MASTER

Energetic, spatial and economical evaluation of installation of energy storage technologies in residential areas

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Award date:
2015

ENERGETIC, SPATIAL AND ECONOMICAL EVALUATION OF INSTALATION OF ENERGY STORAGE TECHNOLOGIES IN RESIDENTIAL AREAS.

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Construction Management and Urban Development 2013-2014

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Date of graduation:
21st August 2014
Eindhoven, the Netherlands

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PREFACE

In front of you is my graduation thesis for Master's program of Construction Management & Engineering (CME) provided by Eindhoven University of Technology. The research is a part of a larger project in an attempt to study the feasibility of energy storage technology when being applied in residential areas. The developed model is expected to help the Eindhoven city as well as different stakeholders who are interested in implementing community energy storage projects to have a quick evaluation about both technical and energetic aspects.

During the six months working on this research I found it a very attractive and helpful, yet challenging topic. I cannot finish my graduation thesis without the supports from supervisors and family and friends. From the University, I would like to thank Bauke de Vries, Paul Masselink and Saleh Mohammadi for their guidance and inspiration. Also, this thesis will be a present for my parents who are always beside me and give me both material and mental supports. Finally, I would like to thank CME friends for their helps and advices.

I can still vividly recall the day of two years ago when I was first time in the Netherlands to study. And now when looking back I never feel regret for the time I was here. This graduation thesis will close a chapter in my life, but all the experience, knowledge and memories will be with me forever.

1. CHAPTER1: INTRODUCTION

This chapter is designed to give the readers a short description about the content of this thesis with basic questions: What is the problem(s) being stated ? Why it is important today and what methodology is used for investigation ? The first paragraph is aimed to analyze the current situation of the energy world to highlight some of emerging problems which will be clearly defined in the second paragraph. Meanwhile, the final section describes the research method and relevant issues.

1.1. Context

This section provides an overview about the energy transition that is happening in many parts of the world including the Netherlands and Noord Brabant province.

1.1.1. Fossil fuels and renewable sources

Although the world of energy is now dominated by fossil fuels, a change toward a cleaner and renewable energy system is inevitable since the conventional energy sources show significant drawbacks. First of all, fossil fuels are the cause of *environmental degradation at local, regional and global level* (Goldemberg, 2006). CO2 is the main culprit of air pollution and *greenhouse effect* which is believed to rise the Earth's temperature by 1.4 ^{o}C – 5.8 ^{o}C causing extreme weather and rising sea level in the 21st century (Dhillon & Wuehlisch, 2013). Secondly, In terms of supply capacity, fossil fuels are not indefinite and one day the world's energy supply sources will be depleted. "*This originates from the simple fact that it takes millions of years for fossil fuels to accumulate while the deposits are extracted rapidly, making it impossible for the rate of creation to keep up with the rate of extraction*" (Hook & Tang, 2013). In a study done by (Shafiee & Topal, 2009), the calculation estimated that fossil fuel depletion time is around 35, 107 and 37 years for oil, coal and gas, respectively. Thirdly, the distribution of oil and gas field in the world is scattered raising serious concerns about security of supply. Many wars and conflicts witnessed today are rooted from energy disputes.

Given this context, renewable energies including solar and wind are getting more attention in recent years due to the fact that they *minimizes the environmental impacts and produces the least amounts of secondary wastes* (Pazheri, et al., 2014). In recent 10 years from 2004 to 2013, the new capital investment for renewable projects has increased significantly from 39.5 to 214.4 Billion dollars with an average growth rate of 23.4% per year (Frankfurt School – UNEP Collaborating Centre for Climate & Sustainable Energy Finance, 2013). Of the seven types of renewable sources, namely solar, wind, biomass & waste, small hydro, biofuels, geothermal and marine, the first two received the most attention. In 2013 the new global investment for solar and wind sectors are 140 and 80 Billion Dollars respectively, equivalent with 57.3% and 32.8% of the total raised capital. In terms of energy capacity, according to the U.S. Energy information administration (EIA, 2013), the current amount of energy provided by renewable sources is about 62.4 to 64.3 Quadrillion Btu, accounted for 11.5% of global energy consumption. This proportion is expected to reach to 13% by 2020 and in 2040 the share of renewable energy could be increased to 119 Quadrillion Btu to cover 14.5% global energy demand (See Appendix A). Energy produced by wind and solar is again predicted to rise considerably. As seen on the chart in Appendix A, both wind and solar energy are expected to grow constantly over the next three decades with the growth rate of 4.7% and 6.8% respectively. In 2020, wind and solar power plants are estimated to provide

479.6 and 156.7 Giga watts of electricity, and these numbers can increase by at least 50% in 2040 to bring 725.6 and 266.3 Giga watts to the world.
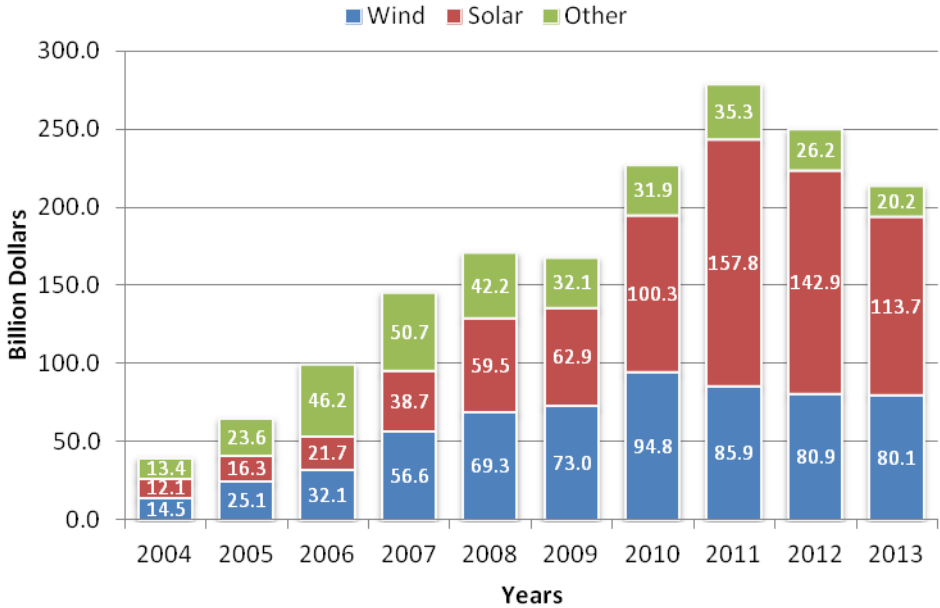
Figure 1: New investment in renewable energy projects all over the world (Frankfurt School – UNEP Collaborating Centre for Climate & Sustainable Energy Finance, 2013)

1.1.2. The context in the Netherlands and Eindhoven

The Netherlands will confront with an energy transition in a near future as it has become a global trend. Although the Dutch gas reserves are sufficient at least until 2030, they will decrease after that, and since early 1990s a number of renewable energy projects have been started. According to CBS (Statistics Netherlands) within two decades from 1990 to 2011, the total renewable share in gross electricity consumption has increased from 1.0% to 10.1% of which wind and biomass accounted for a large proportion. This percentage is expected to grow drastically next years since in its Action Plan for the 2009 Renewable Energy Directive, the Netherlands estimated that 37% of its electricity consumption in 2020 will come from domestic renewable sources. Also, year 2020 is the milestone to finalize the 20 – 20 – 20 reduction target according to European Climate and Energy Package, meaning that 20% less greenhouse gas, 20% more sustainable energy and 20% energy saving. For a further ambition, the country wants to achieve the energy neutral urban environments by 2050.
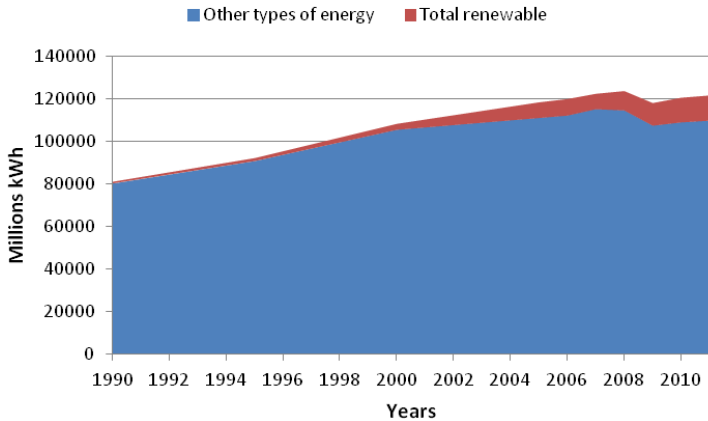
Figure 2: Development of Dutch renewable energy compared with non-renewable sources (CBS, 2011)
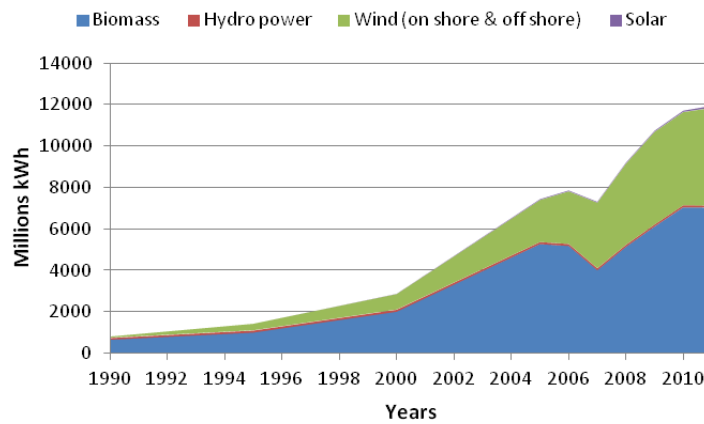
Figure 3: Development of different types of renewable energy in the Netherlands (CBS, 2011)

Following the national energy strategy, province Noord Brabant has set up its own targets for short and long term. From now to 2020, the province has a plan to achieve a number of objectives in the field of energy and climate:

- Increase the share of renewable energy in the total energy production to 20%
- Reach to an energy saving rate of 2% per year
- Reduce greenhouse gas emission by 30% compared to 1990.

In order to realize these targets, the province has focused on seven categories of technology which are also called the seven *spearhead* as shown on the figure below. Especially, solar PV, electric vehicles and some biomass options are important for the long term, while wind, heat, the built environment and some other biomass options are already ready for the market now.
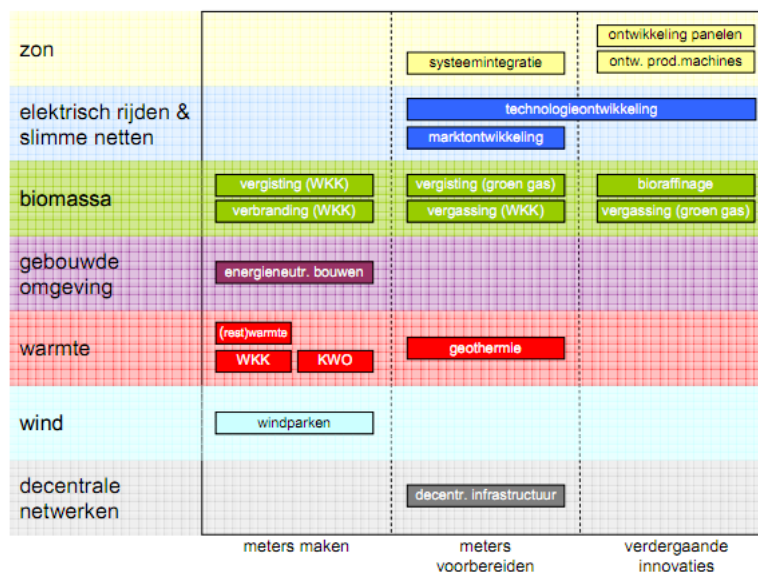
Figure 4: The Brabant spearheads arranged in different categories: currently ready (meters maken), need more preparation (meters voorbereiden) and need further innovations (verdergaande innovaties)

The Eindhoven city, a part of the province, has announced her ambition to become energy neutral in the built environment by 2045. In 2011 the Municipality of Eindhoven gave the assignment to KenW2iB to map the energy situation in Eindhoven and to take the first

exploratory steps towards Eindhoven in 2045 (Eindhoven , 2011). The report gave an overview of the local conditions for the development of renewable energy in the future, and came to a conclusion that the total potential was estimated at 21% of the energy consumption in 2011. Accordingly, the implementation of renewable technology for the city is challenged by a number of difficulties:

- Wind energy cannot be used on a large scale because of the proximity of Eindhoven Airport. However, there is still opportunity to implement some innovative small-size, building-related wind turbines.
- Only locally available biomass is used as fuel to cover just about 1% of the city energy needs.
- Solar energy is only used on 20% of the roofs and can possibly provide around 10% of the energy needs.
- Only limited use is made of geothermal energy because of the ground structure and the current expectation is 5% of the energy need.
- The availability of waste heat is limited because of the low level of energy-intensive industry.
- TES (Thermal Energy Storage) sites are only suitable for major renovation and new building projects.

(den Ouden & Gal, 2014)

Besides this, the city also has to overcome many other barriers in order to implement an energy transition successfully. Fossil fuels cost are still too low, energy storage is not attractive due to the expensive investment, the insufficiency of surface area to build sustainable energy facilities, the uncertainty about subsidies as well as a huge range of possible technologies making it difficult to select appropriate solution are among challenges that the city has to deal with.

1.1.3. Sub-conclusion

To conclude, it is clear that a transition in energy system toward clean and renewable sources is an inevitable trend of the world in next decades since fossil fuels showed many shortcomings, from the environmental degradation to depletion and external dependency. The transition has been happening at different levels: global, regional and local, and the Netherlands is not an exception. The city of Eindhoven still has 30 years to become an energy-neutral zone, yet a series of obstacles needs to be overcome. There will be no single solution that can help the city to solve the problem, but each technology today needs to be researched and improved to get a higher efficiency, yet more affordable and suited well with the building environment.

1.2.   The problem of renewable energy

Renewable energy is not perfect and the road to zero-carbon future has to overcome many technical obstacles. In this section the weak point of renewable sources – the intermittency in operation - will be analyzed, and a possible solution to deal with this problem will also be introduced.

1.2.1. The intermittency of renewable sources

As presented in previous sections, wind and solar energy are the two sectors which received the largest proportion of investment in the world of renewable energy. By exploiting power from sun and wind, renewable plants and generators take advantage of endless natural resources to produce electricity continuously. However, they are also criticized because of the intermittency and uncertainty in generating power. Obviously, PV panels cannot receive solar radiation at night and wind turbines work inefficiently during a windless season. That makes wind and solar less attractive compared to other types of energy. For illustration, look at Figure 5 where the electricity production from 9 energy sources are put together for a comparison. While the power production from hydro, biomass, nuclear and brown coal are very stable and controllable, wind and solar show a fluctuating, intermittent behavior in generating power.
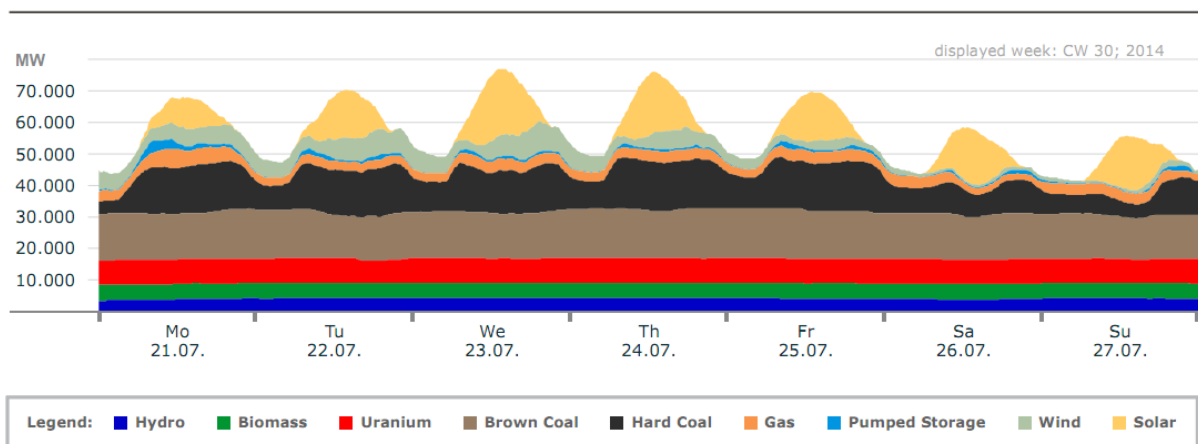
Figure 5: Electricity production from different sources in Germany, week 21 – 27/07/2014 (Burger, 2014)

Apart from the operation of renewable energy plants, the daily electricity usage also exhibits a graph with much volatility. Often, during a day there will be moments called peak hours when electricity consumption suddenly increases and periods when the consumption drops to minimum level (off-peak hours). Importantly, for different electricity use profiles they show fluctuations on different timescales, for instance, the daily fluctuation differs between week and weekend days, and also between summer – winter (Blokhuis, et al., 2011).
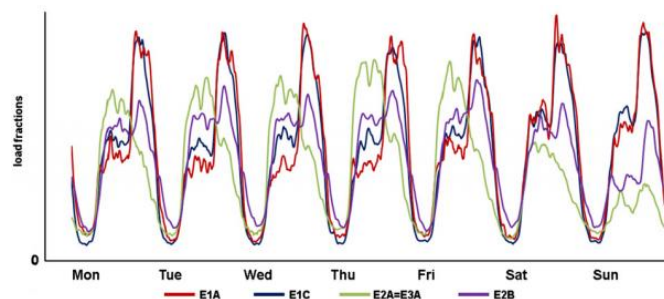
Figure 6: Different EDSN (Energy Data Services Netherlands) profiles for a winter week, 2010 (Blokhuis, et al., 2011)

On the fact that in a not too distant future renewable energy including solar and wind will be integrated widely into building environment, the mismatch between power supply and demand will certainly create a large amount of surplus or unused energy whereas outage occurs when the supply cannot meet the demand. This may facilitate the development of technologies that allow electricity to be stored and extracted based on the relation between

energy demand supply so as to create more reliable and efficient energy systems. These technologies are called *Energy storage.*

1.2.2. The role of energy storage

Energy storages have been invented and developed many years ago with various types and scales. In chapter 2, classification and characteristics of different energy storage technologies will be introduced. Briefly, energy storage can store energy or electricity by utilizing a number of physical principles such as chemical reaction or the energy transition from electrical power to potential and kinetic energy. In terms of purpose of use, energy storages are suitable for stabilizing grid, balancing demand – supply during peak hours and extending ability of renewable power plants and generators. The potential of integrating energy storages into urban environment as a supporting medium to maximize the capacity of renewable energy has been researched and mentioned in literatures, for example (Bortolini, et al., 2013) and (Parra, et al., 2014). However, these studies focus on application of energy storage for single house and building only, but not for a larger scale such as a row of buildings or a neighborhood. This thesis is designed to investigate the feasibility to implement energy storage together with renewable energy for various scales of urban in an attempt to create an energy neutral district.

1.3. Research approach

In this section the approach for this research will be described. First the problem will be defined for this research, followed by the main research question and sub questions. Finally the objective of this research will be clarified.

1.3.1. Problem definition

The contextual analysis can be summed up into four main points:

- Firstly, the municipality of Eindhoven has an ambitious goal to become energy neutral by 2045. To achieve the target, the city has to make enormous effort in order to transit the current energy network toward a sustainable and self-provided system.
- Secondly, conditions for the city to develop renewable power plants and generators are quite limited especially with regards to wind and solar. There is not enough space to build large-scale renewable facilities and the current efficiency still needs to be improved more.
- Thirdly, the operation of wind and solar power plants are criticized because of their intermittency and uncertainty, resulting in the mismatch between demand – supply and the waste of unused energy during off-peak hours.
- Fourthly, energy storage can help to solve the mismatch problem. However researches about integrating energy storage with renewable sources in urban context are now limited to a narrow scope which is for a single building or household. This topic should be extended for multiple buildings or even a neighborhood or a district to see if energy storages are applicable for a large scale.

This thesis is a part of a larger project done by Department of built environment, TU Eindhoven. The purpose of the project team is to investigate potential technologies and solutions that would help the city to fulfill the energy target. Project was divided into smaller tasks such as classifying energy use profiles of different industrial and residential sectors or

making a simulation tool to explore potential locations to build wind turbines or place PV panels based on land-use plan and characteristics of houses/buildings. Assuming that all potential renewable technologies have been implemented in appropriate areas, the next step is to study how energy storage can help to extend the supply capacity of these wind mills or solar panels.

1.3.2. Research question

The thesis will focus to answer the main question:
"How to find the most suitable energy storage solution for a residential district, considering technical feasibility, spatial requirements and investment cost?"

In order to answer the main question, there are sub-questions need to be solved first. These questions are answered in different chapter of the thesis and the conclusion chapter will synthesize everything to give the answer for the main one.

1) What are energy storages and their characteristics ? How can they be applied in energy systems, especially for integrating with renewable energy ? **(Chapter 2)**
2) How to calculate the amount of stored energy from energy storages ? What variables or conditions will be used to evaluate technical, spatial and economical aspects ? **(Chapter 3)**
3) What research methods are suitable with the purpose of the research and why ? **(Chapter 4)**
4) What scenarios will possibly occur in energy industry that would affect the application of energy storage and renewable energy ? **(Chapter 6)**

1.3.3. Objective

The objective of this research is to design a simulation tool which allows modeler to find an optimal energy storage solution for a given residential area as well as to investigate different energy policies and energy storage technologies.

1.4. Research model

The below figure presents different phases of the research, from the beginning steps which involved desk research and data collection to conceive the idea, to practical phases when the model is programmed and scenarios are designed.
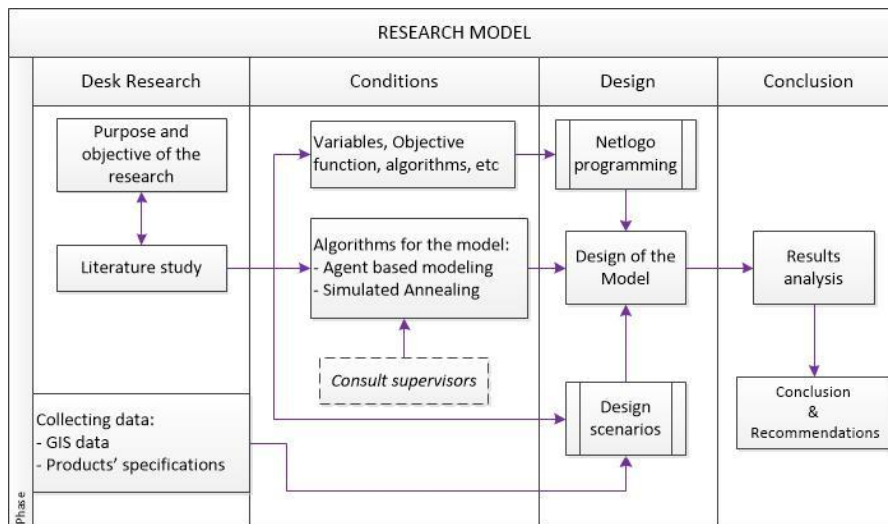
Figure 7: Research model

- The first step of the research is desk research with the purpose to collect all relevant information and data. Literature review only focuses on addressed issues or keywords, such as: energy storages integrated with renewable energy, energy-neutral district, residential area, etc. In addition, technical specifications of current energy storage technologies will be reviewed in order to choose appropriate solutions for the scenario design. Finally, a GIS map of a district in Eindhoven will be selected as the case study.
- In next step, conditions for the model will be based on results of the desk research. Especially, suitable research methods including Agent-based Modeling and Simulated Annealing will be chosen. This decision is based on literature study as well as consultancy from supervisors and experts.
- The third step is to design the model. This is the most time-consuming phase which is constituted from two sub-missions: programming the model and designing scenarios. While the first one involves practical issues like learning to use simulation software, building the demos and testing them, the later requires theoretical research and data collection.
- Once the model is ready, different inputs representing different scenarios will be entered to run the model. After that, outcomes will be aggregated for comparisons and conclusions. Also, recommendation for further studies or improvements will be added at the end of the thesis.

1.5.   Research methods

There are two main research methods applied in this thesis, namely semi Agent-based Modeling and Simulated Annealing algorithm. Both of them will be explained in more detail in next chapters, this section only gives general description about these methods.

1.5.1. Semi Agent-based Modeling

Agent-based Modeling is a bottom-up approach which is designed to investigate unpredictable emerging phenomenon. In an Agent-based model, each agent represents for an entity (human, animal, etc) who acts purposefully following a set of rules in order to maximize its benefits. Agents interact with environment and each other, and by doing so they can *learn* and adapt with new situations. The model used in this research lacks

interaction between agents and environment, and therefore it is just a partial or semi Agent-based model.

