exergyX: A Game on Management of Energy Systems

André Fidalgo Pinto Veloso da Silva
Instituto Superior Técnico
andre.da.silva@tecnico.ulisboa.pt

ABSTRACT

The reduction of carbon dioxide emissions is a trending topic worldwide, as the world struggles to balance sustainable development with clean energy production. The education of students regarding these subjects is, therefore, of the utmost importance. In this respect, we looked into developing a game to improve the teaching of energy-based courses. Games are typically associated with fun and engagement, and can also be a powerful tool for teaching. The result of this project is exergyX, a learning game that has the potential to become a classroom aid for students, helping them assimilate the subjects taught in energy-related courses.

KEYWORDS

Educational Games, Carbon Dioxide Emissions, Energy Efficiency, Macroeconomics

1 INTRODUCTION

Games and Education

As far as entertainment products are concerned, games have recently benefited from a growing relevance in today's world. Their virtual subset, video games (also commonly referred to as "computer games") have enjoyed a steady growth in usage, as well as industry and cultural prominence [8].

Games are typically associated with fun and engagement. Therefore, it is natural for games to be taken into consideration as a means of nurturing the interest of people of various backgrounds. Even in non-game contexts, a principle called gamification — the application of elements commonly found in games to other contexts — is occasionally used in order to increase user engagement and motivation [7].

Based on this knowledge, games developed with the purpose of increasing the engagement of students have been introduced in various classes throughout the world, as an attempt to boost the learning process of students [11].

A Game on Management of Energy Systems

As part of this dissertation, we developed a video game for computers[1] that serves as a learning tool for students taking courses related to energy management. The game is presented as an opportunity of further improving or complementing the current state of teaching energy-based courses at the University level. It was named "exergyX", sharing the name with a Massive Open Online Course (MOOC) created in 2020[2]. While the game developed for this dissertation was initially designed to be used in classrooms, it is expected to become a part of future iterations of the MOOC, as well.

The idea for the game emerged as Portugal and other countries take measures to ensure they accomplish their environmental goals set in the Paris Agreement [14], while at the same time ensuring the good health of their economical growth, allowing for sustainable development.

In the game, players have to manage both the macroeconomic and energy productivity aspects of Portugal. They are given the role of an advisor to the country's government, and are asked to make decisions in order to lower the emission of carbon dioxide (CO2) to the atmosphere, while keeping the citizens happy.

exergyX is a simulation game that takes place over various years until the year of 2050, at which point the players' results are assessed. It requires input from the players every year. This input affects the qualitative and quantitative measures of the game, and has a direct impact on the results of the simulation. This impact has an immediate (albeit small) effect on the results for the following year, and a more pronounced effect on the preview of the results for the final year provided to the players. This allows players to make adjustments to their strategy as they play and know how their strategy impacted the results.

The game started development as part of a project called "Massive Open Online Tool for the design of consistent scenarios for energy consumption and CO2 emissions for 2050". A simplified model based on simulations developed with a methodology introduced at the MEET2030 project [2] served as the basis for the scientific data presented in the game.

The goal of this dissertation is to verify that experts of energy-related subjects (*e.g.*, teachers) recognize that exergyX has the potential to be used as a tool for teaching. We also assess if exergyX provides players with a satisfying game experience, if players use practical experimentation in order to learn the model of the game, and if students wish to have exergyX be used in their classes.

2 STATE OF THE ART

We performed an analysis of studies where games were developed as a tool for learning or as a means to increase

[1] https://exergyx.tecnico.ulisboa.pt, accessed 10th September 2020

[2] https://courses.mooc.tecnico.ulisboa.pt/courses/course-v1:IST+exergyX+2019/about, accessed 11th September 2020

awareness on management of energy, as well as some other relevant projects. The critical approach taken while performing this analysis provided information that we used in order to improve the development of exergyX.

Some of the projects we saw were the DimensionM games [9], which are multi-genre games for the teaching of mathematics; an energy conservation game by the authors in [4], that uses real-life metaphors to facilitate learning; EnerCities, a simulation game about the importance of energy in societies; Power Grid, a board game with a heavy economical component; and the Beer Game, a game about the importance of communication and understanding how a system works.

Looking at the games used in [9] and the results achieved, we obtained valuable data that was later used while developing exergyX.

For example, we identified that a game that includes a story that eases players into the game is more appealing. It also helps players disassociate the "learning" part of the game from school work. A strong context for the game is therefore a plus. Also, it is easier to deduce a relationship between the subject matter and real life when presented via a well-contextualized game.

