GREEN RENOVATOR: A SERIOUS GAME FOR AWARENESS-RAISING IN SUSTAINABLE URBAN ENERGY MANAGEMENT AND BUILDING RETROFITS

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ABSTRACT

GREEN RENOVATOR: A SERIOUS GAME for AWARENESS-RAISING in SUSTAINABLE URBAN ENERGY MANAGEMENT and BUILDING RETROFITS

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This thesis presents Green Renovator, a serious game designed to raise public awareness of city-scale energy management grounded in a real neighborhood dataset. Following a width-over-depth design philosophy, the game puts the player in the shoes of a local authority that is responsible for building retrofit investments, energy supply mix choices, technology adaptations, policy instruments, and public response. It integrates these into a single, comprehensible gameplay loop. Uncertainty and a higher replay value are introduced through a random-event system that models realistic shocks and frictions. At the same time, an in-game encyclopedia and an optional yearly quiz help with reflection and self-directed learning.

The game was evaluated with N = 55 participants using a mixed-methods protocol: the System Usability Scale (SUS), a purpose-built awareness and perceived-learning questionnaire, and a complementary engagement/usability questionnaire, alongside open-ended prompts for qualitative insight. Results indicate acceptable-to-good usability and consistently positive outcomes across all three instruments, with many effects statistically meaningful. Thematic analysis of open-ended responses suggests that players recognized interdependencies among retrofit decisions, energy supply choices, governance tools, and citizen reaction, and highlighted opportunities for expanding event diversity and policy depth in future versions.

Overall, the study offers a practical design for awareness-oriented, city-scale simulation and an evaluation showing educational promise. The findings support the claim that thoughtfully scoped, replayable simulations can make the complexity of urban energy decisions tangible for non-experts while remaining pedagogically effective.

Keywords: Serious Games, Game-Based Learning, Urban Energy Efficiency, UN SDGs

ÖZ

GREEN RENOVATOR (YEŞİL DÖNÜŞTÜRÜCÜ): SÜRDÜRÜLEBİLİR KENTSEL ENERJİ YÖNETİMİ VE BİNA RENOVASYONLARINDA FARKINDALIK ARTIRMAYA YÖNELİK BİR CİDDİ OYUN

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Bu tez, gerçek bir mahalle veri setine dayanan ve kentsel ölçekte enerji yönetimine ilişkin kamu farkındalığını artırmak üzere tasarlanmış Green Renovator adlı ciddi oyunu ele almaktadır. Derinlikten çok kapsamı önceleyen bir tasarım yaklaşımı izleyen oyun, bina renovasyon yatırımları, enerji kaynaklarının yönetimi, teknoloji uygulamaları, politika geliştirme ve kamu tepkisinden sorumlu bir yerel otoritenin yerine koyar. Bu unsurları anlaşılır bir oyun döngüsünde bütünleştirmeyi hedefler. Olasılık temelli bir rastlantısal olay sistemi ile oyunda beklenmedik olayların üstesinden gelme imkânı sunarken aynı zamanda tekrar oynanabilirliği artırmayı hedefler. Oyun içi ansiklopedi ve isteğe bağlı yıllık kısa sınav vasıtasıyla bağımsız öğrenmeyi destekler.

Oyun, N = 55 katılımcı ile karma yöntemli bir protokolle değerlendirilmiştir: Sistem Kullanılabilirlik Ölçeği (SUS), amaç-odaklı bir farkındalık ve algılanan öğrenme anketi ve tamamlayıcı bir etkileşim/kullanılabilirlik anketi uygulanmış; nitel içgörü için açık uçlu sorular eklenmiştir. Bulgular, kullanılabilirliğin kabul edilebilir–iyi aralığında olduğunu ve üç ölçekte de tutarlı biçimde olumlu sonuçlar elde edildiğini; birçok sonucun istatistiksel olarak anlamlı olduğunu göstermektedir. Açık uçlu yanıtlarla yapılan analiz, oyuncuların bina renovasyon kararları, enerji kaynak yönetimi, politik kararlar ve kamu tepkisi arasındaki ilişkileri ve etkileşimleri fark ettiğini belirtmiştir. Gelecek sürümler için içerik çeşitliliğinin ve politik derinliğin artırılmasına yönelik önerilerde bulunmuştur.

Genel olarak çalışma, farkındalık odaklı bir ciddi oyun için uygulanabilir bir tasarım ve eğitsel potansiyeli gösteren bir değerlendirme sunmaktadır. Bulgular, kapsamı iyi değerlendirilmiş bir ciddi oyunun, kentsel enerji yönetiminin detaylarını alan dışı bireyler için somutlaştırırken eğitimsel anlamda etkili olabildiğini desteklemektedir.

Anahtar Sözcükler: Ciddi Oyunlar, Oyun Tabanlı Öğrenme, Kentsel Enerji Verimliliği, BM Sürdürülebilir Kalkınma Amaçları

To the Curious Jolly Kid I Was 25 Years Ago

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TABLE OF CONTENTS

ABSTRACT iv
ÖZ v
DEDICATION vii
ACKNOWLEDGMENTS viii
TABLE OF CONTENTS ix
LIST OF TABLES xii
LIST OF FIGURES xiii
LIST OF ABBREVIATIONS xiv
1. INTRODUCTION 1
1.1. Background and Context 1
1.2. Purpose of the Study 3
1.3. Developed Serious Game and Approach 3
1.4. Contributions and Novelties 4
1.5. Outline of the Thesis 5
2. LITERATURE REVIEW 7
2.1. Urban Sustainability and the UN Sustainable Development Goals (SDGs) 7
2.2. Complex Urban Energy Systems and Stakeholder Dynamics 8
2.3. Serious Games for Sustainability Awareness 10
2.4. Knowledge Gaps in Current Literature and Games 13
3. DESIGN AND DEVELOPMENT OF THE GAME 15
3.1. Data Source and Link to the TÜBİTAK 1004 Program 15
3.2. Game Concept and Design Rationale 16
3.2.1. Game Design Philosophy and Educational Objectives 16
3.2.2. Target Audience and User Experience Goals 18
3.3. Game Mechanics and Gameplay 19
3.3.1 Role of Player as the “Green Renovator” 19

3.3.2 Game Core Loop 19
3.3.3 City Exploration and Navigation....21
3.3.4 Building-Level Inspections and Renovations 21
3.3.5 Heatmap Visualizations....27
3.3.6 Quick Construction Mechanic....29
3.3.7 Management of Energy Sources 30
3.3.8 Political Dynamics and Policies....35
3.3.9 Technology Panel and Tech Trees 39
3.3.10 Encyclopedia Panel....41
3.3.11 Random Events System....44
3.3.12 Quiz Mechanic ("Annual Competency Assessment")....45
3.4. Technical Development in Unity....47
3.4.1 City Environment Creation 47
3.4.2 Integration of ML Model....50
4. METHODOLOGY FOR EVALUATION AND TESTING....53
4.1. Research Design 53
4.2. Procedure for Game Testing....53
4.3. Data Collection Instruments 53
4.4. Data Analysis Methods....54
5. RESULTS AND FINDINGS 57
5.1. Methods Used (in alignment with Chapter 4) 57
5.2. Participant Demographics and Background 57
5.3. Analysis of Awareness Improvement/Impact Questionnaire....58
5.4. Usability Engagement and Aesthetics Questionnaire Evaluation 59
5.5. System Usability Scale (SUS) Evaluation 60
5.6. Demographic Effects and Additional Insights 61
6. DISCUSSION 67
6.1. Interpretations of Findings 67
6.2. Implications for Urban Energy Management Awareness 67
6.3. Reflection on Some Lessons Learned 68
6.4. Limitations of the Study....69

6.5. Recommendations for Future Research 69
7. CONCLUSION 71
REFERENCES 75
APPENDICES 87
APPENDIX A 87
APPENDIX B 89
APPENDIX C 91
APPENDIX D 93

LIST OF TABLES

Table 1: Insulation Properties in the Game by Different Retrofit Grades. 25
Table 2: Unit Costs of Insulation Retrofits. 26
Table 3: Energy Sources with Their Unit Prices and Unit Carbon Footprints.................32
Table 4: Investment Blocks Used in the Game (Turnkey EPC). 33
Table 5: CAPEX ($/kW) and Capacity Factor (CF) Assumptions Used in the Game.....34
Table 6: List of all Available Policies in the Game with their Costs and Effects. 38
Table 7: Results of the Subsections of the Impact Questionnaire....................................58
Table 8: Results of the Subsections of the Usability-Engagement-Aesthetics (UEA) Questionnaire. 59
Table 9: SUS by Demographic Groups...62
Table 10: UEA (Overall) by Demographic Groups. 63
Table 11: Impact (Overall) by Demographic Groups. 64

LIST OF FIGURES

Figure 1: Visualization of the Game Loop. 20
Figure 2: In-Game Top-Down City View. 21
Figure 3: Building Inspection Panel. 22
Figure 4: Hint Panel Explaining U-Values and Infiltration. 23
Figure 5: The Preview of Insulation and the Resulting Heating Energy Changes When the Player Is Hovering on the C-Grade Insulation Upgrade (The Cursor Is Not Visible). 24
Figure 6: Heatmap Visualization Displaying the Total Heating Energy Use Distribution Along the City. 28
Figure 7: Screenshot of the Heatmap Displaying Return on Investments on Buildings as a Percentage. 29
Figure 8: A Screenshot of the "Quick Construction" Mechanic in Action. 30
Figure 9: Screenshot of the Energy Source Management Panel. 31
Figure 10: Energy Capacity Investment Panel. 33
Figure 11: The Policy Panel and the Details of a Policy. 37
Figure 12: The Tech Tree of an Energy Source (Hydroelectric). 40
Figure 13: Screenshot of the Management Systems Technology Tree. 41
Figure 14: Screenshot of the Encyclopedia Panel. 44
Figure 15: A Random Event That Takes Place at the Start of a Turn (Hurricane). 45
Figure 16: A Sample Question from the Annual Competency Test. 46
Figure 17: The Top-Down View of the Initial Neighborhood Model Placed on the 2D Map of the Original Location. 48
Figure 18: The View of the Neighborhood with Aggregated Building Blocks and the New Environment Handling the Neighborhood as an Isolated Town. 49
Figure 19: The View After Placing the 3D Models to the Building Placeholders. 50
Figure 20: System Usability Scale (SUS) Benchmarks with Study Score 61
Figure 21: 7-step Likert Scale used in the Impact Questionnaire. 87
Figure 22: 7-step Likert Scale used in the Usability, Engagement & Aesthetics Questionnaire. 89
Figure 23: System Usability Scale. 91

LIST OF ABBREVIATIONS

α	Cronbach’s alpha (internal consistency)
ACH50	Air Changes Per Hour at 50 Pascals (Blower-Door Test Metric).
AIS	Address Inquiry System (municipal parcel/building database).
AR5	IPCC Fifth Assessment Report
BoS	Balance of System (non-module components in a PV system)
CAPEX	Capital Expenditure (capital cost of building new capacity)
CCGT	Combined Cycle Gas Turbine (natural-gas power plant type)
CF	Capacity Factor (average utilization of a generator)
CI	Confidence Interval
CO2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
CPU	Central Processing Unit
CSV	Comma-Separated Values
df	Degrees of Freedom
EIA	U.S. Energy Information Administration
Ember	Ember (independent energy think tank)
EPC	Engineering, Procurement, and Construction (investment context)
EPCs	Energy Performance Certificates (dataset context)
EPS	Expanded Polystyrene (insulation material)
EU	European Union
GIS	Geographic Information System
GPU	Graphics Processing Unit
IEA	International Energy Agency
IEA PVPS	IEA Photovoltaic Power Systems Programme
IEEFA	Institute for Energy Economics and Financial Analysis
IOD	Indoor Overheating Degree
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
kW	Kilowatt (unit of power)

kWh	Kilowatt-hour (unit of energy)
LCOE	Levelized Cost of Energy/Electricity
ML	Machine Learning
MLP	Multilayer Perceptron
MWh	Megawatt-Hour (unit of energy)
NPS	Net Promoter Score (used for SUS framing)
ONNX	Open Neural Network Exchange (model format)
PHPP	Passive House Planning Package
PWR	Pressurized Water Reactor
PV	Photovoltaic (solar)
Q1/Q3	First/third Quartiles
QHeating	Annual Heating Energy Demand
ROI	Return on Investment
SD	Standard Deviation
SDG	Sustainable Development Goal
SDGs	Sustainable Development Goals
SHURA	SHURA Energy Transition Center
SUS	System Usability Scale
TMY	Typical Meteorological Year
TRY	Turkish Lira
TS 825	Turkish Standard 825: Thermal Insulation Requirements for Buildings
TSE	Turkish Standards Institution.
TÜBİTAK	The Scientific and Technological Research Council of Turkey
UBEM	Urban Building Energy Modeling
UEA	Usability-Engagement-Aesthetics (questionnaire)
UI	User Interface
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
USD	United States Dollar
URP	Universal Render Pipeline (Unity)
VAT	Value-Added Tax
WNA	World Nuclear Association
Wp	Watt-peak (rated PV power per area)
YEKA	Yenilenebilir Enerji Kaynak Alanları / Renewable Energy Resource Areas (Turkey)
YEKDEM	Renewable Energy Support Mechanism (Turkey)

CHAPTER 1

INTRODUCTION

1.1. Background and Context

Rapid urbanization and climate change have made energy efficiency and sustainable energy management critical priorities for cities worldwide. Today, more than half of the world's population lives in urban areas, and this figure is projected to reach nearly 70% by 2050 (Urban Development Overview, n.d.). To accommodate this growth sustainably, cities need to become more energy-efficient and environmentally resilient.

Cities currently consume about two-thirds of the world's energy and generate over 70% of global greenhouse gas emissions (Urban Development Overview, n.d.), making urban areas pivotal in the fight against climate change. Within cities, buildings also play a significant role – "they are responsible for about 40% of global energy consumption and about one-third of global greenhouse gas emissions" (Buildings Are the Foundation of Our Energy-Efficient Future, 2021). Improving the energy performance of buildings and urban systems, therefore, offers enormous potential for reducing emissions and meeting climate targets. Enhancing efficiency is often cited as one of the fastest and most cost-effective ways to bolster energy security, cut costs, and address environmental challenges (Grossman et al., 2018).

Recognizing this urgency on a global scale, initiatives like the United Nations' Sustainable Development Goals (SDGs) have put city sustainability and energy efficiency at the forefront. SDG 11 (Sustainable Cities and Communities) promotes transforming urban energy use and infrastructure in ways that support both people and the planet. SDG 7 (Affordable and Clean Energy), and Target 7.3 to be specific, explicitly calls for doubling the global rate of improvement in energy efficiency by 2030 ("Goal 7," n.d.). Likewise, progress on SDG 13 (Climate Action) relies on curbing urban emissions through cleaner energy and more innovative energy use. Thus, sustainable energy management and efficiency are not just technical targets – they are fundamental to sustainable development, climate stability, and the creation of habitable cities for future generations.

However, despite the evident importance of energy efficiency and these high-level commitments, translating these goals into action on the ground is far from straightforward. Raising public awareness and motivating action at both the individual and community levels remains challenging. Firstly, many people lack accurate information about energy efficiency or underestimate its benefits. Misinformation and personal biases can lead to scepticism about the real impact of individual actions. This scepticism is often exacerbated by the delayed and intangible benefits of efficiency improvements, which typically have upfront costs and payback periods extending over many years. A homeowner may only recover the costs of high-efficiency renovations after 15–20 years, a timeframe that is difficult to appreciate in day-to-day life. Without an immediate payoff, a mindset of "why bother now?" can overshadow consideration of long-term advantages, and conventional awareness campaigns often struggle to communicate these long-term benefits in a compelling way.

Secondly, the scale and complexity of urban energy systems make it hard for individuals to see how their actions fit into the bigger picture. Urban sustainability involves many stakeholders—including residents, building owners, city planners, utilities, and policymakers—and many interdependent decisions. It is challenging for a single homeowner to grasp how their home's energy efficiency contributes to city-wide sustainability goals, or how the collective impact of thousands of similar decisions (or policies like green building codes) truly adds up. Traditional outreach methods (brochures, public service announcements, community workshops, etc.) provide general advice but cannot easily demonstrate city-scale outcomes. As a result, people may not connect their personal actions to broader sustainability goals, or they might feel the issue is too large to influence.

Traditional educational approaches have had limited success in overcoming these challenges. For example, simply reading about kilowatt-hours saved or CO_2 reduced in a pamphlet might convey information, but it rarely inspires action since the experience is neither engaging nor vivid enough.

Given the shortcomings of conventional approaches, educators and researchers have explored more interactive ways to engage the public on energy issues. One promising approach is the use of digital games and simulations to foster learning and motivation. A substantial body of literature shows that well-designed digital games can support learning and retention, often outperforming traditional instructional methods in keeping learners motivated. Meta-analyses have found positive overall effects of digital games on both learning outcomes and motivation (Clark et al., 2016; Wouters et al., 2013). In sustainability and climate education specifically, combining role-play with interactive simulation has yielded significant gains in participants' knowledge, sense of concern, and support for action (Rooney-Varga et al., 2018). Yet accessible city-scale awareness tools that (i) make urban energy trade-offs tangible, (ii) connect building-level retrofit choices to outcomes in annual energy use, emissions, budgets, and even political approval, and (iii) are rigorously evaluated for their impacts on awareness and usability remain comparatively scarce.

1.2. Purpose of the Study

To bridge this gap, this thesis introduces an interactive simulation game developed in Unity engine as a novel tool for raising awareness about energy efficiency and its trade-offs. The idea is to provide an engaging, "safe-to-fail" environment where players can explore different decisions and witness the outcomes firsthand. This serious game is essentially a city-scale energy management simulation that puts the player in charge of making a virtual city more energy efficient and sustainable. The design emphasizes breadth of understanding over technical depth — an "approachable width" philosophy aimed at giving users comparative insights without overwhelming detail. Thus, the game is focused on raising awareness for general audiences rather than providing advanced technical training, though it can easily be adapted for more professional educational settings as well.

1.3. Developed Serious Game and Approach

In the game, players are immersed in a realistic urban scenario. This experience lets them confront complex situations that would be impossible to observe directly in real life, such as the long-term evolution of a city's carbon footprint or energy grid as efficiency measures accumulate. By learning through doing, players gain a tangible understanding of how different actions (like retrofitting homes or implementing city policies) play out over time.

Unlike real life, where the effects of energy investments unfold over decades, the game accelerates time and provides immediate feedback. Players might implement an energy retrofit on a building and then see — within minutes of gameplay — the resulting reduction in energy use, emissions, and costs over the next 20 years of simulated time. This compression of timescales helps users grasp long-term benefits and trade-offs at a glance. Outcomes that would remain "invisible" in day-to-day life become visible on the screen; for example, investing in better insulation today visibly leads to a significant drop in city-wide energy demand and carbon emissions by turn 20, along with financial savings. Such instant feedback makes the value of energy efficiency much more precise and convincing than static numbers in a report.

The game also provides a risk-free sandbox to experiment with different strategies. Players can test various combinations of actions – from upgrading insulation in individual houses, to building solar farms, to enacting new city energy policies – without real-world consequences. This encourages exploration and learning from mistakes. If a strategy does not yield the expected outcome in the simulation, the player can see the shortfall and adjust their approach, all within a safe environment. This trial-and-error freedom helps demystify the complexity of urban energy systems. Players can discover, for instance, how a policy encouraging home retrofits might work better when combined with investments in renewable energy. This kind of interactive, systems-thinking experience is rarely achieved through traditional lessons.

Most importantly, the game is designed to be enjoyable and approachable. By incorporating elements of fun and challenge, it captures and holds users' attention more effectively than a lecture or brochure. The interactive visuals (such as a city energy heatmap and dashboard indicators) make the data intuitive and engaging. Because it feels like play, the experience is not intimidating – users of various backgrounds can dive in without feeling overwhelmed by technical jargon. This lowers the barrier that often exists in sustainability education, making learning about energy both accessible and appealing to the general public. An engaging game can also be replayed, reinforcing learning through repetition. In short, the medium of a serious game turns a potentially dry topic into an interactive story in which the user becomes an active participant.

To evaluate the effectiveness of this game-based approach on awareness raising, the thesis follows a design-science research methodology coupled with human–computer interaction (HCI) evaluation. The game is treated as an intervention, and its value is assessed through a mixed-methods study comprising: (i) post-play self-report measures of awareness and learning; (ii) the System Usability Scale (SUS) questionnaire, interpreted against benchmark scores; and (iii) brief qualitative feedback that captures players' narratives and contextualizes the quantitative results. This combination of methods balances statistical rigor with design insight, following best practices in usability and learning research (Bangor et al., 2009; Brooke, 1996; Clark et al., 2016; Wouters et al., 2013).

1.4. Contributions and Novelties

Taken together, these features directly allow the simulation game to address the awareness barriers discussed earlier. It vividly demonstrates the impact of individual and collective actions on a city's sustainable future, making the once-abstract concept of urban energy efficiency far more concrete and relatable. Immediate feedback and accelerated timelines counter the problem of delayed, intangible benefits by showing outcomes right away, while the city-scale sandbox helps players see how personal choices aggregate to broader impacts. By aligning the gameplay with real-world data and sustainability principles, the tool also aims to reinforce the SDGs by raising players' awareness on practical ways to contribute to goals like SDG 7 and SDG 11 in their communities.

Overall, the focus of this thesis on a serious gaming approach is significant because it offers a novel and effective way to raise awareness about sustainable energy management. By engaging people in a hands-on, experiential learning environment, the project helps close the gap between understanding the importance of energy efficiency and actually taking informed action toward it. The following sections will elaborate on the development of this game-based approach and discuss how it can ultimately help foster a culture of energy consciousness and sustainability at the city scale.

1.5. Outline of the Thesis

Chapter 1 introduces the motivation, problem context, research questions, and contributions of the study, and positions the serious-game approach within urban energy awareness. Chapter 2 reviews the literature on serious games, sustainability education, complex urban energy systems, and awareness tools to establish the conceptual foundation and gaps addressed. Chapter 3 presents the game's data source and link to the TÜBİTAK 1004 program, then details the design philosophy, core mechanics, and interfaces, and the technical implementation in Unity, including supporting systems and integrations. Chapter 4 explains the evaluation methodology, covering participants, instruments (e.g., SUS and purpose-built awareness/engagement measures), data collection procedures, and the analysis plan. Chapter 5 reports the quantitative and qualitative findings derived from these instruments and open-ended responses. Chapter 6 discusses the implications of the results for sustainability awareness and game-based learning, outlines limitations, and proposes directions for future development and research. Chapter 7 concludes by summarizing key insights and contributions, reflecting on practical significance, and offering recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1. Urban Sustainability and the UN Sustainable Development Goals (SDGs)

Rapid urbanization has made cities pivotal in achieving global sustainability targets. Urban areas currently consume the majority of the world's resources and energy, and produce a correspondingly large share of emissions. For instance, cities account for around 65% of global energy use and over 70% of carbon emissions (Almulhim et al., 2024). This could mean that progress on sustainable development is essentially won or lost in cities.