1.5.2. Simulated Annealing algorithms

Inspired by annealing process in metallurgy, the Simulated Annealing algorithms is a probabilistic heuristic for global optimization problems. The model is designed to find the best energy storage solution for the entire district by constantly generating different solutions and excluding ones that will decrease the total benefit. However, this process can easily be trapped in a local optimum meaning that no more higher-benefit solutions can be created but the model still does not reach to the global peak. Simulated Annealing algorithm can solve this problem by accepting some decreases to help the model to overcome the local optimum. This method is a heuristic approach and thus it requires many calibrations and testing for each scenario.

1.5.3. Validation of the model

The construct of the model is supervised by TU/e experts who have experience working with NetLogo and energy storage technologies. The initial version was created with some simple rules and inputs before being updated and checked by supervisors weekly. When the final version was created, it has been tested many times with different inputs to remove errors.

2. CHAPTER 2: ENERGY STORAGE TECHNOLOGY

In chapter 2, the basic concept of energy storage as well as the current technologies and ideas in this field will be introduced and classified. Moreover, the final section discusses state of art of implementation of energy storage in real life situation to see what are prospects and challenges.

2.1. How to store energy

Energy storage is a broad concept. In fact, energies are embodied in surrounding environment with three common forms of carriers: solid, fluid and gaseous. Electricity is also a type of energy which has a lot of advantages over others: the level of flexibility, the absence of waste, and the easy and safe way of connection (Blokhuis, et al., 2011). In this research, the term *"energy storage"* should be interpreted as storing electricity generated from renewable energies or from power grid to be used when necessary.

How to store electricity? The answer given by (Kousksou, et al., 2014) outlined three basic methods to do so:

- **Electrochemical systems** (embracing batteries and flow cells): the battery can derive electrical energy from chemical reactions or facilitating chemical reaction through the introduction of electrical energy.
- **Kinetic energy storage systems**, more commonly referred to as flywheel energy storage: electrical energy will be transferred into rotational energy of a massive rotor (flywheel) rotating with very high speed. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy; adding energy to the system correspondingly results in an increase in the speed of the flywheel.
- **Potential energy**: by definition, potential energy is energy stored in a system of forcefully interacting physical entities. A vivid example of this form of energy storage is pumped hydro system in which water is pumped to a reservoir 100m higher than ground and released to fall down to generate power.

In addition, thermal energy is another way to store energy. However, thermal energy storage is typically utilized to provide a heating or cooling resource, thus its production is not electricity.

Alternatively, Evans, et al., (2012) classified major types of energy storage technologies based on four principles: mechanical, chemical, thermal and electrical. Here, the potential energy and kinetic energy storage are grouped together into mechanical class, and a new method was proposed: electrical energy. In electrical energy storages with representatives are super capacitor or superconducting magnetic energy storage, *the energy is stored in a magnetic field created by a flow of direct current in a superconducting coil* (Ferreira, et al., 2013).

It can be concluded that except for thermal energy storage, there are three main ways to store electricity for latter use:

- **Mechanical methods:** in which electricity is transferred into potential energy or kinetic energy of rotating objects.
- **Chemical energy storage:** electricity is kept by bi-directional reaction between chemical substances.
- **Electrical energy storage:** using magnetic field within a coil comprised of superconducting wire to store electricity.
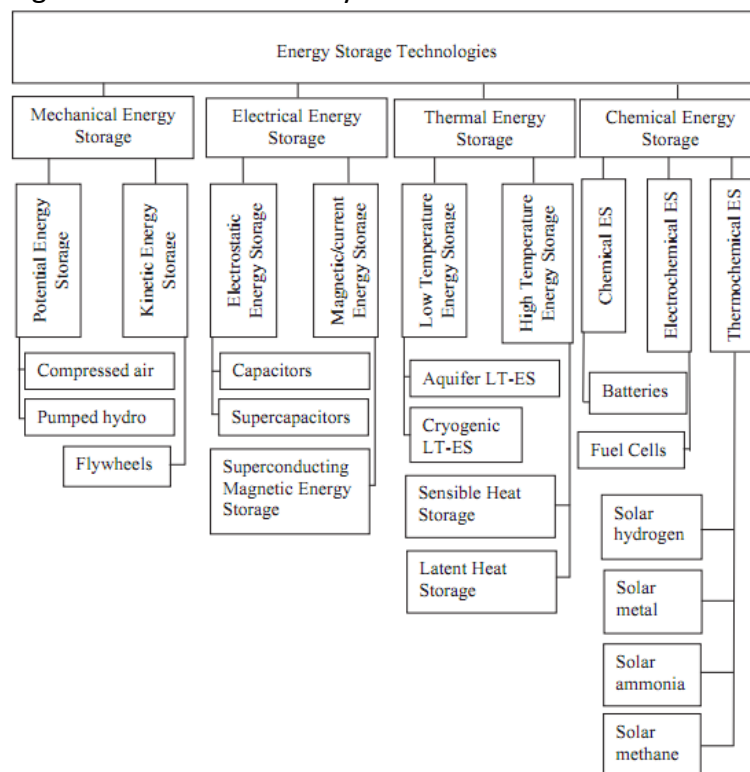
Figure 8: Classification of the major energy storage technologies (Evans, et al., 2012)

2.2. Characteristics of electrical energy storages

Energy storage can be distinguished by its principle of storing energy. Nevertheless, such classification only has meaning in terms of academic research. In order to evaluate the practical usage of energy storage technologies, different aspects are concerned.

According to a review done by Ferreira, et al., (2013) there are six aspects that should be taken into account when evaluating energy storage: efficiency, durability, reliability, response time, energy and power density and energy and power capacity. Efficiency refers to the percentage of energy loss when the storage gives it back to the system. Losses often occur in systems based on physical processes while systems which can store electricity directly are believed to have a very high efficiency. Durability and reliability are used to judge the usability of an energy storage product in real life situations. Response time is also an important factor to recognize the energy storages that can deal with sudden outages (very fast response time) and the one that is purely for storing energy (low response time). Energy and power density are important criterion which determines the weight and the size of a given technology. Meanwhile, energy and power capacity divide energy storages into two groups: technologies that only provide electricity for a short period of time (seconds to hours) and ones that can store energy for latter uses within days or weeks.

In another study done by Chatzivasileiadi, et al (2013), a list of 20 performance parameters has been proposed. Some practical features were considered, such as operating temperature, spatial requirement, investment power and energy cost, maintenance requirements, technical maturity, etc. This extensive list is due to the fact that researchers have looked at ability to be integrated into buildings of energy storage technologies. Nevertheless, in essence a storage can belong to one of the two categories: "*high power*" and "*high energy*" storage system. For example, flywheels and super capacitors are of the first group since they are suitable for high power and short duration application whereas compressed air and pumped hydro energy storage can storage a very large amount of electricity suitable for seasonal storage (Chatzivasileiadi, et al., 2013). Electrochemical batteries such as Lithium-ion battery, on the other hand, are suggested for either high power or high energy systems.

In an attempt to compare different types of energy storages, Ibrahim, et al (2008) discovered that for each field of application, a number of characteristics are more concerned. For example, for low-power permanent applications, the critical feature is a low self-discharge while for power-quality control applications, a quick response time, high power and cycling capacity are necessary. As for small system with a few kWh integrated with intermittent renewable energy, the key element is autonomy which means the maximum amount of time the system can continuously release energy. Meanwhile, a large system used for peak-hour load leveling requires a high energy capacity and a lower cost.

To summarize, there are many ways to classify an energy storage. They could be based on principle of operation or the purpose of use. Two types of battery may differ in terms of method used to store energy but they may belong to a same class of application.

2.3. Introduction of some energy storage technologies

In this section, several types of energy storage will be introduced in terms of technical design, characteristics and scope of application.

2.3.1. Pumped hydro storage (PHS)

When the power demand is low, electricity is used to pump water from lower reservoir to the higher one for reserving. When the power demand is high, water flows back to lower reservoir and activate the turbines to generate electricity. The major drawback of PHS lies in the scarcity of available sites for two large reservoir situated on different height. Open sea or flooded mine shafts or other cavities are technically possible to used as the lower basin (Kousksou, et al., 2014).
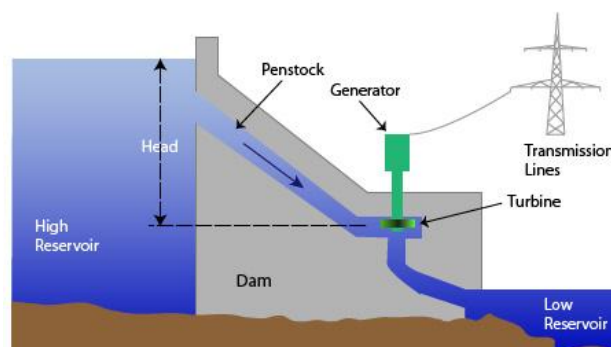

Figure 9: The pumped hydro storage system

Pumped hydro system is a mature technology and has been widely applied in over the world with about 300 systems operating. It has a lifetime of around 30 – 50 years, with a round trip efficiency of 65 – 75%. The response time is considered as "*fast*" (less than 1 min) while the low energy density requires massive civil works to construct the basin for a large body of water. According to (Chatzivasileiadi, et al., 2013), PHS is accounted for 99% of the total installed storage capacity for electrical energy all over the world.

2.3.2. Compressed air energy storage (CAES)

The operation of CAES is nearly similar to PHS except for the fact that CAES uses compressed air within a reservoir to keep the energy. During the off-peak/low-cost hours, the plant's generator operates as a motor to provide mechanical energy needed by compressors which sends compressed air into the reservoir. When the plant discharges, it uses the compressed air to operate its combustion turbine where natural gas is also added to be burnt (Kousksou, et al., 2014).
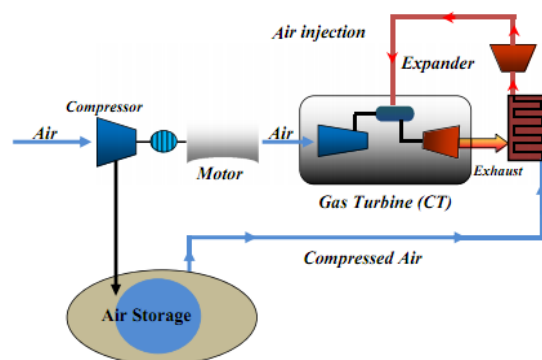
Figure 10: The compressed air storage system

Again, a challenge to build a CAES system is to find an appropriate space to contain the compressed air. Three types of reservoirs are suggested: naturally occurring aquifers (such as those used for natural gas storage), solution-mined salt caverns, and mechanically form reservoirs in rock formations. CAES is not a mature technology but has been realized with a very limited number of plants constructed. The life time of CAES is estimated as long as 40 years with an efficiency of approximately 41% - 54% (Chatzivasileiadi, et al., 2013). Both PHS and CAES are suitable for large scale power and high energy storage application. The CAES however has more advantages over PHS. The capital investment for CAES is significantly lower than PHS, it also requires much less time to construct a CAES plant (while it takes up to ten years for PHS) and also very little impact to the surface environment (Kousksou, et al., 2014).

2.3.3. Micro CAES

To solve the problem of reservoir for compressed air, micro CAES system has been designed in which the air is stored in smaller tanks over the earth surface. In micro CAES the compression and expansion is closer to isothermal than to adiabatic processes happened in large-scale CAES systems. On this way, water or another liquid has to be injected during expansion after which the gas-liquid mixture is led to a separator after the turbine exit and the fluid is used to satisfy cooling loads, then compressed and re-circulated (Karellas & Tzouganatos, 2014).

A micro CAES has various advantages over traditional one. Firstly, the building of a CAES plant is now independent on geographic features of the location since no cavern beneath the earth is required. Furthermore, a micro CAES has a very high efficiency which is up to 80% and they are highly reliable, low investment and running costs, low maintenance requirements, fast installation and very low environmental impact (Chatzivasileiadi, et al., 2013).

2.3.4. Flywheel energy storage (FES)

In a FES system, energy is stored in the rotational mass of a flywheel as kinetic energy, and release out upon demand. Figure 11 illustrates how flywheel energy storage is look like. To reduce friction as much as possible, the mass (rotor) is kept between two magnetic bearings and the entire structure is placed in a vacuum to reduce wind shear.
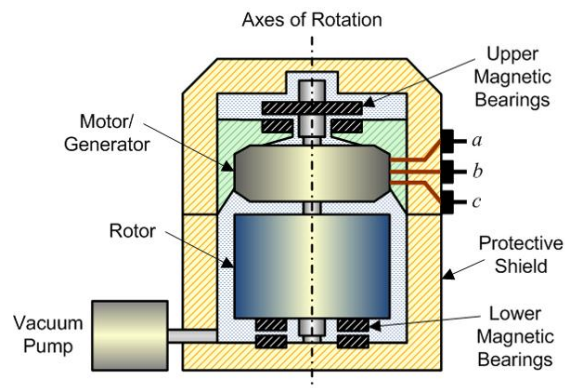

Figure 11: The Flywheel energy storage system

Although FES has a number of advantages such as energy efficiency is very high: 90-95%, allow very high number of charge/discharge cycles, very fast response time (ms) and has no environmental concerns, it shows many drawbacks. Flywheels are relatively poor energy density and large standby losses, and they are not adequate devices for long-term energy. Additionally, due to the precision engineering need the cost to construct a flywheel is very high. Currently, this technology is almost for demonstration purpose and more researches are still required.

2.3.5. Battery energy storage system.

Batteries are electrochemical systems that store and release power through chemical reactions. Essentially, a typical battery consists of four main parts. (i) The negative electrode (called anode) where electrons are released to the load and are oxidized during the electrochemical reaction; (ii) The positive electrode (cathode) which accepts electrons and is reduced during the reaction; (iii) The electrolyte plays as an environment where electrons can move between electrodes; (iv) The separators between positive and negative electrodes.

There are many types of battery but in general the operating principle is as described above. The main differences between them are materials used as electrodes and electrolyte, which determine the specific characteristics of the batteries (Kousksou, et al., 2014). Here, some of the most common types of battery are introduced:

- **Lead-acid battery:** a mature technology which is considered the cheapest one on the market. This battery consists of a lead cathode with sulfuric acid acts as electrolyte.

There two types of lead-acid battery: (i) Flooded batteries, which are the most common design, and valve-regulated batteries which are in research and development stage. Lead-acid battery has a number of advantages: low cost while high reliability and efficiency (70-90%). Yet, it presents also many drawbacks: short life time, necessity for periodic water maintenance and its low specific energy and power.

- **Nickel-based battery:** for this family of battery, the positive electrode is made from nickel hydroxide and the negative electrode use other materials such as cadmium hydroxide in NiCd batteries, zinc hydroxide in NiZn batteries and metal alloy in NiMH batteries. Pros: higher energy density and longer life cycle as well as lower maintenance requirements compared to lead-acid. Cons: costs for Nickel batteries are much more expensive (ten times), and on top of that nickel-cadmium batteries contain toxic heavy metals which can cause health risk in humans (Kousksou, et al., 2014).

- **Sodium-sulfur battery (NaS):** instead of using metal as electrode, in NaS system, liquid sulfur and liquid sodium are utilized as positive and negative electrodes. The electrolyte is now made of solid beta alumina. Pros: NaS batteries show a lot of advanced features, for example energy density is four times that of lead-acid, a long cycle capability, millisecond response and 99% recyclability. Cons: Sodium-sulfur battery is still expensive compared to lead-acid.

- **Lithium-based battery:** although widely integrated into mobile phones and portable electronic devices, this technology has not yet been used for energy storage in the context of an uninterrupted power supply (UPS) system. The main advantages over NiCd and lead-acid batteries are the higher energy density and energy efficiency, their lower self-discharge rate and extremely low maintenance required. Major disadvantages are high cost due to expensive materials, short lifetime and high flammability. (Hadijpaschalis, et al., 2009)

2.3.6. Hydrogen based energy storage (HES)

In a HES system, the electrical current facilitate the electrolysis reaction separating Oxygen and Hydrogen. Hydrogen has been known as one of the most efficient, cleanest and lightest fuels. After the decomposition of water, Hydrogen is stored separately in order to be used in fuel cells. Hydrogen fuel cells posses many advantages, including high energy density, applicability at small and large scale and simple modular use, a long lifecycle which is estimated up to 15 years. On the other hand, a HES system is currently expensive and it suffers from a very low round trip efficiency (20-50%).

2.3.7. Flow battery energy storage (FBES)

This novel system is somewhat similar to a conventional battery except for the fact that the charge and discharge process happened between the two liquid electrolytes of the battery and they are kept in two separate tanks. During operation these electrolytes are pumped through the electro-chemical reactor, in which a chemical Redox reaction takes place and electricity is produced (Kousksou, et al., 2014). Advantages of FBES are low self-discharge rate, a long life with low maintenance, and it is also easily scalable since it depends on the volume of the stored electrolyte.
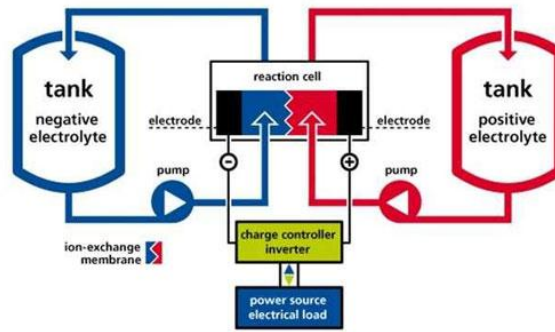
Figure 12: Flow battery energy storage system

2.3.8. Superconducting magnetic energy storage (SMES)

The superconducting magnetic storage system is an energy storage device that stores electrical energy in a magnet field without conversion to chemical or mechanical forms (Nielsen & Molinas, 2010). The key element of a SMES system is the coil made of superconducting cables of nearly zero resistance, generally made of niobiumtitane (NbTi) filament that operate at very low temperature (-270°C). A considerable energy requirement for refrigeration and the complexity of the cooling system hindered application of SMES although it provides a range of advantages (rapid response, high number of charge-discharge times).

2.4. Integration of energy storages in renewable systems

In recent years, energy storages have been integrated with large scale renewable system with the purpose to store surplus electricity and stabilize grid. Many of those renewable energy are generated by wind farms with total power capacity can be as high as dozen of MW. For example, the Chinese Zhangbei national wind PV energy storage project with rated capacity is up to 36MW over 4 to 6 hours, the Japanese Rokasho-Futamata wind farm was equipped with a 34MW energy storage system which is used for load leveling provide an amount of 238 MWh at the full capacity. A number of projects serve as frequency regulators to release a large amount of energy within a very quick time to stabilize grid. One example can be found in USA, the Beacon Power Stephentown Advanced energy storage which utilizes 200 high-speed Beacon flywheels to generate 20MW with a 4 second response time. The common points of these projects are the use of electrochemical batteries (Lithium-ion and NaS batteries) in a very large scale to take advantage of economy of scale. They are often national projects or operated by whole sale energy companies. Many of those energy storages have just been constructed within 5 to 6 years recently.

Figure 13: Flywheel frequency regulation energy storage system (Stephentown, New York, USA)

Figure 14: Sodium Sulfur (NaS) battery energy storage system (Rokkasho, Aomori, Japan)

In a smaller scale, energy storages have also been implemented within a building or a residential area with energy capacity varies from few hundred of kWh to more than 1 MW. For instance, SustainX – an energy solution developer has recently announced the installation of the world's first megawatt-scale isothermal compressed air energy storage to support for their headquarters in Seabrook, New Hampshire, USA. The 1.5 MW is placed in a room as shown in the picture below. In 2013, a community energy storage has been installed in Ontario, Canada to store electricity and provide back for 150 homes in the event of an outage. This system utilizes Lithium iron phosphate batteries to reach to 250kWh in energy and 500kW in power capacity. Especially, the size of the whole system is just as small as 3019mm x 2408mm x1686mm which is very convenient for installing.

Figure 15: isothermal compressed air energy storage

Figure 16: Community energy storage

Nevertheless, these are just demonstration projects. For a wider spread of energy storages into residential communities, more researches to reduce the production cost and improve reliability and safety should be done. Energy companies are now competing to each other to reduce price as much as possible. For instance, AMBRI – a metal liquid battery developed in laboratory of MIT is believed can reduce the cost to only $500 per kWh. At this price level, the producers hope for a radical change in the world of energy. Meanwhile other lithium-ion products are now sold with a price of around $1000. In terms of safeness and reliability, a document provided by American Electric power regulated functional specification of community energy storage in which environmental issues have been emphasized. For example, the noise level is suggested that should not be higher than 48 dBA at 10 meters away from the system and the system shall be designed to function well under outdoor environment.

In conclusion, the integration of energy storages in renewable energy plants has been realized in recent years with a number of large scale projects in USA, Japan, China, etc. Whereas in the residential sector, the implementation is still in testing and demonstrating stage. However the prospect in this field of application is quite good for energy storages since new technologies are being researched and the public is getting used to the idea of installing a megawatt-scale battery right in the middle of a neighborhood or a building.

3. CHAPTER 3: CONSTRAINTS, VARIABLES & OBJECTIVE FUNCTION

This chapter presents prerequisite elements for a spread of energy into a residential area. Besides that, the construct of objective function of the model as well as variables that are linked to the objective will be explained.

3.1. Pre-conditions

Energy storage is the missing link to renewable energy since it can be used to extend the ability of a renewable system in exploiting intermittent sources such as wind or sun. It is therefore necessary to discuss about renewable energy facility as a pre-condition for energy storages.

It is obvious that an energy storage will be useless in an area where very little amount of surplus electricity is generated. The surplus energy is the result of the mismatch between supply and demand sides. On average, the electricity consumption of a family in the Netherlands is roughly 3500 kWh/year according to http://www.deenergiegids.nl/. Ideally, the renewable energy production should be equal or greater than the total amount of consumption
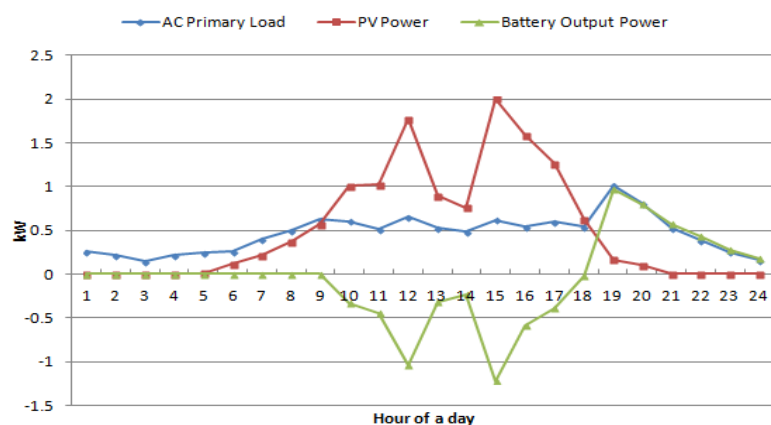
Figure 17: Surplus energy is enough to cover when the outage comes

The energy production however depends on renewable technology applied for that house. For example, for PV panels which are much more feasible in residential communities compared to wind turbines, there are three elements that determine the supply capacity:

- Location. Geographical location affects the level of solar irradiation on the Earth's surface. The average annual sum of irradiation in the Netherlands is about 1000 kWh/year which is higher than some part of the Scandinavian areas but much lower than the global average with 1715 kWh/year.
- Efficiencies. Efficiency of a solar cell refers to the percentage of energy that panel can convert from sun light. Current technologies allow a rate of conversion of 14.8% to 21.5% for commercial products.
- Surface area. A PV power system requires sufficient area to install solar cells. They can be placed on rooftop or walls of a building. Approximately, if a Dutch household wants to install a solar system with efficiency of 14.8% on the rooftop to cover the whole energy consumption, the required area will be:

$$A = \frac{3500}{1000 \times 14.8\%} = 23.6 \; m^2$$

In order to apply energy storages efficiently, the given residential district has to have appropriate number of square meters of PV panels to generate a large enough amount of surplus power.

In the case study area (the district called *Kerkdorp Acht* located at the North West of Eindhoven city), the total surplus (when supply > demand) and outage (demand > supply) energy are 38,684 kWh and 38,076 kWh respectively meaning that in theory the district can become an energy neutral zone by using batteries to balance the surplus and outage.

3.2. Objective function and variables

As mentioned before, the purpose of this thesis is to evaluate the application of energy storages on three aspects: spatial requirements, technical aspects and economic value. This section explains how objective functions for each purpose are constructed and what variables that are linked to these functions will be considered.

