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Implementing Renewable Energy-Driven Energy Storage Systems in a Sustainable Smart City

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Team Introduction

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Summary

Elysia is thriving to be a leading example of a sustainable and energy-efficient smart city. Elysia at first is occupied by 10 000 residents, but its framework is designed for expansion. For Elysia to be scalable it must have a wide yield of energy storage systems. Elysia utilizes for the most part Electrochemical systems, since they are both easily scalable and efficient. But also, multiple other storage systems, such as flywheels and liquid energy storage are used to make the power grid as reliable as possible.

Elysia's energy consumption monitoring is essential since the city is powered by multiple renewable energy sources – wind, solar and hydro – which depend highly on weather conditions and are inconsistent. The SCADA system improves energy efficiency by adjusting storage and backup power according to real-time data, while the EF system forecasts Elysia's energy needs by analysing weather data and past consumption patterns.

The Wattpeer app is one of the ways Elysia promotes community engagement and the integration of renewable energy resources. The app offers among other things a CO_2 impact tracker and personalized energy usage graphs. Elysia also supports sustainability through green loans, tax credit incentives along with easier approval processes that encourage the development of energy storage solutions.

1 System Capacity and Scalability

1.1 Present energy consumption

Our Smart City, Elysia is in Southern Europe, where temperatures rarely drop below zero. In these regions, average energy consumption is typically lower than in other parts of Europe, due to the mild climate. According to Eurostat’s (2024)” Available energy, energy supply and final energy consumption per capita” statistics for 2023 the annual final energy consumption in Southern European countries such as Greece was around 60 000 Megajoules per capita annually, while in Spain it was approximately 67 000 Megajoules per capita annually. For Elysia we will estimate the energy consumption to be 63 000 Megajoules per capita. So, the annual overall energy consumption of an average city with 10 000 inhabitants in Southern Europe would be 175 GWh due calculation below.

$$10\ 000 \times 63\ 000\ MJ = 630\ 000\ GJ$$
$$\frac{630\ 000}{3.6} = 175\ GWh$$

Because our city aims to achieve better energy efficiency than an average European city, the total energy consumption would likely be lower than 175 GWh. For example, according to Judith Thompsen (2024) energy consumption in buildings would likely reduce to half if smart technologies were implemented. Energy consumption can also be reduced by up to 90 percent with the use of autonomous vehicles instead of traditional vehicles with human drivers (Tektelic, 2025). A study on the other hand found out that with the help of reinforced learning the yearly energy consumption of a smart city could be potentially lowered by more than 35%–40%. The study applies reinforcement learning, which is an artificial intelligence algorithm, using multiple agents – systems or programs – that together try to find the best strategy to distribute energy in the city (Orduei, 2023, p. 1). Based on the multiple research examples mentioned beforehand achieving significant energy reductions, our city, Elysia, aims to use at least 30 % less energy. So Elysia will aim to use 70 % of the average energy of a Southern European country, which was calculated earlier, which would accumulate to 122.5 GWh.

1.2 Future energy needs

If the population of Elysia were to grow by 5% annually in the next 10 years Elysia would have approximately 16 300 residents. If energy consumption per capita were to stay the same for the time period, the energy demand would be 199.675 GWh annually according to the calculation below.

$$16\,300 \times \frac{122.5\ GWh}{10\,000} = 199.675\ GWh$$

To meet this requirement, the energy storage system should be capable of supporting approximately 200 GWh per year and an additional 10–15% capacity should be added in case of energy peaks and new infrastructure. This would accumulate to around 230 GWh for the total scalable target for the next 10 years. To accommodate to the possible population growth Elysia will be designed flexibly ensuring it can be scaled efficiently as the city’s energy demands develop. This involves having a wide range of energy storage technologies. Elysia’s power grid will rely primarily on electrochemical storage, such as lithium-ion batteries, which are easily scalable. Electric vehicles and energy storage systems will also play a critical role in the power grid offering dual-directional energy flow. Additionally, physical storage technologies and Liquid Air Energy Storage will be also utilized.

