Developing an Educational Environmental Game

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By Natural Premier

Abstract:

With the steady improvement of technological power and accessibility, games have become widespread and popular among all ages. Educational games especially have the potential to foster learning efficiently and enjoyably. The goal of this project was to create an environmental game that was simultaneously engaging and real enough to inform players about the nuances of climate change. The game was built completely in the Unity game engine, and relies on an environmental model to make climate simulations based on actions taken by the player in-game. The model runs in the background within the game. The end product achieved this goal, though with a limited scope. The game, called NP (Natural Premier) Enviro(mental) Game 24, makes use of both active and passive user action to engage players. The game was designed to gamify important methods of climate action to give players inspiration on real world climate problems. The Environmental science is also easily digestible, allowing for an enjoyable experience regardless of the player's level of background knowledge. Though much of the project is the game itself, this paper is intended to provide context on the purpose of the game, design choices, and further steps beyond this project.

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Introduction:

About 4 in 10 people worldwide played video games last year, according to IGN. Popular games like Call of Duty Mobile and Candy Crush amass hundreds of millions of downloads each year. On a mechanistic level, the most popular games are relatively simple to learn but have many niche strategies that allow one to win more frequently. This is called a "gameplay loop" and is what most players strive to master as they play games longer. Most games across all mediums involve fictional worlds and thus have gameplay loops and mechanics that are about as useful in the real world as trivia knowledge about a fantasy book series. Of course, games serve as entertainment rather than education, but what if they could serve as both?

Take for instance the popular video game franchise Pokemon. Pokemon are monsters that have various unique attributes like type, hit points, attacks, and abilities. Pokemon players typically will remember statistics about countless pokemon, sometimes hundreds depending on the devotion of the player. Imagine if players memorized elements on the periodic table in the same way as memorizing pokemon. Knowledge of elemental appearances, atomic weight,and other properties would be learned with no need for boring memorization.

My Thesis Project, *NP Enviro(nmental) Game 24* aims to simplify and gamify aspects of the climate problem, encouraging learning in an entertaining way. The Environmental game is backed by a Dynamic Integrated Climate Economy Model (DICE Model) that anchors the game to reality. Both behind the scenes and within the user-facing ends of the game, design choices were made in order to facilitate learning and understanding of complex topics like the greenhouse effect, carbon sequestration, and radiative forcing, just to name a few. Though user outcomes and feedback are not explicitly a part of this project, the Environmental game was designed with user engagement as a top priority.

Model Review:

The Dynamic Integrated Model of Climate and the Economy (Dice Model) is a model that represents and models climate change on earth (or regionally) through the use of economic, scientific and policy predictions. The model views climate change using neoclassical growth theory, a system in which economies make investments in capital, education, and technologies today (reducing current consumption) to increase future consumption. Climate change and emissions are viewed as abatable processes that will cost more in the future if they are left unchecked. The DICE model, though a low complexity model, makes accurate climate prediction without needing too much processing power. The model has been iteratively improved by its creator, William Nordhaus, since 1992. The model features equations concerning Economics, Emissions, and Climate feedbacks as well as equations for an objective function which attempts to replicate human economic tendencies. The version of the model used for this project, the 2018 Dice Model, has over 20 intermingled equations that make up the model. The 20+ Equations of the model can be grouped into Objective Function Equations, Economic Equations, Emissions Equations, and Climate/Environmental Equations.

Objective Function Equations:

These equations are necessary for the objective function which the model optimizes to determine variables like emissions control rate.

$$(1) \quad W = \sum_{t=1}^{T\,max} U[c(t), L(t)]R(t)$$

The Social Welfare function is the discounted sum of the population weighted utility of per capita consumption. The variables of interest within this equation are U[c(t),L(t)] (utility function), R(t) (discount factor), c(t) (per capita consumption), L(t)(population/ Labor force).

$$(2) \quad U[c(t), L(t)] = L(t)[c(t)^{1-\alpha}/(1-\alpha)]$$

The utility function. This is maximized by the model in order to determine variables like emissions control rate and saving rate. New variable of interest is α (alpha, elasticity of the marginal utility of consumption).

$$(3) \quad R(t) = (1+\rho)^{-t}$$

Discount factor equation. New variable of interest is P (rho, pure rate of social time preference)

Economic Equations:

These equations are the majority of equations in the model and drive emissions and environmental outcomes.

$$L(t) = L(t-1)[1 + g_L(t)]$$

Labor force/ population over time (capped at 11 billion). New variable(s) of interest: g_L(t) (growth rate of L(t)).

$$g_L(t) = g_L(t-1)/(1+\delta_L)$$

Growth rate of L(t). Influenced by population growth rate constant. New variable(s) of interest: δ_L (population growth rate constant).

$$A(t) = A(t-1)[1 + g_A(t)]$$

Total factor productivity over time. New variable(s) of interest: A(t) (total factor productivity), g_A(t) (growth rate of A(t)).

Growth rate of A(t). New variable(s) of interest: δ_A (TFP growth rate constant)

$$(4) \quad Q(t) = [1 - \Lambda(t)] A(t) K(t)^{\gamma} L(t)^{1-\gamma} / [1 + \Omega(t)]$$

Output net of damages and abatement. New variable(s) of interest: Λ(t) (Abatement Costs), K(t) (capital stock and services), Ω(t) (Damages costs), γ (capital elasticity on production function).

$$(5) \quad \Omega(t) = \psi_1 T_{AT}(t) + \psi_1 [T_{AT}(t)]^2$$

Damages Costs. New variable(s) of interest: ψ1, ψ2 (constants associating temperature and coast of damage), T_at(t) (mean surface temperature).

$$(6) \quad \Lambda(t) = \theta_1(t) \mu(t)^{\theta_2}$$

Abatement Costs. New variable(s) of interest: θ(t) (Fraction of output required to reduce emissions to 0), Ч(t) (emissions control rate).

$$(7) \quad Q(t) = C(t) + I(t)$$

Output net of damages and abatement. This time in terms of total consumption and gross investment. New variable(s) of interest: New variable(s) of interest: C(t) (total consumption), I(t) (gross investment).

$$(8) \quad c(t) = C(t) / L(t)$$

Per capita Consumption.

$$(9) \quad K(t) = I(t) - \delta_K K(t-1)$$

Capital Stock and Services.

Emission Equations:

These equations relate to Carbon Dioxide Emissions.

$$(10) \quad E_{Ind}(t) = \sigma(t)[1 - \mu(t)] A(t) K(t)^{\gamma} L(t)^{1-\gamma}$$

Industrial Emissions. New variable(s) of interest: σ(t) (carbon intensity)

$$\sigma(t) = \sigma(t-1)\left[1 + g_{\sigma}(t)\right],$$

Carbon intensity over time. New variable(s) of interest: g_σ(t)(growth rate of sigma)

$$g_{\sigma}(t) = g_{\sigma}(t-1) / (1 + \delta_{\sigma})$$

Sigma growth rate equation. New variable(s) of interest: δ_σ (growth constant of carbon intensity)

$$(11) \quad CCum \geq \sum_{t=1}^{T\,max} E_{Ind}(t)$$

Limit of total carbon fuel resource equation. This makes sure that Emissions are limited by the total amount of carbon based fuel we have in reserve.

Environmental Equations:

These equations relate to Temperature and aspects of Earth's Atmosphere and Oceans.

$$(12) \quad E(t) = E_{Ind}(t) + E_{Land}(t)$$

Total Emissions. New variable(s) of interest: E_land(t) (Land CO2 Emissions (From forests etc))

$$(13) \quad M_{AT}(t) = E(t) + \phi_{11} M_{AT}(t-1) + \phi_{21} M_{UP}(t-1)$$

Atmospheric Carbon Concentration. New variable(s) of interest: Φ_ij (flow parameters between carbon reservoirs (ocean, atm)), M_up(t) (Carbon in upper ocean).

$$(14) \quad M_{UP}(t) = \phi_{12} M_{AT}(t-1) + \phi_{22} M_{UP}(t-1) + \phi_{32} M_{LO}(t-1)$$

Carbon Concentration in the Upper Ocean.

$$(15) \quad M_{LO}(t) = \phi_{23} M_{UP}(t-1) + \phi_{33} M_{LO}(t-1)$$

Carbon Concentration in the Lower Ocean.

$$(16) \quad F(t) = \eta\{log_2[M_{AT}(t) / M_{AT}(1750)]\} + F_{EX}(t)$$

Change in radiative forcing from greenhouse gasses over time. New variable(s) of interest: η (forcings due to CO2), F_ext(t) (Exogenous forcings).

$$(17) \quad T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)]\}$$

Temperature of Earth's Surface over time.

(18) $T_{LO}(t) = T_{LO}(t-1) + \xi_4\{T_{AT}(t-1) \ - T_{LO}(t-1)]\}$

Temperature of Earth's Lower Ocean over time.

$$\Delta T_{AT} = \Delta F(t) / \xi_2$$

Change in Temperature equals additional warming caused by forcing.