In addition, a mission or objective-based approach may help students focus and feel a sense of accomplishment when they are successful. Since students who played the games outside of the classroom reported no increase to their levels of motivation, it was important to think about where exergyX would be played while developing it.

Students in [4] appeared to have no problem interacting with the games. The user interfaces were easy to understand. This allowed for a low barrier of entry and demonstrates the importance of following rigorous game usability methodologies. We concluded that the way users interact with our game should, therefore, be simple and use protocols that are familiar to the players.

It should be noted, however, that the games developed for this study are quite simple, have very little gameplay elements, and are almost completely devoid of any challenge. Challenge begets critical thinking, which stimulates learning [3].

Players of EnerCities liked its strategic component. This highlights that strategy and challenge is important in a simulation game. Players like to feel like they are effectively planning something with meaning, something that makes them feel challenged.

On the other hand, some players felt lost while playing the game. This highlights the need to have well-defined objectives in the game. Players should know exactly what they are working towards. Providing clues as well as feedback on the effects of the players' actions on the scenarios is very important.

Power Grid places a lot of emphasis on the production of power through renewable means, as well as the management of resources. It displays a link between energy and the economy. For exergyX, it was important to state the importance of investing in renewable power while keeping the distribution of resources under control.

The bullwhip effect that the Beer Game generates showed us the importance of properly communicating how to use systems and other information. In our opinion, players of exergyX should feel that all relevant information for playing the game is communicated clearly to them.

3 ARCHITECTURE

Theoretical Background

Before introducing the architecture of the model that serves as the back end for exergyX (in Section 3), it is necessary to provide an overlook of the concepts behind it, in order to provide context.

For the purposes of explaining the theoretical domain of the game, there are two key concepts that need to be introduced: **Energy** and **Exergy**.

Energy is, in physics, a quantitative property that represents the capacity for doing work. The survival and growth of all human and animal life, as well as the development of society, is dependent on the consumption of energy [5].

Exergy is a measure of the quality of energy in a system. It is the maximum amount of work obtainable from the system as it comes into equilibrium with the environment. For example, in an environment at 25°C, the exergy of 105 MJ of steam at 160°C and 3 bar is 22 MJ while the exergy of 105 MJ of water at 50°C is 2 MJ. As such, in a system that has reached thermodynamic equilibrium, the available exergy is zero. Unlike energy, exergy can be irreversibly destroyed as a consequence of the Second Law of thermodynamics [12].

In addition, there is a close link between Energy and Economy. An economy's growth appears to be strongly related with energy [6]. Specifically, with the amount of useful exergy that is used by the economy (since this is the energy that is effectively used to produce economic value), and with the overall efficiency in converting final exergy to useful exergy (because this affects the cost of useful exergy).

exergyX uses the scenarios for Portugal developed in the MEET2030 project [2] as the basis for its scientific model. These scenarios follow the rules demonstrated in the conceptual map in Fig. 1.

Following the map, we see that Energy and Exergy are key components of the different **stages of energy flow**.

The first stage of energy, primary energy, is the kind of energy that has not undergone any sort of transformation (*e.g.*, coal). This energy may be stored in either renewable or

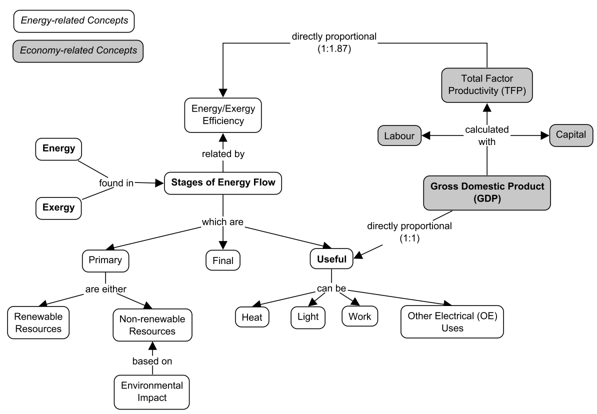

Figure 1: A conceptual map demonstrating the relationship between energy- and economy-based concepts

non-renewable resources, with the use of the latter having an impact on the environment.

Final energy is the energy after it has been converted and delivered to consumers, ready to be used.

The final stage, **useful energy**, is energy as it is used by consumers. It can have various uses, such as heat, light, and work. Uses that don't fall into any of these groups are classified as Other Electrical Uses.

All of the three stages also apply for the flow of exergy [5].

It was found in [12] that useful exergy has a proportional relation to Portugal's **Gross Domestic Product (GDP)** (1 megajoule per euro of GDP), facilitating the creation of simulations and further validating the link between energy consumption and economic growth.