2 Renewable Energy Integration

To ensure sustainable and reliable energy sources in Elysia, various energy sources are essential. Wind power, solar energy and hydroelectric generation serve as Elysia's main energy sources. These sources are integrated to ensure Elysia's self-sufficient energy systems.

Wind turbines are located further away from neighborhoods to ensure safety and to minimize noise pollution. The strategic placement of these turbines ensures the maximization of kinetic energy from the wind. Electromagnetic induction generates that energy into electricity. The proficiency of a wind turbine is typically between 20–40 % (EPA, p.2). In Elysia, two turbines generate enough energy to power all residential homes and some public buildings in the city. Wind energy does not produce any operational emissions (EPA, p.3), with only slight maintenance emissions.

Solar panels are installed on the rooftops. This minimizes both landscaping issues and centralizes energy sources. This approach minimizes transmission losses and narrows the need for large power plants. Solar panels convert energy from the sun into thermal and electrical energy through photovoltaic effect. Solar energy has high installation costs, but the investment into solar power is a long-term one with solar power being the greenest energy available.

A river flows through Elysia, making it possible to integrate hydroelectric power into the energy system. A dam is built to regulate water flow, creating a steady energy source. The function of hydropower in Elysia is to support other forms of energy and to serve as a backup energy source in a time of emergencies.

To include citizens in sustainability and sourcing energy sustainably, Elysia has kinetic tiles in some high-traffic areas such as intersections. They produce minor amounts of energy, their main purpose being promotion of sustainable energy. These kinetic tiles face mechanical stress from cars and pedestrians which is then converted into low-voltage electrical output.

3 Grid Stability and Reliability in Elysia

Reliable power production is the basic pillar of modern society. In the sustainable smart city of Elysia, grid reliability and stability are crucial for integrating renewable energy sources such as wind and solar power. One of the most effective solutions would be to install advanced energy storage systems (ESS) that can provide real-time backup power in case of power failures and suppress swings in power supply (Wu et al., 2019). These systems play an important role in building grid resilience by balancing demand and supply, frequency regulation and stable power supply.

To make this possible, the infrastructure of Elysia will consist of grid-connected storage technologies with fast response times and intelligent control algorithms that regulate them. These technologies allow the system to react in real-time to variations in energy flow, making them essential for frequency control and voltage support. For instance, when there is a sudden decrease in solar output due to cloud cover, the storage system can inject power stored in the grid instantly which prevents instability or blackout (Wu et al., 2019).

Large energy users such as electric trains, power plants, and electric buses will benefit from the ESS as they will charge at off-peak hours when electricity is less expensive and get discharged at high-demanding times. It not only helps to save on energy costs but also takes loads off the grid. For households, backup power systems are starting to become in-demand, especially in times of power blackouts. Such systems can be stored or used in combination with solar panels to supply power at peak usage or power outages. In addition, electric vehicles (EVs) in Elysia serve as transporters as well as mobile energy storage. EVs can supply power back to the grid by using vehicle-to-grid (V2G) technology and balance demand (Wu et al., 2019). As EV uptake goes up in Elysia, it will help develop energy storage capacity and make a cleaner, more stable power system.