Game Engine Review:

A game engine is a software program that simplifies and accelerates the process of making a game or user experience. Game engines typically handle the technical aspects of physics, lighting, sound, and graphics, allowing media developers to focus on design and higher level concepts within their projects. The Unity game engine was developed by David Helgason, Joachim Ante and Nicholas Francis in Denmark around 2005 (Haas, 2014). The original release of Unity was meant for 3D games and the projects made using this version were limited to MAC OS X and a few other platforms. Currently, Unity Technologies, the company behind Unity game engine, has grown to become a multi million dollar media company. The latest version of Unity with Long Term Stability was version 2022 LTS. Projects made with 2022 LTS can be exported to most platforms including mobile phones and AR/VR technologies. These innovations clearly demonstrate that since their first release in 2005, Unity has been iteratively improving their product.

One of the goals since the release of Unity 1.0, alongside monetary gain, was to “democratize the gaming industry”. By 2009, Unity had gone from a single full access product to a multi-tiered product, with the lowest tier being the 200$ “indie” tier intended for independent game developers. This same year Unity Technologies decided to make this indie tier into an accessible, “Unity Free” tier. The reasoning behind this was that the indie tier was not very profitable regardless, and the more people who were using the Unity game engine the better. This decision was also intended to boost Unity popularity among game development hobbyists and the small game developers community.

All signs indicate that this calculated decision paid off. Almost 15 years later, among an incredibly saturated and fast paced games industry, Unity still remains one of the most popular and well resourced game engines available. A simple google search for “Unity tutorial” reveals almost three times as many results (190 million vs 64 million) than the next biggest competitor, Unreal engine. The collective buy-in of the Unity community has taken years to cultivate, but has created a network of small creators who share and amass knowledge on how to use Unity. This community is very similar to communities that grow around other software like operating systems or programming languages.

The large community focused around Unity is a double edged sword, however, as their missteps and any bad decisions they make are felt and criticized by a large audience. One recent example of when the Unity small creators community voiced concern over Unity’s decisions was during late 2023. Amid huge layoffs and uncertainty within the gaming community as a whole, Unity decided to roll out a new pricing scheme that charged Unity game creators a fee per download of their game, regardless of whether their game was actually making revenue or not. This proposed new pricing model was strongly disliked by not only the Unity small creators community, but game developers from other communities as well (Tassi, 2023). The vitriol and publicity became so negative that Unity retracted the new pricing scheme. The mistrust and resentment this created among the game development community still persists, however, and has left Unity's future in the industry uncertain.

Existing Games Review:

An Environmental game is a game that has a primary or major focus on climate change or environmental activism in its gameplay mechanics and main narratives. Environmental games have existed for decades, with many of the earliest being point and click simulator type games in which users are given the power to make important decisions that have climate related consequences. One of the earliest examples of an Environmental role playing game is Fate of the World (King, 2020), an Environmental game where you make decisions to influence the environmental, social, and political state of the world.

This project (NP EnviroGame 24) was largely inspired by classic environmental games since these are what players have come to expect from environmental games when they play them. The 2022 Financial times climate game was particularly inspirational. This game, created by a small non-profit team, is backed by a low complexity climate model called the MAGICC model. Decisions made by players are converted into parameters for the model, which then runs on the backend of the game's website to update climate and emissions predictions. The game takes place across three rounds over the span of 28 years total (from 2022 to 2050). Players are given a set amount of "effort points" in the beginning that they may use to implement regulations or projects they fancy. The player also chooses an "advisor" at the beginning, which gives the player bonuses depending on their advisor's specialty area. In each round, players are presented with 7 "questions", each of which they must respond to with an action that costs effort points. In between rounds, players can see their realized progress in the form of a dashboard. Players also receive awards for addressing aspects of the climate problem like jobs, health, equity, nature and growth (Financial Times et al., 2022).

Elements of the 2022 Financial times climate game utilized by this project are: the round based approach, realization of climate decisions using passage of time, decisions that influence the climate both in real time and in the future, a finite currency used to take climate action, and a low complexity model reflecting in game decisions in real time. A few deviations this project takes compared to this game are: a longer timeframe (almost triple the length), more randomness in climate decisions put before the player, more gamification of climate decisions, less climate jargon, and more perception of realized and future climate pathways.

Another game that was incorporated into this game is the isometric 3D action/adventure game *Hades*. In this game you take control of a prince of the underworld seeking to escape from his home in the underworld and live among his relatives on Mount Olympus. Though not an educational game, Hades is critically acclaimed and is well known for its fun, addictive gameplay loop. Games like Hades keep players stimulated through engaging and fast paced gameplay. The action phases of this project are nowhere near as intense as levels from Hades. Nevertheless, implementing the isometric combat format that Hades uses is meant to grab and hold the user's attention.

Literature Review:

Alongside the expansion of new technology like Augmented and Virtual reality, as well as the proliferation of smartphones and computers to people around the world, unorthodox methods of learning and teaching have increased in popularity within the past few years. Even though change can be slow to reach the inside of a classroom, the beautiful thing about educational games and media especially is that students can interact with this media so long as they have limited internet access and some kind of computer. Even though the majority of learning ought to be expected within the classroom, if students opt to learn at home as well, better educational games are a good way of facilitating this learning.

Outlooks on educational games especially have improved with the increased focus and resources being given to the metaverse and other large scale virtual projects. Though a few studies have indicated that the effects of educational games in the classroom can be harmful on particular tests (Dominguez 2013), many other studies laud the ability of gamification and educational games to motivate students. A strange paradigm seems to emerge also where higher education classrooms tend to be the ones that implement gamification or educational games, however younger learners stand to gain more from educational games since the attention spans of children are shorter and kids prefer play over non-interactive learning.

Many studies demonstrate the ability of games to foster learning in a unique way that engages and motivates students. In one study, a subset of physical education and recreation students were given an educational game , “PaGamO”, to help prepare them for a written test. The study reports that the mean impact of studying using the game was positive (Cheung et al, 2021).

The impact of games on education is also qualitatively different. Some educational games foster a completely different learning process where games cause students to enter a “flow state” (Paras et al., 2005). The flow state is a term coined by psychologist Mihály Csíkszentmihályi, referring to a state of focus in which an individual is perfectly challenged and stimulated by their task, as as a result enters a state of focus and engagement that can cause them to be lost in their work or task. Educational games may help students enter the flow state, producing better learning outcomes.

There is also a huge potential for immersive learning in games. When game environments transport players into another world, one in which simply the act of experiencing the game becomes a method of learning, learning happens subconsciously. One case against educational games is that learning also requires time for reflection of information taken in, a process which may not be given time depending on the pace of the game. If a game is to facilitate effective learning, it must offer time for reflection in between stimulating sequences (Paras et al., 2005).

Methods and Implementation:

Constructing the Dice Model

Dice Model Parameters

The 2016 DICE model used for this project has 18 Main groups of equations , containing 40 constants and 22 ongoing parameters. Variables were classified this way to easily group, when running the model, variables that would continue growing versus variables that remain constant.
The constants, and handoffs (dynamic variables) are all described in the supplements at the end of this paper (Supplement 1).

After Successfully building the DICE model in python, the model required further adjustment and modification to run stepwise, run as a function of parameters that could be changed between steps, and save the relevant plots as images. This processing is addressed by making 3 Layers of interaction with the model, each handled by a particular function. The layers are described below:

- Layer 1: The actual model runs on data it has been given. The model is given parameters including how long to run for and what parameters initialize the run. This layer receives parameters and returns data.
- Layer 2: The intermediate step that makes data from the model digestible and stores it or shows it. This is the layer that involves creating plots using data from layer 1 and parameters from layer 3.

- Layer 3: The user facing layer, this is where the model is configured to run based on parameters like variables and where plots and data are stored or prepared for display.

Layer 1:

The most fundamental part of creating desired simulation runs using the DICE model is to run the actual model based on the initialization parameters it is given. There are over 40 constants used by the model, and over 22 "handoff" values. Constants are values like growth rates that stay the same throughout the entire simulation run. "Handoffs" (they must be handed off between model runs) are values that change across the run of the model. The value of each of these parameters is recorded in a list data structure (for constants) and a dictionary data structure (for handoffs). The entire implementation is designed to run the dice model multiple times allowing for parameters to be adjusted in between seamlessly. After parameters and handoffs are provided to the model, the following operations occur:

1. Exogenous processes like exogenous radiative forcings are initialized
2. Equations are defined as functions to be minimized later
3. Objective function is run to find utility value
4. Optimization function is run to find optimal emissions control rate and savings rate to maximize utility.

Layer 2:

The functions of Layer 2 serve more as controllers, calling those in Layer 1 based on parameters given in Layer 3. The controller's main objective is to to display and save good visual representations of the data returned from a full simulation run (multiple model runs). This is accomplished through plotting, mainly using python's matplotlib library. There are around 20 measurements available for plotting and processing after the DICE Model is run, including Atmospheric temperature, emissions control rate, cost of damages caused by climate change, gross output, total carbon emissions, and more. For each plot specified by the user, the plotting function plots data from all model runs into one coherent plot, with data from each step shown in a different color.

Layer 3:

The first step towards creating desired simulation runs using the DICE model is to configure the simulator to run the DICE model based on parameters. These parameters can be adjusted partway through running the model, which makes the model truly dynamic. Also the length of the simulation run and which plots are desired from the simulation are parameters the user must set. Lastly, layer 3 bridges the gaps between layers 1 and 2 by controlling when to call the layer 1 dice model function and when to call the layer 2 plotting function.