3.2.1. Spatial constraints

In literatures the spatial aspects of energy storages are defined as energy density per square meter or cubic meter or per kilogram. For example, the energy density of Lithium-ion battery is about 75-200 Wh/kg (Evans, et al., 2012), in terms of kWh/m^3 it is between 250-620 kWh/m^3 (Chatzivasileiadi, et al., 2013).

The location to install a battery is also determined by other factors such as the safety and noise nuisance. Lithium-ion batteries are currently used in many applications but they may catch fire in some circumstances. Lead-acid batteries are also known for negative impacts they may cause to environment. Once being installed in a residential area, the design of the enclosure of an energy storage must be weatherproof and tamper resistant (according to *Functional specification for Community energy storage unit – American electric power*). Furthermore, when operating the noise level of an energy storage is suggested not to exceed 48 dBA at 10 meters away from the system.

It is difficult to find a function for site selection of energy storage since this task may depend on experience of technicians and availability of the given area. In a number of demonstration projects, energy storages are implemented in the basement of a building or on a green patch nearby to support the surrounding inhabitants.

Figure 18: A 25 kWh Community energy storage installed in Ohio (USA)

In this thesis, spatial requirements for a successful implementation of a community energy storage are twofold:

- There must be a site with an appropriate function to allow that energy storage to be built. An *"appropriate function"* might be a green park or an abandoned garage which are suitable to locate the storage as well as for latter operation and maintenance. The size of the location is
- The distance from the site to its target households has to be within an appropriate range. There is no clear regulation about how far it should be from a battery to its supporting households but a distance of $100 - 200$ meters may be the maximum.

For energy storages that could fit in a parcel or a building, the condition is that they have to be proven to be qualified in terms of safety, ease of use and sizes.

3.2.2. Energetic aspects

Various features of energy storage have been introduced in chapter 2 – Theoretical background, but only the most important and relevant characteristics are taken into account for technical aspects. This is due to the fact that the model should be kept simple with a main focus on capacity of storing energy. In this way, an energy storage supports a PV system to store surplus energy when unusable energy is generated and give it back when demand is higher than supply. In the case when both PV panels and battery are not able to provide energy, the household will use electricity from grid. The following figure is borrowed from (Bortolini, et al., 2013) to illustrate the operation of an energy storage which is integrated with a PV system.
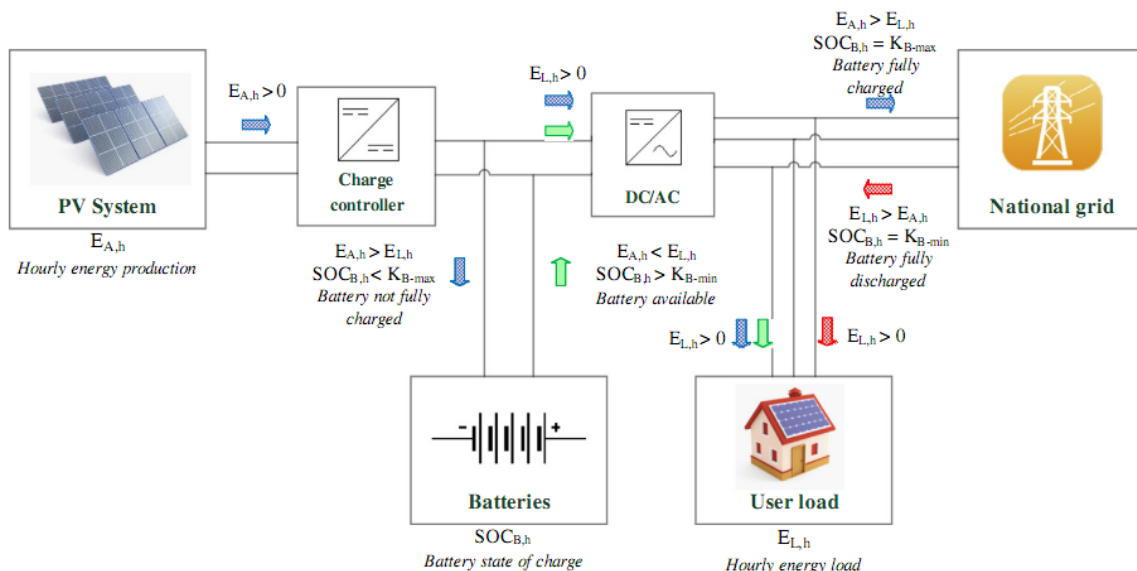
Figure 19: Reference diagram for a grid connected PV – Battery energy storage system

$E_{A,h}$: energy supplied by PV system for hour h (kWh)

$E_{L,h}$: energy load for hour h (kWh)

$SOC_{B,h}$: state of charge of energy storage for hour h (kWh)

K_{B-max}: energy storage maximum capacity (kWh)

K_{B-min}: energy storage minimum capacity (kWh). K_{B-min} has a relation with K_{B-max} by the following equation:

$$K_{B-min} = K_{B-max} \times (1 - DOD)$$

Where DOD is the depth of charge (%) of the energy storage. The value (1 – DOD) defining the minimum allowed percentage of energy within a battery. Below this threshold, the battery switches to *stand-by* mode.

The objective function to assess the energy capacity of an energy storage is therefore to calculate the state of charge of that storage based on the relation of supply side and load, the maximum storage capacity and the depth of charge of that battery. The detailed calculation is presented in chapter 5 – Design model. In this section, the variables which are linked to that function are being explained in the Table 1

Table 1: Description of variables

Variables	Unit	Description
Surplus/Outage energy	kWh	Surplus/Outage = Supply – Demand If Supply is smaller than Demand, an outage will occur and energy from the battery or the grid is required If Supply is greater than Demand, surplus energy is generated and may be used to charged the battery if it is not full.
Energy capacity	kWh	The maximum energy contained in a battery.
Power capacity	kW	Power capacity defines how much energy an energy storage can receive in one hour as maximum level. For instance, a 100 kWh battery with power capacity of 25kW can be fully charged within at least 4 hours
DOD (depth of discharge)	%	An energy storage often does not use all of its energy capacity, but a proportion of that. DOD defines how many percentage of energy within a battery can really transfer to the system. In a number of commercial products, this value is designed at 80% meaning that below the level 20% of energy, a battery will stop discharging to protect itself.

3.2.3. Economic evaluation

The objective function for economic evaluation is given as follow:

$$B = P \times E - C$$

Where B is the monetary benefit (€) offered by an energy storage; P is the electricity price (€/kWh); E is the energy (kWh) saved by the energy storage for the entire lifecycle; C is the installation cost (€)

E has been introduced in previous section whereas some examples of electricity price *(P)* and installation cost *(C)* will be presented in chapter 6 – Design scenarios.

4. CHAPTER 4: CONDITIONS FOR THE MODEL

This chapter introduces two main research methods that will be used to construct the model: Agent-based Modeling and Simulated Annealing algorithm, and explains why they are suitable with the purpose of the research as well as what limitations they have.

4.1. Agent-based Modeling (ABM)

4.1.1. Introduction about ABM

The early research about agent based model has been started over 50 years ago with relatively simple concept in the late 1940s. This research approach was then not widely introduced until 1990s when powerful computational tools such as computer and software programs, Swarm and Netlogo for example, were developed. With the ability to simulate emerging, unpredictable phenomenon in large scale ABM can be applied to solve complex problems in economics and social science. Especially, ABM has been used in many researches to deal with urban planning and management. A number of examples can be found in studies done by Feitosa, et al (2011) who simulated the segregation process in São José dos Campos, a medium-sized city in southeast Brazil or Gaube & Remesch (2013) who tried to investigate the impact of urban planning on the spatial pattern of urban energy use for the city of Vienna. That is a glimpse of ABM and its scope of applications, the following paragraphs will explain in detail the components of an Agent based model and why this technique was chosen for this thesis.

In principle, the ABM is a bottom-up research approach in which a number of simplistic notions that are both obvious and banal (Batty, et al., 2012) is assigned to a lower level of system in order to investigate the emergence of higher levels. In ABM the *'lower level of system'* is agents which are an analogy to individuals in a social system. Among many definitions about ABM, which are largely similar to each other, Batty, et al (2012) have given a relatively understandable comment: "*Agents generate actions that occur in time as well as space, that influence their wider environments and that cooperate as well as conflict with one another over the use of space*".

4.1.2. Describe an Agent-based model

As mentioned above a social system can be considered as a collection of individuals (agents) who interact with each other according to a number of certain principles. Generally speaking, an agent always act and interact purposefully, meaning that can decide for themselves whether (under what conditions) to perform some actions. More specifically, in the book *Agent-based model of geographical systems (2012),* Andrew T. Crooks and Alison J. Heppenstall summarized three basic characteristics of an agent:

- **Autonomous**: Agents are free to process information and exchange them to others, at least at a limited range of situations to make independent decisions.
- **Heterogeneity**: agents permit the development of autonomous individuals e.g. an agent representing a human could have attributes such as age, sex, job etc.
- **Active:** Activities of an agent are very diverse, including 1) Goal-directed: having a goal to achieve, for example to maximize their own utilities; 2) Reactive/Perceptive: having an awareness of sense of their surrounding; 3) Interactive: agents can query other agents and/or the environment within a neighborhood; 4) Mobility: agent can roam within the space of the model; 5) Adaptation/Learning: Agent can be designed to alter their state

depending on previous state; 6) Bounded Rationality: agents can be configured with '*bounded*' rationality (through their heterogeneity) allowing agents to make inductive, discrete choices that move them towards achieving goals.

Another important term referred in definition of ABM is "*environment*". According to Teahan (2010), an environment is described as "*everything in the world that surrounds the agent that is not part of the agent itself. This is where the agents 'lives' or operates, and provides the agent with something to sense and somewhere for it to move around*" (Teahan, 2010). An example of environment can be found in land-use model in which agents live and interact within a set of square cells called patches. Each patch contains features that influence behaviors of agents, such as land-use (residential area, semi-build, traffic, recreation, etc), gas demand and electricity demand.

4.1.3. Pros and cons of ABM

Agent based model has many advantages over other types of modeling techniques; one of them is ability to deal with complexity. It comes from the nature of this approach. In ABM the modeler tries to keep the rule as simple as possible at micro scale and observe the development trend of the whole system as the result of numerous operations and interactions between agents occurring simultaneously. Outcomes of such process are often complicated, non-linear and unpredictable. Besides this, agents can be representations of any type of autonomous entity, from people, insect, cars to buildings or land parcels (Batty, et al., 2012). This characteristic makes ABM a very flexible and adaptive system suitable for various research domains including urban planning and management.

On the other hand, ABM is also challenged by some limitations.

Firstly, "*A model has to be built at the right level of abstraction for every phenomenon, judiciously using the right amount of detail for the model to serve its purpose*" (Couclelis, 2002). In this sense, an agent-based model with too much detail or too simple level of abstraction are both considered inappropriate. It is therefore an art rather than a science to make an agent-based model.

Secondly, an agent-based model usually contains factors that are *difficult to quantify, calibrate and sometimes justify, which complicates the implementation and development of a model, as well as the interpretation of its simulation output* (Heppenstall & Crooks, 2012). Especially, in models which involve knowledge from social science such as science about human being with complex psychology, behaviors of agents are often not understood fully or predicted accurately. It leads to a discussion about whether the output of agent-based model should be used for qualitative analysis or quantitative estimation. The answer is not very clear, as Heppenstall & Crooks have pointed out that it is determined by *degrees of accuracy and completeness in the model inputs*.

There are more critics about the use of ABM and the two problems mentioned above are just the most typical. They can be summarized in the statement given by Conclelis (2002) that: *In particular, ABMs are very sensitive to initial conditions and to small variations in interaction rules,* and thus a lot of challenges in applying ABM in predicting phenomenon still remains.

4.1.4. Sub-conclusion

In conclusion, agent-based modeling is a newly-developed simulation theory which takes advantage of powerful computational tools such as computer and software programs. Two main components of an agent-based model are '*agents*' who act and interact actively and purposefully to achieve a goal, and *'environment'* – the surrounding space where agents live, operate and receive information. The greatest advantage of ABM is that it generates complex phenomenon from simple, obvious rules in micro level (level of agent of group of agents). Nevertheless, ABMs are very sensitive when small changes are made and requires modelers a huge effort in verifying and/or calibrating. In many cases, the outputs from ABMs are only used for qualitative research rather than accurate quantitative forecast.

4.2.   The energy storage model as a semi Agent-based model

This section discusses why agent-based modeling is a suitable approach for the research and also the uniqueness of the energy storage model will be explained to see that the model is not fully qualified as an agent-based model. In this section, only the most important features of the model will be examined. For the full description of model design, please look at chapter 5.

4.2.1. Why ABM ?

To begin with, it is necessary to recall the motivation and purpose of making this model. There are several reasons. Firstly, although a large quantity of literatures mentioned the energy storages and their feasibility to be applied into energy system, very few focuses on how to implement these technologies in urban environment and to what scale they should be. For example, Parra, et al (2014) studied the integration of battery and hydrogen storage into a PV generation system of a single household to investigate the benefit or Yan, et al (2014) looked at techno-economic and social aspects of energy storages installed in commercial buildings. Nevertheless, these studies are conducted only on one object (single house or a building) rather than taking into account multiple-scale of urban space. Secondly, the development of community energy storages which has been introduced in USA or Germany has demonstrated that by using energy storages collectively, more benefits in terms of economic and social can be achieved. Especially when massive energy storage technologies are increasingly being improved allowing cheaper, smaller and higher capacity system to be commercialized, it is time to consider how these batteries will be allocated in urban environment and what impacts they make on society. And thirdly, this research was aspired by a Master thesis done by Broersen, C. M (2012): *A complex model for generating sustainable land use plans.* This thesis utilized agent-based model programmed on Netlogo platform to investigate possible locations within Noord-Brabant province for constructing renewable power plants (wind turbines, solar panels and biomass). The thesis showed that it is possible to use agent-based model as a bridge to bring different disciplines (energy technology and spatial planning) together. This arises from the nature of agent-based theory which is very flexible and adaptive.

The energy storage model is therefore designed to investigate the scenario when various types of battery are installed and households in a residential area are able to connect to use the battery collectively. There are a lot of questions with uncertainty to answer: Which kind of battery should be applied in order to get the optimal benefit in terms of economic and social? On what scale households should connect to each other, are they clusters of 10 to 20

families or maybe much larger, up to 100? Besides this, the model concerns at least three different domains of research: the spatial management (space to locate these battery, the distance between households about to be connected, etc), the economic assessment (monetary benefit) and the technical aspects related to capacity of batteries and supply – demand profile of each household.

From these above requirements, agent-based modeling was chosen as the most suitable research method. Agent-based models can simulate emerging phenomenon similar to this case where households are changing their state from standing alone to joining into a larger network.

4.2.2. The model is designed not to be a complete ABM

Obviously, each household has different characteristics and interests which trigger them to follow different strategies when searching for connections. The nature of agents with flexibility and heterogeneity allow these characteristics simulated. The bellow table represents the analogy between a household in the real world and an agent who is modeled in virtual environment.

Table 2: Comparing characteristics between agents and households in the real world

Agent's characteristics	In real world (households, families)	In simulated world (an agent)
Autonomous	- A household is free to make a group with others so that they can share an energy storage system.	- Each agent makes its own decisions, too. But from a collection of agent it is chosen randomly, therefore some agents have to *'wait'* for their turn.
Heterogeneity	- Each family is unique. They differ in many aspects: electricity demand – supply profile, location and address.	- Agents have attributes to represent their uniqueness. For instance, each agent has two attributes: *'demand'* and *'supply'* to contain information about electricity consumption and production. Auxiliary info such as *'street'* or *'number'* which are necessary for grouping agents are also added. - There are no identical agents.
Active		
- *Goal directed*	- A household agrees to participate into an energy project if it can help them to save energy and money	- An agent agrees to take an action (joining/leaving a group) if its new benefit indicator is higher than the old one, otherwise it stays the same
- *Reactive/Perceptive*	- N/A	- N/A
- *Interactive*	- Negotiation happens between families in a neighborhood. - A family may be convinced to join a group or choose to step out.	- Agents are able to query other agents within a range of distance (for example, 50 meters). - An agent can interact with its neighbors and force them to change the attribute *'group-id'* under some circumstances.

- Mobility	- In the real world, owner of a house can move to another city or even country leaving the old house for new comers	- This behavior is not simulated in the model. All the households are assumed to stay in one place forever.
- Adaptive	- People remember their experience in the past and they would have a huge impact on decision making process.	- For modeling, the leaning process is much simpler. Agents '*try*' to change their state (for instance from standing alone to be in a group) and record both old and new benefit indicators. A comparison will be made after that to choose the appropriate strategy.
- Bounded rationality	- In reality, people are not always intelligent enough to make perfect decisions. They are limited by a number of factors: level of education, experience with technology or age or gender.	- In the model, agents behave to maximize the global benefit and they always perform calculation with absolute accuracy. - However, there are some exceptions. If an agent cannot find enough space to install an energy storage, he cannot use it even though it is the best solution in terms of economy.

Nevertheless, in the energy storage model the role of '*environment'* is almost unimportant making it hard to be qualified as a full agent-based model. By definition, environment in agent-based model is where agents live and operate and provides agents with something to sense and somewhere to move around. The agents indeed live and interact within the environment of the model (query neighbor agents, calculating distance and drawing links with others) but they do not move around. More importantly, agents do not get information from environment and their activities absolutely have no impact on environment. The model was designed to get initial set up from external sources which are GIS data and electricity supply – demand profiles. Agents will record all of those information and process and interchange with others. When the model runs, only agents' attributes are changed while environment is kept intact. Therefore, it can be considered as partial agent-based model rather than a full qualified one.

4.3. Netlogo

4.3.1. Netlogo: advantages

To assist the development of agent-based models, a number of different platforms have been developed. These platforms vary in how much support they provide. Some agent-based modeling platforms provide fixed sets of rules that can be used with some chosen parameters, but these are often too restricted to capture the wide range of phenomena that one might want to model. According to Railsback, et al. (2006) "*Netlogo the highest-level platform, providing a simple yet powerful programming language, built-in graphical interfaces, and comprehensive documentation".*

One of the benefits of using NetLogo is its interface. The interface contains a 2D spatial view of the model environment (in the newest version, 3D view was available), which is a square lattice. The 2D view has several different options that prove useful in modeling. The size of grid can be changed, as well as the size of the cells. The edges of the world can be changed to reflect the system the model is to represent; the model can choice between treating it as walls or cells of the opposite sides.

In addition, the Netlogo programming language is appreciated more than other software due to the fact that "*Its programming language includes many high-level structures and primitives that greatly reduce programming effort, and extensive documentation is provided*" (Railsback, et al., 2006). Unlike other platforms such as MASON, Repast and Swarm which are considered as "*framework and library*" (Railsback, et al., 2006), Netlogo offers an open, authoring environment *that is simple enough to enable students and researchers to create their own models, even if they are not professional programmers* (Tisue & Wilensky, 2004).
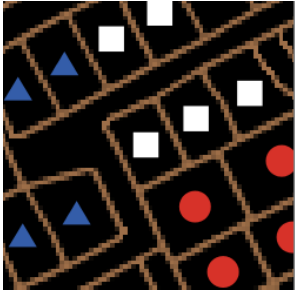
Since Netlogo is an Agent-based platform which was designed to support un-professional users with an intuitive display and sufficient instruction documents, it was chosen as the main tool to design the model for this thesis.

4.3.2. Netlogo: Components.

In Netlogo, "*modelers can give instructions to hundreds or thousands of independent agents all operating concurrently, in order to explore connections between micro-level behaviors of individuals and macro-level patterns that emerge from their interactions*" (Tisue & Wilensky, 2004). There are four types of agent in Netlogo including turtles, patches, links and observers:

▪ **Turtles:** by definition, turtles are agents who move around the environment and interact with each others. In the energy storage model, there are three types of turtles, namely: parcels, green-parcels and batteries. This table gives a short description about each type of turtles and what the role it is in the energy storage model.

Table 3: Description of "turtles" of the model

PARCELS

Figure 20: Parcels with different colors and shapes depending on which type of battery they are using

A parcel represents for one household/family/building that is standing on a piece of land. Parcels cannot move but they can interact with neighbor parcels and make connection between them. a parcel is generated and located at the center of the geometry that shapes the plot of land.
Parcels can be displayed under different colors and shapes depending on the battery technologies they are using. However, their attributes are always the same.

Attributes	Value	Description

Function	*"woonfunctie"*	Showing the land use of that parcel. Because the object of the research is residential area, only parcels with function *"woonfunctie"* (in English: "*residential function*" are kept)
Parcel-id	*Integer number*	To identify parcels. Each parcel will get its corresponding electricity use profile with its id number.
Group-id	*Integer number*	Parcels who are sharing a battery will get the same group-id number. When a parcel leaves its previous group, the value of group-id also changes.
Demand	*[1 2 3 4 … 168]*	This attribute is a list containing 168 (7days x 24 hours) numbers showing the hourly power consumption of a parcel in one week.
Supply	*[1 2 3 4 … 168]*	Similar to the list of demand, this list represents electricity production which is generated by PV panels.
Parcel-surplus	*[1 2 3 4 … 168]*	Showing how much surplus energy was created during a week by subtracting supply by demand.
Battery-type	*1, 2, 3*	Which type of battery that the parcel is currently using.
Near-a-park?	*1 or 0*	This attribute has a binary value meaning that for every parcel they have only two states: close or not close to a park. A park or green area is the requirement to install a community battery. Maximum distance to a park is a flexible variable which can be adjusted by modeler. If a parcel is too far from a park or green area, they have to install a battery which can be built inside the house or land.
Street	*"Verzetsheldenlaan"*	Name of street where the parcel is located
Number	*Integer number*	The address number of the parcel. Street name and address number are necessary for drawing links between parcels of the same group so that the drawing will look more tidy and less chaos.

GREEN-PARCEL

Figure 21: A green-parcel denoted by plant symbol

A green parcel simply marks the place where is suitable for placing an energy storage. It could be a green area, an abandoned garage or any other eligible constructions. In this research, only green parcels are taken into account. For this purpose, a green-parcel does not have any special attribute. They simply stand on their own places and act as landmarks for other parcels to search around.
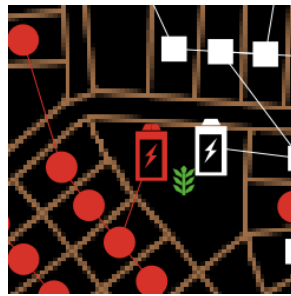
BATTERIES		
Figure 22: Batteries on a green parcel		
Parcels in one group connect to a mutual battery which is installed on the nearest park (or green-parcel). The battery therefore indicates where the optimal location is and some other information which is needed for data analysis.		
Attributes	**Value**	**Description**
Number-of-connectors	*Integer number*	Showing how many parcels are now sharing this battery.
Technology	*1, 2, 3*	Used to recognize which type of battery it is.
Stored-energy	*Decimal number*	This feature shows how much energy that battery has stored from the connected parcels within 1 week.

- **Links:** the link-agents stands between turtles indicating a connection. In the model, links only exist between parcels of a same group and between parcels and the battery they are sharing. The links are therefore meaningful only in terms of visual display and they have no important properties.
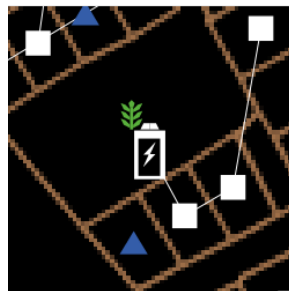

Figure 23: Links between parcels and battery

- **Observer:** The observer is, like the name all ready describes, someone that observes the environment of turtles and patches. Through the command center, user enters instructions to the turtles and patches and observer will return results.

Figure 24: Command Center and observer

- **Patches:** patches are agents who form the environment surrounding turtles. As mentioned in previous section, in this model the environment was ignored. The role of patches, hence, can be put aside.

