TurbineAll: *Includes a list of all possible turbines in the game*

TurbineAvailable: *Includes a list of turbines available to be purchased at a given time*

TurbineType: *Represents a turbine type with power curve information*

Turbine: *One turbine of a certain type that exists in a wind farm*

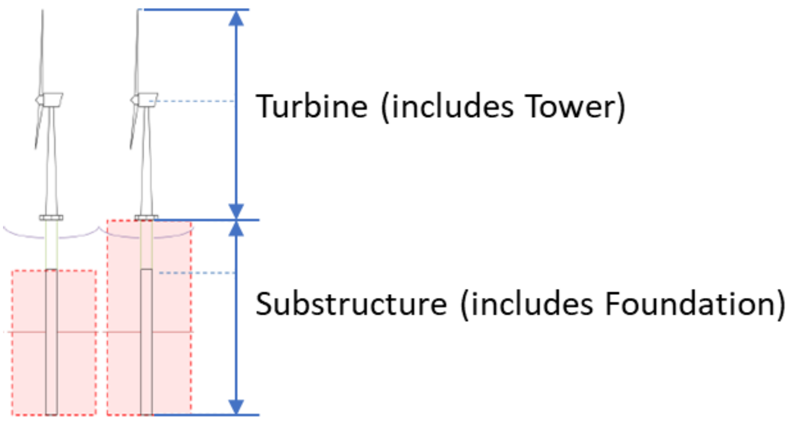


Figure 3.11: Wind turbine and support structure components (Miñambres, 2012)

Typically, the wind turbine model is selected early in the design process (even before site investigation) as it will influence the electrical system, design capacity, and grid connection. Limited prior knowledge of offshore wind farm design may negatively inform the player's selection. Therefore, Vindby prompts for the turbine selection after site selection.

According to 4C Offshore's offshore turbine database, the range of available turbines goes up to 8.8 MW, with 10 MW in prototype or concept stages only. Vindby is not meant to be a catalog for actual turbine technology, which is why the options displayed are 3, 5, 7, 10, and 15 MW to capture existing and future technology. Discrete values were chosen for simplicity. The 10 and 15 MW turbines only become available after playing Vindby for a certain amount of time, to simulate development of technology with time. The game may integrate an actual research and development object as opportunities to invest. This would more adequately simulate development of technology and is currently stubbed out in the prototype.

Wind speed distribution and power curves of the turbine together determine energy production. The selection of turbine determines production potential. The power curve is a curve plotting power output of a turbine as a function of wind speed. These curves for turbines are typically guaranteed to function as designed, although availability can be lower than expected. Values for cut-in, cut-out, and rated output speeds were determined from (Matysik & Bauer, 2018).

Site specific and generic power curve adjustment and high wind hysteresis (procedures used to optimize power efficiency) were considered beyond the scope of this study and are stubbed out in the prototype. The mechanics of turbines are not explored in this study or in Vindby.

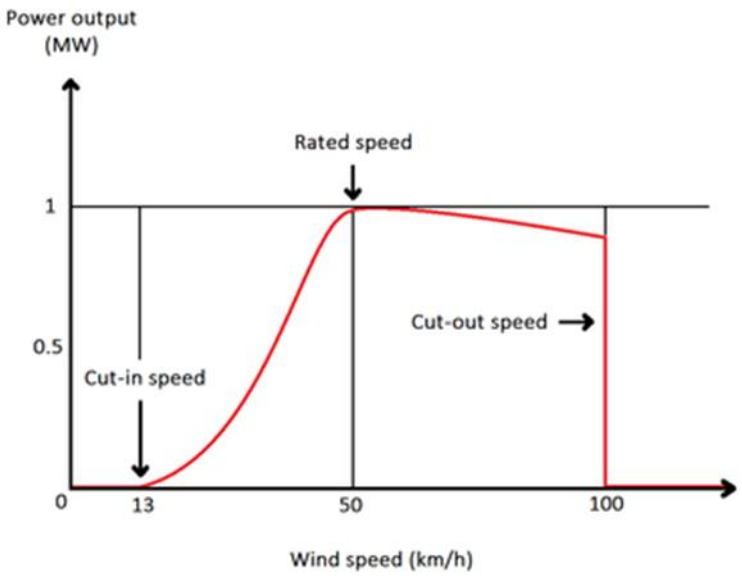


Figure 3.12: Wind turbine power output with steady speed (Windpower program, 2018)

In the Vindby prototype, the power curves use straight lines for simplicity, but possibility to use polynomial curves is stubbed out using similarly rated turbines as reference. Table 3.1 presents values used for the turbine power curves as stored in the power curve object.

PowerCurves: *Contains information about the power curves for all turbine types*

Table 3.1: Vindby simplified turbine power curves

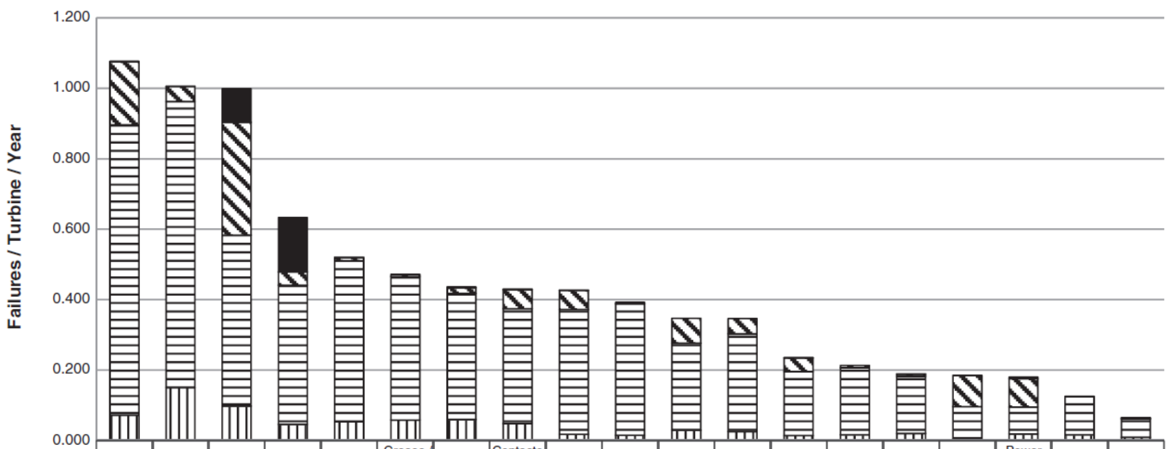
Turbine Rating [MW]	Cut-in [m/s]	Slope	Rated speed [m/s]	Cut-out [m/s]
3	3	0.3	12	23
5	3	0.5	11	25
7	4	0.8	13	25
10	3	1.2	11	25
15	4	1	15	25

Additional emphasis can be made on the multi-megawatt advantage that offshore wind has to onshore wind. This may be introduced in the form of an onshore market object.

Turbines exist in different states that describe reliable and automatic operation of wind turbines. Such states that react to transient wind conditions and faults are: testing, standstill, start-up, waiting, running-up, part-load operation, full-load operation, shut-down, immobilization, fault shut-down, and emergency shut-down (Heier, 2014). Vindby addresses operational, waiting mode, automatic shut-down, and fault-shut down. The addition of turbine states is stubbed out and may be implemented to employ and test control system strategies. This, along with O&M, has a strong potential to make an impact on the training characterizing goals.

Each turbine has its own failure rates based off a baseline value, which is stored in a failure rates object (the turbine specific rate is stored in the turbine object itself). This allows for flexibility and introduction of varying failure distributions and testing different control systems. Baseline failure rates are based off (Carroll, McDonald, & McMillan, 2015), which provides failure rates in failure per turbine per year based on a database provided by a leading wind turbine manufacturer. Failures are categorized by turbine component and by cost category (minor repair, major repair, and major replacement). A total of 19 components are compared in terms of failure rate (Figure 3.13), repair times, repair cost, and technicians required per repair.

FailureRates: *Contains baseline failure rates for all turbine, structure, wind farm, and cables*



	Pitch / Hyd	Other Components	Generator	Gearbox	Blades	Grease / Oil / Cooling Liq.	Electrical Components	Contactor / Circuit Breaker / Relay	Controls	Safety	Sensors	Pumps/ Motors	Hub	Heaters / Coolers	Yaw System	Tower / Foundation	Power Supply / Converter	Service Items	Transformer
Major Replacement	0.001	0.001	0.095	0.154	0.001	0.000	0.002	0.002	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.005	0.000	0.001
Major Repair	0.179	0.042	0.321	0.038	0.010	0.006	0.016	0.054	0.054	0.004	0.070	0.043	0.038	0.007	0.006	0.089	0.081	0.001	0.003
Minor Repair	0.824	0.812	0.485	0.395	0.456	0.407	0.358	0.326	0.355	0.373	0.247	0.278	0.182	0.190	0.162	0.092	0.076	0.108	0.052
No Cost Data	0.072	0.150	0.098	0.046	0.053	0.058	0.059	0.048	0.018	0.015	0.029	0.025	0.014	0.016	0.020	0.004	0.018	0.016	0.009

Figure 3.13: Failure rate per year for turbine components and by cost category (Carroll, McDonald, & McMillan, 2015)

Six of the most significant failures are used in Vindby. They are chosen based on the highest expected costs, i.e. failure rate times the cost of failure, as shown in Table 3.2. The cost of each failure was found by adding the cost of repair plus the labor cost (number of technicians times repair time times cost of one technician). The cutoff was six because the next most significant failure type is “Other components”, which does not contribute to learning or fun in a game.

Table 3.2: Expected costs of turbine failures per turbine per year (top 6 of 19)

Expected cost	Gearbox	Generator	Pitch /Hydraulics	Blades	Power Supply	Hub
Major Replacement	€59,895	€8,132	€ 18	€332	€132	€214
Major Repair	€202	€1,956	€735	€ 43	€534	€312
Minor Repair	€327	€376	€855	€422	€ 65	€197
sum	€60,424	€10,464	€1,608	€797	€731	€723
Percent of total	76.9%	13.3%	2.0%	1.0%	0.9%	0.9%

For use in Vindby, the failure rates are converted to failures per turbine per one hour because the game simulation runs on a one-hour time step. Although failure rates vary throughout the turbine lifetime, majority of studies and industry practice use the simplification of constant failure rates (Scheu, Kolios, Fischer, & Brennan, 2017). There is work that explores the various distributions as shown in Figure 3.14.

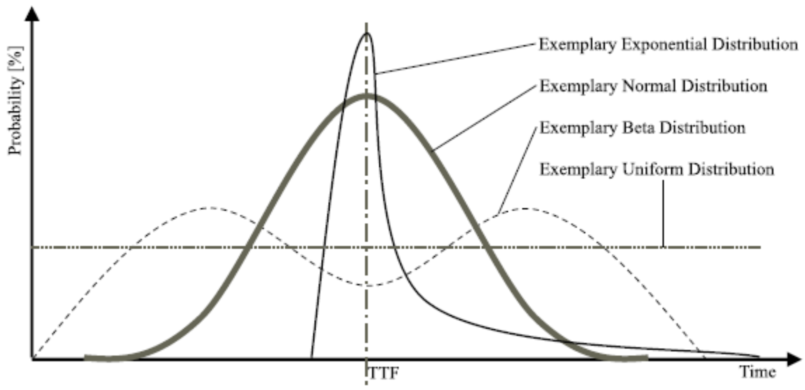


Figure 3.14: Time to failure distributions (Scheu, Kolios, Fischer, & Brennan, 2017)

Many studies estimate life time failure distribution as a bathtub curve. Given the uncertainties remaining in the reliability of stochastic models (there is generally a lack of publicly available reliability data) the failure rates are constant throughout the turbine original 20-year lifetime. The player has the option to extend the farm lifetime by five years, twice. During lifetime extension, turbine failure rates are increased by 50% to add consequence to extending farm lifetime and enhance player decision making. The initial failure rates for turbines in Table 3.3 are the same for all turbine sizes, although they may be altered to be higher for larger turbines.

Table 3.3: Failure rates per turbine per hour

Failure Rate per turbine per hour	Pitch /Hydraulics	Generator	Gearbox	Blades	Hub	Power Supply
Major Replacement	1.14E-07	1.08E-05	1.76E-05	1.14E-07	1.14E-07	5.71E-07
Major Repair	2.04E-05	3.66E-05	4.34E-06	1.14E-06	4.34E-06	9.25E-06
Minor Repair	9.41E-05	5.54E-05	4.51E-05	5.21E-05	2.08E-05	8.68E-06

An important measure in wind energy is the capacity factor, which is the ratio of actual electricity produced to the maximum possible. A capacity factor of 1 results from a wind speed maintained at the rated speed constantly for one hour, which is hardly the case. Capacity factors are lower than 1 because of fluctuations in the wind and downtime due to failure. Typically, offshore wind capacity factors (averaged over the lifetime) range before 0.25 and 0.75 depending on season, and average at about 0.4 (Wind Europe, 2017). The capacity factor for wind farms in Vindby are updated each loop and presented to the player to indicate how efficiently wind farms are running and what the consequences are of certain O&M decisions.

Support Structures

Throughout available literature, the capital cost of wind turbines and their support structures (acquisition and installation) account for the largest contribution to overall wind farm cost. There are four objects utilized to construct support structures in Vindby.

SubstructureAll: *Includes a list of all possible substructures in the game*

SubstructureAvailable: *Includes a list of substructures available to be purchased at a given time*

SubstructureType: *Represents a substructure type with a function to calculate unit cost*

Substructure: *One substructure of a certain type that exists in a wind farm*

The two main categories of support structure types are bottom fixed and floating. Bottom fixed structures include monopile, gravity, jacket, tripod, and tripile, and their supports can be categorized by three foundation types: pile, gravity based, and suction bucket. Floating structures include spar, semi-submersible, and tension-leg platform, and can be categorized by three mooring systems: pile, anchor, and suction bucket (Miñambres, 2012). There are 21 possible combinations of support structure and foundation types that may be explored. To not overwhelm the player, seven support structures (Figure 3.15), are combined with foundation types in Vindby.

The three floating concepts only become available to the player after a certain amount of wind farms are in operation to demonstrate industry growth with time. Furthermore, this is intended to reflect the research concerning whether new support structure concepts can surpass existing ones as prospects of moving to deeper water increases. Floating offshore wind structures are both important to industry development and considered a hot-topic in research and the general public. The floating concepts in Vindby are introduced in order of decreasing cost in deep water: semi-submersible, tension leg, and spar.

Additional structure types and foundation combinations can be integrated into future versions of Vindby. Separate foundation objects may be created to emphasize the impact of design drivers, soil conditions, and more.

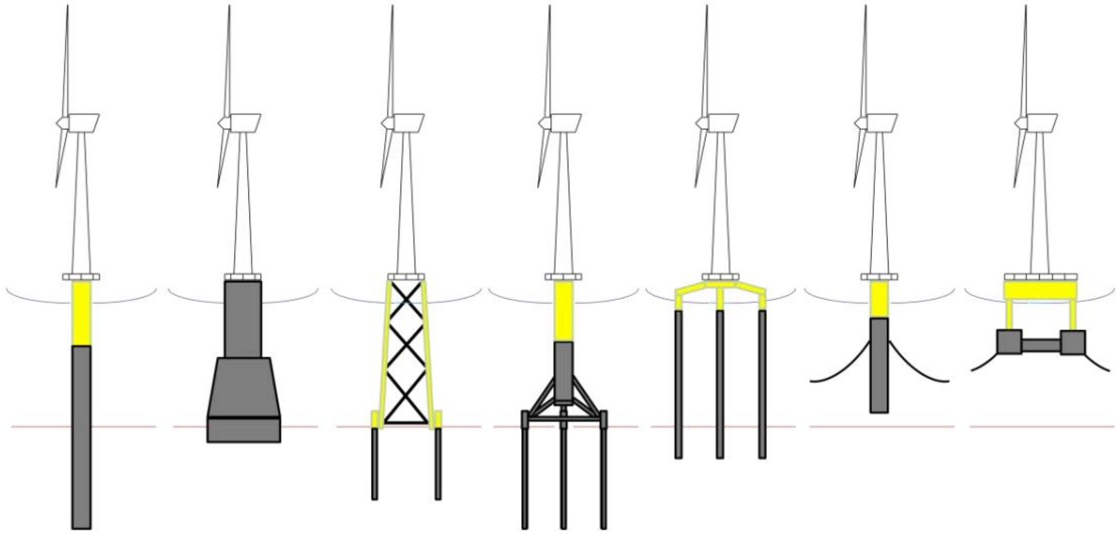


Figure 3.15: Vindby's support structure concepts. (Left to right: monopile, gravity base, jacket, tripod, tension leg, spar, and semi-submersible) (Miñambres, 2012)

In Vindby, the cost of the support structure is a function of water depth and soil type. Certain substructures are depth limited due to either economical scale or physical feasibility. Rather than restrict the use of certain structures to certain water depths, Vindby employs a depth factor for structures that makes them very expensive for water beyond a certain depth. This unrealistic feature is meant to enhance creativity in the game and is explored in detail in the costs section.

Advantages and disadvantages of each support structure as it relates to reliability in Vindby is in Table 3.4 (information on floating structures is relative to other floating structures.)

Table 3.4: Advantages and disadvantages of Vindby support structures (Miñambres, 2012) and (Jonkman, 2018)

Structure	Water Depth [m]	Advantage	Disadvantage
Monopile	15-30	Proven Concept Simple and quick fabrication	Highly susceptible to scour Limited water depth
Gravity	0-15	Reduced fatigue sensitivity Low corrosion potential	Not suitable on soft seabed Limited to shallow water
Jacket	30-50	Suitable for many soil types Good load transmission	Complex fabrication Large number of joints susceptible to corrosion
Tripod	30-50	Good load transmission Suitable for many soil types	Complex fabrication Slow fabrication
Tension leg	50-150	Feasible in deep water Better damping/ stability	Difficult installation
Spar	50-150	Feasible in deep water Lower wave sensitivity	Challenging with large turbines
Semi-submersible	50-150	Feasible in deep water Suitable for larger turbines	Higher sensitivity to wave loads

A fundamental characterizing goal of Vindby is to enhance the players understanding of design drivers. For training purposes, this might be to understand how to address poor soil conditions or rough sea states, and for dissemination purposes, this might be to learn about failure modes and the complexity of designing structures offshore. Unlike turbine failures, structural failures (within the limit state) are not acceptable, and a designer does not choose and design a structure based on the number of acceptable failures. Rather, a structure is designed to withstand loads within a limit state. Structural failure rates in Vindby are not designed to represent realistic occurrence probability, rather to point the player as directly as possible to which parameters affect which substructures more than others. The experience of developing these rates is a creative balancing task between engineering accuracy and game mechanics.

Each substructure has its own failure rates based on the mean wave height on the cell, soil quality, structure type, and turbine size. This feature makes the reliability and availability of turbines flexible. Table 3.5 presents the support structure failure rates used in Vindby.

Table 3.5: Support structure failure rates

	Baseline	**gravity**	**monopile**	**tripod**	**jacket**	**floating tension leg**	**floating semi-submersible**	**floating spar**
Scour	1E-04	0.0001 for poor soil	0.0001 for poor soil	0	0	0	0	0
Fatigue	1E-05	0.00001 x Wave height	0.00001 x Wave height	0.000005 x Wave height	0.000005 x Wave height	0.00002 x Wave height	0.00002 x Wave height	0.00002 x Wave height
Corrosion	1E-05	0	0.00001	0.00002	0.00002	0.00001	0.00002	0.00001
Bearing	1E-04	0.0001 for Medium soil and 0.0002 for poor soil	0	0	0	0	0	0
External Load	1E-06	0.0000005 x Turbine size	0.000001 x Turbine size	0.0000005 x Turbine size	0.000001 x Turbine size	0.0000005 x Turbine size	0.000001 x Turbine size	0.000001 x Turbine size

Vindby uses scour as an example of addressing reliability in structural design. For each design, the player is prompted to pay for scour protection and is briefly informed which structures and which soil conditions lead to scour (and what scour is). If scour protection is not provided but was not needed in the first place, nothing happens. If it was needed, the scour failure rate was chosen in a way that guarantees scour failure soon after construction. The player must then pay for scour protection for the entire farm at a significantly higher price. A similar concept is used for gravity structures and bearing failure, which refers to the large movement of soil underneath a footing and is calculated based on the footing size and properties of the soil.

Layout

The layout for an offshore wind farm involves many tradeoffs. For example, array spacing must consider array losses from energy production and electrical costs and efficiency. Given that the cell depth and soil properties is homogenous, the layout design is dictated by energy production (EWEA, 2007). Wake effects and losses are not considered in Vindby currently, although may be easily integrated into the prototype in the future. Therefore, turbine spacing is considered constant throughout the sea grid at 1 km (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014). Grid like layouts are optimal in terms of energy generation and minimizing cable lengths (Kaiser & Snyder, 2012). Using a grid layout and 1 km spacing, a resulting cell of 10 x 10 km could hold a maximum of 100 turbines, which falls within the realistic scale of existing farms as shown in Figure 3.16: European offshore wind farm size correlations .

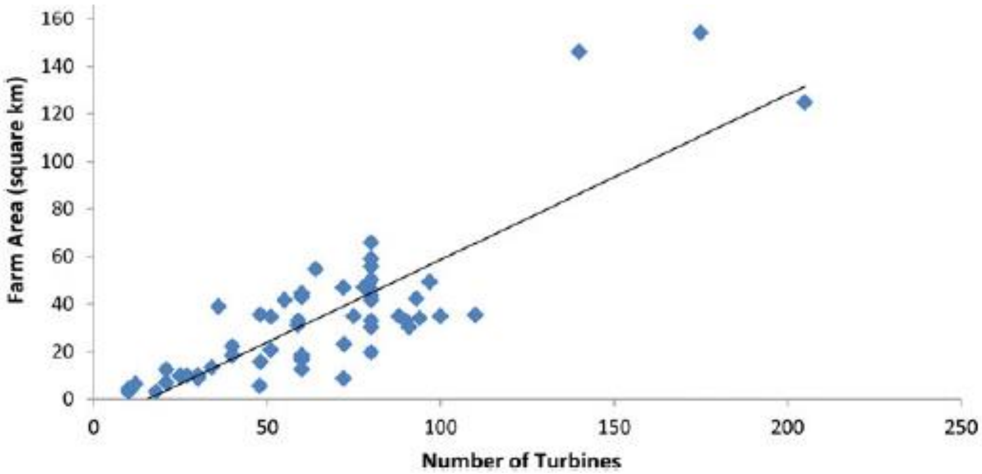


Figure 3.16: European offshore wind farm size correlations (Kaiser & Snyder, 2012)

While noise and visual footprints often dictate layout designs for onshore wind, they are typically less impactful offshore. There is a quantifiable visual impact for offshore wind turbines relatively close to shore. According to (DTI, 2005), visual effects are classified as:

- Possible major visual effects for distances less than 13 km from shore.
- Possible moderate visual effects for distances between 13 and 24 km.
- Possible minor visual effects for distances greater than 24 km.

Grid Integration

The high capacity of offshore wind farms requires a coordinated cost-efficient grid feed with long transmission cables. According to (Heier, 2014), basic knowledge and experience on the various transmission concepts and system behavior can take years to develop. Grid integration is therefore greatly simplified in Vindby, although is encouraged to be expanded on with input from subject matter experts. The topics that are addressed include: subsea cable lengths, wind farm clusters, alternating vs direct current transmission, and onshore vs offshore substations. Vindby uses objects to represent all the wind farms in the game and the onshore substation.

WindFarmGrid: *Includes reference to all wind farms in the sea grid and their connections*

OnshoreSubstation: *Represents the onshore substation, whose capacity is increased when needed.*

In Vindby, subsea cable lengths are initially computed as straight-line distances to the onshore substation connection point. The actual design and placement of subsea cables must consider subsea surface conditions, soil properties, current conditions, debris, and navigation.

For a long time, offshore wind farms have been largely individual projects. With a growing number of installations, many advantages can be gained through coordination of offshore installations and the use of gathered wind farms in clusters that feed their electrical output into common nodes (Heier, 2014). In Figure 3.17, the left diagram presents an arrangement with separate linkages of offshore farms joining at common transformer stations onshore. The right diagram shows clustered wind farms that use less cables and a smaller number of sea platforms.

In general, using clusters achieves more economical grid loads. The tradeoff between capital cost and actual investment and losses depends greatly on the operating voltages and number and size of cable infrastructure (Heier, 2014). In Vindby, the player has the option to connect to the closest possible wind farm if it results in shorter cable lengths. Given their connection, grid and cable failure would affect the connected farm. In other words, if farm A is connected to farm B, and farm B has a grid or cable related failure, both farm A and B are unavailable.

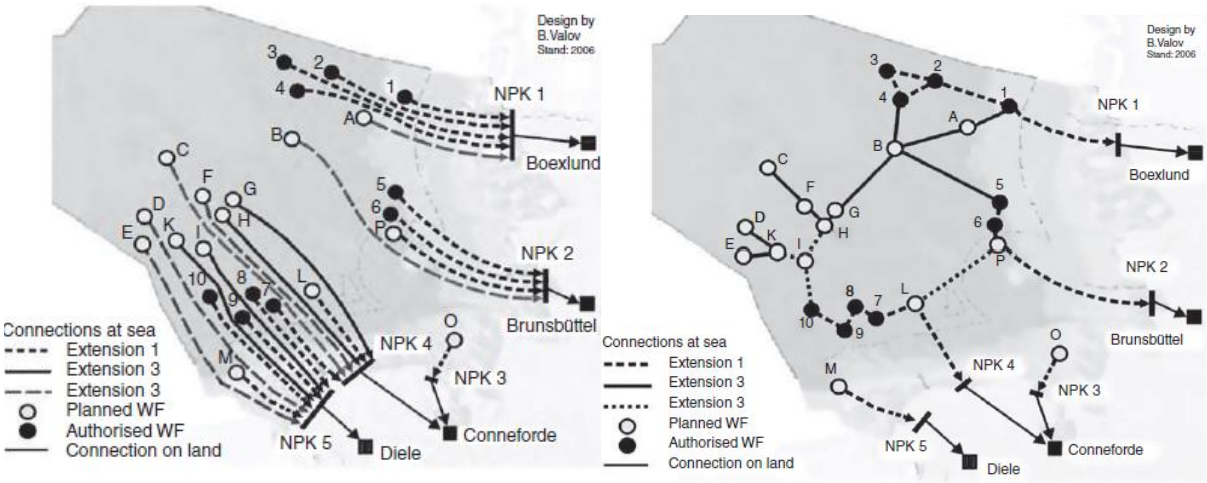


Figure 3.17: Concepts of connections of offshore wind farms. Left is separate, right is cross-connected clusters (Heier, 2014)

Offshore wind farms require a substation, either onshore or offshore. For conventional frequencies of electricity transmission, alternative current technology does not require an offshore converter station. Offshore substations are built to increase the voltage of electricity generated at the turbine. For connection to high voltage grids and for high distances to shore (more than 100 km,) direct current transmission cables and offshore substations may reduce energy losses (Heier, 2014). In Vindby, all farms at a distance greater than 100 km from the onshore substation are required to build an offshore substation. Additionally, the onshore substation starts with a 500 MW capacity, and increases in increments of 500 MW as needed by the construction of the new farms.