The United Nations Sustainable Development Goals (SDGs), adopted in 2015 as part of the 2030 Agenda for Sustainable Development, provide a comprehensive and ambitious framework for addressing global challenges such as poverty, inequality, environmental degradation, and climate change. These 17 goals aim to tackle the three inseparable pillars of sustainable development: the economy, social development, and the environment. These pillars of sustainable development are so reliant on each other that none can stand without one.

Among the SDGs, SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) are particularly relevant to the urban energy landscape and will be elaborated further for the purpose of this thesis.

SDG 7 (Affordable and Clean Energy)

Promoting universal access to reliable and equitable energy, SDG 7 "aims to achieve 'energy for all' by improving energy security for the world's poor while supporting a global transition toward low-carbon energy sources" (Burke & Melgar, 2022).

SDG 11 (Sustainable Cities and Communities)

The definition of Goal 11 as part of the UN Sustainable Development Agenda for 2030 represents the recognition of the importance of addressing the link between urbanization and sustainable development (Blasi et al., 2022). This goal specifically aims to "ensure inclusive, safe, resilient, sustainable urban and human settlements by providing inexpensive transit solutions, decreasing urban sprawl, enhancing urban governance involvement, improving the protection of cultural assets and addressing urban resilience and climate change issues" (Kufeoglu, 2022).

SDG 13 (Climate Action)

It is imperative to undertake urgent measures to address climate change and its associated impacts. SDG 13 mandates reductions in greenhouse gas emissions and the strengthening of climate resilience. Considering that urban areas are significant contributors to emissions, decarbonizing urban energy systems is essential for achieving SDG 13.

These three goals are deeply interconnected in urban contexts. Achieving cleaner energy (SDG 7) in cities yields co-benefits for climate mitigation (SDG 13) and is a core strategy for sustainable urban development (SDG 11).

It can now be recognized that to thrive sustainably, clean energy provision, resilient infrastructure, and climate responsiveness must be integrated. SDGs 7, 11, and 13 are mutually reinforcing: affordable clean energy sustains services; sustainable cities can provide equitable, low-impact living; and climate action ensures long-term stability and resilience. Urban policies are increasingly reflecting this convergence through the implementation of integrated planning, energy sufficiency measures, and climate preparedness initiatives, thereby fostering cities that are just, efficient, and prepared for the future.

2.2. Complex Urban Energy Systems and Stakeholder Dynamics

Urban energy systems are complex socio-technical systems, encompassing not only physical infrastructure but also human and institutional elements. Technically, an urban energy system includes the hardware and software of energy generation, distribution, and consumption – power plants, grids, pipelines, buildings, appliances, and more. However, equally important are the social and political dimensions since “urban energy systems are socio-technical systems not only comprising of technical components like pipes, cables, transformers and the like, but also of social aspects pertaining to end-consumers, customer preferences, institutions, regulation, social structures and social practices” (Keirstead et al., 2012). Because of this, transforming urban energy systems is not merely a technical endeavor “there must be a more deliberate focus on issues such as power dynamics, political considerations, and social justice within smart city initiatives to ensure that they align with the broader social objectives encapsulated in the SDGs”(Sharifi et al., 2024). In line with this, literature stress that “the way in which cities can best address conditions of change and restructuring is to adopt a holistic and integrated approach to city development” which technocentric urban planning may lack (Blasi et al., 2022).

Within this broader framing, stakeholder dynamics are at the center. Multiple stakeholders – from public, private, and civil society sectors – are involved in urban energy decision-making. Key stakeholder groups include: local governments (municipal authorities and city planners), national or regional government agencies, energy utilities and companies (both public and private), industry and businesses, community organizations, and individual citizens/energy consumers. Each brings a unique role and perspective. For instance, city governments shape local energy policy and land use; they are often instrumental in implementing projects like transit electrification or building retrofits.

Indeed, local authorities are seen as “instrumental in achieving national commitments and objectives” regarding energy and sustainability, acting as the interface between community action and broader goals (IEA, 2024). Additionally, the private sector provides investment and innovation, operating much of the energy infrastructure under regulatory oversight. Communities and residents are both the end-users of energy and increasingly active participants (for example, as rooftop solar producers or through community energy cooperatives). Evidently, “in the United Kingdom, more than 200,000 people are engaged in projects and have contributed to reduced bills for participants worth over GBP 3 million” (IEA, 2024). Therefore, engaging the public is also essential, as citizen behavior directly impacts outcomes.

The relevant literature emphasizes such diversity requires collaboration as “sustainable energy development at the local level depends on an interplay between local government agencies, Non-Governmental Organizations (NGOs), central government agencies, local communities, and private sector organizations” (Qudrat-Ullah et al., 2020). Each stakeholder holds certain responsibilities – for example, national governments can set enabling policies or funding, municipalities can enact and enforce local ordinances (like building codes or urban plans for energy), utilities manage grid reliability and integrate new energy sources, and community groups can voice local priorities or pilot projects. “A range of stakeholders needs to take many different actions, including investing in renewable energy technologies, increasing the energy efficiency of buildings and appliances, and changing energy use behavior into energy-saving habits and practices” (Ouariachi et al., 2018).

Although the collaboration is essential, the interactions among stakeholders can be complex. There may be differing priorities (economic vs. environmental goals, for instance) or imbalances in influence and power among the stakeholders. For this reason, effective governance and coordination are critical. Scholars highlight the need for multi-level governance, emphasizing that “a sustainable energy transition requires a transformation in both the energy sector and society. This requires actions to be transposed into energy and climate policies developed in the coordination of multiple levels of government. However, the realization of the energy and climate goals cannot be achieved only through top-down activities from a national government.”(Dobravec et al., 2021).

In order for these challenges to be addressed properly, they “should be tackled in multiple dimensions -technology, society, economics, law, regulations, and politics- at different temporal and spatial scales. Holistic approaches will enable technological solutions to be supported by socio-economic motivations, adequate incentive regulation to foster investment in green infrastructures coherently integrated with adequate energy provisioning schemes” (Ajmone-Marsan et al., 2012).

2.3. Serious Games for Sustainability Awareness

Definition and Historical Development of Serious Games

“Serious games” are games created with a purpose other than pure entertainment—typically to educate, inform, or have an influence on important issues. The term was first introduced by Clark C. Abt in 1970, acknowledging the potential of game-playing for education and training. In today’s context, Michael and Chen (2006) define serious games as “games that do not have entertainment, enjoyment, or fun as their primary purpose” (Michael & Chen, 2006). To put it another way, serious games are essentially purpose-driven, even though they are still aimed to be entertaining and engaging. The field of serious games has grown over the last 20 years in tandem with advancements in digital technology. Initiatives such as the Serious Games Movement, led by Ben Sawyer and others, encouraged the use of video games for social and educational objectives in the early 2000s. Since then, a variety of industries, including healthcare, military training, and environmental education, have made use of serious games. From basic analog simulations (such as board games and role-playing activities used in workshops or classrooms) to sophisticated digital simulations and virtual reality experiences, the development history spans a broad spectrum.

Notably, serious games come in both analog and digital formats (Maxim & Arnedo-Moreno, 2025). Analog serious games include board games, card games, or live-action role plays designed with learning objectives. Digital serious games, however, run on computers or mobile devices and often allow single-player or online multiplayer interactions in a simulated environment. Each format has its advantages. Analog games excel at face-to-face interaction, discussion, and social learning in group settings. Digital games offer greater scalability and flexibility, “their flexibility in use and scalability offer important advantages over traditional formats. An online game is scalable as it can, once developed, teach large groups of trainees with no extra costs per person” (Dankbaar et al., 2017). Because of these benefits, digital serious games are often seen as preferable when the aim is broad dissemination and easy iteration of the content. A software-based sustainability game can be distributed widely and improved continuously, whereas a physical game might be limited to workshop contexts.

In sustainability contexts, we find both types. For example, Cordaid’s Urban Collaboration Game is a tabletop serious game developed to help stakeholders collectively address urban planning challenges (CORDAID, 2014), whereas digital games like SimCityEDU or Mission 1.5 (a UN climate action game) leverage technology to engage players on environmental issues. The key is that all serious games, analog or digital, harness the motivational aspects of gameplay – competition, narrative, problem-solving – in the service of learning about real-world issues.

Case Studies of Serious Games on Sustainability

Using games to promote sustainability awareness has proven to be a powerful approach. Serious games can translate complex environmental and energy concepts into interactive experiences, allowing players to learn by doing. Research in environmental psychology and education has generally found that well-designed serious games increase players' knowledge and awareness of sustainability issues (Chen et al., 2024). By immersing players in simulated scenarios – such as managing a city's energy grid or coping with climate disasters – games provide experiential learning that traditional instruction often cannot. For example, the review by Chen et al., 2024 notes that environmental serious games have effectively enhanced players' understanding across topics like waste management, water conservation, agriculture, and energy use.

Several serious games focused on sustainability have been developed and thoroughly analyzed. These encompass both digital simulations and traditional analog games, as well as hybrid formats that combine elements of both. Several illustrative case studies include:

- EnerCities: EnerCities is a digital simulation game in which players build and expand a virtual city while managing its energy resources and environmental impact. The game was used in European schools to educate students about renewable energy, efficiency, and urban sustainability. It was found that the game increased students' energy-related knowledge and led to more positive attitudes regarding daily energy-related behaviors (Knol & De Vries, 2011). EnerCities exemplifies how a city-management game can convey the trade-offs between economic development and environmental protection in a playful format.

- We Energy Game: The We Energy Game is an analog serious board game developed in the Netherlands to create awareness on the challenges regarding the provision of energy from renewable sources (Ouariachi et al., 2018). In this game, players take on roles (such as municipality, energy company, citizens) and work together to supply a town with renewable energy, aiming for an energy-neutral community. The game uses real-world data and challenges players to negotiate solutions that balance different interests. The We Energy Game is often played with mixed groups of officials, experts, residents and students bringing different parties together (Ouariachi et al., 2018). Its "added value is that it brings multiple parties together", sparking dialogue between municipal authorities and community members (Entrance, n.d.). Ouariachi et al. (2018) found that the game successfully increased participants' understanding of the complexities of renewable energy planning (cognitive engagement) and also evoked interest and concern (affective engagement). The We Energy Game demonstrates how a serious game can serve as a stakeholder engagement tool, not just an educational tool – it facilitates conversations that might not happen in a typical meeting format.

- Climate Action Simulation (role-play): This is an in-person simulation game (developed by Climate Interactive and MIT) where groups of participants role-play the different stakeholders and explore solutions regarding energy climate change policies.

“Participants gain an understanding of the scale and urgency of climate action, the impact of different policies and actions, and the dynamics and interactions of different policy choices” (Rooney-Varga et al., 2018). While not digital, it is a serious game in workshop form. Studies on this simulation indicate that participants gain insight into the policy choices and experience a greater sense of urgency and empowerment regarding climate action after the game (Rooney-Varga et al., 2018). This case underlines the value of role-playing games for building empathy and understanding in sustainability contexts.

- Other Digital Games: Beyond the examples discussed above, many digital serious games address sustainability challenges. Fate of the World is a PC strategy game that puts the player in charge of global climate policies over the 21st century, teaching the difficult balance of economy, politics, and emissions. Eco is a collaborative online game where players create a civilization in a detailed ecosystem, forcing them to consider environmental limits. Even entertainment games like SimCity or Cities: Skylines have been recognized for their educational value in urban planning and sustainability, leading to specialized scenarios/mods (e.g., scenarios about greening a city) that effectively function as serious game content. These digital games offer the advantage of scale – thousands of players worldwide have tried them – and they can be iteratively improved or customized for different learning outcomes.

One of the reasons serious games are considered effective for sustainability education is their ability to make abstract problems concrete and to engage emotions and values, not just intellect. Players experience consequences (a city running out of power, a forest degrading, etc.) in a simulated environment, which can make the learning “stick” better than reading a report. Games also provide immediate feedback and allow for experimentation; players can try out different approaches (e.g., invest more in solar energy vs. fossil fuels) and see simulated outcomes, learning from failure in a safe space. Moreover, the fun and competitive elements of games can motivate continued engagement with topics that might otherwise seem daunting or dry. That said, researchers caution that serious games are not a panacea since “virtual environments may inadvertently lead to misconceptions among players, blurring the lines between in-game actions and real-life environmental behavior. Moreover, to enhance gameplay enjoyment, developers might oversimplify or inaccurately represent environmental information. Lastly, immediate post-game evaluations may not accurately capture long-term psychological shifts among participants”(Chen et al., 2024). If a game is too simplistic or if players fail to connect it to reality, its impact may be limited. Therefore, current best practices in serious gaming for sustainability emphasize careful design (with real data and stakeholder input for realism) and integration of games into broader educational or engagement strategies.

Serious games have emerged as a promising approach to raise awareness and knowledge about sustainability. Digital games, especially, can act as an important tool when designed carefully, engaging the public and stakeholders on complex urban sustainability issues in a way that is interactive, memorable, and action-oriented.

2.4. Knowledge Gaps in Current Literature and Games

Despite the growing use of serious games for sustainability, there are notable gaps and limitations in the existing literature. One key gap is that many serious games remain in pilot or prototype stage and are not widely accessible or utilized outside research or educational settings. There is a gap in understanding how to scale up serious games from small group interventions to broader public engagement tools. Therefore, educators and practitioners often lack guidance on integrating serious games into curricula or community programs. As Ouariachi et al. (2018) note, despite interest in using games for sustainability education, teachers often report lacking information on "the nature of these resources, as well as on how to implement them in formal education". This indicates a need for more practical research into implementation strategies and best practices for serious games in real-world settings.

There are also gaps in the breadth of stakeholder engagement achieved by current sustainability games. Many existing serious games target either a general audience or a specific group (such as students or professionals). However, few are designed to bring multiple stakeholder groups together in the same gameplay experience. The earlier example of the We Energy Game is an exception, aiming to facilitate dialogue between local officials and citizens. The success of that approach highlights an unmet need: most sustainability games do not explicitly foster multi-stakeholder interaction. Given that urban sustainability challenges require collaboration among government, business, and communities, more games could be developed to simulate and encourage that collaboration. In the literature, this is a gap – studies seldom examine games in which, say, policymakers and residents play together and learn from each other. Yet such approaches could strengthen mutual understanding and co-learning. In short, the social dynamics of gameplay (who plays with whom, and how that influences outcomes) is an area for further research. Engaging typically underrepresented groups (for example, youth in urban planning or marginalized communities in climate adaptation) via serious games is another aspect that warrants more attention.

Additionally, while serious games tend to perform well in boosting knowledge and changing attitudes, their record on behavior change is mixed and constitutes a gap in impact. Some studies have found only modest or temporary changes in energy use or other behaviors following game interventions (Ouariachi et al., 2018; Chen et al., 2024). The We Energy Game evaluation, for instance, showed strong cognitive and affective engagement but was "less successful in motivating attitudinal or behavioral engagement" (i.e., translating awareness into action)(Ouariachi et al., 2018). This suggests that additional measures (like real-life action projects, mentorship, or repeated gameplay and reflection sessions) might be needed to convert game-based learning into tangible behavior change. The literature would benefit from exploring how serious games can be coupled with such measures, or how game design can better target behavior (through commitment devices, feedback on real-life actions, etc.).

Moreover, researchers caution about oversimplification in games; to make games fun and manageable, designers often simplify real-world systems, but this can lead to misconceptions if not handled carefully (Chen et al., 2024). For example, a climate game might ignore political barriers to focus on technical solutions, potentially giving players

an incomplete picture. Acknowledging and addressing this tension between simplicity and realism is a current challenge.
Finally, an interesting gap in the literature is connecting serious games explicitly with the SDG framework. While we know that games can teach sustainability concepts, few studies frame their results in terms of SDG targets or assess how a game might help achieve, for example, SDG 7 or 11 in a community. Sharifi et al. (2024) highlighted the importance of linking smart city initiatives to SDG outcomes; similarly, it could be argued that serious games for urban sustainability should also be evaluated on how they contribute to SDG-related indicators (like awareness of clean energy solutions, or engagement in climate action campaigns). This connection is seldom made explicit in current research and represents an opportunity for future work.

How This Research Addresses the Gaps:

The present study is designed to respond to several of the gaps identified above. First, our research will develop a serious game focused on urban energy and sustainability that actively involves multiple stakeholder groups. Whereas many existing games are single-player or targeted at students, our game brings together diverse participants – for example, city officials, energy experts, and local citizens – within a shared simulation of a city's energy system.

Third, this research explicitly links the content of the game to SDG goals and targets, bridging a gap between game outcomes and global frameworks. The game scenarios are aligned with SDG 7, 11, and 13 challenges – for instance, players must work to provide clean energy for all (SDG 7) in their city while improving urban sustainability (SDG 11) and keeping emissions within climate-safe limits (SDG 13). By framing the win conditions and metrics of the game in terms of SDG indicators (e.g., percentage of renewable energy, carbon reduction, social inclusion in energy planning), we can evaluate the game's success in a manner that resonates with the SDGs. This approach not only helps players learn about the SDGs in a concrete way, but also allows us to discuss how game-based learning might contribute to real-world SDG progress (for example, increasing public awareness and support for policies that the SDGs advocate).

In conclusion, by developing a multi-stakeholder serious game with rigorous evaluation and SDG alignment, this research addresses key gaps identified in the literature. It advances understanding of how complex urban energy issues can be taught and tackled through gameplay, how such interventions can be scaled and measured for long-term impact, and how serious games can be strategically used as part of the toolkit for urban sustainability and climate action. Through filling these gaps, the study aims to contribute both theoretical insights and practical guidance for future applications of serious games in sustainability education and stakeholder engagement.

CHAPTER 3

DESIGN AND DEVELOPMENT OF THE GAME

3.1. Data Source and Link to the TÜBİTAK 1004 Program

The primary dataset used in this thesis was obtained from a component of the TÜBİTAK 1004 program (Project No. 22AG019) namely “P8-2 Kentsel ölçekte bina enerji analitiği platformu (Urban-Scale Building Energy Analytics Platform).” The thesis is not a formal continuation of that program; rather, the project’s data products were used as external inputs to initialize and calibrate the serious game developed herein. Still, the developed serious game can be considered as an output of the project since it lays the informational foundation. Out of respect for confidentiality, no in-text references to internal project documents are provided in this section. Instead, publicly accessible, peer-reviewed descriptions of the same neighborhood-scale modeling workflow and the derived machine-learning (ML) predictors are cited to document scope, methods, and assumptions (Akyol et al., 2025; Iseri et al., 2025).

The dataset reflects real, building-level information from the Aşağı Bahçelievler neighborhood of Ankara. The study area covers approximately 0.57 km² and includes 593 residential buildings that were modeled at apartment (zone) resolution, yielding 6,452 zones in total; in each building, a single apartment unit is treated as one thermal zone. These case-study characteristics are documented in the published UBEM/ML studies cited above and align with the inputs used here.

For each building, envelope and insulation indicators were provided alongside geometric descriptors (e.g., wall areas, roof areas, total floor area, and number of apartments). The UBEM sources report that building-level and zone-level semantic attributes (e.g., U-values, boiler efficiency, window-to-wall ratios, internal loads, and heating setpoints) were compiled from municipal GIS, the Address Inquiry System (AIS), Energy Performance Certificates (EPCs), and national statistics, with missing fields completed using probabilistic data imputation/generation (KDE/NPDE). This approach preserves statistical consistency while enabling zone-level simulation in data-scarce contexts—an assumption consistent with the dataset received for this thesis.

Rooftop solar-electricity generation potential was also included. Although PV outputs are not detailed in the cited articles, the urban context shading and solar-gain handling that underpin such estimates are explicitly modeled in the published UBEM (each building acts as a shading obstacle to neighbors within a predefined range), and solar radiation metrics are tracked in the weather features; these practices were mirrored in the dataset used here.

Data were delivered in tabular (CSV) form and were imported with minimal cleaning and normalization to establish the game's baseline city model. Within the game, these attributes are used to set initial conditions, constraints, and performance targets at the building scale (e.g., retrofit feasibility, expected benefits, and budget allocation). For simplicity and responsiveness, the runtime system employs only the 2020 ("W2020") climate features from the underlying workflow; in the published work, W2020 is the typical-meteorological-year (TMY) file prepared for Ankara.

In addition, a predictive artificial-intelligence component, trained on the same UBEM dataset and released by the METU team, was incorporated to provide immediate, simulation-free feedback on the impacts of envelope/insulation modifications. In the peer-reviewed study, multi-layer perceptron models predict annual heating energy (QHeating) and Indoor Overheating Degree (IOD) using UBEM-derived features; the models, code, and weights are publicly released for reproduction and reuse, which supports the adaptation performed in this thesis.

The contribution of the TÜBİTAK 1004/P8-2 team, particularly in curating building-level data for Aşağı Bahçelievler and in producing solar-potential estimates and the predictive model, is gratefully acknowledged. All interpretations, transformations, and uses of these data for the purposes of this thesis and the associated serious game remain the responsibility of the author.

3.2. Game Concept and Design Rationale

3.2.1. Game Design Philosophy and Educational Objectives

This game has been designed as an awareness-oriented serious game that favors width over depth. The core philosophy is to present players with a wide spectrum of interrelated concepts in urban energy management—spanning energy sources, building-scale efficiency, policy instruments, governance actors, and technology investments—without attempting to reproduce a high-fidelity engineering simulator. The intent is to enable non-expert audiences to encounter many of the moving parts that shape city-scale sustainability and to spark curiosity for further inquiry, rather than to provide professional training or operational decision support. In this sense, the game is positioned to introduce fundamental ideas, trade-offs, and stakeholder roles through accessible mechanics, lightweight data representations, and concise feedback.

Two design commitments follow from this philosophy. First, the game deliberately abstracts technical detail to avoid overwhelming players with complexity that would add extraneous cognitive load. Richard Mayer's "coherence principle" regarding multimedia learning shows that learning is more effective when unnecessary detail is minimized, and the "multimedia principle" suggests that essential relationships should be presented clearly through both words and visuals (Mayer's 12 Principles of Multimedia Learning | DLI, n.d.). Accordingly, the game's user interface, information density, and interaction patterns have been constrained to highlight causal links (e.g., how building envelope choices, fuel mix, and policy settings interact) while omitting lower-level engineering parameters that are unnecessary for introductory learning.

Second, the game embraces schematic realism rather than photorealism. In serious-game research, learning and retention benefits have been demonstrated even when visual realism is limited; in fact, meta-analytic evidence indicates that schematic serious games can outperform more realistic ones as well as cartoonlike serious games on learning outcomes (Wouters et al., 2013).

Within this frame, the educational objectives are defined at introductory levels appropriate to an awareness-raising experience:

Conceptual Recognition and Understanding

Players should be able to recognize the main determinants of urban and building-scale energy performance (e.g., insulation quality, system efficiencies, fuel mix, demand profiles), and explain at a basic level how these determinants interact.

Stakeholder Literacy

Players should identify key actors (residents/citizens, local governments, national regulators, utilities, and industry) and distinguish their levers of influence (e.g., household actions, municipal retrofitting programs, fiscal instruments, and technology investments). The aim is to cultivate a systems view in which multiple actors contribute to outcomes.