4.4. Simulated Annealing

4.4.1. Greedy algorithm

Basically, the final goal of the model is to bring the system into a state in which the global benefit is maximized and stable. In this sense, the mission of the model is to find an optimal solution among numerous combinations of solutions. There is one way to solve this problem by applying the "*greedy algorithm*". According to greedy algorithm, the model at each stage tries to make locally optimal choice with the hope that a global optimum will finally be found. The design of the model can be as follow:

- At the beginning, the model adapts one random solution as the initial set up.
- After that, through interactions between agents who follow a set of programmed tactics the model constantly changes its state so that the new state generates higher benefits compared to the old one.
- Until the moment when no more benefit can be achieved, the model is believed to reach its maximum and stop running

Nevertheless, the greedy paradigm receives severe criticisms due to the fact that in many cases it fails to find the global optimum. Instead, what it returns is just a local one. Mathematical researches done by Gutin, et al (2002) and Bang-Jensen, et al (2004) have pointed out the main drawbacks when using greedy algorithm and that "*it should be used with great care, since for many optimization problems its usage seems impractical even for generating a starting solution*" (Bang-Jensen, et al., 2004). A well-known example illustrating the failure of greedy paradigm is the *climbing hill* problem in which the traveler is trapped at a local maximum (or minimum) and is not able to escape to climb on global top.
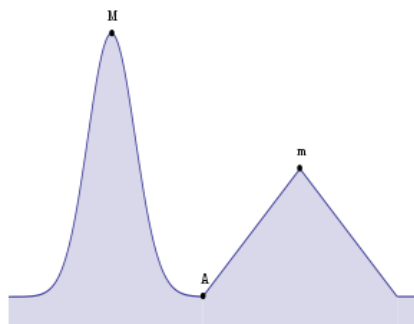

Figure 25: For example, Starting at A, a greedy algorithm will find the local maximum at "m", oblivious of the global maximum at "M"

4.4.2. Simulated Annealing (SA) algorithms

To solve disadvantages of the greedy model, a local search technique called *"simulated annealing"* (SA) was proposed and applied in the model. In this section the definition of simulated annealing will be explained and a comparison between the two methods will be made to see why SA is well suited for the context of this model.

In a general description, Henderson, et al., (2003) defined SA as *"a local search algorithm (meta-heuristic) capable of escaping from local optima"* while Busetti (2003) explained the origin of the name of this method which *"exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process)"*. Through literature review it can be concluded that there are three main features characterize the SA method. 1) SA is a search algorithm which is used to find the optimum (min/maximum) state of a system, 2) SA provides a mean to escape local optima by allowing moves which worsen the objective function value (Henderson, et al., 2003), and 3) The acceptance of disadvantageous moves is governed by a parameter called *"temperature"* which is inspired by affection of temperature in annealing process. At the beginning the temperature is kept high enough so that all possible minimum values (valleys) are explored. As the temperature gradually declines the system becomes trapped in relatively small range of valleys.

Assuming the goal of a system is to solve a minimization problem, the algorithm of SA is as follow. The algorithm employs a random search which not only accepts changes that decrease the objective function f but also some changes that increase it. The latter are accepted with a probability:

$$p = e^{\frac{-\delta f}{T}}$$

Where δf is the increase in f and T is *"temperature"* – a control parameter (Busetti, 2003). The structure of the SA algorithm is described in the flow chart below:
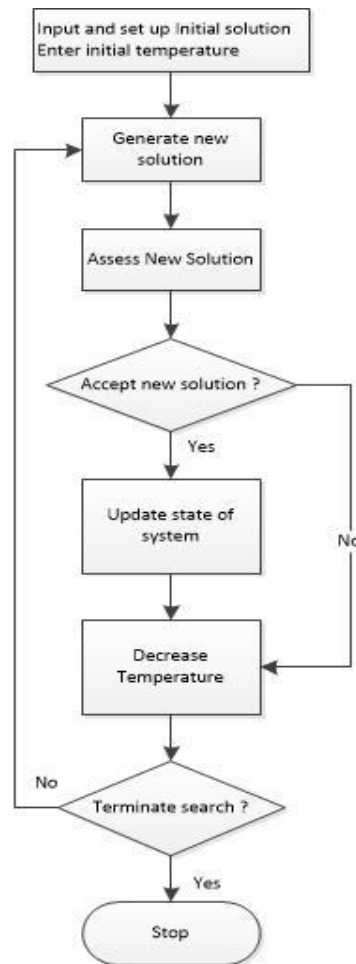
Figure 26: Simulated Annealing algorithm

In order to perform a simulated annealing paradigm successfully, there are three parameters need to be specified:

- An initial temperature T(0).
- The end temperature to stop.
- A rule for decrementing the temperature.

Busetti (2003) summarized a number of simple heuristic methods to define those parameters. Accordingly, a suitable initial temperature should result in an average increase of acceptance probability p(0) of about 0.8. In other words, there is an 80% chance that a change which increases the objective function will be accepted. T(0) is then given by:

$$T_0 = \frac{-\delta f^+}{\ln{(0.8)}}$$

Look at the expression it can be seen that the value of T(0) clearly depends on the scaling of f and, hence, be problem-specific. It can be estimated by conducting an initial search in which all increases are accepted and calculating the average objective increase observed δf^+.

The end temperature to stop algorithm should be determined by two conditions:

- No improvement (i.e. no new best solution) being found
- Or the acceptance ratio falling below a given (small) value p_f

Finally, to decrease the temperature the most common and simplest rule is exponential cooling scheme

$$T_{k+1} = \propto T_k$$

Where α is a constant close to but smaller than 1 (often, α = 0.95 → 0.99) (Busetti, 2003)

To put it in a nutshell, SA is a local search algorithm which is able to avoid becoming trapped in local minimum and as the result, it has been proved that by carefully controlling the rate of cooling of the temperature, SA can find the global optimum (Busetti, 2003).

SA was chosen to be applied in the energy storage model because of its ability to deal with high degree of complexity and chaos. The model simulates a complex, non-linear process in which parcels connect to each other in different scales and various types of battery are included in the calculation. There are too many ways for the model to *"climb"* to a higher position but it can be sure that the direction is leading to the global optimum. In addition, the actual time for the model to finish one simulation is at an acceptable level. SA is criticized since *there is a clear tradeoff between the quality of the solutions and the time required to compute them* (Busetti, 2003). In reality, it took the model with 1010 parcels and 3 types of battery few hours to finish and the time would have been multiple if more parcels or more batteries were taken into account or if some constraints are removed. Nevertheless, with the current set up the run time is acceptable.

5. CHAPTER 5: DESIGN MODEL

In previous chapters, the variables and conditions as well as objective function for the model have been constructed. This chapter will make a further step by explaining how these settings are linked together in the model and what are micro strategies for the agents when interacting with each other. Also, the user interface and external data sources will be introduced.

5.1. General structure

The energy storage model was programmed on Netlogo platform and comprises of three main components:

- The external data source which contains fixed input data for the model.
- The interface of model where users can observe and make changes over input variables.
- The code – where the model is programmed and all calculations and instructions are defined. This part can be divided into three smaller modules:
  - The micro strategy setup for each parcel: explaining how parcels act and interact.
  - The benefit calculation: This module calculates stored energy/electricity in each group of parcels and their monetary value. This is the basis for guiding behaviors of parcels.
  - Displaying part: which is responsible for visual displaying (drawing links, coloring parcels, locating batteries, etc)

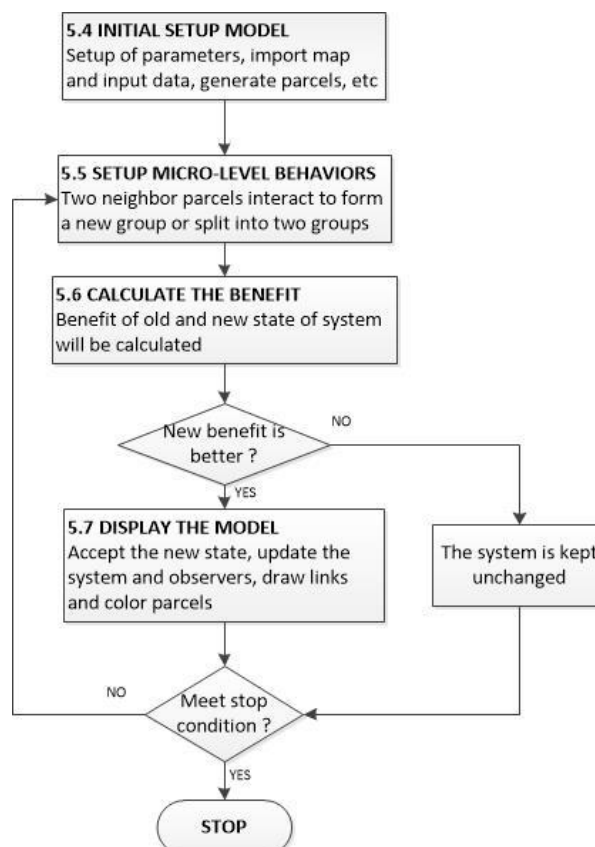This flowchart determines the steps which the model will take:

Figure 27: Overall structure of the model

5.2. External sources: GIS and Demand – Supply profile

The model has to access to some external data in order to set up the initial conditions of the given area. This research utilizes the data of a district called *Kerkdorp Acht* in the North-West of Eindhoven city. These external data are GIS and Demand – Supply profile of the researched area.

5.2.1. GIS data

GIS stands for *Geographical Information System* which contains all types of geographical and social data such as geometry, land use, energy, etc. However this thesis does not have ambition to explore further about this discipline and its applications since the model only utilizes GIS as the inputs data.

GIS data which is stored in separate files located in a same folder with Netlogo file will be loaded into the model at set up stage. There are two types of data contained in GIS files: geometric and non-geometric information. Geometric information is actually a map representing shapes and locations of parcels in the research area. The map is a collection of points, lines and polygons which is then reproduced in Netlogo interface (see next section) and ready to be managed. Non-geometric information, on the other hand, shows attributes associated with a specific parcel. A sheet table displays all of those attributes, for instance, function of the land, built year, surface area or energy label. Within the framework of this thesis only a number of properties are retrieved:

- GEBRUIKSDO (function): showing the purpose of the land use such as *"woonfunctie"* (residential function) or *"industriefunctie"* (industrial function).
- ID: unique identification of a parcel used to recognize different parcels
- STRAAT (street): street name where the parcel is situated
- NR (number): address number of the parcel

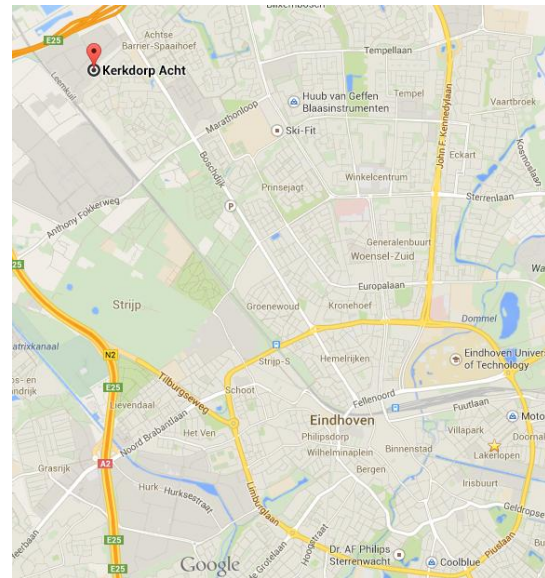**Figure 28: The researched area (*"Kerkdorp Acht"*) presented in GIS program**

Figure 29: District *"Kerkdorp Acht"* and Eindhoven city

Figure 30: Attribute table where non-geometric data is displayed in GIS

5.2.2. Demand – Supply profile

Demand and supply profile are saved in .csv extension and stored in the same folder with Netlogo file. The demand profile is provided by a local electricity operator who recorded energy consumption data every hour. Data of one parcel is written on one line with the first number indicates the ID of that parcel. The supply side is presented under the same layout. It is however a theoretical profile which estimates how much renewable energy a parcel can possibly produce in theory. The supply profile is a part of a larger project being studied by PhD candidates of Department Built Environment, TU Eindhoven.

Originally, demand and supply provide a stream of data for 24 hours a day and 365 days of a year meaning that 8760 values are recorded. However, with the purpose to accelerate speed of the model, the data of one year has been averaged into one week. Inputs for the model are therefore contained in a list of only 168 numbers.
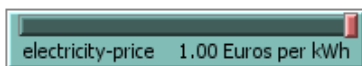

Figure 31: How the demand - supply profile look like

5.3. The interface of model

The user interface which is shown in Appendix B has three parts: input variables, the map and outcomes observer.

On the left side there are input variables. As the model was designed with a high degree of flexibility, all input variables are adjustable. They are:

Electricity-price: the cost a parcel has to pay on average for one kWh. According to the Netherlands regulation the more energy was consumed, the higher price and tax it is. With purpose of simplicity, the model applies only one price policy.
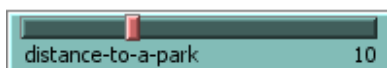
Distance-to-a-park: A park is a suitable space to install sizable energy storages. This variable regulates maximum distance from a parcel to the nearest park. Beyond that distance, the parcel can only use small battery types which can be put inside a house or a garden.

Range: indicates the distance within which parcels can communicate and query each other.
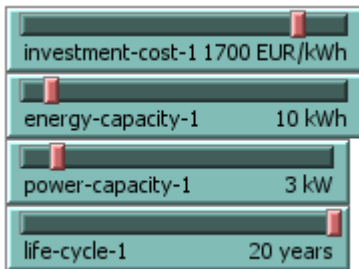

Cooling-rate : speed of cooling down the temperature according to the rule:

$$T_{k+1} = \propto T_k$$

Number-of-battery-type: shows how many battery technologies are going to be employed in the model.

A group of variables including: investment cost per stored energy unit, energy capacity, power capacity and lifecycle is used to characterize different battery types.

At the centre of the interface, a map imported from GIS source is presented. This map assists users to observe and inspect all parcels and interactions between them. An agent parcel appears at the center of land plot which they are representing for. At the set up stage, colors are used to distinguish parcels which are close to green parks and which are not. Accordingly, the green indicates close enough parcels and the white marks parcels which stand too far.

The right side of interface is place for graph and output observers. The graph shows the variation of objective function; in this case it is the global benefit. Meanwhile, other observers display statistic numbers related to the number of batteries of each type have been deployed, number of parcels using them and amount of energy/electricity has been saved per week. These data is necessary in analyzing and comparing battery technologies as well as in analyzing different scenarios.
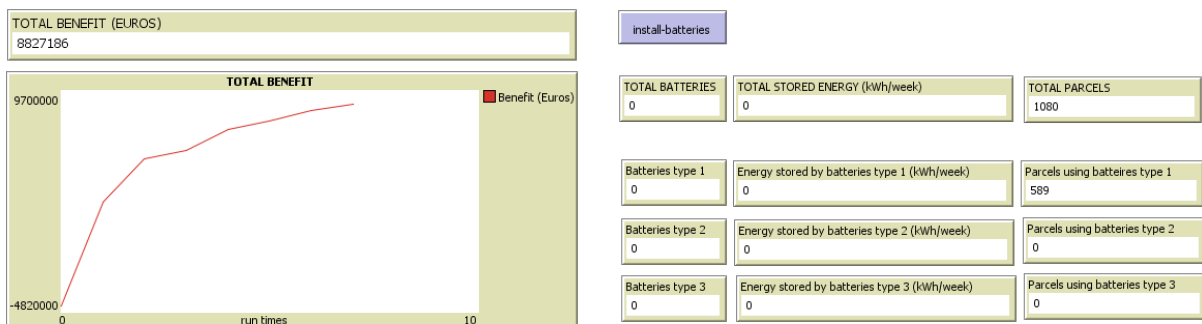

Figure 32: Graph and output observers

5.4. The setup of model

The setup procedure has to be implemented at the beginning by clicking on button *'setup'*

[setup] . The setup procedure prepares all necessary pre-conditions for the model to function normally and correctly:

- Clear all data generated by previous run to bring the model to an *'empty'* state
- Import the map
- Create parcels and transmit relevant data from GIS and Demand-Supply profile into parcels' attributes.

After finishing, the model stops to wait for further instructions from users. In this event, the modeler has to press button *'go'* to force the model run. The setup of *'go'* procedure is presented in next sections.

5.5. Simulation of micro-level behaviors

Micro-level behaviors stipulate the way a parcel acts and interacts with its neighbor parcels. On the contrary, macro-level pattern is what can be seen holistically as the result of emergence of those interactions. The objective of micro behaviors is to bring the system to a new state where a higher benefit score is achieved (sometimes a lower benefit is also accepted due to the Simulated annealing algorithm – see chapter 4). To do so, parcels constantly change their battery technologies and connections with others.

5.5.1. The interaction

In the beginning, one technology is selected for the entire parcels as the starting point. A random parcel will query its neighbors and try to establish a relationship with another one. Here, we call them parcel X and parcel Y respectively. Two relationships exist between X and Y: belong to a same group or NOT:

- If X and Y are currently not in a group, Y will *'try'* to join with X's group and, one by one change the battery technology to see if a better combination can be found. For example, if three battery types are available there will be 3^2 = 9 combinations of choice of technology between them.
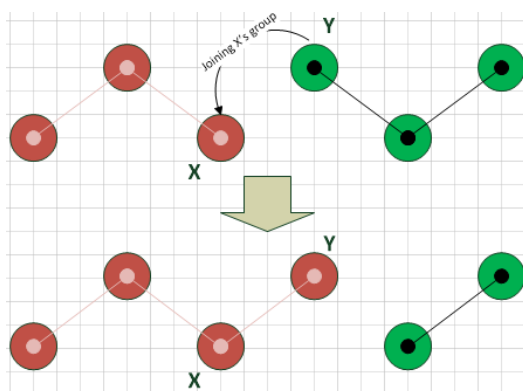
Figure 33: Parcel Y joins with new group and change battery type.

Group X	Group Y
Battery type 1	Battery type 1
Battery type 1	Battery type 2
Battery type 1	Battery type 3
Battery type 2	Battery type 1
Battery type 2	Battery type 2
Battery type 2	Battery type 3
Battery type 3	Battery type 1
Battery type 3	Battery type 2
Battery type 3	Battery type 3

- If X and Y have currently been in a same group an opposite process occurs: Y *'tries'* to leave group to stand alone. The leaving will be accepted if a new combination of battery

technology that could generate higher benefit is found. Again, the maximum number of combinations is n^2, where n is the number of available techs.
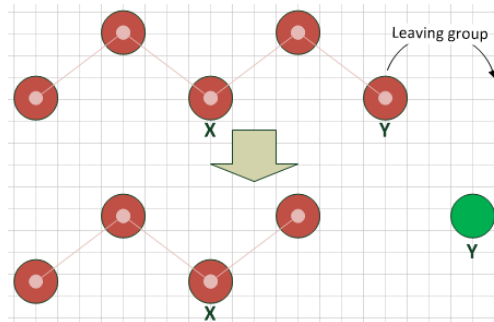
Figure 34: Parcel Y is separated from the group to stand alone

Of n^2 solutions, the one that yields highest benefit is selected for further assessment:

- If the best solution can give a higher benefit compared to the old state (the previous arrangement of groups and technologies), then it will be chosen as the new state.
- If the best solution generate a lower benefit, there is a probability for it to be accepted according to the simulated annealing formula: $p = e^{\frac{\delta f}{T}}$
- In the event that there is no chance to deploy a new allocation, parcel X and Y will come back to previous state and the system is kept unchanged.

5.5.2. The constraints

Nevertheless, interactions of parcels are limited by a number of constraints. These constraints are made to keep the model less complex and easier to program.

- Parcels are not allowed to make cross-road connections. This is based on assumption that a cross-road connection would be too expensive and requires extra civil works which are not estimated thoroughly. This also limits the group formation happening in a neighborhood scale but not district or a city scale.
- Parcels with the same spatial condition are able to connect. In other words, parcels which are close to green parks do not connect with parcels which are too far. Furthermore, the latter can only installs small-size batteries instead of a large one.
- The maximum distance between two neighbor parcels must not exceed an allowed threshold. This limit is determined by variable *"range"*. For example, if the model was set up with range = 5 patches (equivalent to 45 meters), a parcel will then only communicate with other parcels not further than 45 meter from its position.
- A parcel cannot leave its group if it causes a large gap between the rest members. Any distance which is greater than the value of *"range"* will be denied. Otherwise, it would lead to an unexpected situation when very far away houses are able to connect with each other.
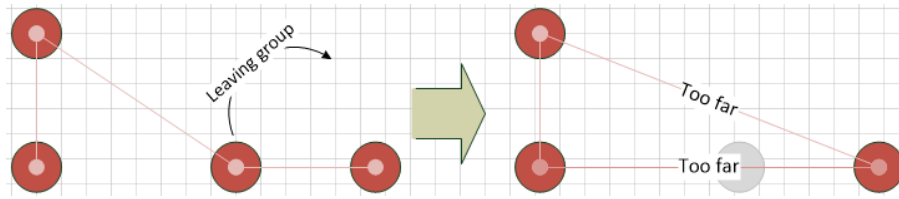
Figure 35: Large gap between parcels when the middle parcel leaves

The micro-level behaviors are triggered by pushing button *'go'* ( ) after which parcels begin interacting. After a number of runs, 1000 times for instance, the *'temperature'* will be decreased and a new loop starts again. Until the moment when end temperature is reached, the model stops. The following flowchart illustrates the algorithm with 3 battery types in which type 1 can be built inside home while type 2 and 3 need green spaces:
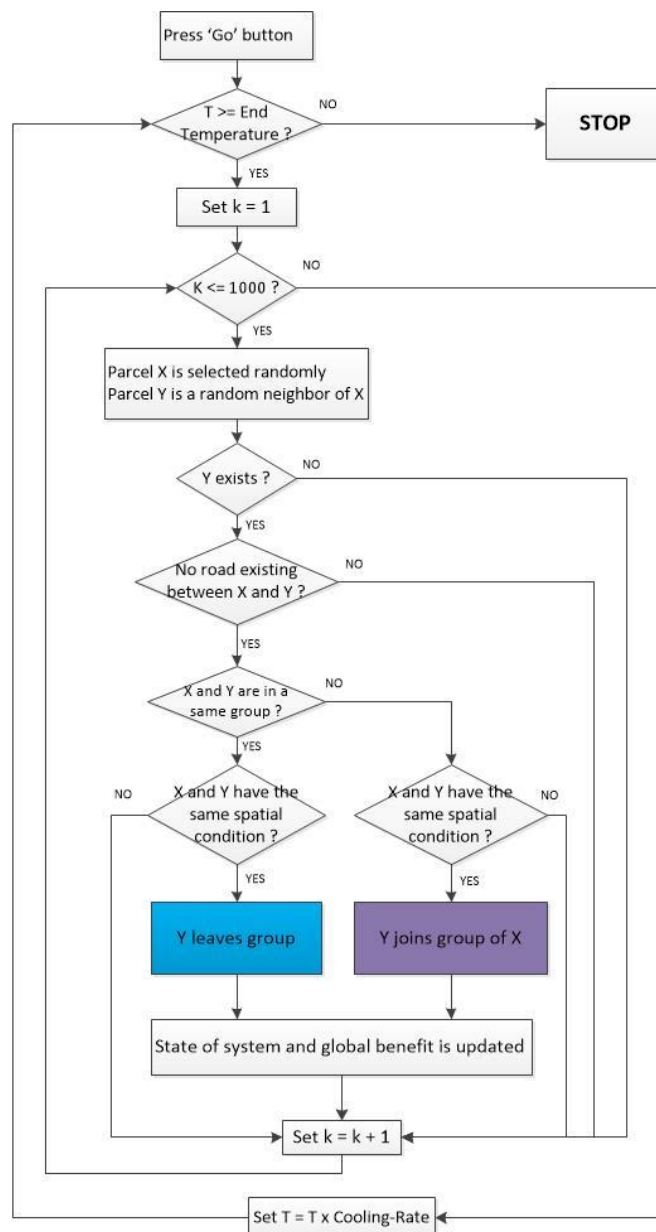

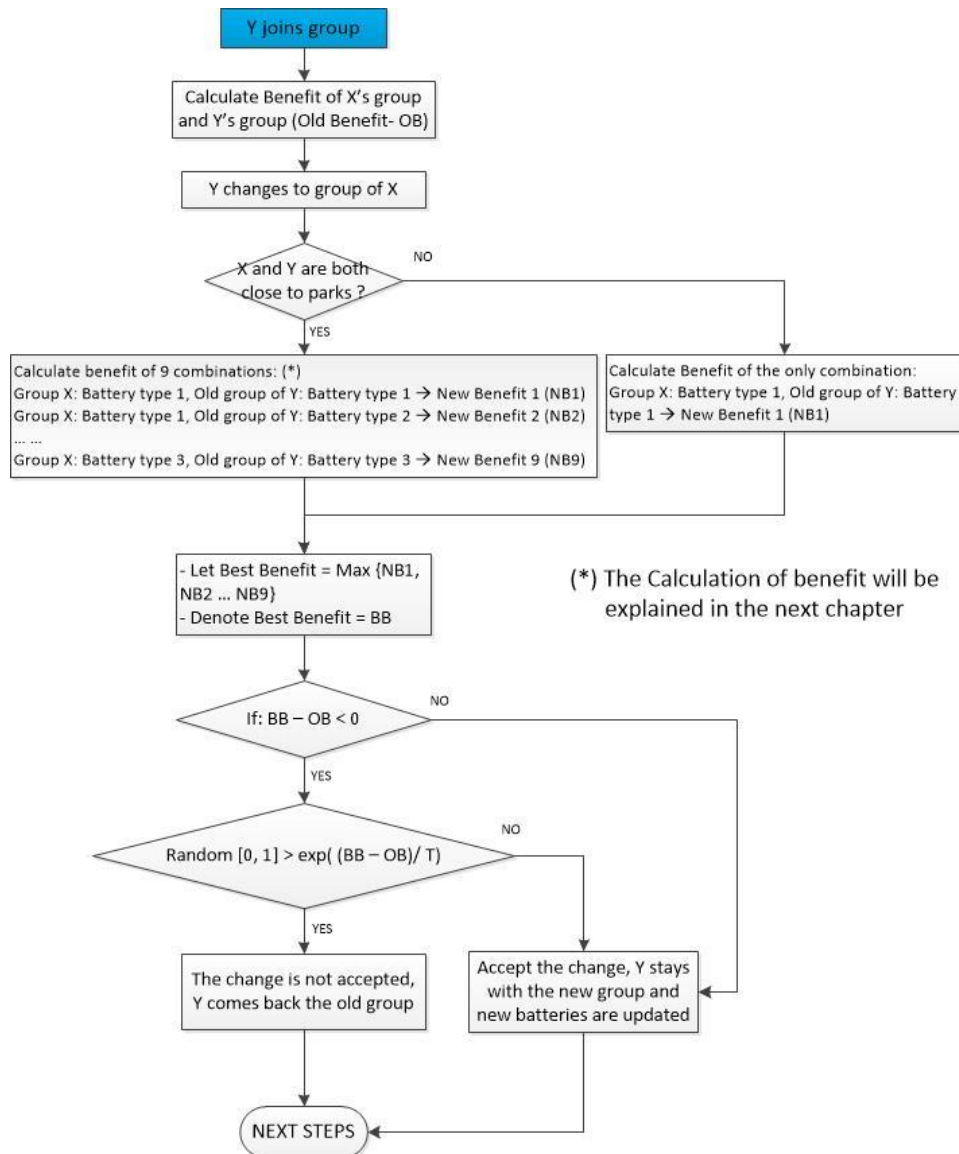**Figure 36: Algorithm of micro strategy of parcels (*'go'* procedure)**

Figure 37: Algorithm for procedure *'join group'*, for procedure *'leave group'* the flowchart is almost the same except for the fact that Y is separated to stand alone.