Inter-array cable lengths are determined from number of turbines. Vindby does not include wake effects although they affect turbine layout. The total length of inter-array cables assumes an economic, linear layout and is estimated following (Shafiee, Brennan, & Espinosa, 2016):

$$L = \max(0.8 \times N_{turbines}\,, 1.6 \times N_{turbines} - 16)$$

Construction

Logistical constraints regarding fabrication yard and port capacity to handle offshore wind farm elements is not included in Vindby because Vindby's onshore infrastructure is not constructed in detail. The construction time is roughly estimated on a project basis. Construction is modelled by assuming duration of construction as follows:

- Laying cable at a rate of 9,000 m per day (FOWIND, 2016).
- Support structure and turbine installation time based on (Lacal-Aránteguia, Yusta, & Domínguez-Navarro, 2018) varying between 1 to 5 days per MW per turbine-substructure set.
- Construction may be slowed down by a slow contractor, resulting in delayed commissioning.
- Construction accidents may occur, which must be addressed manually. If left unaddressed, the wind farm does not get built and the contractor cost continues to rise.

The resulting construction time is significantly underestimated considering the many stages between design and commissioning including: fabrication and procurement of wind turbines, structure, foundation, power transmission system, and monitoring system; port staging; transportation of all elements; and then installation. Significant detail in construction time calculation and feedback is reduced as it may distract the player and cause impatience (even at maximum game speed) with respect to when the wind farm becomes operational. The characterizing goals in this prototype do not cover installation times and requirements.

Decommissioning and disposal

The average designed lifetime of an offshore wind farm is 20-25 years. Decommissioning is the final phase of a project's lifecycle and includes the removal of all physical elements to return the offshore area to its original pre-farm state. Decommissioning may also include repowering of the farm by replacing the turbine components with power powerful ones. The decision to decommission early, on schedule, or repower depends on the site factors, the farm size, the regulations, the price of power, operating costs, and the expected profitability of the repowered or extended lifetime farm compared to the actual market (Topham & McMillan, 2016). It is also possible to decommission before the full lifetime. The first offshore wind farm to be decommissioned was Yttre Stengrud in 2016 after 14 years of operation because the turbine technology was outdated and costlier to operate than not.

The lifetime of all wind farms in Vindby is 20 years. There is no option to decommission early, but it is possible to extend the lifetime by 5 years, twice. These options may be expanded in a future version of Vindby. The cost of decommissioning is based off (Shafiee, Brennan, & Espinosa, 2016) and includes port preparation, removal, waste processing, waste transportation, landfill, and post decommissioning monitoring. The cost of decommissioning is estimated at €376,000 per MW. A significant portion of the wind farm materials can be recycled. The cost of salvaging materials is €30,000 per MW. Decommissioning subsea cables is estimated according to (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014) as 10% of the installation cost.

3.4.3 Operation and maintenance strategies

Operation of an offshore wind farm includes rental/lease agreements, insurance, and transmission (Shafiee, Brennan, & Espinosa, 2016). Operation activity and costs are not included in detail in Vindby only because the costs and risks does not seem to strongly contribute to the characterizing goals of training or dissemination. The cost of transmission is added as an annual fee.

Maintenance of an offshore wind farm consists of addressing failed components, maintenance of turbines including repair and replacement, and regularly scheduled inspections. The challenge of applying maintenance efficiently is maximizing turbine availability (minimizing downtime) while minimizing costs associated with unexpected failures (Shafiee, Brennan, & Espinosa, 2016). Based off a combination of strategy organizations in literature, Vindby uses maintenance strategies in three categories. Vindby uses an O&M manager object to manage and repair failures based on the three strategies. The repair vessel object represents the fleet of vessels that complete repair. This object is not fully refined to capture the activity of separate vessels but can be revised to do so in a future version of the game.

OMoptions: *Includes a list of all possible O&M strategies.*

OMmanager: *Runs all activity related to operation and maintenance for one farm based on the selected strategy.*

RepairVessel: *Performs all repairs and updates wind farm objects about repairs done.*

The three O&M strategies in Vindby are:

1. Calendar based maintenance – failures are repaired at the end of the month. Cost savings are attained by using the same vessel for multiple repairs; however, a lot of downtime is accumulated.
2. Condition based preventative and unplanned corrective – for an upfront cost for a monitoring system (condition monitoring systems are connected to operator visa a Supervisory Control Alarm and Data Acquisition system), certain failures can be predicted ahead of time and repaired immediately at a reduced cost. For failures that cannot be or are not prevented, either they are repaired automatically at the end of the month, or they can be repaired immediately (includes cost of sending a vessel out, but with no downtime).
3. Corrective maintenance – minor failures are delayed for repair at the end of the month, but certain expensive repairs prompt the player to decide if the high cost of immediately repair is necessary to keep the productivity going.

Each wind farm has an O&M manager that manages failures based on that farms selected O&M strategy, which can be switched during the game. Downtime is reported for failures as the time that has passed between the occurrence and repair of a failure. Repair costs are estimated using a fixed repair duration per failure based on (Carroll, McDonald, & McMillan, 2015) multiplied by a daily vessel rate plus the cost of the repair itself. The vessels utilized in Vindby are: Crew Transfer Vessels for minor repairs, Field Support Vessels for major repairs, Heavy Lift Vessels for major replacements, and Anchor Handling Tug Supply Vessels for subsea cable repairs. Actual repair times and therefore costs are not well understood largely because of data availability, and the difference amongst literature regarding the definition of failure. Vindby's fixed rates for repair duration and daily cost may be upgraded to represent different distributions.

Programming of the maintenance strategies involved many iterations to capture accurate representation and playability. One big challenge is not overwhelming the player with decision making over maintenance issues so focus can be kept on building farms and achieving the overall goal. Some decision making is required for the training / dissemination of maintenance knowledge. The frequently sited solution to this issue is a well establish interface, which is out of scope of this study.

3.4.4 Energy demand and climate change

Creating a story is a game element that fits in nicely to Vindby because the story includes reality about energy demand and climate change. In future versions of Vindby, the story may be scaled up or down depends on the size of the virtual space being examined. In this version, the global energy demand and climate change effects are considered as objects.

EnergyDemand: *Represents the game energy demand and non-renewable energy supply.*

CO2: *Runs all calculations for CO2 emissions in million tons and concentration in parts per million due to non-renewable and renewable energy, households powered by offshore wind, and temperature increase.*

To give context to the player about electricity supply, there is some electricity demand that must be met. The starting value for the yearly electricity demand is 3000 TWhr, based on the 2017 electricity consumption in the EU (Wind Europe, 2017). Prediction of growing demand is based on (EWEA, 2007) using back-calculated annual rates equal to 1.3% the first year, decreasing by 0.3% of the growth rate per year. Prediction in Vindby runs until 2100, which is the time limit on the game (theoretically, this time limit can be extended).

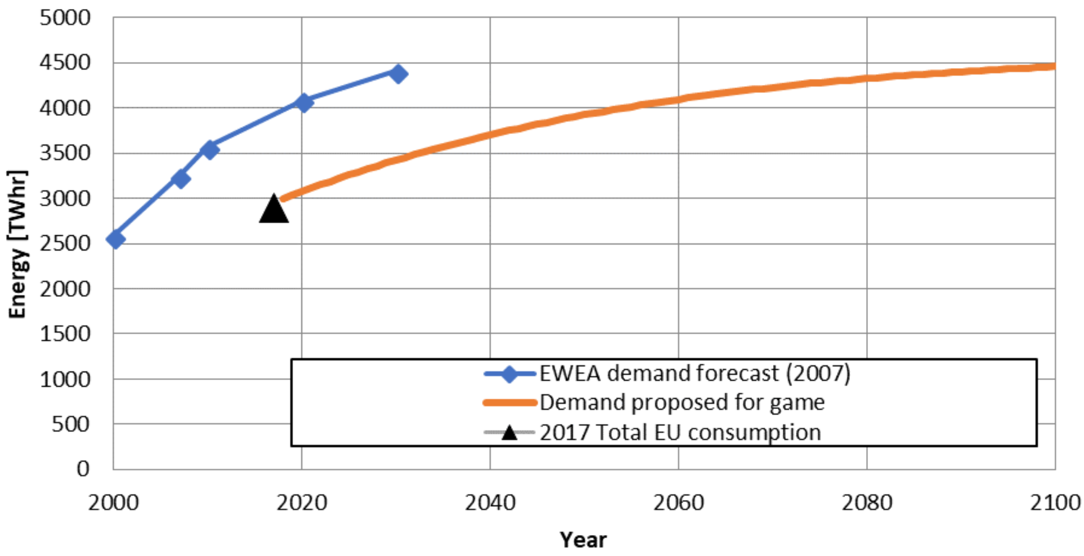


Figure 3.18: Growing energy demand in Vindby

The scale of Vindby in this prototype does not allow for full capacity to be met by offshore wind. One principle that is stubbed out in the game is the investment in other renewables to demonstrate how to address storage and variation in wind speeds. More specifically, an additional characterizing goal may be needed to teach users about long term integration costs of variable renewable energy.

Combatting climate change and reducing CO_2 emissions is arguably the core goals of why the player should be building offshore wind farms. One characterizing dissemination goal that that the player at a minimum understands that energy produced by offshore wind is replacing energy replaced by typical electricity generation (such as coal) which releases large quantities of CO_2 into the atmosphere, only half of which is absorbed by earth's surface. The growing CO_2 concentration, which is measure in parts per million (ppm) is slowly increasing the global temperature. Only CO_2 emissions are used to measure the effect on climate change.

The value of CO_2 released from non-renewable energy sources and offshore wind energy (on average due to maintenance and operation) is 0.95 and 0.012 t CO_2 per MWhr respectively (EWEA, 2007). The amount of CO_2 release during construction is based on the fabrication and transportation of materials. A rough estimate was derived following (Hinrichs, Goldsmith, Cepeda Haro, & Niaparast, 2010)

$$CO_{2,construction}\ [\text{t } CO_2] = 20{,}000 + N_{turbines} * (892)$$

The increase in CO_2 concentration is 1 ppm per 7.81 Gt CO_2. Global CO_2 concentrations is affected by factors other than electricity generation (although energy is the largest contributor to greenhouse gas emissions) (IPCC, 2014). An additional fraction is added to the CO_2 concentration every year. This also makes the game more difficult to reach temperature goals.

With the CO_2 concentrations known, the temperature increase estimate entirely depends on which climate scenario is considered. The scenarios in (IPCC, 2014) are categorized by temperature change in 2100. A scenario resulting from lower CO_2 concentration estimates would be expected to allow for a greater impact of offshore wind energy (and a greater chance of the player reaching the goal), which after much testing was difficult to attain. Therefore, the scenario of 430 ppm CO_2 by 2100 resulting in a likely chance that 2100 temperatures will remain below 2 degrees Celsius is chosen. To present the player with round and clear numbers, the scenario CO_2 concentration (due to energy and non-energy activity) was modified to achieve two things: one, a temperature increase just over 1 degree Celsius by 2050 without any offshore wind, and; two, a temperature increase below 1 degree Celsius by 2050 with 5 GW of installed offshore wind operating each year working at full capacity.

Relatable feedback is also presented in terms of households powered, equivalent cars taken off the road, and acres of forest reclaimed. The average household annual demand is assumed to be 3,900 KWh per household (renewableUK, 2018). Vindby demonstrates in the GUI that because wind power generation varies with times, theoretically the number of homes powered by offshore wind is not constant as well.

3.4.5 Finance and costs

Vindby includes resource management of an initial investment, expenditures, revenues, fines, and bonuses. The value for all finance parameters are represented in euros and based off realistic values when information is available. Relevant characterizing dissemination and training goals including recognizing the influence of O&M costs and gaining a sense of scale for offshore wind farm costs. More specifically, the player must use limited resources to make better design and operation decisions. If the player's balance runs out, the game is over. The resource manager object is called the player's wallet, to which money can be withdrawn and deposited.

Wallet: *Used to hold all the player's money. Used in the game to withdraw, deposit, and keep track of cash.*

Economics

The initial investment deposited into the player's wallet at the start of the game depends on the game goal that is selected. The scale of investment is chosen based on €7.5 billion, which is the investment made in offshore wind in 2017 (Wind Europe, 2017). For the lower duration games (goals 1 and 2,) the initial investment is €1 billion. This amount intends to encourage exploration of the game before moving on to more difficult game goals. For the longer duration games (goals 3, 4, and 5) the initial investment is €10 billion, to allow for more activity and farm building to reach the ambitious goals.

Inflation is the annual rate of increase in economy-wide prices. Inflation is influential when analyzing life-cycle costs over the course of many years, as is the case in Vindby. According to (Trading Economics, 2018) the European Union inflation rate was recorded at 2% in May of 2018, which was used in Vindby as the annual inflation rate for all costs.

Costs

Costs are developed for all items in Vindby and are based either on realistic values when data is available or arbitrary chosen to enhance game flow and playability. The full list of costs used and a description of their source is provided in Appendix D as is capture in a game object.

Costs: *Lists the baseline monetary value for all items in the game (objects, fines, rewards). Subject to yearly inflation.*

An example of when realistic costs and playability factors are used together is in the support structure costs. Following the comprehensive analyses done by (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014) and (Rosenauer, 2014), the cost per meter water depth is derived for all structures and foundation production and installation. Foundation pile lengths for bottom fixed structured are initially assumed to equal the dimension of water depth for simplicity (should be updated in a future version.) The pile length is then factored by a value depending on the soil quality: 1 for good soil, 1.5 for medium soil, and 2 for poor soil. Given the discreteness and simple categorization of soil quality, the factors are chosen arbitrarily, and should be updated as soil characteristics (like type, strength, and unit weights) are introduced.

An interesting challenge to balancing realistic parameters with playability is to capture the applicability of certain structures for water depths outside of their typical range. For example, monopiles typically reach their water depth limit around 30 m, when the design reaches engineering limits for pliable diameters and wall thickness. Similarly, jack structures are limited to 50 m due to economic viability and gravity-based structures are limited by transportability (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014). Rather than imposing strict depth limits in Vindby regarding what structure the play can build where, the concept of having the option to build outrageously sized and priced structures is both amusing and indicative of the real world. To accomplish this, an amplification factor is assigned to bottom fixed structures after a certain depth that greatly increases their cost which otherwise would simply increase linearly with depth. This factor is selected based on a careful balancing of all bottom-fixed structure costs with depth to ensure that at different depths and soil qualities, different structures become the most economic option. Without this consideration, the same structure would be the cheapest every time.

Similarly, floating structures, which are only introduced in Vindby after the player has at least seven operating wind farms, are not always viable or economical in shallow waters because of clearance. A cost is then applied to floating structures for depths lower than a certain value. The cost is an estimation of dredging volumes needed to clear the structure. The volume is based on the structure footprint estimated from (NREL, 2004) and difference in depth from the threshold. Soil quality does not play a role in the costs of floating structures.

Table 3.6 presents the costs per substructure for different water depths in million euros. The shading of the cells indicates the least (light) to most (dark) costly choices. This shading is used while selecting factors for each structure to balance the costs relative to other structures.

Table 3.6: Vindby Support structure cost for different water depths with good quality soil (€ million)

Water Depth [m]	Monopile	Jacket	Tripod	Gravity	Floating semi sub	Floating spar	Floating tension leg
0	0.0	0.0	0.0	0.0	11.1	25.7	25.8
10	0.8	1.1	1.6	1.4	9.5	23.5	23.6
20	1.6	2.1	3.2	2.7	8.0	21.4	21.5
30	3.3	3.2	4.8	6.5	8.0	19.2	19.4
40	4.4	4.2	6.4	8.7	8.0	17.1	17.2
50	5.4	5.3	8.0	10.9	8.0	14.9	15.1
60	6.5	6.4	9.6	13.1	8.0	12.7	12.9
70	7.6	7.4	11.2	15.2	8.0	10.6	10.8
80	8.7	8.5	12.8	17.4	8.0	8.4	8.7
90	9.8	9.5	14.4	19.6	8.0	6.3	6.5
100	10.9	10.6	16.0	21.8	8.0	4.1	4.4
110	12.0	11.7	17.6	23.9	8.0	4.1	4.4
120	13.1	12.7	19.2	26.1	8.0	4.1	4.4
130	14.1	13.8	20.8	28.3	8.0	4.1	4.4
140	15.2	14.8	22.4	30.5	8.0	4.1	4.5
150	16.3	15.9	24.0	32.6	8.0	4.1	4.5

Costs can also be leveraged to incorporate rewards and repercussions for certain game actions. For example, a reward is offered when a wind farm pays back its initial investment. Fines are deducted when a wind farm is constructed in an environmentally sensitive area without performing mitigation measures.

Selling Cost

A wind farm's selling cost is the price at which electricity is purchased. In Europe, there are two main approaches for supporting renewable energy: tradeable green certificates and feed-in tariffs (FIT). Under tradeable green certificates, renewable generators are given certificates for generated electricity and sells its power at market price. The certificates can be traded and sold between retailers. Under FIT, the policy-maker offers a fixed price of electricity to the generator and is guaranteed to be paid for all electricity generated. Often the FIT is reduced after ten years of operation (Green & Vasilakos, 2009). Vindby utilizes a FIT approach because of its simplicity, although future versions of Vindby could integrate both approaches for comparison. A FIT is generated for each wind farm using the object market.

market: *Used to calculate the feed-in tariff selling price for a wind farm.*

The FIT value depends on technology used, distance to shore, and mean wind conditions on site. The difficulty in setting FITs is that if it is too low, little or no development will occur and if it is too high, wind farm generators will make excess profit (Green & Vasilakos, 2009).

The method of calculating the exact value of FIT is not transparent in literature or in online resources. This is due to the sensitivity of the FIT to current economic conditions, which vary greatly between countries and from year to year. Values between 40 and 130 euro per MWh were found for two different wind farms in the same country (EREF, 2007). Throughout Europe, FITs tend to range between 100 to 150 euro per MWh depending on farm characteristics and year of commissioning. Vindby uses an interpolation scheme to calculate the FIT for each farm using three factors. Each factor is interpolated on a scale of 33 to 50 euros per MWh so that the sum results in a range of 100 to 150 euros per MWh. The method to calculate the FIT is based on factors noted throughout many resources including (Green & Vasilakos, 2009) and (offshoreWIND, 2015) and was constructed as follows:

- Turbine technology: to encourage to use of higher capacity technology, higher FITs are awarded for higher capacity turbines. Interpolation is based on the minimum and maximum turbine capacity available in the game at time of calculation.
- Installed capacity: Higher capacity wind farms benefit less from FITs than smaller farms and are awarded lower FITs. Interpolation is between 10 and 500 MW total farm capacity, regardless of turbine technology used.
- Mean wind speed: Often site with the best wind conditions are paid less in FITs because the national targets require that even less windy sites be developed, which rely on FITs to just become profitable, where better sites would collect excess profit. Interpolation is between the maximum and minimum mean wind speeds in the sea grid.

The profit that the player is encouraged to realize is the difference between the selling cost and the levelized cost of energy (LCOE). The LCOE, which is itself an object, is updated monthly to account for maintenance activities.

LCOE: *Represents the levelized cost of energy for a wind farm updated on some interval.*

The LCOE is typically calculated as a lifetime cost at the start of a project by discounting all costs to net present value. Because Vindby accounts for inflation and is update monthly, the costs do not have to be discounted. The LCOE is calculated as:

$$LCOE = \frac{\sum_0^T C_t + O_t}{\sum_0^T E_t}$$

Where T is wind farm expected lifetime, t is the current year, C is capital cost (€), O is O&M cost (€), and E is electricity produced (MWh). After the initial investment is paid off, the cost to produce electricity from offshore wind energy is extremely low and in theory, the electricity price would go down. The longer amount of time that the wind farm is operating after the farm is paid back, the more profitable the investment. (EWEA, 2009).

Various fines and rewards are used in Vindby to introduce positive and negative consequences for specific player decisions. The values are not based on any research, but rather scaled to values that have an impact on the player's emotion regarding their decision. The fines include:

- Building in an environmentally sensitive area
- Building in an environmentally protected area (which also results in farm decommissioning, with no money returned)
- Building in an area with an active vessel route

Rewards include:

- Breaking even on capital cost of a wind farm
- Breaking even on CO_2 emissions during construction of a wind farm vs CO_2 prevented in electricity generation

3.4.6 Stakeholders

Part of the characterizing training and dissemination goals is to recognize the influence that stakeholders have on offshore wind projects. The background behind the values considers a broad understanding of what impacts certain actions have on stakeholders. The effect of stakeholder reactions does not consider current research or actual events, but rather is incorporated as points used as indicators for the player. Each stakeholder is a sub-object of the main object stakeholder.

Stakeholder (Government, Public, Shareholders): *Represents one group of stakeholders, which hold meetings to determine how happy / unhappy they are with certain game activities.*

In Vindby, each stakeholder influence is measured with point rewards and deduction as follows:

1. Government
    a. When an additional 1,000,000 household can be powered by offshore wind: +1
    b. When a wind farm is built in an environmentally sensitive area: -3
    c. When a wind farm is built in an environmentally protected area: -5
    d. When a wind farm is built in an area with a shipping route: -3
    e. When a wind farm breaks even on CO_2 emissions: +3
2. Public
    a. When an additional 1,000,000 household can be powered by offshore wind: +1
    b. When a wind farm is built in an environmentally sensitive area: -3
    c. When a wind farm is built in an environmentally protected area: -5
    d. When a wind farm is built in an area with a shipping route: -1
    e. When a wind farm is built within 13 km of the shoreline: -5
    f. When a wind farm is built within 24 km of the shoreline: -3
    g. When a wind farm breaks even on CO_2 emissions: +1
3. Shareholders
    a. When a wind farm breaks even on capital cost: +5
    b. When a wind farm starts to bring in profit (LCOE < selling cost): +3
    c. Every year that the capacity factor is above 0.7: +0.5
    d. Every year that the capacity factor is below 0.3: -0.5

In a future version of Vindby, research may be done to measure how stakeholder satisfaction influences offshore wind markets. Instead of a large initial investment, perhaps there are periodic investments made depending on stakeholder satisfaction with past activities.

3.4.7 Optimization functions

One of the subtasks outlined in the original thesis proposal is to build an optimization algorithm (artificial intelligence) that "solves" the game, i.e., which can efficiently determine optimal playing strategies – corresponding to optimal design or operational management of a wind farm. This is especially interesting since procedural generation is used, so that each run a completely different scenario will be presented to the user, and a large number of scenarios can be tested.

Throughout the research and integration of serious games, simplified offshore wind design, and Python programming, it was agreed that the development of a fully integrated optimizer that acts as the "computer player" is outside of time limitations of this thesis. Nonetheless, using optimization strategies as a form of feedback for the player is incorporated into Vindby in the form of small optimizer functions in an optimizer object.

Optimizer: *Contains the individual optimizing functions used at various points in the game.*

These optimizers include:

1. Operation and maintenance: Once a year, the optimizer returns a short report of the costs, downtime, and savings associated with O&M strategies at each farm. It also returns the estimated costs, downtime, and savings associated with the other two strategies had they been selected at the wind farm. This is helpful feedback because the player has the option to update the O&M strategy of a farm mid-game.
2. Substructure choice: After construction of a wind farm, the substructure optimizer looks up what the least expensive substructure would have been at the site and calculates the structure reliability as the sum of all structure failure probabilities (see Table 3.5) considering specific site conditions. The optimizer returns a 'design tip' to the player reporting:
    a. Whether or not the most economical structure was selected, and which it would have been.
    b. Whether or not the most reliable structure was selected, and which it would have been.

3.5 Game design

The final game design is the product of many iterations internally tested for accuracy of scale, accuracy of weather prediction, and most of all, playability. Feedback is a game mechanic vital to the player's understanding and grasp of game content as well as general enjoyment. This is also the mechanics that experienced the most iteration. Feedback given by the game to the player is done through two means: the python console and a GUI. The GUI presents information that changes throughout the game as well as a graphical representation of the sea grid. The prototype Vindby GUI is shown in Figure 3.19. As mentioned earlier, minimal effort was applied to make the GUI graphically appealing.

Please refer to the enclosures to this report for all game related program files.

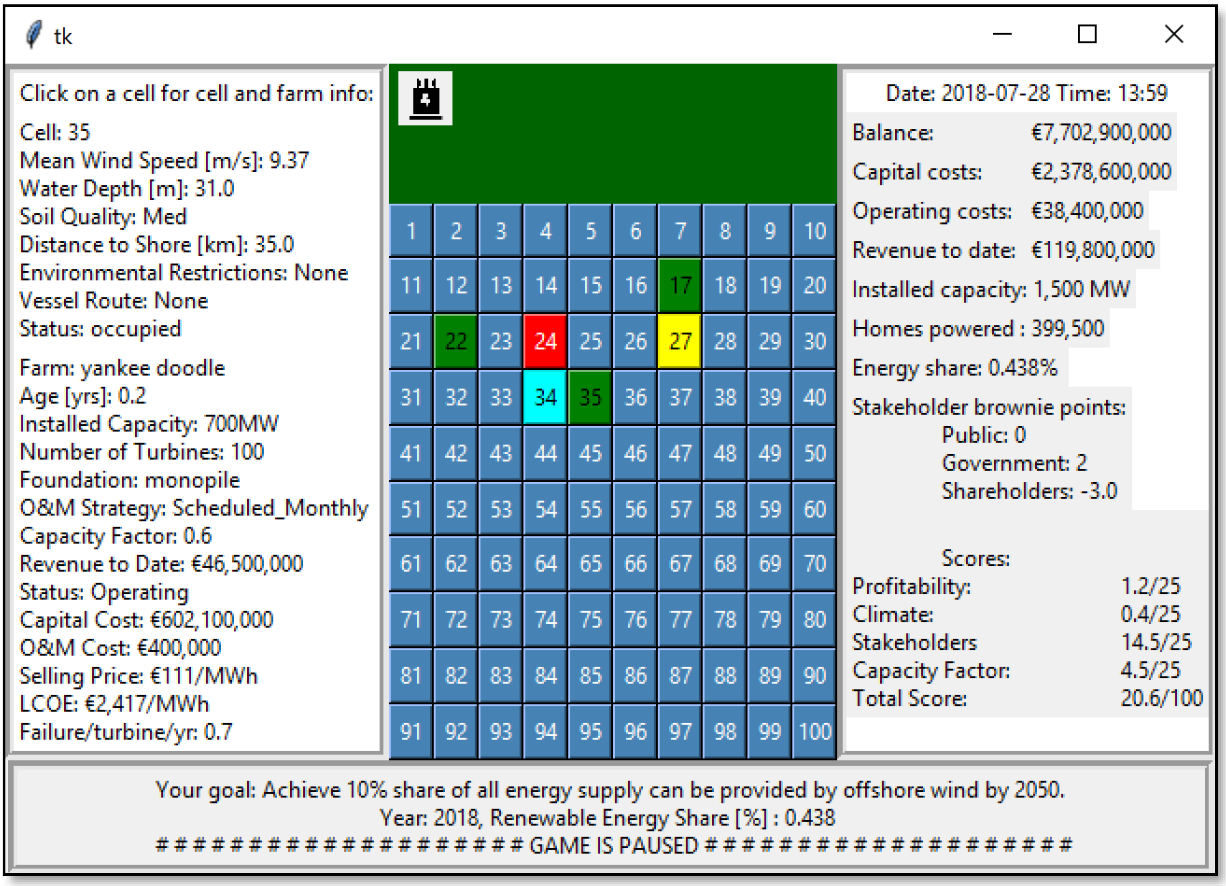


Figure 3.19: Vindby graphical user interface

Feedback provided in the console is provided based on individual actions and occurrences in the game and in the form of regular reports. The default report is issued annually and presents game information (some of which is repeated in the GUI) with additional information about wind farm activity including a list of wind farms, list of investigated cells and their results, construction activity, climate change details, and details about stakeholder satisfaction. The report is issued by an object.