Affecting the calculation of the GDP are the following measures: Labour, which is a measure of hours worked [13, p. 468]; Capital, which is the sum of the values of all fixed assets still in use [13, p. 456]; and the Total Factor Productivity (TFP) (also known as Multi-factor Productivity), which is a measure that takes account of the productivity that cannot be explained by labour or capital [13, p. 470]. GDP can be calculated with Equation 1.

$$GDP = TFP \times K^{\alpha} \times L^{\beta} \tag{1}$$

In Equation 1, α and β represent, respectively, the share of payments (in total income) for capital (K) and labour (L) [5].

An empirical relationship explained in [2] demonstrates a proportionality between final-to-useful exergy efficiency and the TFP, one that indicates that if that efficiency experiences a 1% annual growth rate (for example), then the TFP will grow up by approximately 1.87% in that same period.

Model for the Game

exergyX relies on a scientific model in order to process all the calculations the game performs. This allows the game to provide results that are consistent with the subjects taught in energy-based courses. This model was developed in conjunction with Professor Tânia Sousa, and PhD students Laura Felício and João Santos, from Instituto Superior Técnico (IST). It is an adapted version of the model developed for the MEET2030 project [2].

In exergyX, there are two goals that players must meet in order to win the game. They must:

- Lower Portugal's CO2 emissions below a certain threshold (in the current version this threshold is set at 14 Mt CO2).
- Maintain or improve the happiness levels of the average citizen of the country.

The aforementioned "happiness levels" shall henceforth be referred to as "utility". Utility is a measure of happiness and general well-being used by economists.

Since the model was developed for the game, the end result of its application will be an annual value of emissions and utility. The model was designed to be iterative, with a number of equations using values from the previous year. This also means that a number of starting values ("year zero values") need to be fed to the model in order for it to work.

What follows is the detailed description of the model, from start to finish, broken down in subsections. In every equation, y refers to the current year in the model.

Power per Source. Every year, the player chooses how much power (in gigawatts) to add to the existing annual production. The chosen power is then shared between infrastructures using one of three different renewable sources: solar, wind, and biomass.

The power to be installed is usually divided by 3, in order to be fairly distributed for each source. However, there is a maximum amount of power that can be produced per source. The algorithm in Listing 1 indicates how distribution is managed in all cases.

A check is then performed to see if any source will exceed maximum power production after the new power is added. If so, the power to be added is adjusted so that the total stays at maximum.

Finally, each source's power for the year is calculated following Equation 2, with P_{so} being the installed power per source and NP_{so} being the new power to install per source.

$$P_{so}(y) = P_{so}(y-1) + NP_{so}(y) \tag{2}$$

Cost of Power. Each renewable source has an independent cost for power production (in euros). This cost C_so is calculated using the installed power obtained in Equation 2 and

```
if(!max_reached_solar && !
   max_reached_wind && !
   max_reached_biomass):
      new_solar_power = new_power / 3
      new_wind_power = new_power / 3
      new_biomass_power = new_power /
         3
elif(!max_reached_solar && !
   max_reached_wind &&
   max_reached_biomass):
      new_solar_power = new_power / 2
      new_wind_power = new_power / 2
elif(!max_reached_solar &&
   max_reached_wind &&
   max_reached_biomass):
      new_solar_power = new_power
elif(max_reached_solar && !
   max_reached_wind && !
   max_reached_biomass):
      new_wind_power = new_power / 2
      new_biomass_power = new_power /
         2
elif(max_reached_solar && !
   max_reached_wind &&
   max_reached_biomass):
      new_wind_power = new_power
elif(!max_reached_solar &&
   max_reached_wind && !
   max_reached_biomass):
      new_solar_power = new_power / 2
      new_biomass_power = new_power /
         2
elif(max_reached_solar &&
   max_reached_wind && !
   max_reached_biomass):
      new_biomass_power = new_power
```

Listing 1: Algorithm for the distribution of power to be installed

$G_s o$, which represents the costs per gigawatt for each source, which are constant.

$$C_{so}(y) = P_{so}(y) + G_{so} \tag{3}$$

The cost of each source is then combined to obtain the total cost of renewable power generation for the year.

$$C(y) = \sum^{s} C_{so}(y) \tag{4}$$

Capital Investment. Capital investment (I) refers to a percentage of the country's GDP to be used for capital that year. This percentage is represented by constant P. The total cost of renewable power generation is taken from this value. Since capital investment is presented in billions (10^9) of euros, the cost of power needs to be converted into the same unit for the purpose of our calculations.