Policy and Trade-Off Sensitivity

Players should appreciate that progress towards sustainable energy systems involves trade-offs (cost, emissions, comfort, reliability) across policy choices, technology paths, and time horizons. Rather than pursuing optimization, the game introduces multiple plausible actions and their approximate consequences to foster informed reflection.

Motivational Activation and Future Learning

The experience is intended to motivate further exploration of sustainability topics. Meta-analyses report that serious games can improve learning and retention and often engage learners, especially when games are supplemented with brief instructional supports—an approach also used here via in-game prompts and short readings (Wouters et al., 2013).

The width-over-depth decision is therefore not an omission but a pedagogical choice. First of all, cognitive efficiency suggests that limiting extraneous detail supports novice understanding (Mayer's 12 Principles of Multimedia Learning | DLI, n.d.). Secondly, serious games can yield meaningful gains without maximal realism and are most effective when paired with concise scaffolds (Wouters et al., 2013). Finally, the design recognizes that awareness-oriented games do not substitute for professional training. Therefore, the game is intentionally broad, concept-rich, and accessible, aiming to reach diverse audiences with clear, engaging encounters that seed accurate mental models of how urban energy decisions interconnect.

3.2.2. Target Audience and User Experience Goals

The game was developed for young adult audiences, with an intended age range of 18–39. This group was prioritized because it includes university students, recent graduates, and young professionals who are likely to engage with complex urban sustainability questions in the near future and who may later hold decision-making roles. Playtesting and survey participation were therefore conducted primarily with university students and young professionals within this age bracket, spanning a variety of disciplinary backgrounds to capture diverse perspectives on energy and urban policy. Research with minors was deliberately avoided due to ethical and operational complexities.

The user experience (UX) goals were set to ensure approachability for non-specialists while maintaining engagement for more technically informed players. The intended experience can be summarized as engaging, immersive, light-hearted, approachable, not overly technical, enjoyable, visually attractive, and re-playable, with a design philosophy that prioritizes width over depth. In practice, this meant favoring breadth of content, exposing players to the interdependencies among energy sources, building stock, and policy tools, over highly detailed, domain-specific modeling.

To operationalize these goals, three design commitments were made:

1. Approachability and low cognitive barrier:

   Interfaces and mechanics were structured to minimize technicality for first-time players. Jargon and engineering units were reduced in the main loop, with more detailed information available in the “Encyclopedia” panel.

2. Sustained engagement through clear goals, feedback, and balanced challenge:

   Core loops emphasize immediately clear goals, frequent feedback, and challenge calibrated to evolving player skill so that the experience remains absorbing without becoming too punitive. These elements are well recognized in models of player enjoyment; the Gameflow framework highlights concentration, challenge–skill balance, control, clear goals, feedback, immersion, and social engagement as pillars of enjoyable gameplay (Sweetser & Wyeth, 2018). This framing informed the pacing of information, tutorials, and feedback timing so that players who are unfamiliar with energy topics could still experience momentum and “small wins.”

3. Re-playability and breadth-first exploration:

In the game, scenario variability and multiple viable strategies were preferred over a single optimal path to encourage replay value. This choice serves the project's overarching aim, which is awareness-raising about the multi-actor, multi-constraint nature of city-scale energy decisions, by inviting players to explore different mixes of interventions rather than mastering one narrow system.

A breadth-oriented, approachable design minimizes initial cognitive burden while leveraging engagement mechanisms known to foster attention and motivation. The target population and the user experience goals were therefore aligned to maximize accessibility for non-engineers, maintain sufficient depth for meaningful reflection, and promote repeated play, conditions judged most suitable for the project's awareness-raising objectives.

3.3. Game Mechanics and Gameplay

3.3.1 Role of Player as the "Green Renovator"

Green Renovator is a resource-management game about managing the energy issues of a city, featuring a detailed economy and multiple balancing elements. With many tools in their shed, the player is expected to explore their authorities in the game and decide where to invest their resources and time. The real challenge is to figure out the trade-offs of different decisions and make strategic calls as seen fit.

The main goal of the game is to reach pre-defined targets of reducing the total energy use, the total carbon footprint from energy use, and the total cost of energy expenditure while keeping the public content. Since the main goal is to have educational value and to provide a free space for experimentation, the game has been designed to minimize frustration. There is no time limit or limit on the number of years the players can play. A forgiving environment with minimal pressure is meant to be provided for the players to let them explore at their own pace.

The game starts by notifying the player that they have been assigned as the "Green Renovator" of the city. That role is further described in the welcoming tutorial pages. The player is informed about the tasks that they will be responsible for. These tasks encompass not only building-level renovations to improve building energy sustainability but also responsibilities on a grander scale, including management of the city's energy sources, policy implementation, and technology investments. The role is not meant to cover all duties of a mayor; instead, it only focuses on the energy management aspect of the city. These tasks and responsibilities will be discussed in detail in the following chapters.

3.3.2 Game Core Loop

The game is designed to be a turn-based game, where each turn represents a year.

The game loop goes as follows;

- The player is offered to take a small quiz (the competency test). If the player succeeds, they get an extra budget on top of their annual budget.

- A random event may trigger, affecting some game parameters to represent real-life possibilities.

- The player receives an annual budget and is shown a summary panel for the start of the year, displaying key metrics to assess the starting conditions for the year. If there are active policies or random events that might affect the annual budget, it may differ.

- The management phase starts. The player is free at this stage to inspect and manage anything they wish and decide on their investments. Building renovations, energy source management, policy implementations, and technology investments are all done in that main phase.

- After the player decides to end the year, or they run out of funds to do anything, they end the turn. They are shown an end report that displays the changes on the key metrics such as total energy demand, total carbon footprint, total energy expenditure, along with some game parameters such as public approval, funds, etc., for the turn that has just been played, as well as the previous years (turns).

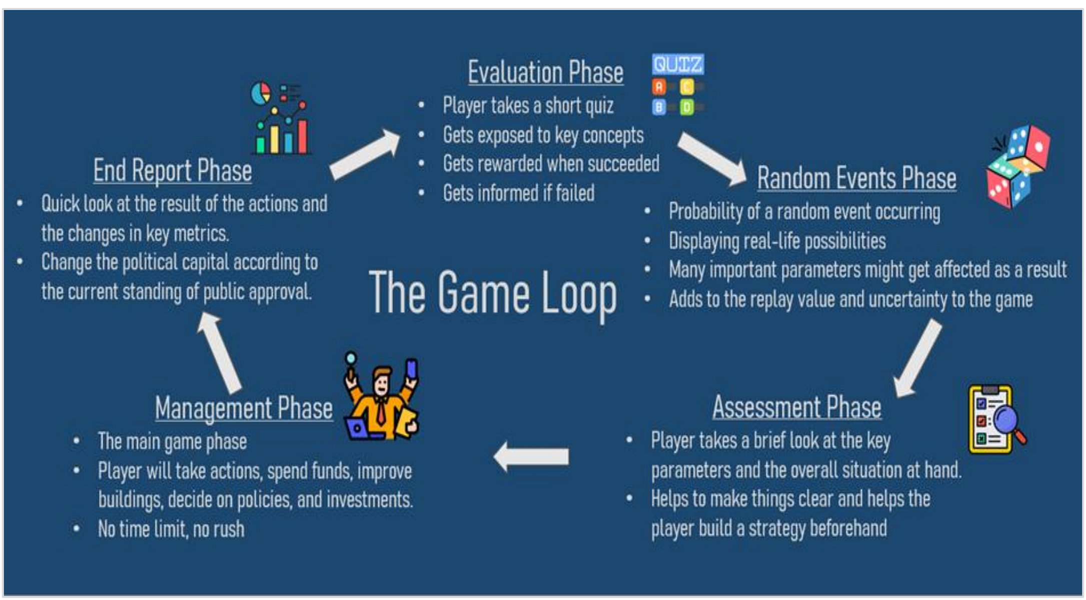

Figure 1: Visualization of the Game Loop.

3.3.3 City Exploration and Navigation

The game has a 3D environment with a top-down view. The player is free to roam around the city and inspect buildings or apply building upgrades while still in a top-down view. A camera and navigation system have been developed to feel “natural” for those who are familiar with games or 3D tools in general. The player can navigate around the city with the “W-A-S-D” keys and use the Q and E buttons to rotate, which is very typical for a PC strategy game. Navigation can also be done via just the mouse; panning by holding right-click, rotating by clicking and holding the mouse wheel, and zooming in and out by rolling the mouse wheel. The camera system is also designed to provide a smoothly changing camera angle when zooming in and out; the camera angle becomes steeper as the player zooms out and becomes more horizontal as the player zooms in to provide a good view in any position.

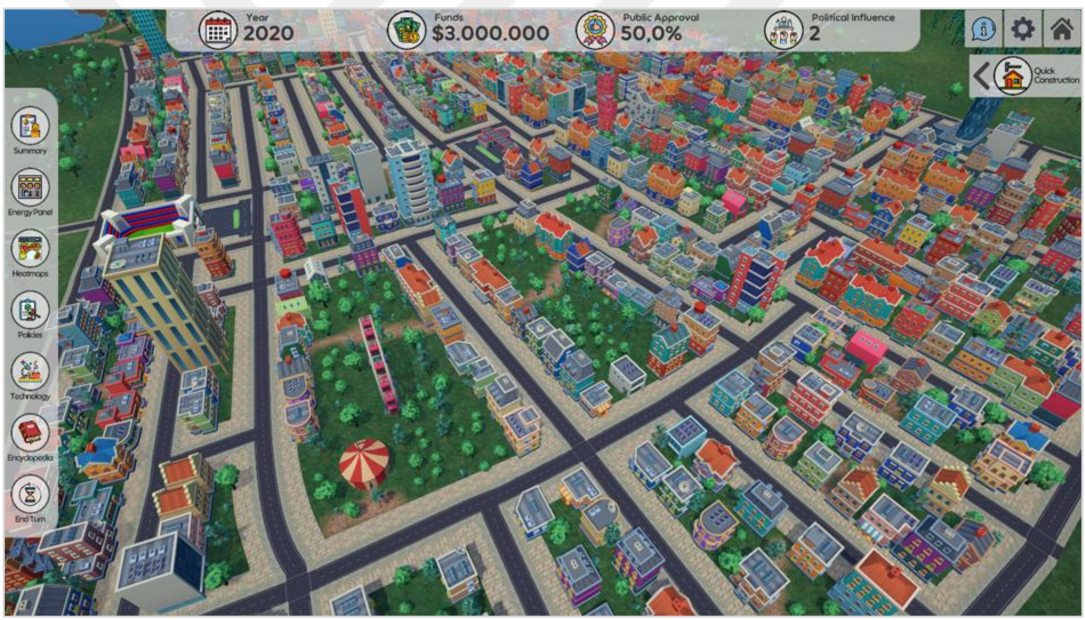

Figure 2: In-Game Top-Down City View.

3.3.4 Building-Level Inspections and Renovations

While navigating through the city, the players can double-click a building to inspect it. In that building inspection panel, there are many details provided for the player to see (see the image below).

Figure 3: Building Inspection Panel.

On the left side of the panel, the values describing the building's envelope properties (insulation quality) are displayed: thermal transmittance (U-values) of external walls (U-Wall), windows (U-Window), roofs (U-Roof), and ground floors (U-Ground), along with infiltration rate, which represents the air-tightness of the building. Since these are technical terms that might mean nothing to a player or overwhelm them, a "hint" panel that describes them with a short but concise text has been added for those who would wonder what they are and wish to learn at that point. This help panel is highlighted with an animated image of a question mark on top. When the player hovers over that question mark, the following text pops up:

"U-Value: Measures how well a building element (wall, window, roof, or ground) conducts heat. Lower values mean better insulation, keeping your building warmer in winter and cooler in summer. The unit, W/m²·K, means 'watts of heat lost per square meter of surface for every degree of temperature difference.

Infiltration: Represents the rate of air leakage through the building envelope due to gaps or cracks. Lower values mean better airtightness and energy efficiency. The unit, m³/m²·s, means cubic meters of air leaking per square meter of surface every second."

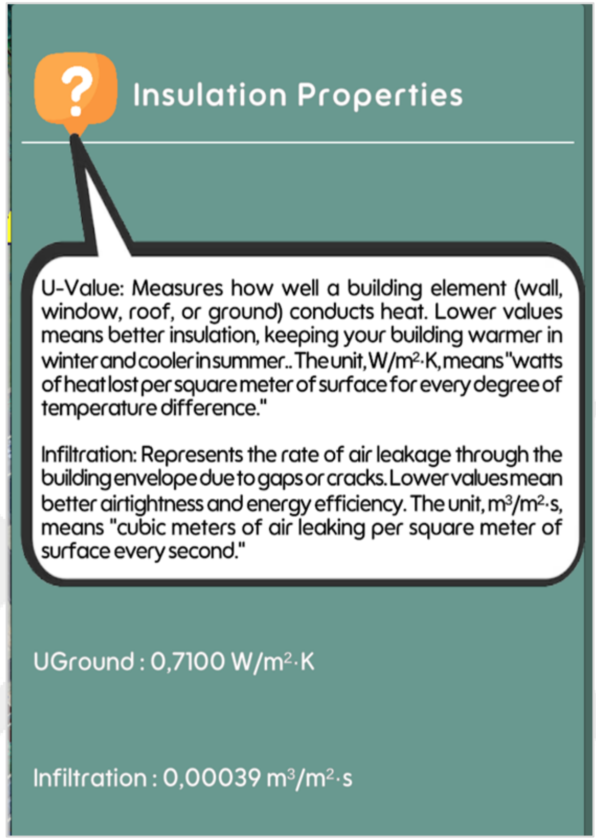

Figure 4: Hint Panel Explaining U-Values and Infiltration.

Under the title "INFO", the building's current state of heating energy use per sqm (annual average), total heating energy use, carbon footprint due to that energy use, the construction date, the number of apartments in the building, and an additional game parameter called "renovation willingness" (more on that later in the Chapter 4.2.5 - Political Dynamics) can all be inspected.

At the bottom of the panel, the renovation options that could be done on the building are displayed. These renovations include the installation of photovoltaic solar panels on the roof of the building, and the installation of three levels of retrofit insulation quality: C-grade (baseline compliance with Turkish standards), B-grade (cost-optimal mid-level upgrade), and A-grade (high-performance retrofit aligned with EnerPHit/passivhaus-like standard). This structure provides players with meaningful strategic choices while reflecting realistic technical and economic trade-offs found in actual retrofit scenarios. Each upgrade button displays its current price on it. Before spending their funds, the player can preview the changes that would take place in the building when an insulation upgrade is done. They can preview the changes in envelope properties of the building, as well as the total heating energy change that would come with it. It is designed that way to give players a rough sense of what to expect from different levels of insulation upgrades/retrofitting.

Figure 5: The Preview of Insulation and the Resulting Heating Energy Changes When the Player Is Hovering on the C-Grade Insulation Upgrade (The Cursor Is Not Visible).

The C-grade values are based on the TS 825 standard, Turkey's official thermal insulation regulation, particularly for the coldest climate zones (Zone 4). The maximum U-values for external walls, roofs, floors, and windows are approximately 0.40 W/m²·K, 0.25 W/m²·K, 0.40 W/m²·K, and 2.4 W/m²·K, respectively (TSE, 2008). This level of infiltration indicates a "medium sealing" classification, equivalent to roughly 7–10 air changes per hour at 50 Pa (ACH_{50}), which corresponds to 0.0040 m³/m²·s.

The B-grade reflects a cost-effective retrofit scenario as often modeled in European retrofit studies. It features moderate improvements in insulation (U_wall = 0.30 W/m²·K, U_roof = 0.20), low-E double-glazed windows (U_window = 1.80), and reduced infiltration (0.0020 m³/m²·s). These values are supported by research on cost-optimal energy efficiency levels in Turkey and Europe (Ecofys, 2016; European Commission, 2021), and are achievable through widely available commercial materials and methods.

The A-grade level targets a performance close to the EnerPHit standard — a recognized framework by the Passive House Institute for retrofitting existing buildings. It adopts very low U-values (0.17–0.18 W/m²·K) for opaque elements, triple-glazed windows (U_window = 1.10), and a highly airtight envelope with 0.0005 m³/m²·s, equivalent to ~1.0 ACH_{50}. Although EnerPHit recommends slightly lower window U-values (⩽0.85 W/m²·K), values around 1.0–1.2 are commonly used in high-quality commercial retrofits, especially in milder climates or constrained renovation conditions (Passive House Institute, 2016).

Table 1: Insulation Properties in the Game by Different Retrofit Grades.

Grade	U_{wall} (W/m²·K)	U_{window} (W/m²·K)	U_{roof} (W/m²·K)	U_{ground} (W/m²·K)	Infiltration (m³/m²·s)
A	0.17	1.10	0.15	0.18	0.0005
B	0.27	1.80	0.21	0.24	0.0020
C	0.40	2.40	0.25	0.40	0.0040

In this game, retrofit costs are expressed in USD per square meter of total exterior wall area, serving as a proxy for the total envelope upgrade cost. This simplification enables scalable cost estimation across diverse building types while aligning with established practices in energy modeling and retrofit planning tools. Component-based cost normalization is standard in the Passive House Planning Package (PHPP) and several EU-funded initiatives such as ENEFIRST and RenoValue, where upgrade scenarios are evaluated using fixed window-to-wall ratios and unit costs for envelope elements. Similarly, serious games and building simulation tools adopt m²-based costing to model upgrade decisions in an accessible yet meaningful way (Oikonomou et al., 2020; European Commission, 2021).

The cost values in this model are denominated in USD to ensure price stability, considering the exchange rate volatility in Turkey (USD/TRY ≈ 40.65 as of August 2025). Each unit price bundles the cost of thermal insulation, window replacement, and airtightness improvements, inclusive of labor, materials, contractor overhead, and VAT. These values were derived from published Turkish market reports and international retrofit benchmarks. The Turkish Energy Efficiency Association and İZODER estimate full envelope retrofit costs at approximately 3,000–7,000 TRY/m² in 2023–2024, corresponding to roughly $75–170/m² at current exchange rates. Accordingly, the game uses:

- **$90/m²** for C-grade retrofits (TS 825-compliant, minimal glazing replacement),
- **$115/m²** for B-grade (cost-optimal insulation, double glazing, moderate airtightness), and
- **$150/m²** for A-grade (EnerPHit-level triple glazing, >15 cm insulation, high airtightness).

This structure supports comparative analysis and strategic decision-making within the game while remaining grounded in real-world retrofit economics.

Table 2: Unit Costs of Insulation Retrofits.

Grade	Unit Price (USD/m^2)	Typical Insulation Thickness	Window Type	Airtightness Standard
A	$150	≥15 cm (mineral wool or EPS)	Triple-glazed, insulated frame	EnerPHit (~1.0 ACH_{50} or lower)
B	$115	10–12 cm	Low-E double-glazed	Improved (3–5 ACH_{50} approx.)
C	$90	~5–6 cm (basic EPS)	Basic or single low-E	Meets TS 825 (medium sealing ≈7–10 ACH_{50})

This envelope property structure allows players to make impactful upgrade choices grounded in real-world benchmarks, while also supporting the game's educational aim of illustrating the relationship between building physics and sustainable decision-making.

The other renovation option, which is the installation of rooftop photovoltaic solar panels on top of buildings, also utilizes real-world data, which has been acquired through the TÜBİTAK project mentioned before. The data provided the annual potential solar energy generation for each building, based on its size, geometry, and annual sun exposure due to its position. The player can inspect the energy generation potential and the cost of installation, and decide to invest in solar microgeneration in the building.

A solar PV installation cost of **$160 per square meter** of panel area is assumed for the game. This unit price is treated as a turnkey installation cost (inclusive of panels, balance-of-system, and installation labor) and aligns with recent photovoltaic pricing data for Turkey. For example, PwC Türkiye (2024) reports 2022 on-grid solar plant installation costs in Türkiye around **$690/kW**, utility-scale values that do not include the higher soft costs typical of rooftop systems. PwC IEEFA (2019) documents residential rooftop projects in Turkey with installed costs constructed from component and labor assumptions equating to roughly **$0.96 – $1.20/W** at the time (modules ≈ $0.35/W, BoS ≈ $0.61/W, labor ≈ 15% of installed cost; pp. 5 – 6, 9). IEEFA IEA PVPS (2024) places residential system prices in the **$0.78 – $2.60/W** range worldwide in 2023, with large distributed systems starting around **$0.70/W** (pp. 81 – 84). IEA-PVPS Using mainstream module efficiencies of ~19 – 22% (≈ 190 – 220 Wp/m²), **$160/m²** corresponds to roughly **$0.73 – $0.84/W**, which falls within these ranges while remaining conservative for a turnkey rooftop offering (Fraunhofer ISE, 2025, pp. 6, 31–32). In 2018, IRENA reported Turkish utility-scale PV installed costs near **$1,200/kW**, with costs declining substantially thereafter, supporting the view that a **$160/m²** assumption for 2025-era rooftop retrofits is not understated (SHURA, 2020, pp. 25–26; PwC Türkiye, 2024, p. 48).

If the building generates more energy with its solar panels than its energy needs, the buildings sell its excess energy back to the city's energy grid. The city buys that excess energy at the average cost of energy at that moment. That way, the players can see the investments still generate some return on investment even if it overreaches their needs.

The right side of the building inspection panel is where the players can inspect the results of their investments. They can see how much money has been spent on that building, and consequently how much energy, carbon, and money have been saved by the investments. Also, if the building generates some excess energy, the total earnings from energy sellbacks are displayed. The way these "annual savings" are calculated is to compare each year to the current state of the building at the end of each year.

- The energy demand is directly compared to the initial baseline at the start of the game; the difference is noted as the annual energy saving.

- The carbon saving is a bit more complex; the initial baseline is calculated using the city's initial energy source distribution and the average CO2 footprint per kWh, multiplied by the initial energy use, and the baseline annual CO2 footprint is calculated. Then, each year the process is repeated. So, if the general CO2 footprint is decreased due to changes in the city's energy sources, the building shows some cumulative CO2 savings even if the building's energy expenditure does not change.

- Similar to the calculation of CO_2 savings, the money savings of a building are calculated using the city's overall average energy cost per kWh. The initial baseline is calculated by multiplying the annual energy demand of the building by the initial average energy cost per kWh of the city. As the energy demand on the building, or the average cost of energy, decreases, the annual differences in energy expenditures are noted as cumulative money savings.

Ultimately, the player can observe how much of an ROI (return on investment) has been made on that building over the years. The primary purpose is to provide an understanding of the expected return on investment from building renovations, in terms of energy, carbon footprint, and money.

3.3.5 Heatmap Visualizations

Given the hundreds of buildings in the game, expecting players to inspect each one individually and make informed comparisons and investment decisions is not realistic. A more straightforward way of displaying the key parameters and visualizing the differences between buildings was needed. The heatmap visualizations come into play for that matter. The player can use the heatmaps to see how a parameter is distributed along the city. They can then easily prioritize the most critical investments according to their strategy.

Figure 6: Heatmap Visualization Displaying the Total Heating Energy Use Distribution Along the City.