Report: *Publishes reports with game summary information on a regular interval.*

Vindby's final game design includes a simulation loop that runs the engineering simulations with a timestep of 1-hour. Many ticks of this loop are performed in a game-time interval determined by the player's preferred game speed (e.g. if the game speed is 1-week per second, the simulation loop runs 24*7 = 168 times). This is followed by a dynamic pause to maintain a constant game speed, then by the processing of any keyboard entry that occurred during the simulation, and then returning to the simulation loop to pick up where it left off.

This process is displayed in Figure 3.20 describing the overall game dynamics and mechanics. Figure 3.21, Figure 3.22, and Figure 3.23 present a further breakdown of the processes displayed in the overall figure. The sea grid characteristics are shown in Figure 3.8, Figure 3.9, and Figure 3.10

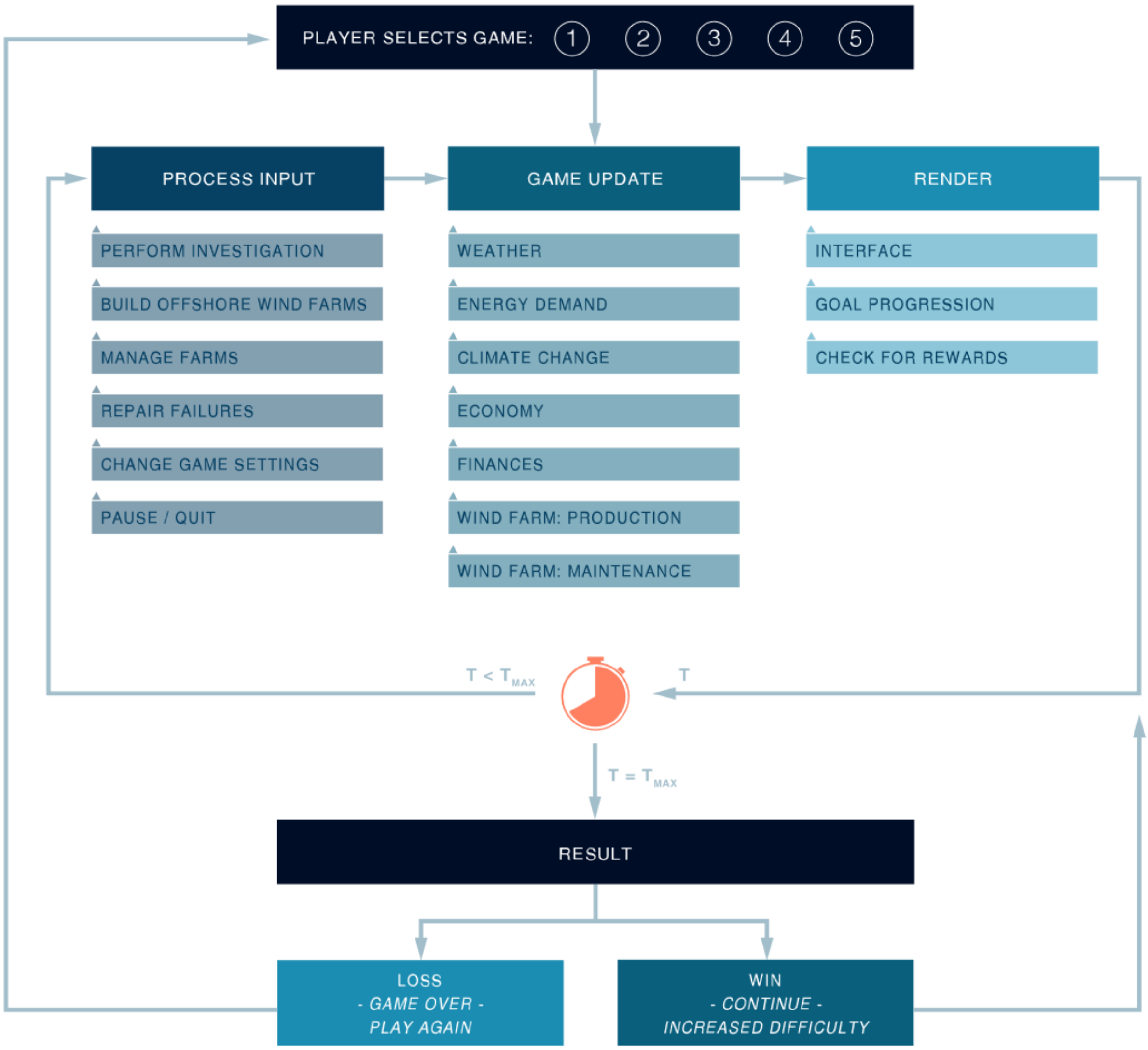


Figure 3.20: Vindby game dynamics, mechanics, and loop

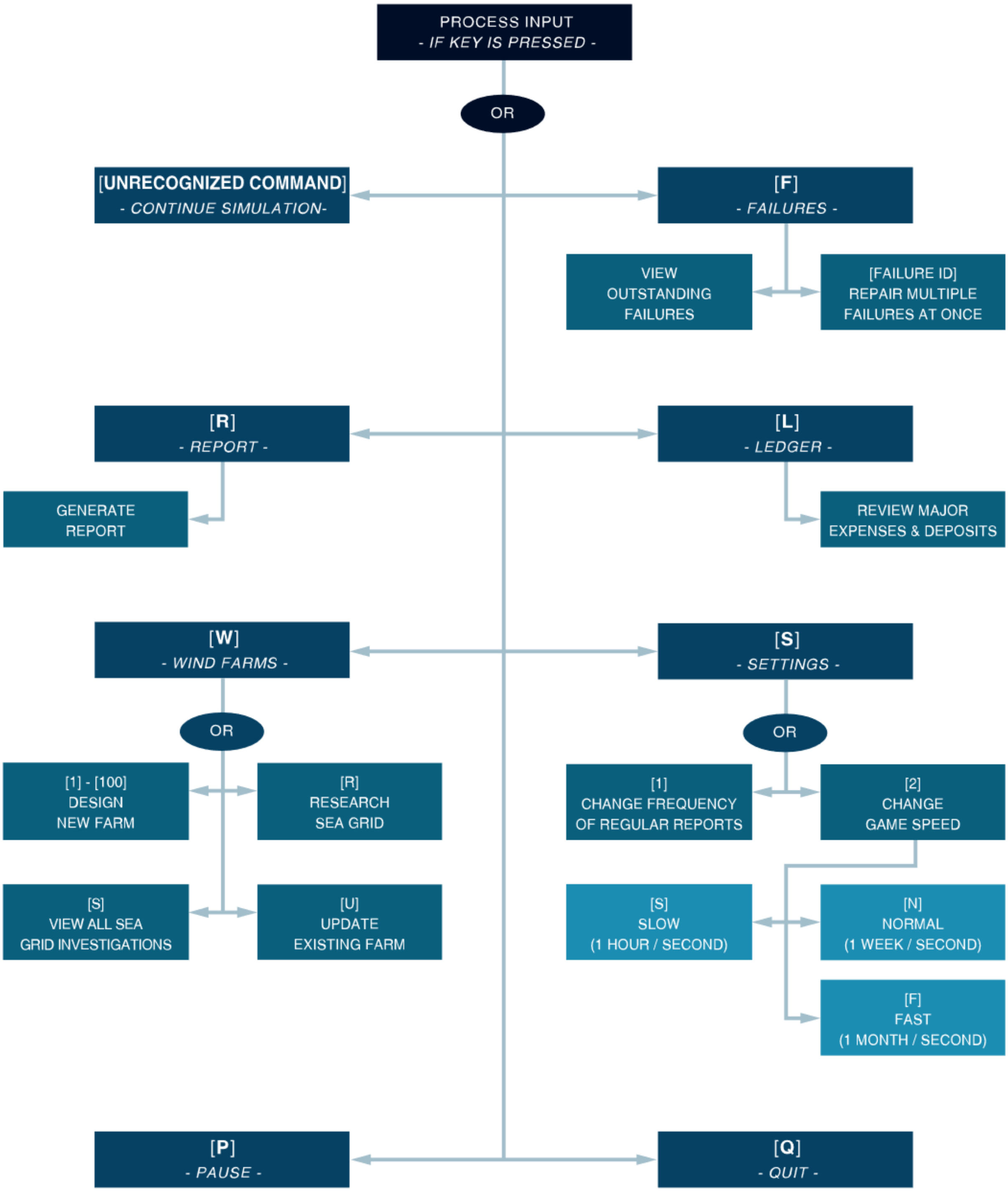


Figure 3.21: Vindby game mechanics: processing input (Main Menu)

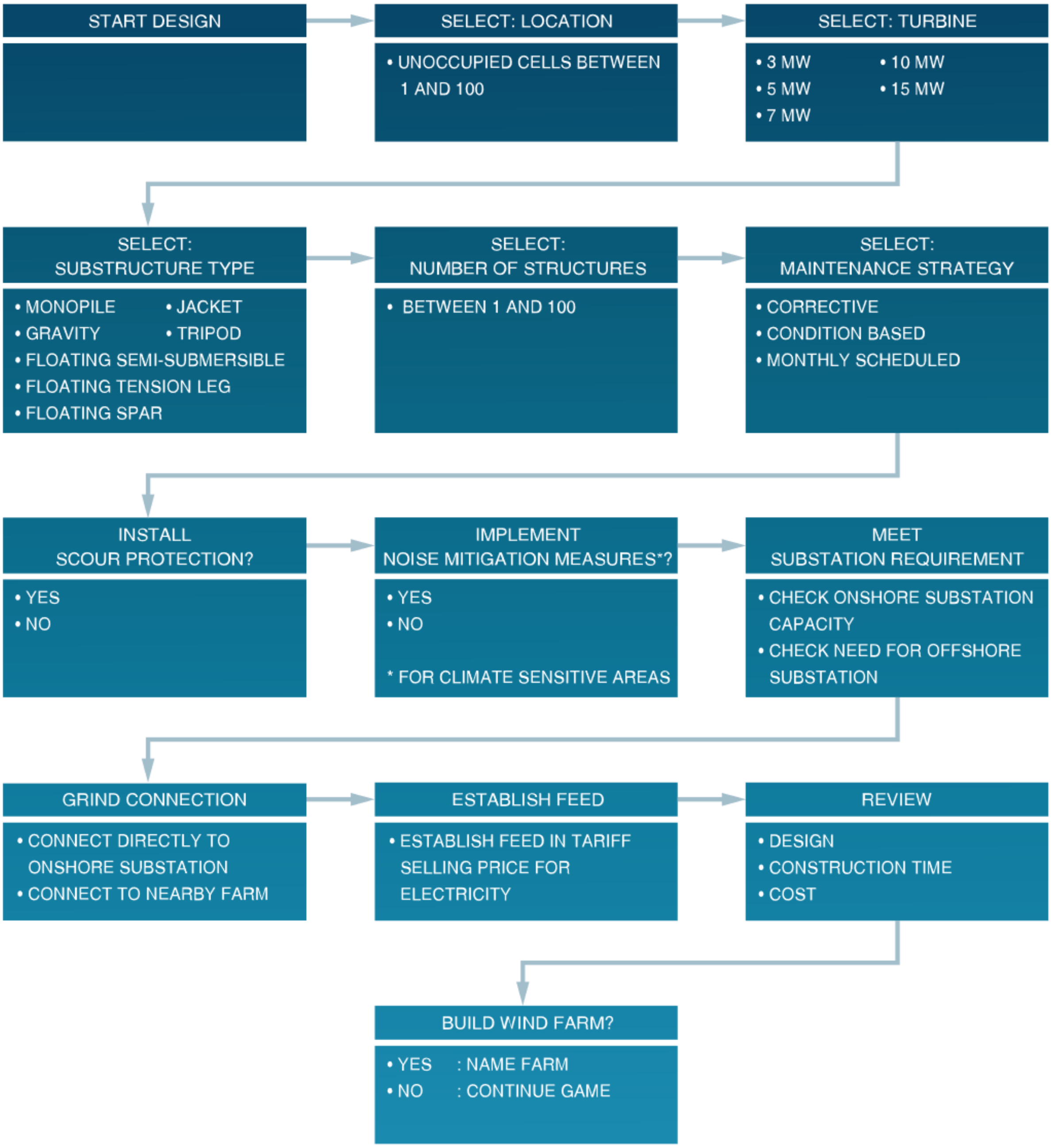


Figure 3.22: Vindby game mechanics: offshore wind farm design

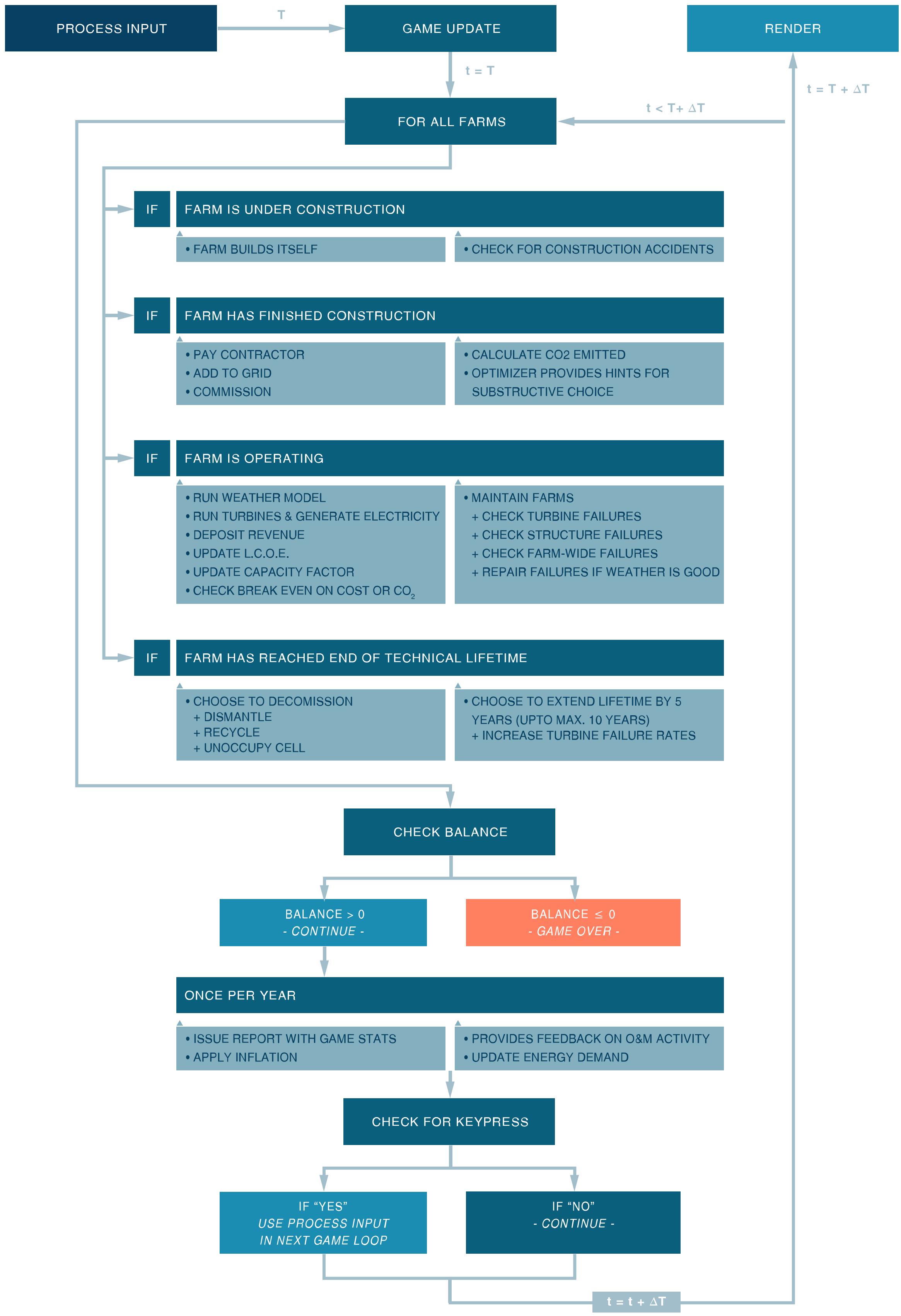


Figure 3.23: Vindby game mechanics: game update (main simulation).
't' is simulation resolution – 1 hour and 'T' is game speed interval

4. Game Results

In the previous sections, various game design parameters are explored to guide the design of a serious game. The game content, simplified offshore wind farm design, is described using turbine technology, farm logistics, and external factors to explore the needs of training in offshore wind energy. Additional detail is presented on the weather model simulation to illustrate that the serious game, although simple, may incorporate complex models to increase accuracy without sacrificing playability. Game mechanics are specified and features that may be added to the existing prototype are noted as being stubbed out.

This section presents the final game prototype and its performance. First, weather prediction model results are presented and described in terms of how the model is integrated into Vindby. Next, various game runs are compared to existing offshore wind farm values and a base case validation. Finally, the game simulation is measured in terms of computational efficiency.

4.1 Weather model

For the main game loop to run accurately and efficiently, all the embedded simulations must independently run with the same expectation. The results of the 40 runs at 10 years each for the alternative weather models is presented in this section.

The results of the weather model runs are distinguished by the “wave to wind” (using a Markov matrix to generate wave heights and conditional probability to generate wind speeds) versus ‘wind to wave’ methods (using a Markov matrix to generate wind speeds and conditional probability to generate wave heights). Another distinction is made regarding the method to sample ten-minute wind speeds for each hour using a ‘Markov’ (using a Markov wind chain using ten-minute wind data) versus ‘Gaussian’ (using measured standard deviations of ten-minute speeds within an hour) approach.

Table 4.1 illustrates the mean wave height and mean wind speed for the observed and simulated data without wind speed factors. The simulations using the wind Markov matrices produce lower percent errors than for the wind speed (derived by conditional probability) and those using the wave Markov matrices perform similarly for wave height. The hourly distribution of ten-minute wind speeds is closer to the observed value using the Gaussian approach. Using the Markov matrix to simulate 10-minute wind speeds, the distribution within the hour is much wider. This is likely due to the use of discrete bins that are 1 m/s wide while using Markov matrices, which are then uniformly sampled. In the end, the wave to wind Gaussian simulation method is implemented in Vindby, as it enables more accurate wind speeds and wave heights.

The accuracy of the selected model is evaluated based on its ability to reconcile different mean wind speed and significant wave height resolutions for integration in the game loop, imitate persistence of weather windows for offshore wind farm maintenance activities, and produce up- or down-scaled time series to represent either more or less severe sea states.

The relative errors found are close to the errors found in (Hagen, Simonsen, Hofmann, & Muskulus, 2013), which presents a similar analysis using a different dataset and resolutions. The reported relative error for mean wind speed is 1.0% and this model’s relative error for mean wind speed is 1.2%. The reported relative error for mean significant wave height is 2.8% and this model’s relative error for mean significant wave height is 1.18%.

Table 4.1: Weather model results for mean wave height and wind speed for 10-year simulation

Simulation	10-minute simulation	Mean Wave Height [m]	Mean Wind Speed [m/s]	10-minute wind speed hourly σ [m/s]	Error Wave Height	Error Wind Speed
Observed	Observed	1.51	9.37	0.55		
wave to wind	Markov	1.52	9.55	0.75	0.55%	1.97%
wave to wind	***Gaussian***	***1.49***	***9.48***	***0.56***	***-1.18%***	***1.20%***
wind to wave	Markov	1.47	9.38	0.73	-2.66%	0.12%
wind to wave	Gaussian	1.47	9.35	0.56	-2.73%	-0.25%

Table 4.2 presents the mean wind speed and mean wave height when using wind speed factors in the 'wave to wind' simulation. Each point in the observed data was amplified by the wind speed factor for comparison to the models using that same factor. The results from the non-factored models are repeated in this table for comparison. Statistics of the simulations were compared to original data amplified by the same factor.

Table 4.2: Weather model results using wind speed factors for 10-year simulation

Original Data Wind speed factor	Simulation Wind speed factor	Mean Wave Height [m]	Mean Wind Speed [m/s]	10-minute wind speed hourly σ [m/s]
1	-	1.51	9.37	0.55
1	1	1.49	9.48	0.56
1.2	-	1.81	11.24	0.66
1	1.2	1.77	11.37	0.68
0.8	-	1.21	7.5	0.44
1	0.8	1.18	7.55	0.45

The persistence of sea states is calculated based on the time between a down crossing and subsequent up crossing of a threshold sea state. The persistence of wave height less than 2 m and wind speed less than 15 m/s was measured for the observed data and the 'wave to wind' model using a Gaussian distribution of ten-minute wind speeds. Table 4.3 presents the observed and simulated persistence as the length of weather windows over the duration of the series for the different wind sped factors. A threshold wave height of 2 m was used because the boundaries for vessels are typically between 1.5 and 2.5 m (Scheu, Matha, & Muskulus, 2012).

Table 4.3: Observed and simulated persistence of weather windows

Wind Speed Factor	Observed Persistence [%]	Simulated Persistence [%]
1.0	73.4%	71.2%
1.2	60.9%	58.5%
0.8	85.1%	83.4%

The cumulative distribution function (CDF) of the run-length distributions for wave height and wind speed were compared between the observed and modelled persistence as shown in Figure 4.1 and Figure 4.2.

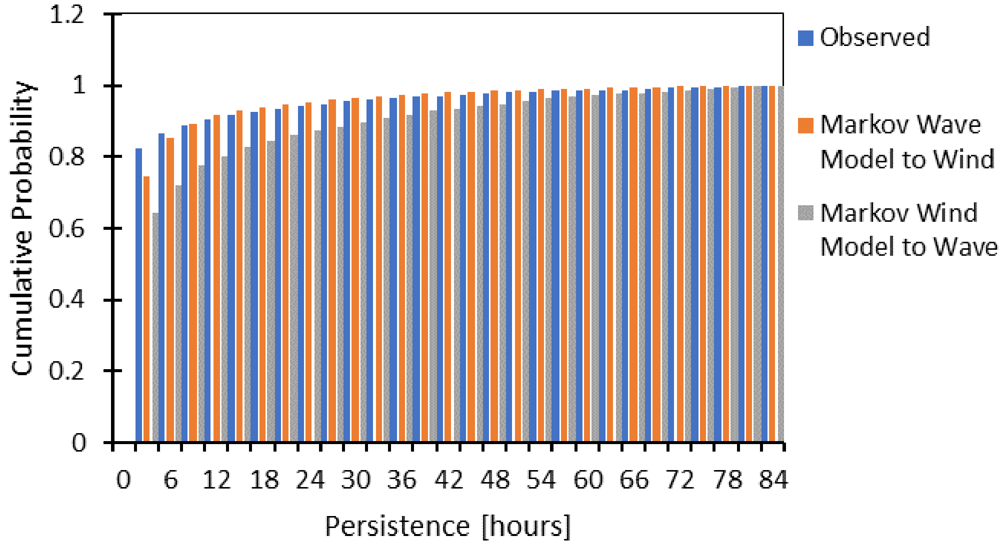


Figure 4.1: Cumulative distribution of wind speed persistence for wind speeds < 15 m/s

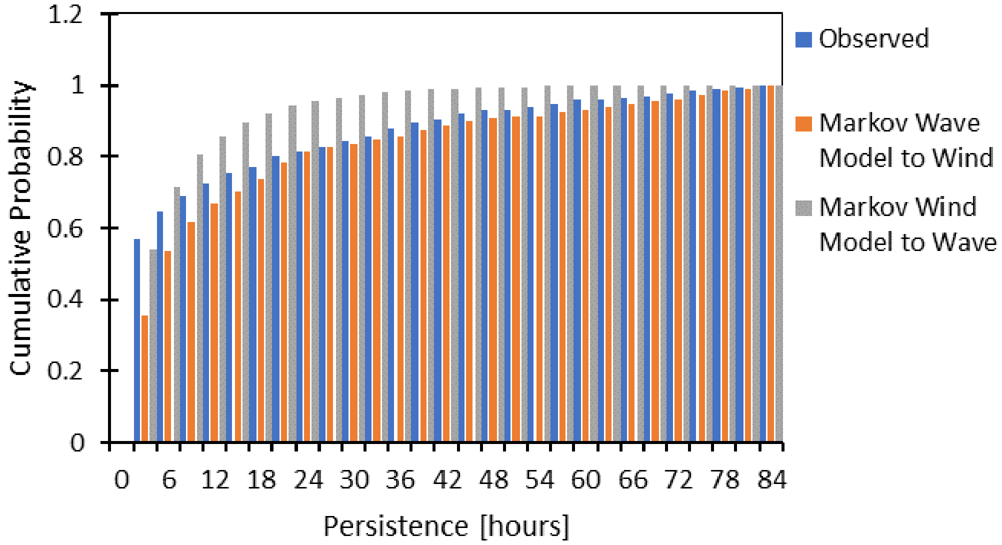


Figure 4.2:Cumulative distribution of wave height persistence for wave heights < 2 m

The CDFs were compared by calculating the Kolmogorov-Smirnov (K-S) distance, which is the maximum vertical difference between the two CDFs (Table 4.4). By observing the K-S distance and CDF shape, the wind weathers based on wave heights < 2 m appear to be underestimated for durations shorter than 24 hours. The same is true for wind speed but with a smaller difference for a shorter duration. The persistence of weather windows for wave heights < 2m and wind speeds < 15 m/s appears to be captured reasonably well by this approach (Scheu, Matha, & Muskulus, 2012).