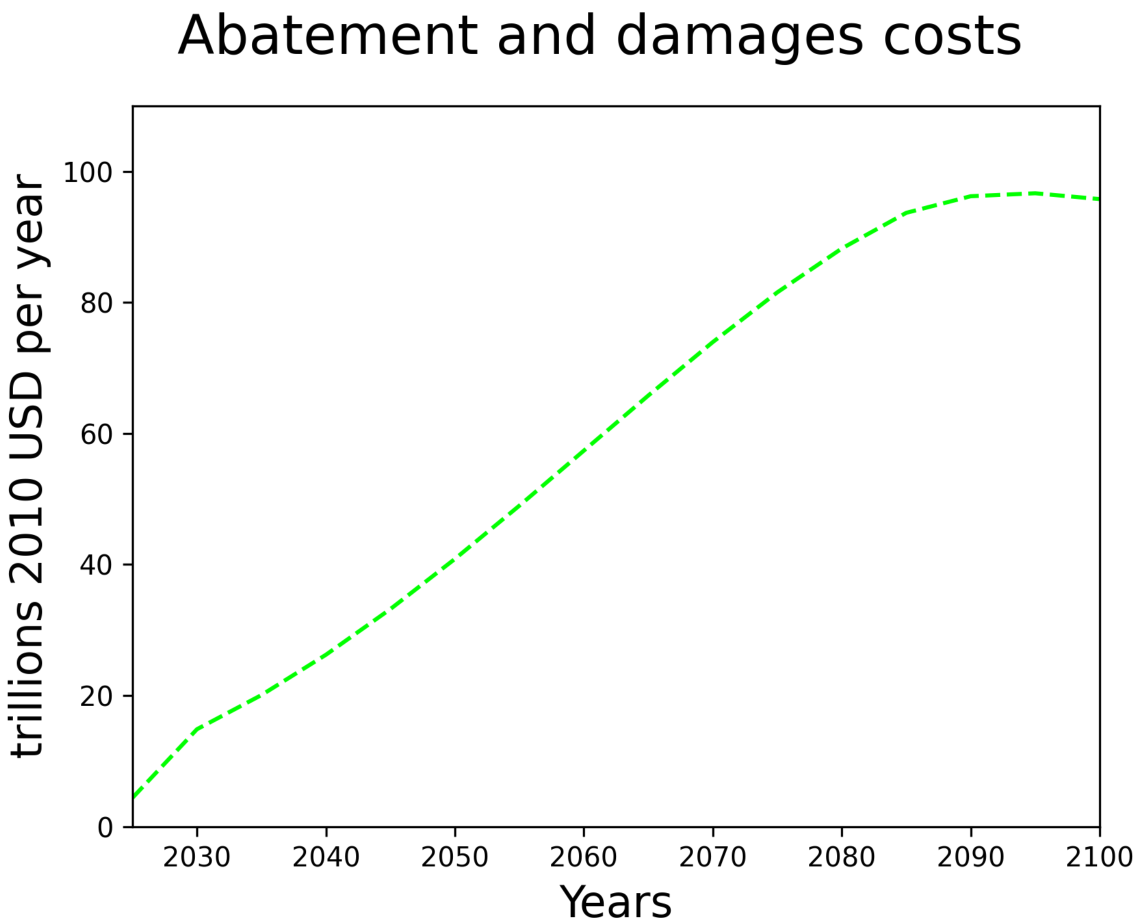

Figure 0.1: A generic run of the DICE Model in one step

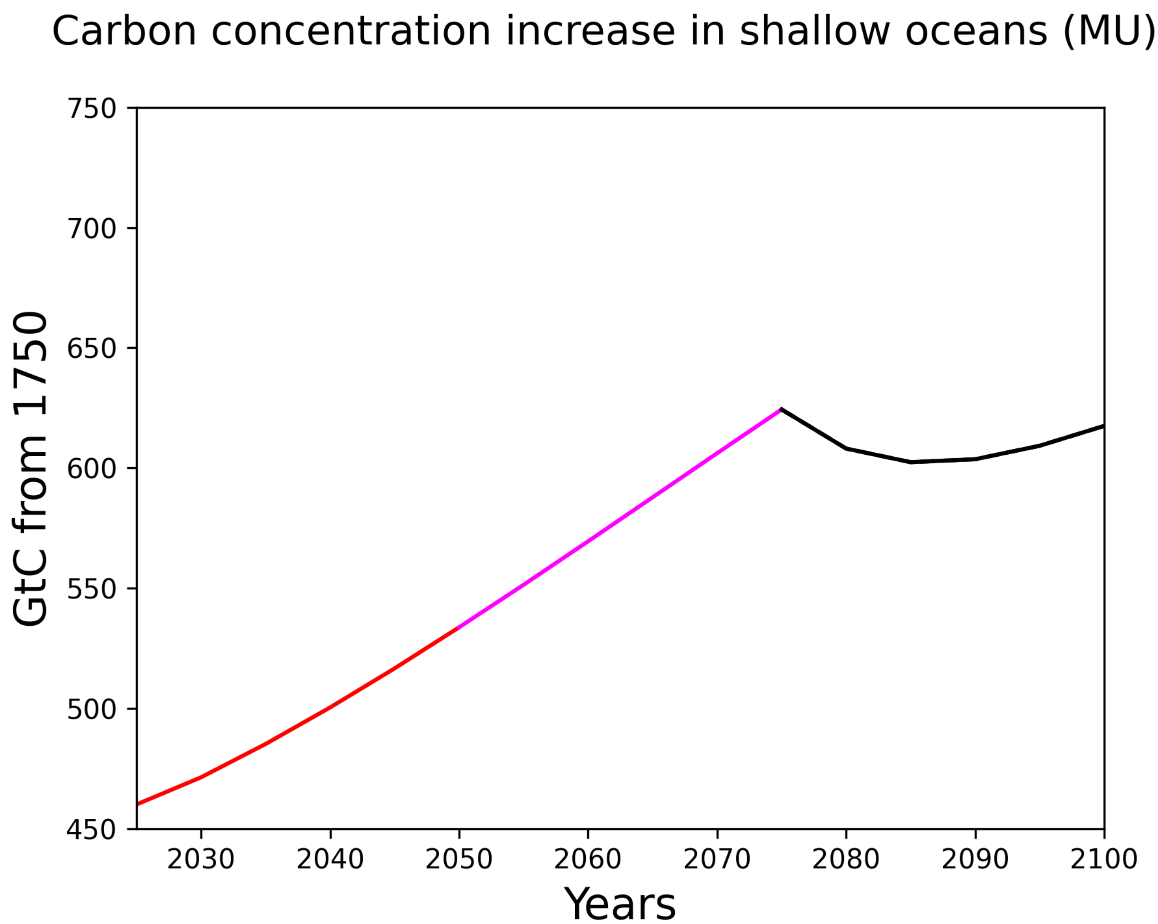

Figure 0.2: 3 Stepwise Runs of the model, each in a different color

As illustrated with the figures above, a generic DICE model is typically designed to allow for only one singular run of the model over the entire time span of interest. My task was making the model run smoothly in steps over the time period of interest.

Creating the Game Within a Game Engine

The game relies on a balanced combination of the game and the environmental model.

Choosing a Game Engine

The first step towards building the game was choosing the appropriate game engine. A game engine is a platform that handles many of the technical and trivial aspects of a game (physics, lighting, updating the position of game objects) so that developers may focus on the higher level details. The game engine chosen for this project was Unity Engine, which is a free game engine with many resources and tutorials available.

Integrating the model and Unity game engine

Unity actually does not have built in python support within the editor, or within completed projects. To bypass this lack of support, it became necessary to run an embedded version of Python within c#, the language of Unity Engine. Using the .NET language made it possible to to give commands to the embedded python module and run the model as needed. This integration process creates a python application that runs alongside the C# of the game engine.

Creating Game Objects from Plot images:

After successfully integrating the model into the game engine, next the plots from the model needed to be converted into gameobjects, which was done by reading the plot images into arrays of bytes and then converting these arrays into textures for image gameobjects.

Core Game Development:

Making Objects and various “Managers”:

- Net handler - The interface used to hold and interact with the dice model and the ongoing data held by the Dice Model
- Graph Handler - The interface used to create interactive plots and graph using data from the Nethandler
- Card Manager- Used to manage all this related to decision subphase cards. Implementing card Effects required cooperation between Card Manager and Graph/ net handlers.
- Game Manager - general game controller allowing for game to be paused/ resumed, and helping to organize game scenes as desired.

The rest of the game making process was making the appropriate Game Objects and scripting them according to their role in the game. The complexities of this process are beyond the scope of this paper.

Game Design

General Gameplay Loop

The Project is Environmental game in which a user can both actively and passively impact the earth's climate up until the year 2100 through decisions and actions done with a virtual "agent". The game is very similar to conventional Environmental games in that the player is given the power to change human behavior like emissions rate, spending habits, and other things. This project differs from the conventional ones in that it is meant to also have a more engaging user experience through the action subphases. One of the pillars of this game is having a dynamic environmental model, one that models over 20 environmental/ economic variables as the game progresses. This model influences in game experiences, and in turn your decisions in the game influence the model. The game is broken up into three "rounds", each containing an Observation subphase, Action Subphase, Decision Subphase, and time skip. The time skip is roughly 25 years long. This repetition of rounds and subphases creates a reliable gameplay loop in which each subphase feeds into the next subphase and each round influences the subsequent rounds.