The player can visualize the annual heating energy use per square meter, total annual energy use, annual carbon footprint, construction dates, renovation willingness percentages, return on investment, and the number of apartments for the buildings. Whenever a parameter is selected, the city dynamically shifts colors and displays a gradient heatmap distribution of the selected parameter, along with an explanatory legend at the side. The legend displays the parameter name, upper and lower limits, unit of the selected parameter, and the appropriate legend image showing whether the higher value or the lower value is positive. Positive values are shown in green, and negative values are shown in red. For example, higher values of total energy use are shown in red, while higher values of construction date, meaning a younger building, are shown in green.

When displaying return on investments, the buildings that have not yet received any investments are drawn in dark gray. The ones that have received some investments display their current return on investments as a percentage (see the image below).

Figure 7: Screenshot of the Heatmap Displaying Return on Investments on Buildings as a Percentage.

A custom-built shader developed in Unity's shader graph enables seamless switching from the normal colors of the buildings to the heatmap colors. It also enables the dynamic updating and renewal of the heatmap at runtime. The color changes are all done gradually to avoid abrupt visual jumps and to have a more professional feel.

3.3.6 Quick Construction Mechanic

As mentioned previously in building inspection and renovations, players can choose to invest in three different levels of insulation upgrade or the installation of rooftop solar panels in buildings. In order to provide an easier, quicker, and more useful way of implementing these renovations, a "Quick Construction" mechanic is provided in the game. Since most people would decide on their next building investments using the heatmaps, having to open building details, then going back to the heatmap constantly, would harm the immersion of the game and could have caused frustration in most players. Some unofficial tests with students during the development stage also confirmed that. The development of that mechanic is done to avoid such issues.

The way quick construction works is simple:

- ➢ The player opens the heatmap and chooses a parameter to base their investment decisions on.
- ➢ Opens up the sliding quick construction panel on the top right corner.

➢ Chooses the renovation they want to implement.

➢ The price of the selected renovation is displayed for each building, hovering above it.

➢ Player can then easily do renovations on numerous buildings just by clicking on them.

➢ Buildings that just got the upgrade, and the buildings that already have the selected upgrade applied to them, are painted dark grey to let the player see only the available investments.

Figure 8: A Screenshot of the "Quick Construction" Mechanic in Action.

3.3.7 Management of Energy Sources

As mentioned before, the player's main aim is to reduce the total energy demand, the total CO2 footprint, and the total money spent on energy. Making buildings more efficient through renovations is one approach, but the sources of the spent energy can be just as important. The game also lets the player control the overall energy sources to reach their goals. The main purpose of this aspect of the game is to help develop an understanding of some basic knowledge and trade-offs between different energy sources. This energy source management is done through the "Energy Management Panel," which can be opened from the left panel in the game.

When opened, the players can observe the initial state of energy source shares and their distribution in a dynamic pie chart. The initial state of energy source shares is based on

Turkey's energy supply. According to Türkiye's Ministry of Energy and Natural Resources, the 2024 electricity-generation mix was approximately coal 35.2%, natural gas 18.9%, hydroelectric 21.5%, wind 10.5%, solar 7.5%, and geothermal 3.2% (with the remaining ~3.2% from other sources; nuclear had no output in 2024) (Ministry of Energy and Natural Resources, 2025). Independent datasets report nearly identical shares: coal 35.6%, gas 18.5%, hydro 22%, wind 10.7%, solar 7.5%, and confirm the broader picture that renewables supplied ~46% of generation in 2024 (Ember, 2025; SHURA, 2025).

The unit cost and the unit carbon footprint of each energy source can also be observed. These values are openly displayed for players to study and form their own judgements about their trade-offs. Each energy source has a "total available capacity", and the players can decide on how much of that total capacity will be used in the energy supply as the "active capacity". As long as they meet the city's total demand, they can adjust and lower the active capacity percentages for the sources to meet their goal. For example, suppose the player needs to lower their carbon footprint. In that case, they may decide to lower the coal used in the total supply gradually, or if the player needs to lower the total energy cost at a moment, they may decide to gradually decrease the share of pricier sources such as solar or nuclear, etc.

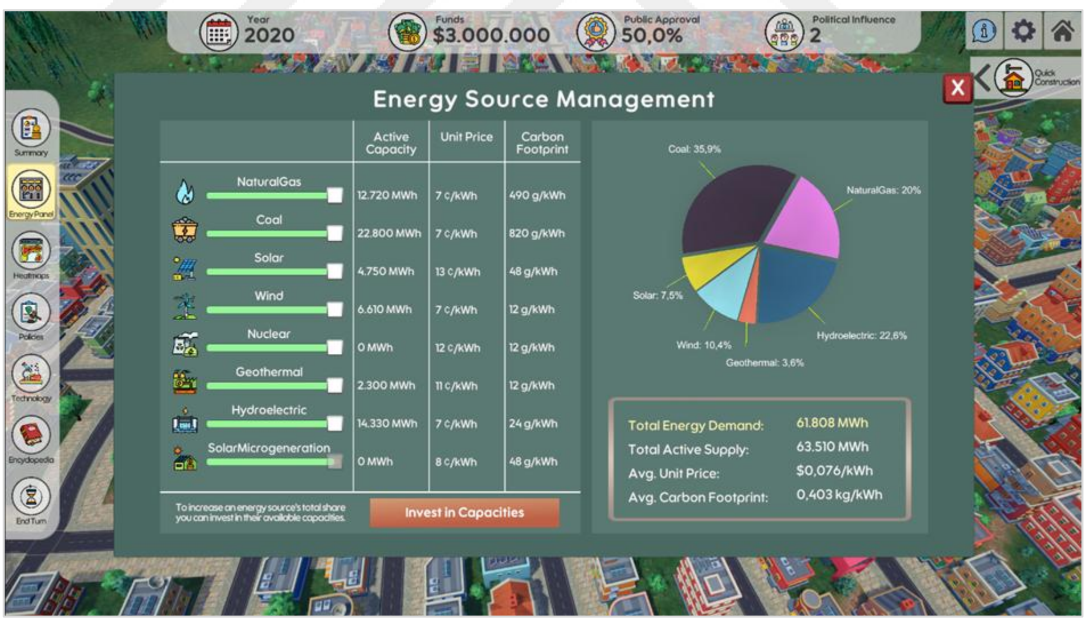

Figure 9: Screenshot of the Energy Source Management Panel.

Real-life values of unit prices and life-cycle carbon factors are chosen to be used in the game for all seven energy sources, prioritizing Turkey-specific price signals and widely cited scientific assessments for emissions. For coal and natural gas, costs are anchored to SHURA's Turkey modeling, which reports utility-scale solar LCOE (levelized cost of electricity) of 63 USD/MWh in İzmir—about 6% lower than coal and 10% lower than gas, implying coal at ≈67 USD/MWh (0.067 \$/kWh) and gas at ≈70 USD/MWh (0.070

$/kWh) (SHURA Energy Transition Center, 2020, p. 7). For renewables, Turkey's former YEKDEM feed-in tariffs provide clear national benchmarks: hydro 7.3¢/kWh, wind 7.3¢/kWh, geothermal 10.5¢/kWh, and solar 13.3¢/kWh (International Energy Agency [IEA], 2021, p. 79). These sit alongside recent YEKA (Yenilenebilir Enerji Kaynak Alanları / Renewable Energy Resource Area ((Ministry of Energy and Natural Resources, n.d.)) auction outcomes for wind at 3.48–4.56¢/kWh, confirming that the rounded inputs remain conservative and credible for the game (IEA, 2021, p. 81). For nuclear, the Akkuyu power-purchase agreement fixes 12.35¢/kWh for a defined share of output (IEA, 2021, pp. 105–106).

Carbon factors use life-cycle (cradle-to-grave) medians from the IPCC's harmonized assessment (AR5, Annex III, Table A.III.2), ensuring consistent comparability across technologies: coal ~0.82 kg CO_2e/kWh, natural gas ~0.49, geothermal ~0.038, hydro ~0.024, solar PV ~0.048, wind ~0.011–0.012, and nuclear ~0.012 (Intergovernmental Panel on Climate Change [IPCC], 2014, p. 6). These values explicitly retain the non-zero footprints of low-carbon options (manufacturing, construction, fuel cycle), aligning with the design goal to reflect hidden upstream impacts rather than portraying "zero-emission" energy source.

Table 3: Energy Sources with Their Unit Prices and Unit Carbon Footprints.

Energy Source	**Unit Price (¢/kWh)**	**Carbon Factor (g CO_2/kWh)**
Coal	6.70	820
Natural Gas	7.00	490
Solar PV	13.30	48
Wind	7.30	12
Nuclear	12.35	12
Geothermal	10.50	12
Hydropower	7.30	24

Together, the Turkey-based prices and the IPCC-based carbon factors create a valid and credible portrayal of the energy source without oversimplification. It offers players to weigh cost vs. emissions trade-offs that mirror Turkey's real policy landscape and global scientific consensus (IEA, 2021, pp. 77–82, 105–106; IPCC, 2014, p. 6).

Players are also allowed to make new energy capacity investments in the game. The game starts with a balanced energy supply and demand. If the player wishes to lower the share of some sources, like fossil fuels, and still meet the total demand of the city, they may need to invest in other energy sources to increase their total available capacities. These investments are made through a panel accessible via the energy control panel, where the player is shown a list that displays the capacity investment opportunities for each energy source, with their minimum size of investment in terms of kWh/year and the price of that investment. This game mechanic is designed to demonstrate to players that investments in different energy sources require varying scales and incur different costs per unit of energy produced. For example, nuclear requires a significant investment, but it yields a vast amount of total available capacity, whereas solar farms can be built in smaller chunks.

Table 4: Investment Blocks Used in the Game (Turnkey EPC).

Type	Minimum Capacity (MWh/year)	Cost for Minimum Investment (USD)
Natural Gas	5,000	$650,000
Coal	5,000	$1,300,000
Solar PV	500	$170,000
Wind (Onshore)	1,000	$530,000
Nuclear	8,000	$6,500,000
Geothermal	1,000	$630,000
Hydroelectric	1,500	$1,230,000

Figure 10: Energy Capacity Investment Panel.

To keep the game's "investment blocks" intuitive, each option has been expressed as an annual energy increment (MWh/year) and price the block using standard power-sector practice: convert annual energy to an equivalent nameplate capacity with a representative capacity factor (CF), then multiply by energy source specific turnkey EPC (Engineering, Procurement, and Construction) capital cost ($/kW). Formally:

$$Required\ MW = \frac{Addition\ to\ the\ Annual\ Energy\ Supply\ (MWh/year)}{CF * 8760}$$

(8,760 = hours in a year. Capacity factor = average utilization, e.g., PV 18%, wind 35%.)

$$Cost\ \approx Required\ kW \times Capital\ Expenditure\ \text{(USD/kW)}\ (CAPEX)$$

Turkey-based CAPEX values come primarily from SHURA's "Net Zero 2053" Table 8 (coal, gas, hydro, geothermal, nuclear, wind, solar) and are cross-checked with UNCTAD's Türkiye study (PV, onshore wind, coal). Capacity-factor anchors use recent Türkiye observations where available (Ember's Türkiye Electricity Review 2024) and widely used international benchmarks when local observations are not reported at the energy source level (e.g., nuclear). The resulting numbers are deliberately rounded for playability but remain within the ranges implied by these sources. See the details of utilized CAPEX and capacity factors for each of the energy sources below.

Table 5: CAPEX ($/kW) and Capacity Factor (CF) Assumptions Used in the Game.

Energy Source	**CAPEX (US$ / kW, turnkey-EPC)**	**Capacity Factor Used (%)**	**Source for CAPEX**	**Source for Capacity Factor**
Natural gas (CCGT)	680	60	SHURA, *Net Zero 2053*, Annex 3, Table 8.	EIA, *Electric Power Monthly*, Table 6.07.A (U.S. CC monthly CF ~47–75% → we adopt 60% as a conservative proxy). (U.S. Energy Information Administration, n.d.)
Coal (hard coal, representative)	1,350	60*	SHURA, *Net Zero 2053*, Annex 3, Table 8.	Ember, "Domestic coal is far from providing a baseload in Türkiye" (2023 CF: lignite ~49%, imported coal ~75%) → 60% as a single blended figure is adopted*. (Ember, 2024)
Solar PV (utility-scale)	790	18	SHURA, *Net Zero 2053*, Annex 3, Table 8.	Ember, *Türkiye Electricity Review 2024* (annual solar CF 18%), p. 13. (Ember, 2024)
Wind (onshore)	1,100	33	SHURA, *Net Zero 2053*, Annex 3, Table 8.	Ember, *Türkiye Electricity Review 2024* (annual wind CF 33%), p. 16. (Ember, 2024)
Nuclear (PWR, reference)	6,600	81.5	SHURA, *Net Zero 2053*, Annex 3, Table 8.	World Nuclear Association, *World Nuclear Performance Report 2024* (global average CF 81.5% in 2023), pp. 2–5.
Geothermal (flash/binary mix)	3,750	70	SHURA, *Net Zero 2053*, Annex 3, Table 8.	EIA, *Electric Power Monthly*, Table 6.07.B (U.S. geothermal monthly CF ~60–74% → we adopt 70% as a mid-range proxy). (U.S. Energy Information Administration, n.d.)
Hydroelectric (dam)	2,000	23	SHURA, *Net Zero 2053*, Annex 3, Table 8.	Ember, *Türkiye Electricity Review 2024* (annual hydro CF 23% in 2023), p. 22. (Ember, 2024)

A final important remark needs to be made to clarify the scope and modelling approach here, under the energy management. Although the game primarily quantifies space-heating demand at the building level (since that is the main scope of the data at hand), the game presents a single energy portfolio (wind, solar, hydro, geothermal, nuclear, coal, natural gas) and purely for comparability and simplification, treats the heating energy demand as if it were supplied by the city's electric grid. This deliberate, didactic simplification serves the study's primary aim of awareness-raising: it places all options on a common kWh basis and highlights the cost–carbon trade-offs across different energy sources using the literature-informed unit prices and life-cycle emission factors justified in the preceding section. We acknowledge that this abstraction does not replicate Turkey's current end-use heating fuel split (which is largely non-electric), and we therefore interpret results as scenario insights, not as a precise forecast or policy appraisal of Ankara's present heating system. This clarification is stated here to avoid misinterpretation: the pie chart reflects the electricity generation mix used in the game to cover heating, while the game's conclusions concern relative impacts and trade-offs, not exact real-world shares. Future iterations of the project can relax or tighten this assumption by introducing more detailed, fuel and demand-specific management, or by adding further abstraction to dilute and simplify the issue, potentially reaching a more inexperienced or younger audience.

3.3.8 Political Dynamics and Policies

The political layer in the game has been designed as a simplified system that makes the social acceptance of urban energy actions visible and consequential for strategy. This design choice follows the broader understanding of games as formal systems that model—and deliberately simplify—selected aspects of reality to produce tractable, quantifiable outcomes suitable for player decision-making (Salen & Zimmerman, 2004, pp. 88–90, 92–93).

Renovation Willingness (per-building social acceptance proxy):

Each building is assigned a Renovation Willingness value on a 0–100 scale that represents the share of occupants presumed to support energy-efficiency improvements at that address. This variable is a synthetic, game-specific parameter (i.e., not drawn from an empirical dataset) and is surfaced to the player through both the Building Inspection Panel and the Heatmaps layer. Its purpose is to operationalize the "human factor" behind city-scale retrofits: even when technical and economic potential exists, uptake depends on social acceptance at multiple levels (e.g., socio-political, community, and market acceptance) (Wüstenhagen, Wolsink, & Bürer, 2007, p. 2684).

The separation between stated willingness and realized renovation also reflects a well-documented gap: households frequently express positive attitudes toward efficiency upgrades, yet actual adoption remains lower due to financial, informational, and practical frictions (Wilson et al., 2015, pp. 12–14). By making willingness observable while leaving action contingent on player choice and budget, the model preserves that asymmetry within play.

Public Approval (city-wide political mood):

Public Approval aggregates residents' perceived satisfaction with the mayor (or the green renovator in the game's context) as a political figure. Implementing renovations in buildings with high Renovation Willingness increases Public Approval; proceeding against low-willingness signals tends to decrease it. The magnitude of the effect depends on the number of apartments in that building. The mechanic allows politically expedient choices (e.g., investing in highly willing but already efficient buildings) while intentionally exposing trade-offs between short-term popularity and system-level efficiency or cost objectives.

In the overall victory condition, Public Approval must be maintained at or above 65% alongside meeting the city's technical targets (lower total energy use, emissions, and energy expenditure). This creates a dual-objective structure that mirrors how social acceptance can condition the feasibility and durability of urban energy transitions (Wüstenhagen et al., 2007, p. 2684).

Political Influence (policy-making capacity):

At the end of each turn (one in-game year), the player's Public Approval translates into Political Influence, the currency required to design and enact new policies. The mapping is intentionally discrete and is shown as:

- > 85% Public Approval → +3 Political Influence
- 60 – 85% → +2
- 40 – 60% → +1
- 20 – 40% → +0
- < 20% → – 1 (if any Influence is held)

These thresholds are balancing parameters rather than empirical estimates. They embody the simplifying assumption that higher approval generally expands a leader's capacity to pursue an agenda, consistent with research linking public opinion to policy responsiveness on salient issues (Page & Shapiro, 1983, p. 175).

Policies panel (costs, prerequisites, and effects)

Policies are accessed via the Policies button in the left-side UI. Each policy lists a monetary cost, a Political Influence cost, and an Effects section that specifies the resulting effects if the policy is activated. Policies can be inspected before commitment; adoption is gated by available treasury funds and accumulated Political Influence. Policies are organized under Energy Management, Governance, International Relations, Public

Relations, and Taxes. Each policy specifies (i) a Political Influence cost, (ii) a one-time and/or recurring fiscal cost, and (iii) a compact list of modeled effects. Effects operate either as additive deltas (Δ) or multiplicative factors (×) on internal model parameters. In the current build, the targeted parameters are:

- **Public Approval**: Additive changes in citywide approval (percentage points).
- **Citywide energy demand index**: Multiplicative changes in overall electricity/energy demand.
- **Citywide energy costs index**: Multiplicative change in unit energy prices.
- **Renovation cost index**: Multiplicative change in retrofit/renovation costs.
- **Annual tax/fee revenue**: Additive changes to annual revenues.
- **External grant to treasury**: One-off fiscal transfers (grants/aid).
- **Solar cost indices**: Multiplicative cost reductions for solar microgeneration programs.
- **Political Capital**: Additive change to a diplomatic score used for unlocking/qualifying international instruments.

Policies marked "toggleable" act as on/off levers (e.g., Carbon Tax, Transparency Dashboard, several standards/mandates). One-shot actions (e.g., grants, festivals) are non-toggleable and apply their effects once.

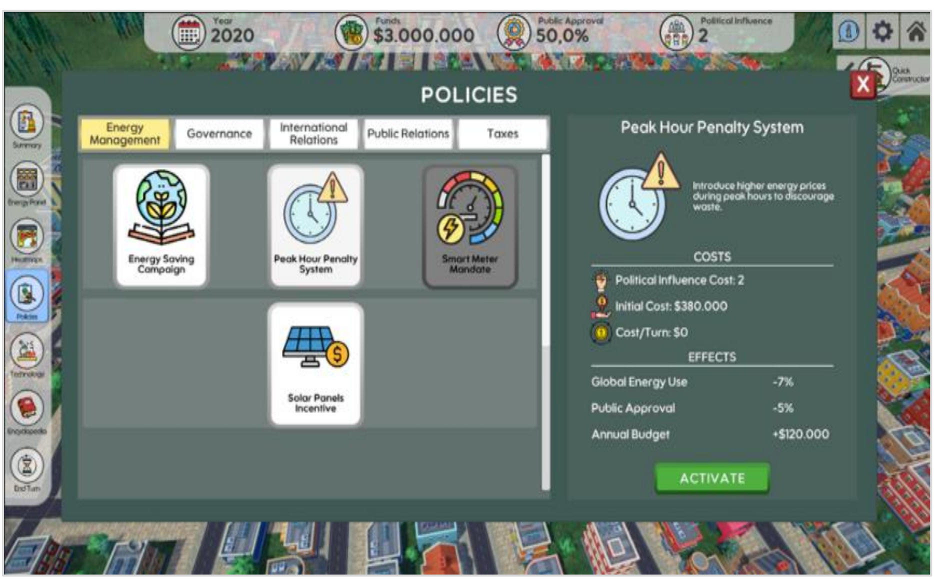

Figure 11: The Policy Panel and the Details of a Policy.

Table 6: List of all Available Policies in the Game with their Costs and Effects.

Policy (Category)	**Category**	**Political Influence**	**One-time $**	**Recurring $/yr**	**Toggleable**	**Key effects (Δ or ×)**
Peak Hour Penalty System	Energy Management	2	380,000	0	✓	Energy demand ×0.93 Public Approval Δ−5 Annual revenue Δ+120,000
Smart Meter Mandate	Energy Management	3	340,000	160,000	✓	Energy demand ×0.96 Renovation costs ×1.02 Public Approval Δ−3
Solar Panels Incentive	Energy Management	2	480,000	130,000	✓	Solar cost indices ×0.90
Energy Saving Campaign	Energy Management	1	570,000	0	✗	Energy demand ×0.98 Public Approval Δ+2
Energy Efficiency Standards	Governance	2	250,000	60,000	✓	Energy demand ×0.97 Renovation costs ×1.04
Green Building Code Update	Governance	3	540,000	20,000	✗	Renovation costs ×1.03 Energy demand ×0.95
National Green Renovation Fund	Governance	3	1,090,000	0	✓	Renovation cost ×0.85 Public Approval Δ+5
Solar Renovator Certification	Governance	3	540,000	0	✗	Solar cost indices ×0.95
Climate Diplomacy Tour	International Relations	2	260,000	0	✗	Public Approval Δ+2 Political Influence Δ+3
Global Climate Fund (International Relations)	International Relations	3	40,000	0	✗	External grant Δ+$2,500,000
Join the International Retrofit Alliance	International Relations	2	360,000	0	✗	External grant Δ+$1,000,000 Renovation cost ×0.97 Energy demand ×0.97
Bilateral Green Aid Agreement	International Relations	4	40,000	0	✗	External grant Δ+$3,500,000
Charity Gig	Public Relations	1	600,000	0	✗	Public Approval Δ+8
Green Festival Sponsorship	Public Relations	2	270,000	10,000	✗	Public Approval Δ+5
Sustainability Influencer Program	Public Relations	1	340,000	0	✗	Public Approval Δ+3 Energy demand ×0.99
Transparency Dashboard	Public Relations	1	540,000	0	✓	Public Approval Δ+4
Carbon Tax	Taxes	3	110,000	0	✓	Annual revenue Δ+200,000 Public Approval Δ−16 Energy demand ×0.96
Clean Tech VAT Discount	Taxes	3	270,000	0	✓	Energy demand ×0.98 Public Approval Δ+2
Green Property Tax Breaks	Taxes	2	300,000	90,000	✓	Renovation cost ×0.95 Public Approval Δ+4
Industrial Carbon Tax Reform	Taxes	2	200,000	0	✓	Public Approval Δ−6 Annual revenue Δ+210,000 Energy costs index ×1.10

Design rationale and limitations:

Renovation Willingness is explicitly fictionalized to communicate social acceptance; it should be read as a didactic device, not a measurement. 2) The approval→influence schedule was tuned for gameplay clarity and pacing. 3) Because some players may pursue popularity by investing in already efficient, high-willingness buildings, the scoring system preserves cross-objective tensions rather than collapsing them into a single composite metric. This aligns with the intention to let players experience how public sentiment can enable—or constrain—policy trajectories even when technical solutions are known (Wüstenhagen et al., 2007, p. 2684; Page & Shapiro, 1983, p. 175).