5.6.   Calculation of benefit

The benefit of a group of parcels sharing a common energy storage is given by the objective function which has been mentioned in chapter 3:

Benefit = Stored Energy x Electricity Price x Lifecycle – Installation Cost

From the above equation, it can be seen that the central issue is to calculate the amount of energy stored (or the amount of energy released by) in those batteries which are installed for a single or multiple parcels. Again, this issue has been introduced in chapter 3. In this section the algorithm and function to measure energy flows in and out a battery will be explained in more detail.

5.6.1.   Basis to calculate stored energy

The amount of electricity flows into and out of an energy storage is determined by three factors

Firstly, it depends on the supply and demand profile of a single parcel (when it stands alone) or a group of parcels when they are connecting and sharing a storage together. Supply and demand sides are given in a data set of 168 values represent for 7 days. For instance: *[0.97 0.82 0.54 0.81 0.92 1.00 1.49 1.86 … … 2.02 2.23 2.02 3.82 3.05 1.98 1.47 0.95 0.60].*

When many parcels come together, these data is aggregated by summarizing all the value at the same position giving a Supply or Demand list of the whole group. When supply is higher than demand, surplus energy is generated and transmitted into batteries to be stored. It is therefore required calculating surplus energy profile for parcel or group of parcels by subtracting supply to demand. An example of surplus energy list: *[-1.65 -1.53 -1.43 -1.11 -1.53 -2.67 1.69 10.75 12.40 … … … 1.57 -0.03 -0.67].* Here, negative numbers indicate that supply is smaller than demand and vice versa.

Secondly, the amount of stored energy depends on power capacity (kW) of a particular battery. This specification determines the maximum energy that an energy storage can receive per hour. Assume that we have a Lithium-ion battery with *energy capacity* = 75 *kWh* and *power capacity = 25 kW* integrated into a solar system which can peak to 40 kW/h if the weather conditions are favorable. Due to the limit of power capacity of the battery, during the peak hour only 25 kWh can be received instead of 40 kWh. The same thing happens when the battery is discharging. In this model, the *power capacity* is used as threshold for both charge and discharge process.

Thirdly, another constraint is the depth of discharge (DOD) of the battery which is shown as percentage of maximum electricity being stored. State of charge (SOC) is another term which is related to DOD, indicating the current energy state of a battery. Their relationship is presented in the equation:

$$\min(SOC) = 100\% - DOD$$

Obviously, the SoC cannot be higher than 100% and on the other hand, it cannot be lower than a threshold either. If DOD = 80%, then the lowest SOC will be 20%. When a battery reaches to this state, it stops the discharge process and wait for being charged. In the model, 100% and 20% are used as the upper and lower SoC threshold.

5.6.2. The algorithm

Based on these above technical conditions, an algorithm to calculate SoC of a battery is proposed. Depending on relation between demand-supply and power capacity, energy will flow into or out from the battery and make change on its SoC. The value of SoC only varies between 20% and 100%. Once SoC is defined the total stored (or released) energy will be retrieved easily.
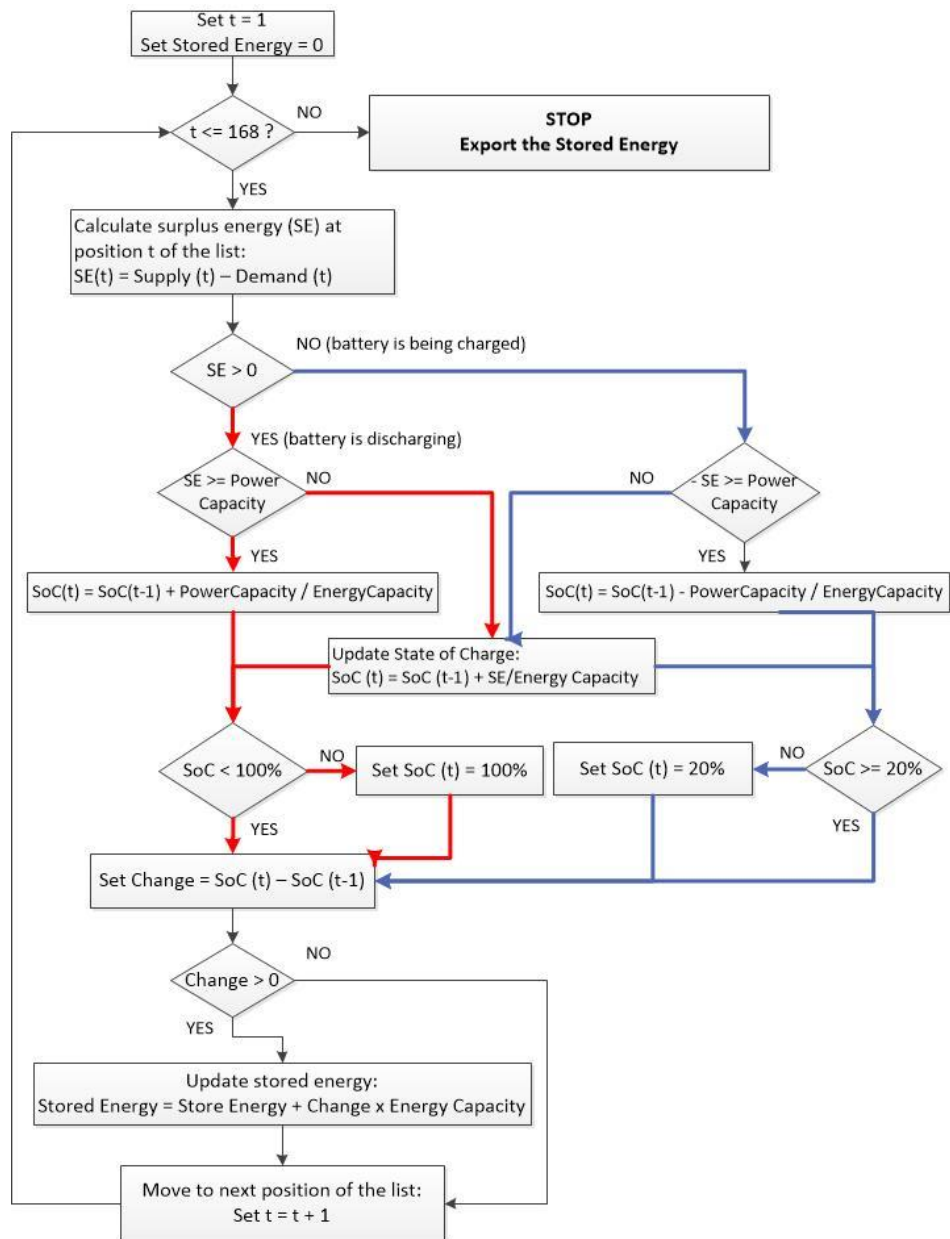
Figure 38: Algorithm to calculate stored energy with thresholds for SoC are 20% (DOD = 80%)

5.7. Displaying the model

After finishing the simulation, the model has to present results on the map using color codes, icons and links. Different battery types are marked by different icons and colors. For example, Figure 39 shows three shapes of icon with three colors have been applied to distinguish three battery technologies.

Furthermore, links between parcels of a same group are drawn to give a better visual layout. The rule for these connections are:

▪ Parcels located on the same street are connected first. After that parcels of different street will be linked. This rule ensures the entire group will be in the network.
▪ Each parcel tries to make one or two connections as maximum. Otherwise the map would be very chaotic with numerous lines are created.

- Links are made between odd number addresses or even number addresses according to ascending order so as to keep the map neat and tidy (see Figure 40)
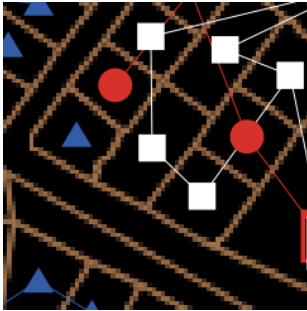

Figure 39: Different battery types are drawn by different shapes and colors
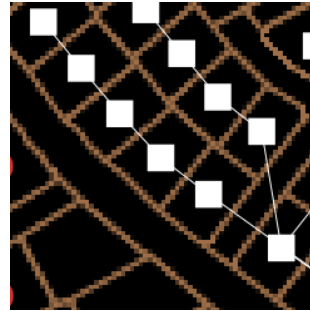

Figure 40: Parcels on a same street are linked together, odd by odd and even by even in an ascending (descending) order

In addition, the model was designed with button *'install batteries'* which triggers the procedure in which suitable locations to place batteries will be searched. This procedure simply queries all of possible green parks to choose the nearest one to install the selected battery. A battery icon is placed on the desired green area and a line is drawn from that position to the closest parcel. Not only that, procedure *'install batteries'* even goes further by providing the number of users sharing that battery and how much energy has been saved over one week (see Figure 41)
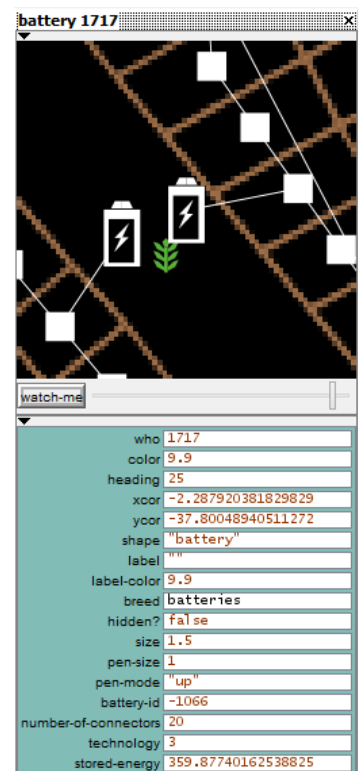

Figure 41: Batteries are located on a green field

6. CHAPTER 6: SCENARIOS DESIGN & RESULTS ANALYSIS

The initial purpose of the model is to create a tool for allocating energy storages in different scale of urban space. Accordingly, a list of energy storages are put into a comparison under given conditions. The candidate technologies will be assessed on three aspects: spatial requirements, technical parameters and economical benefits to see which battery type or which combination of them would be the optimal choice.

More importantly, the simulation is not only a benchmarking instrument, but it is also an attempt in developing a more sustainable world of energy. Taken into account the volatility of renewable sources and increasing electricity price, it would be reasonable to state that energy storage will be widely applied in a near future. It is therefore necessary to design scenarios in which some of future conditions are considered so as to give a clearer view about prospect of energy storage. This chapter introduces four scenario designs as well as the rational ground for choosing them and the results analysis. Except for the first scenario – the basis one, the other three tried to simulate a future context when energy price becomes more volatile and energy storage technologies gain new achievements allowing cheaper but more efficient products to be implemented.

6.1. Scenario base case

This scenario is designed to incorporate the current situation of energy management and the current energy storage technologies. Base case scenario will then be used to compare with the other two.

6.1.1. Electricity price

The Dutch energy price reflects a traditional forward market model meaning that the price level is set before delivering and will be adjusted after a period of time. This forward market model is in contrast with real time (or spot) market model which will be explained in the second scenario. On top of that, VAT and electricity as well as environmental taxes accounts for approximately 70% of the final bill. The table below shows the newest update of electricity tariff in the Netherlands in 2014

Table 4: Regulatory energy tax (REB) in Netherlands, 2014

Type	From	To	Price (EU) excl. VAT
1	0 kWh	10.000 kWh	0,1185
2	10.001 kWh	50.000 kWh	0,0431
3	50.001 kWh	10 Million kWh	0,0115
4 Business	10 Million kWh	-	0,0005
5 Non Business	10 Million kWh	-	0,0010

For a normal household, the average energy consumption of a year is around 3500 kWh (according to http://www.deenergiegids.nl). As a result, the first tier of tariff is applied. Table 5 explains how a typical energy bill is calculated.

Payment	Price	Description
- Commodity price	€ 0.06100	Depends on the policy of the operator. Each company has its own price and it depends as well on the type of contract (1 year, 3 years or 5 years).
- Energy tax (REB)	€ 0.11850	Based on Regulatory energy tax (REB) of 2014.
- Environmental tax	€ 0.00230	Also known as *tarieven milieubelastingen* in Netherlands. This is applicable for consumption which is less than 10,000 kWh (see http://www.belastingdienst.nl).
- Sub total	**€ 0.18180**	(to calculate VAT).
- VAT (21%)	€ 0.03878	
Total price	**€ 0.22058**	

To sum up, the electricity price used for base case scenario will be **€ 0.22/kWh**

6.1.2. Energy storage technologies

In this section, three battery types which are suitable for three scales of residential area will be chosen. These technologies are currently available or has already been introduced in some demonstration projects.

1) YOE battery

YOE is a mini size lithium-ion battery using titanate technology. YOE was designed and being commercialized by YOUNICOS, a company active in the energy industry with main activity is creating sustainable energy solutions, including energy storage technologies.

Using titanate technology which replaces carbon anode with a lithium-titanate nano-crystal surface, YOE has a number of advantages compared to other lithium-ion batteries. The nano-crystal surface increases the contact area up to 100 square meters per gram compared to 3 square meters of carbon making the battery to be charged very quickly. Especially, unlike traditional lithium-ion batteries, YOE is very safe and has no risk of fire when using. In addition, the battery has a long lifespan and a small, artistic design. These convenient features allows YOE to be installed right inside a house. The main drawback of this technology is the high price and a limited storage capacity. The energy capacity of YOE is from 4 to 12 kWh and the price is believed more expensive than normal lithium-ion batteries. Due to fact that there is no chance to get information about installation cost from producer, the price will be assumed. Based on literature, the cost per kWh for a lithium-ion battery can vary from USD 600 – 2500 (Ferreira, et al., 2013) or even higher up to USD 4000 (Evans, et al., 2012). From some informal sources, the titanate battery is said to be as expensive as USD 2000. To sum up, the cost per kWh of YOE battery will be chosen as USD 2000 equivalent to EUR 1500.
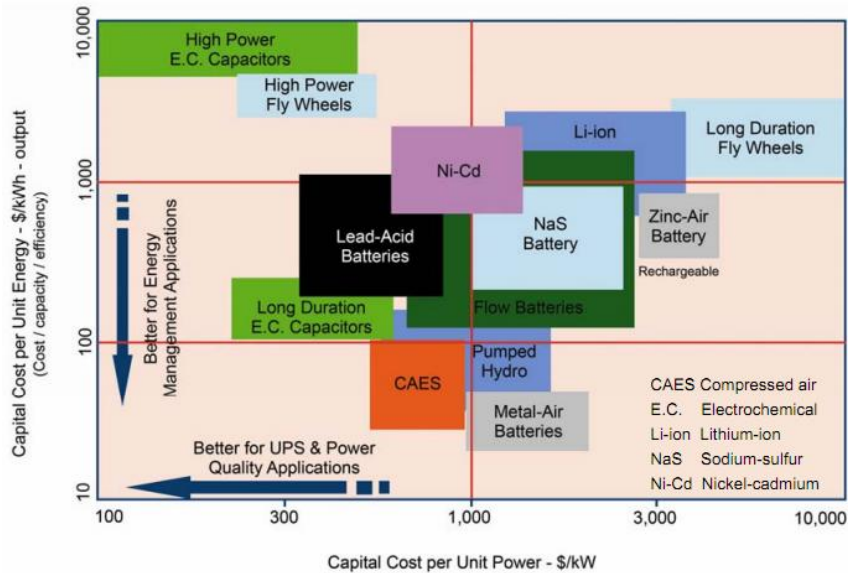
Figure 42: Storage capital costs by technology type (source: electricity storage association)

The table below summarize the main characteristics of YOE battery:

Table 6: Specifications of battery YOE

Features	Value	Unit
Energy capacity	12.0	kWh
Power capacity	4.0	kW
Investment	1500	EU/kWh
Lifecycle	20	Years

Figure 43: Illustration of YOE battery

2) ZEN Freedom PowerBank battery

ZEN is a South Australian energy firm who in 2012 has claimed that they got a breakthrough in Lithium-ion technology to make cheaper batteries. Again, it is hard to find an official source where the detail cost of ZEN batteries is presented. However, through media some estimation about price has been revealed by Sydney Morning Herald (a local news agency http://www.smh.com.au/business/carbon-economy/energy-firm-claims-battery-storage-breakthrough-20121010-27dc0.html). Accordingly, a typical module with a capacity of 20 kWh will be sold for $30000 and with the rapid development of the company as well as their technology the price is predicted to drop to $20000 when the firm scales up production. From these assumptions, a reasonable price for ZEN system will be between $1000 and $1500 per kWh which is equivalent to €750 → €1100. These numbers are also consistent

with literature studies (see Figure 42). To sum up, the price will be set at €900 – the average value.

In Table 7, technical parameters of ZEN's battery are given. Basically, their Freedom PowerBank constitutes of a number of modules, each has 20 kWh in energy capacity and 5 kW power utilizing Lithium Iron Phosphate technology. In this scenario, a system of three modules will be tested to see if they are able to provide energy to a cluster of parcels. The module is integrated with a smart software in order to maximize the operation and lifespan, and *also provides for future business models in which a retailer or utility may participate by controlling a portion of the stored energy for an agreed subsidy or compensation* (zenenergy.com.au, 2014).

Table 7: Specifications of battery ZEN

Features	Value	Unit
Energy capacity	60.0	kWh
Power capacity	15.0	kW
Investment	900	EU/kWh
Lifecycle	15	Years

Figure 44: ZEN batteries being installed

3) eCamion's community energy storage (CES)

Early 2013, in North York of Ontario, Canada, a sizable energy storage system has been installed providing 250kWh/500kW to the neighbor residential area. This project is a collaboration between eCamion, Toronto Hydro, Dow Kokam and the University of Toronto in an attempt to build a large enough CES to support residential street in the event of an outage.

Figure 45: CES module is being installed (source: www.ecamion.com)

The CES system compacts arrays of lithium batteries to generate a significant amount of electricity yet keep it small and easy to assemble. To be precise, dimensions of a 250kWh module is as small as 3019mm x 2408mm x1686mm. The chosen technology was Lithium Polymer, Nickel Manganese Cobalt (NMC) giving a round-trip efficiency of 90% and 5000 lifecycles. Another noticeable advantage of the system is a very high rate of power (500kW) which allows the CES responses very fast in the event of an outage. There is however no clue for the installation cost since this project was simply a demonstration. An assumption will be made based on literature reviews about conventional Li-ion batteries giving a price of $1000 (≈ €750). The table below represents the specification of a CES system.

Features	Value	Unit
Energy capacity	250	kWh
Power capacity	500	kW
Investment	750	EU/kWh
Lifecycle	15	Years

6.2. Scenario time-varying pricing

This scenario is designed with the purpose to investigate whether a stimulate electricity pricing can create incentives for the installation of energy storage.

At present, the Dutch energy system applies the fixed-price policy in which consumers pay retail electricity price that is fixed for months or years depending on the contract. However, there are more price policy that should be considered. At least two other pricing has been used now:

- **Real-time pricing or day-ahead pricing**. In these pricing, the retail providers announce the price level hourly or daily. For example, in day-ahead model the price of a day is set on the prior day whereas in real-time approach the price for each hour is determined between 15 to 90 minutes prior to the beginning of that hour. The time-varying prices in retail is not applicable in the Netherlands but a number of examples can be found in USA.
- **Time of use pricing.** The electricity price also varies within a day according to some blocks of hours instead of each hour. Normally, the time scale can be divided into peak and off-peak hours with different price policy.

(Arslan, 2012)

In a future world when renewable energy is ubiquitous adding stochastic behaviors and mismatch between supply and demand to the energy system, time-varying price would be a possible choice. According to Asrlan (2012) if being implemented correctly, the real-time approach does not only help energy operators to increase comparativeness but also reduce the electricity cost for households (in theory the reduction could be up to 30% less than the conventional fix pricing case). Moreover, a more flexible pricing system can facilitate the development of energy storage. Owners of energy storages can capture the value from their facilities by storing electricity during the day time when solar energy is excessive and bringing them back during the evening when demand peaks and prices are favorable.

It is therefore worth studying the scenario in which a theoretical real-time pricing or time of use pricing is applied. The latter seems to be suited well with retail consumers while the first one has already been applied for the wholesale sellers. Unfortunately, the data for time of use pricing is difficult to find, the model will make use of real-time approach borrowed from research of Arslan (2012). Table 9 shows the data of one typical day in 2012 which can be

observed in APX[1] website. This profile will replace the fixed price parameter in the model to be the new basis to calculate monetary benefits of the simulation.

Table 9: Hourly APX prices of 16/02/2012

Hours	Retail Electricity Price (cents/kWh)	Total price after adding energy tax, environmental tax and VAT (cents/kWh)
00:00	4.612	20.197
01:00	4.352	19.883
02:00	4.145	19.632
03:00	3.769	19.177
04:00	3.546	18.907
05:00	3.905	19.342
06:00	4.331	19.857
07:00	6.142	22.049
08:00	8.967	25.467
09:00	7.852	24.118
10:00	6.719	22.747
11:00	6.580	22.579
12:00	5.945	21.810
13:00	5.576	21.364
14:00	5.840	21.683
15:00	9.271	25.835
16:00	12.538	29.788
17:00	13.045	30.401
18:00	10.617	27.463
19:00	12.761	30.058
20:00	10.617	27.463
21:00	6.996	23.082
22:00	6.067	21.958
23:00	5.219	20.932
Average	**7.059**	**23.158**

6.3. Scenario low-cost technologies

In this scenario, a low-cost technology which is still under R&D progress will be deployed into the model. The new technology should not be as expensive as current products and its capacity should also be powerful enough in order to deal with large scale energy networks. Therefore, the chosen technology is AMBRI liquid metal battery – an advanced technology which is being developed at MIT in the lab of Professor Donald Sadoway. Compared to other battery types, the AMBRI has a number of advantages. First of all, it is cheap. AMBRI utilized materials which are available and abundant such as salt or magnesium. Its design is also simple and easy to manufacture. Secondly, it is a powerful electricity storage since a small AMBRI core (see the picture) which constitutes of 32 smaller packs can achieve a capacity of

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[1] APX Group is an European energy exchange operating the spot markets for electricity in the Netherlands, the United Kingdom, and Belgium.

200 kWh. And if 10 of them are connected together to create a 2 MWh system the total size is just as large as an average room. In addition, the producer assures that AMBRI batteries can have a lifespan as long as more than 15 years and they operate in a quiet, safety and reliable manner. (http://www.ambri.com, 2014)

The commercial price for an AMBRI system is difficult to define at the moment. However, in an interview done by Bloomberg (http://www.bloomberg.com/news/2014-03-06/mit-s-liquid-metal-stores-solar-power-until-after-sundown.html), MIT researchers revealed that their target is to create liquid-metal batteries that will store power for less than $500 a kWh (equivalent to €300). Compared to other types of battery, especially with popular Lithium-ion batteries which have been deployed in many projects with the cost is around $1000 / kWh, that price is a great competitive advantage.