On Observation subphases

The benefits of running the model dynamically each phase is the ability to create and display predictions and realized measurements in real time to the player. The "observation subphase" allows players to see the measurements of climate variables like atmospheric/oceanic temperature changes and atmospheric/oceanic carbon concentrations, as well as emissions and carbon control rates and more. The model measurements predicted for the future are also shown, encouraging further action from the player in order to shift the world onto the IPCC best case scenario pathway.

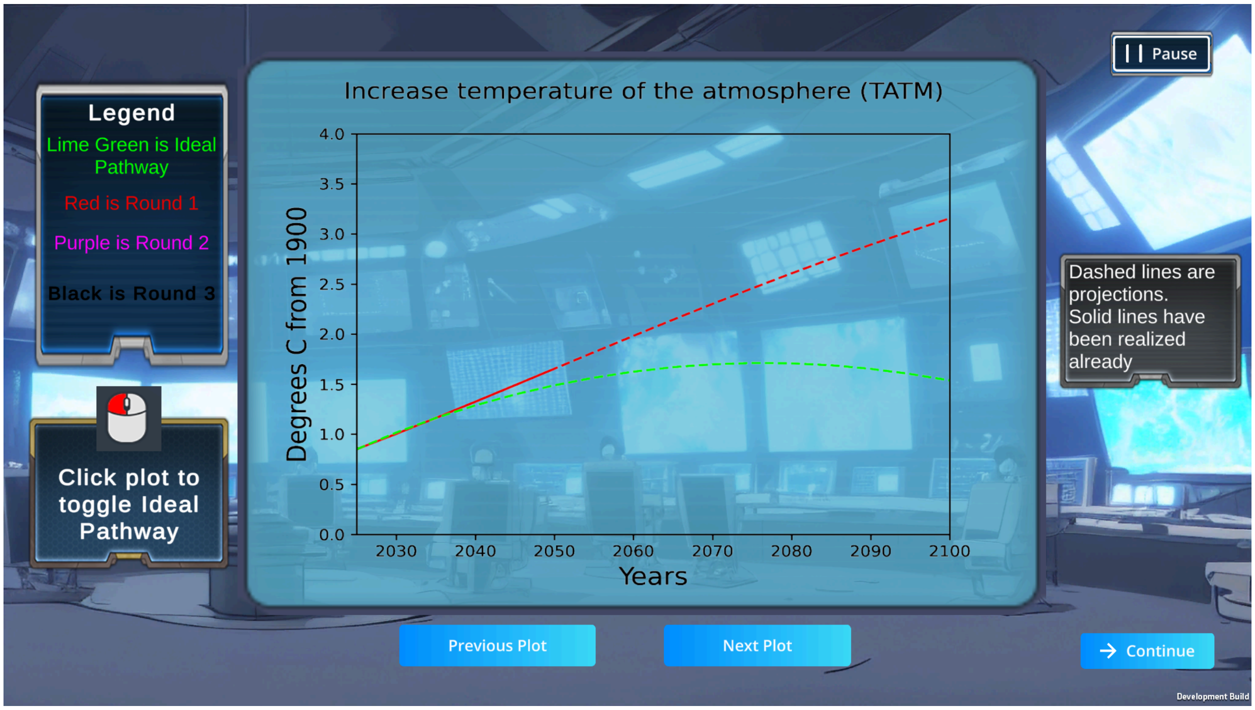

Figure 1: Observation Subhase Display

Demonstrated in Figure 1 above, the observation subphase is designed around allowing the user to see their realized environmental situation, as well as projections for the future. A variety of legends and tooltips help users navigate the 10+ plots that can be cycled through using the two buttons below the graph display. In red is the realized global increase in atmospheric temperature (solid red line) along with the projected temperature increase (assuming no further actions are taken). The lime green line is the RCP 1.9 pathway trajectory. This line is used as a reference to the player. If the player's values are below the line, they are not on track to win the game (they are on a different climate pathway than RCP 1.9).

On Action subphases

During "Action subphases", Users take control of a player avatar and actively "fight" against pollution and emissions by fighting fantastical representations of greenhouse gasses. These action subphases are set in various environments of interest like wildfire stricken forests, melting arctic tundra, and everyday forests. The player uses futuristic tools like a handheld carbon sequestration membrane to dissipate clouds of greenhouse gasses like carbon dioxide, methane, and NOx. The Action subphases are very engaging and despite the fictitious approach to representing greenhouse gasses, aspects like the relative strength of greenhouse gasses to each other, the speed at which they spread, and their molecular shape are learned by the player during the action subphases. The amount of gasses dissipated in these subphases is directly deducted from the earth's atmosphere following an Action subphase.

Action subphases are limited to 60 seconds each, during which the player attempts to sequester as many gas enemies as they can. The player also has a “health bar”, and when this bar falls to 0 the action subphase may end early.

Figure 2: Action Phase Example

Above is an example of an action phase in progress. Gas enemies approach the player.

After the Action subphase ends, users are given their performance metrics. They are given the amount of gas enemies sequestered as well as how much carbon this will remove from the atmosphere.

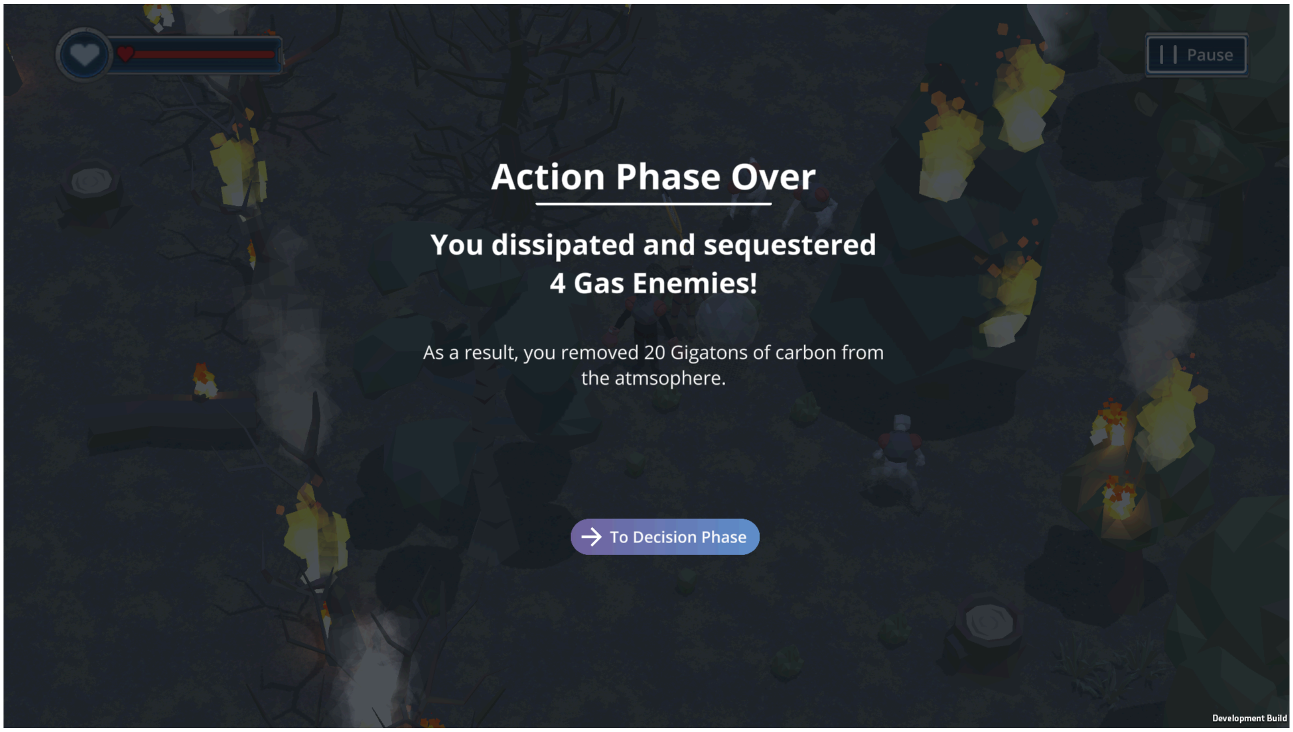

Figure 3: Post Action Phase Screen

On Decision subphases

During "Decision subphases" players make decisions from a pool of "Decision Cards" that affect the parameters of the model. For example, a "Carbon Tax" Decision Card will increase the base price of carbon in the model. One of the critical drivers of learning is that players will challenge their assumptions about climate action through outcomes they cause and experience in the game. There are multiple rounds within the decision phase where various decision cards are presented to the user. Each round of a decision phase, players are given a set amount of "action points" and money, both of which are used to buy decision cards and adjust the model.