This political subsystem is a purposeful abstraction. It (a) surfaces building-level social heterogeneity through Renovation Willingness; (b) couples city-wide Public Approval to policy capacity via Political Influence; and (c) requires players to navigate the tension between technically optimal retrofits and politically sustainable rollout paths. As a model embedded in a game, it does not aim to reproduce the full complexity of real-world institutions or opinion dynamics; rather, it offers a clear decision structure that keeps human factors visible in an otherwise data-driven urban energy simulation (Salen & Zimmerman, 2004, pp. 92–95; Wilson et al., 2015, pp. 12–14).

3.3.9 Technology Panel and Tech Trees

The Technology Panel is designed as a management-phase interface through which research choices are planned and applied to the city's energy system. Within this panel, players review thematic research trees ("tech trees") and unlock discrete improvements that modify model parameters governing generation, demand, investment costs, energy unit prices, and retrofit costs. The panel has been implemented to provide a structured space for technological progress, distinct from policy instruments. In practice, this separation clarifies the respective roles of politics (rules, incentives, constraints) and technology (conversion efficiency, capital efficiency, and operational know-how), and supports transparent reasoning about cause–and–effect relationships in the game.

Functionally, the panel is organized into nine tabs. Seven tabs correspond to the primary energy sources represented in the game: coal, natural gas, wind, solar, hydroelectric, geothermal, and nuclear. Each of these energy-source tabs contains three parallel research trees targeting their capacity leverage, levelized cost of energy (per-kWh cost) reduction, and reduction of capacity investment costs specific to that source. Each energy source tab features technologies that are thematically appropriate for that source (e.g., drilling and heat-exchange optimizations in geothermal; hub-height and siting tools in wind; per-module electronics and mounting innovations in solar; licensing and share-purchase mechanisms for small modular nuclear participation). The source-specific content communicates how technological pathways differ among fuels and generation modes. The capacity investments are handled in the energy management panel, but the capacity trees in the Technology Panel focus on operating as efficiency multipliers and prerequisite gates rather than as direct capacity grants. In other words, capacity is built through the investment interface, while the corresponding technology tree improves the effectiveness of that investment and the yield of installed assets over time.

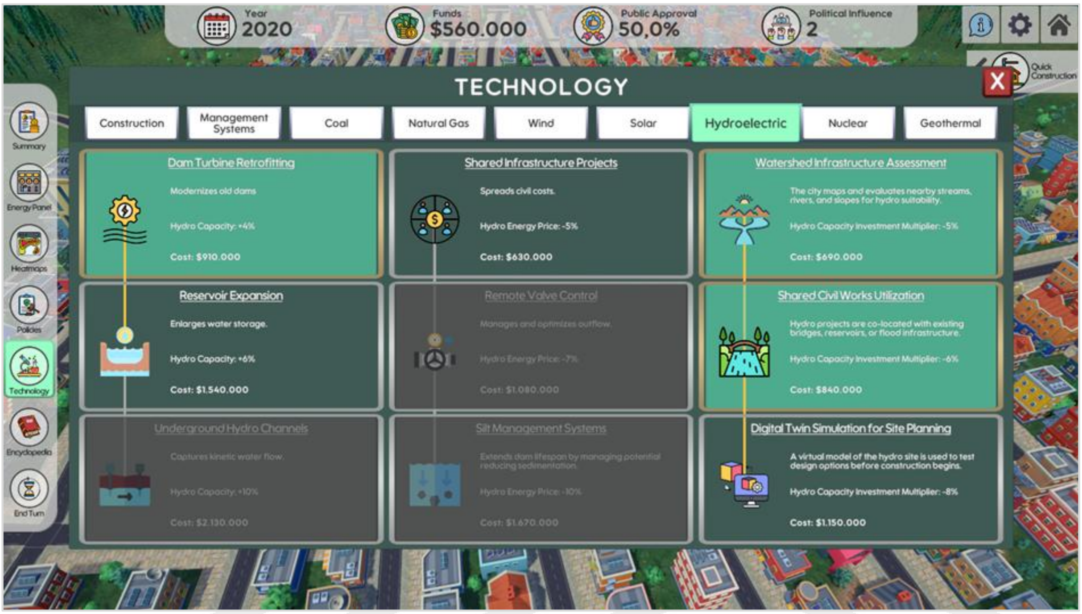

Figure 12: The Tech Tree of an Energy Source (Hydroelectric).

In addition to the seven source-specific tabs, two tabs address more globally affecting issues in the city. The Retrofitting / Construction tab concentrates on cost improvements for building upgrades without altering the underlying insulation outcomes. Separate trees are provided for wall insulation, window/glazing retrofits, and rooftop solar microgeneration fitting. These trees emphasize standardized components, improved installation methods, and tooling or diagnostics that lower material, labor, or logistics costs while leaving thermal performance constants unchanged. A maintenance-focused tree for rooftop solar is also included to reduce ongoing cleaning, inspection, and replacement costs (e.g., through self-cleaning coatings, remote diagnostics, and automated inspection methods), thereby lowering lifecycle expenditure without altering energy output.

The Integration & Management Systems tab targets system-level coordination rather than asset-level upgrades. One tree reduces overall consumption by enabling metering, adaptive scheduling, neighborhood-level optimization, and predictive load forecasting; another tree lowers global energy costs through decentralized billing systems, dynamic pricing, smart routing from least-cost sources, and analytical decision support. Together, these trees are intended to represent the types of savings that can be realized through information, coordination, and market design, even when physical infrastructure remains fixed.

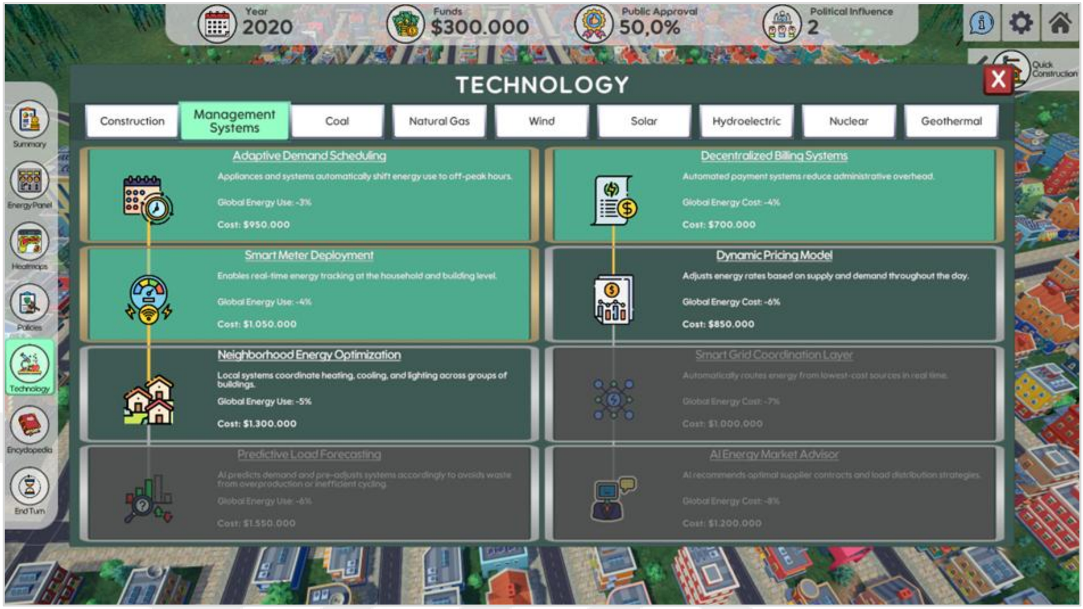

Figure 13: Screenshot of the Management Systems Technology Tree.

Across all tabs, technologies are presented with short explanations, expected effects, and costs. Unlocking a technology applies a change in the relevant in-game parameter, such as energy cost multipliers, renovation cost multipliers, etc. Effects are tuned to maintain internal balance of the game economy and to keep scenario outcomes legible at the neighborhood scale. They are not claimed to be predictive of real-world magnitudes. This design stance is deliberate: technology names and structures are drawn from plausible practices and emerging methods, but numerical effects are calibrated to support engaging play, meaningful trade-offs, and clear feedback without overfitting to any single empirical dataset.

The Technology Panel serves two purposes. First, it communicates the plausible levers, technological, organizational, and informational, through which urban energy systems can be improved, even in the absence of new policy authority. Second, it provides replay value and depth to the game by enabling alternative research sequences and different strategies. As a result, the panel supports exploration of "what-if" paths in a controlled environment, emphasizing systems thinking and the cumulative impact of many small, comprehensible improvements.

3.3.10 Encyclopedia Panel

In order to support the educational and awareness-raising goals of the game, an in-game Encyclopedia Panel has been integrated as a supplementary resource for players. This panel is designed to provide players with structured, concise, and reference-informed background information about key concepts, systems, and terminology encountered during gameplay. While the game's core mechanics simplify many of these concepts for playability and accessibility, the Encyclopedia offers a space where curious players can explore these topics in greater depth.

The Encyclopedia Panel is accessible at any time during gameplay and is entirely optional; it does not influence the mechanics of the game directly, nor is it required for progress. However, by offering this panel as an embedded informational tool, the game enables players to actively engage with the material at their own pace, supporting both self-directed learning and deeper cognitive reflection.

Each entry in the Encyclopedia was written in a brief but informative style (typically corresponding to a 2–3-minute read), accompanied by proper references where appropriate. The texts were intentionally designed to remain accessible to a general audience, while still providing a realistic and credible overview of each topic. Although academic references were not heavily foregrounded in the UI, all texts were written based on real sources, and the most relevant reference materials were listed at the end of each entry in APA format, including page numbers to enable verification.

The Encyclopedia is navigated through a scrollable list of categorized titles, located on the left-hand side of the panel. When a title is selected, the corresponding text is displayed on the right-hand side of the interface. Rather than fragmenting the interface into multiple sub-windows, a single display panel was used to improve usability and encourage uninterrupted reading. The categorization of topics (e.g., energy sources, urban sustainability, building efficiency) enhances navigation and reflects the structure of real-world knowledge systems.

The content of the Encyclopedia includes 25 distinct entries, grouped under six overarching thematic categories. These titles are as follows:

- Sustainable Development and Cities
  - What is a Sustainable City?
  - The Role of Cities in Climate Action
  - Urbanization and Its Environmental Impact
- UN Sustainable Development Goals (SDGs)
  - Overview of the UN Sustainable Development Goals (SDGs)
  - SDG 7: Affordable and Clean Energy
  - SDG 11: Sustainable Cities and Communities
  - SDG 13: Climate Action

- Building Efficiency and Retrofitting
  - Building Energy Efficiency Basics
  - Understanding Insulation (Walls, Roofs, Windows)
  - Retrofitting Existing Buildings
  - Thermal Bridging and Air Leakage
  - Passive House Standards
  - When Sustainable Choices Don't Pay Off
- Solar and Renewable Technologies
  - What is Solar Microgeneration?
  - Challenges of Rooftop Solar
  - Cost, Maintenance, and Payback Time
- Energy Systems and Trade-offs
  - Overview of Energy Sources
  - Fossil Fuels vs. Renewables
  - Comparative Pros and Cons of Energy Sources
  - Decentralized Energy Systems
- Governance, Participation, and Future Visions
  - Government Policy & Incentives
  - The Role of Local Authorities
  - Citizen Actions for Energy Efficiency
  - Barriers to Sustainable Urban Energy
  - Innovations in Green Building Technologies
  - Vision for 2050: A Climate-Resilient City

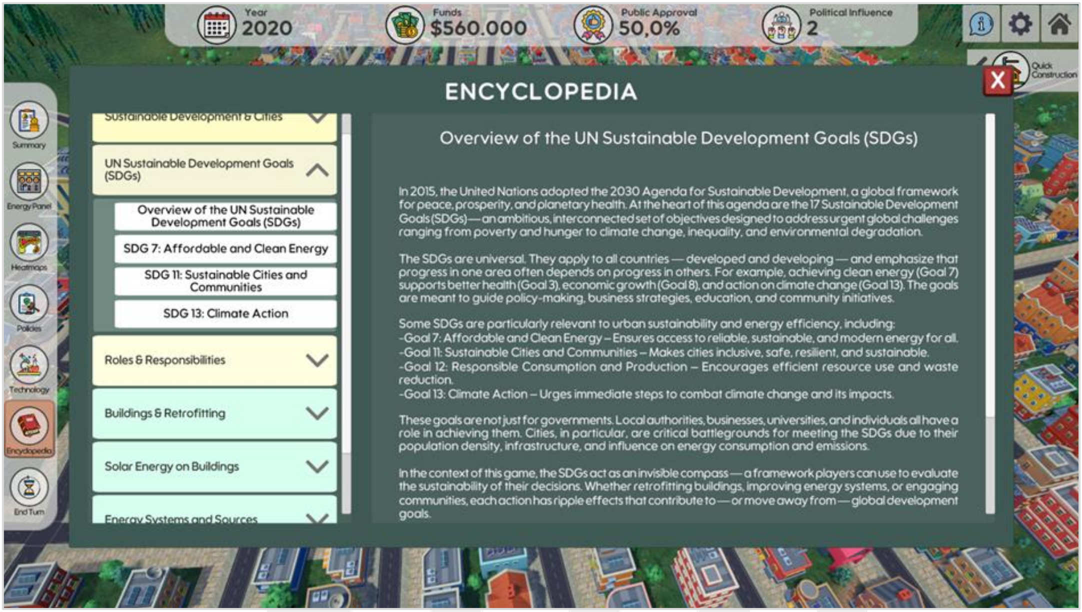

Figure 14: Screenshot of the Encyclopedia Panel.

By incorporating this Encyclopedia, the game attempts to bridge the gap between interactive experience and factual knowledge. It does not aim to replicate formal instruction but instead seeks to spark curiosity, clarify misunderstood concepts, and offer voluntary learning opportunities. This approach aligns with the overall pedagogical strategy of the game, which favors width over depth, encouraging players to grasp the broader system-level dynamics of urban sustainability and energy management without overwhelming them with technical complexity.

3.3.11 Random Events System

The game incorporates a Random Event System to introduce controlled uncertainty. Each turn corresponds to a calendar year, and at the start of every year, a probability-weighted draw is executed from an event pool, with the possibility that no event occurs. The Random Event System was designed to add replay value, uncertainty, fun, and a sense of realism that would reflect real-life urban energy management. This is a way of reflecting that no matter how good a local authority thinks they are, they should always expect the unexpected and be ready to react and adapt to crises. The event pool covers climatic anomalies that shift energy demand or solar yield; natural disasters that can render older, more vulnerable buildings out of service and erase site-level investments such as rooftop solar (with rebuilding outside the player's renovation mandate); crises that curtail annual budgets and depress public approval; macroeconomic shocks that raise or lower construction and retrofit costs; socio-technical incidents like cyberattacks that increase electricity consumption and prices; and occasional positive or light-hearted developments, including international grants, public awareness events, or minor media flare-ups that nudge approval without destabilizing balance. By introducing bounded randomness at meaningful timescales, the system encourages risk-aware planning, prevents successive playthroughs from converging on identical outcomes, and communicates that even well-planned programs must absorb shocks and adapt. The present set of events is intentionally illustrative rather than exhaustive; the underlying structure allows the pool to be expanded easily in later versions to represent additional contingencies without altering core gameplay.

Figure 15: A Random Event That Takes Place at the Start of a Turn (Hurricane).

3.3.12 Quiz Mechanic ("Annual Competency Assessment")

A quiz mechanic has been implemented as a low-stakes, opt-in learning intervention that reinforces the game's educational focus on city-scale energy management. The instrument is designed to expose players to concise, domain-relevant facts and stimulate curiosity about sustainability topics encountered in the game. The broader aim is to guide players to notice unfamiliar concepts and, with the newly sparked curiosity, to consult the in-game encyclopedia or to conduct their own research.

The game proceeds in annual, turn-based cycles. Beginning with the second turn (i.e., all years after the initial year), a prompt is presented at the start of each turn: "The ministry offers additional budget for those who prove their competency with an annual test. Would you like to test your knowledge with a quiz?" The quiz is strictly optional; the player may decline without penalty. If accepted, a short assessment is administered before management decisions are taken for that year, and success is rewarded with additional funds.

Each quiz consists of three multiple-choice questions drawn at random without replacement from a larger question pool. Questions are intentionally "bite-sized" and target foundational knowledge within the game's targeted educational scope. The pool covers, among others: building envelope and insulation fundamentals (e.g., U-value/R-value concepts, air sealing, glazing), building heating demand and efficiency measures, microgeneration, comparative characteristics of energy sources, economic notions such as upfront investment cost per kWh, payback/ROI, levelized cost of energy, the UN Sustainable Development Goals, as well as societal and policy dimensions. To increase engagement, several question types are included: straight recall (direct terminological questions), application-type (applying a concept to a short scenario, constraint, or simple comparison), and "which is NOT…" type questions. Distractors are written to be plausible rather than obvious. If an item is answered incorrectly, the correct answer is displayed to promote immediate correction of misconceptions. Players are implicitly encouraged to consult the encyclopedia for deeper coverage.

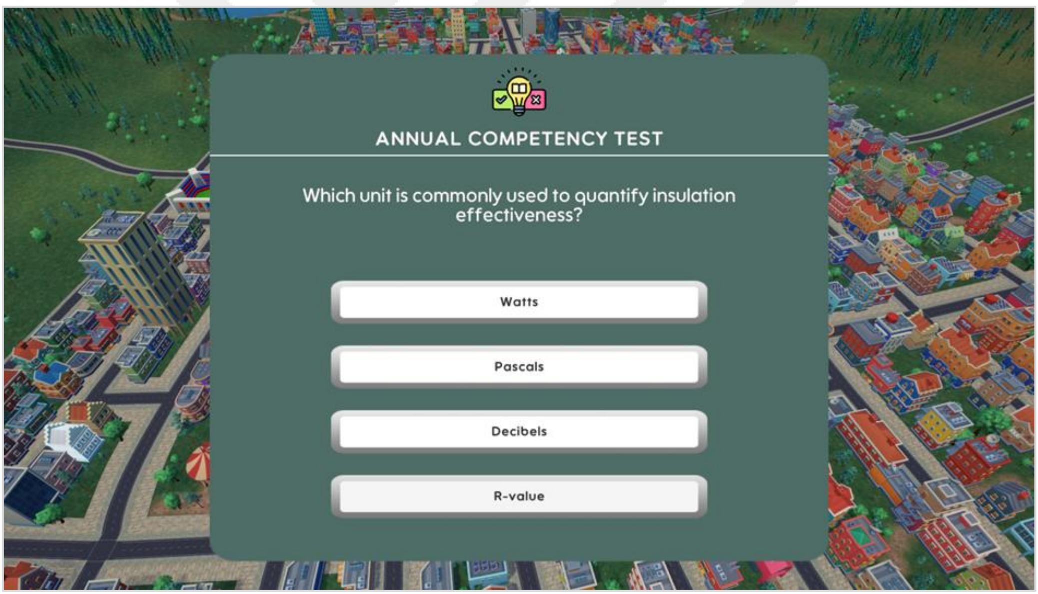

Figure 16: A Sample Question from the Annual Competency Test.

The base annual budget available to the player is 3,000,000 USD. The quiz confers an additive budget bonus according to performance: a perfect score (3/3 correct) yields +500,000 USD (≈16.7% of the base annual budget), a score of 2/3 correct yields +250,000 USD (≈8.3% of the base annual budget), and a score of 0 – 1/3 correct yields no bonus.

Overall, the quiz functions as a recurring, lightweight reinforcement mechanism aligned with the game's learning goals. The mechanic is intended to strengthen recognition of key sustainability concepts, nudge players toward reflective inquiry, and translate improved conceptual understanding into more informed decisions both in and out of the game.

3.4. Technical Development in Unity

3.4.1 City Environment Creation

The development of the game has been carried out using Unity 6 (v6000.0.32f1 to be precise) with URP (Universal Render Pipeline). These choices were adopted to balance visual quality with broad hardware reach. The selection of URP was also made to enable the development of custom shaders using the shader graph in Unity. The terrain of the environment has been created using Unity's terrain tools. The lighting and post-processing are also carried out without external tools.

The initial 3D model of the city originated from the TÜBİTAK project mentioned before, and was exported from Rhino as axis-aligned rectangular prisms. That model represented the positions and sizes of the buildings inside the neighborhood in dwelling-unit granularity. Rather than building-level meshes, the source encoded dwellings (apartments) individually. These apartments were represented with rectangular prism-shaped simple objects. 593 buildings were represented, each containing dozens of flats, which yielded 7,165 prismatic objects after export. Each prism arrived as a distinct mesh, and although the shapes looked like simple boxes, the meshes were actually unnecessarily heavy with high vertex counts. These created three immediate issues in Unity:

- Unnecessarily high vertex counts in seemingly simple shapes, resulting in high GPU load.
- Collider mismatch and placement difficulty for arbitrary imported meshes. The simple box colliders only fit these prisms as "bounding boxes", meaning they would often be bigger than the actual prism because the way it works is to simply cover min X to max X, min Y to max Y, min Z to max Z. The collider would not align and properly fit the prism, and this would create many problems in gameplay, like faulty clicking boundaries, etc.
- Poor opportunities for batching or GPU instancing due to excessive mesh variety (Unity batches objects that share the same material; GPU instancing further requires identical meshes and a single material) (Unity Technologies, n.d.).

Figure 17: The Top-Down View of the Initial Neighborhood Model Placed on the 2D Map of the Original Location.

To transform the city model and avoid the issues mentioned above, a custom "Fit-Cube-to-Prism" procedure was implemented. For every imported apartment prism, the algorithm computed its world-space position, orientation, and dimensions, then replaced the original mesh with a Unity primitive cube that exactly matched those parameters. The effect was threefold. First, vertex counts were dramatically reduced because a primitive cube uses a minimal triangle budget compared with many Rhino-exported prisms that contained redundant vertices and split faces. Second, colliders became trivial and exact: each primitive cube was assigned a Box Collider that tightly fit its extents, eliminating the loose axis-aligned bounding behavior observed when arbitrary meshes were used. Third, material and mesh uniformity enabled standard rendering optimizations (e.g., static batching or instancing) that would have been impractical with thousands of unique meshes.

Because the original data were modeled at the apartment level, a second transformation aggregated units to their parent buildings. During import, dwelling metadata were grouped by building identifier. Per-building placeholders (again, primitive cubes) were created by fusing the spatial extents of each building's constituent units and storing the building-level attributes required by downstream systems (e.g., counts of dwellings, energy metadata, selection IDs). This step yielded one clean placeholder object per building while preserving a reliable anchor for subsequent runtime visualization.

Figure 18: The View of the Neighborhood with Aggregated Building Blocks and the New Environment Handling the Neighborhood as an Isolated Town.