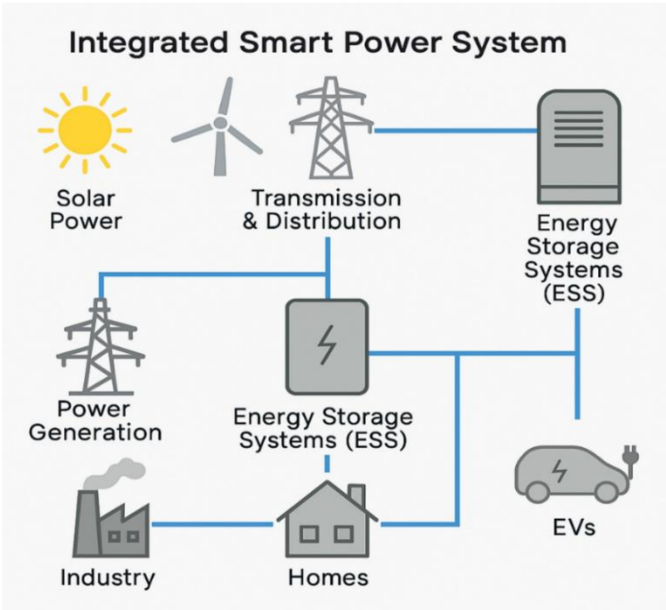

Figure 1 Integrated smart power system

3.1 Key Energy Storage Technologies

There are several energy storage technologies that will be utilized in Elysia. They have pros and cons depending on the use. Electrochemical systems (e.g. lithium-ion batteries) are both scalable and efficient. They mainly play the role of smoothing output of hybrid wind generation. Lithium-ion battery works by moving lithium ions (Li^+) between two electrodes. Metal oxide or sulfide are used as the positive electrode and carbon as the negative electrode. When discharging, the ions return to the positive electrode and create an electric current. Lithium-ion batteries (e.g. $LiFePO_4$, $LiCoO_2$ and lithium titanate) provide safety, durability and stable performance (Wu et al., 2019). Lithium-ion batteries are therefore suitable for smart grid use.

Physical storage systems like flywheels offer fast response and long lifespan. The system mainly includes three parts: rotor for storing energy, bearings that support the system and motor/generator Flywheel energy storage uses an electric motor to drive a rotor at high speed. The electric energy is converted into mechanical energy that will be stored. During energy demand, the speed is decelerated and the motor acts as a generator to produce electricity from stored kinetic energy (Wu et al., 2019).

Liquid Air Energy Storage (LAES) stores electricity in the form of liquid air. Liquid air is stored in cryogenic vessels placed anywhere. The process involves three parts: charging, storage and discharging. In the charging process, ambient air is filtered, compressed, cooled and expanded to the liquefaction point. The liquid air is stored at very low temperatures. Heat generated due to compression is stored for later use. In the discharging process, liquid air is pumped, heated and expanded to generate electricity. The cold energy can be stored to improve the next charging cycle or used for cooling.

LAES is especially used due to its lack of geographical constraint, high energy density and adaptability to waste heat (She et al., 2024). Elysia's LAES plants would be capable of achieving round-trip efficiencies of around 70%, with power output levels at commercial scale in the range of 10–100 MW and capacities of several hundred megawatt-hours of energy (O'Callaghan & Donnellan, 2021).

4 Energy Management and Optimization

Elysia's energy storage systems, production and consumption, i.e. the grid will be managed by a control center in the city. The control center incorporates two functions a SCADA-system for real-time feedback of the grid, and secondly a forecasting system to analyze the city's energy production and consumption to determine whether backup power sources must be activated. The control center will be in the city center and employ two energy management officers who'll look over the energy management system.

4.1 SCADA-system

SCADA is an acronym for supervisory control and data acquisition. SCADA-systems function as centralized controlling and observing points for grids. SCADA-systems are made of remote terminal units (RTUs), communication infrastructure, central systems and a human machine interface (HMI) (Björk, 2014). At Elysia there will be multiple RTUs for the wind park, factory, city and other major power users, consumers and storages.

The control center with the help of the SCADA-system will supervise that power usage nor production exceeds the grids capability to keep the grid reliable. In cases of too little power produced the SCADA-system will notify the energy officer and energy storages e.g. flywheels can be activated to balance the grid. On the contrary when there is too much energy produced the SCADA-system will notify the operator, and excess energy will be automatically stored in the city's energy storages. Therefore, the SCADA-system helps to manage the grid in real time and with it the operator can adjust it remotely for balance.

The SCADA-system will prove to be beneficial for Elysia, as the city has multiple unreliable sources of power, thus, it's crucial to have real time monitoring and management of the city's energy production, consumption and storage. This is how Elysia will manage its energy in real time as a smart city.