Figure 4 (Above): Decision Phase Layout

Figure 5 (above): Card Selected , ready to submit

Figure 4 (above) is what is presented to the player during a round of the decision subphase. Players decide between the various decision cards, each of which has a cost at the top of the card. At the top of the player's screen is a bar displaying the action points and money the player has. Once the player is ready to choose a card, they select it with their mouse and click the submit button. After Submission, the effect of the card is applied to the model.

Final Graph Alterations and Time Skip:

Following each of the 3 subphases, graph variables have already been changed. Now, during the "time skip", the model is run for a set amount of time on the adjusted variables to realize some of the environmental actions and decisions of the phase. Then the loop repeats itself.

To reiterate, the Gameplay loop up until the end of round 3 is:

Observation Subphase -> Action Subphase -> Decision Subphase -> **Repeat**

Game Over:

At the end of the game, depending on whether the user was on the RCP 1.9 pathway, they receive a different ending screen at the 2100. There are essentially 3 ending scenarios, based on 3 temperature ranges: under 1.9℃, 1.9℃ - 2.9℃, and over 2.9℃.

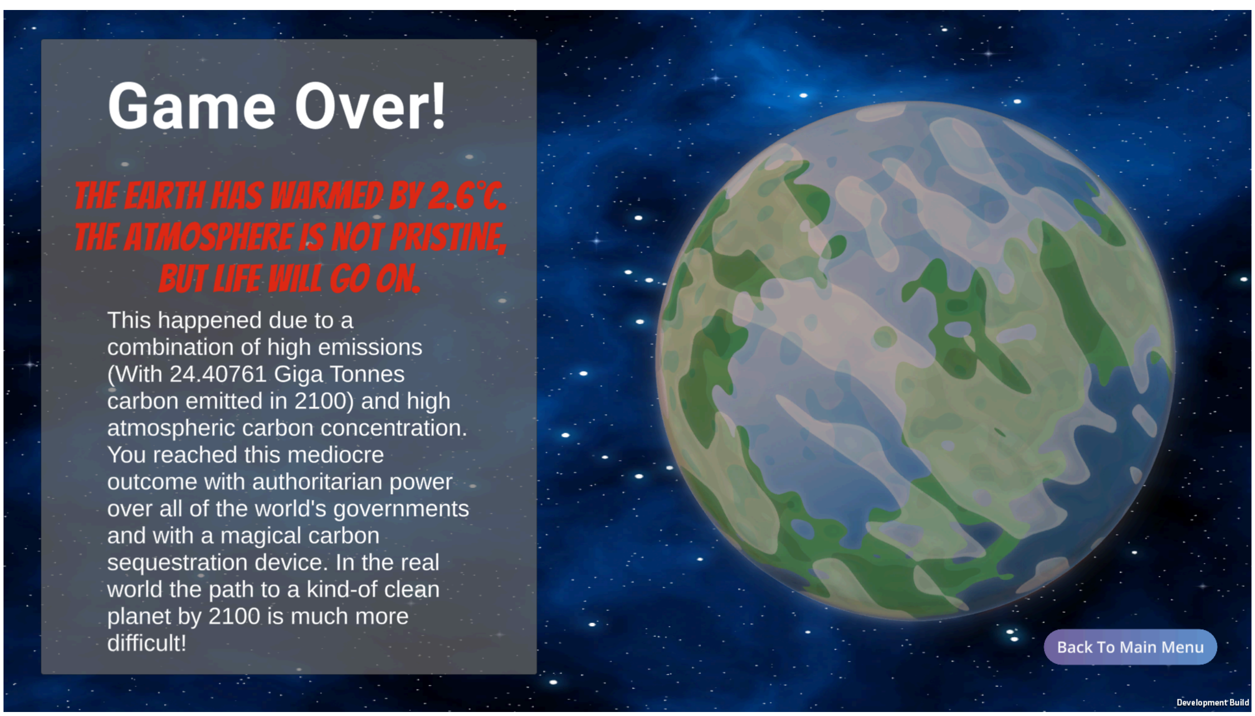

Figure 6: Example Game Over Screen

Player/ Enemy Design:

The Player is designed to look like a Humanoid tree. The Player uses a handheld carbon sequestration device.

Basic CO_2 Gas Enemies (Shown left), are slightly transparent and incorporate a carbon dioxide Molecule into their design.

Methane (CH_4) has stronger radiative forcing effects than CO_2 when released into the atmosphere. As a result, methane is represented as a bigger gas enemy that sequesters more carbon when dissipated. A methane molecule has been incorporated into the design.

Parameterizing aspects of the Game based on Studies and Literature

This project aims to simulate and predict real economic/environmental behaviors stemming from in-game actions. Thus, parameterizing the model based on in-game actions requires measurements and data from existing studies and literature.

Parameterizing “Decision Cards”

There are roughly 27 Unique Decision Cards, most of which directly influence parameters within the DICE model. Some only affect things in the game like which other Decision Cards can be chosen, others are continuations of the effects of previous decision cards. The Cards can be grouped into 3 categories, those being standard cards, extension cards that extend standard cards, and money cards that cost money rather than action points. Below cards are grouped in terms of how similar the cards were to parameterize, for example all cards that simulate deforestation are placed together.

Decision Card Table:

Card Group	Card Title	Description	Parameter Adjustment	Action Point Cost	Money Cost
Carbon Tax	Carbon Tax! (I)	mandate global carbon tax	carbon base price = 16.87	1	0
	Carbon Tax! (II)	continuation of Carbon Tax(I)	carbon base price = 25	1	0
	Carbon Crackdown!	continuation of Carbon Tax(II)	carbon base price = 50	1	0
	Albedo Boost	reduce radiative forcing from greenhouse gases	2015 Forcings of non-CO2 GHG reduced by 26% 2100 Forcings of non-CO2 GHG reduced by 26%	1	0
Forest Sink/Source Cards	Slash and earn	Burn Amazon, gain money	Land Carbon Emissions increase immediately by 123 Gtc. Emissions from trees reduced by 10%	0	0
	Slash and turn	Burn Amazon, expand wind energy	Land Carbon Emissions increase immediately by 123 Gtc. Emissions from trees reduced by 10% Carbon intensity reduced by	1	0

			40%		
	Slash and Flash	Burn Amazon, expand solar energy	Land Carbon Emissions increase immediately by 123 Gtc. Emissions from trees reduced by 10% Carbon intensity reduced by 20%	1	0
	Tree Spree	plant billions of trees, sequester carbon	Carbon concentration in atmosphere reduced by 31.488 Gtc	0	1
	Tree Spree 2	continuation of Tree Spree	Carbon concentration in atmosphere reduced by 31.488 * 2 Gtc	0	1
Vehicle Regulation	Hybrid Vehicle Mandate	Mandate hybrid cars	Carbon intensity reduced by 5%	1	0
	Electric Vehicle Mandate	continuation of Hybrid Mandate	Carbon intensity reduced by another 5%	1	0
	Eat This!	Globally phase out animal products	Carbon concentration in atmosphere reduced by 25Gt * time skip length(years) * .25(realism constant) Gtc Carbon intensity reduced by 5.8%	2	0
	Nuclear Boom!	add more nuclear to global energy portfolio	Carbon intensity reduced by 3.526%	1	0
	Green Buildings	make buildings more energy efficient	Carbon intensity reduced by 5.25%	1	0
Point Source Carbon Capture	Scrubber Mandate	implement point source carbon capture	Carbon intensity reduced by 49.77%	2	0
	Point Source Unicorn	continuation of Scrubber Mandate	Carbon intensity reduced by a further 21.02%	2	0
Anthropogenic Carbon Sequestration	iterative climate control	sequester carbon from atmosphere, better each use	Carbon concentration in atmosphere reduced by 5*(1+.2*(previous uses of climate control)) Gtc	0	1
	Climate Control	sequester carbon from atmosphere	Carbon concentration in atmosphere reduced by 5Gtc	1	0

	Deep Sea Algae Bloom	reduce upper ocean carbon	Carbon concentration in upper ocean strata decreased by 30%	1	0
	Consumerist propaganda	increase per capita consumption, gain money	Elasticity of marginal utility of consumption increased by 10%	0	0
	Anticonsumerist propaganda	decrease per capita consumption	Elasticity of marginal utility of consumption decreased by 10%	1	0
	Activism	more ap next phase		1	0
	Activism +	even more ap next phase		2	0
	Reinvest	gain more money in future phases		0	1

Carbon Base Price Increase Cards:

Each of these cards concerns the climate outcomes of a mandated carbon price or carbon tax on various countries. Since the model only takes in global carbon base price as a parameter, the effects on regional carbon taxes are reflected in terms of the global mean carbon base price. Global mean carbon base price was calculated by the following equation:

$$\text{(Global Mean carbon Base price)} = \sum \left(E\_c * Cprice\_c * 100\right) / |c|$$

Where E_c is the contribution to global emissions of the country c and Cprice_c is the maximum between any carbon pricing system or emissions trading system the country has. The above is essentially the emissions weighted average carbon price across all countries in the world.

After configuring a system of equations to dynamically adjust the global base carbon price (Ritchie et al., 2022), the next step was to decide which countries would implement carbon taxes, and the amount of the tax. A study by the IMF, *Proposal for an International Carbon Price Floor Among Large Emitters*, gave a useful hypothetical study. In this proposal, the environmental outcomes of a Carbon floor among the Global Top 6 emitting countries is investigated, with the effects of 25$, 50$, and 75$ carbon floors explored (IMF, 2021).