To create a game-ready, visually attractive city environment, a 3D asset package was used. This package contained many cartoon-styled low-poly building models. The next step was to use these models to create the city without changing the buildings' positioning and the information they carry. To align the procedural visualization with building scale, a categorical mapping from dwelling count to visual archetype was defined. The rule was defined as:

- 0–6 dwellings → Single-story archetypes
- 6–12 dwellings → Two-story archetypes
- 12–18 dwellings → Three-story archetypes
- 18–24 dwellings → Four-story archetypes
- 24 dwellings → Mid-rise archetypes

The asset package provided multiple variants per category (e.g., several single-story options, several two-story options, etc.).

A limited-randomized method for city generation has been developed that would pick and place a 3D building asset at the placeholder building cubes according to their apartment counts. The selection was randomized among category-appropriate variants to introduce visual diversity while remaining consistent with the underlying data. Placement used the placeholder's transform to drive the position, orientation, and uniform or axis-specific scaling needed to fill the footprint. Because the placeholders carried the building IDs and aggregated metadata, the instantiated visuals retained a stable link to data systems for selection, highlighting, querying, and UI binding.

Figure 19: The View After Placing the 3D Models to the Building Placeholders.

By converting thousands of apartment-level prisms into standardized primitive placeholders, then aggregating and mapping them to building-level visual archetypes, a scalable and maintainable city environment was achieved. The workflow preserved data fidelity, supported efficient collision and selection, and enabled flexible visual replacement without altering the underlying spatial or gameplay logic.

3.4.2 Integration of ML Model

This game integrates multilayer-perceptron (MLP) predictors trained on a zone-level Urban Building Energy Model (UBEM) of Ankara's Aşağı Bahçelievler, covering 593 residential buildings and 6,452 apartment-zones. The released weights has been exported to ONNX to run them in Unity via Barracuda for real-time inference (Akyol et al., 2025; Iseri et al., 2025). The original studies model each apartment as a thermal zone (non-archetype, high-resolution UBEM) and publicly release the code/models to support reuse, which aligns with this implementation.

The model's original scope is at the apartment (zone) level rather than the whole-building scale. Within the game, unit-level predictions are therefore computed for each building's constituent units at runtime and aggregated to produce building-level results that drive the feedback shown to the player. For simplicity and responsiveness, the in-game implementation uses only the 2020 ("W2020") climate features and dataset at runtime (i.e., it does not query the 2050/2080 scenarios during play), even though the source work trains and reports combined-year models for 2020/2050/2080.

Operationally, the game maps building/zone features to the model inputs and performs batched ONNX inference after each relevant player action (e.g., envelope retrofit, policy toggle). The resulting values are then bound to the UI so that, when the player proposes envelope modifications (e.g., insulation changes), the displayed performance update is driven by these ML predictions.

The predictors estimate annual heating demand (QHeating) and Indoor Overheating Degree (IOD). Although the IOD values haven't been implemented as a game parameter, the main focus was kept on the annual heating demands of the buildings. Reported validation indicates very high fidelity ($R^2 \approx 0.98$ for QHeating; $R^2 \approx 0.96$ for IOD) and a substantial speed advantage (~430 × faster than full UBEM simulations). This fast response time of the model makes the approach well-suited for interactive gameplay, enabling per-action feedback without perceptible lag (Akyol et al., 2025).

CHAPTER 4

METHODOLOGY FOR EVALUATION AND TESTING

4.1. Research Design

A cross-sectional, convergent mixed-methods user study was implemented to evaluate the game's usability, user experience, and perceived educational impact. A one-group posttest design was used: all participants played the PC-based game and then completed post-session instruments. Quantitative data (structured questionnaires) and qualitative data (open-ended responses) were collected within the same session and later integrated during interpretation to obtain complementary perspectives (Creswell, 2009, pp. 189–201; Creswell & Plano Clark, 2018, Convergent Design). In-person sessions were conducted in a quiet room at the Informatics Institute of Middle East Technical University. Participants (N = 55) were young adults (18–39), primarily students and early-career professionals; an effort was made to keep gender representation balanced. Each participant used an institute laptop configured with the Windows build. Participation was voluntary with written informed consent, and procedures followed the ethical principles of respect for persons, beneficence, and justice (National Commission, 1979). Likert-type ratings were chosen to quantify attitudes and perceptions. A seven-point format was adopted for the custom instruments to increase response sensitivity without undue burden, consistent with evidence on response-category optimization (Dawes, 2008, pp. 61–77; Preston & Colman, 2000, pp. 1–15).

4.2. Procedure for Game Testing

Upon arrival, participants were briefed on the project's purpose, scope, and data handling, and signed the consent form. They were briefly shown the basic interaction paradigm and informed that an in-game tutorial was available. Participants then played independently; the researcher remained nearby solely for clarification when requested and did not provide strategic guidance. No time limit or completion requirement was imposed. Some participants explored for extended periods—including replaying alternative paths—while others completed the core goals in approximately 20–40 minutes. Immediately after gameplay, participants completed the questionnaires in the following order: custom instruments, System Usability Scale (SUS), and open-ended prompts.

4.3. Data Collection Instruments

Two custom questionnaires and one standardized instrument were administered, followed by open-ended questions:

Impact Questionnaire: A multi-item instrument (19 items) designed to capture perceived learning and attitudinal shifts attributable to gameplay (e.g., awareness of trade-offs, reflection on energy policy, motivation to seek further information). Items were derived deductively from the game's learning objectives and the intended outcomes of digital serious games. Responses used a seven-point Likert-type scale (1 = Strongly disagree, 7 = Strongly agree). The seven-point choice was intended to provide finer discrimination while maintaining clarity for respondents (Dawes, 2008, pp. 61–77; Preston & Colman, 2000, pp. 1–15). Negatively keyed items, where present, will be reverse-scored during analysis.

Usability-Engagement-Aesthetics (UEA) Questionnaire: A 15-item scale that consolidates three experience dimensions often reported in game evaluation: (i) usability (perceived effectiveness/efficiency and clarity of the interface), (ii) engagement (attention, immersion, enjoyment, and motivation), and (iii) aesthetics (visual and auditory appeal). Items were worded to reflect single constructs and to remain consistent with the usability definitions of effectiveness, efficiency, and satisfaction in a given context of use (ISO 9241-11:2018). The same seven-point Likert-type format was employed to keep measurement consistent across custom instruments.

System Usability Scale (SUS): The 10-item SUS (10 items captured in the dataset) was included to provide a benchmarked, single-score usability index that facilitates comparison with prior studies (Brooke, 1996, p. 4; Bangor, Kortum, & Miller, 2009, pp. 114–123). SUS items are rated on a five-point scale, and the standard scoring procedure yields a score from 0 to 100 (Brooke, 1996, p. 4). Including SUS supports external comparability and strengthens the interpretability of the custom usability findings.

Open-ended questions: Short prompts invited participants to describe notable learnings and to suggest improvements. These qualitative responses were included to surface themes not anticipated by fixed items and to capture participants' phrasing and priorities, complementing the quantitative scales.

4.4. Data Analysis Methods

To implement quantitative preprocessing and scoring, all Likert responses were treated as integers 1–7. Composite scores were computed as participant-level means across the items in each predefined scale/subscale. For the Impact questionnaire, subscales were fixed to 5–5–4–3 items in this order: (1) Awareness of Urban Energy Efficiency (items 1–5), (2) Awareness of Strategic Decision-Making (6–10), (3) Attitudes & Behavioral Intentions (11–14), and (4) Game Experience & Educational Value (15–17). Items 18–19 are open-ended and excluded from quantitative scoring. For UEA, sections followed 5–5–5: (A) Usability & Interface (1–5), (B) Engagement & Immersion (6–10), (C) Aesthetics & Design (11–15). The System Usability Scale (SUS) was scored via the standard Brooke (1996) rule (odd: score − 1; even: 5 − score; sum × 2.5 → 0–100).

To display descriptive statistics and confidence intervals for each composite and subscale, we report the mean, standard deviation (SD), and 95% confidence interval (CI) for the mean using the t-distribution with df = N − 1. For SUS, we additionally report quartiles (Q1, Median, Q3) and the proportion of scores ⩾ 68 as a commonly cited benchmark (Bangor, Kortum, & Miller, 2009).

Internal consistency was assessed with Cronbach’s alpha (α) on the item sets for each subscale/section. We interpret α following common guidance—α ⩾ .70 acceptable; α ≈ .60–.70 tolerable in exploratory contexts (Hair, Black, Babin, & Anderson, 2019). Where α is modest for short subscales, we contextualize results accordingly rather than treating it as evidence of poor measurement.

To provide descriptive context (no inferential testing), we computed two-group differences using Cohen’s d with pooled SD (Cohen, 1988). Demographic groupings were operationalized a priori as follows:

- Gamer identity: Yes vs. No + Somewhat.
- Gaming frequency: Frequent = Very Frequently/Frequently vs. Infrequent = Occasionally/Rarely/Never.
- Strategy/simulation/resource-management familiarity: High = Moderately/Very/Expert vs. Low = Slightly/Not familiar.
- Prior serious-game experience: Yes vs. No + Not sure.
- Gender: Male vs. Female.

For each split we report n(A), n(B) and group means for SUS (0–100) and per-item means for UEA and Impact (1–7). No t-tests/ANOVAs were run; effect sizes are presented descriptively.

- The qualitative open-ended questions, (Impact items 18–19) were analyzed using a light-weight content/thematic pass: text cleaning, tokenization (English/Turkish stop-word removal), frequency scan, and manual theme aggregation (e.g., learning/awareness; strategy/decision-making; visuals/aesthetics; feedback/clarity; difficulty/pacing; performance/technical; motivation/engagement). Themes are summarized with counts and representative quotations; open-ended responses are not included in any numeric composites.

- Composites and α were computed listwise at the subscale level (participants with complete items for that subscale/section). Subgroup counts (n) in tables reflect the observed number per group after recoding; A and B always sum to the analytic N = 55 for a given comparison.

- When contextualizing SUS, we reference (i) acceptability bands and adjective ratings (Bangor et al., 2009) and (ii) letter-grade bands (Sauro & Lewis, 2016). For orientation we also note the NPS-style promoter/passive/detractor framing sometimes presented alongside SUS (Sauro, 2011). These frameworks are interpretive, not inferential.

CHAPTER 5

RESULTS AND FINDINGS

5.1. Methods Used (in alignment with Chapter 4)

This chapter reports descriptive and reliability results computed from the administered questionnaires. The following methods were employed;

- Descriptive statistics: means, standard deviations (SD), and 95% confidence intervals (CIs) for composite and subscale scores.

- Composite scoring for custom instruments: category and section scores were calculated as the arithmetic mean of their constituent Likert items (1–7). Internal consistency reliability was assessed using Cronbach's alpha (Hair, Black, Babin, & Anderson, 2019, pp. 794–805).

- System Usability Scale (SUS): scores were computed with the standard Brooke (1996) algorithm and summarized with mean, SD, 95% CI, and the proportion above the 68-point benchmark; benchmark interpretation follows Bangor, Kortum, and Miller (2009, pp. 114–118) and Sauro and Lewis (2016, pp. 204–210).

- Simple subgroup comparisons (exploratory): where shown, two-group differences are expressed with Cohen's d using a pooled standard deviation; no null-hypothesis tests (t-tests/ANOVAs) were performed, and effects are interpreted descriptively (Cohen, 1988).

5.2. Participant Demographics and Background

Participants (N = 55) were predominantly university students or early-career graduates, with balanced gender representation. Age and gaming background distributions are detailed in the instrument dataset; these profiles provide context for interpreting usability and learning outcomes.

- Ages ranged from 18 to 40 years (mean = 28.5; median = 29, σ = 5.01).

- The sample was 61.8% male and 38.2% female.

- Regarding education, 65.5% reported graduate-level studies, 32.7% undergraduate, and 1.8% high school.

- Under gaming habits and familiarity, self-reported play frequency skewed toward active players: 30.9% played very frequently (almost daily), 16.4% frequently, 27.3% occasionally, 20.0% rarely, and 5.5% never.

- Familiarity with strategy/simulation/resource-management games was distributed as 7.3% expert-level, 23.6% very familiar, 30.9% moderately familiar, 23.6% slightly familiar, and 14.5% not familiar at all.

- Prior exposure to educational/awareness games was mixed: 34.5% yes, 25.5% not sure, 40.0% no.

- Devices and gamer identity. The most common device context included PC in some form (41.8% PC-only; further combinations with mobile/console/browser comprised much of the remainder).

- Self-identification as a gamer was 34.5% yes, 25.5% somewhat, and 40.0% no.

5.3. Analysis of Awareness Improvement/Impact Questionnaire

For each predefined Impact category: (1) Awareness of Urban Energy Efficiency, (2) Awareness of Strategic Decision Making, (3) Attitudes and Behavioral Intentions, and (4) Game Experience and Educational Value, item responses (1–7) were averaged per participant to produce a category score. The table below reports the mean, standard deviation (σ), 95% CI (confidence interval), number of items (k), sample size (N), and Cronbach's alpha (α) where applicable (Hair et al., 2019). See "Appendix A" for further details.

Table 7: Results of the Subsections of the Impact Questionnaire.

Sub-Category	k	N	Mean	σ (SD)	95% CI Low	95% CI High	Alpha
Awareness of Urban Energy Efficiency	5	55	5.982	0.764	5.775	6.188	0.703
Awareness of Strategic Decision Making	5	55	6.138	0.749	5.936	6.341	0.778
Attitudes and Behavioral Intentions	4	55	6.073	0.731	5.875	6.270	0.695
Game Experience and Educational Value	3	55	6.636	0.502	6.501	6.772	0.345

Category means were uniformly high (on a 1–7 scale), supporting the conclusion that the game enhanced awareness and intended behavioral directions. Where α is modest, the result is interpreted in light of short subscales rather than as evidence of poor measurement (Hair et al., 2019).

In addition to these categories, two open-ended questions were present in the Impact Questionnaire; one asked "*What is one important thing you learned or realized while playing this game?",* the second asked *"Do you have any suggestions for improving the game experience?".* Analysis of these open-ended items showed that we received 84 open-ended responses across the two Impact prompts. Comments clustered around sustainability actions, frequent mentions included sustainable, buildings, solar, and public policies, with many participants noting that the experience increased their awareness of how policy choices and retrofit strategies shape outcomes. A sizable share praised the visuals/aesthetics and how information is presented, while others asked for clearer guidance and feedback (e.g., brief tooltips or "why" explanations for outcome changes). Several respondents highlighted difficulty/pacing, suggesting a gentler early curve or optional "guided" scenarios, and a smaller group requested more strategic levers (e.g., additional renewable options, policy/permit dynamics, or goal-oriented presets). Only isolated remarks touched on technical performance. Overall, the qualitative feedback aligns with the quantitative results: perceived educational impact is strong, and the most actionable refinements involve micro-feedback/clarity and early-game scaffolding to support less frequent or less experienced players.

5.4. Usability Engagement and Aesthetics Questionnaire Evaluation

The Usability–Engagement–Aesthetics (UEA) questionnaire consists of its sub-sections: (A) Usability and Interface, (B) Engagement and Immersion, and (C) Aesthetics and Design. Section scores are participant-level means across items (1–7). Table 8 reports the section mean, standard deviation (SD), 95% confidence interval (CI), number of items (k), sample size (N), and internal consistency (Cronbach's α). Following common guidelines, α≥.70 is typically considered acceptable, and α≈.60–.70 is tolerable in exploratory studies (Hair et al., 2019).

Table 8: Results of the Subsections of the Usability-Engagement-Aesthetics (UEA) Questionnaire.

Section	k	N	Mean	σ (SD)	95% CI Low	95% CI High	Alpha
Engagement and Immersion	5	55	6.367	0.594	6.207	6.528	0.732
Aesthetics and Design	5	55	6.375	0.724	6.179	6.570	0.763
Usability and Interface	5	55	6.436	0.518	6.296	6.576	0.628

All sections achieved very positive evaluations near the "agree/strongly agree" region. In your data (Table 8), Usability and Interface attained the highest central tendency (M = 6.44, SD = 0.52, 95% CI [6.30, 6.58], α = .63), followed closely by Aesthetics and Design (M = 6.38, SD = 0.72, 95% CI [6.18, 6.57], α = .76) and Engagement and Immersion (M = 6.37, SD = 0.59, 95% CI [6.21, 6.53], α = .73). Confidence intervals are tight (widths ≈0.30 – 0.40), indicating substantial agreement among participants and suggesting that perceived usability, engagement, and aesthetics are all consistently high.

Internal consistency is acceptable for Engagement and Immersion (α = .73) and Aesthetics and Design (α = .76). The Usability and Interface section shows marginal internal consistency (α = .63), which remains reasonable in an exploratory evaluation and may reflect the broad coverage of interface items or a ceiling effect when scores cluster near the top end of the scale (Hair et al., 2019). Overall, the sections are tightly clustered (6.37–6.44), indicating no obvious weak link within the UEA triad.

The UEA results support a clear conclusion: the system is easy to use, engaging, and aesthetically pleasing. With scores already near the top of the scale, future iterations should target selective micro-enhancements that deepen engagement and polish aesthetics while preserving the current usability strengths.

5.5. System Usability Scale (SUS) Evaluation

SUS was scored with the standard Brooke (1996) rule—odd items scored as (score − 1), even items as (5 − score), summed and multiplied by 2.5 to yield a 0–100 index (Brooke, 1996). For reporting, we provide the sample mean, SD, 95% CI, quartiles, and the share of participants above the widely cited 68-point benchmark (Bangor, Kortum, & Miller, 2009).

Our results. With N = 55, the mean **SUS was 82.05** (SD = 13.61), 95% CI [78.37, 85.72]; quartiles were Q1 = 73.75, Median = 85.00, Q3 = 93.75. 83.6% of participants scored at or above 68 (Brooke, 1996; Bangor et al., 2009).

Interpretation across common classes;

- On the adjective scale of Bangor et al. (2009), a score of ~82 **falls in Good, close to the Excellent boundary** (~85).
- On the acceptability scale, it is clearly **Acceptable** (⩾70) (Bangor et al., 2009).
- Using the letter-grade convention summarized by Sauro & Lewis, 80–89 corresponds to a **B grade**, again indicating performance that is Good and approaching Excellent (Sauro & Lewis, 2016).

- On the NPS-style promoter/passive/detractor framing sometimes shown alongside SUS, a score of ~82 sits in the **Promoter** band (≈80–100), indicating a high likelihood of recommendation (Sauro, 2011).

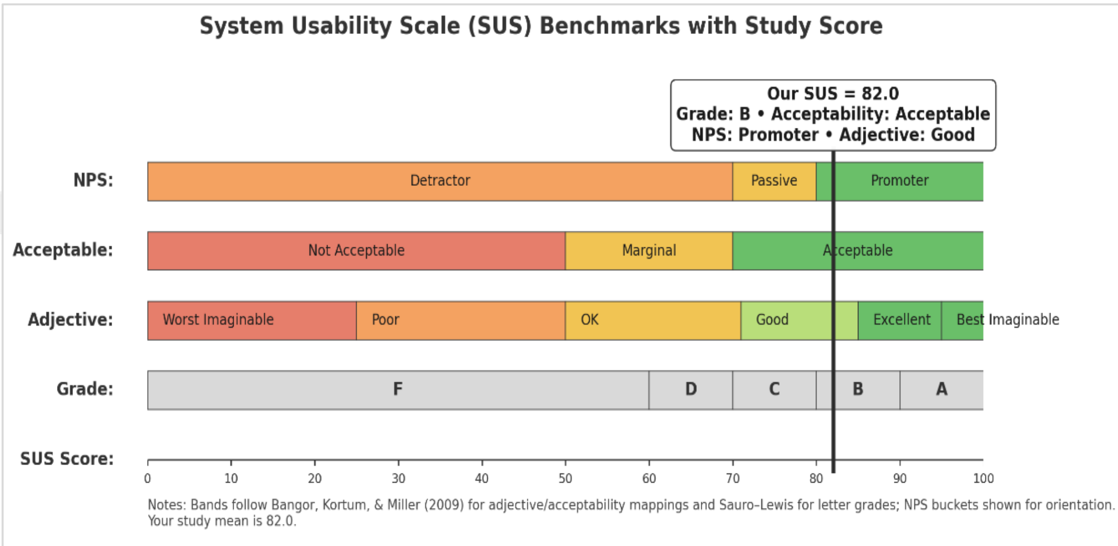

Figure 20: System Usability Scale (SUS) Benchmarks with Study Score

5.6. Demographic Effects and Additional Insights

Exploratory two-group comparisons were computed for key demographics. Group definitions were: Gamer identity (Yes vs. No + Somewhat), Gaming frequency (Frequent: Very Frequently/Frequently vs. Infrequent: Occasionally/Rarely/Never), Familiarity with strategy/simulation/resource-management games (High: Moderately/Very/Expert vs. Low: Slightly/Not familiar), Prior experience with educational/awareness games (Yes vs. No + Not sure), and Gender (Male vs. Female). For each split, we report means for SUS (0–100), and per-item means (1–7) for UEA overall and Impact overall, together with Cohen's d as an effect-size indicator using pooled SD (Cohen, 1988). No hypothesis tests were run; patterns are descriptive and intended to provide context rather than inference.

Table 9: SUS by Demographic Groups.

Comparison	A	n(A)	Mean(A)	B	n(B)	Mean(B)	Cohen d
Gamer identity (Yes vs. No + Somewhat)	Yes	19	80.00	No + Somewhat	36	81.76	-0.15
Gaming frequency (Freq/Very Freq vs. Never/Rarely/Occ.)	Frequent (Freq/Very Freq)	26	80.58	Infrequent (Never/Rarely/ Occ.)	29	83.36	-0.20
Familiarity with strategy/simulation/resource management games (High vs. Low)	High (Moderate/Very /Expert)	34	83.59	Low (Not/Slightly familiar)	21	78.72	0.37
Prior experience with educational/awareness games (Yes vs. No + Not sure)	Yes	19	77.22	No + Not sure	36	83.99	-0.55
Gender (Male vs. Female)	Male	34	80.81	Female	21	84.05	-0.24

Table 10: UEA (Overall) by Demographic Groups.

Comparison	A	n(A)	Mean(A)	B	n(B)	Mean(B)	Cohen d
Gamer identity (Yes vs. No + Somewhat)	Yes	19	6.37	No + Somewhat	36	6.41	-0.06
Gaming frequency (Freq/Very Freq vs. Never/Rarely/Occ.)	Frequent (Freq/Very Freq)	26	6.32	Infrequent (Never/Rarely/ Occ.)	29	6.46	-0.26
Familiarity with strategy/simulation/resource management games (High vs. Low)	High (Moderate/Very /Expert)	34	6.46	Low (Not/Slightly familiar)	21	6.25	0.35
Prior experience with educational/awareness games (Yes vs. No + Not sure)	Yes	19	6.22	No + Not sure	36	6.49	-0.47
Gender (Male vs. Female)	Male	34	6.36	Female	21	6.45	-0.18

Table 11: Impact (Overall) by Demographic Groups.