4.2 Energy forecasting system

Elysia's energy needs face some challenges as the city operates with multiple renewable energy sources e.g. wind and solar. These two require sunlight and wind within certain levels to function. The city has a factory and other essential processes which require a reliable source of power. Hence, the energy management of the city needs to know when energy storages are needed, and backup power is needed to be turned on. The control center will tackle this by using an energy forecasting system (EF-system), which is able to do intra-day production predictions locally within the city. The EF-system predicts the city's power consumption, solar and wind power production by numerical weather prediction models and historical forecasts to up to 6 hours in the future.

The city's energy demand will be predicted using a historical forecast, which uses real time data from the SCADA-system and historical data of the city's demand. With this model the city's energy demand will be predicted and with open communication with the local factory's production management department. Therefore, the city's energy demand can be reliably predicted using a historical forecast that considers the SCADA-systems real-time data.

The EF-system will use a numerical weather prediction model, satellite imagery and machine learning models. Chen (2024) describes an intra-day forecast that uses geostationary satellite imagery, numerical weather prediction, combined with a machine learning model to create an accurate and reliable solar power prediction model (Chen 2024). The EF-system will use the same forecasting model for estimating solar power production. Wind power will be predicted using in situ local weather data with a numerical weather prediction model, as done by the National Renewable Energy Laboratory (Tian et al., 2016). To summarize, the EF-system uses numerical weather prediction models, geostationary satellite imagery for solar and in situ weather data for wind power prediction.

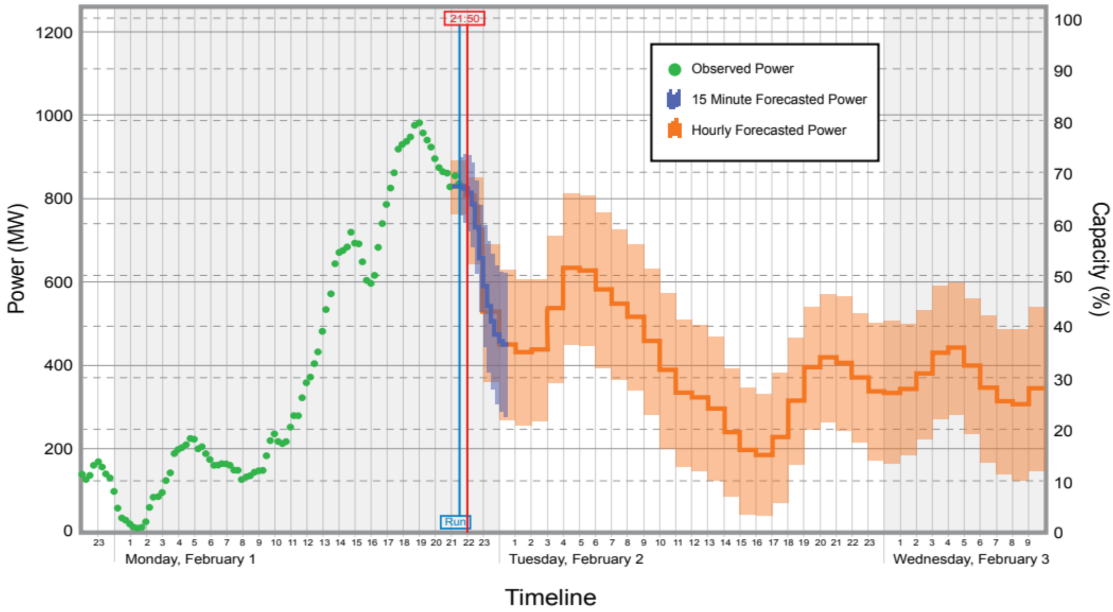

Figure 2: Tian et al. (2016) graph of intra-day power production with NWP-model

The EF-system works hand in hand with the SCADA-system as seen in figure **X**. The SCADA-system is automated to use power from energy storages or turn on backup power, if the EF-system predicts that wind or solar power will decrease, and the city requires more power. Thus, the energy management SCADA-system is optimized using EF-systems forecasting.