For those reasons, AMBRI liquid-metal battery is selected as the future technology. **Error! eference source not found.** summarizes the input parameters which characterize this battery type.

Table 10: Specifications of battery AMBRI

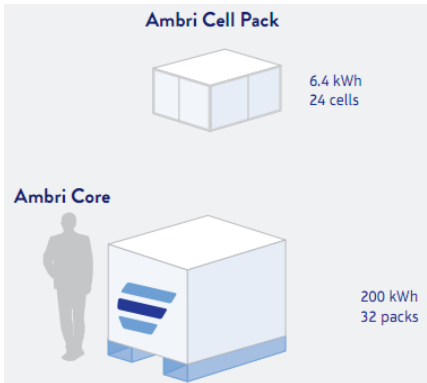| Features	Value	Unit
Energy capacity	200	kWh
Power capacity	50	kW
Investment	300	EU/kWh
Lifecycle	15	Years

Figure 46: Demonstration of an AMBRI battery

6.4. Scenario low cost technology & real-time pricing

In this scenario design, a low cost technology will be combined with the real-time pricing in order to create a synergy in economic efficiency as well as storing capacity. The eCamion's community energy storage will be replaced by AMBRI battery since they are both large scale batteries but AMBRI has a better cost per kWh. In addition, the fixed pricing mode will be switched to real-time mode.

6.5. The general setup

All of the four scenarios have a same general setup as follows:

- Distance-to-a-park: 13 patches equivalent to 150 meters
- Range: indicates the maximum distance between two neighbor parcels. It was set a value of 4 patches which is equivalent to 50 meters
- Cooling-rate = 5%, meaning that the temperature will be decreased 5% after each step of running.
- Initial temperature T(0) = 700000. This value was chosen because of the assumption that: at the beginning if a parcel wants to change its battery from type 1 to type 3 which is much more expensive, a loss of about 12 * 1500 − 250 * 700 = -157000 will be

considered. In order to make this event happen with probability of 80%, the corresponding temperature should be:

$$T(0) = \frac{\delta f}{\ln (0.8)} = \frac{-157000}{-0.223} = 703583$$

- The stop temperature is 1000.
- At each temperature level, the model performs 1100 iterations. As the total number of parcels is 1079, with 1100 iterations every parcel has at least one chance to make its own moves.
- The initial state of charge (SoC) of batteries as well as the minimum SoC are set at 20%. It means that batteries are not able to provide electricity at the beginning hours.
- The setup procedure determines that at time zero, each parcel has already installed an YOE battery (the small size battery). Initial calculations of benefits and energy will be based on this type of battery giving results of time zero as follow:
  o Total benefits = € - 15,150,275
  o Total discharged energy = 16,688 kWh/week
  o Installation cost of 1079 YOE battery = 19,422,000
  o Total surplus energy (when supply > demand) of the entire district is 38,684 kWh/week and the total outage (supply < demand) is -38,076. These numbers are fixed because they only depends on Demand – Supply profile.
  o The Curves of global surplus/outage and charge/discharge are given in Appendix G

6.6. Outcomes

This section shows results of running the four simulations. Some of them will be graphed for a better illustration.

6.6.1. Scenario base case

Output results of scenario base case are presented in the table below. In general, battery type 2 (medium size ZEN system) overwhelms type 1 (small size YOE system) in terms of energy capacity. ZEN batteries can provide an amount of electricity as large as three time of YOE. Meanwhile the number of parcels which installs or shares a medium battery is just slightly higher than small batteries users (587 compared to 492). A large-scale community energy storage, however, has no chance to be implemented in this scenario.
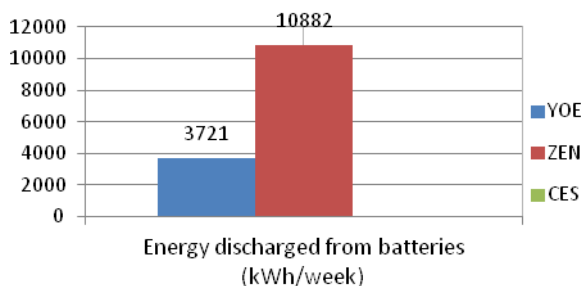

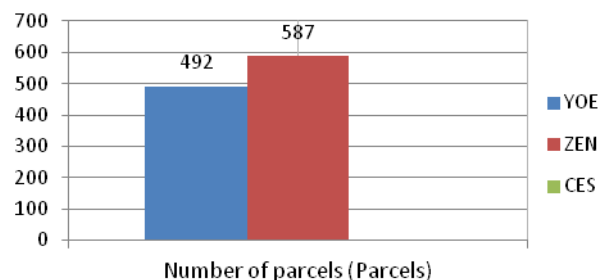**Figure 47: Energy discharged by different battery types (scenario base case)**

Figure 48: Number of users of different battery types (scenario base case)

Outcomes	Value	Unit
Total benefit	**- 395,162**	**€**
Total batteries	**107**	**Batteries**
▪ Number of battery #1	74	Batteries
▪ Number of battery #2	33	Batteries
▪ Number of battery #3	0	-
Total investment	**3,114,000**	**€**
▪ Investment in battery #1	1,332,000	€
▪ Investment in battery # 2	1,782,000	€
▪ Investment in battery #3	0	-
Total discharged energy per week	**14,604**	**kWh/week**
▪ Energy discharged by battery #1	3721	kWh/week
▪ Energy discharged by battery #2	10,882	kWh/week
▪ Energy discharged by battery #3	0	-
Total number of parcels	**1079**	**Parcels**
▪ Parcels using battery #1	492	Parcels
▪ Parcels using battery #2	587	Parcels
▪ Parcels using battery #3	0	-

Curves of global surplus/outage and charge/discharge for one typical week: see Appendix G

Figure in Appendix C illustrates the allocation of energy storages on the entire district. It can be seen that very few neighborhood can be able to have only one solution. Most of residential areas on the south of the district combine two or more batteries of the same or different technologies. On the other hand, some streets located on the north and north-west side only need one battery to store and distribute energy. These areas also have a higher density of buildings with sizes of parcels are smaller than the south part.

6.6.2. Scenario real-time pricing

In this scenario, all three batteries appeared on the map. Although YOE system has covered more than 50% of total parcels its energy capacity is far lower than ZEN batteries which are used by 40% of parcels but can deliver up to 60% of total energy. eCamion's CES seems to be the most effective storage since this technology provided 33.7 kWh/week/parcel on average, while these values of YOE and ZEN are only 7.2 and 20.1 respectively.
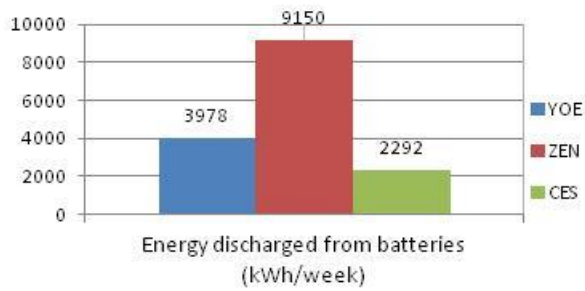
Figure 49: Energy discharged by different battery types (scenario real-time pricing)

Figure 50: Number of users of different battery types (scenario real-time pricing)

Table 12: Outcomes of scenario real-time pricing

Outcomes	Value	Unit
Total benefit	**228,796**	**€**
Total batteries	**107**	**Batteries**
▪ Number of battery #1	77	Batteries
▪ Number of battery #2	28	Batteries
▪ Number of battery #3	2	Batteries
Total investment	**3,248,000**	**€**
▪ Investment in battery #1	1,386,000	€
▪ Investment in battery # 2	1,512,000	€
▪ Investment in battery #3	350,000	€
Total discharged energy (per week)	**15,420**	**kWh/week**
▪ Energy discharged by battery #1	3978	kWh/week
▪ Energy discharged by battery #2	9150	kWh/week
▪ Energy discharged by battery #3	2292	kWh/week
Total number of parcels	**1079**	**Parcels**
▪ Parcels using battery #1	556	Parcels
▪ Parcels using battery #2	455	Parcels
▪ Parcels using battery #3	68	Parcels

Curves of global surplus/outage and charge/discharge for one typical week: see Appendix G

The final view of the map shown in Appendix D presents the arrangement of energy storages on the district. Battery type 3 (the large scale CES) can be installed for an entire neighborhood whereas the usage of battery YOE and ZEN is more flexible. Within a residential area, two or three batteries ZEN can be implemented together with several YOE systems. Especially, on the North and North West side of the map where the density of buildings is higher, only one ZEN battery is enough for a street.

6.6.3. Scenario low cost technology

A cheaper production cost allows large scale energy storages to spread easier into residential areas. As can be seen in Figure 51 and Figure 52, the low cost AMBRI battery

account for 67% of the total energy and 41% of users. ZEN battery cannot compete with AMBRI since it only occupies a small proportion of energy and users which are 13% and 9% respectively. YOE systems are installed in more than 50% parcels but the total amount of electricity they can provide is very small compared to AMBRI's.
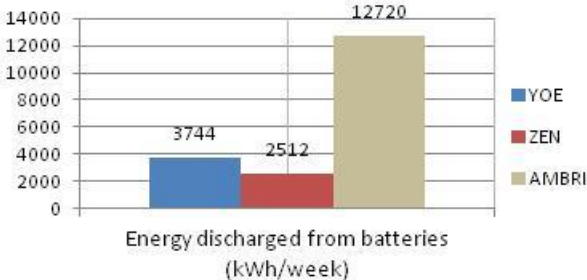

Figure 51: Energy discharged by different battery types (scenario low cost technology)

Figure 52: Number of users of different battery types (scenario low cost technology)

Table 13: Outcomes of scenario low cost technology

Outcomes	Value	Unit
Total benefit	**344,427**	**€**
Total batteries	**104**	**Batteries**
▪ Number of battery #1	73	Batteries
▪ Number of battery #2	8	Batteries
▪ Number of battery #3	23	Batteries
Total investment	**3,126,000**	**€**
▪ Investment in battery #1	1,314,000	€
▪ Investment in battery # 2	432,000	€
▪ Investment in battery #3	1,380,000	€
Total discharged energy (per week)	**18,976**	**kWh/week**
▪ Energy discharged by battery #1	3744	kWh/week
▪ Energy discharged by battery #2	2512	kWh/week
▪ Energy discharged by battery #3	12,720	kWh/week
Total number of parcels	**1079**	**Parcels**
▪ Parcels using battery #1	537	Parcels
▪ Parcels using battery #2	97	Parcels
▪ Parcels using battery #3	445	Parcels

Curves of global surplus/outage and charge/discharge for one typical week: See Appendix G

The map given in Appendix E illustrates a scenario in which one or two AMBRI systems are implemented for an entire neighborhood. The medium size ZEN batteries are used as a supplementary equipments to support AMBRI in order to cover the rest of a street. Nevertheless, in a number of areas, YOE batteries are widely used despite the fact that there is enough room to place a large scale energy storage and no spatial constraints are found.

6.6.4. Scenario low cost technology & real-time pricing (combined)

For short, this scenario will be called the combined scenario. Battery AMBRI is now prevailing over others in terms of both energy capacity and number of users. Small size YOE, although covers up to 42% of total parcels, is the least efficient system as they only provide an amount of energy that is equal to ZEN's which has less than 15% of total customers.
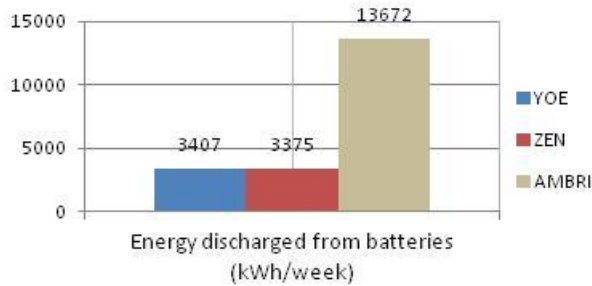
Figure 53: Energy discharged by different battery types (combined scenario)

Figure 54: Number of users of different battery types (combined scenario)

Table 14: Outcomes of combined scenario

Outcomes	Value	Unit
Total benefit	**1,069,140**	**€**
Total batteries	**104**	**Batteries**
▪ Number of battery #1	69	Batteries
▪ Number of battery #2	11	Batteries
▪ Number of battery #3	24	Batteries
Total investment	**3,276,000**	**€**
▪ Investment in battery #1	1,242,000	€
▪ Investment in battery # 2	594,000	€
▪ Investment in battery #3	1,440,000	€
Total discharged energy (per week)	**20,455**	**kWh/week**
▪ Energy discharged by battery #1	3407	kWh/week
▪ Energy discharged by battery #2	3375	kWh/week
▪ Energy discharged by battery #3	13,672	kWh/week
Total number of parcels	**1079**	**Parcels**
▪ Parcels using battery #1	456	Parcels
▪ Parcels using battery #2	153	Parcels
▪ Parcels using battery #3	470	Parcels

Curves of global surplus/outage and charge/discharge for one typical week: see Appendix G

The allocation of energy storages on the map (given in Appendix F) is relatively similar to the third scenario – low cost technology, except for the fact that the white AMBRI now appears in more areas. Again, there is no single silver bullet that will solve all the energy storing

problems. One battery may be enough for the need of a neighborhood area while two or three batteries of different types are required for another street.

6.7. Results analysis

Results of the four simulations are aggregated and compared with regards to the economic efficiency, energy storing capacity and spatial aspects. The analysis tries to explore if there are general rules to explain the spread of energy storages among residential areas and what implication it would be.

6.7.1. Economic aspects

First of all, it is easy to notice that by connecting and sharing energy storages together, households in a neighborhood can gain much higher benefits than installing them individually. The initial setup situation when each parcel has its own battery resulted in a huge loss both in terms of installation cost and benefits (19,4 Mil and -15,1 Mil respectively). Whereas the final outcomes of all of the four scenarios give a much better value. Of the four scenarios, only the Base case generates a negative benefit meaning that it is still difficult to apply energy storages in residential areas with the current conditions of technology and electricity market. Nevertheless, if the production cost of technologies is lower or the pricing policy is more attractive, an increase of benefit can be observed clearly. The scenario *real-time pricing* and *low-cost technology* which are possible to happen in a near future show that a positive benefit is completely achievable. Finally, by combining inexpensive technologies with a flexible pricing the benefit chart witnesses a surge when the benefit was almost tripled compared to the *low-cost technology* scenario. It can imply that when favorable conditions come together, the total effect on development of energy storages will be a synergy.

With regards to the total installation cost of the entire district, through the four simulations the cost does not change much although in the third and the fourth scenario a cheaper battery has been applied. This is due to the fact that a large number of parcels are using battery type 1 (YOE systems) of which installation cost is kept the same. Besides that, when the price of large-scale batteries drops, more of them are built and make the total investment to rise again.
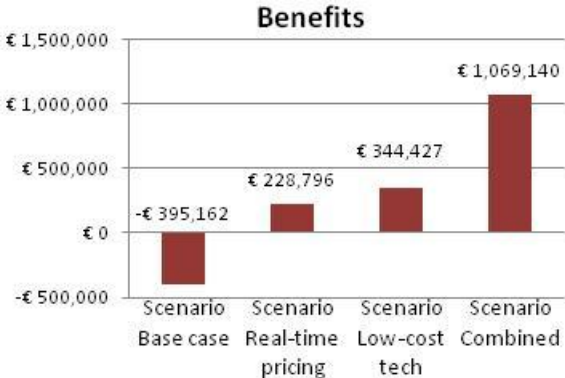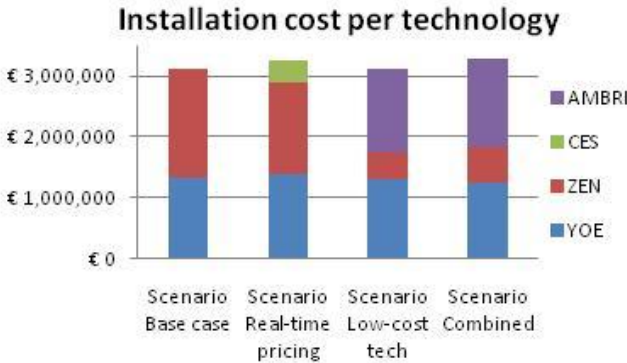

Figure 55: Benefits of the four scenarios

Figure 56: Installation cost per technology of the four scenarios

6.7.2. Energetic aspects

The electricity discharged from energy storages increases gradually from scenario *base case* to the scenario *combined*, corresponding with the chart of benefits. Compared to the initial setup in which 16,688 kWh/week can be achieved by assigning to each parcel one YOE battery, scenario *base case* and *real-time pricing* have a lower energy capacity. Meanwhile the *low-cost technology* and *combined scenario* have the best results. However, compared to the total surplus energy of the district (38,684 kWh/week), **even scenario combined only meets a half of potential renewable energy**.
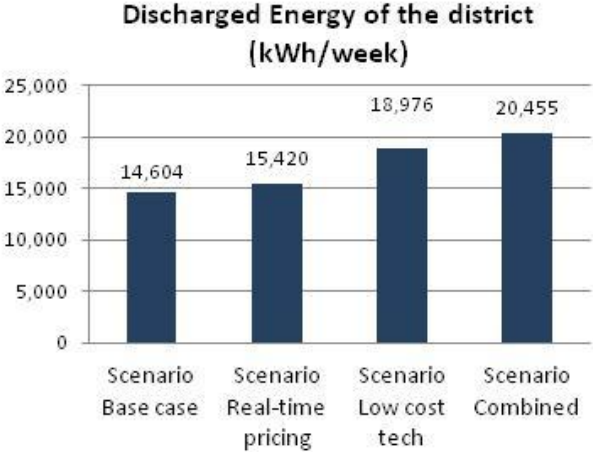
Figure 57: Energy discharged from batteries of the four scenarios

6.7.3. Spatial aspects

An energy storage is only effective if it is implemented in a certain scale of urban. Approximately, the average number of parcels who share a common battery is presented in the figure below. The YOE system has the smallest scale with only 7 parcels. The Community Energy Storage (CES) system requires up to 34 parcels in order to achieve the highest efficiency. Whereas ZEN and AMBRI are suitable for medium scale networks with 12 to 20 parcels connected. Nevertheless, this is just a rough estimation since parcels differ in terms of energy demand and supply. One parcel may double others in the size of demand and supply and thus making it equal to two average parcels.
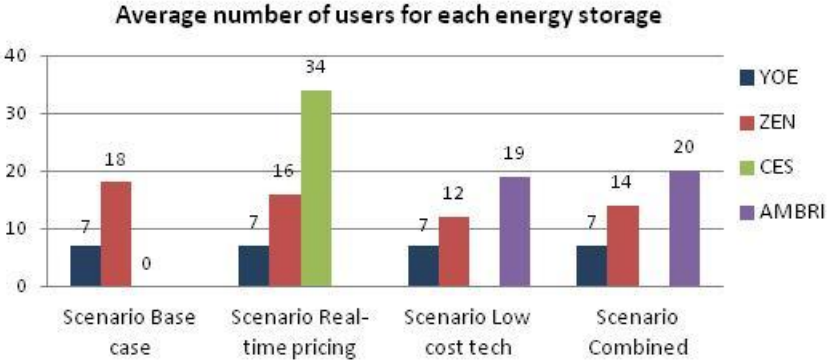
Figure 58: Average number of users per technology

By analyzing the map of distribution of energy storages in the four scenarios, it comes to a conclusion that: the applicability of a large scale energy storage, in terms of spatial requirements, is determined by two elements. Firstly, the intended area has to have enough space to install the battery. It can be placed in a green field, an abandoned garage or store house that is not too far away but also not too close because of safety and security concerns. In the neighborhoods where there is no appropriate sites for energy storages, parcels have only one choice that is the small-size batteries. Secondly, the high density of buildings is a favorable condition for large scale energy storages to be constructed. If parcels are situated closer to each other the connection will be easier to be created.

A part from spatial elements, the relation between supply – demand also affects the type of energy storage to be installed. For example, if a cluster of parcels have just a few amount of surplus energy, it would be a waste to build an AMBRI battery there. On the other hand, if a large enough amount of surplus electricity is generated and the two spatial requirements are met, a neighborhood may only need one large-size battery.

7. CHAPTER 7: CONCLUSION, DISCUSSION & RECOMMENDATION

7.1. Conclusion

In this chapter the final results and findings of the case study will be summarized, and more importantly an answer for the research question as well as the usefulness of the model will be presented.

7.1.1. Outcomes of the model

The model performs four simulations for a given residential district which is located at the North of Eindhoven city, the Netherlands. Each simulation is also called a scenario representing a unique condition of technology and market. The model considers three types of energy storage: small, medium and large size in terms of economical aspects, energy capacity and spatial requirements to find an optimal solution for the entire district. It constantly generates various solutions and makes comparisons between them in order to select the best one which has the highest possible benefit. It must be admitted that results provided by the model are not ultimate solutions to the problem since the randomness when running the model may affect the outcomes.

Comparing results of different scenarios has led to a number of clear findings:

- First of all, the model shows that by saving the surplus energy collectively, households in a neighborhood can gain a benefit which is far higher than doing by individuals. Furthermore, the monetary benefits can be increased considerably if inexpensive technologies combined with a stimulate energy pricing are realized.
- Secondly, the amount of electricity which is captured by energy storages is substantial, yet just exploits a proportion of surplus energy from renewable generators. The fourth scenario generates the highest energy capacity with 20,455 kWh which is powerful enough to light nearly 6000 bulbs of 20W continuously for 1 week. This amount of energy however only accounts for 52% of overall surplus energy meaning that the potential of energy storages is still very much.
- Thirdly, in terms of spatial requirements, there are three conditions which may facilitate the implementation of a community energy storage: 1) An appropriate number of parcels with an appropriate amount of surplus energy to be saved, 2) A suitable site nearby to place the storage and 3) Parcels have to be close enough to each other so that the connection will be more conveniently. Without these elements, the energy storage network will be more dispersed with various types of battery exist in the same neighborhood instead of unifying under only one energy storage.

To sum up, the feasibility of energy storages to be applied in residential areas is very optimistic. By connecting to share the energy storage facilities collectively, households can achieve much higher benefit than doing by individuals. A stimulate pricing and low cost technologies may be the key to facilitate the penetration of energy storage into market. Besides that, a high density of buildings, the availability of installation sites as well as the surplus of renewable energy are favorable conditions to implement an energy storage project.

7.1.2. Answering the research question

The main question for this research is : "*How to find the most suitable energy storage solution for a residential district, considering technical feasibility, spatial requirements and investment cost?*"

In order to answer the above question, an *energy storage model* has been developed in which Agent-based modeling was the centre combined with Simulated Annealing algorithm and GIS data. Information about parcels, their locations and energy status are loaded from GIS sources and a separate Demand – Supply profile. The Agent-based modeling set up micro behaviors for agents (parcels) to maximize their benefit taking into account the spatial constraints and some other elements. Meanwhile the Simulated Annealing algorithm makes sure that the system will not be trapped in a local maximum. The model also visualizes connections between parcels and locations where batteries should be installed.

Results of the model give a *"YES"* answer to the research question. With a given residential district and a list of energy storages to be deployed, the model is able to provide an optimal solution in which the benefit is the highest. All of the three issues: technical aspects, spatial requirements and investment/benefits are taken into a consideration. Therefore, if specifications of an energy storage are changed or the installation cost is adjusted it will lead to a totally new result. Modelers can utilize the model as a tool to support the decision making process when comparing different types of battery or when testing different energy policies*.*

7.2.   Discussion

7.2.1. Discussing the model

The initial purpose when creating the model is to find an optimal solution, however it also can be developed to be a designing tool. In this way, instead of running the model for thousands of iteration, the user just simply assigns which energy storage will be implemented in a certain part of the district. The model will execute the calculation and estimate the benefits as well as the saved energy. It requires a lot of improvements of the model but it is worth doing because now users are not able to change the allocation of batteries so as to make them more realistic and reasonable.

The model was built on an assumption that each parcel stores energy for the need of itself or for others who are in a same group. As a result, the entire district will become a neutral energy zone, at least in theory. However, a feed-in tariff model is also another choice in which when surplus energy is beyond the consumption of the whole group, it can be sold to the grid to earn money from the feed-in tariff. It would be interesting if the two business models are integrated in one model to give a better insight.