$$I(y) = P \times GDP(y-1) - C(y) \times 10^{-9} \tag{5}$$

Total Capital. The total capital (K), introduced in Section 3, is obtained by adding capital investment to the previous capital of the country. Capital, Labour, and the TFP

$$K(y) = K(y-1) + I(y) \tag{6}$$

Labor. Labor (L), introduced in Section 3, is the number of hours worked by all of the economy's working individuals. While usually the equation for labor is obtained by using data such as work rate, unemployment rate, and others, in order to simplify the game we use Equation 7 instead.

$$L(y) = \alpha \times Pop \tag{7}$$

In this equation, α is a constant that represents the substituted data with an approximation of the usual results. Pop represents the country's population of working age. For the purposes of this model, Pop is a constant as well.

Total Factor Productivity. The TFP, introduced in Section 3, is calculated in this model as a function of aggregate efficiency EFF (seen in Section 3). It uses the value of the aggregate efficiency in 1960 as a reference.

$$TFP(y) = \left(\frac{EFF(y-1)}{EFF(1960)}\right)^{1.93} \times 0.00000102 + 0.00000039 \tag{8}$$

Gross Domestic Product. The GDP uses, as previously stated, Equation 1. α and β are given a distribution of 0.3 and 0.7, respectively.

$$GDP(y) = TFP(y) \times K(y)^{0.3} \times L(y)^{0.7} \tag{9}$$

The GDP obtained comes in billions of euros.

Useful Exergy. The amount of useful exergy of the year $UEx(y)$ comes from the GDP, using the relation from [12].

$$UEx(y) = GDP(y) \times 10^3 \tag{10}$$

The megajoule value from the relation is converted to terajoules (multiplied by 10^3) in order to facilitate future calculations.

Final Exergy. We go backwards in the stages of exergy flow in order to find the final exergy value ($FEx(y)$) in terajoules, which is obtained by applying the previous year's aggregate efficiency to the useful exergy found before.

$$FEx(y) = \frac{UEx(y)}{EFF(y-1)} \tag{11}$$

Final Exergy Shares per Sector. The user decides on the distribution of final exergy per each sector on the game ($DEx_s(y)$). By applying this distribution to the previous year's shares, we get the current year's final exergy shares per sector ($SFEx_s(y)$), as a percentage. If the distribution does not equal 100%, a correction is applied.

$$SFEx_s(y) = \frac{SFEx_s(y-1) + DEx_s(y)}{\sum^s (SFEx_s(y-1) + DEx_s(y))} \tag{12}$$

Final Exergy per Sector. A simple multiplication of the final exergy shares per sector by the total amount of final exergy finds us the amount of final exergy per sector ($FEx_s(y)$) in terajoules.

$$FEx_s(y) = FEx(y) \times SFEx_s(y) \tag{13}$$

Sector Electrification. The users can decide ($DEl_s(y)$) to increase the amount of power that each sector gets from electricity ($El_s(y)$).

$$El_s(y) = El_s(y-1) + DEl_s(y) \tag{14}$$

Final Exergy Shares per Sector per Carrier. There are six energy carriers that are part of this model: coal, petroleum, natural gas, renewable fuels, and heat. By applying Equation 15 to every permutation of carrier and sector, we can find out the individual shares of final exergy ($SFEx_{s_c}(y)$), which are percentages.

$$SFEx_{s_c}(y) = SFEx_{s_c}(y-1) \times \frac{1 - El_s(y)}{1 - El_s(y-1)} \tag{15}$$

Final Exergy per Sector per Carrier. We use the same logic here as in Section 3.

$$FEx_{s_c}(y) = FEx_s(y) \times SFEx_{s_c}(y) \tag{16}$$

Efficiency per Sector. By calculating each sector's useful exergy through the efficiency of every carrier per sector, we obtain the total percentage of each sector's efficiency ($EFF_s(y)$).

$$UEx_s(y) = \sum^c (FEx_{s_c}(y) \times EFF_{s_c}) \tag{17}$$

$$EFF_s(y) = \frac{UEx_s(y)}{FEx_s(y)} \tag{18}$$

Aggregate Efficiency. The country's aggregate efficiency ($EFF(y)$), obtained from all sectors. We also use this step to update the values of useful and final exergy with more accurate values.

$$UEx(y) = \sum^s UEx_s(y) \tag{19}$$

$$FEx(y) = \sum^s FEx_s(y) \tag{20}$$

$$EFF(y) = \frac{UEx(y)}{FEx(y)} \tag{21}$$

Final Exergy per Carrier. We check every sector in order to obtain the total final exergy per carrier ($FEx_c(y)$).