5 Environmental Sustainability

Energy systems ensure reliability and minimize environmental sustainability. The mission of Elysia's energy system is to be as green as possible and to promote zero-emission policies of Elysia. Energy storage technologies like lithium-ion batteries, flow batteries and pumped hydro storage are chosen in Elysia for their low environmental impact.

Lithium-ion batteries are the most common battery type, and they are found in almost everything. In these batteries lithium ions pass from cathode to the anode. When the flow reverses, it releases the power from the battery. Batteries are commonly used in solar systems due to their efficiency and scalability. Lithium-ion batteries have no operational emissions which makes them a great green option for systems. Lithium-ion batteries work best when energy is stored for short term. Elysia's solar energy is stored in these lithium-ion batteries.

Unlike lithium-ion batteries, flow batteries are better for long term energy storage. In a flow battery chemical reaction between two liquid electrolytes in a electrochemical cell store release energy. Flow batteries store Elysia's wind energy and some solar energy, when there are periods of lower energy generation. Flow batteries have longer lifespans than lithium-ion batteries, but lower energy density. Flow batteries are easily managed, and their capacity is easily increased by increasing their size. That makes them a good choice for a city like Elysia.

Pumped hydro storage (PHS) is the oldest and most widely used form of large-scale energy storage. It works by moving water between two reservoirs at different elevations to store and generate electricity based on demand.

It is a form of mechanical energy storage and is especially effective for balancing renewable energy systems like solar and wind.

In Elysia, a natural river allows for the development of a small-scale pumped hydro system: A dam helps regulate flow and create an upper reservoir. During peak solar/wind production, water is pumped upstream using surplus renewable energy. During low production or high demand, water is released to generate electricity reliably.

6 Community Engagement and Education

Elysia's community engagement strategy is a critical part of its framework, aiming to create awareness and responsible energy consumption among residents. To support this goal, Elysia has created Wattpeer, an innovative app designed to educate citizens about their energy usage while motivating them to adopt more efficient habits. Through rewards and valuable data on renewable energy, Wattpeer endorses users to make more sustainable choices.

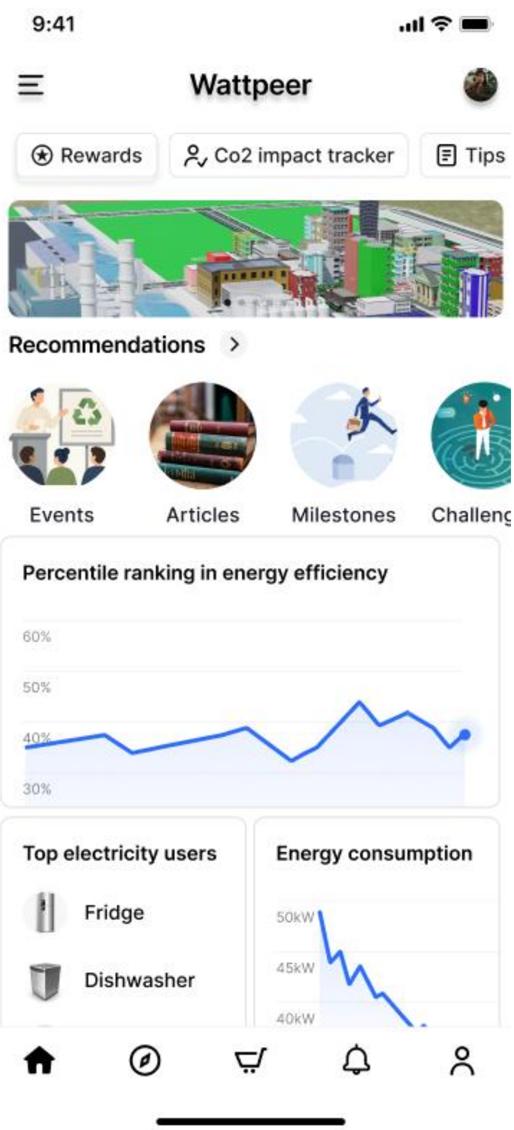

Image 1. User interface of Wattpeer

The Wattpeer app includes a CO_2 impact tracker, providing residents with clear data on their energy consumption and its environmental effects. Additionally, the app offers personalized energy usage graphs, helping users make informed decisions by deepening their understanding of their consumption patterns.