Table 4.4: Kolmogorov-Smirnov distance to observed data for wind speed and wave height

	Wind Speed < 15 m/s	**Wave Height < 2.0 m**
Markov Wind Model to Wave	0.182	0.151
Markov Wave Model to Wind	0.075	0.213

The variation of mean wind speed and wave height by month are shown in Figure 4.3 and Figure 4.4. For the wave to wind model, wave height monthly relative errors vary from 2.4 % in January to 24.0% in March (average 10.2%), and wind speed monthly relative errors vary from 0.29% in November to 15.9% in March (average 6.7%). There did not seem to be any pattern in relative errors based on month.

Although the overall mean wind speed relative error is similar compare to the work in (Hagen, Simonsen, Hofmann, & Muskulus, 2013), the monthly relative errors are much higher. This is likely due to the difference in wave height resolution in the Markov matrices used in both studies. Additionally, there are large gaps in the observed data during spring time. This study uses 0.4 m and the compared value is 0.1 m.

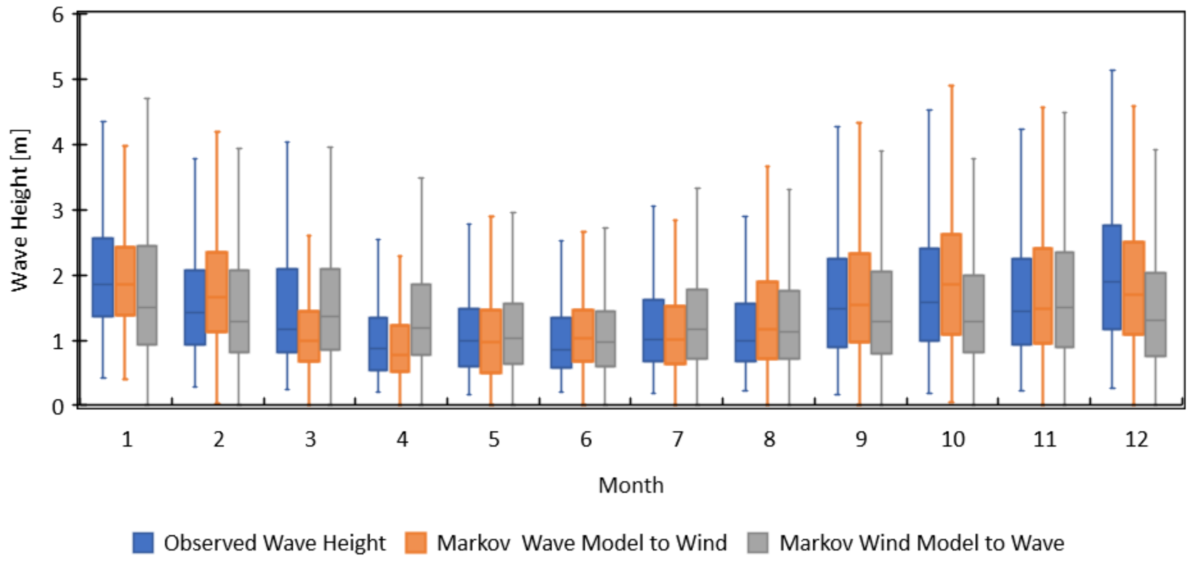


Figure 4.3: Wave height mean value distribution for 10-year simulation

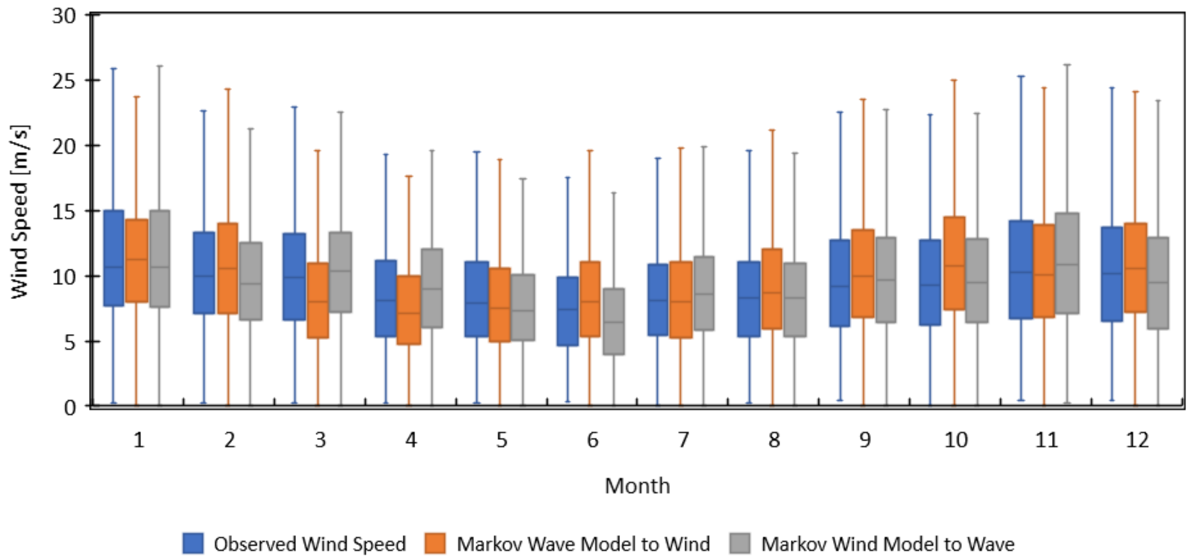


Figure 4.4: Wind speed mean value distribution for 10-year simulation

4.2 Offshore wind energy

The ability of Vindby to simulate realistic offshore wind farm parameters is presented in this section. Three simulations with different O&M strategies are run for the same farm. The results are compared amongst themselves and among real world data for offshore wind farms.

An approach and reference case for verifying and validating O&M simulation models for offshore wind farms is described in (Dinwoodie, Endrerud, Hofmann, Martin, & Sperstad, 2014). The wind farm established for the simulation model consists of 80 3-MW turbines with a hub height of 90m located in cell 43. Monopiles are selected with scour protection. Cell 43 is 45 km from shore with a water depth of 34 m and poor soil quality. The mean wind speed is 9.4 m/s (wind speed factor of 1). After a 20-year lifetime, the game values were averaged across runs and are summarized in Table 4.5. The game values pertaining to LCOE, carbon payback period, capacity factor, turbine failures, and O&M strategy are compared in greater detail and are listed below.

Table 4.5: Vindby offshore wind farm design cost validation results for 80 3-MW turbines

Item	Value
Game duration	20 years
Simulation time	5.53 minutes
LCOE at end of lifetime	€ 46 /MWh
Energy share	5.80%
CO_2 prevented	20.02 million tons
Time to break even on CO_2 emissions	0.44 years
Time to break even on capital cost	6.26 years
Capacity Factor	0.42
Failures/turbine/year	3.2

LCOE: The LCOE of existing offshore wind farms varies greatly between wind farms, countries, and years of construction. Estimates vary between €100 and €200 per MWh over the farm lifetime. The LCOE in Vindby starts off high because of capital costs but eventually stabilizes to the lifetime value after some years of operation. The LCOE typically stabilizes around a value lower than €100 per MWh, however, as seen in Figure 4.5. This could be the result of a general underestimation of costs.

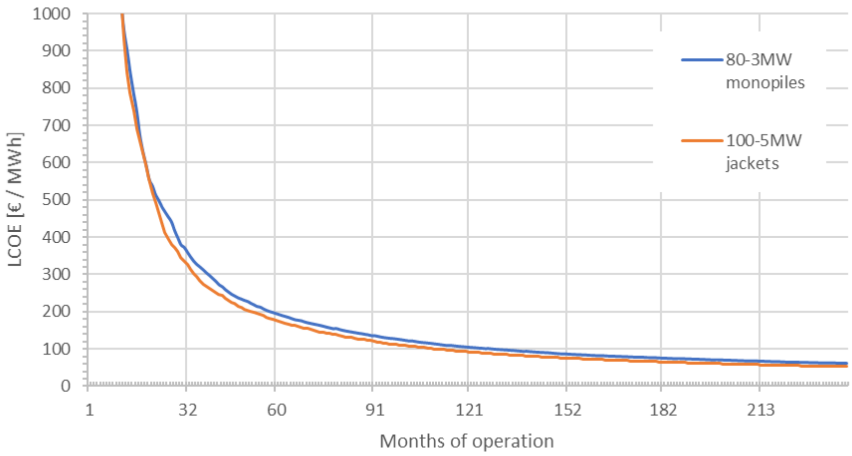


Figure 4.5: Vindby LCOE results

Carbon payback period: The average carbon payback period for 2012 was 0.63 years for all offshore wind farms (Thomson & Harrison, 2015). As 80 turbines represents a relatively large farm, it is expended to have a shorter payback period.

Capacity factor: The average capacity factors of all offshore wind farms in Europe are between 0.29 and 0.48 (Wind Europe, 2017). The capacity factors in Vindby generally vary greatly depending on the player's choices. The example above falls within an acceptable range for a good wind design.

Turbine failures: Empirical results from (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014) indicate a failure rate of 8.3 per turbine per year; however, reference literature in the same report cites 3.4 failures per turbine per year. This value varies between 1 and 4 in Vindby between games, although generally is closer to 3 failures per turbine per year.

O&M Strategy: The metrics used to compare O&M values are shown in Table 4.6. Time-based availability is the percentage of time that turbines can generate electricity over the farm's age. Annual loss of production is the capital loss of production given by production in MWh lost due to unavailability times the electricity price, which is taken as the selling price over the farm's age. The Annual direct O&M cost is the total O&M costs over the farm's age. The results for the three O&M strategies, and the average of base case identified in (Dinwoodie, Endrerud, Hofmann, Martin, & Sperstad, 2014) converted to euros are presented in Table 4.6.

Table 4.6: Vindby O&M results for 80 3-MW turbines

	Scheduled Monthly	Corrective	Condition Based	Base case
Time-based availability	85.40%	94.80%	95.04%	83.16%
Annual production losses [€]	€ 18.3 m	€ 7.6 m	€ 7.2 m	€ 19.1 m
Annual O&M cost [€]	€ 17 m	€ 16.5 m	€ 15.5 m	€ 22.4 m

The base case values are closest to Vindby's scheduled monthly maintenance strategy. The difference of over 10% by the time-based availabilities of corrective and condition-based is likely the result of the discrete nature of Vindby's O&M. Specifically, if the weather is acceptable, the repair is done immediately, and downtime is zero. In more sophisticated simulations and in (Dinwoodie, Endrerud, Hofmann, Martin, & Sperstad, 2014), even for immediate repairs, downtimes increase due to travel times, mobilization times, unexpected delays, and time between shifts. Vindby only accounts for repair time in the calculation of vessel and repair cost.

O&M costs: The lower annual O&M costs for all strategies compared to the base case is due to the over-simplification of O&M costs in Vindby. While the simplification of models is acceptable to make games such as Vindby possible, the simplification accuracy can always be improved. Vindby uses accurate cost information for vessels and repair times. Simplified additions of travel costs, mobilization costs, and technician wages can be introduced to increase accuracy of the annual O&M cost.

Vindby’s O&M optimizer uses basic calculations to speculate O&M costs for an individual farm under alternative strategies. Table 4.7 presents a comparison of the O&M costs (not considering annual maintenance) under the three strategies with the optimizer’s speculation of the other two strategies and actual value for that strategy in that game played. The percent error from the measured cost is in parenthesis. The estimated cost for corrective maintenance is the most accurate optimizer. The estimated condition-based savings errors are likely overestimated due to added uncertainty of whether the monitoring system detects failures early or not.

Table 4.7: Vindby's O&M optimizer results for 80 3-MW turbines (with relative error)

	Scheduled monthly game	Corrective game	Condition-based game
Estimated scheduled lifetime cost	€ 93.4 m	€ 63.8 m (31.7%)	€ 56.4 m (39.7%)
Estimated corrective costs	€ 94.5 m (12.2%)	€ 84.2 m	€ 77.2 m (8.3%)
Estimated condition-based savings	€ 22.2 m (76.6%)	€ 26.5 m (111.2%)	€ 12.5 m

Lifetime costs: As the base case literature does not include information about lifetime costs, (Shafiee, Brennan, & Espinosa, 2016) is used. The results of (Shafiee, Brennan, & Espinosa, 2016) are based on a wind farm with 100 5-MW wind turbines on jacket structures at 45 m water depth and 40 km from shore. Therefore, this wind farm is built in cell 47 with 45 m water depth and 45 m to shore with poor soil quality. Because the cell is environmentally sensitive, mitigation will be included in design. The comparison is presented in Figure 4.6. The large difference in decommissioning cost is likely the result of the decommissioning cost for subsea cables, which was calculated from (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014) as it was not explicitly stated in (Shafiee, Brennan, & Espinosa, 2016).

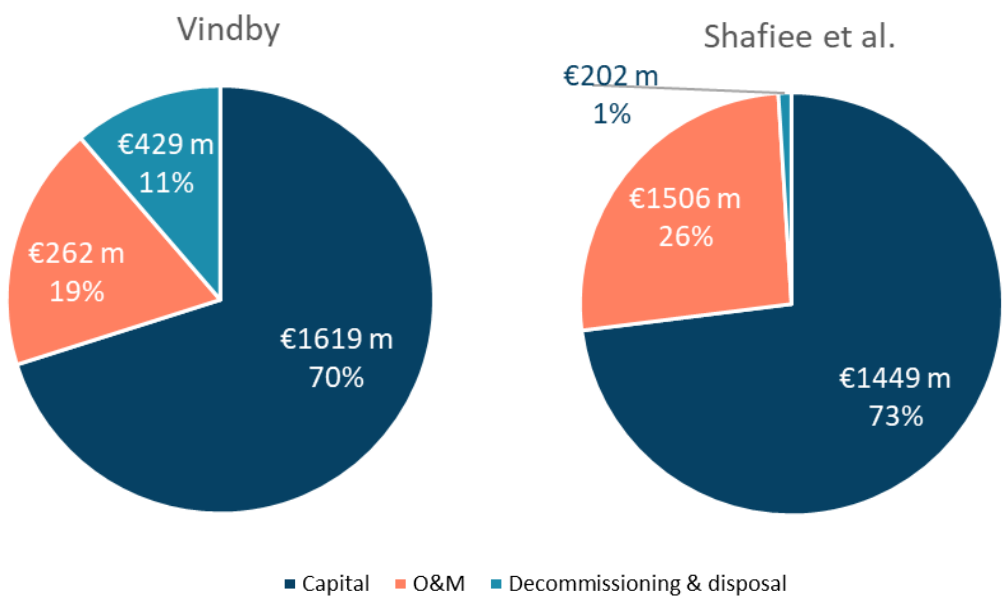


Figure 4.6: Cost breakdown of Vindby and (Shafiee, Brennan, & Espinosa, 2016)

4.3 Game design

The game design results are measured in the prototype program's ability to translate game mechanics from paper into a functioning prototype. Vindby's programmed game mechanics were tested daily during development to eliminate program bugs and enhance code efficiency. The playability of these mechanics was assessed through playtesting (section 5).

The game waiting time is governed by start-up time and simulation time. The average start-up time for the game is 16.6 seconds. Approximately half of this start up time is used for setting up the sea grid. The remainder is spent loading all relevant text files and objects. Simulation time is a major concern for the game because the player must experience the game at the desired game speed to enhance the potential for learning. Simulation speeds with and without wind farms are recorded to keep track of which code sections are the most time consuming. The simulated game speeds are presented in Table 4.8 for slow, normal, and fast game speeds that can be selected by the player. Each simulated farm includes 100 turbines to capture the maximum computations per farm. The total computational speed is the number of seconds for one tick in the main game loop (whose interval is determined by the game speed), and the weather simulation speed is the number of seconds for the weather prediction model. A sleep function is added to the computational speed at the end of the game loop tick to make the speed consistent. The sleep value is equal to the maximum of zero and one minus the total computational speed. The total seconds per game loop tick is ideally 1 second. The computational efficiency is the ratio of the desired versus realized simulation time.

Table 4.8: Vindby simulation speeds

Number of farms	Total computational speed [sec]	Weather simulation [sec]	Sleep [sec]	Total seconds per game loop tick [sec]	Efficiency
Slow (1 hour per second)					
No wind farms	0.004	0	0.996	1	100%
1 farm	0.011	0.002	0.989	1	100%
2 farms	0.012	0.003	0.988	1	100%
5 farms	0.025	0.009	0.975	1	100%
Normal (1 week per second)					
No wind farms	0.009	0	0.991	1	100%
1 farm	0.572	0.225	0.428	1	100%
2 farms	1.026	0.486	0	1.026	97%
5 farms	1.980	1.188	0	1.980	51%
Fast (1 month per second)					
No wind farms	0.025	0	0.975	1	100%
1 farm	1.372	0.473	0	1.372	73%
2 farms	2.857	1.042	0	2.857	35%
5 farms	5.992	3.543	0	5.992	17%

Simulations running with efficiencies of 100% are stable, and below 100% are unstable. For slow speeds, the simulation is consistently stable. For normal speeds, the simulation begins to slow down after 200 turbines. At fast speed, the addition of just one turbine was separately calculated and makes the simulation unstable with a total computational time of 1.102 seconds. At five 100 turbine farms, the simulation is very unstable at 17%. Weather simulation and electricity generation (turbines running themselves) were identified as the most time consuming.

The weather simulation, which is only run for cells with existing wind farms, accounts for about half (ratio changes with no apparent pattern) of the computation time due to the random generation of numbers. The three random number generation functions used are normal, choice, and uniform distributions. The choice distribution type is a distribution whose probabilities are determined by the Markov matrix. This function takes on average 80% of the weather simulation time. For the fast speed setting, this account for approximately 0.0016 seconds times 730 hours per month or 1.168 seconds per game loop tick per farm, just for weather.

It is suspected that the game speed can be improved by running the weather prediction model for a long period of time at a certain interval (yearly or greater), followed by reading from the simulation every hour. In other words, instead of generating random numbers every hour, the simulation would generate a time series at the start of every year and feed the sea states directly to the game.

Electricity generation is calculated six times per hour per turbine by using wind speed and reading the power curve. This process accounts for the next most time-consuming simulation function.

The program was largely stripped of methods that included the storage of information and replaced with summary values. For example, rather than storing the energy production from every hour in the game, only the cumulative sum is used. When values are continuously stored, the game becomes slower over time

5. Playtesting

This section describes the work done to involve individuals outside of the study team to develop and test the game. External testers are necessary to investigate how players will eventually experience and approach the game (Adams & Dormans, 2012). Playtesting is used to evaluate the game prototype's playability as well as its adequacy in achieving the predefined educational goals.

Playtesting consisted of three phases. First, a pre-game questionnaire was used to collect information about characterizing training goals that may be incorporated into Vindby. Second, a playtesting session was held where participants played the Vindby prototype. Third, pre- and post-game surveys were conducted to measure game effectiveness in teaching.

Invitees included master's students and PhD candidates of the Department of Civil and Environmental Engineering at NTNU. It was assumed that the individuals with an engineering background would provide feedback most relevant to this stage of game development. Future versions of Vindby should include additional playtesting phases with a greater variety of backgrounds amongst players to measure better measure characterizing dissemination goals.

5.1 Pre- game questionnaire

This section describes the pre-game questionnaire that was sent out by Google Form on April 25 to 61 individuals and 53 responses were received, 21 of whom also signed up for playtesting. Ten questions were asked to identify specific items of interest among participants. Participants were asked to select their background knowledge of offshore wind energy from four categories:

A. I don't know anything
B. I generally understand the concept, but cannot describe it in detail
C. I understand the concept and can describe some components of offshore wind
D. I study or know more about offshore wind energy than the average person

Participants were then asked for their first and second choice of topic that they would be most interested to learn. The topics presented were:

- The physical components of offshore wind farms - What is available in the industry right now? And what are the engineering concepts and how are they modelled?
- The operation and maintenance of offshore wind farms over their lifetime
- The costs of offshore wind farms and the energy they produce
- The influence of stakeholders (public, government, & shareholders)
- I have no interest to learn about offshore wind

The full questionnaire results are provided in Appendix F . Approximately 63% of individuals were identified to have knowledge of offshore wind (response C or D). There was a close uniform distribution between selection of the five topics of interest, with some noteworthy trends based on who made the selections. The topics were consolidated from five to two categories as shown in Table 5.1. To account for the unequal distribution of player background types, the number of responses in each topic category by each player background type was normalized by the total responses (2 per individual) from that player background type. There is a higher interest in the physical components of offshore wind and the O&M strategies among individuals with some knowledge or background of offshore wind. Participant with little to no knowledge of the topic were more interested in in the costs and the stakeholder influence.

Table 5.1: Topics of interests chosen by player type, normalized

Player background type (Total number of responses)	Physical components and O&M	Costs and stakeholder influence
A (4)	0.20	0.60
B (34)	0.37	0.35
C (24)	0.44	0.22
D (42)	0.49	0.25

When prompted with the opportunity to ask questions freely, 25 individuals provided additional areas of interest and posed some specific questions about offshore wind energy. The two most frequently addressed issues were payback period on carbon emissions and environmental impacts of offshore construction.

5.2 Playtested games

This section describes the method of playtesting and results of the games played that indicate the effectiveness of game mechanics in achieving characterizing training goals. Game instructions that were provided to playtesters is provided in Appendix E .

Of the 21 individuals who original signed up for playtesting, 8 of them participated in the final event. Two hours were allotted for playing Vindby with the intention that players would be able to play more than once. Players appeared to be engaged judging by the fact that several players played an average 15 extra minutes after the ending time and had to be asked multiple times to quit to proceed to the survey. This suggests that the game provides motivation and engagement.

The games played were saved using an output file that saved certain game parameters at the end of the game. These results were observed to understand how much exploration the players were experiencing, and if they felt comfortable with the game instructions and mechanics to strive towards the game goal. Table 5.2 and Table 5.3 summarize the number of games played and several parameters about the games played. This suggests the actual amount of playtime, as opposed to stagnant waiting for the session to finish.

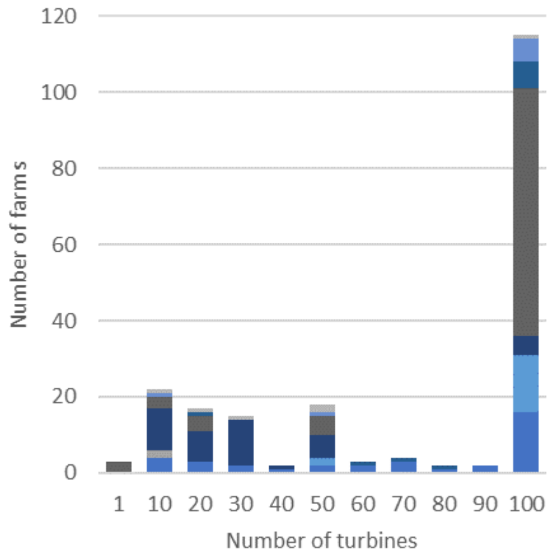
Table 5.2: Games played and results

Game Played	Total	Wins	Losses
1. Profit	11	6	5
2. Compete	4	2	2
3. Dominate	5	5	0
4. Save the Planet	3	3	0
5. Free4all	1	1	0

Table 5.3: Playtesting results of game parameters for all games played

Parameter	Unit	Average	Minimum	Maximum
Simulated duration	years	7.37	0.50	26.31
Total capital investments	M€	4,521	74	21,095
Total operating costs	M€	1,335	4	7,367
Total revenue	M€	5,931	3	44,151
Total return-on-investment	-	1.01	0.04	1.55
Installed capacity	MW	4,518	20	22,120
Number of investigated cells	-	22	1	102
Number of wind farms constructed	-	8	1	29
Number of grid connections between farms	-	4	0	15
RES share	%	1.2	0.0	5.7
Public score	-	4.2	-5.0	32.0
Government score	-	4.0	-6.0	26.0
Shareholder score	-	11.0	-13.5	93.5

Various parameters of games played are summarized in Appendix F . Figure 5.1 presents the number of farms by the number of turbines and by capacity factor. This indicates that players understood the value in installing as much capacity as possible (100 turbines max per farm) during design.



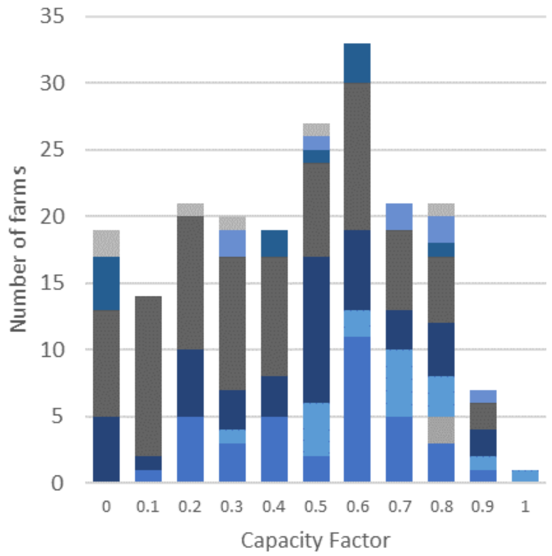


Figure 5.1: The number of farms with number of turbines per farm (Left) and the number of farms with their capacity factors (Right). Colors represent games by participant

A total of 203 farms were built over 24 games and an average of 8 farms per person per game. The size and complexity of farms varied greatly among players and among games played by one player, indicating a sense of exploration. Figure 5.2 presents the wind farms constructed by farm capacity and capital cost to indicate diversity in farms constructed.

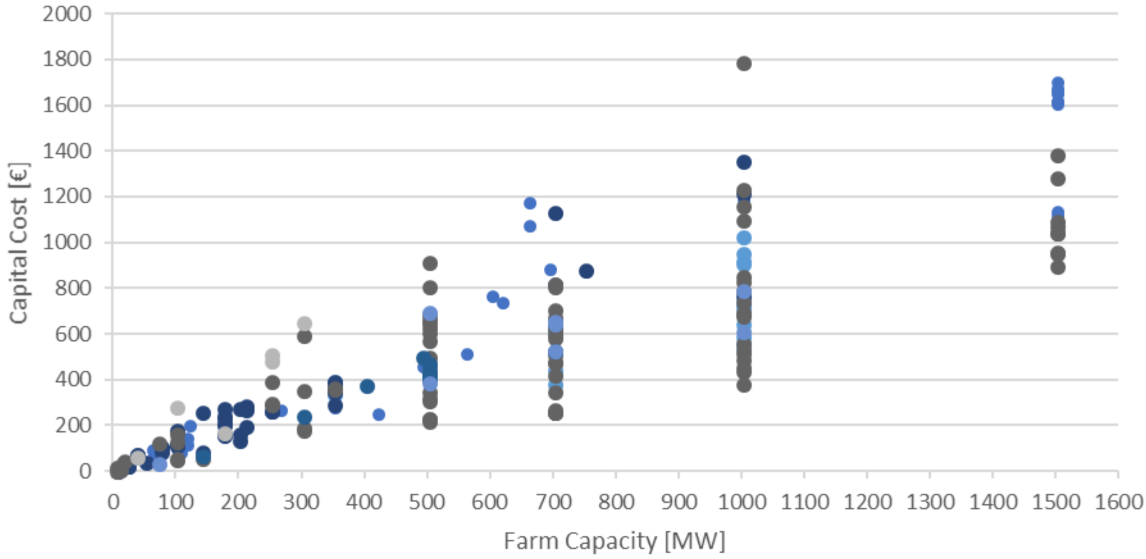


Figure 5.2: Playtesting results for capital cost and farm capacity for all wind farms
Colors represent games by participant

The degree to which players utilized site investigations in their decision making can be determined by viewing the overlap of investigations performed and farms constructed on each cell for each game played by each player. The number of instances where cells were or were not investigated and/or built on is presented in Figure 5.3 and Figure 5.4. The key findings on site investigations are listed hereafter:

- *Player adoption*: The cells that were investigated and not built on (within one game played by one player) were broken down by site conditions to identify where players made informed decisions. Out of 344 instances, 137 of such decisions were made on a restricted area (environmental or navigation), 92 were made in areas with lower wind speeds (wind speed factor less than 1), and 118 were made in areas with poor soil quality. These instances are non-exclusive, i.e. they may overlap.
- *Investigation*: Across all games played (one player excluded), 99% of farms were constructed in cells that had been investigated. The one player excluded performed investigations for only 6 cells of 46 farms constructed. This indicates that most players quickly learned about the value of information needed to make informed decisions about building farms, and subsequently actively sought out that information.
- *Other restraints*: In environmentally sensitive or protected cells, 81% of investigations resulted in not building farms in that cell. In cells on a shipping route, 79% of investigations resulted in not building farms in that cell.
- *Substructures*: Out of 169 farms built on investigated areas, 12% were built on cells with poor soil quality, but 100% those farms were constructed using substructures that are suitable for poor soil (not monopile or gravity). This is a strong indicator that players made informed decisions about substructure choice.