Comparison	A	n(A)	Mean(A)	B	n(B)	Mean(B)	Cohen d
Gamer identity (Yes vs. No + Somewhat)	Yes	19	5.99	No + Somewhat	36	6.23	-0.44
Gaming frequency (Freq/Very Freq vs. Never/Rarely/Occ.)	Frequent (Freq/Very Freq)	26	6.00	Infrequent (Never/Rarely/Occ.)	29	6.31	-0.54
Familiarity with strategy/simulation/resource management games (High vs. Low)	High (Moderate/Very/Expert)	34	6.22	Low (Not/Slightly familiar)	21	6.05	0.27
Prior experience with educational/awareness games (Yes vs. No + Not sure)	Yes	19	5.93	No + Not sure	36	6.29	-0.59
Gender (Male vs. Female)	Male	34	6.06	Female	21	6.34	-0.49

Observed effects were small to moderate and broadly consistent with expectations. Higher familiarity with strategy/simulation games was associated with higher SUS and higher UEA (small–to–moderate d), suggesting easier onboarding and lower extraneous load among experienced players. Participants who played less frequently tended to report higher Impact (and slightly higher UEA), a pattern consistent with a novelty or contrast effect whereby unfamiliar mechanics and content may feel more educationally salient.

Likewise, those without prior serious-game experience reported higher SUS/UEA/Impact than their counterparts with prior exposure (moderate d), plausibly reflecting higher expectations or a stricter evaluation standard among experienced users. Gender differences favored female participants on Impact (and modestly on SUS), but effect sizes were modest and may reflect sample composition and topic alignment rather than stable population effects. Importantly, all subgroups rated the system positively, and the main conclusions (good usability and perceived educational value) hold across demographic splits. Given the exploratory nature of these comparisons, results should be interpreted cautiously; future work could use stratified sampling and multivariable models to test interactions and adjust for confounds while controlling Type-I error.

CHAPTER 6

DISCUSSION

6.1. Interpretations of Findings

This chapter interprets the empirical results in light of the study's objectives—namely, to examine whether a city-scale, management-style serious game could raise awareness about urban energy management, while remaining usable and engaging for a broad audience. Quantitative results indicated uniformly high scores on perceived impact and user experience, supported by reliability checks; the standardized usability index (SUS) fell in the "Good" range, near the Excellent boundary, providing convergent evidence that the interface and flow enabled players to access the educational content effectively. Where relevant, observations collected during testing contextualize the numerical findings.

Link between gameplay and awareness improvement. Category-level impact means were consistently high on a 1–7 scale—including Awareness of Urban Energy Efficiency, Awareness of Strategic Decision Making, Attitudes and Behavioral Intentions, and Game Experience and Educational Value—suggesting that short exposure to the management loop and its embedded trade-offs was sufficient to prime reflection on energy efficiency, policy decisions, and consequences. The pattern is consistent with the game's deliberate width-over-depth design, where multiple entry points (e.g., investments, policy toggles, technology options, and events) repeatedly surface interconnected factors and invite players to reason about them.

Effectiveness of serious games in sustainability education. SUS averaged approximately 82, the median was near 85, and roughly four-fifths of participants exceeded the widely used 68-point benchmark. According to common interpretations of the SUS scale, scores in this range typically correspond to an Excellent experience and are associated with high acceptance and learnability (Brooke, 1996; Bangor, Kortum, & Miller, 2009; Sauro & Lewis, 2016). Section scores for the custom Usability–Engagement–Aesthetics (UEA) questionnaire were similarly strong, with Engagement and Immersion marginally leading. Researcher observations corroborated these metrics: even in a research setting, several participants played cautiously and deliberatively—at times behaving as if in a competitive scenario—indicating meaningful involvement with the decisions presented (see the procedure notes in Chapter 4).

6.2. Implications for Urban Energy Management Awareness

The results imply that a single, self-paced session with a well-scaffolded simulation can initiate awareness gains around urban energy trade-offs without compromising usability. Because the design surfaces multiple, interacting levers (e.g., retrofit choices, operating-cost impacts, and policy settings), players are repeatedly prompted to consider co-benefits and opportunity costs. For stakeholders, such as municipal units, university outreach programs, NGOs, and utility communication teams, this suggests that lightweight, scenario-based interventions can complement traditional awareness activities by offering hands-on, consequence-driven exploration.

Practically, the instrument structure used here (impact and UEA sections alongside SUS) offers a straightforward template for evaluating awareness-oriented games in constrained time windows. The combination captures perceived learning, engagement, and benchmarked usability within a single sitting, enabling rapid iteration of content and interface elements between deployments.

6.3. Reflection on Some Lessons Learned

Lessons learned from design and technical challenges.

- First, representing many stakeholders and per-building controllers increased code complexity and created a dense web of dependencies. Although this granularity supported authenticity and repeated exposure to trade-offs, it also raised maintenance costs and slowed iteration.

- Second, the in-game economy was intentionally detailed to reflect realistic budgeting constraints. Designing and balancing this system required substantial parameter tuning to avoid dominant strategies while keeping the model transparent enough for educational purposes.

- Third, performance emerged as a limiting factor on lower-end devices. Scene complexity, numerous update loops, and diverse meshes occasionally reduced frame-rate headroom. Optimizations (pooling, culling, baking, and selective visual simplifications) were helpful but not sufficient to eliminate all stutter in stress cases, especially in low-performance devices. This underscores the need to budget performance early when pedagogical breadth leads to many concurrent systems.

- Fourth, the realism–abstraction balance required continuous negotiation. For general audiences, excessive technicality risks cognitive overload; for specialist audiences, insufficient detail reduces perceived credibility. A modular content strategy—where realism can be dialed up (e.g., richer metrics and units) or down (e.g., simplified labels and presets)—appears essential for portability across cohorts.

- Fifth, educational clarity must remain a first-class constraint in the user-experience layer. Despite the positive SUS and UEA outcomes, tutorial phase and interface cues can be further refined to encourage exploration of alternative strategies rather than satisficing on the first promising path.

6.4. Limitations of the Study

Several limitations should be acknowledged. First, sampling was restricted to a convenience cohort of young adults, primarily students and early-career participants at a single institution, which limits generalizability to broader populations. Second, the evaluation followed a one-group, post-session design with self-report instruments; no control group, pretest–posttest comparison, or behavioral outcomes were collected (see Chapter 5). Third, only a single session was observed for most participants, preventing assessment of retention and transfer; repeated exposure would likely yield more stable estimates of learning effects.

Fourth, the analysis intentionally focused on descriptive summaries and internal consistency, and did not include inferential tests or multivariate models (see Chapter 5). While appropriate for a first deployment, this choice limits the strength of causal interpretations. Fifth, the simulation's scope, by design, emphasizes residential buildings within a neighborhood, while city-scale energy dynamics also include industrial loads, district services, etc. So, a full picture of a city, therefore, could not be represented.

6.5. Recommendations for Future Research

Potential expansions and improvements could be;

- Adopting a pretest–posttest or longitudinal design (with follow-ups at one to four weeks) to estimate retention and transfer of learning.
- Recruiting more diverse cohorts (e.g., high-school learners, municipal staff, and lay residents) and comparing subgroup trajectories to tune difficulty and language.
- Introducing adjustable realism tiers (basic vs. advanced units, glossaries, and optional deep-dive panels) to serve both generalist and specialist users.
- Expanding domain coverage incrementally (e.g., industry and public services) and deepening the policy/tech trees where they most influence player reasoning.
- Hardening performance with early budgets and telemetry (frame-time budgets per system, pooled updates) so that pedagogical breadth does not regress fluidity.
- Comparing the game against alternative awareness interventions (e.g., short videos or infographics) using matched exposure times to estimate incremental benefit.
- Instrument learning analytics in privacy-respecting ways to triangulate self-report measures with in-game behavior.
- Tracking/logging in-game decisions and mapping them to the reported results of the player.

- Exploring how replayability mechanisms (e.g., stochastic events and scenario variations) affect exploration depth and concept coverage

- Exploring whether cooperative or competitive modes amplify engagement without compromising reflection

- Inspecting cross-cultural replications to clarify the extent to which framing and policy labels need localization to sustain usability and impact across contexts

CHAPTER 7

CONCLUSION

This thesis presented Green Renovator, a data-informed serious game designed to cultivate public awareness of city-scale energy management. The game adopts a width-over-depth strategy to foreground systemic interdependencies rather than fine-grained engineering detail. A real neighborhood dataset underpins the experience, ensuring that insulation quality, building characteristics, and solar potential are represented with recognizable realism while remaining playable within an annual, turn-based game loop.

Within this loop, players balance retrofit investments, management of energy sources, technology adaptations, and a set of policy instruments spanning energy management, governance, public relations, taxation, and international dimensions. Uncertainty and replay value are supported by a curated random-events system that exposes players to plausible shocks and trade-offs. Light-touch learning supports, like the in-game encyclopedia and an optional three-question quiz with a modest in-game incentive, were included to reinforce key concepts without disrupting the flow. In this framing, breadth is treated not as a compromise but as a deliberate asset: it enables the representation of multiple perspectives and trade-offs in a common, comprehensible decision space.

A user study (N = 55) evaluated Green Renovator's impact, experience, and usability. SUS averaged 82.05 (SD = 13.61; 95% CI [78.37, 85.72]) with 83.6% of participants at or above the 68-point benchmark; this corresponds to Good on the adjective ratings, a clear Acceptable band, and roughly a B letter grade, near the Excellent boundary ($\approx$85), and aligns with a Promoter-range likelihood to recommend. On the Impact questionnaire (1–7 scale), category means were uniformly high: Awareness of Urban Energy Efficiency M=5.98 (α=.70), Awareness of Strategic Decision-Making M=6.14 (α=.78), Attitudes & Behavioral Intentions M=6.07 (α=.70), and Game Experience & Educational Value M=6.64 (α=.35; a short 3-item scale). The UEA sections were likewise high and tightly clustered: Usability & Interface M=6.44, Aesthetics & Design M=6.38, Engagement & Immersion M=6.37, with acceptable internal consistencies for two sections and a marginal yet tolerable α for the usability section in this exploratory context. Taken together, the instrument results indicate that the system achieves high usability, strong engagement and aesthetics, and meaningful gains in awareness and intended behavior.

Beyond the study's specific metrics, the findings add to accumulating evidence that games can function as effective learning and training tools when the target competency is reasoning about complex, coupled systems. By externalizing trade-offs in a safe, replayable sandbox—and by giving immediate, comprehensible feedback on choices—serious games like Green Renovator can complement lectures, reports, or dashboards. They are especially useful for convening stakeholders around shared mental models of urban energy challenges, where the pedagogical goal is insight and reflection rather than procedural skill.

The system's breadth also makes it adaptable to distinct stakeholder roles—for example, flat/building owners, municipal authorities, national-level policymakers, manufacturers and system vendors, funding bodies, and grid operators—whose objectives and constraints often conflict. Through actor-specific parameterization and role-based scenarios, the same decision space can be customized to disciplinary needs and made legible to diverse audiences. If configured for specific actor archetypes and used in collaborative sessions, the platform can further support cross-disciplinary dialogue, helping participants "learn from one another" by testing how incentives, constraints, and risk tolerances interact in common scenarios. In other words, the game can also be used as a medium of negotiation.

The project's contributions are threefold. Conceptually, it demonstrates a practical recipe for framing urban energy management as an accessible, replayable decision space—anchored in real data yet tractable for non-experts. Methodologically, it offers an evaluation protocol that triangulates standardized usability (SUS), targeted awareness/perceived-learning instruments, and qualitative thematic insights. Because the mechanics make trade-offs visible and negotiable within minutes, the game is suitable for workshop warm-ups, classroom demonstrations, or public exhibitions. By lowering entry barriers to complex topics, the tool has potential societal benefit in the form of improved energy literacy, more realistic public expectations about policy constraints, and broader readiness to participate in local conversations on retrofit programs and energy mixes.

Limitations must be acknowledged, however. The evaluation sample, while adequate for a first study, was not population-representative and was time-bounded to single-session play. System models were intentionally simplified, and only one city context was implemented in depth. Longitudinal retention of knowledge and transfer to real-world decision-making were not measured. Moreover, several parameters that users may encounter—such as costs, technology performance, and CO_2 pricing—are time, geography, and context-sensitive. To reduce the risk of misinforming users, a clear update policy and per-context calibration are necessary. These constraints suggest clear avenues for future work: multi-district and multi-city datasets; expanded event libraries and scenario authoring; deeper (yet still legible) economics and behavior models; adaptive guidance to tailor challenge and explanation; performance and accessibility improvements; and longitudinal and comparative studies.

In sum, the thesis demonstrates that a carefully scoped, data-grounded serious game can be usable, engaging, and educationally meaningful for city-scale energy awareness. The combination of authentic context, explicit trade-offs, and lightweight learning supports was shown to promote engagement and to prompt awareness and reflection without sacrificing playability. Green Renovator does not claim to replace expert analysis; rather, it offers a shared, comprehensible space where non-specialists and specialists alike can explore the logic of retrofit investments, energy supply choices, policy design, the role of technology, and public reaction. It is hoped that Green Renovator will serve as a practical bridge between technical planning and public understanding, and as a platform upon which richer educational and participatory tools for sustainable urban energy can be built.

REFERENCES

Akyol, I., Halaçlı, E., Ucar, S., Iseri, O., Yavuz, F., Güney, D., . . . Gürsel Dino, İ. (2025). Machine learning based prediction of long-term energy consumption and overheating under climate change impacts using urban building energy modeling. *Sustainable Cities and Society, 130*, 106500. doi:10.1016/j.scs.2025.106500

Allais, M. (1953). Le Comportement de l'Homme Rationnel devant le Risque: Critique des Postulats et Axiomes de l'Ecole Americaine. *Econometrica, 21*, 503-546.

Anderson, S., Damasio, H., Jones, R., & Tranel, D. (1991). Wisconsin card sorting test performance as a measure of frontal lobe damage. *Journal of Clinical and Experimental Neuropsychology, 13*, 909-922.

Andreassi, J. (2006). Pupillary response and behavior. In *J.* L. Andreassi, Psychophysiology: Human Behavior & Physiological Response (5 ed., pp. 350-371). New Jersey: Lawrence Erlbaum Assoc.

Bangor, A., Kortum, P., & Miller, J. (2008). An empirical evaluation of the System Usability Scale. *International Journal of Human–Computer Interaction, 24*, 574–594. doi:10.1080/10447310802205776

Bangor, A., Kortum, P., & Miller, J. (2009). Determining what individual SUS scores mean: Adding an adjective rating scale. *Journal of Usability Studies, 4*, 114–123.

Baron, J. (2005). Normative models of judgment and decision making. In *Blackwell Handbook of Judgment and Decision Making (pp.* 19-36). London: Wiley-Blackwell.

Beatty, J., & Lucero-Wagoner, B. (2000). The pupillary system. In *Handbook of Psychophysiology (pp.* 142-162). New York: Cambridge University Press.

Bechara, A. (2004). The role of emotion in decision-making: Evidence from neurological patients with orbitofrontal damage. *Brain and Cognition, 55*, 30-40.

Bechara, A., & Damasio, A. (2005). The somatic marker hypothesis: A neural theory of economic decision. *Games and Economic Behavior, 52*, 336-372.

Bechara, A., Damasio, A., Damasio, H., & Anderson, S. (1994). *Insensitivity to future consequences following damage to human prefrontal cortex.* Cognition, 50(1-3), 7-15.

Beer, R. (2000). Dynamical approaches to cognitive science. *Trends in Cognitive Sciences, 4*, 91-99.

Bernoulli, D. (1954). *Exposition of a new theory on the measurement of risk - Originally published in 1738; translated by Dr.* Louise Sommer. Econometrica: Journal of the Econometric Society, 23-36.

Blais, A., & Weber, E. (2006). A Domain-specific risk-taking (DOSPERT) scale for adult populations. *Judgment and Decision Making, 1*, 33-47.

Blakemore, S., & Robbins, T. (2012). Decision making in the adolescent brain. *Nature Neuroscience, 15*, 1184-1191.

Bradley, M., Miccoli, L., Escrig, M., & Lang, P. (2008). The pupil as a measure of emotional arousal and autonomic activation. *Psychophysiology, 45*, 602-607.

Breiter, H., Aharon, I., Kahneman, D., Dale, A., & Shizgal, P. (2001). Functional imaging of neural responses to expectancy and experience of monetary gains and losses. *Neuron, 30*, 619-639.

Brooke, J. (1996). SUS: A 'quick and dirty' usability scale. In *Usability evaluation in industry (pp.* 189–194). London, UK: Taylor & Francis.

Buelow, M., & Suhr, J. (2013). Personality characteristics and state mood influence individual deck selections on the Iowa Gambling Task. *Personality and Individual Differences, 54*, 593-597.

Busemeyer, J., & Johnson, J. (2005). Computational models of decision making. In *Blackwell Handbook of Judgment and Decision Making (pp.* 133-154). London: Wiley-Blackwell.

Camerer, C. (1999). Behavioral economics: Reunifying psychology and economics. *Proceedings of the National Academy of Sciences of the United States of America, 96*, 10575-10577.

Camerer, C., & Loewenstein, G. (2004). Behavioral economics: past, present, future. In *Advances in Behavioral Economics (pp.* 3-51). New York: Princeton University Press.

Caplin, A., & Dean, M. (2009). Dopamine, reward prediction error, and economics. *Quarterly Journal of Economics, 123*, 663-701.

Cavanagh, J., Wiecki, T., Kochar, A., & Frank, M. (2014). Eye tracking and pupillometry are indicators of dissociable latent decision processes. *Journal of Experimental Psychology: General, 143*, 1476-1488.

Cessac, B. (2010). A view of neural networks as dynamical systems. *International Journal of Bifurcation and Chaos, 20*, 1585-1629.

Chiu, Y., Lin, C., Lin, S., Lee, P., & Hsieh, J. (2008). Immediate gain is long-term loss: Are there foresighted decision makers in the Iowa Gambling Task? Behavioral and Brain Functions, 4(1), 13-22.

Clark, L., Lawrence, A., Astley-Jones, F., & Gray, N. (2009). Gambling near-misses enhance motivation to gamble and recruit win-related brain circuitry. *Neuron, 61*, 481-490.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences (2nd ed.* Lawrence Erlbaum.

Critchley, H., Mathias, C., & Dolan, R. (2001). Neural Activity in the Human Brain Relating to Uncertainty and Arousal during Anticipation. *Neuron, 29*, 537-545.

Damasio, A., Everitt, B., & Bishop, D. (1996). The somatic marker hypothesis and the possible functions of the prefrontal cortex. *Philosophical Transactions of the Royal Society B: Biological Sciences, 351*, 1413-1420.

de Gee, J., Knapen, T., & Donner, T. (2014). Decision-related pupil dilation reflects upcoming choice and individual bias. *Procedings of the National Academy of Sciences of USA, 111*, 618-625.

de Vries, M., Holland, R., & Witteman, C. (2008). Fitting decisions: Mood and intuitive versus deliberative decision strategies. *Cognition and Emotion, 22*, 931-943.

Duchowski, A. (2007). *Eye Tracking Methodology: Theory and Practice (2 ed.* Springer.

Edwards, W., & Fasolo, B. (2001). Decision technology. *Annual Review of Psychology, 52*, 581-606.

Einhäuser, W., Koch, C., & Carter, L. (2010). *Pupil dilation betrays the timing of decisions.* Frontiers Human Neuroscience, 4: 18.

Einhäuser, W., Stout, J., Koch, C., & Carter, O. (2008). Pupil dilation reflects perceptual selection and predicts subsequent stability in perceptual rivalry. *Proceedings of the National Academy of Sciences of the United States of America, 105*, 1704-1709.

Ellsberg, D. (1961). Risk, ambiguity, and the savage axioms. *Quarterly Journal of Economics, 75*, 643-669.

Ernst, M., & Paulus, M. (2005). Neurobiology of Decision Making: A Selective Review from a Neurocognitive and Clinical Perspective. *Biological Psychiatry, 58*, 597–604.

Eshel, N., Nelson, E., Blair, R., Pine, D., & Ernst, M. (2007). Neural substrates of choice selection in adults and adolescents: development of the ventrolateral prefrontal and anterior cingulate cortices. *Neuropsychologia, 45*, 1270-1279.

Evans, J., Barston, J., & Pollard, P. (1983). On the conflict between logic and belief in syllogistic reasoning. *Memory & Cognition, 11*, 295-306.

Eysenck, S., Pearson, P., & Allsopp, J. (1985). Age norms for impulsiveness, venturesomeness and empathy in adults. *Personality and Individual Differences, 6*, 613-619.

Fecteau, S., Knoch, D., Fregni, F., Sultani, N., Boggio, P., & Pascual-Leone, A. (2007). Diminishing Risk-Taking Behavior by Modulating Activity in the Prefrontal Cortex: A Direct Current Stimulation Study. *The Journal of Neuroscience, 27*, 12500-12505.

Fellows, L. (2004). The cognitive neuroscience of human decision making: a review and conceptual framework. *Behav Cogn Neurosci Rev, 3*, 159-172.

Fiedler, S. (2012). *The dynamics of decision making in risky choice: An eye-tracking analysis.* Frontiers in Psychology, 3(335).

Figner, B., & Weber, E. (2011). Who takes risks when and why? Determinants of risk taking. *Current Directions in Psychological Science, 20*, 211-216.

Figner, B., Knoch, D., Johnson, E., Krosch, A., Lisanby, S., Fehr, E., & Weber, E. (2010). Lateral prefrontal cortex and self-control in intertemporal choice. *Nature Neuroscience, 13*, 538-539.

Figner, B., MacKinlay, R., Wilkening, F., & Weber, E. (2009). Affective and deliberative processes in risky choice: Age differences in risk taking in the Columbia Card Task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*, 709-730.

Finucane, M., Mertz, C., Slovic, P., & Schmidt, E. (2005). Task complexity and older adults' decision-making competence. *Psychology and Aging, 20*, 71-84.

Geangu, E., Hauf, P., Bhardwaj, R., & Bentz, W. (2011). Infant pupil diameter changes in response to others' positive and negative emotions. *PLoS ONE, 6*, 1-10.

Glimcher, P., & Fehr, E. (2013). *Neuroeconomics: Decision Making and the Brain (2 ed.* Academic Press.

Glimcher, P., & Rustichini, A. (2004). Neuroeconomics: the consilience of brain and decision. *Science, 306*, 447-452.

Glöckner, A., & Herbold, A. (2011). An eye-tracking study on information processing in risky decisions: Evidence for compensatory strategies based on automatic processes. *Journal of Behavioral Decision Making, 24*, 71-98.

Gupta, R., Koscik, T., Bechara, A., & Tranel, D. (2011). The amygdala and decision-making. *Neuropsychologia, 49*, 760-766.

Hair, J., Black, W., Babin, B., & Anderson, R. (2019). *Multivariate data analysis (8th ed.* Cengage.

Haken, H., Kelso, J., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics, 51*, 347-356.

Hakerem, G. (1967). Pupillography. In *A Manual of Psychophysiological Methods (pp.* 335-349). Amsterdam: North-Holland Publishing Co.

Harlé, K., Chang, L., & Sanfey, A. (2012). The neural mechanisms of affect infusion in social economic decision-making: A mediating role of the anterior insula. *NeuroImage, 61*, 32-40.