Beyond the app, Elysia is committed to fostering a broader understanding of sustainability through various initiatives. These programs work in cooperation with *Wattpeer* to create a comprehensive educational system that promotes environmental awareness and encourages responsible energy usage. Community-led workshops, public sustainability talks, and local energy conservation challenges provide residents with practical knowledge and hands-on experience. Additionally, Elysia collaborates with local businesses and organizations to introduce green incentives, such as discounts on energy-efficient appliances and rewards for sustainable lifestyle choices. By integrating these initiatives with *Wattpeer*, Elysia ensures that sustainability education is both accessible and actionable for all residents.

Educating Elysia's youth is a top priority, with schools placing increasing emphasis on sustainability and renewable energy. Through themed days and interactive events, students collaborate to develop a deeper understanding of these topics, ensuring that sustainability remains a core value for future generations.

7 Regulation & Policy for Sustainable Growth

Regulations and policies play a crucial role in Elysia's growth. With an expected annual growth rate of 5%, hence, Elysia's energy needs will increase cumulatively, as shown in figure 3. To address the increasing energy demand Elysia has implemented green loans, tax credit incentives and a simplified permitting process for energy storage projects. These incentives and regulations are designed to encourage development and expansion in the city's energy infrastructure, ensuring that it can meet the growing demand efficiently and sustainably.

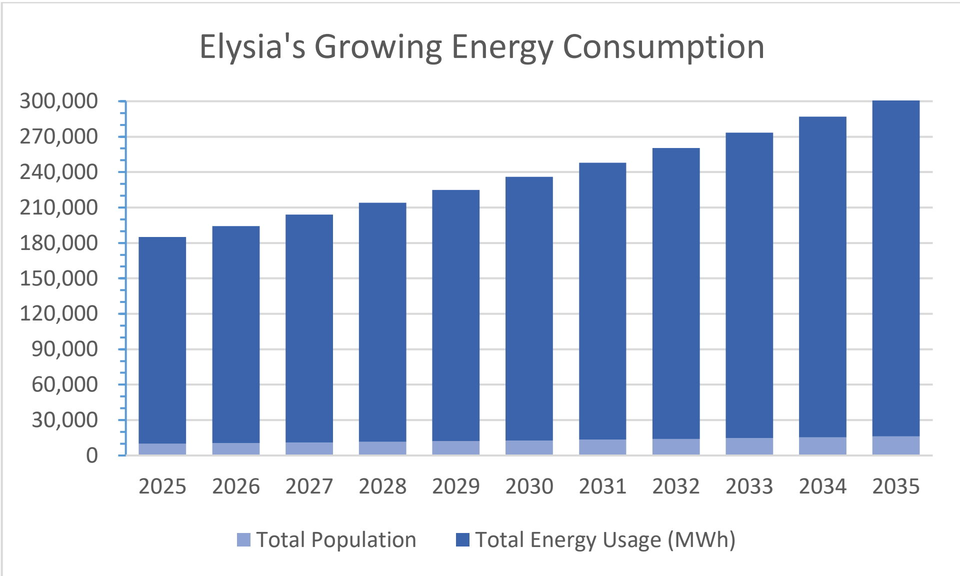

Figure 3: Elysia's growing energy consumption

To fulfill the growing consumption that a 5% annual population growth causes, Elysia aims to provide green loans and tax credits as incentives for private and public sector investments. These investments are in renewable energy and energy storage systems. The city guarantees green loans aimed at investments that have high initial costs e.g. solar panel installation for houses. Tax credits are given to private sector investments that invest in renewable energy and are given a 30% tax credit, which aims to ease the energy transition. Therefore, with the proposed incentives Elysia will continue growing as a sustainable city matching its annual growth rates growing energy demand.