Figure 5.3: Number of instances where a cell was investigated and not built on

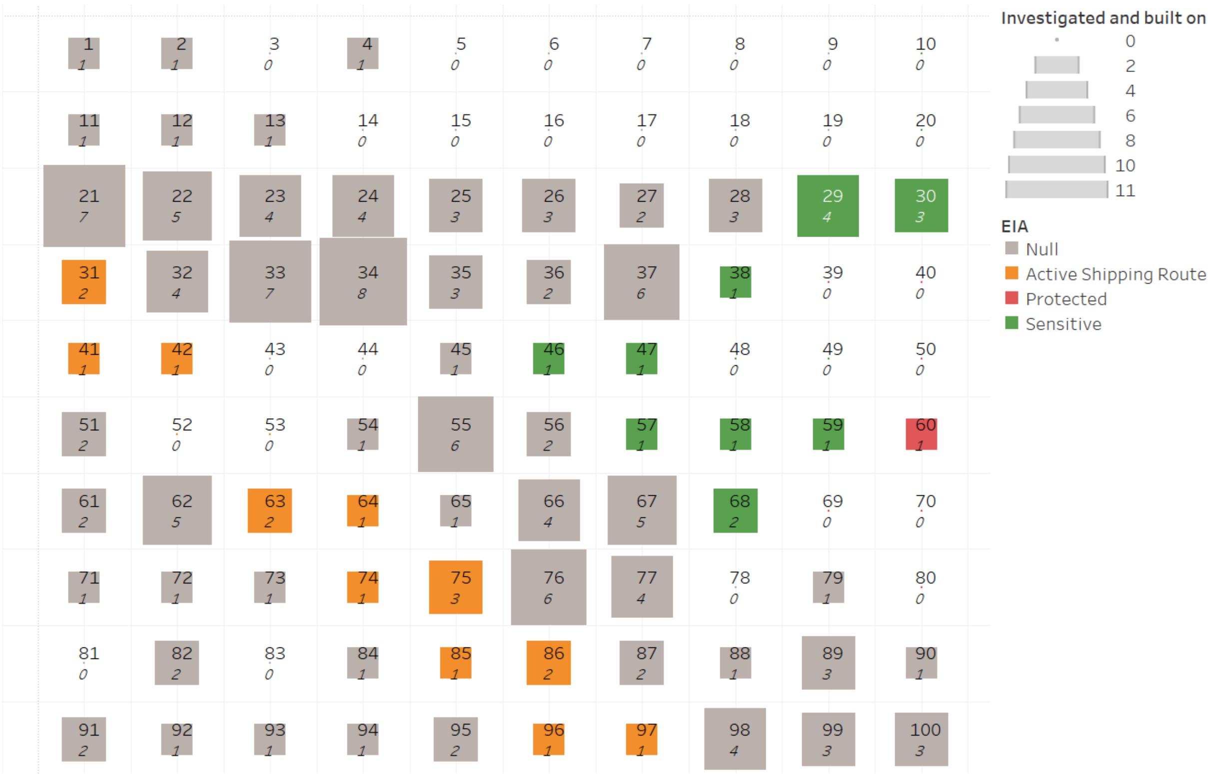


Figure 5.4: Number of instances where a cell was investigated, and a farm was built on

5.3 Post-game survey

Playtesting was held at NTNU July 26, 2018. The participants filled out a pre-game survey before playing Vindby. The questions coincide with the predefined educational goal and were used to measure the prototype's effectiveness in achieving said goal. The main takeaways from the pre- and post-game survey responses are summarized in this section and are fully reported in Appendix G .

The differences noted in the answers from all players before and after the games were played are consolidated. Table 5.4 displays these differences for each question.

Table 5.4: Playtesting results: changes in knowledge after playing Vindby

Question posed before and after playing Vindby	New observations expressed by one or more players after playing Vindby
What is the main purpose of an offshore wind farm?	To cut carbon emissions by replacing non-renewable energy with renewable energy, combat climate change, deliver power from offshore to shore, possibly generate revenue, keep stakeholders and public happy and healthy, and create jobs.
What are four physical components of an offshore wind farm?	Substructures, substation, cables, wind speed, water depth, soil quality, and distance to shore.
Name three factors that drive the lifetime cost of an offshore wind farm.	Cost of O&M, reliability of structures, reliability of turbines, issues during construction, price of electricity, and cost of substructures.
Name three factors that drive the design of an offshore wind farm.	Water depth, soil quality, environmental impact parameters (shipping routes and environmentally sensitive areas), distance from shore, presence of nearby wind farms, and soil quality.
What kind of failures can occur during the lifetime of an offshore wind farm?	Construction accidents, scour, gearbox failures, ship collision, generator failures, blade failures, turbine failures, and grid failures.
What is the capacity factor, and why is it an important measure?	All four of the players who did not define the capacity factor correctly before playing were able to define correctly after playing.
What are risks of investing in offshore wind?	Uncertainty in weather, turbine reliability, high investment, high maintenance costs, and environmental costs.

The playtesting was followed by a group discussion to share and exchange reactions to the game. The feedback that was not reflected in the surveys is summarized hereafter.

1. There was a consensus that players learned about previously unknown terms and strategies such as substructure options, connectivity, and failures.
2. Players enjoyed receiving positive feedback about game accomplishments, such as powering more households with offshore wind.
3. Players noted that it was difficult to measure the effects of more or of less reliability of substructures in the long-term.
4. Several players mentioned that they felt improvements to the GUI would have helped in keeping track of the game status, and that using text commands in the console was distracting.
5. Several players expressed the desire to have consolidated information presented in the GUI, as well as the option to retrieve additional information about specific items if desired.
6. Some players felt that the game goal was extremely clear and that they could easily track progress, where others found it difficult to determine why their progress was improving or not.

6. Discussion

6.1 General discussion

The goals of this study are *to develop a digital game for the design and the operational management of offshore wind farms to be used for the purposes of training and dissemination* and *to measure game effectiveness in terms of its simulations and educational power*. After identifying the core components of serious games and methods for simplified wind farm design, a complete game framework was established and integrated into a prototype. The prototype was tested by volunteers in a playtesting session. This chapter includes discussions on various results and challenges that arose as an outcome of this work.

Balancing accuracy and playability in game design

The product of this study, Vindby, is an interactive simulation that integrates two topics: simplified offshore wind farm design and the design of a serious game. A holistic approach to game design was employed throughout this study. This ensured that the game is not a mere add-on to simplified offshore wind design or that a simplified offshore wind farm design was merely added to an unaltered entertainment game (Dörner, Göbel, Effelsberg, & Wiemeyer, 2016). This approach affected decisions made on the overall game dynamics and framework as well as the finer details of the game mechanics and the engineering processes. Great attention and detail were applied to developing an accurate weather prediction model to ensure that each game played is different than the next.

The other offshore wind farm topics were modelled by starting from the basic definition of elements and adding details that would be valuable to the player's learning. This required a method of finding the appropriate level of detail, which was subsequently applied throughout the simulation. For example, substructure definitions were introduced as a fundamental element to offshore wind farm design. Subsequently, the reliability and costs were added to build game mechanics around choosing different substructures for different farms. The reliability and costs of the substructures vary with year of construction and site selection to teach and cost design drivers to the player. This level of detail was considered sufficient, as there was ample information to generate the same outcome without adding more computations. Playability requires meaningful feedback, and unnecessary details may be detrimental to learning. In the example of substructures, this meant that the choice of most economic and most reliable structure would be the same with or without further refinement of failure rates and specific costs.

In the end Vindby managed to incorporate the all the investigated game content into game rules and functions that resulted in an engaging game.

Simulation efficiency

Simulation efficiency directly impacts the speed at which the game runs. A digital game ideally runs at a speed consistent between computers and other platforms (e.g. mobile devices) for all game speed settings (slow, normal, and fast). The analysis of Vindby's performance showed that the game runs with adequate, yet suboptimal efficiencies. The random generation of numbers in each game tick greatly slows down the simulation. While the selected weather model suits the game mechanics (variation in time and space,) adjustments should be made to increase efficiency of calculations. This could be achieved by generating random time series for longer periods, and then reading these series in each game tick.

Memory usage is another factor in simulation efficiency. Values and attributes of nearly all objects are updated or checked every tick of the game loop. The storage of these values was kept to a minimum in the prototype although it can be further reduced. This is possible by refining the game mechanics and minimizing the storage of unnecessary information. Furthermore, advanced programming modules may be incorporated for serializing object structure, saving memory in the game module itself. Future programming should improve simulation efficiency without sacrificing feedback necessary for the player.

Alternatively, simulation efficiency can be improved by increasing the game loop interval resolution (currently set at one hour). This value may be increased to a day or even a week to decrease the number of updates and checks performed. In this case, adjustments must be made to ensure that production and weather are being updated the correct number of times within the new interval. Additionally, the value of failure rates and unit costs must be either updated to a higher resolution or checked in the code to update on an hourly basis.

Optimizer

The optimizer was originally indicated as a prominent feature in the game and was intended as a dynamic function capable of independently running the game to produce large amounts of feedback. The development of such a sophisticated optimizer proved to be beyond the time scope of this study. Small optimizer functions were created, however, to provide feedback to the player on individual topics at specified points in the game. This approach is considered more static as it only runs these specific functions when instructed. This simplified strategy was used during gameplay and may be expanded to cover more topics. Alternatively, the original concept may be revisited through the incorporation of deep learning.

Game Feedback

Following playtesting, players shared and expressed their game experience in a group discussion. Players recognized that they felt engaged in the game and wanted to keep playing. The main point for improvement was considered to be improvements in the feedback provided by the game. Several players felt that they could not properly assess the long-term impacts of certain choices, e.g. for substructure reliabilities. Additionally, the frequent notifications for corrective or condition-based maintenance were deemed distracting rather than informative, despite being recognized as information necessary to make better O&M choices. The game feedback can be improved by providing more direction on the long-term impact of choices and by consolidating unnecessary information (which can be accessed if sought out). The improved feedback system and additional work on the GUI are expected to improve playability in future versions.

6.2 Strengths and weaknesses

The boundary conditions and methodology of this study has several strengths and weaknesses.

The need for alternative training and dissemination tools in offshore wind energy is proposed to be addressed using a serious game. Training tools for engineers and researchers typically exist in the form of simulations developed with the goal of maximum accuracy. Dissemination of scientific knowledge currently exists in the form of serious games for sustainability, onshore wind, and renewable energy, among other topics. Serious games are a proven concept capable of teaching motivated players about serious content. The innovative nature of this study lies in the dual education goals for one serious game to be used by engineers and researchers as well as by the general public. This study was envisioned as a first step towards developing a final deployable game.

The prototype game was playtested to measure the game's effectiveness in accomplishing the characterizing goals. All the participants who volunteered had an engineering background, some in offshore wind energy. The playtesting session provided results almost entirely useful for the characterizing training goal, but less for dissemination. Responses to playtesting revealed that a more advanced GUI without a text console would have helped to keep track of game status and enable players to make better strategic decisions. This reveals the drawback of restricting game production (attractive user experience) to minimal effort in this study.

As the game was meant to use procedural generation to present a different scenario to the user for each run, functions that generate random numbers were incorporated into the game's program. These functions proved to slow down the game to an undesirable rate. There are suggestions in the previous discussion section on how to improve this rate and maintain procedural generation.

The prototype game was developed in Python using OOP. This organization style separates game content logically and allows for expandability where additional elements can be added to the simulation. Future expandability is an important feature of this game and has been provided with a framework of how simplified design of offshore wind farms may be created in the form of a game simulation. This study documents the simplification process of offshore wind farm design, outlining the fundamental elements necessary with an indication of where additional detail may be added to improve accuracy in simulation results. In doing so, this study has provided a starting point to engage the public, game developers, professionals, and researchers to develop a new type of tool and understanding for offshore wind energy.

7. Conclusions and Recommendation

7.1 Conclusions

Game Design

The first goal of this study was *to develop a digital game for the design and the operational management of offshore wind farms to be used for the purposes of training and dissemination.* The characterizing goals were defined following a review of where the knowledge gaps and misconceptions are among engineers/researchers and the public. Sections 3 and 4 summarize the methodology and results of the development of the digital game.

First, the game framework was established with respect to offshore wind energy. The game framework included the definition of five different game objectives for the player to choose from. Next, the game dynamics and elements were explored and established based on the most effective approach for a training and dissemination tool. This resulted in a timed game focusing around construction with rewards, resources, scoring, story, chance, and strategy. The game mechanics, i.e. the specific internal rules and functions of the game, were shaped throughout the investigation of simplified offshore wind farm design in section 3.4. Python using OOP was the selected approach to construct the game prototype because of its computational power and ease of expandability. Finally, the game content (i.e. domain-specific knowledge of a serious game) included weather prediction, offshore wind farm design, O&M, energy demand, climate change, finance, costs, and stakeholder presence.

An adequate balance between simulation accuracy and playability was achieved by referring to the characterizing training and dissemination goals and including only details that were necessary to produce the same result. An optimizer in the form of tips and tricks was introduced to address the original goal of developing an algorithm that optimizes the entire game. The O&M optimizer proved to be more accurate for corrective and scheduled maintenance strategies than in estimating savings with condition-based maintenance due to the additional uncertainty in failure prediction.

To highlight the potential of the game for advanced use in training applications, a relatively sophisticated weather prediction model was developed. This model uses a Markov chain matrix and is intended to generate different sea states for different virtual areas in the game's sea. The results of the weather prediction model showed that using the same dataset and the Markov chain, the simulated wave height and wind speed had average percent errors of 2.1% and 1.0%, respectively. The persistence of weather windows for sea states was well represented with a slight underestimation of weather windows for periods of 12 to 24 hours.

The result of programming the game mechanics was a functioning serious game prototype named Vindby. Flowcharts were used to illustrate the main game loop and internal functions (Figure 3.20 through Figure 3.23). The prototype is available as an attachment to this thesis.

Game effectiveness

The second goal of this study was *to measure game effectiveness in terms of its simulations and educational power*. The game was playtested in three segments.

First, a questionnaire was sent out to collect information on specific areas of interest by potential users. From 53 responses, the two most common topics in the free response section were payback period on carbon emissions and environmental impacts of offshore construction. These, among other suggestions, were integrated into the game mechanics. Second, a playtesting session was organized for volunteers to play the final prototype game to analyze the educational strength of the game. Third, surveys were distributed before and after playtesting to identify potential shifts in knowledge. Additionally, surveys and a group discussion were used to identify playability issues and recommendations for improvements of the game.

A total of 203 wind farms were constructed in a total 24 games played by 8 people. The results from each game were saved and post-processed. The variation in wind farm characteristics (number and size of turbines, project costs, and capacity factors) indicated that the game encouraged exploration. The degree to which players recognized value in site investigation information was measured by overlapping the investigated sites with sites with constructed wind farms. Across nearly all games played, 99% of farms constructed were in cells that had previously been investigated. This indicates that players quickly learned about the value of information to make informed decisions about building farms, and that they actively sought out that information. Various other statistics showed that players generally made the effective choices (choice of substructure, or whether to build at all) about building on sites after they had investigated the site.

A comparison a pre- and post-game survey answers revealed that learning had taken place during playing the game. The changes in answers most frequently focused on turbine and structural failures, electricity price, grid connections, O&M, and wind speed.

Overall

The final prototype of Vindby is a functional simulation capable of reproducing realistic values of offshore wind farm parameters including weather, site investigation, design, O&M, climate impacts, and costs. The game mechanics were constructed around simplified wind farm design and are documented in detail in this study. Game elements including rewards, resources, scoring, story, chance, and strategy are discussed in reference to offshore wind farm design. Following a playtesting session, game players revealed many improvements regarding game feedback and interaction. Through pre- and post-game surveys, the game has proven successful at achieving its characterizing goals of learning about offshore wind farms. The engagement and exploration of the players in the game demonstrated that playability of the game was overall successful.

7.2 Recommendations for future work

The success of a deployed version of a serious game about offshore wind energy in the future will depend on the improvement on various aspects of game design, simulation improvements, and interface development. The recommendations for future work are listed below:

Simulation improvements

The game speeds must be improved to acquire 100% efficiency. This may be done by re-examining the simulation resolution. The program may be modified to preserve 1-hour weather sampling and 10-minute production estimates while performing the remaining calculations once every 24 hours. Another approach to improving game speeds is to consolidate the weather generation computations. Rather than generating random values every hour, a synthetic time series may be generated either at the start of every year, or while the game is paused. The waiting time during regular game play will then be minimized or eliminated.

Augment simplified offshore wind farm design

The simplified offshore wind farm design as represented in the game simulation currently includes a fraction of possible topics that can be explored and integrated. Some key topics that have been discussed and suggested to add to the game include inter-farm and inter-turbine wake effects, turbine control systems, transmission losses, different types of site investigations, balancing costs in other nonrenewable energies, and investments in R&D.

Playtesters reacted well to stakeholder scores, although impact to game mechanics is minimal. Additional research should be done on specific impacts that the public, government, and shareholder satisfactions have on offshore wind energy.

To improve overall simulation accuracy and sensitivity, additional detail should be provided to costs, soil conditions, and reliability of substructures. The feedback in the game regarding O&M strategies and choices must be improved alongside the refinement of strategies and introduction of uncertainties. Alternative feedback mechanisms should be explored and tested.

Advance optimizer

Playtesters paid attention to the small optimizer functions for O&M strategies and substructure selection. Further development of more optimizer functions regarding other design elements such as turbine selection, O&M decisions, and site selection may accelerate learning. Alternatively, a new large-scale optimizer may be developed that solves the entire game and offers complete optimally designed wind farms for the player to study for comparison.

Expand platforms

For expanded use and playing, the game platform should be adapted for multiple platforms and settings. The ability to save and return to games would be valuable for continued use. A multiplayer platform (competitive or cooperative) may also broaden the outreach capabilities.

Develop game interface

One of the most influential changes in terms of game experience that can be made is a user interface that not only includes all game functions (without the use of a text console,) but also creates an attractive user experience. Figure 7.1 presents an inspiration for a future interface.

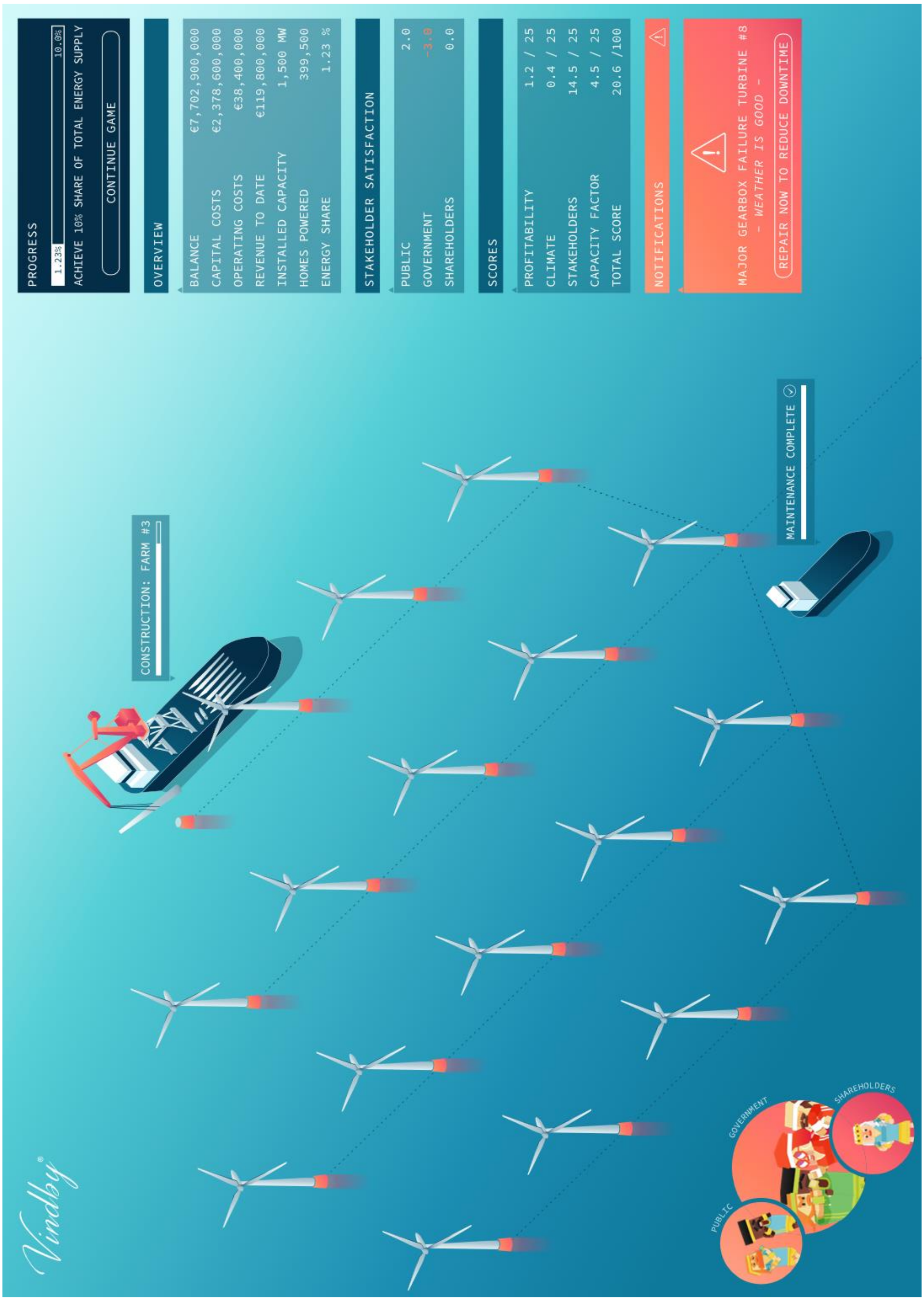


Figure 7.1: Conceptual gamer user interface

8. Reflection

This research project has presented the author with a number of opportunities and challenges with respect to offshore wind farm design in the context of a serious game.

Two key challenges are achieving a balance between precise engineering and unfamiliar scientific fields of game design and pedagogy, as well as learning a new programming language and style in a relatively short amount of time.

The investigation of game design principles and offshore energy was performed side by side. The intention was to develop one product representative of both research elements. More importantly, the main goal of this product was to teach new concepts to players. Throughout the process of game design, difficult choices had to be made to balance the level of detail in offshore wind engineering principles with player immersion and motivation. Generally, the pursuit and integration of offshore wind subjects presented few barriers; however, the abstract and unfamiliar nature of developing an educational program (and all the psychological aspect that this entails) proved more challenging.

The level of detail of each aspect of the program directly influenced whether it would become an over-simplified engineering simulation or a colorful yet unsubstantial game. The input from several project advisors and colleagues who were familiar with offshore wind and/or serious gaming proved to be instrumental during this process. Knowledge of game design and offshore wind energy can be readily acquired, but the integration, interaction, playtesting, agreements, and arguments informed the most challenging choices.

Many hours were spent learning how to program in Python and how to use OOP, both of which were entirely new to the author. Time dedicated to testing and evaluating new game mechanics was often used to understand syntax and programming structure and efficiency. Nonetheless, the resulting prototype program consists of approximately 3,000 lines of well-documented, functioning code. No game features had to be sacrificed as a result of limited programming knowledge. Resources on the web, books, and the help of colleagues were indispensable in achieving this feat.

Although the project presented numerous challenges, it also presented an array of opportunities. Two key opportunities are analyzing offshore wind farm design from an all-encompassing view at the required level of detail, as well as working on a short-term project with long-term potential and great interest.

The final game prototype includes a wide range of civil engineering subjects including offshore construction, environmental load prediction, maintenance strategies, cost estimation, and environmental impact. The opportunity to not only explore them individually, but explore their relationships was rewarding and inspiring. I would have thoroughly enjoyed the opportunity to continue exploring these topics in more detail.

Lastly, the interest expressed by colleagues and external parties in the thesis result served as an additional motivation to produce a high-quality prototype that can serve as a strong foundation for the future development of serious games. It may open the door for collaborations across disciplines to enhance user experience, and content accuracy. This serious game not only has the potential to educate a large number of users but may also serve as a research tool which can contribute to the direct progression of offshore wind in research and industry.

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Appendices

Appendix A : Thesis task description

NTNU

Faculty of Engineering Science and Technology
Department of Civil and Environmental Engineering

Date: **February 12th, 2018** page 1 of 5 pages

MASTER THESIS
(TBA4920 Marine Civil Engineering, master thesis)

Spring 2018
for
Esther Dornhelm

Simplified wind farm design as a serious game

Forenklet design av vind farm som et seriøst spill

OPPGAVETEKST (To fill in on DAIM)

The main task is to develop a simulation game for design and/or operational management of an offshore wind farm. This should allow users to play with various design options (e.g. wind turbine types, support structure types, inspection schedules, control strategies) for a large number of different site conditions and other constraints (e.g. financial, contractual). An underlying simulation shall then quickly determine the costs and revenues over the lifetime of the wind farm. In addition, an optimizer shall be developed that will calculate the optimal strategy and its value, so that users will get valuable feedback about their strategic choices. The concept shall be tested with people who will be interviewed about their experiences.