Hooper, C., Luciana, M., & Conklin, H. (2004). Adolescents' performance on the Iowa Gambling Task: implications for the development of decision making and ventromedial prefrontal cortex. *Developmental Psychology, 40*, 1148-1158.

Hsu, M., Bhatt, M., Adolphs, R., Tranel, D., & Camerer, C. (2005). Neural systems responding to degrees of uncertainty in human decision-making. *Science, 310*, 1680-1683.

Huettel, S., Stowe, C., Gordon, E., Warner, B., & Platt, M. (2006). Neural signatures of economic preferences for risk and ambiguity. *Neuron, 49*, 765-775.

Iseri, O., Duran, A., Canlı, İ., Akgül, C., Kalkan, S., & Gürsel Dino, İ. (2025). A method for zone-level urban building energy modeling in data-scarce built environments. *Energy and Buildings, 337*, 115620. doi:10.1016/j.enbuild.2025.115620

Jepma, M., & Nieuwenhuis, S. (2011). Pupil diameter predicts changes in the exploration-exploitation trade-off: Evidence for the adaptive gain theory. *Journal of Cognitive Neuroscience, 23*, 1587-1596.

Jones, C., & Sutherland, J. (2008). Acoustic emotion recognition for affective computer gaming. In *Affect and Emotion in Human-Computer Interaction (Vol.* 4868). Heidelberg, Germany: Springer.

Juliusson, E., Karlsson, N., & Garling, T. (2005). Weighing the past and the future in decision making. *European Journal of Cognitive Psychology, 17*, 561-575.

Kahneman, D., & Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. *Econometrica, 47*, 263-291.

Kang, O., & Wheatley, T. (2015). Pupil dilation patterns reflect the contents of consciousness. *Consciousness and Cognition, 35*, 128-135.

Kelso, J., & Zanone, P. (2002). Coordination dynamics of learning and transfer across different effector systems. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 776-797.

Klinger, J., Kumar, R., & Hanrahan, P. (2008). *Measuring the task-evoked pupillary response with a remote eye tracker.* Proceedings of the 2008 symposium on Eye tracking research & applications, 69-72.

Kloosterman, N., Meindertsma, T., Loon, A., Lamme, V., Bonneh, Y., & Donner, T. (2015). Pupil size tracks perceptual content and surprise. *European Journal of Neuroscience, 41*, 1068-1078.

Knoch, D., Gianotti, L., Pascual-Leone, A., Treyer, V., Regard, M., Hohmann, M., & Brugger, P. (2006). Disruption of Right Prefrontal Cortex by Low-Frequency Repetitive Transcranial Magnetic Stimulation Induces Risk-Taking Behavior. *The Journal of neuroscience: the official journal of the Society for Neuroscience, 26*, 6469-6472.

Kovalchik, S., Camerer, C., Grether, D., Plott, C., & Allman, J. (2005). Aging and decision making: a comparison between neurologically healthy elderly and young individuals. *Journal of Economic Behavior & Organization, 58*, 79–94.

Kuhnen, C., & Knutson, B. (2005). The neural basis of financial risk taking. *Neuron, 47*, 763-770.

Lauriola, M., Panno, A., Levin, I., & Lejuez, C. (2014). Individual differences in risky decision making: A meta-analysis of sensation seeking and impulsivity with the Balloon Analogue Risk Task. *Journal of Behavioral Decision Making, 27*, 20-36.

Lejuez, C., Aklin, W., Zvolensky, M., & Pedulla, C. (2003). Evaluation of the Balloon Analogue Risk Task (BART) as a predictor of adolescent real-world risk-taking behaviours. *Journal of Adolescence, 26*, 475-479.

Lejuez, C., Read, P., Kahler, W., Richards, J., Ramsey, E., & Stuart, L. (2002). Evaluation of a behavioral measure of risk taking: The Balloon Analogue Risk Task (BART). *Journal of Experimental Psychology: Applied, 8*, 75-84.

Lerner, J., Li, Y., Valdesolo, P., & Kassam, K. (2015). Emotion and decision making. *Annual Review of Psychology, 66*, 799-823.

Lighthall, N., Sakaki, M., Vasunilashorn, S., Nga, L., Somayajula, S., & Chen, E. (2012). Gender differences in reward-related decision processing under stress. *Social Cognitive and Affective Neuroscience, 7*, 476-484.

Lin, C., Chiu, Y., Lee, P., & Hsieh, J. (2007). Is deck B a disadvantageous deck in the Iowa gambling task? Behavioral and Brain Functions, 3(1), 16-25.

Loewenstein, G., & Lerner, J. (2003). The role of affect in decision making. In *Handbook of Affective Sciences (pp.* 619-642). Oxford: Oxford University Press.

Loewenstein, G., Rick, S., & Cohen, J. (2008). Neuroeconomics. *Annual Review of Psychology, 59*, 647-672.

Loewenstein, G., Weber, E., Hsee, C., & Welch, N. (2001). Risk as feelings. *Psychological Bulletin, 127*, 267-286.

Macmillan, M. (2000). Restoring Phineas Gage: A 150th retrospective. *Journal of the History of the Neurosciences, 9*, 46-66.

Maia, T., & McClelland, J. (2004). A reexamination of the evidence for the somatic marker hypothesis: What participants really know in the Iowa gambling task. *Proceedings of the National Academy of Sciences of the United States of America, 101*, 16075-16080.

Maia, T., & McClelland, J. (2005). The somatic marker hypothesis: Still many questions but no answers. *Trends in Cognitive Sciences, 9*, 162-164.

Marcus, B. (2003). An empirical examination of the construct validity of two alternative self-control measures. *Educational and Psychological Measurement, 63*, 674-706.

Marx, S. (2015). Reward modulates perception in binocular rivalry. *Journal of Vision, 15*, 1-13.

Marx, S., Gruenhage, G., Walper, D., & Rutishauser, U. (2015). Competition with and without priority control: Iinking rivalry to attention through winner-take-all networks with memory. *Annals of the New York Academy of Sciences, 1339*, 138-153.

Moretto, G., & Mattioli, F. (2010). A psychophysiological investigation of moral judgment after ventromedial prefrontal damage. *Journal of Cognitive Neuroscience, 22*, 1888-1899.

Morris, G., Nevet, A., Arkadir, D., Vaadia, E., & Bergman, H. (2006). Midbrain dopamine neurons encode decisions for future action. *Nature Neuroscience, 9*, 1057-1063.

Murphy, P., O'Connell, R., O'Sullivan, M., Robertson, I., & Balsters, J. (2014). Pupil diameter covaries with BOLD activity in human locus coeruleus. *Human Brain Mapping, 35*, 4140-4154.

Nicholson, N., Soane, E., Fenton-O'Creevy, M., & Willman, P. (2005). Personality and domain-specific risk taking. *Journal of Risk Research, 8*, 157-176.

Orquin, J. (2013). Attention and choice: a review on eye movements in decision making. *Acta Psychologica, 144*, 190-206.

Orquin, J., & Bagger, M. (2013). Learning affects top down and bottom up modulation of eye movements in decision making. *Judgment and Decision Making, 8*, 700-716.

Panno, A., Lauriola, M., & Figner, B. (2013). Emotion regulation and risk taking: Predicting risky choice in deliberative decision making. *Cognition and Emotion, 27*, 326-334.

Partala, T., & Surakka, V. (2003). Pupil size variation as an indication of affective processing. *International Journal of Human-Computer Studies, 59*, 185-198.

Paulus, M. (2005). Neurobiology of decision-making: quo vadis? Cognitive Brain Research, 23(1), 2-10.

Payzan-LeNestour, E., Dunne, S., Bossaerts, P., & O'Doherty, J. (2013). The neural representation of unexpected uncertainty during value-based decision making. *Neuron, 79*, 191-201.

Peter, C., & Beale, R. (2008). *Affect and Emotion in Human-Computer Interaction.* Heidelberg: Springer.

Phelps, E., Lempert, K., & Sokol-Hessner, P. (2014). Emotion and decision making: multiple modulatory neural circuits. *Annual Review of Neuroscience, 37*, 263-287.

Platt, M., & Huettel, S. (2008). Risky business: the neuroeconomics of decision making under uncertainty. *Nature Neuroscience, 11*, 398-403.

Plous, S. (1993). *The Psychology of Judgment and Decision Making.* McGraw-Hill.

Preuschoff, K., & Hart, B. (2011). Pupil dilation signals surprise: evidence for noradrenaline's role in decision making. doi:10.3389/fnins.2011.00115

Privitera, C., Carney, T., Klein, S., & Aguilar, M. (2014). Analysis of microsaccades and pupil dilation reveals a common decisional origin during visual search. *Vision Research, 95*, 43-50.

Rabiner, L., & Juang, B. (1986). An introduction to hidden Markov models. *ASSP Magazine, IEEE, 3*, 4-16.

Rao, H., Korczykowski, M., Pluta, J., Hoang, A., & Detre, J. (2008). Neural correlates of voluntary and involuntary risk taking in the human brain: An fMRI Study of the Balloon Analog Risk Task (BART). *Neuroimage, 42*, 902-910.

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review, 85*, 59-108.

Ratcliff, R., & McKoon, G. (2008). The diffusion decision model: theory and data for two-choice decision tasks. *Neural Computation, 20*, 873-922.

Rayner, K., Pollatsek, A., Ashby, J., & Clifton, C. (2011). *Psychology of Reading (2 ed.* Psychology Press.

Reid, R. (1986). The psychology of the near miss. *Journal of Gambling Behavior, 2*, 32-39.

Reimann, M., & Bechara, A. (2010). The somatic marker framework as a neurological theory of decision-making: Review, conceptual comparisons, and future neuroeconomics research. *Journal of Economic Psychology, 31*, 767-776.

Rogers, R., Owen, A., Middleton, H., Williams, E., Pickard, J., Sahakian, B., & Robbins, T. (1999). Choosing between small, likely rewards and large, unlikely rewards activates inferior and orbital prefrontal cortex. *The Journal of neuroscience: the official journal of the Society for Neuroscience, 19*, 9029-9038.

Rolfs, M. (2009). Microsaccades: Small steps on a long way. *Vision Research, 49*, 2415-2441.

Ruff, C., & Huettel, S. (2013). Experimental Methods in Cognitive Neuroscience. In *Neuroeconomics: Decision Making and the Brain (2 ed.* , pp. 77-108). Academic Press.

Rustichini, A. (2009). Neuroeconomics: what have we found, and what should we search for. *Current Opinion in Neurobiology, 19*, 672-677.

Sanfey, A., & Chang, L. (2008). Multiple systems in decision making. *Annals of the New York Academy of Sciences, 1128*, 53-62.

Sauro, J. (2011). *A practical guide to the System Usability Scale: Background, benchmarks & best practices.* Denver, CO: Measuring Usability LLC.

Sauro, J. (2011). *Relating the System Usability Scale (SUS) to the Net Promoter Score (NPS). MeasuringU*. Retrieved from https://measuringu.com/sus-nps/

Sauro, J., & Lewis, J. (2016). *Quantifying the user experience: Practical statistics for user research (2nd ed.* Morgan Kaufmann.

Schonberg, T., Fox, C., & Poldrack, R. (2011). Mind the gap: bridging economic and naturalistic risk-taking with cognitive neuroscience. *Trends in Cognitive Sciences, 15*, 11-19.

Shah, A., & Oppenheimer, D. (2008). Heuristics made easy: An effort-reduction framework. *Psychological Bulletin, 134*, 207-222.

Shen, L., Wang, M., & Shen, R. (2009). Affective e-Learning: Using "emotional" data to improve learning in pervasive learning environment. *Journal of Educational Technology & Society, 12*, 176-189.

Simpson, H., & Hale, S. (1969). Pupillary changes during a decision making task. *Perceptual and Motor Skills, 29*, 495-498.

Sitkin, S., & Weingart, L. (1995). Determinants of risky decision-making behavior: A test of the mediating role of risk perceptions and propensity. *Academy of Management Journal, 38*, 1573-1592.

Smith, D., Xiao, L., & Bechara, A. (2012). Decision making in children and adolescents: impaired Iowa Gambling Task performance in early adolescence. *Developmental Psychology, 48*, 1180-1187.

Sykes, J. (2010). Affective games: How iOpiates elicit an emotional fix. In *Affective Computing and Interaction: Psychological, Cognitive and Neuroscientific Perspectives (pp.* 344-358). New York: IGI Global.

Taskin, K., & Gokcay, D. (2015). *Investigation of Risk Taking Behavior and Outcomes in Decision Making with Modified BART (m-BART).* Affective Computing and Intelligent Interaction. Xi'an: The Association for the Advancement of Affective Computing.

Taskin, K., & Gokcay, D. (2016). *Temporal aspects of decision making: Pupillary responses reveal alternating levels of arousal related to dynamic risk-taking states.* International Journal of Human Computer Interactions.

Tobler, P., Christopoulos, G., O'Doherty, J., Dolan, R., & Schultz, W. (2009). Risk-dependent reward value signal in human prefrontal cortex. *Proceedings of the National Academy of Sciences, 106*, 7185-7190.

Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty, 5*, 297-323.

van Gelder, T. (1998). The dynamical hypothesis in cognitive science. *Behavioral and Brain Sciences, 21*, 615-665.

von Neumann, J., Morgenstern, O., Kuhn, H., & Rubinstein, A. (2007). *Theory of Games and Economic Behavior (60th Anniversary Commemorative ed.* Princeton University Press.

Wakker, P. (2010). *Prospect Theory: For Risk and Ambiguity.* Cambridge University Press.

Wakker, P., & Fennema, H. (1997). Original and cumulative prospect theory: a discussion of empirical differences. *Journal of behavioral decision making, 10*, 53-64.

Wallsten, T., Pleskac, T., & Lejuez, C. (2005). Modeling behavior in a clinically diagnostic sequential risk-taking task. *Psychological Review, 112*, 862-880.

Weber, E., & Johnson, E. (2008). Decisions under Uncertainty: Psychological, Economic, and Neuroeconomic Explanations of Risk Preference. In *Neuroeconomics: Decision Making and the Brain (pp.* 127-144). London: Academic Press.

Weber, E., Blais, A., & Betz, N. (2002). A domain-specific risk-attitude scale: Measuring risk perceptions and risk behaviors. *Journal of Behavioral Decision Making, 15*, 263-290.

Weller, J., Levin, I., Shiv, B., & Bechara, A. (2007). Neural correlates of adaptive decision making for risky gains and losses. *Psychological science: a journal of the American Psychological Society, 18*, 958-964.

West, R., Toplak, M., & Stanovich, K. (2008). Heuristics and biases as measures of critical thinking: Associations with cognitive ability and thinking dispositions. *Journal of Educational Psychology, 100*, 930-941.

White, T., & Lejuez, C. (2008). Test-retest characteristics of the Balloon Analogue Risk Task (BART). *Experimental and Clinical Psychopharmacology, 16*, 565-570.

Wu, G., Zhang, J., & Gonzalez, R. (2005). Decision under risk. In *Blackwell Handbook of Judgment and Decision Making (pp.* 299-423). London: Wiley-Blackwell.

Yu, A., & Dayan, P. (2005). Uncertainty, neuromodulation, and attention. *Neuron, 46*, 681-692.

Zak, P. (2004). Neuroeconomics. *Philosophical Transactions of the Royal Society B: Biological Sciences, 359*, 1737-1748.

Zeelenberg, M. (1999). Anticipated regret, expected feedback and behavioral decision making. *Journal of Behavioral Decision Making, 12*, 93-106.

Zuckerman, M. (1994). *Behavioral expressions and biosocial bases of sensation seeking.* Cambridge: Cambridge University Press.

APPENDICES

APPENDIX A

IMPACT QUESTIONNAIRE

Questionnaire to measure the intended impact of the serious game.

All questions from 1-17 originally had the image below in the copies handed to the participants, displaying the 7-step Likert scale;

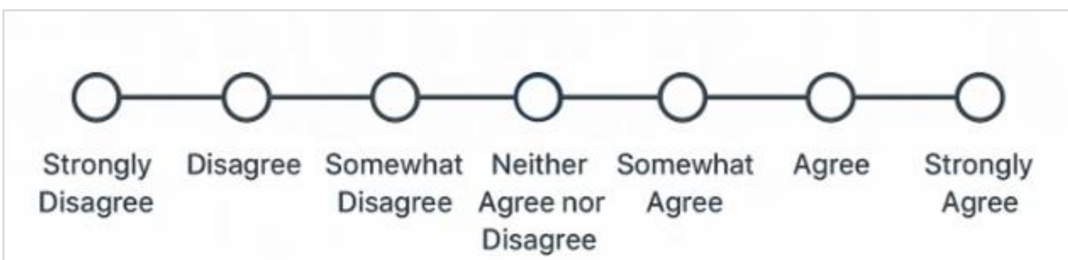

Figure 21: 7-step Likert Scale used in the Impact Questionnaire.

Category 1: Awareness of Urban Energy Efficiency

1. *I am now more aware of how building insulation affects energy consumption.*
2. *The game helped me realize that balancing the environmental benefits of building retrofitting with its costs and payback times can be challenging.*
3. *I am now more aware of the inherent advantages/disadvantages of different energy sources.*
4. *I am now more aware of the trade-offs between upfront costs and long-term energy savings*
5. *I am now more aware of the impact of solar microgeneration as an energy source.*

Category 2: Awareness of Strategic Decision-Making

6. *The game made me reflect on the trade-offs decision-makers face when trying to implement green policies.*
7. *I now realize that reaching grand scale sustainability goals requires participation of many different parties.*
8. *I became more aware of the limits and challenges of implementing sustainable solutions in real cities.*
9. *I am now more aware of the multifaceted and complex nature of sustainable urban energy management.*
10. *I am now more aware of the potential impact of different actors involved in sustainable urban energy management.*

Category 3: Attitudes and Behavioral Intentions

11. *I am more likely to support public investments for sustainable urban energy after this experience.*
12. *The game made me reflect on what could be done to improve energy sustainability in my own city or neighborhood.*
13. *The game made me more curious about sustainable urban energy.*
14. *If more people played this game, I believe awareness of urban energy issues would improve.*

Category 4: Game Experience and Educational Value

15. *I would prefer learning through interactive games like this rather than traditional methods.*
16. *I would like to continue to play this game or a future version of it to learn more about these concepts.*
17. *Overall, I feel the game achieved its goal of raising awareness about sustainable urban energy management.*

Category 5: Open-Ended Questions & Reflections

18. *What is one important thing you learned or realized while playing this game?*
19. *Do you have any suggestions for improving the game experience?*

APPENDIX B

USABILITY, ENGAGEMENT & AESTHETICS QUESTIONNAIRE

Purpose: To evaluate the overall game experience in terms of interface, interaction, immersion, delivery, and design quality.

All questions originally had the image below in the copies handed to the participants, displaying the 7-step Likert scale;

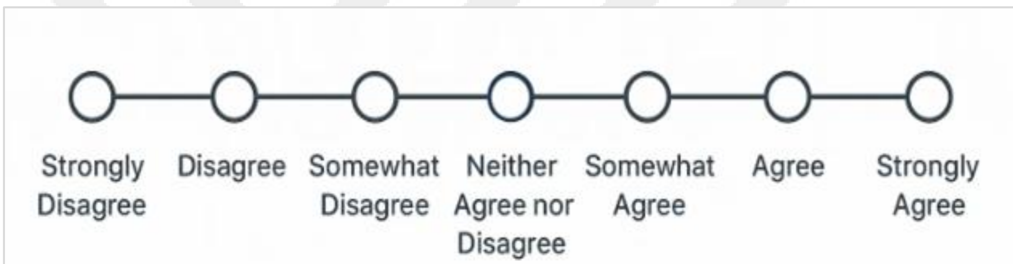

Figure 22: 7-step Likert Scale used in the Usability, Engagement & Aesthetics

SECTION A – Usability & Interface (5 items)

1. *I found the game interface easy to understand and navigate.*
2. *The instructions provided were clear and sufficient for me to start playing.*
3. *I was able to interact with the game mechanics without technical difficulty.*
4. *I understood how my actions influenced the game's outcomes.*
5. *I did not experience confusion or frustration while trying to play the game.*

SECTION B – Engagement & Immersion (5 items)

6. *I found the game enjoyable and mentally stimulating to play.*
7. *The game maintained my attention and focus throughout the session.*
8. *I felt immersed in the decision-making process during the game.*
9. *I was motivated to complete the game and see the results of my actions.*
10. *The game encouraged me to try different approaches and reflect on their outcomes.*

SECTION C – Aesthetics & Design (5 items)

11. *I found the visual design of the game (colors, images, layout, style) appealing.*
12. *The user interface (menus, buttons, panels) was visually clear and well-organized.*
13. *The game's audio elements (music, sound effects) supported the overall experience.*
14. *The visualization methods and visual style of the game matched its educational purpose.*
15. *The overall aesthetic of the game contributed positively to my engagement.*

APPENDIX C

SYSTEM USABILITY SCALE QUESTIONNAIRE

System Usability Scale

For each of the following statements, please mark one box that best describes your reactions to the game today.

		Strongly disagree				Strongly agree
1.	I think that I would like to use the game frequently.	1	2	3	4	5
2.	I found the game unnecessarily complex.	1	2	3	4	5
3.	I thought the game was easy to use.	1	2	3	4	5
4.	I think that I would need the support of a technical person to be able to use the game.	1	2	3	4	5
5.	I found the various functions in the game were well integrated.	1	2	3	4	5
6.	I thought there was too much inconsistency in the game.	1	2	3	4	5
7.	I would imagine that most people would learn to use the game very quickly.	1	2	3	4	5
8.	I found the game very cumbersome (awkward) to use.	1	2	3	4	5
9.	I felt very confident using the game.	1	2	3	4	5
10.	I needed to learn a lot of things before I could get going with the game.	1	2	3	4	5

Figure 23: System Usability Scale.

APPENDIX D

DEMOGRAPHICS QUESTIONNAIRE

1. Age:

2. Gender:

- ☐ Female
- ☐ Male
- ☐ Non-binary
- ☐ Prefer not to say

3. Department / Field of Study or Expertise:

4. Level of Education:

- ☐ Undergraduate (Bachelor's)
- ☐ Graduate (Master's or PhD)
- ☐ Other: ________

5. How often do you play digital games?

- ☐ Never
- ☐ Rarely (less than once a month)
- ☐ Occasionally (a few times a month)
- ☐ Frequently (a few times a week)
- ☐ Very frequently (almost daily)

6. How would you rate your familiarity with strategy/simulation/resource management games?

- ☐ Not familiar at all
- ☐ Slightly familiar
- ☐ Moderately familiar
- ☐ Very familiar
- ☐ Expert-level

7. Have you ever played a game designed for educational or awareness-raising purposes?

- ☐ Yes
- ☐ No
- ☐ Not sure

8. What device(s) do you usually use to play games? *(Multiple selection)*

- ☐ PC / Laptop
- ☐ Mobile phone / Tablet
- ☐ Console (e.g., PlayStation, Xbox, Handhelds)
- ☐ Web browser
- ☐ Other: _______

9. Would you describe yourself as a gamer?

- ☐ Yes
- ☐ No
- ☐ Somewhat

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