$$FEx_c(y) = \sum^s FEx_{s_c}(y) \tag{22}$$

CO2 Emissions (Except Electricity). In this step we find the CO2 emitted (in kg CO2) through all means except the production of electricity ($CO2_{ne}(y)$).

$$CO2_{ne}(y) = \sum^c Fex_c(y) * EmF_c \tag{23}$$

Electricity from Renewable Sources. In this equation, PrF_{so} refers to a source's factor of production, while H is the number of hours in a year. The electricity calculated here ($Elec(y)$) is measured in GWh (gigawatts hour).

$$Elec(y) = \sum^{so} P_{so}(y) * PrF_{so} * H \tag{24}$$

Non-renewable Electricity. We convert final exergy from electricity ($FEx_{Elec}(y)$) from terajoules to gigawatts hour (1 GWh = 3.6 TJ), and we apply a factor of inefficiency in the transition from primary to final exergy ($INEFF$). From the obtained value we subtract $Elec(y)$ in order to obtain the non-renewable electricity of the year in GWh.

$$NElec(y) = \frac{FEx_{Elec}(y)}{3.6} \times INEFF - Elec(y) \tag{25}$$

Non-renewable CO2 Emissions. In this equation, $EFF_{Elec_{NG}}$ refers to the efficiency of electricity production by using natural gas. EmF_{NG} is the factor of emission of natural gas. EmF_C is the factor of emission of coal. $EFF_{Elec_{NG}}$ and EFF_{Elec_C} are the efficiencies of electricity production with natural gas and coal, respectively. MAX_{NG} is the maximum electricity produceable via the use of natural gas.

$$NCO2(y) = \begin{cases} 0, & \text{if } NElec(y) \leq 0 \\ \dfrac{NElec(y) \times 3.6}{EFF_{Elec_{NG}}} \times EmF_{NG}, & \text{if } NElec(y) \leq MAX_{NG} \\ \Big(\dfrac{MAX_{NG} \times 3.6}{EFF_{Elec_{NG}}} \times EmF_{NG} \\ + \dfrac{NElec(y) - MAX_{NG}}{EFF_{Elec_C}} \\ \times EmF_C\Big), & \text{otherwise} \end{cases} \quad (26)$$

Total CO2 Emissions. **One of the goals of the game.** Obtained by the sum of all emissions, in kg CO2.

$$CO2(y) = CO2_{ne}(y) + NCO2(y) \quad (27)$$

Expenditure. Money spent (in billions of euros) by the economy.

$$E(y) = GDP(y) - I(y) \quad (28)$$

Utility. **The other goal of the game.** A measure of happiness.

$$U(y) = (E(y) \times 10^9)^2 \times \frac{e^{\frac{-1 \times CO2(y)}{10000000000}}}{Pop} \quad (29)$$

4 IMPLEMENTATION

Game Overview

When starting exergyX, players are introduced to their role in the game, where they are assigned the title of advisor to the Portuguese government. They are given two well-defined objectives (reduction of CO2 emissions and management of utility) and work toward them during the full extent of their play time.

exergyX was implemented with an interface that is simple to use and understand. The main screen of the game contains three panels that include, respectively, the previsions and the utility and emissions goals for the final year of the game (the expected results of the game), the data for the current year in the game, and the decisions to be made for the next year. These decisions are the new renewable power to be installed (*new_power* in Listing 1), the distribution of final exergy per each sector ($DEx_s(y)$ in Equation 12), and the electrification of each sector ($DEl_s(y)$ in Equation 14).

Players who prefer a more visual representation of data have the option to access a sub-screen with graphs showing their past data and forecasts. It is also possible to check the results of previous decisions, allowing a player to plan ahead effectively depending on their results. This sub-screen displays more data than that which is available in the main screen for players who wish to understand even further how their actions influence the country.

Chosen Technology

exergyX was developed using the free, open-source game engine Godot[3]. It was chosen for this project due to its ability to export HTML5 games, which are playable on any modern web browser. This increases the accessibility of the game, as students are able to play the game using their existing devices. In addition, the logic for the game, as well as the model, were implemented using the complementary GDScript programming language.

Programming

There are two crucial parts to the game: the front end (the game interface and its logic), and the back end (the game model). They have been implemented independently and (excluding deliberate points of access) they can also operate independently of each other. When a player makes a set of yearly decisions, the game communicates these decisions to the model. The model then performs all of its calculations, and stores a copy of the results in variables that are accessible by the game. The game then updates its interface with the new data.