ADDITIONAL INFORMATION

BACKGROUND (On why and how)
Wind farm design and operational management is a complex task. Many factors contribute to the overall cost of energy, and it is even for experienced engineers sometimes difficult to correctly judge the relevance of different cost factors and design drivers. There is therefore a need for novel training tools and techniques. In addition, the general public is concerned about both the price of energy from wind energy, as well about the costs of the research to improve it. There is therefore also a need for educational outreach activities. A modern approach to improve this situation is suggested here: To develop a serious game that, during playing, teaches people important facts and lessons about wind energy. The "game" will actually be driven by an underlying, complex simulation based on engineering models, packaged in the form of an optimization challenge. Development of this simulation and its optimizer is the main scientific contribution of this project.

TASK DESCRIPTION (Tentative work for the thesis)
Description of task
The project consists of two inter-connected tasks. The first task is to develop a concept for a serious game in wind farm design / operational management. The game shall be completely defined and documented, and there should exist a playable prototype. However, at this stage no effort shall be undertaken to make it an attractive user-experience, i.e., no work shall be invested in graphical design or similar. The second task is to verify (by playtesting and interviews with test persons) whether the game achieves its educational aims.

Aims and purpose
A primary aim is to evaluate new, alternative forms of training and dissemination of scientific knowledge in the form of a game. A secondary aim is the development of a suitable optimization algorithm that "solves" the game, i.e., which can efficiently determine optimal playing strategies – corresponding to optimal design or operational management of a wind farm. This is especially interesting since procedural generation will be used, so that each run a completely different scenario will be presented to the user, and a large number of scenarios can be tested.

Subtasks and research questions
The first task is to get familiar with the design of wind farms and their operational management, but also with (board-) games in general. The main task is the concept development, which will be intensive work together with the supervisor and co-supervisor based on start-up philosophy. Different game concepts will be discussed, possibly tested, evaluated, etc. until all features have been frozen. The game mechanics should be documented with e.g. flowcharts. A prototype then needs to be implemented using minimal effort, e.g. in Python, used mainly for bookkeeping purposes and for random number generation. Then (or in parallel) the optimization of the strategic choices shall be investigated and an optimizer (artificial intelligence) shall be developed and implemented. Depending on the actual game mechanics and the depth of the game, this could be an easy task using a brute-force evaluation of all possible strategies offline, or a more complex task using heuristics. After this, what remains is to populate the minimal game with enough content to make it playable (and somewhat enjoyable) and test it extensively.
As this is an ambitious project, both the supervisor and co-supervisor (PhD student) will contribute to these activities.

Suggested schedule (total of 20 weeks)
1. Familiarization with the topic, literature study, testing of games that work [2 weeks]
2. Intensive development of the core concept: educational, scientific, and engaging [6 weeks]
3. Programming the prototype [3 weeks]
4. Development of the optimizer [3 weeks]
5. Filling in the details: make it interesting and more realistic [2 week]
6. Playtesting, improvements, and evaluation: does it work? [2 weeks]
7. Documentation: Writing of thesis [2 weeks]

General about content, work and presentation
The text for the master thesis is meant as a framework for the work of the candidate. Adjustments might be done as the work progresses. Tentative changes must be done in cooperation and agreement with the professor in charge at the Department.

In the evaluation thoroughness in the work will be emphasized, as will be documentation of independence in assessments and conclusions. Furthermore the presentation (report) should be well organized and edited; providing clear, precise and orderly descriptions without being unnecessary voluminous.

The report shall include:

- Standard report front page (from DAIM, http://daim.idi.ntnu.no/)
- Title page with abstract and keywords. (MScTitlePage[IBM]).
  CoMEM students must include CoMEM as one of the keywords.
- CoMEM page (Only CoMEM students) (CoMEM MSc title Page templateNTNU).
- Preface
- Summary and acknowledgement. The summary shall include the objectives of the work, explain how the work has been conducted, present the main results achieved and give the main conclusions of the work.
- Table of content including list of figures, tables, enclosures and appendices.
- A list explaining important terms and abbreviations should be included.
- List of symbols should be included
- The main text.
- Clear and complete references to material used, both in text and figures/tables. This also applies for personal and/or oral communication and information.
- Thesis task description (these pages) signed by professor in charge as Attachment 1.
- The report musts have a complete page numbering.

The thesis can as an alternative be made as a scientific article for international publication, when this is agreed upon by the Professor in charge. Such a report will include the main points as given above, but where the main text includes both the scientific article and a process report.

Advice and guidelines for writing of the report is given in: "Writing Reports" by Øivind Arntsen. Additional information on report writing is found in "Råd og retningslinjer for rapportskriving ved prosjekt og masteroppgave ved Institutt for bygg, anlegg og transport" (In Norwegian). Both are posted on It's-learning.

Submission procedure
Procedures relating to the submission of the thesis are described in DAIM (http://daim.idi.ntnu.no/). Printing of the thesis is ordered through DAIM.

On submission of the thesis the candidate shall submit also to the professor in charge a CD/DVD with the paper in digital form in pdf and Word (editable) version, the underlying material (such as data collection, time series etc., if possible) in digital form.

Documentation collected during the work, with support from the Department, shall be handed in to the Department together with the report.

According to the current laws and regulations at NTNU, the report is the property of NTNU. The report and associated results can only be used following approval from NTNU (and external cooperation partner if applicable). The Department has the right to make use of the results from the work as if conducted by a Department employee, as long as other arrangements are not agreed upon beforehand.

TBA4920 Marine Civil Engineering, Master Thesis 5
Master thesis for Esther Dornhelm, Spring 2018

Tentative agreement on external supervision, work outside NTNU, economic support etc.
Separate description is to be developed, if and when applicable.
Health, environment and safety (HSE) https://innsida.ntnu.no/hms-for-studenter
NTNU emphasizes the safety for the individual employee and student. The individual safety shall be in the forefront and no one shall take unnecessary chances in carrying out the work. In particular, if the student is to participate in field work, visits, field courses, excursions etc. during the Master Thesis work, he/she shall make himself/herself familiar with "Fieldwork HSE Guidelines". The document is found on the NTNU HMS-pages at
https://innsida.ntnu.no/wiki/-/wiki/English/Fieldwork+-+for+participants

The students do not have a full insurance coverage as a student at NTNU. If you as a student want the same insurance coverage as the employees at the university, you must take out individual travel and personal injury insurance.

Start and submission deadlines
The work on the Master Thesis starts on February 12^{th}, 2018

The thesis report as described above shall be submitted digitally in DAIM at the latest August 20^{th}, 2018 at 3pm.

Professor in charge: Michael Muskulus

Other supervisors: Helene Seyr

Trondheim, 09.07.2018

Michael Muskulus

Professor in charge (sign)

Appendix B : Vindby prototype object-oriented programming summary

Generally, each object is contained in its own python file with the same name preceded by an "m" (stands for module).

Table. B-1: Vindby class object register

File	Class	Description	Properties	Methods
PlayVindby.py	Game	Represents the game	userName, seaGrid, tn, gameClock, windClock, windFarmGrid, wallet, availableTurbines, availableSubstructures, failureRates, costs, energyDemand, renewEnergySupply, co2, OMoptions, interact, settings, tool, optimizer, market, goals, myGoal, RepairVessel, govt, public, shareholders, menu, simulationTimer, paused, quit	setup, kcallback, playame, pause, unpause, roundTo, checkkeypress, endGame
GUI.py	App	Open Interface	game, sea, clock, photos, labels, indicator, cellButtons, infopanel	callback, displayCellInfo, run, updateCellColor, updateCellName, roundTo, update, displayInfo
mCell.py	Cell	Represents one cell in the sea grid	id,xcoor, ycoor, area, depthclass, depth, status, meanU90, meanH, dist2shore, env_protection, shipping_channel, soilqual, wind_ampfactor, myFarm	identify
mCO2.py	CO2	Represents CO2 in the worlds atmosphere	energy, renewableEnergySupply, conc, emissions, emissions_prevented, emissions_construction, ppm, nonEnergyppm, temp, nonrenewableRate, renewableRate, homes, maxhomes	energy2CO2, CO2prevented, updatetemp, homescalc, CO@fromConstruction, display
mCosts.py	Costs	Represents the costs of things	costlist, inflationRate	read, inflation
mEnergy Demand.py	EnergyDem and	Represents the worlds energy demand	timeInerval, starting_value, demandYearly, demandHourly, increaseRate, deltaIncreaseRate, renewableShare	update, peakOil
mFailure Rates.py	FailureRat es	Represents default failure rates	failureRates, turbineFailureRates, structureFailureRates, farmFailureRates ConstFailureRates, otherfailures, preventableFailures	read, sort, update

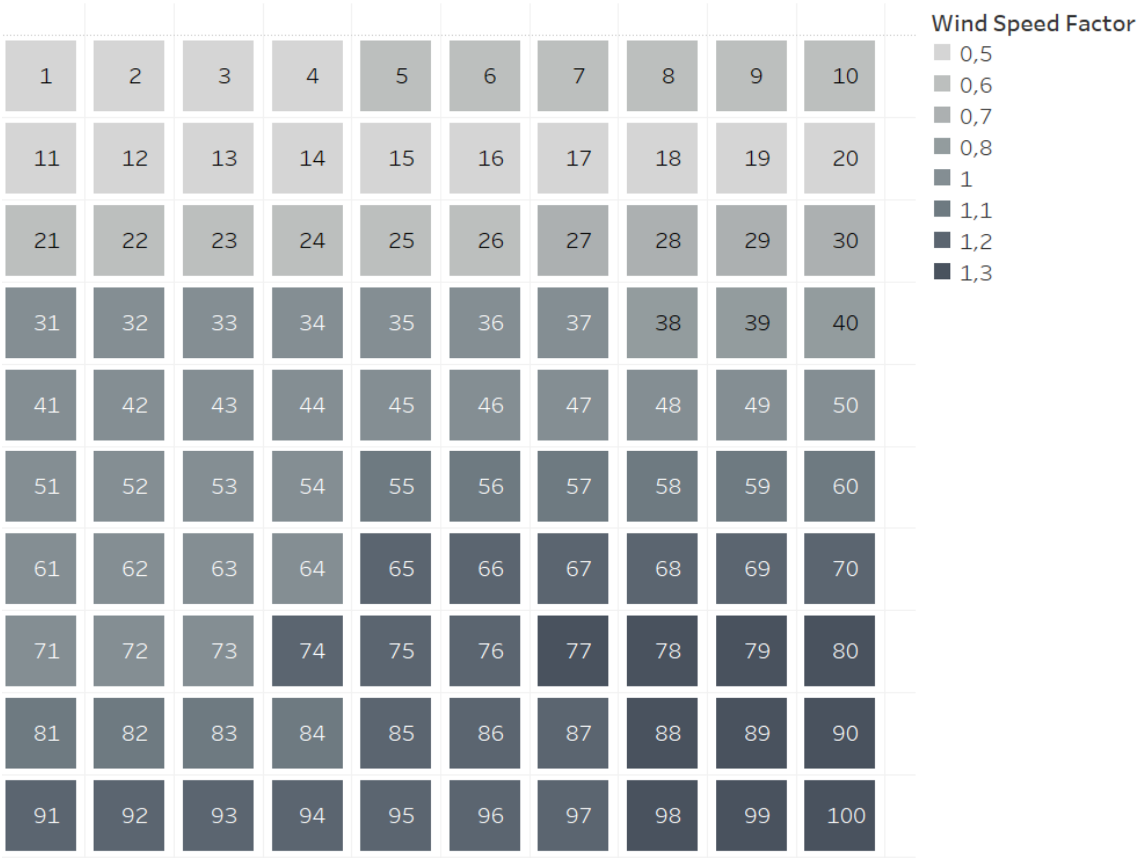
File	Class	Description	Properties	Methods
mGameTools.py	gameTools	Represents tools used by game so as not to crowd the game file	game, reportIntervals, news, header, date, time, rewardMeasures, rewardGranted, scores, Rlfarms, goal_items, result	setup, convertTime, regularReports, newspaper, checkDidYouDoYourResearch, checkRewards, CheckCF, checkGoal, breakEven, updateScore, roundTo, endgame
mInteraction.py	Interaction	Compilation of user interaction methods	game, user, investigatedCells	intro, designwindfarm, namewindfarm, managefailuresinput, endoflifetime, decommissionWindarm, adjustsettings, YesorNo, roundTo
mLCOE.py	LCOE	Represents the LCOE for one farm	value, displayValue, year	update
mMarket.py	market	Defines Feed-In Tariff (FIT) selling price for the game, and farm selling price	turbineRange, windRange, capacityRange, FITRange, FIT	setup, sellingPrice
mMarkov.py	Markov	Represents the weather generation in the game	markovWave, wave2WindCorr, metOceanStats, waveObservations, windObservations, windObservations10min, windHourlyStdev, wind_stdev_bymonthandbin	setup, generateMarkov, initalize, waveMarkov, windData, conditionalProbability, generateProbabilities
mOandM.py	Ommanager	Represents all O & M activities for one farm. Called each game tick	strategy, farm, game, repairLog, failureLog, previousRepair, pofit_per_hour_per_turbine, totalSpent, totalDownTime, reportNumberFailures, reportDownTime, failuresPerTUrbinePerYear	setup, maintain, vesselCost, annualInspection, monthlyRepairs, corrective, scheduledMonthly, conditionBased, manageFailures, logFailures, logRpairs, downtime_todate, scourRepair, roundTo, endGame

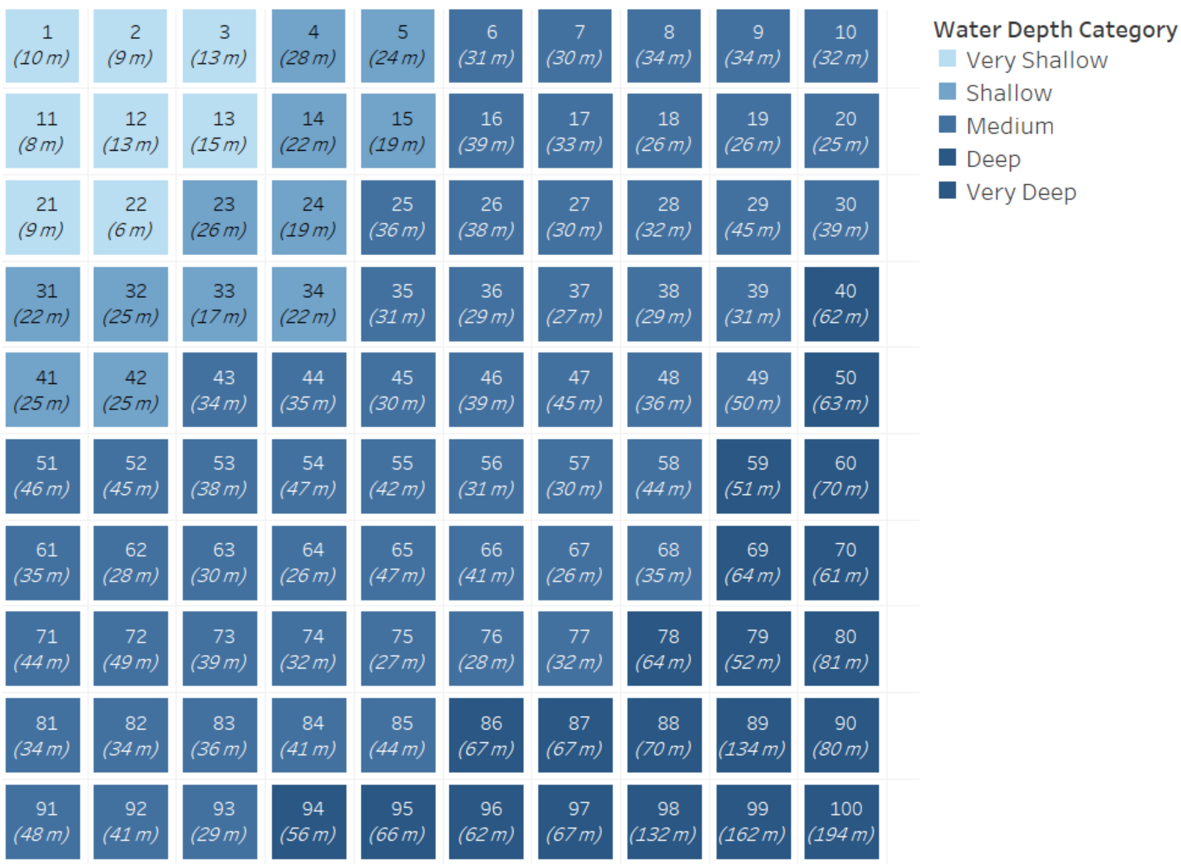
File	Class	Description	Properties	Methods
mOM options.py	Omoptions	Represents all O & M options	strategyDescriptions, strategyList	displayOptions
mOnshore Substation.py	onshoreSubstation	Represents the onshore substation	capacity, exist, capacityIntervals	build, addCapacity
mOptimizer.py	Optimizer	Stores methods to provide feedback to the user on optimization of wind farm design	game, optimizedFarms	report, optimizeOANDM, monthly_scheduled_estimator, optimizeStructures, roundTo
mPower Curves.py	PowerCurves	Represents power curves for all possible turbines	powerCurveList	read, grab
mRepair Vessel.py	RepairVessel	Represents one repair vessel.	busy	process, repairTurbine, repairStructure, repairFarm, repairConstruction
mReport.py	Report	Represents a report issued by the game	game, issueTime, type, intervals, goal items	regularReports, roundTo, issue
mSeaGrid.py	SeaGrid	Represents the cells in the sea grid	cellList, windInterval	read, occupy, unocupy
mStakeholder.py	Government	Represents one stakeholder	influence, satisfaction, events, eventCounter	display, meeting

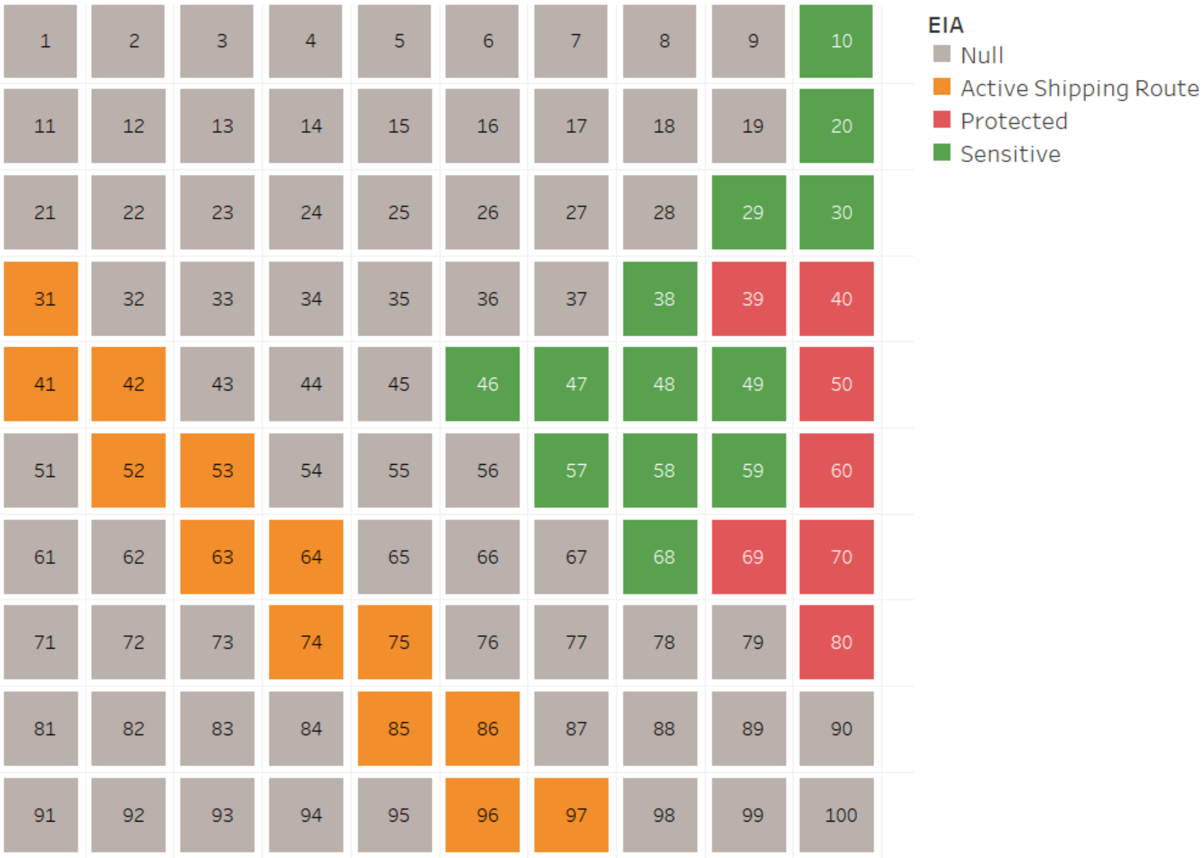
File	Class	Description	Properties	Methods
mStakeholder.py	Public	Represents one stakeholder	influence, satisfaction, events, eventCounter	display, meeting
mStakeholder.py	Shareholders	Represents one stakeholder	influence, satisfaction, events, eventCounter	display, meeting
mSubstructure.py	Substructure	Represents one substructure	id, type, name, myStructureFailureRates, notification, structureFailure	setup, checkFailure
mSubstructureAll.py	SubstructureAll	Represents all possible support structures	substructureListAll	read, display
mSubstructureAvailable.py	SubstructureAvailable	List of available support structures	substructureList, count, unlock, prices	read, display, roundTo
mSubstructureType.py	SubstructureType	Represents one type of Support Structure	type, structureUnitCost, foundationUnitCost, depthLimit, depthFactor, price, installationDaysPerMW, fabricationDaysPer	priceQuote
mTurbine.py	Turbine	Represents one turbine	id, type, name, myTurbineFailureRates, power, turbineFaiulre, notification	setup, run, checkFaiulre, readPowerCurve
mTurbineAll.py	TurbineAll	Represents all possible turbines	turbineList, pwoerCurveList	read

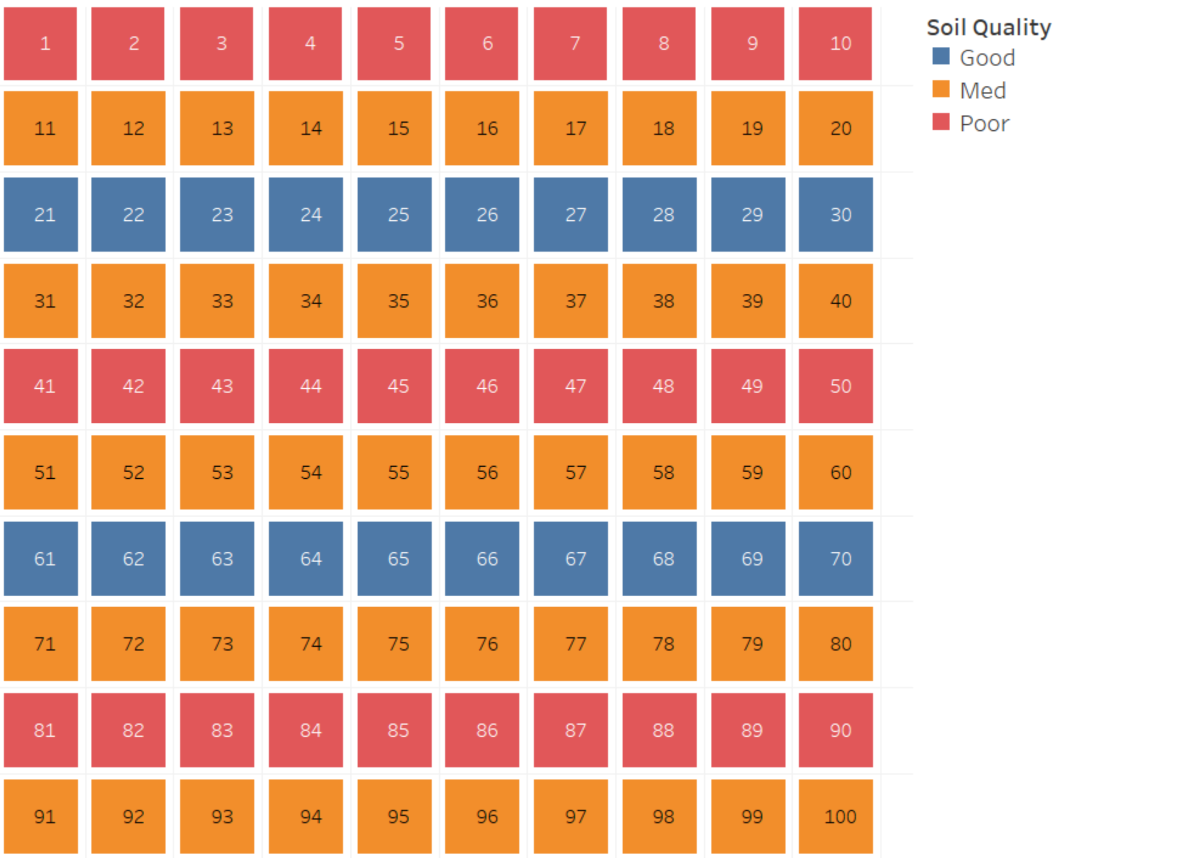
File	Class	Description	Properties	Methods
mTurbineAvailable.	TurbineAvailable	List of available turbines	allTurbines, turbineList, powerCurveList, count, unlock	read, grab, display, roundTo
mTurbineType.py	TurbineType	Represents one type of turbine	cap, cutIn, slope, ratedSpeed, cutOut	identify
mWallet.py	Wallet	Represents users available money	balance, record, profits, investments, initialInvestment, operatingCosts, capitalCosts	checkBalance, withdraw, deposit, display, displayLedger, roundTo
mWeather.py	Weather	Represents the weather conditions in one cell	markovWave, wave2WindCorr, metOcean, windHourlyStdev, waveHeight, windSpeed_1hr, windSpeed_10min, amplification	setup, simulation, previousWaveBin
mWindFarm.py	WindFarm	Represents a wind farm	name, myCell, myTurbineList, mySubstructureList, costs, windSpeed, waveHeight, farmFailure, failures, notification, turbineCatalog, substructureCatalog, capacityFactor,installedCapacity, cableLength, interarray_cableLength, connection, myFailureRates, revenue, energyOverLifetime, co2prevented_byfarm, co2install, breakEven, contractorCost, status, constructiontime=, news, lifetime, OandM, substation, cables, sellingPrice, LCOE	design, build, newspaper, checkFaiulre, run, updateLCOE, display, roundTo
mWindFarmGrid.py	WindFarmGrid	Compilation of all wind farms	windFarmList, retiredWindFarms, failureList, failureHistory, installedCpacity, connections, availableConnections, onshoreSubstation, windfarmnames	add, displayConnections, listFailures, display, displayFailures, retireFarm

Appendix C : Sea grid properties









Appendix C : Sea grid properties

Appendix D : Cost details

Sources frequently referenced while calculating costs include (Shafiee, Brennan, & Espinosa, 2016) and (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014). Both studies utilize a comprehensive dataset to model lifetime costs. Costs were all converted in euros.