The card effects are organized into three tiers, the first simulating the top 6 Emitters implementing a floor of 25$, next seeing all countries implementing a floor of 25$, and the last raising the floor to a global 50$ base price.

Tier 1 (Carbon Tax 1): The 6 largest emitters since the last survey in 2022 are: China (30.6%), United States (13.61%), European Union (8.29%), India (7.61%), Russia (4.44 %), Japan (2.83%) (Ritchie, 2019). These emitters make up 67.48% of all total emissions.

.6748 * 25 = 16.87 new global base price (at minimum)

Tier 2 (Carbon Tax II): A sweeping mandate of 25$ per tonne CO_2 would make the global mean base price 25$.

New Global Base Price = 25$

Tier 3 (Carbon Tax III): A sweeping mandate of 50$ per tonne CO_2 would make the global mean base price 50$

New Global Base Price = 50$

Exogenous Forcings Decrease Card(s):

This card is intended to explore how artificially injecting aerosols into the atmosphere could reduce radiative forcing caused by greenhouse gasses.

Excerpt from *Scattering and absorbing aerosols in the climate system* (Li, et al 2022):

> Globally, anthropogenic aerosols are estimated to produce a net cooling ~−1.3 ± 0.7 W m^{-2} at the top of the atmosphere; −0.3 ± 0.3 W m^{-2} is attributed to the aerosol–radiation interaction (ARI), −1.0 ± 0.7 W m^{-2} to aerosol–cloud interactions, ~−1.15 W m^{-2} to total forcing from scattering aerosols and ~+0.12 W m^{-2} to BC[4]. This combined aerosol forcing offsets roughly one-third of the warming from anthropogenic greenhouse gasses (GHGs). However, the large spread in the estimated aerosol forcing leads to large discrepancies in climate sensitivity[5,6]. Thus, aerosols are considered to be the largest contributor of uncertainty in quantifying present-day climate change[4].

Using this figure of anthropogenic aerosols offsetting ⅓ of greenhouse gas warming, this card is meant to offset another ⅓ through the hypothetical use of injected aerosols.

The model makes use of two forcing constants to calculate exogenous radiative forcing of greenhouse gasses. By reducing these forcing constants, a hypothetical reduction in greenhouse gas forcings can be simulated.

Forest Carbon Sink Manipulation Cards:

Perhaps some of the most thought provoking cards, these cards all simulate what happens if humans were to immediately cut down forests around the world that altogether amount to the land area and carbon content of the Amazon Rainforest. What is done with this deforested land varies by card. The “Tree Spree” card explores replenishing forests.

The Amazon is used as a reference due to the large amount of literature on carbon fluxes in the Amazon rainforest. Also using an “Amazon Rainforest” as a point of reference for deforestation creates a memorable and straightforward point of comparison for deforestation concepts throughout the game.

Though many studies have been done estimating the carbon content of the Amazon, *Amazonia as a carbon source linked to deforestation and climate change* (Gatti et al., 2021) is particularly recent and very thorough in its calculations. This paper is used as a reference for carbon density of the Amazon as well as hypothetical carbon fluxes of the amazon as well .

Since all cards in this group must simulate deforesting the Amazon, those calculations are done first. The Amazon contains approximately 123 ± 23 Petagrams of carbon stored within it, equivalent to 123 Gtc (Gatti et al). This implies 123 Gtc emitted into the atmosphere if the Amazon is burned down. The Amazon is responsible for approximately 10% of the world's terrestrial primary productivity (Melillo et al., 1993). This means that carbon emissions from land (for subsequent years) would immediately fall by 10%.

For the “Slash and Flash” and “Slash and Turn” Cards specifically, land deforested by burning the Amazon is repurposed for renewable energy. Alta Wind Energy Center is one of the largest wind farms ever built. The entire Alta wind project has an area of 130km^2, nameplate capacity of 1,550 Mw and an annual net output of 3,189 GWh. It is estimated to have a capacity factor of .235 (Alta Wind, 2010). Assuming the full area of deforested land was utilized, hypothetically 7,256,362/ 130 = 55818 Alta Wind farms could be built. The cost of the Alta Wind farm was approximately 3 billion USD, however, so realistically even with global subsidies and funding only a fraction of the theoretical farms could be built. There are three hypothetical sources of capital for these projects, depending on three grand assumptions. The first source of capital stems from the assumption that in exchange for burning down the rainforest countries agree to pay the cost they would have paid to not burn down the rainforest as a lump sum, resulting in a few trillion dollars of capital to use for renewable projects. The second major source of capital is from the assumption that private companies in agriculture and other fields that have a vested interest in using the land freed up by burning down the Amazon. The last assumption is that the costs of building these projects are still largely subsidized by world governments in exchange for the jobs they create. We then settle on about 5,000 Wind farms built, with a simplified annual generating capacity of 2000 GWh and an adjusted capacity factor of .2.

2000 * 5,000= 1 × 10^7 GWh / year = 1 × 10^4Twh/year

According to recent data from 2022, the Global non-renewable energy demand is 904.15(oil) + 6443.6(Gas) + 10212.22(Coal) = 17560 TWh (Ritchie et al., 2020). These wind farms would cut the non-renewable energy demand by over half. To maintain some sense of realism, we reduce this fraction to 40% of the non-renewable energy demand. We settle on a reduction of 40% to the global mean carbon intensity.

Similar assumptions are made for the “Slash and Flash” card, namely that capital is provided for the renewables projects. For “Slash and Flash”, the Copper Mountain Solar facility is used as a model project. This facility takes up around 4,000 acres of land total, and has an annual net output of about 1,348 GWh (EIA, 2016). Since solar energy requires almost full dedication of land to energy generation and nothing more, we initially dedicate a smaller portion of the land to solar projects, 5,500,000 km^2 (from 7,256,362 km^2).

5,500,000 km^2 / 16.8 = 327380

Approximately 300,000 copper mountain solar farms could be built in the deforested land. Again considering the fact that land converted to a solar farm is effectively locked for 30 years, we assume 1/100 possible farms can actually be built. This leaves about 3,000 copper mountain sized solar projects. For simplicity in calculations and due to variability in solar energy depending on where projects are built, we use 1000GWh as our annual net output (down from 1,438 GWh).

3000 * 1000 = 3 *10^6 Gwh/ year = 3* *10^3 Twh/year

Using the same nonrenewable energy demand as above,17560 TWh:

3000/17560 = 0.171%

We end up with 17% of global energy demands, which we round up to 20%.This means a reduction in Carbon intensity of 20%.

For All Slash Cards:
Cumulative Emissions from land reduced by 10%
Land Carbon Emissions increase immediately by 123 Gtc.

For Slash and Turn:
Carbon intensity reduced by 40%

For Slash and Flash:

Carbon intensity reduced by 20%

The “Tree Spree” cards are largely inspired by a real tree planting campaign, *1 Trillion Trees*. This campaign, started in 2018, aims to plant 1 Trillion Trees by the year 2030. So far in pursuit of its ambitious goals , the campaign has successfully managed to plant 13.96 billion trees, and has acquired pledges for 12 billion more trees by 2030 (The trillion Tree Campaign, 2020). Since the progress 6 years into the campaign is (13.96 + 12 billion trees), we assume that by the end of the campaign in 6 years, at least double this amount of trees is actually planted.

(13.96 + 12)* 2 billion trees = 51.92 billion trees

The Amazon is estimated to contain around 350 billion trees (Ferro, 2015). This means that the 1t tree campaign will plant 14.8%(roughly 15%) of the Amazon Rainforest. The Amazon rainforest is estimated to have 123 * 10^9 tons CO2 = 123 Gtc stored within it. Considering a planted forest is not as carbon rich as a prehistoric rainforest, the carbon content of the planted forest is discounted by .2.

.8 * .16 * 123 = 15.744 Gtc Sequestered.

Considering the campaign aims to plant 1 trillion trees, we double the amount of trees planted in hopeful optimism.

Tree Spree Card:
31.488 Gtc Sequestered immediately from Atmosphere

Transportation Emissions Manipulation Cards:

The transportation industry is one of the prominent culprits of climate change, with cars, trucks, and planes being everyday reminders of how our machines interact with the environment. As a result, however, people may overinflate the importance of the transportation sector over energy or other sectors. Effects of changes to our transportation habits are incredibly well documented, with various studies on the comparative efficiency and lifelong impacts of different types of vehicle. This project offers two main decision cards based on the transportation sector: Hybrid Mandate and Electric Vehicle mandate. These cards differ from most other cards because cars, rather than energy or even food, are made and sold in factories by companies. This means that even if the car being sold is an electric car, the energy used to ship the car’s components, manufacture the car, and transport the finished product all ought to be considered alongside the actual lifelong outcomes of the car itself. Thankfully, many studies have done the work to fully account for the energy used along an electric or hybrid car’s lifespan. One particular study from MIT was very relevant (Gross et al., 2019):

> For similar-sized vehicles in the U.S. today, per-mile lifecycle (including vehicle and battery production) greenhouse gas emissions for battery electric vehicles run on the present U.S.-average grid electricity are approximately 55% of the emissions from conventional internal combustion engine vehicles. Per-mile greenhouse gas emissions for hybrid, plug-in hybrid, and fuel cell electric vehicles (run on hydrogen generated by steam methane reforming) are all approximately 72%–73% of emissions from conventional vehicles.