Another issue in that model is the use of Simulated Annealing (SA) algorithm. Traditionally, SA is applied in the system where each step of moving causes an increase or decrease or no changes. But in *energy storage model,* a move of a parcel can result in n^2 solutions many of which are increases. For example, when a parcel tries to join with a new group it may create a list of 9 possible changes like this [-4 -3 -2 -1 0 5 6 7 8]. Here, only the highest change (= 8) is chosen whereas it should give possibility for other positive or negative changes. Consequently, the curve of benefit is quite smooth instead of a fluctuating behavior as often

seen in SA models. One possible solution is that at each move, only one change will be made randomly instead of n^2 and the number of running loop will increase n^2 time. This algorithm can change the behavior of the model to become more similar to a SA model, and thus may give a better result, but it also increase the running time drastically.
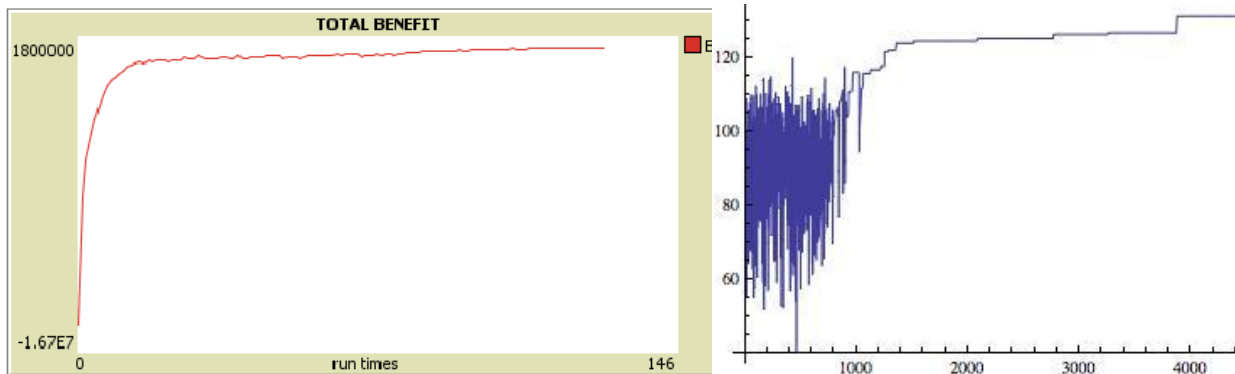
Figure 59: The curve of the model (left) and a typical curve in SA method (right)

Finally, the model is designed with an assumption that the users' behavior do not change over time although it is not true. People may change their living place every year and their house may become abandoned or be occupied by other owners who have a complete different energy profile. Also the surplus of energy can make people feel less worried about saving energy and the electricity demand may rise even much more. Therefore the model and its outcomes should be used carefully.

7.2.2. Discussing the application

The *energy storage model* can be a useful tool for different stakeholders ranging from urban planners, grid operators or energy companies to the citizens. For planners who work to execute the ambition of Municipality to achieve the zero carbon target in next decades, the model can give them an insight about how a community energy storage will be deployed in large scale and what spatial elements need to be taken care. Energy companies may be interested in building a business model and testing different plans and scenarios to choose the most suitable one. For the citizens who are living in the affected areas, they may have a skeptical attitude toward energy storage. By showing the monetary benefit of an energy network, it could change the awareness of the users and facilitate the diffusion of this technology much more.

7.3. Recommendation

For further research, it is recommended to refine the model. More performance parameters should be added to characterize the batteries better. For example, the round trip efficiency and the wear level of batteries can be included on the interface of the model. Moreover, a parcel should have opportunity to step away from energy storage in the case that they have a very little amount of surplus to store. This will help to avoid the waste of money and materials for implementing unnecessary batteries. In a higher level, the Simulated Annealing algorithm should be improved so that the final result would be more optimal.

Alternatively, a further research can focus on a business model that would help to finance those energy storage. Currently, the installation cost is divided among parcels of a group

although there are parcels who contribute much more energy than others. A business model may create a smart management to compensate for the family who has much surplus energy to store and prevent free riders. For instance, the electricity meter may observe activities of different parcels in a group. By the end of a month or year, the meter indicates the final result of energy has been sent or extracted from the common battery. The more energy a parcel contributes to the group, the more benefit they can earn and if a parcel only extract the energy without giving back, they have to pay more money.

Finally, it is important to pay attention to the development of energy storage technology. The future of energy storage is prospective since a number of ambitious projects has been announced and looking for capital investments. It could be a possibility that new inventions within the field of energy storage may occurs shortly after the graduation of this thesis making a disruption in the way people use energy.

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APPENDICES

Appendix A – Renewable energy forecast
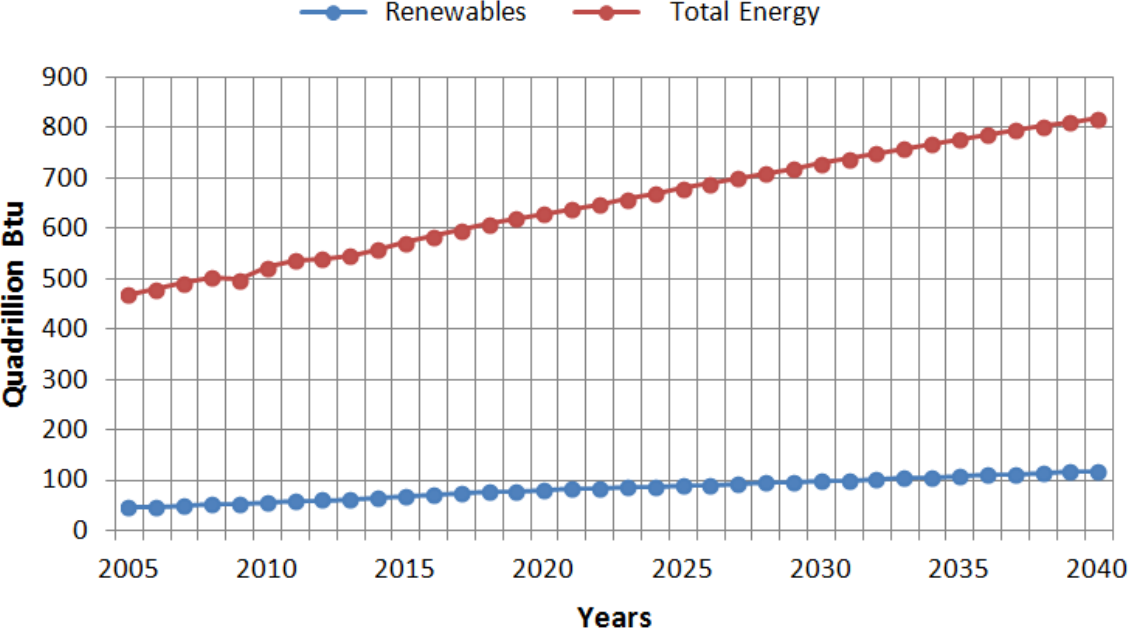
Consumption of renewable energy compared with total world's, outlook toward 2040 (EIA, 2013)
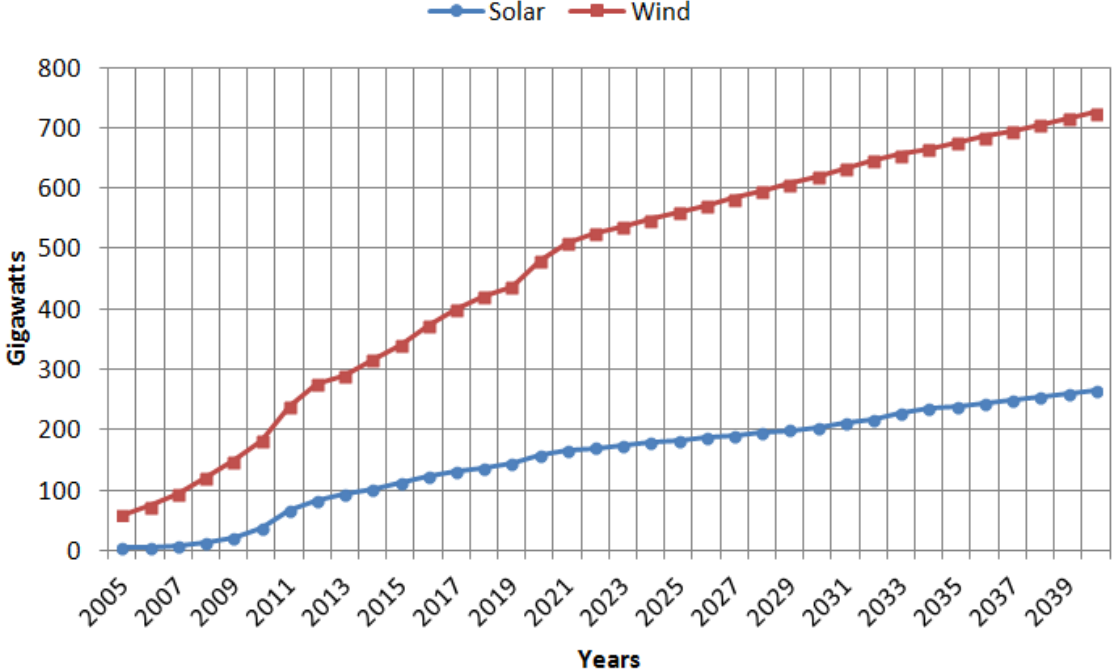
World's installed solar-powered and wind-powered generating capacity, outlook toward 2040 (EIA, 2013)
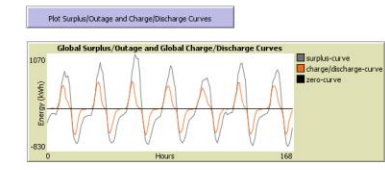
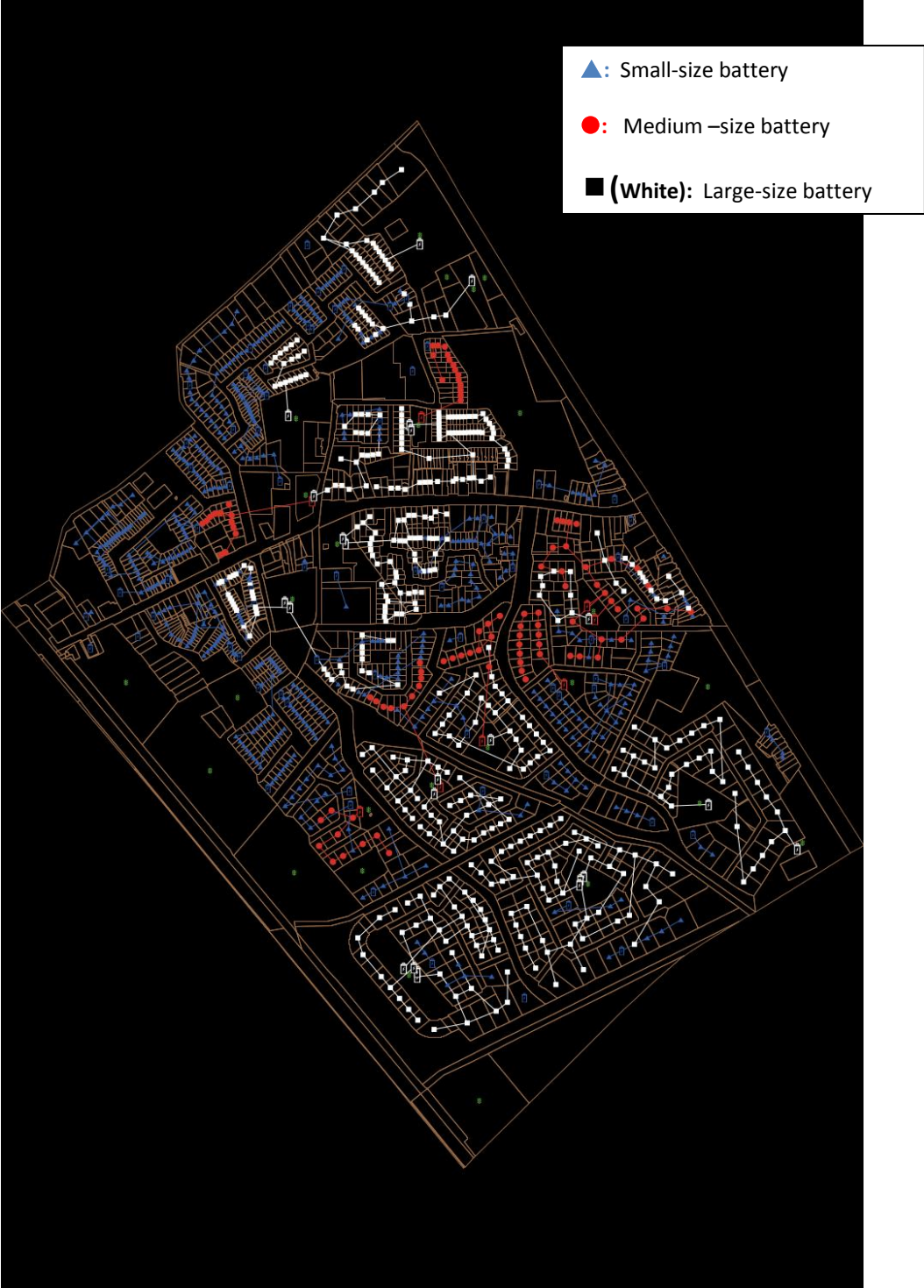# Appendix B - User interface of the Model

Appendix C - Result for scenario base case
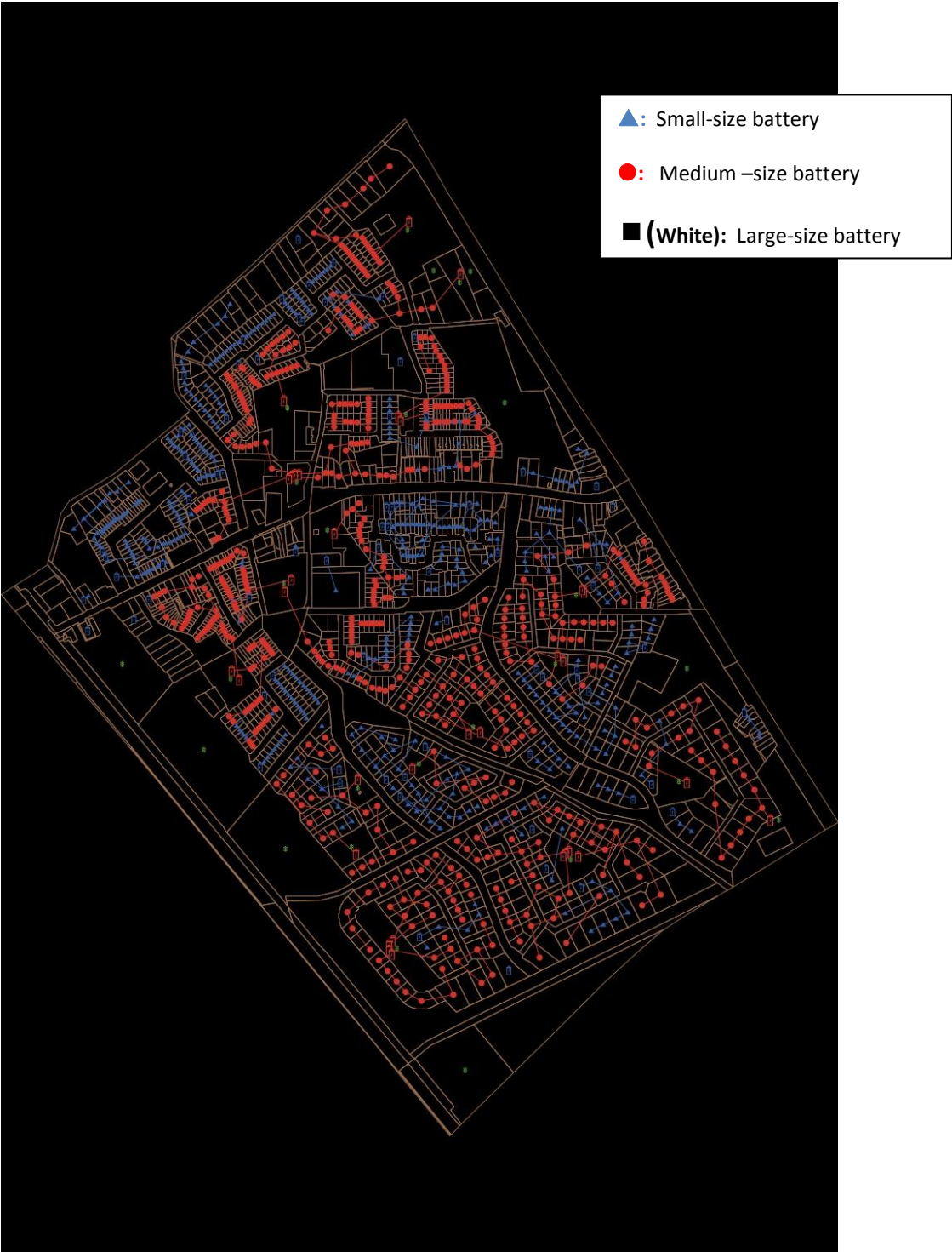
Appendix D - Result for scenario real-time pricing
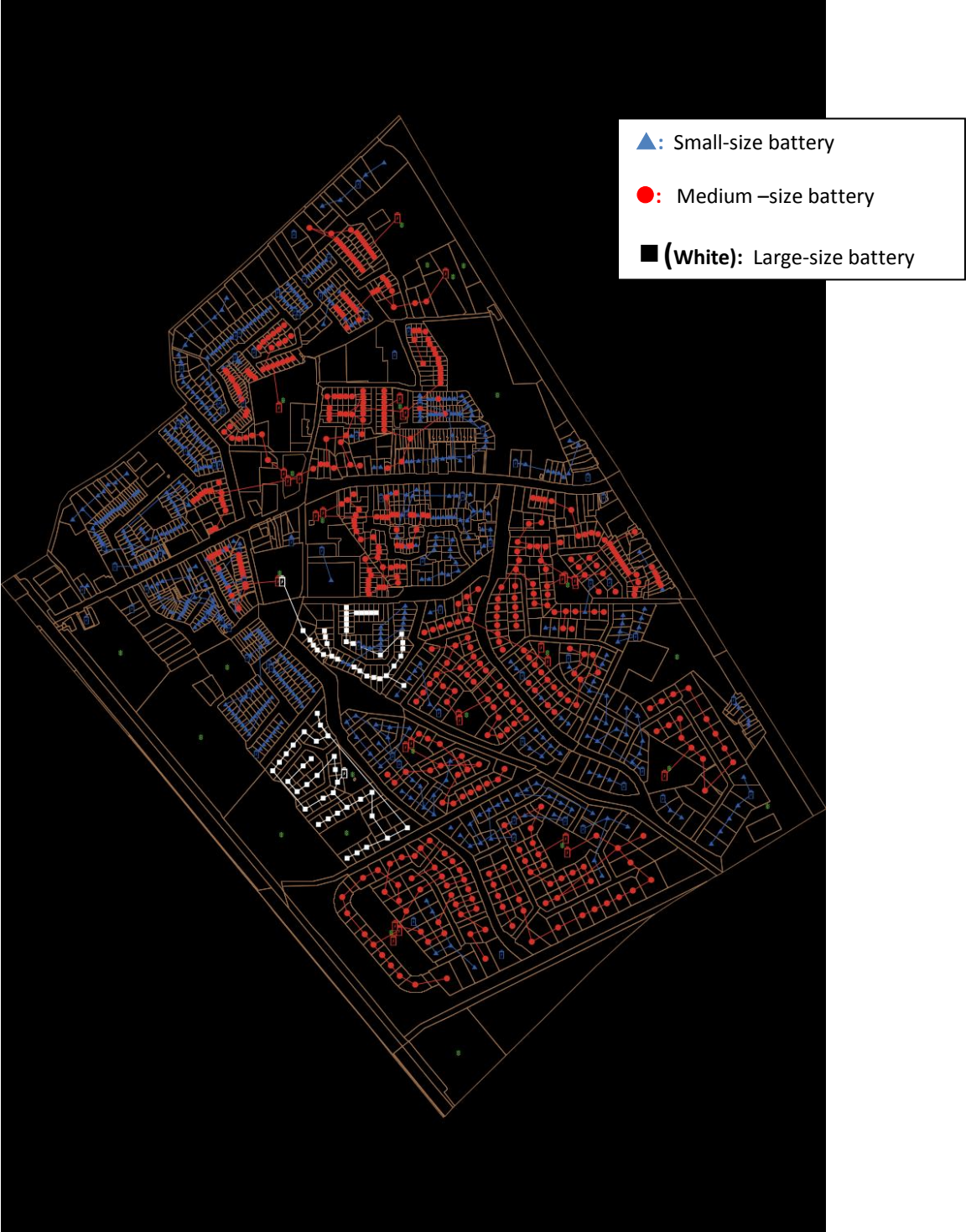
Appendix E - Result for scenario low-cost technology
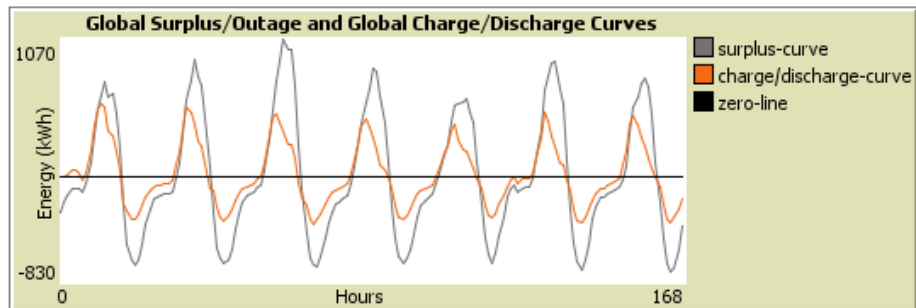

Legend:
▲: Small-size battery
●: Medium –size battery
■ (White): Large-size battery

Appendix F – Result for scenario combined

Legend:
- ▲: Small-size battery
- ●: Medium –size battery
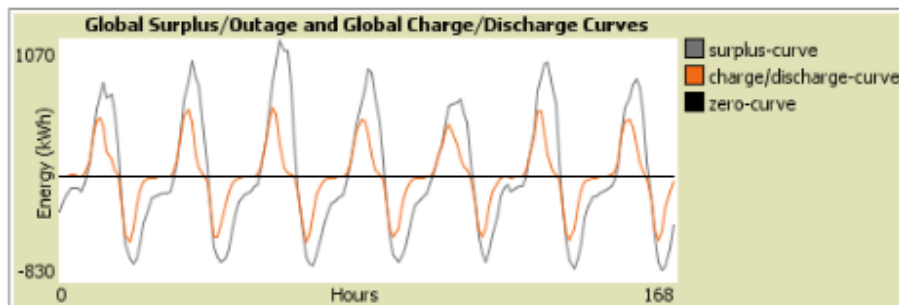- ■ (White): Large-size battery
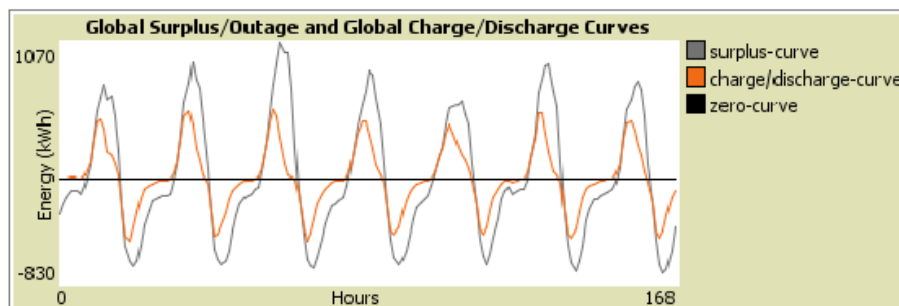
Appendix G (1)

This Appendix shows the curves of surplus/outage and charge/discharge for the entire area. The grey curve is the result of total supply energy minus total demand while the orange curve measures how much energy has been stored (the positive side) and how much has been extracted (the negative side).
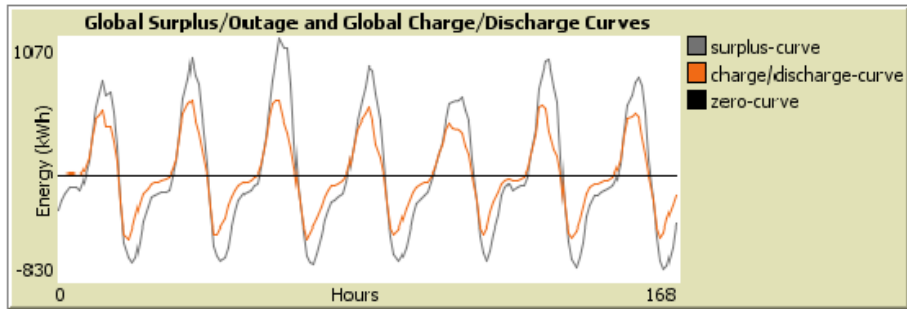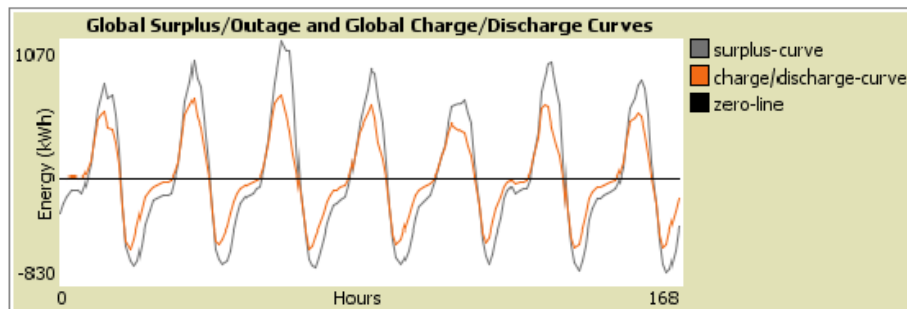

Initial setup

Scenario Basis

Scenario real-time pricing

Scenario low-cost technology

Scenario combined

ABSTRACT

Although renewable energy is expected to replace fossil fuels in the future energy system, they are criticized because of intermittency and uncertainty in operation, especially for wind and solar, leading to the mismatch between demand and supply. One possible solution for this problem is energy storage technology which allows unused energy stored when demand is low and released during the peak hours. This thesis utilizes the theory of Agent-based modeling and Simulated Annealing algorithm to design a model which is able to allocate different energy storages into a given residential area in order to get the highest benefit. Three aspects will be taken into account, namely: spatial requirements, energy capacity and economical benefit. The research is a part of a larger project being done by TU Eindhoven to investigate the feasibility of implementing renewable energy in large scale to assist the city to achieve their goal becoming energy-neutral by 2045.