Table. D-1: Vindby costs and sources

Item	Cost	Reference
Initial balance in player's wallet	Varies	Based on game goal selection
Annual inflation rate	2.0%	From LCOE calculation in (Levitt, Kempton, Smith, Musial, & Firestone, 2011)
3 MW turbine, each	€2,600,000	Material cost of wind turbine as shown in (Shafiee, Brennan, & Espinosa, 2016) C = 3,000,000 x ln (Rated capacity in MW) – 662,400
5 MW turbine, each	€4,200,000	Same as above
7 MW turbine, each	€5,200,000	Same as above
10 MW turbine, each	€6,200,000	Same as above
15 MW turbine, each	€7,500,000	Same as above
Transition piece	€ 400,000	(Zaayer, 2013) Using an average size transition piece
Field investigation	€2,500,000	Survey cost from (Shafiee, Brennan, & Espinosa, 2016) assuming the average size wind farm in 2017: 500 MW (Wind Europe, 2017)
Monopile per m water depth	€ 48,000	See section 3.2.5 (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014) and (Rosenauer, 2014)
Jacker per m water depth	€ 85,000	Same as above
Tripod per m water depth	€ 144,000	Same as above
Gravity per m water depth	€ 136,000	Same as above
Floating semi-submersible, each	€ 7,956,000	Same as above
Floating spar, each	€ 4,082,000	Same as above
Floating tension leg, each	€ 4,185,000	Same as above
Monopile foundation per m length	€ 32,000	(Myhr, Bjerkseter, Agotnes, & Nygaard, 2014)
Jacket foundation per m length	€ 21,000	Same as above
Tripod foundation per m length	€ 16,000	Same as above

Item	Cost	Reference
Floating semi-submersible moorings, per m water depth	€ 300	Same as above
Floating spar moorings, per m water depth	€ 300	Same as above
Floating tension leg moorings, per m water depth	€ 200	Same as above
Interarray subsea cables per m	€ 281	Same as above
Export subsea cables per m	€ 443	Same as above
Onshore substation	€71,500,000	Assuming 500 MW capacity (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014)
Offshore substation	€143,000,000	Assuming 500 MW capacity (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014)
Contractor cost per day	€1,538,000	Duration estimated per project. Cost per day (Myhr, Bjerkseter, Agotnes, & Nygaard, 2014)
Dismantling a wind farm per MW	€ 376,000	(Shafiee, Brennan, & Espinosa, 2016)
Dismantling subsea cables per km	€ 28	(Shafiee, Brennan, & Espinosa, 2016)
Recycling wind farm components per MW	€ 30,000	(Shafiee, Brennan, & Espinosa, 2016)
AHTS vessel per day	€14,500	(Dinwoodie, Endrerud, Hofmann, Martin, & Sperstad, 2014) Converted to euros with a rate of 0.77.
CTV vessel per day	€2,300	(Dinwoodie, Endrerud, Hofmann, Martin, & Sperstad, 2014) Converted to euros with a rate of 0.77.
FSV vessel per day	€12,400	(Dinwoodie, Endrerud, Hofmann, Martin, & Sperstad, 2014) Converted to euros with a rate of 0.77.
HLV vessel per day	€19,480	(Dinwoodie, Endrerud, Hofmann, Martin, & Sperstad, 2014) Converted to euros with a rate of 0.77.
Monitoring system upfront cost	€2,500,000	Based on €5,000 per MW for a typical 500 MW farm. (Shafiee, Brennan, & Espinosa, 2016)
Fine for construction in a shipping route, cost of navigation measures	€20,000,000	Arbitrary
Fine for construction in an environmentally sensitive area	€20,000,000	Arbitrary

Item	Cost	Reference
Cost of environmental mitigation in planning phases	€500,000	Arbitrary
Annual inspection of one turbine. Includes operating costs	€ 24,000	(Dinwoodie, Endrerud, Hofmann, Martin, & Sperstad, 2014)
Repair of a turbine Hydraulics Major Replacement	€ 18,000	(Carroll, McDonald, & McMillan, 2015)
Repair of a turbine Generator Major Replacement	€ 86,000	Same as above
Repair of a turbine Gearbox Major Replacement	€ 389,000	Same as above
Repair of a turbine Blades Major Replacement	€ 332,000	Same as above
Repair of a turbine Hub Major Replacement	€ 215,000	Same as above
Repair of a turbine Converter Major Replacement	€ 27,000	Same as above
Repair of a turbine Hydraulics Major Repair	€ 5,000	Same as above
Repair of a turbine Generator Major Repair	€ 7,000	Same as above
Repair of a turbine Gearbox Major Repair	€ 6,000	Same as above
Repair of a turbine Blades Major Repair	€ 5,000	Same as above
Repair of a turbine Hub Major Repair	€ 9,000	Same as above
Repair of a turbine Converter Major Repair	€ 7,000	Same as above
Repair of a turbine Hydraulics Minor Repair	€ 2,000	Same as above
Repair of a turbine Generator Minor Repair	€ 1,000	Same as above
Repair of a turbine Gearbox Minor Repair	€ 1,000	Same as above
Repair of a turbine Blades Minor Repair	€ 1,000	Same as above

Item	Cost	Reference
Repair of a turbine Hub Minor Repair	€ 2,000	Same as above
Repair of a turbine Converter Minor Repair	€ 1,000	Same as above
Mitigating an environmental concern of a farm during operation	€ 50,000	Arbitrary
Mitigation public disapproval of a wind farm	€ 50,000	Arbitrary
Repair of subsea cable per km	€ 14,000,000	Average repair cost (Transmission Excellence Ltd, 2017)
Fix an accident that occurred during construction	€10,000,000	Arbitrary
Scour protection per turbine if designed pre-emptively	€ 80,000	(DHI, 2012)
Scour protection per turbine if installed after scour has already occurred	€ 150,000	(DHI, 2012)
Repair of structure that failure due to external loading	€ 200,000	Arbitrary
Repair of structure that failure due to fatigue loading	€ 200,000	Arbitrary
Repair corrosion of structure	€ 200,000	When performed on-site, up to 1000 €/m^2. Value estimated for 6m diameter monopile with 10 m coating length (Price & Figueira, 2017)
Repair to structure that is experiencing bearing failure	€ 200,000	Arbitrary

Appendix E : Game instructions

June 27, 2018: PLAYTESTING AGENDA

1. Fill in page 1 and 2 of the pre-test survey sent out by email.
2. Run **PlayVindby.bat** on the desktop, choose **Run**, and wait for the game to load (takes a minute or two)
3. Read the introduction, and choose a goal 1 through 5
4. You're ready to start playing. An interface window will appear (look at the next page of this handout.) Actions and notifications in the game take place in the console and the interface is mostly for information, so you should keep an eye on both. **It is suggested to keep the console and interface side by side**.
5. Use the **main menu** to complete actions in the game and get details by typing the letter in [brackets].

   NOTE: The game is running in the background, waiting for a keypress. The moment you hit a key, it will register either a main menu command and pause the simulation or keep simulating if the key pressed isn't part of the main menu. This means you can't use the keyboard even for other programs when the game is simulating. Press [P] to pause the game and use other programs if desired.
6. Where do I start?? Start by doing research on sea "cells" to gather information that will be helpful for building (Main Menu [w], then [r], then choose a cell). Then start building by going to Main Menu [w], and type in the cell where you'd like to build. Keep following instructions. (Use the last page of this handout to get more information about building windfarms.)
7. Make sure to keep an eye on the cell color during a farm's construction. If it turns red, you should go to Main Menu [f] and repair the construction failure ASAP. Otherwise, the contractor will keep billing you!
8. Keep building until you reach your goal. You can speed up the game in [s]ettings
9. Try to playtest each of the five goals, or as many as you can get to.
10. At the **END** of the playtesting sessions (lunchtime), **return to the google survey link from the start of the playtesting and complete the rest of the surveys.** Your games are being saved automatically.

    Good luck!

Page 1 of 4

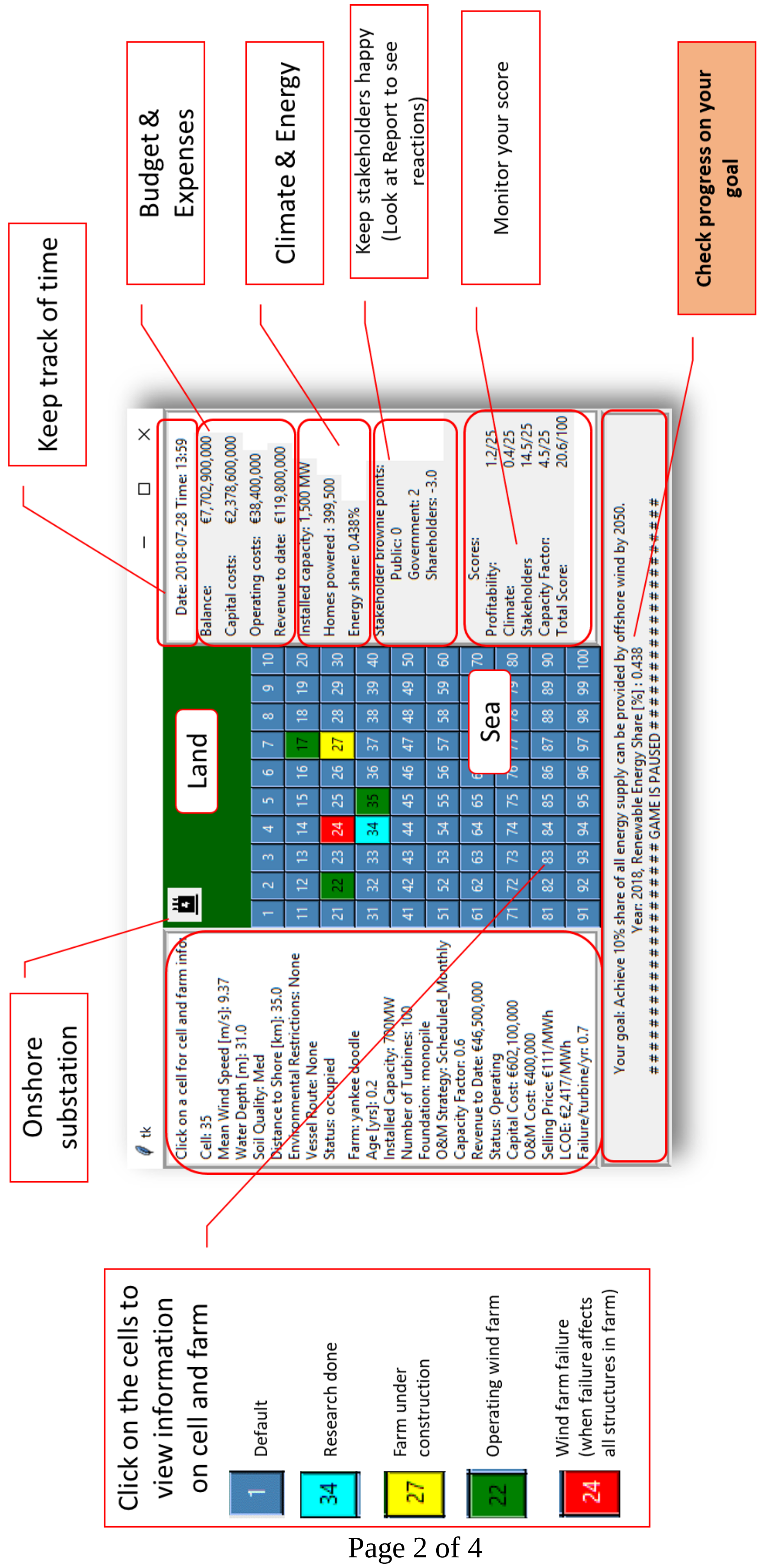


Figure 1: Game interface

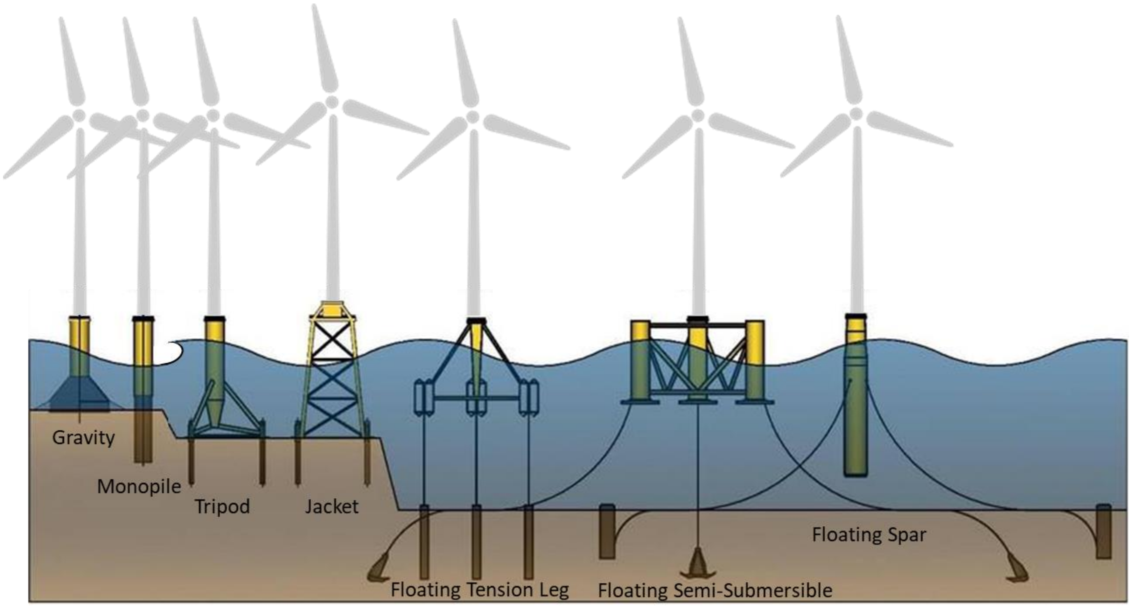


Figure 2: Substructure graphics- *Nothing to do with turbine spacing*![1]

- **Failures and reliability:**
  - Farm-wide failures: some failures affect the entire wind farm such as grid failures and shut down due to political or public involvement.
  - Structural failures: failures of structures supporting the turbines (shown in Figure 2) can occur due to:
    - Scour – depends on soil conditions and structure type
    - Fatigue – depends on wave and wind environment and structure type
    - Corrosion – depends on structure material and assembly
    - Bearing – depends on structure type and soil conditions
    - External load – depends on turbine size and wave conditions
  - Turbine failures: these are the most frequent failures at the turbine generator, gearbox, blades, hub, power supply, and pitch hydraulics. Classified as:
    - Minor repair – depends on wind farm age
    - Major repair – depends on wind farm age
    - Major replacement – depends on wind farm age

[1] Bhattacharya, Subhamoy, Georgios Nikitas, Laszlo Arany, and Nikolaos Nikitas. 2017. *Soil–structure interactions for offshore wind turbines*. Guildford, UK: Engineering & Technology Reference.

- **Glossary:**

Scour: A phenomenon that occurs when strong currents stir up sandy soil at the seabed, often creating a hole around offshore structures

Power: Electrical power in MW. A 5MW turbine has capacity to produce a maximum of 5 MW of power in one hour when the wind is in the ideal range for that model. The turbine will produce less power when wind speeds are low.

Energy: The power production over a period of time. When a 5MW turbine is running at full capacity for 1 hour, the energy produced is 5MW*1 hr=5 Megawatt-hr (MWh): When wind speed is low, this may be 3 MW * 1 hr = 3 MWh

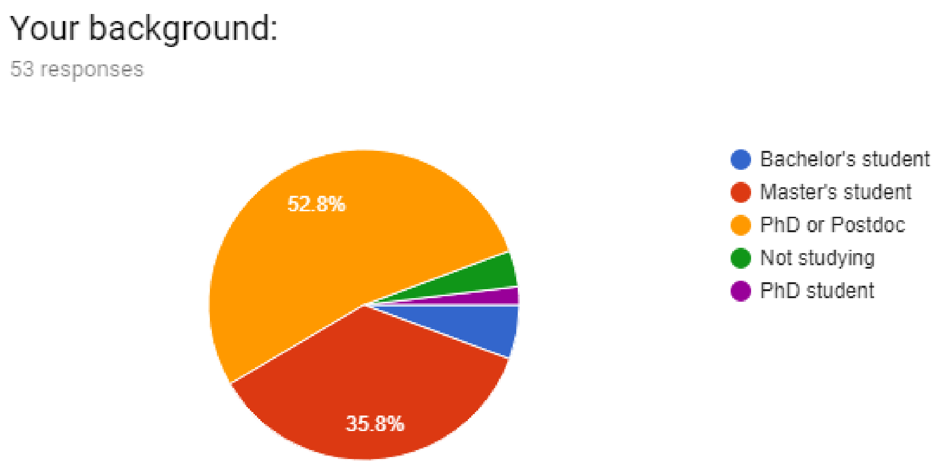
Capacity Factor (CF): $\frac{Actual\ electricity\ output\ (MWhr)}{Maximum\ possible\ electricity\ output\ (MWhr)}$ … Lower when wind speeds are low or when turbines are turned off when there is a failure. A higher value indicates higher productivity -> higher revenue. When a 5MW turbine produces 3-MWh, the capacity factor for that hour is 3 MWh/ (5 MW* 1 hr) = 0.6

Levelized Cost Of Energy (LCOE):. $\frac{Life\ costs\ (construction+operation)(\$)}{Electricity\ produced\ during\ lifetime(MWh)}$…When compared to the selling price of energy (cost per MWh of electricity), a low LCOE implies affordability and economic feasibility without too much government assistance. A high LCOE implies the project costs more money than its worth.

Selling Price: The fixed price per MWh of electricity. This value is often agreed upon with the government to make sure the electricity produced by offshore wind if purchased and to accelerate investment in renewables.

Appendix F : Questionnaire responses

A total of 54 responses were received for the April questionnaire.



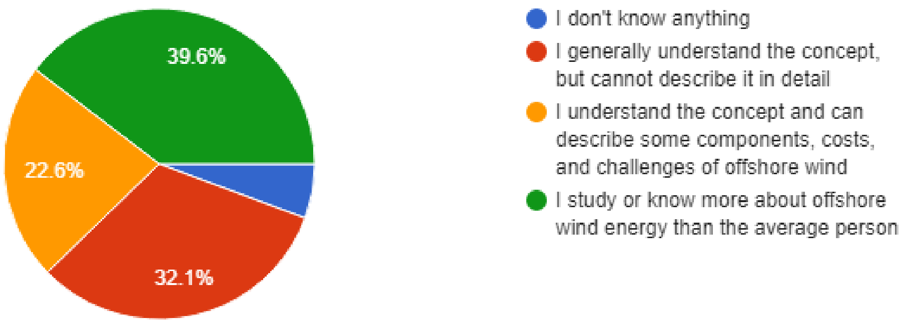
Your field of study or work:

51 responses

Offshore wind	bio informatics	Environmental engineering
Electrical/mechanical engineering	Geotechnical engineering	Water management
Environmental engineering	Ice	Product Design Engineering
Industrial Engineering	acoustics	Environmental sciences
Coastal Engineering	Water treatment	Offshore wind energy
Wind Energy	Engineering geology	material science
condition monitoring of wind turbines	Dam safety	Offshore wind energy (!)
Wind energy integration	Geotechnics	Mechanical Engineering
Wind Energy	Energy Engineering	Civil Engineering
Wind turbine modeling	Coastal Engineering	Civil Engineering - Arctic Technology
Coastal engineering	Civil Engineering	Coastal and Marine Engineering
Wind power integration into power systems	IT	Offshore wind
Marine Technology	Coastal Engineering	Transport engineering
coastal engineering	political sciences	Wind energy, O&M
Numerical geotechnical engineering	Energy Engineering	Geotechnical engineering
Road engineering	Nordisk	Hausfrau
Sea ice	Marine engineering	Energy-efficient buildings

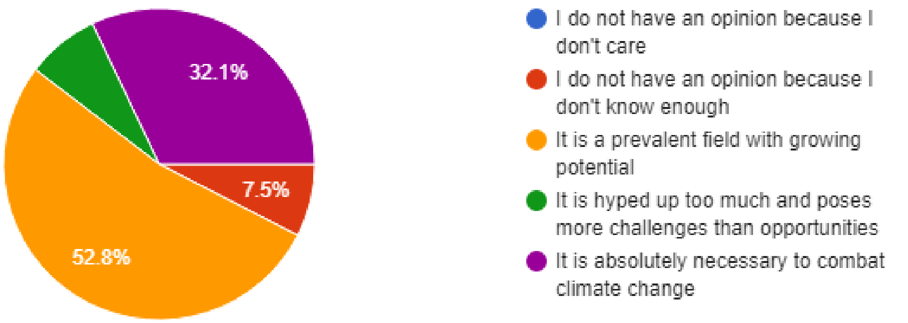
Your knowledge of offshore wind energy includes:

53 responses



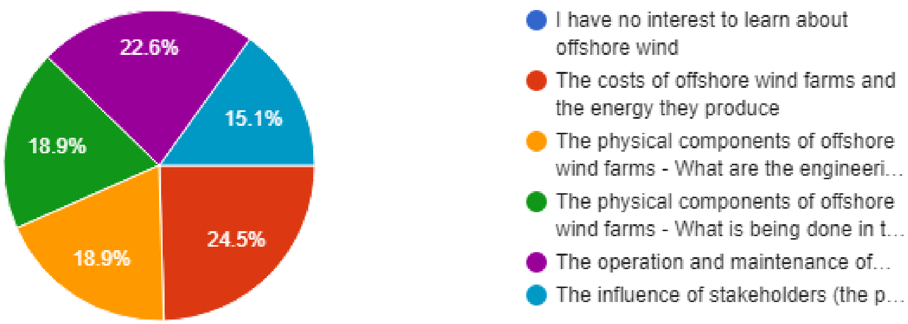
Your opinion of offshore wind energy is:

53 responses



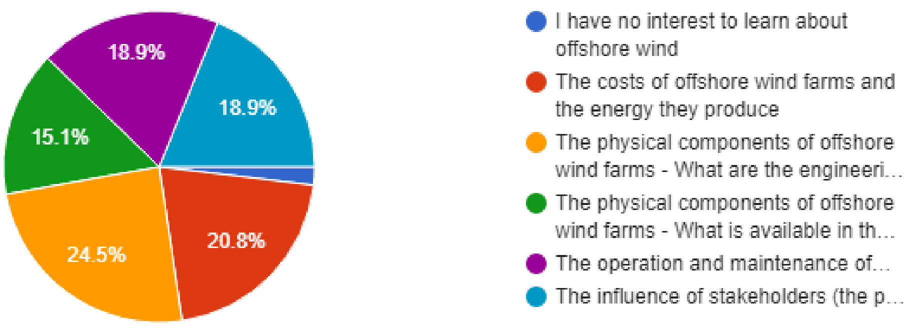
What topic would you be most interested to learn more about? First choice:

53 responses



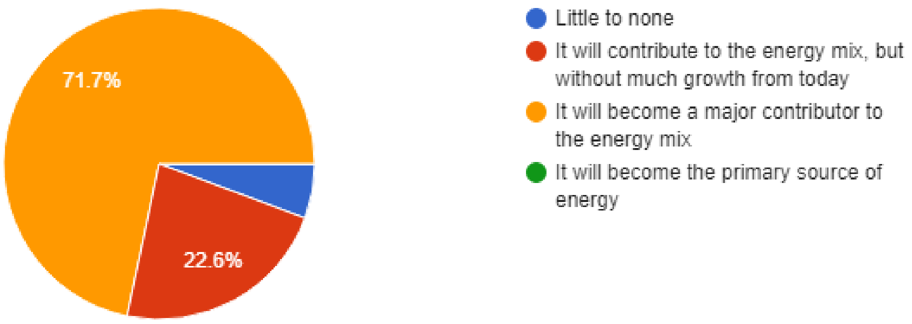
What topic would you be most interested to learn more about? Second choice:

53 responses



What role do you predict offshore wind energy will play in the world's energy future?

53 responses



Given the chance to speak to an expert in the field, do you have any additional questions or interests about offshore wind energy?

28 responses

Why are we hardly considering the emissions of the manufacturing of the wind turbines when talking about "clean energy"?
How about comparison of bottom-fixed and floating concepts and its consequences for the costs, loads, turbine design etc.? O&M strategies for different distances to shore (CTV, SOV vs helicopter etc.)? Differences from 5MW to 10MW turbines? Shadowing effects if there are 'too many' wind farms e.g. in the North Sea?
Differences compared to onshore (both advantages and disadvantages)
With regard to the future, how do you think offshore wind energy will contribute to the sustainable development of the planet?
What is the life cycle footprint (COS, other "dangerous materials)?
How long does a wind mill take to assimilate (energy, cost, CO2 footprint- including building new infrastructures to the wind farm)? How long is the life expectancy of a wind mill? How can an old windmill be recycled, and to which extend?
How 'sustainable' is the production/construction/maintenance compared to other types of energy?
"Renewable energy harnessing systems such as offshore wind and solar have undergone a metamorphosis in recent decades owing to rapid advances in technology. This is a paradigm shift in many ways and provides a glimmer of hope to combat the detrimental impacts of climate change. However, governmental policies still back non-renewables (in the form of subsidies) whereas little or no support is offered towards burgeoning clean energy technologies. This is quite counter-intuitive. I would expect all the available support directed towards renewables. Do you see a possibility in the near future that renewables can compete with oil even with the odds tipped in the favor of oil? and what are your thoughts on lobbying on behalf of oil influencing decision making? As far as the game is concerned, I can suggest a thing or two (if you haven't considered it already) We know that offshore wind and solar are intermittent energy source. This means that a balancing source of energy is required for power supply during shortages. This brings in possibility of including nuclear and hydro into the mix. But these come with shortcomings (radiation, waste disposal, effect on ecology etc.). So, a tax (not carbon tax, but sort of an accountability tax) can be imposed on these. It would be great to include subsidies and lobbying into the mix as trump cards or something. You can also think of including the regulations of the Paris climate accord into the game. New advances (unexpected advances) in technology can be included as special cards. For example, Teslas Giga factory promises to produce affordable batteries on a massive scale. This can greatly help offshore wind in energy storage What about using decommissioned offshore oil drilling plants for offshore wind production? You can easily install 3-4 units on a platform. So, in the game, you can try and bankrupt an oil company and take hold of all their offshore oil drilling facilities and build your wind farms
I've worked on onshore windfarm and I would ask him about details of WTG base and transmission issues in offshore windfarm.
Including but not limited to manufacture, installation, operations, and maintenance, what are the different returns on investment (carbon/energy, money, &c.). Example: it takes a certain amount of carbon/energy in order to manufacture, install, and maintain a wind farm; how many years of operation are needed before it becomes carbon negative/energy positive?