The front end was developed using a combination of the Godot visual editor and code. The visual editor allowed us to place elements such as buttons and text on the screen at will, with the behavior and theming of the elements being delegated to GDScript code.

The back end can run without the need for the game's interface, as long as its calculations are performed in the order described in Section 3. Due to this versatility, we considered that some experts might be interested in accessing all the data the model provides without having to play the game, in order to more efficiently harness its usefulness. As a result, we have also developed a version of the game that includes a simulator that exclusively uses the model[4]. This version was also used to debug the model during its implementation.

Iterative Design

exergyX was developed using iterative design, with the project being regularly tweaked and improved based on feedback and testing. There were some end goals that guided the development process. We knew that exergyX would have a short play time in order to more easily be introduced in the final minutes of a class. We also knew that the goals the players must obtain would be quite ambitious, with the adjustment of strategies mid-game being necessary in most cases. We also wanted all information to be communicated clearly to the players.

In the beginning of the process, we created paper prototypes that depicted the game's interface and the data that

[3]https://godotengine.org, accessed 13th September 2020

[4]https://exergyx.tecnico.ulisboa.pt/model, accessed 15th September 2020

would be displayed. This prototype was later turned into the first version of the game, using mock data (see Figure 2).

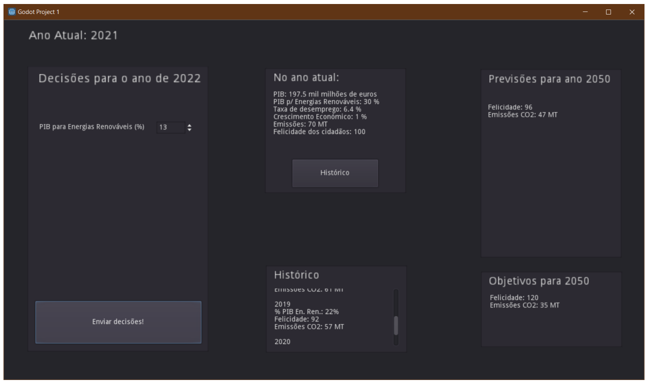

Figure 2: The first version of exergyX

This interface underwent internal testing, and it was decided that the elements of the game should be easier to read, with larger text and better spacing. We revamped the look of the interface (while maintaining the data that was displayed), and obtained the look that can be seen in Figure 3.

Figure 3: The second version of exergyX, with an improved look

We considered that this look was an acceptable starting point to develop the rest of the game, and development focus shifted towards functionality, with the implementation of the player decisions and generation of data. The aspect of the game at the end of this step can be seen in Figure 4. The "History and Predictions" button was non-functional at this time.

The next version was the biggest breakthrough of the project, as this was the first version to communicate with the game model. This meant that the game could now stop using mock data (see Figure 5). Using data from the model revealed a few bugs with its implementation, so we took this opportunity to fix the model as well.

Figure 4: The third version of exergyX, already including most of the main screen data

Figure 5: The fourth version of exergyX. Some bugs with the data from the model can be seen. After fixing the model, we used this version for user testing

At this point, we implemented the "History and Predictions" button, which includes a graph (see Figure 6). After a few final tweaks, the game was ready for user testing.

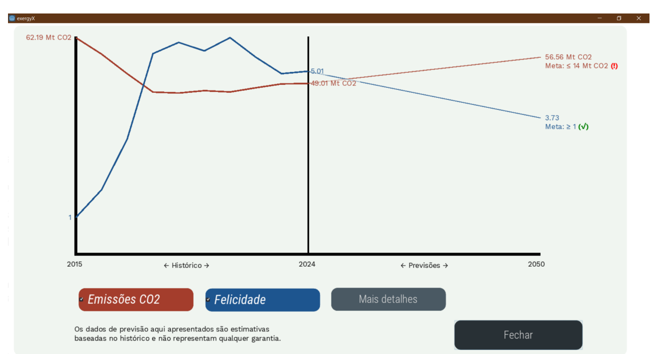

Figure 6: The "History and Predictions" area of the game

Three students participated in user testing. The tests were performed via online video call with screen sharing. The users were asked to play the game from start to finish and to make any comments they wished, while we took notes.

Using the feedback from this test we built the final version of exergyX (see Figure 7). One of the users had trouble identifying which elements of the Decisions panel were clickable, so we added a round button background to them to make them more obvious. We also noticed some confusion in identifying the goals of the game, so we gave them their own section. We also made it so that the player can hover their mouse cursor over any element of the game in order to obtain help, in an effort to prevent any confusion. We also expanded on the initial screen of the game (where the players are given the role of advisor) in order to further explain how the game works and what the player can do.