Keywords: Energy storage, renewable, energy-neutral district, residential, Agent-based Modeling, Simulated Annealing, NetLogo.

INTRODUCTION

Intermittency of renewable energy & Energy storage solution

Renewable power plants and generators take advantage of clean, endless natural resources such as wind and solar to produce electricity continuously, however this is also their disadvantage. Due to the intermittency and uncertainty of those resources, the operation of renewable power plants cannot match with the demand side and thus creating an amount of unused energy. In this aspect, wind and solar energy are less attractive compared to other conventional energy types. For illustration, look at the figure below where the electricity production from 9 energy sources are put together for a comparison. While the power production from hydro, biomass, nuclear and brown coal are very stable and controllable, wind and solar show a fluctuating, intermittent behavior in generating power. It should be kept in mind that the daily electricity usage also exhibits a graph with many volatilities varying on different time scales, for example between day – night, weekdays – weekend,

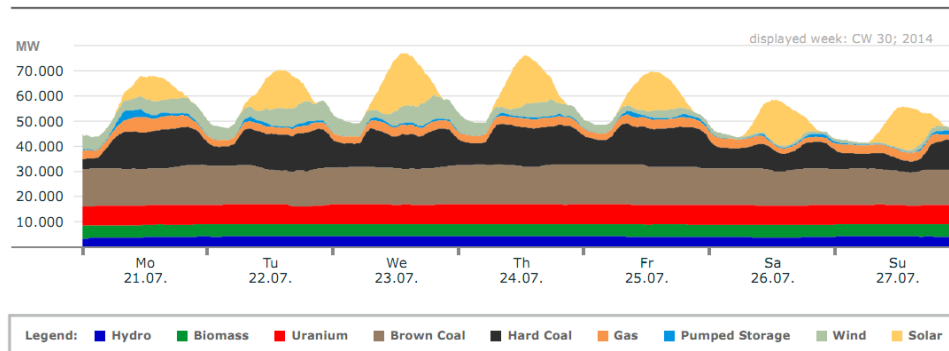Winter - Summer. How to match the demand and supply sides which are both fluctuating is a big question.

Figure 1: Electricity production from different sources in Germany, week 21 – 27/07/2014 (Burger, 2014)

One possible solution for this problem is by using energy storages. Briefly, an energy storage can store energy or electricity by utilizing a number of physical principles such as chemical reaction or the energy transition from electrical power to potential and kinetic energy. In terms of purpose of use, energy storages are suitable for stabilizing grid, balancing demand – supply during peak hours and extending ability of renewable power plants and generators. The potential of integrating energy storages into urban environment as a supporting medium to maximize the capacity of renewable energy has been researched and mentioned in literatures, for example (Bortolini, et al., 2013) and (Parra, et al., 2014). However, these studies focus on application of energy storage for single house and building only, but not for a larger scale such as a row of buildings or a neighborhood. This thesis is designed to investigate the feasibility to implement energy storage together with renewable energy for various scales of urban in an attempt to create an energy neutral district.

The problem of Eindhoven
The municipality of Eindhoven has an ambitious goal to become energy neutral by 2045 and for a shorter term, to reduce greenhouse gas emission by 30% compared to 1990 while raising the share of renewable energy in the total energy production to 20% in 2020. However, in 2011 a report conducted by KenW2iB about the local conditions for the development of renewable energy in the future showed a number of challenges. Accordingly, wind energy cannot be used on a large scale because of the proximity of Eindhoven Airport and Solar energy is only used on 20% of the roofs providing around 10% of the energy needs. Moreover, the implementation of energy storage is said to be quite costly while subsidization for this technology is uncertainty.

The purpose of the thesis
This thesis is a part of a larger project done by Department of built environment, TU Eindhoven. The purpose of the project team is to investigate potential technologies and solutions that would help the city to fulfill the energy target. Project was divided into smaller tasks such as classifying energy use profiles of different industrial and residential sectors or making a simulation tool to explore potential locations to build wind turbines or place PV panels based on land-use plan and characteristics of houses/buildings. Assuming that all potential renewable technologies have been implemented in appropriate areas, the next step is to study how energy storage can help to extend the supply capacity of these wind mills or solar panels. The thesis will focus to answer the main question: *"How to find the*

most suitable energy storage solution for a residential district, considering technical feasibility, spatial requirements and investment cost?". The objective is to design a simulation tool which allows modeler to find an optimal energy storage solution for a given residential area as well as to investigate different energy policies and energy storage technologies.

METHOD

For this study, different research methods are used and combined, including literature review, collecting data, defining variables and constraints, choosing research model, etc.

Literature review about energy storage

Energy storage is a broad concept. In fact, energies are embodied in surrounding environment with three common forms of carriers: solid, fluid and gaseous. Electricity is also a type of energy which has a lot of advantages over others: the level of flexibility, the absence of waste, and the easy and safe way of connection. In this research, the term *"energy storage"* should be interpreted as storing electricity generated from renewable energies.

How to store electricity? Combining answers given by Kousksou, et al., (2014) and Evans, et al., (2012) outlined four basic methods to do so:

- *Electrochemical systems:* the battery can derive electrical energy from chemical reactions or facilitating chemical reaction through the introduction of electrical energy.
- *Kinetic energy storage systems:* electrical energy will be transferred into rotational energy of a massive rotor (flywheel) rotating with very high speed. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy
- *Potential energy*: by definition, potential energy is energy stored in a system of forcefully interacting physical entities. A vivid example of this form of energy storage is pumped hydro system in which water is pumped to a reservoir 100m higher than ground and released to fall down to generate power.
- *Electrical energy storage:* using magnetic field within a coil comprised of superconducting wire to store electricity.

(Kousksou, et al., 2014) and (Evans, et al., 2012)

In addition, thermal energy is another way to store energy. However, thermal energy storage is typically utilized to provide a heating or cooling resource, thus its production is not electricity.

The classification of energy storage can also be based on the purpose of use and their technical characteristics. Generally speaking, an energy storage is characterized by a number of features such as: efficiency, durability, reliability, response time, energy and power density and energy and power capacity (Ferreira, et al., 2013). While response time is used to recognize the energy storages that can deal with sudden outages (very fast response time) and the one that is purely for storing energy (low response time), energy and power capacity divide energy storages into two groups: technologies that only provide electricity for a short period of time (seconds to hours) and ones that can store energy for latter uses within days or weeks. From the business perspective, there are more features should be

concerned: investment power and energy cost, maintenance requirements, technical maturity, operating temperature, spatial requirement, etc (Chatzivasileiadi, et al., 2013). Alternatively, energy storages can be categorized according to the purpose of use. For example, , for low-power permanent applications, the critical feature is a low self-discharge while for power-quality control applications, a quick response time, high power and cycling capacity are necessary (Ibrahim, et al., 2008).

There are various types of energy storage technology currently available on the market or being researched and developed, for example:
- *Pumped hydro storage (PHS):* Water is pumped during the low-demand period from lower reservoir to the higher one for reserving. Accounting for 99% of the total installed storage capacity for electrical energy all over the world, PHS also density requires massive civil works to construct the basin for a large body of water.
- *Compressed air energy storage (CAES):* CAES is nearly similar to PHS except for the fact that CAES uses compressed air within a reservoir to keep the energy. The capital investment for CAES is significantly lower than PHS, it also requires much less time to construct a CAES plant.
- *Battery energy storage system (BESS):* Including lead-acid battery, Nickel-based battery, Sodium-sulfur battery (NaS) and Lithium-based battery. In principle, BESS are electrochemical systems that store and release power through chemical reactions. Currently, BESS has been chosen for a number of large-size energy storage project, for example, the Japanese Rokasho-Futamata wind farm (NaS) with capacity of 34MW or the Chinese Zhangbei national wind PV energy storage project (Lithium-ion) with rated capacity is up to 36MW over 4 to 6 hours.

Apart from large energy storage projects which are often built next to renewable power plants, in smaller scale energy storages have also been implemented within a building or a residential area with energy capacity varies from few hundred of kWh to more than 1 MW. For instance, SustainX – an energy solution developer has recently announced the installation of the world's first megawatt-scale isothermal compressed air energy storage to support for their headquarters in Seabrook, New Hampshire, USA. In 2013, a community energy storage has been installed in Ontario, Canada to store electricity and provide back for 150 homes in the event of an outage. Meanwhile, new technologies are being developed in order to lower the investment cost of batteries. For example, AMBRI – a metal liquid battery developed in laboratory of MIT is believed can reduce the cost to only $500 per kWh. It is reasonable to believe that in a near future, energy storages can be found everywhere in the built environment.

Constraints, variables and objective function
This section presents constraints or prerequisite conditions for a spread of energy storage into a residential area. Besides that, the construct of objective function of the model as well as variables that are linked to the objective will be explained.

Pre-conditions
Energy storage is the missing link to renewable energy since it can be used to extend the ability of a renewable system when exploiting intermittent sources such as wind or sun. It is obvious that an energy storage will be useless in an area where very little amount of surplus

electricity is generated. The surplus energy is the result of the mismatch between supply and demand sides. Ideally, the chosen area to install energy storages should have an amount of surplus energy that is large enough to cover the outage period when demand exceeds supply. That is the pre-condition for a successful implementation of energy storage. The following graph illustrates a shift of unused energy from day to night.
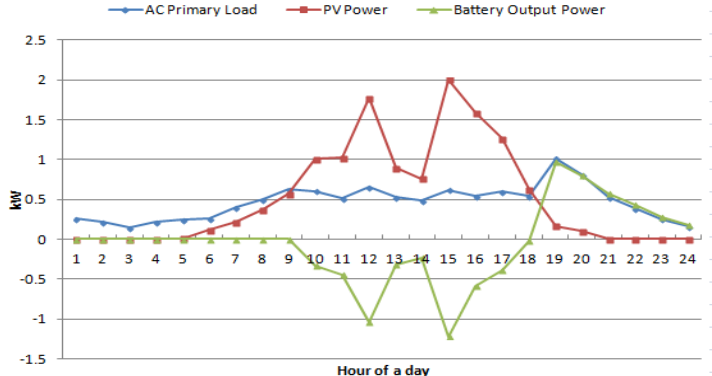

Figure 2: Surplus energy is stored to be used latter

Variables

First of all, the operation of an energy storage system which is integrated with renewable energy must be defined. The model borrowed from (Bortolini, et al., 2013) will give the answer. In this model, the battery system only stores energy from PV panels (not from the grid like in some other models) and when the state of charge of the battery drops below a level (20%) energy from grid will be extracted. Here, the concerned variables are: Supply/Demand energy (kW), Energy capacity of the battery (kWh), Power capacity (kW), Depth of discharge (%).Figure 3 illustrates the algorithm to calculate input/output energy of a battery for 168 time steps equivalent to 168hours or 7days.

Spatial Constraint

In literatures the spatial aspects of energy storages are defined as energy density per square meter or cubic meter or per kilogram. However, in reality the location to install a battery is also determined by other factors such as the safety, noise nuisance, weatherproof or tamper resistant. It is therefore difficult to find a function for site selection of energy storage since this task may depend on experience of technicians and availability of the given area. In a number of demonstration projects, energy storages are implemented in the basement of a building or on a green patch nearby to support the surrounding inhabitants. In this research, spatial constraints for a successful implementation of a community energy storage are twofold: (i) There must be a site with an appropriate function (green park/abandoned garage) to allow that energy storage to be built; (ii) The distance from the site to its target households has to be within an appropriate range (for example, not further than 100m).

Objective function

The objective function for economic evaluation is given as follow:
$$B = P \times E - C$$
Where B is the monetary benefit (€) offered by an energy storage; P is the electricity price (€/kWh); E is the energy (kWh) saved by the energy storage for the entire lifecycle; C is the installation cost (€)

E will be calculated by flowchart in **Figure** whereas some examples of electricity price *(P)* and installation cost *(C)* will be presented chapter Design scenarios.
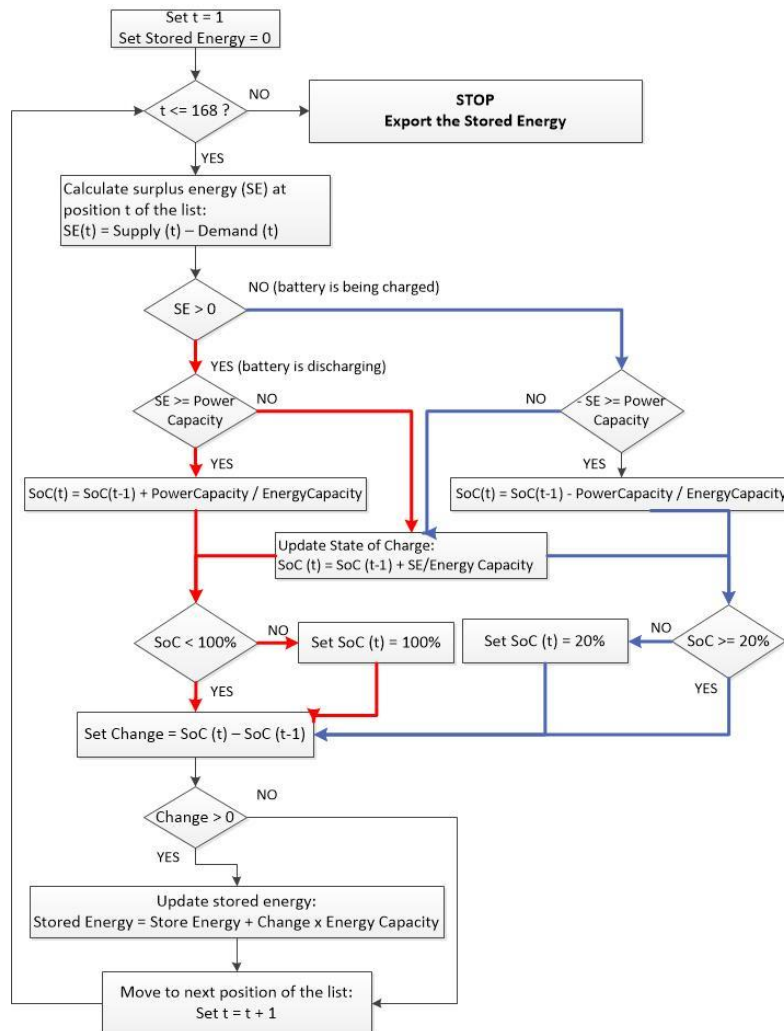

Figure 3: Algorithm to calculate stored energy with thresholds for SoC are 20% (DOD = 80%)

Agent-based Modeling (ABM)

In principle, the ABM is a bottom-up research approach in which a number of simplistic notions that are both obvious and banal (Batty, et al., 2012) is assigned to a lower level of system in order to investigate the emergence of higher levels. In ABM the *'lower level of system'* is agents which are an analogy to individuals in a social system.

The purpose of this research is to investigate the feasibility of energy storages in residential area in which each household and family has its own characteristics which drive them to adapt this technology on different scales: standing alone or joining for a larger network to share the energy. An Agent-based model is able to simulate those characteristics and behaviors quite well. For example, an agent can describe a household with many different aspects: location or energy supply – demand profile making them unique and distinguishable. Moreover, an agent is also goal-directed, interactive and adaptive which are similar to the real world where families make decisions based on the benefit they can earn, the chance to co-operate with others to reduce the cost and the past experience.

Nevertheless, the model lacks a number of characteristics of a complete Agent-based model making it to be just a semi one. Firstly, there is no interaction between agents and environment, and the environment only plays the role of a map for visualization. Secondly, mobility is not presented in the energy storage model since households are assumed to stay in one place forever and their electricity use profiles do not change over time.

NetLogo

NetLogo is the programming platform chosen to develop the desired Agent-based model. The model's user interface consists of three parts: (i) *The input parameters:* allows modelers to adjust the variables such as electricity price or energy capacity, (ii) *The map:* where the parcels of the given area, their connections and energy storages will be presented, (iii) *The graphs and outcomes:* show results of the simulation. Besides that, the model is able to access to electricity use profile and GIS data which are put into separate files of the same folder.

Simulated Annealing (SA) method

SA is a search algorithm which is used to find the optimum (min/maximum) state of a system, by allowing moves which worsen the objective function value (Henderson, et al., 2003). The acceptance of disadvantageous moves is governed by a parameter called *"temperature"* which is inspired by affection of temperature in annealing process. At the beginning the temperature is kept high enough so that all possible minimum values (valleys) are explored. As the temperature gradually declines the system becomes trapped in relatively small range of valleys. Assuming the goal of a system is to solve a minimization problem, the algorithm of SA is as follow. The algorithm employs a random search which not only accepts changes that decrease the objective function f but also some changes that increase it. The latter are accepted with a probability:

$$p = e^{\frac{-\delta f}{T}}$$

Where δf is the increase in f and T is *"temperature"* – a control parameter (Busetti, 2003).

Design scenarios

This section introduces four scenario designs as well as the rational ground for choosing them. Except for the first scenario – the basis one, the other three try to simulate a future context when energy price becomes more volatile and energy storage technologies are mature enough allowing cheaper but more efficient products to be implemented.

Scenario base case

In this scenario, the electricity price is calculated based on the 2014's data which is €0.22/kWh and this value will be fixed over the lifecycle of an energy storage (up to 15 years). Three "candidate" technologies which are suitable for different urban scales will be chosen. They are:

- YOE battery system: a mini size lithium-ion battery using titanate technology. YOE was designed and being commercialized by YOUNICOS, a company who provides energy solutions including energy storage. A YOE battery has a small energy capacity: 12kWh/4.0 kW but a relatively high cost: €1500/kWh with a lifetime of 20 years.
- ZEN PowerBank battery: a Lithium-ion medium-size battery, produced by ZEN, a South Australian energy firm. A system of ZEN with three modules is able to give 60kWh in

energy capacity, 15kW of power with the installation cost of €900/kWh and lifecycle of 15 years.

- eCamion's community energy storage (CES): This is a sizeable energy storage made by multiple arrays of lithium batteries. This technology has been implemented for a residential area in Canada (2013) providing 250kWh/500kW to a neighborhood. Price and lifecycle are estimated €900/kWh and 15 years respectively.

Scenario time-varying pricing

In this scenario, a real-time pricing will be applied, meaning that the electricity price will be changed by operators every hour based on relation of demand – supply. The model will make use of real-time approach borrowed from research of Arslan (2012)

Scenario low-cost technologies

In this scenario, a low-cost technology which is still under R&D progress will be deployed into the model. The new technology should not be as expensive as current products and its capacity should also be powerful enough to deal with large scale energy networks. Therefore, AMBRI liquid metal battery – an advanced technology which is being developed at MIT in the lab of Professor Donald Sadoway is selected. An AMBRI system can provide 200kWh/50kW with the cost of only €300/kWh in 15 years.

Scenario low cost technology & real-time pricing

In this case, the eCamion's community energy storage will be replaced by AMBRI battery since they are both large scale batteries but AMBRI has a better cost per kWh. In addition, the fixed pricing mode will be switched to real-time mode.

FINDINGS

Results of the four simulations are aggregated and compared with regards to the economic efficiency, energy storing capacity and spatial aspects. The analysis tries to explore if there are general rules to explain the spread of energy storages among residential areas and what implication it would be.

Economic aspects

First of all, it is easy to notice that by connecting and sharing energy storages together, households in a neighborhood can gain much higher benefits than installing them individually. Secondly, if the production cost of technologies is lower or the pricing policy is more attractive, an increase of benefit can be observed clearly **(Figure 4)**
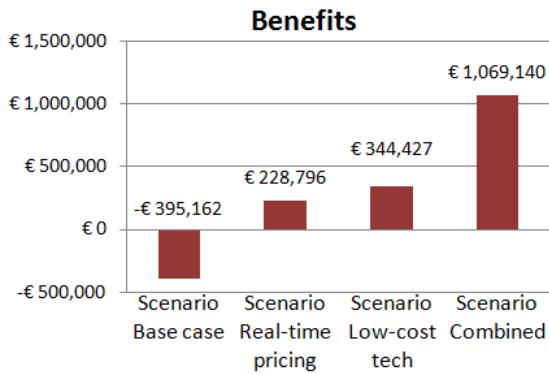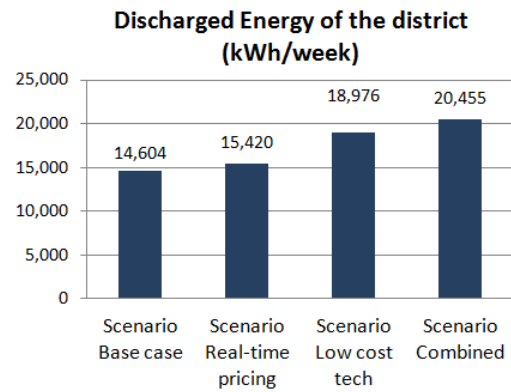
Figure 4: Benefits of the four scenarios

Figure 5: Stored energy of the four scenarios

Energetic aspects

The electricity discharged from energy storages increases gradually from scenario base case to the scenario combined (Figure), corresponding with the chart of benefits. Compared to the initial setup in which 16,688 kWh/week can be achieved by assigning to each parcel one YOE battery, scenario base case and real-time pricing have a lower energy capacity. Meanwhile the low-cost technology and combined scenario have the best results. However, compared to the total surplus energy of the district (38,684 kWh/week), even scenario combined only meets a half of potential renewable energy.

Spatial aspects

By analyzing the map of distribution of energy storages in the four scenarios, it comes to a conclusion that: the applicability of a large scale energy storage, in terms of spatial requirements, is determined by two elements: (i) The availability of public space to install energy storages and (ii) The high density of buildings is a favorable condition for large scale energy storages to be constructed.

CONCLUSION & RECOMMENDATION

The research has developed a model which is able to provide an optimal energy storage solution for a given residential district. Furthermore, through the scenarios simulation the model has proven that the feasibility of energy storages to be applied in residential areas is very optimistic. By connecting to share the energy storage facilities collectively, households can achieve much higher benefit than doing by individuals. A stimulate pricing and low cost technologies may be the key to facilitate the penetration of energy storage into market. Besides that, a high density of buildings, the availability of installation sites as well as the surplus of renewable energy are favorable conditions to implement an energy storage project.

Two possible further researches may focus on improving the performance of the model or to study about a business framework that is able to commercialize the energy storage services. More parameters such as the *round-trip efficiency* or *wear level* may be added. The algorithm of SA can also be improved since the behavior of the model is still similar to Greedy Algorithm. Alternatively, developing an appropriate business model to exploit the value of energy storage would be an attractive topic. Currently, the installation cost is divided among parcels of a group although there are parcels who contribute much more energy than others. A business model may create a smart management to compensate for the family who has much surplus energy to store and prevent free riders

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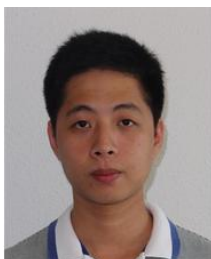
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