Given that, wind energy has a big share in a grid, how should be the energy demand be balanced when the wind does not blow.
I am interested in whether the harmful impacts on wildlife/ecology/ocean currents are myths or if there's truth to them. Mythbusters: offshore wind edition!
I'm curious about the type of foundations actually, since I have a bachelor’s in civil engineering
What are the environmental impacts of offshore wind farms? (Like impact on marine life)
What are the main social-technological barriers that hinder a faster implementation of this energy source?
How environmental friendly is the technology when taking into account the whole life cycle?
What are the problems with offshore wind?
Does the offshore wind farm influence the sea environment?
Does talking to myself in the mirror count? This question isn't really meant for me, is it?
Which are the offshore locations worldwide with highest benefits?
Is there any upcoming breakthrough in sight? A game changer that will revolutionize the offshore wind industry? Or are there only minor improvements left and a goal to cover more areas with wind farms?
Which components of wind turbine are the hotspot for this device. In other words, improvement in which components are more influential in production, cost reduction and so on.
How easy is it to link the offshore wind farms to the electricity grid? And for this reason, is it reasonable to think about solutions in deep sea (floating Wind turbines) for offshore wind?
Energy storage, power electronics, grid problems
The role of offshore wind energy in the future.
It would be mainly related to real failure and cost data.
What are the environmental impact of installation and operation of wind turbines offshore?

Appendix G : Pre-game and post-game survey responses

A total of 8 participants playtested the prototype. An effort was made to increase this sample size; however, the prototype was ready after many students already left for summer break. The response to the pre- and post-game surveys are presented for offshore wind farm related responses, and then game experience responses.

A word cloud was generated to demonstrate key words that appeared in individual survey responses after playing, that did not appear beforehand. This word cloud is presented in Figure. G-1.

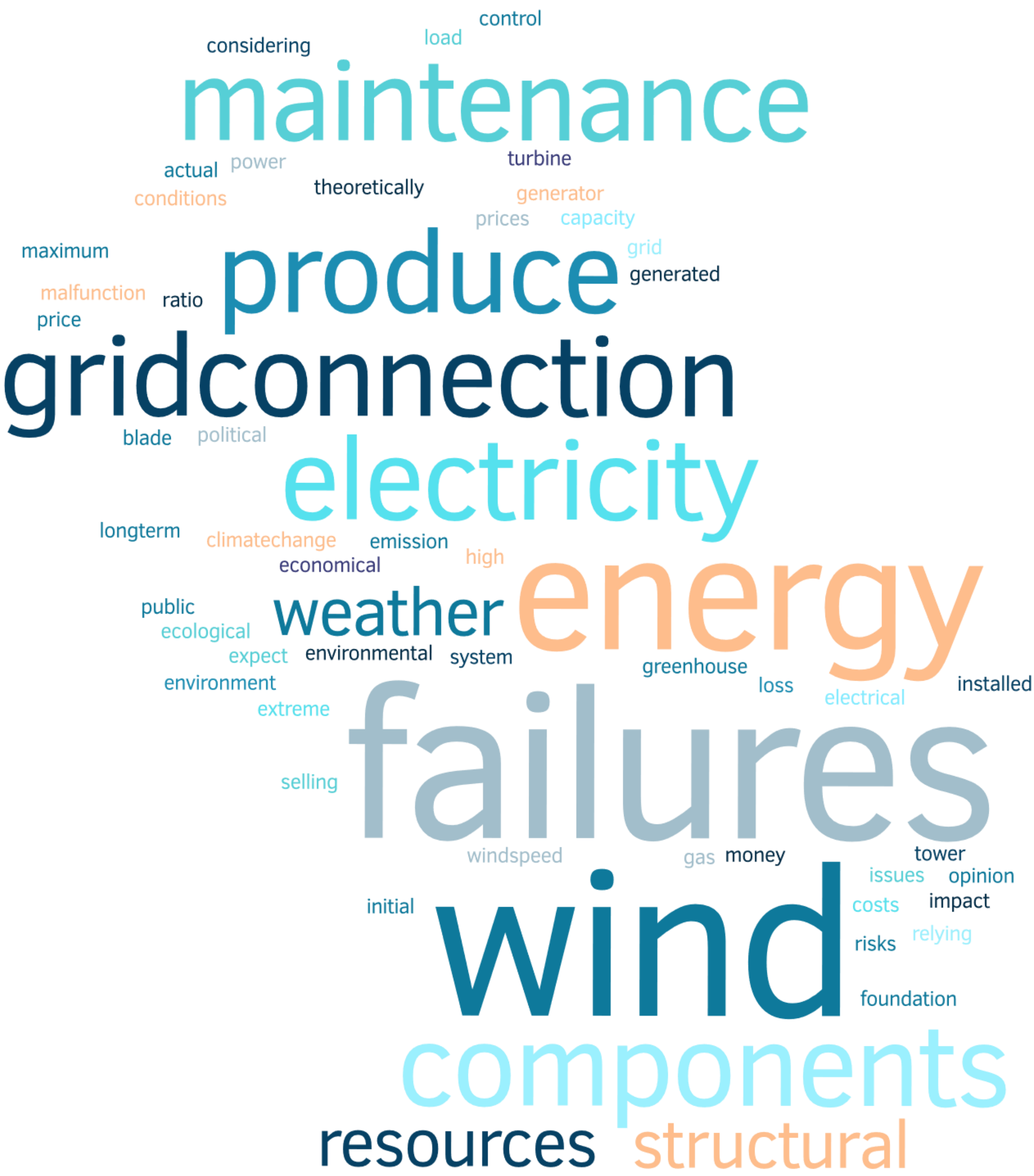


Figure. G-1: Word cloud highlighting new terminology expressed in playtesters' survey answers

Offshore wind farm responses

Participant	Pre-game	Post-game
What is the main purpose of an offshore wind farm?		
Participant 1	To produce renewable energy with an intention of addressing the issue of greenhouse gas emissions from usage of fossil fuel sources	Produce economically viable renewable energy to address global greenhouse gas emission crisis
Participant 2	To make money from selling electricity generated from wind	To make money from selling electricity generated from wind
Participant 3	to produce electrical power	produce electricity and supply that to the grid (households) while simultaneously helping to prevent the global temperature from rising due to the cut in carbon emissions
Participant 4	To generate electricity from wind	Generate carbon-friendly electricity from wind and deliver it to the shore
Participant 5	It is a sustainable way for generating energy	Replacing the nonrenewable sources of energy with renewables
Participant 6	To create electricity offshore using wind energy.	create energy
Participant 7	generate energy from wind	revenue, clean energy
Participant 8	Produce sustainable energy	clean energy, happy stakeholders, environmentally friendly, making jobs
What are four physical components of an offshore wind farm?		
Participant 1	Turbines, generators, transformers and power supply network	Turbines, substructures, scour protection, noise protection and power supply network
Participant 2	Rotor/blades, generator, tower, electrical grid connection	Rotor/blades, generator, tower, electrical grid connection
Participant 3	turbine, cables, substation	turbines, substation, cables, substructure
Participant 4	(global) the area/cell, (individual) foundation/mooring (if floating), tower, turbine	Farm location, foundation type, turbine type, to-shore cables
Participant 5		wind speed, water depth, soil quality, distance to shore
Participant 6	Sub-structure, Super-structure, electricity generator, cables to transport the electricity.	

Participant 7	wind turbines, platform structures, sea defense,	support structure, turbine
Participant 8	Substructure-Foundation-Turbine-blade	substructure, turbine, shaft,
Name three factors that drive the lifetime cost of an offshore wind farm.		
Participant 1	Construction costs, maintenance costs, power prices (selling prices)	Installation investment, operation and maintenance costs and power price
Participant 2	Energy price, maintenance, weather	Energy price, maintenance, weather
Participant 3	wind speed at the location, turbine type, electricity market price	construction cost, maintenance cost, electricity price, lcoe, reliability of structures, slow contractors
Participant 4	Research (tech used and local conditions), initial cost/installation, maintenance	O&M, initial cost, research of area
Participant 5		installation, maintenance, selling price
Participant 6	Construction, Maintenance, Operation	Construction, Maintenance, Operating costs
Participant 7	durability of materials, probability of failure, amount of energy desired	energy
Participant 8	Construction, maintenance, operation	maintenance, substructure and construction
Name three factors that drive the design of an offshore wind farm.		
Participant 1	Wind rosette (depicting annual wind speed and direction stats), location (offshore or onshore) and power demand	Water depth, soil quality, wind speed
Participant 2	Soil conditions, wind resources, grid connection	Soil conditions, wind resources, grid connection
Participant 3	soil conditions, weather conditions, local laws	wind speed, water depth, shipping channels, environmental restrictions, distance from shore, existence of other wind farms/substations (close by)
Participant 4	Depth, soil conditions, distance from shore	Depth, soil,
Participant 5	I guess, they are; wind speed, possible wave impacts on the structure of wind turbines, distance from the farm to city	public concern on using nonrenewable sources, CO2 emission targets, scarcity of resources
Participant 6	The conditions related to the sea (waves), wind and sea bottom	Mean wind speed, water depth, Soil quality
Participant 7	reducing cost, more energy, less noise	

Participant 8	environmental loads, wind capacity of location, and stakeholder needs	depth, environmental loads and distance from the shore
What kind of failures can occur during the lifetime of an offshore wind farm?		
Participant 1	mechanical failures, natural disasters (tornadoes or hurricanes), collapse of supply network	Construction failure, mechanical failures and environmental disasters
Participant 2	Fatigue failure of structural components, extreme load failures of structural components, grid loss, control system malfunction, etc.	Fatigue failure of structural components, extreme load failures of structural components, grid loss, control system malfunction, etc.
Participant 3	fatigue failures (e.g. tower, blades, gearbox), random failures (electrical systems), failures due to human involvement (sabotage, vessel collisions)	gearbox failures, blade failures, construction accidents, scour
Participant 4	fatigue, collision, corrosion, extreme environmental event beyond design guidelines (can be too strong of wind/waves)	gearbox, blade, construction accident, ship collision, generator, converter
Participant 5	I guess, the structural failure in case of storms.	structural failure and turbine failure
Participant 6	Damages due to strong wind, waves or geo-tech related problems	Turbine failures, Structural failures, farm-wide failures
Participant 7	mechanical and electrical failure, structural failure	
Participant 8	turbine failure, environmental impact, structural failure	gear box failure, turbine failure
What is the capacity factor, and why is it an important measure?		
Participant 1	It’s the ratio of annual energy production to the maximum power production capacity of the wind farm. It’s of significance as it demonstrates the actual capacity used in a year as compared with the maximum installed capacity	Ratio of power produced in a year to maximum plant capacity. Depicts the percentage of the potential used
Participant 2	The ratio between how much energy you are actually producing (or how much you expect to be able to produce) and how much you could theoretically produce given the installed capacity.	The ratio between how much energy you are producing (or how much you expect to be able to produce) and how much you could theoretically produce given the installed capacity
Participant 3	the percentage of the installed capacity that is actually being produced	it is the rate of actual power output over the possible power output, shows how productive/reliable the wind farm is

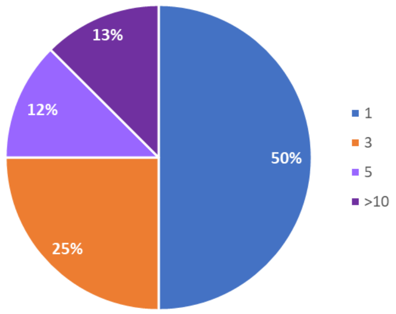
Participant 4	Guess: actual generation / theoretical capacity for an area	actual energy produced / maximum potential energy; indicator of downtime/repair costs
Participant 5		the ratio between the actual energy generation rate to the maximum energy generation rate
Participant 6	Maybe this shows how much is the maximum electricity can be produces.	
Participant 7		actual electricity output to maximum
Participant 8	MW is the rate of energy production and it is a measure of energy production	the ratio of produced to what it should produce
What are risks of investing in offshore wind?		
Participant 1	High power production prices can render the operation economically nonviable, competing with cheap nonrenewable energy entails significant risks, dependent on governmental policy making	Risk of failure, economic viability risks
Participant 2	Changes in energy prices, failure of components leading to high maintenance costs, grid issues of various kinds, relying on weather/the environment to provide the right kind of wind resources (especially long term when considering climate change), public/political opinion, environmental/ecological impact, ...	Changes in energy prices, failures of components leading to high maintenance costs, grid issues of various kinds, relying on weather/the environment to provide the right kind of wind resources (especially long term when considering climate change), public/political opinion, environmental/ecological impact, ...
Participant 3	climate change in laws/subsidies/public opinion, experimental technology, uncertainty in the prediction of electricity prices in the future	uncertainty in the weather, failures of the turbines, high investments, unexpected legal restrictions or public opposition
Participant 4	Changing markets/attitudes/cheaper energy sources making offshore wind too expensive, climate change increasing loads beyond design, climate change altering wind patterns,	None. It's easy to make a profit. (in reality, costs, environment like marine life, maintenance costs, outdated technology, failures)
Participant 5	I think the risk is very low	Maintenance costs, failures, environmental costs, but overall, I think it has low risk if it is well-designed and the location is good
Participant 6	There might not be wind for a given period of time, the electricity cannot be stored, and it is difficult to be	Having investment costs higher than the revenues due to not having done proper research and failures.

	transported. There might not be good markets for it.	
Participant 7		losing money
Participant 8	The costs become more than benefits	environments and
Your opinion on offshore wind energy is:		
Participant 1	It is absolutely necessary to combat climate change	It is absolutely necessary to combat climate change
Participant 2	It is a prevalent field with growing potential	#N/A
Participant 3	It is a prevalent field with growing potential	It is hyped up too much and poses more challenges than opportunities
Participant 4	It is a prevalent field with growing potential	It is a prevalent field with growing potential
Participant 5	It is a prevalent field with growing potential	I do not have an opinion because I don't know enough
Participant 6	I do not have an opinion because I don't know enough	I do not have an opinion because I don't know enough
Participant 7	It is absolutely necessary to combat climate change	It is a prevalent field with growing potential
Participant 8	It is absolutely necessary to combat climate change	It is absolutely necessary to combat climate change
What role do you predict offshore wind energy will play in the world's energy future?		
Participant 1	It will become a major contributor to the energy mix	It will become a major contributor to the energy mix
Participant 2	It will become a major contributor to the energy mix	#N/A
Participant 3	It will become a major contributor to the energy mix	It will contribute to the energy mix, but without much growth from today
Participant 4	It will become a major contributor to the energy mix	It will contribute to the energy mix, but without much growth from today
Participant 5	It will become a major contributor to the energy mix	It will become a major contributor to the energy mix
Participant 6	It will contribute to the energy mix, but without much growth from today	It will become a major contributor to the energy mix
Participant 7	It will become a major contributor to the energy mix	It will become a major contributor to the energy mix
Participant 8	It will become a major contributor to the energy mix	It will contribute to the energy mix, but without much growth from today

Game Experience

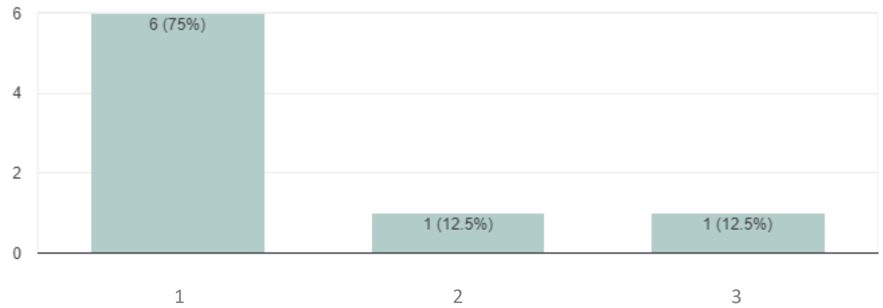
How many games did you play?

8 responses



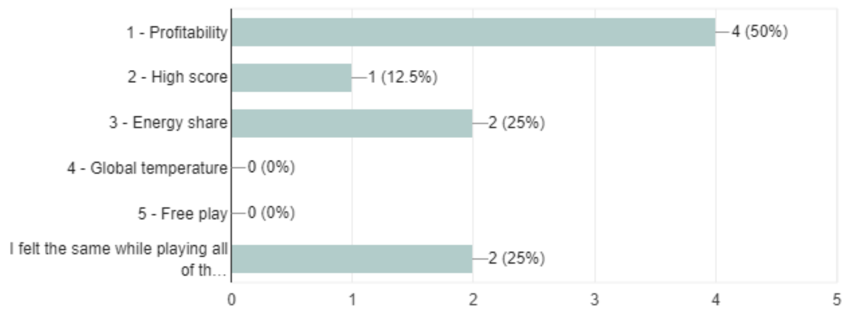
About how many games did it take you to "get into" the flow of the game?

8 responses



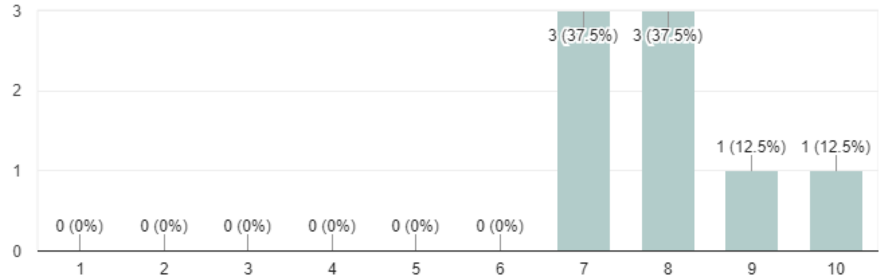
Of the five game goals offered, which did you enjoy the most?

8 responses



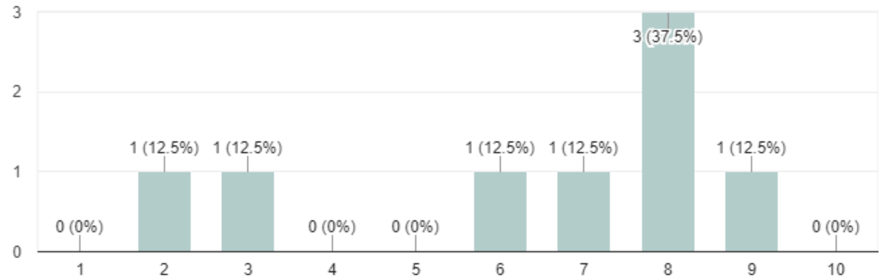
What is fun?

8 responses



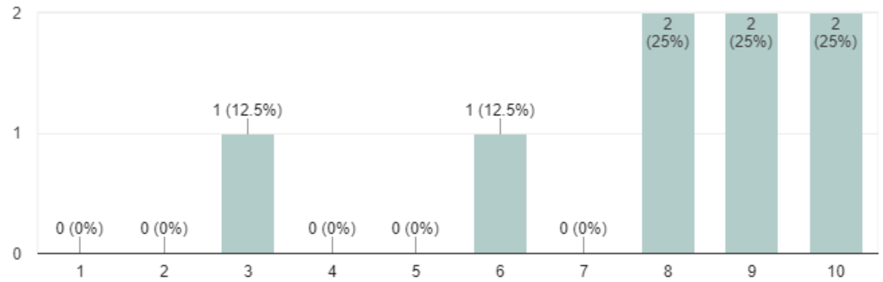
Please rate the clarity of game instructions

8 responses



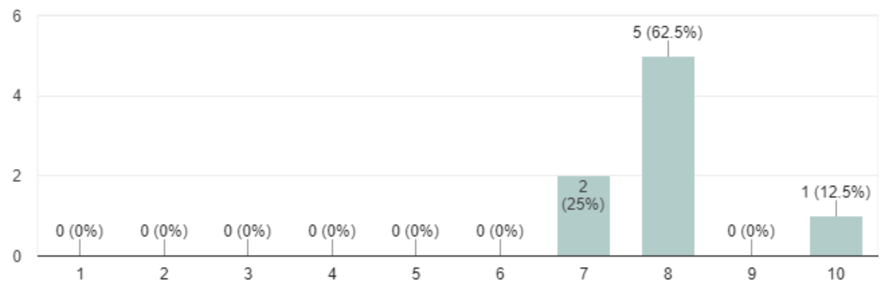
How would you rate the intuitiveness of game controls?

8 responses



How much did you enjoy the game?

8 responses



Core Dynamics: Name an existing game that this reminded you of.

8 responses

Monopoly
Sim City
lego land (i think this is very close to the roller coaster tycoon as well, which is more known), there you also build things and have to watch the money while trying to please the "guests" in your amusement park
Minesweeper
Maybe SimCity
None
none
not a gamer

Game Mechanics: List one to three rules that stood out as good or bad (Examples of game rules are: collect $200 when you pass go (Monopoly,) or the bishop may not jump over other pieces (Chess).

8 responses

I think its easier to just discuss this one
Being able to change the flow of time and pause (good).
you cannot change the number of turbines in a farm or change the cabling after you initially built it - i would have enjoyed to add additional cables later in the game; you can build anywhere - but with consequences - i think this is great, because you can try out unusual things as well; the farms are built faster if you give them a name of a real wind farm - this gives me reason to study the existing wind farms
It's a balance sheet. Cost/MW if you want to turn a profit
Sorry, didn't get the question
Having to take care of the environmental restrictions
you have to mitigate environmental risks, paying fines for vehicle routes

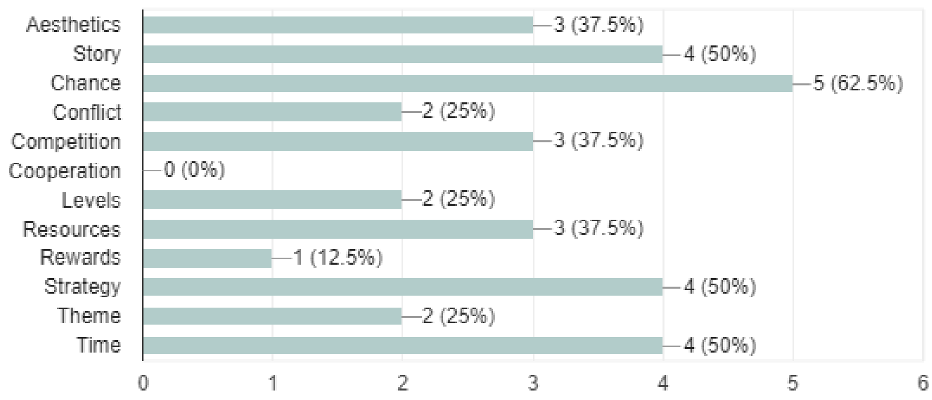
What, if any, game strategies did you use to achieve you goal?

4 responses

Changing the flow of time.
i tried to build as many farms as possible to reach my goal, started with smaller ones and then tried to go bigger and bigger
Cost per MW
Producing more energy and minimizing costs

Game Elements: Check the game elements that stood out to you

8 responses



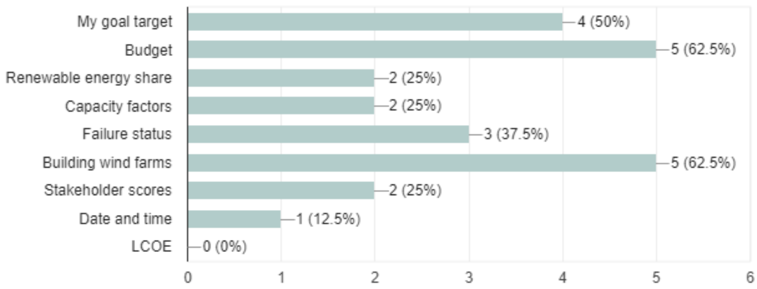
How did you know how well/poorly you were doing in the game? What feedback did you get?

8 responses

Scores (investment, profit etc.) and constant reminders at the bottom of the screen regarding the target to be achieved
The numbers
i didn't finish it, but i got some good and bad feedback on the choices i made
Score at bottom, reports
My knowledge of the field is very limited. I needed more time to understand better the game.
I did terribly as I got to 0.182 % by 2030
score and revenue
Compare myself with someone sitting next to me

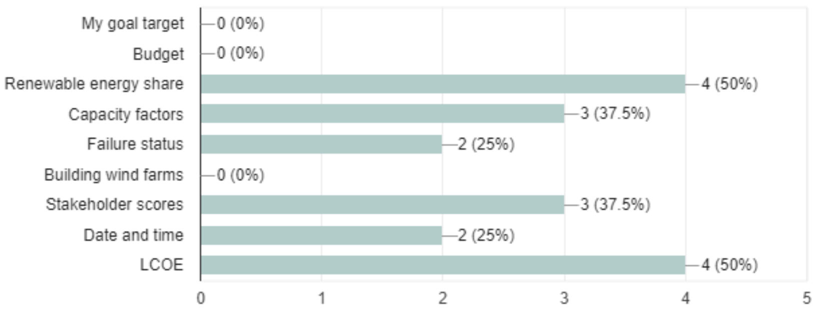
On which parameter(s) did you find yourself focusing more on that the others?

8 responses



On which parameter(s) did you find yourself not focusing on at all?

8 responses



Name the most significant thing you learned during the game that you didn't know before.

6 responses

That offshore wind development can be discombobulating

that tripods are very reliable options and that tension leg platform substructures are actually quite a good option in some cases

It's easy to turn a profit.

It takes only 9 days from design to production of the wind turbine

I didn't have much knowledge from before, so most of it was new to me.

Capacity factor

Name other things you learned during the game that you didn't know before, if any.

6 responses

Regarding substructures
that you consider substructures in addition to the turbines
15MW turbines are a ripoff
was very interesting the decision making process based and how complex that could be.
cost ranges
failure types, capability of using other farms capacity due to reduction in cable cost

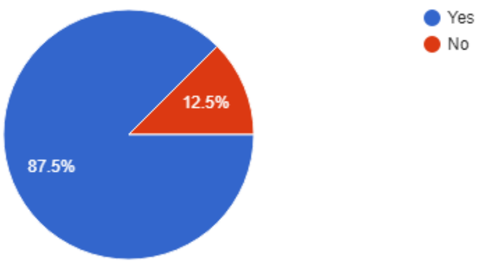
Which element(s) in the game would you have liked to explore more (detail or in general)?

8 responses

Regarding noise management and power supply network interconnection
Failure rates
i am still not quite sure how the condition monitoring maintenance is better
How to know what foundation type is the most reliable
I was very interested in the financial aspects
The maintenance strategies
researching wind farms
maintance strategies and failures

Given the chance, would you play this game again in your free time? (given updates/improvements)

8 responses



Please describe any suggestions for improvements you would like to see for futher development. This may be features related to the game function (rules or rewards) or to game design (aesthetics or feedback)

5 responses

A lot of issues with the interface

the ledger is a bit overwhelming

Mostly UI related. Especially after you have many farms, you have constant messages for conditions based O&M, it's hard to navigate all the messages when trying to fix a farm failure, things like that.

I think I needed more explanations on the different choices I had to make.

I will learn from this game epecially if I am looking for entering industry in this field. But there are some concepts that I need more especially in maintanace and failure possibilities. It worth play game and do research. Maybe you can add some documents as an appendix for anyone who wants to read something like MATLAB's F1