Figure 7: The final version of exergyX, implemented after user testing

5 EVALUATION

The implementation of the model in Section 3 was reviewed by Laura Felício and João Santos, co-authors of the original model in [2], who confirmed its correctness.

Two groups of users tested the game. One group was composed of experts in teaching energy-based courses, while the other was composed of students of Management of Energy Systems (MoES), a course taught in IST. Each of the groups received a different questionnaire with its own set of questions.

Experts

A questionnaire was sent to experts in the field with 4 questions about the game's potential as a teaching tool. Of these, 1 was a yes or no question and the remaining 3 were open-ended questions.

All experts recognized potential in using exergyX as a teaching aid (Figure 8), mentioning as contributing factors how the game exposes the connection between CO2 emissions, the GDP, and utility, as well as how energy consumption impacts on economic growth.

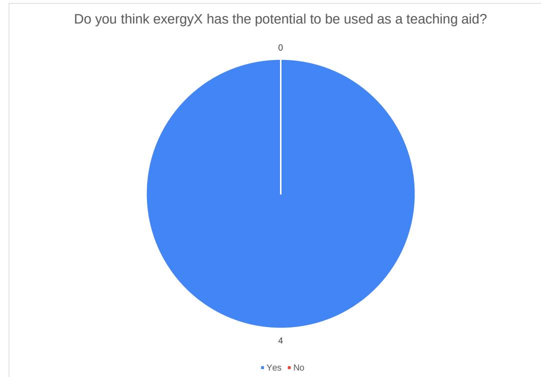

Figure 8: Answer to the question 'Do you think exergyX has the potential to be used as a teaching aid?"

Students

A questionnaire was sent to the students of MoES with 22 questions about their game experience — based on the questions in [1] — and the game's ability to reinforce the subjects taught in the course. The questionnaire was composed of yes or no questions, questions using a Likert scale from 1 to 5 [10], and open-ended questions. A total of 6 students replied to the questionnaire.

The students reported satisfaction with the overall game experience. The game had an average curiosity score of 4.17 out of 5 (σ: 0.75), average ease of control of 4.17 out of 5 (σ: 0.75), average challenge score of 3.83 out of 5 (σ: 0.75), and average clarity of goals and rules of 4.83 out of 5 (σ: 0.41) (Figure 9).

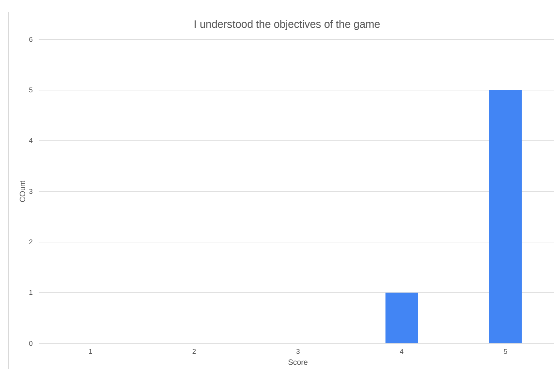

Figure 9: Answer to the question "I understood the objectives of the game"

The game was also able to reinforce the subjects taught in the class with all the students reporting that they were able to identify in the game the subjects reported in the course and that the game portrayed the subjects properly (Figure 10).

Two of the students who answered the questionnaire added in the open-ended questions that they were able to recall parts of the subjects from the course through playing the game.

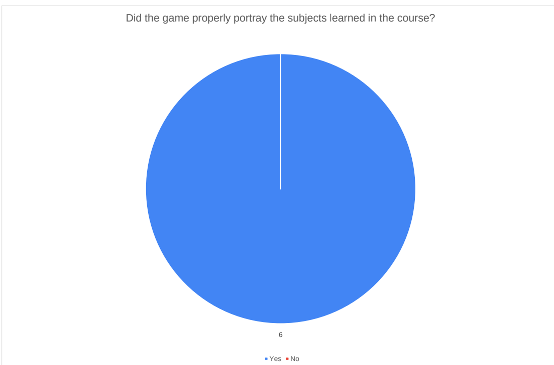

Figure 10: Answer to the question "Did the game properly portray the subjects learned in the course?"

All students showed interest in playing the game as part of their class — with an average score of 4.5 out of 5 (σ: 0.84) (Figure 11). The students showed less interest in playing the game in their homes as an out-of-class exercise — average: 2.67 out of 5, σ: 1.21.