Hybrid vehicles over the course of their entire life cycle release around ¾ of the emissions, while electric vehicles emit about half of their conventional counterparts. The transportation industry makes up about 16.2% of global emissions. Since a Hybrid mandate would result in cars that emit ¾ as much, a hybrid mandate would reduce transportation emissions by 25%. We will assume similar replacement of buses, trucks, and planes.16.2*.25 = 4.05% reduction in carbon intensity. We will bump this up to 5%.

For the next level, a sweeping electric vehicle mandate, since electric vehicles emit approximately 25% less than hybrid vehicles, we may use the same calculations as above for an electric vehicle mandate as well. 16.2*.25 = 4.05% reduction in carbon intensity. We again bump this to 5%.

For Hybrid Mandate Card:
Reduce Carbon intensity by 5%

For Electric Vehicle Mandate Card:
Reduce Carbon intensity by 5%

Agriculture Emissions Manipulation Cards:

These cards are meant to adjust the land use and agricultural sectors of the global emissions. Even though these emissions make up roughly ⅕ of global emissions, the greenhouse gasses emitted by land like methane and Nitrous oxide are many times more potent than CO_2. They also have the potential to dissipate from the atmosphere faster.

According to the literature (Eisen et al., 2022), a phaseout of livestock to agriculture would have the same effect as a roughly 25 Gt/ year decrease in CO_2 until the end of the century. This is due to the large amount of Methane (CH_4) and nitrous oxide (N_2O) produced by the livestock industry.

Immediate carbon drop = 25Gt * time skip length(years) * .25(realism constant)

According to World in Data emissions by sector (Ritchie et al., 2020), Livestock and manure make up 5.8% of Global GHG emissions per year. In addition to the decrease in atmospheric carbon, carbon intensity is reduced by 5.8%.

Eat This! Card:
(Happens Once)

carbon intensity is reduced by 5.8%
(Happens each phase)
Reduce atmospheric carbon by 25* (time skip length)*.5

Green Energy Cards:

These cards represent an immediate increase in renewables thanks to mandates and subsidies. Since wind and solar were already implemented within the forest card group, this group focuses on Nuclear energy. For this card group we assume the world can muster 500 Billion USD to invest into nuclear projects, and that Nuclear projects are greenlit globally, and that nuclear project regulations become consistent. This also means we assume that additional costs of nuclear projects from delays and regulatory changes will no longer be encountered by future projects.

We will use the Georgia Vogtle 3 plant as an example, the most recent new nuclear power plant to reach criticality in the US (Clifford, 2023). It is also the first to do so in almost a decade. Vogtle 3 and 4, two nuclear units that are a part of the same plant, both initially were supposed to cost 14 Billion. They are projected to result in a true cost of 35 Billion by the time Vogtle 4 is completed. The generating capacity of Vogtle 3 is 1,100 MW. The average nuclear annual capacity factor is 92.7%, meaning Nuclear power plants typically achieve 92.7% of their generating capacity each year (Shah, 2023).

8760 hrs / year

1,100MW * 8760 hours/year = 8932572MWh annually

Since the Vogle plant has 2 units of the same size, multiply by 2

8932572MWh *2 = 17865144MWh annually.

We will clamp this amount to 17.2 * 10^3 GWh/ year, the number described by energy.gov (Shah, 2023). We also assume that the cost of building future Vogtle 3 & 4 sized plants will be the initial planned cost of the plants before added costs from delays and regulatory changes, which was 14 Billion USD.

(17.2 * 10^6 MWh) = 17.2 *10^3 GWh = 17.2 Twh

17.2 Twh of nuclear power for 14 Billion

500/ 14 = 36 roughly

17.2 * 36 = 619.2 Twh

904.15 + 6443.6 + 10212.22 = 17560 TWh (Total Nonrenewable energy demand)

619.2/17560 = 3.526% decrease in carbon intensity

Nuclear Boom Card:
(Happens Once)
Carbon intensity decreases by 3.526%

Building Energy Efficiency Cards:

It is interesting to note here that various studies on LEED certifications reveal that a higher LEED standard rating has no statistically significant effect on actual energy saved by buildings (Amiri et al., 2019). This is because LEED is really a certification on building materials like insulation, but factors like energy use are determined by the inhabitants of the building. Things like smart metering may help to always save energy, but the main factors considered in the certification cover much more than energy efficiency.

Cards in this group will directly address energy use of buildings rather than certification standards for this reason. The effects will still be lessened to demonstrate the low impacts of energy efficient buildings. We begin by considering the share of energy used by buildings. This is 17.5% of total annual emissions. According to the U.S. department of energy, 30% of energy in commercial buildings is wasted (U.S. Department of Energy, 2020). We will make an assumption that this wasted energy percentage extends to residential buildings as well. This card mandates the acquisition of better insulation, use of energy-efficient appliances and lighting, use of natural lighting and ventilation, and better energy usage habits. The implementation of these mandates will return that 30% of wasted energy back in full.

17.5 * .3 = 5.25% Carbon intensity reduced directly

Green Buildings Card:
(Happens Once)
5.25% Carbon intensity reduced directly

Point Source Carbon Capture Cards:

Better efficiency in existing fossil fuel based energy sources are one of the lesser talked about pathways of fighting climate change. This is likely because the fossil fuel industry prioritizes making profits over just about all else, and has a history of disregard for the environment. Nevertheless, the right regulations or the emergence of the right technology can make point source carbon capture much more viable, and fossil fuels are going to be necessary for the transition to sustainable energy whether we like them or not. Modern point source carbon capture methods, though expensive, are actually quite effective. As Moseman points out, capturing up to 90% of Carbon in exhaust is possible with a modest amount of planning and up front capital when building power plants. Capturing beyond 90% of carbon in exhaust gasses becomes an “engineering puzzle and economics problem”, however (Moseman, 2021).

One assumption to note is that, since the use of carbon scrubbers does not replace carbon based energy but rather prevents emissions of carbon based energy sources, a scrubber mandate ideally would not solely affect the carbon intensity. The model is not equipped to consider point source carbon capture so carbon intensity is used as a proxy, essentially treating point source carbon capture power plants as a kind of renewable energy source.

The two cards in this group are a basic “Scrubber Mandate” card and a card called “Point Source Unicorn”. For the Scrubber Mandate card, we will reduce emissions from carbon based energy by 90%. As the name implies, Point Source Unicorn is a card that suggests a technology is found to make point source carbon capture up to 99% efficient. Because of this utility it is also one of the most expensive decision cards in the game.

The applicable emissions sectors for the basic scrubber mandate card are all but transportation, land use, and waste:

5.8 + 7.8 + 17.5 + 24.2 + 16.2= 55.3% Percent applicable emissions

55.3 * .9(90% point source carbon capture) = 49.77 % reduction in carbon intensity

For Point Source Unicorn, we may add transportation emissions (16.2%), and reduce applicable emissions by 99%

5.8 + 7.8 + 17.5 + 24.2 + 16.2 = 71.5% Percent applicable emissions

99% * 71.5 = 70.79% reduction in carbon intensity (21.02% further reduction).

Scrubber Mandate Card:
49.77 % reduction in carbon intensity

Point Source Unicorn Card:
70.79% reduction in carbon intensity (21.02% further reduction from scrubber mandate)

Anthropogenic Carbon Sequestration Cards:

Another potential defense against the accumulation of greenhouse gasses in our atmosphere is carbon sequestration. Many methods of sequestration are still in their infancy, however with enough capital and effort sequestration is possible. Due to the dynamic and ever evolving nature of the carbon capture industry, the price of sequestering carbon is hard to approximate, as some experts have observed (Baylin-Stern, 2021):

> CCUS applications do not all have the same cost. Looking specifically at carbon capture, the cost can vary greatly by CO_2 source, from a range of USD 15-25/t CO_2 for industrial processes producing “pure” or highly concentrated CO_2 streams (such as ethanol production or natural gas processing) to USD 40-120/t CO_2 for processes with “dilute” gas streams, such as cement production and power generation. Capturing CO_2 directly from the air is currently the most expensive approach, but could nonetheless play a unique role in carbon removal.

We will use a price of 100$/ tonne of sequestered carbon pulled directly from the air, assuming carbon sequestration companies will slightly subsidize the costs. We will assume we have 500 Billion USD to fund sequestration efforts.

$500 * 10^9 / 10^2 = 500 * 10^7 = 5 * 10^2 * 10^7 = 5 * 10^9$ tonnes carbon sequestered = 5 Gtc carbon removed from atmosphere using modern carbon sequestration methods.

As an added bonus, we consider the fact that an injection of 500 Billion dollars into this industry will likely make the technology and methods better. We will reflect this by making each subsequent use of the “Climate Control” card cost 20% less, meaning the sequestration is 20% more efficient.