For the city’s energy regulation will be a unique simplified permitting process. Permitting is a sluggish process in infrastructure projects, thus, Elysia implements a permitting process where all the required permits for the project are admitted at once e.g. land usage, electricity and others. The city will establish its own green energy permitting office and increase the number of officials, consequently, reducing queue times and streamlining the energy infrastructures construction processes. Therefore, Elysia establishes a simplified permitting process and its own green energy permitting office to streamline energy infrastructures construction processes.

7.1 Growth Outlook for Elysia

Elysia is expected to continue growing at its annual rate, serving as a model of sustainability and smart city development for smaller cities. With the energy transition being a breakthrough point, being a forerunner will be beneficial for the city. Through the investments that the private sector makes in renewable energy technologies Elysia’s population will keep growing, its employment opportunities will continue to increase, and the city will gain international recognition. In the end, Elysia's dedication to innovation and sustainability will improve the quality of life for its residents and set an example for other cities, sparking a wave of positive change around the world.

Sources

Björk, M. (2014). SCADA system for off-grid energy solutions on remote islands. Novia University of Applied Sciences. https://urn.fi/URN:ISBN:978-952-5839-91-3

Chen, S., Li, C., Stull, R., & Li, M. (2024-08-01). Improved satellite-based intra-day solar forecasting with a chain of deep learning models. Energy conversion and management, 313, 118598. https://doi.org/10.1016/j.enconman.2024.118598

Eurostat. (20.12.2024). *Available energy, energy supply and final energy consumption per capita.* [Data set]. https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_esc__custom_16027154/default/table?lang=en

Judith Thompson. (12.12.2024). *COP29 : Smart cities help maintain balance in the power system.* Retrieved 2.4.2025 from https://blog.sintef.com/energy/cop29-smart-cities-help-maintain-balance-in-the-power-system/

O'Callaghan, O., & Donnellan, P. (2021). Liquid air energy storage systems: A review. *Renewable and Sustainable Energy Reviews*, *146*, 111113. https://doi.org/10.1016/j.rser.2021.111113

Ordouei, M. (2023). *Optimization of energy consumption in smart city using reinforcement learning algorithm.* Bepress. https://works.bepress.com/mohammad-ordouei/4/

She, X., Wang, H., Zhang, T., Li, Y., Zhao, X., Ding, Y., & Wang, C. (2024). Liquid air energy storage – A critical review. *Renewable and Sustainable Energy Reviews*, *208*, 114986. https://doi.org/10.1016/j.rser.2024.114986

Tian,, Tian,, & Chernyakhovskiy, Ilya (2016). Forecasting Wind and Solar Generation: Improving System Operations, Greening the Grid. https://www.osti.gov/biblio/1236672

Tektelic. (21.2.2025*). Possible Ways of Reducing Energy Consumption In Smart City.* Retrieved 2.4.2025 from https://tektelic.com/expertise/possible-ways-of-reducing-energy-consumption/

United States Enviromental Protection Agency, (2013). *Renewable Energy Fact Sheet: Wind Turbines.*
https://www.epa.gov/sites/default/files/2019-08/documents/wind_turbines_fact_sheet_p100il8k.pdf

Wu, F., Yang, B., & Ye, J. (2019). *Grid-Scale energy storage systems and applications*. Academic Press.

Appendix

Attachment 1. Energy Consumption Calculations

Time (years)	Population	Energy Usage (MWh)	Energy Use Per Capita
2025	10000	175000	63000
2026	10500	183750	17.5
2027	11025	192937.5	
2028	11576	202584.4	
2029	12155	212713.6	
2030	12763	223349.3	
2031	13401	234516.7	
2032	14071	246242.6	
2033	14775	258554.7	
2034	15513	271482.4	
2035	16289	285056.6	