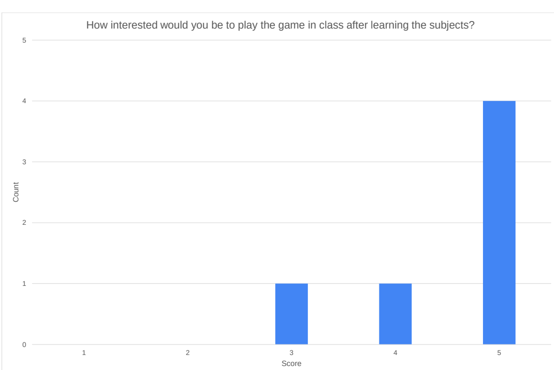

Figure 11: Answer to the question "How interested would you be to play the game in class after learning the subjects?"

6 CONCLUSIONS AND FUTURE WORK

Following the evaluation of the game, we can see that exergyX has the potential to become a classroom aid for students to play with and assimilate the subjects in energy-related courses. Students appear to have enjoyed experimenting and seeing how their actions would affect the results. We can also assess that students felt engaged and were able to reinforce their memory of the subjects taught in their course. There appears to be a particular interest in playing the game as part of a class, as well.

Something that can be done to further improve engagement scores is the addition of more challenges. For example, adding events to the game such as natural disasters could add an interesting twist to the game and make players adapt their strategies. Another suggestion is adding a scoreboard to the game, allowing players to try and beat their highest score.

There are also some improvements that can be done in order to improve the game experience, such as increasing the pace of the game and being more explicit as to the effect of the distribution arrows in the Decisions panel.

We consider that exergyX can also be used as a basis for the creation of learning games for other areas. Since the model is mostly separated from the game, a tweak of the interface with a new model would be a good starting point for a new game.

REFERENCES

[1] Vero Vanden Abeele, Katta Spiel, Lennart Nacke, Daniel Johnson, and Kathrin Gerling. 2020. Development and validation of the player experience inventory: A scale to measure player experiences at the level of functional and psychosocial consequences. *International Journal of Human-Computer Studies* 135 (2020), 102370.

[2] António et al. Alvarenga. 2017. Towards a carbon neutral economy how is Portugal going to create employment and grow? – Technical Report. *MEET2030* (2017).

[3] Elizabeth Boyle, Thomas Connolly, and Thomas Hainey. 2011. The role of psychology in understanding the impact of computer games. *Entertainment Computing* 2 (12 2011), 69–74. https://doi.org/10.1016/j.entcom.2010.12.002

[4] Ugyen Dorji, Patcharin Panjaburee, and Niwat Srisawasdi. 2015. A Learning Cycle Approach to Developing Educational Computer Game for Improving Students' Learning and Awareness in Electric Energy Consumption and Conservation. *Educational Technology & Society* 18 (01 2015), 91–105.

[5] Laura Felício. 2017. *Portugal societal exergy accounting - Past and Future.* Master's thesis. Instituto Superior Técnico, Universidade Técnica de Lisboa.

[6] Roger Fouquet. 2009. A brief history of energy. *International Handbook on the Economics of Energy* (01 2009), 1–19.

[7] Juho Hamari, Jonna Koivisto, and Harri Sarsa. 2014. Does Gamification Work? — A Literature Review of Empirical Studies on Gamification. *Proceedings of the Annual Hawaii International Conference on System Sciences.* https://doi.org/10.1109/HICSS.2014.377

[8] Tim Harford. 2017. The surprising ways video games have shaped the economy. https://www.bbc.com/news/business-40028628. Accessed

12th September 2020

[9] Mansureh Kebritchi, Atsusi Hirumi, and Haiyan Bai. 2010. The effects of modern mathematics computer games on mathematics achievement and class motivation. *Computers & Education* 55, 2 (2010), 427 – 443. https://doi.org/10.1016/j.compedu.2010.02.007

[10] Rensis Likert. 1932. A technique for the measurement of attitudes. *Archives of psychology* (1932).

[11] Angela McFarlane, Anne Sparrowhawk, Ysanne Heald, et al. 2002. *Report on the educational use of games*. TEEM (Teachers evaluating educational multimedia), Cambridge.

[12] André Serrenho. 2013. *Useful Work as an Energy End-Use Accounting Method - Historical and Economic Transitions and European Patterns*. Ph.D. Dissertation. Instituto Superior Técnico, Universidade Técnica de Lisboa.

[13] SNA. 2008. System of National Accounts 2008 - UNSD. *The United Nations* (2008).

[14] UNFCCC. 2015. The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. Accessed 16th May 2019