Climate control:

Atmospheric carbon reduced by $5*(1+.2*(\text{previous uses of climate control}))$ GtC

Parameterizing Actions taken during Action Phases

In action phases, you fight against waves of greenhouse gasses on a time limit. Each gas enemy sequestered during an action phase removes 5 Gtc directly from the atmosphere. This value was decided using a combination of playtesting and calibration of the model. The model does not easily allow for negative emissions within the next 75 years, so sequestering gas enemies is a good way to achieve that effect with user input. Tougher enemies like methane gas plumes count as multiple enemies when sequestered, meaning more gas is removed from the atmosphere if stronger enemies are defeated.

Conclusions and Further Steps

Areas of Improvement

A game has many moving parts. A complete game is expected to have music, visuals, working game mechanics, and some kind of narrative. As a singular person with limited skills and time, I put the most time and effort into making sure the mechanics work properly. Also I had to limit the game to a demo or prototype version since making a complete game is a process that can take years. As a result, the finished project ended up with far fewer levels than I had planned. With the addition of more levels, I can highlight more aspects of the climate problem since each level is meant to focus on one of the many sides of the climate/ pollution problem.

Games have varying levels of “polish”, which is how good they look, sound, and play. Things like smooth animations when actions are taken, as well as user intuitive layouts and sounds are all polish. These things also tend to take time and effort to implement, which is why my completed Thesis will still be relatively unpolished. I hope to add polish to the game step by step after the Thesis deadline.

There are also some improvements that could be made to what was already implemented within the project. Realism in the decision cards is one area for improvement. Though I achieved a decent variety of decision cards, most change the same parameter in the model, which is carbon intensity related to energy. Even though the kind of energy we use is important, discussions around green energy are rather mainstream and a game meant to inform ought to illuminate alternative ways of reversing climate change. The realism of decision cards even in how they adjust the model could be improved as well. With a more thorough literature review and perhaps a more strict system of action and money value (like a uniform value or time span per action point), the cards could be much more realistic in how they adjust the model.
The model itself is great for the purpose of the game, but does not offer very much natural variability in climate outcomes. Each time you run the models with a set of parameters, the outcomes will be the same, a tendency that does not reflect the true natural variability of the climate. For a game in which repeated play is meant to reliably improve in-game outcomes, the feature of natural climate variability must be handled carefully. Nevertheless, adding this variability would better reflect the nuances of climate change.

Further Steps in Development

With more time to develop this project, I would prioritize adding a cohesive narrative, more decision cards that illustrate more facets of climate change, more levels or “rounds” between the start of the game and 2100, and better control of the model. The current structure of the game offers little to no narrative cohesion or motive. The player is thrust into the game and told to save the world with no context. Creating a captivating and memorable narrative behind the game would make the experience more enjoyable and memorable for users. As the main source of randomness in the game, adding decision cards could potentially spotlight more topics related to climate change. Existing decision cards would also be tweaked.

In the project's current form, rounds occur every 25 years, meaning a large amount of time passes during which the user cannot interfere. Adding more levels allows more chances for user interference. One very important limitation while implementing this project was that parameterizing the model can only be done once each round, meaning climate processes that ought to be expressed in increments over time had to be generalized and applied all at once instead. The model offers parameters like growth rates and growth factors to simulate incremental change, however things like yearly emissions reduction must be applied at once for a 25 year span, which is not optimal.

With more time put into development, an updated project would have a better narrative, more levels with objectives in each level (rather than endless waves of gas enemies), and better mechanics that are more realistic and interconnected.

Conclusion

Criticisms aside, the project turned out well and I achieved what I set out to accomplish. My original thoughts behind the project were that if people were going to memorize and subconsciously remember useless facts in the games they play like the fire rate of an alien gun or the relative strengths of different dragons, they might as well memorize useful facts and methods too. If more people remember ideas like "Energy is key to reducing emissions" or "burning down the Amazon is incredibly hard to recover from", perhaps collectively more impacts will be made with these topics in mind.

The goal was to create a user experience that teaches about climate activism in an engaging way. Many people may feel apathy about global warming because they feel like their actions do not really matter when compared to the actions of big corporations or governments. Since games are opportunities to escape from reality, a goal of this project was to make users feel like they can make a difference. In doing so the hope is that people take this feeling away from the game and into the real world.

Supplements

Supplement 1 (All Constant and Handoff Parameters in Dice Model)

Constants	Handoffs (Dynamic Variables)
Total unused fossil fuels	World Population
Elasticity of marginal utility of consumption	capital value
Initial rate of social time preference per year	level of total factor productivity
Capital elasticity in production function	growth rate for total factor productivity
Growth rate to calibrate to 2050 population projection	growth of carbon intensity
Asymptotic population	Carbon emissions from land
Depreciation rate on capital	Industrial emissions
Initial world gross output	cumulative emissions of trees
Decline rate of total factor productivity	cumulative industrial carbon emissions
Decline rate of decarbonization	cumulative total carbon emissions
Decline rate of land emissions	Carbon concentration in atmosphere
Initial emissions control rate for base case	Carbon concentration in upper ocean strata
Equilibrium concentration constant for atmosphere	Carbon concentration in lower ocean strata
Equilibrium concentration constant for upper strata	Carbon intensity
Equilibrium concentration constant for lower strata	Ocean lower stratum temperature change (from 1900)
Compartmental flow parameters * 7	Atmospheric temperature change (from 1900)
Equilibrium temperature impact (degrees celsius per Doubling Co2)	Cost of Backstop
2015 Forcings of non-CO2 GHG	Base carbon price
2100 Forcings of non-CO2 GHG	Emissions control rate
Climate equation coefficients * 3	Saving rate

Forcings at equilibrium per CO_2 doubling	Abatement cost
Initial climate damage intercept	
Initial damage quadratic term	
Climate Damage intercept	
Climate Damage Quadratic term	
Climate Damage Exponent	
Exponent of control cost function	
Cost decline of backstop per period	
Upper limit on control rate after 2150	
Emissions control threshold	
Growth rate of base carbon price per year	
Model scaling coefficients *2	

Supplement 2 (Decision Card Table):

Card Group	Card Title	Description	Parameter Adjustment	Action Point Cost	Money Cost
Carbon Tax	Carbon Tax! (I)	mandate global carbon tax	carbon base price = 16.87	1	0
	Carbon Tax! (II)	continuation of Carbon Tax(I)	carbon base price = 25	1	0
	Carbon Crackdown!	continuation of Carbon Tax(II)	carbon base price = 50	1	0
	Albedo Boost	reduce radiative forcing from greenhouse gases	2015 Forcings of non-CO2 GHG reduced by 26% 2100 Forcings of non-CO2 GHG reduced by 26%	1	0
Forest Sink/Source Cards	Slash and earn	Burn Amazon, gain money	Land Carbon Emissions increase immediately by 123 Gtc. Emissions from trees reduced by 10%	0	0
	Slash and turn	Burn Amazon, expand wind energy	Land Carbon Emissions increase immediately by 123 Gtc. Emissions from trees reduced by 10% Carbon intensity reduced by 40%	1	0
	Slash and Flash	Burn Amazon, expand solar energy	Land Carbon Emissions increase immediately by 123 Gtc. Emissions from trees reduced by 10% Carbon intensity reduced by 20%	1	0
	Tree Spree	plant billions of trees, sequester carbon	Carbon concentration in atmosphere reduced by 31.488 Gtc	0	1
	Tree Spree 2	continuation of Tree Spree	Carbon concentration in atmosphere reduced by 31.488 * 2 Gtc	0	1
Vehicle Regulation	Hybrid Vehicle Mandate	Mandate hybrid cars	Carbon intensity reduced by 5%	1	0
	Electric Vehicle Mandate	continuation of Hybrid Mandate	Carbon intensity reduced by another 5%	1	0

	Eat This!	Globally phase out animal products	Carbon concentration in atmosphere reduced by 25Gt * time skip length(years) * .25(realism constant) Gtc Carbon intensity reduced by 5.8%	2	0
	Nuclear Boom!	add more nuclear to global energy portfolio	Carbon intensity reduced by 3.526%	1	0
	Green Buildings	make buildings more energy efficient	Carbon intensity reduced by 5.25%	1	0
Point Source Carbon Capture	Scrubber Mandate	implement point source carbon capture	Carbon intensity reduced by 49.77%	2	0
	Point Source Unicorn	continuation of Scrubber Mandate	Carbon intensity reduced by a further 21.02%	2	0
Anthropogenic Carbon Sequestration	iterative climate control	sequester carbon from atmosphere, better each use	Carbon concentration in atmosphere reduced by 5*(1+.2*(previous uses of climate control)) Gtc	0	1
	Climate Control	sequester carbon from atmosphere	Carbon concentration in atmosphere reduced by 5Gtc	1	0
	Deep Sea Algae Bloom	reduce upper ocean carbon	Carbon concentration in upper ocean strata decreased by 30%	1	0
	Consumerist propaganda (cprop)	increase per capita consumption, gain money	Elasticity of marginal utility of consumption increased by 10%	0	0
	Anticonsumerist propoganda	decrease per capita consumption	Elasticity of marginal utility of consumption decreased by 10%	1	0
	Activism	more ap next phase		1	0
	Activism +	even more ap next phase		2	0
	Reinvest	gain more money in future phases		0	1

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