MASTER

A techno-economic energy model for business premises

the creation of a spatial energy model for the allocation, and optimization of renewable energy technologies in the urban fabric

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A Techno-Economic Energy Model for Business Premises

The creation of a spatial energy model for the allocation, and optimization of renewable energy technologies in the urban fabric

In partial completion of the Master track Construction Management and Engineering at the University of Technology Eindhoven.

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Preface

The energy system is slowly shifting from a hierarchical fossil fuel based systems, to a distributed network based renewable energy system. This transformation is driven by a governmental push, a social desire, and market effects. This transition requires extensive planning to provide a reliable, and cost efficient energy system. The complex, and diffuse nature of the built environment leaves city planners, and system designers with a great challenge to incorporate sufficient renewable energy generators in the built environment, without administrating large adjustments to the existing structure.

The purpose of this research is to develop a techno-economic energy model which incorporates GIS data to allocate, and generate the most optimal solution for the integration of renewable energy technologies in the built environment. More specifically, to allocate renewable energy technologies on business premises. An attempt is made to incorporate spatial constraints, and thereby develop a spatial decision support tool to help system designers with the allocation of renewable in the built environment.

Now in front of you lie the results of this research; my graduation thesis for the master Construction Management and Engineering at the Eindhoven University of Technology. I have chosen for this topic to try to make a contribution towards the transition from a fossil fuel based energy system to a distributed and renewable based energy system.

Furthermore, I would like to thank Saleh Mohammadi and Brano Glumac for their patience during this graduation process. Also, I would like to thank my girlfriend, my parents, and my friends who supported me, and who helped me develop new insights in this problem.

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Management Summary

The energy system is transforming from a centralized fossil fuel based system towards a distributed renewable energy system were energy is locally produced, and consumed. However, the implementation of distributed renewable energy resources in the built environment is complicated for decision makers due to the complex and diffuse nature of the built environment, and the restrictions for renewable energy technologies in this urban fabric.

Spatial Decision Support Systems (SDSS) can provide the comprehensive models needed to capture the aspects of the urban environment to support decision makers. Several renewable energy models are developed to aid decision makers in developing sustainable blocks, district or cities, or to assess the potential of renewable energy technologies in the built environment (Bernal-Agustin & Dufo-Lopez, 2009; Borowy & Salameh, 1996; Deshmukh & Deshmukh, 2008; Maclay, Brouwer, & Samuelsen, 2007; Mohammadi, Hosseinian, & Gharehpetian, 2012).

However, the main consumer within the built environment is often neglected, as a matter of fact according to Timmerman et. al. (2014) no significant research is done for the development of energy models for the use on business premises. For this reason a spatial decision support system for the integration of energy technologies is developed for the use on business premises.

To find an optimal solution which would also spark the interest for the located entrepreneurs and their businesses the aim is to find a solution or configuration which would be financial feasible. An optimization is made which combines the energy generation with the capital costs, and O&M costs.

The used renewable energy technologies in this energy model are the most commonly used namely, the wind turbine, and the PV modules. For the allocation of these renewable energy technologies a vector based GIS map is used, consisting of the parcels and their properties. The GIS-map present the research area, and the spatial constraints of this area. The parcels enclose several parameters which are used to decide if a renewable energy technology is allocated. These parameters include; the total surface of the parcel, the surface of which is build, the free available surface, vulnerability of the present building, and also two parameters for the wind atlas methodology. The allocation of the renewable energy technologies is based on conditional statement which check a parcel on its fitness to host a certain renewable energy technology.

For the allocation of wind turbines the fitness test for a parcel are tested on their available surface area for installing a wind turbine, if there is a vulnerable building, and if there is a nearby wind turbine in the proximity. The fitness test for nearby wind turbines supersedes the parcel level, and also checks surrounding parcels.

For the allocation of PV modules only the check is made if there is sufficient roof surface to allocate PV modules. This choice is made due to the fact that for the allocation of PV modules on roofs no additional procedures are required. Which implies that anybody is free to install PV modules on the roof, unless it concerns a monument.

Furthermore, multiple methods are incorporated to calculate the energy generation of the renewable energy technologies, using hourly meteorological data is to estimate the renewable energy generation of the energy technologies.

For the estimation of wind potential a logarithmic wind profile method is used to adjust the measured wind speeds on a nearby field to a specific location on the research area. This method, proposed by Millward et. al. (2013a), is known as the wind atlas methodology. This method incorporated the roughness length, and the displacement height to deal with the rough surface of the urban environment. The first step adjusted the measured wind speed to the urban boundary layer, it is assumed that objects on the ground surface have no effect on the wind speed at this height, and is often set on 200 meters above ground level. The second step is the adjustment of the wind speeds at the urban boundary layer to the blending height. The blending height is set on twice the average building height of the fetch area. The fetch area is thereby donated as the area of 3 to 5 km downwind of the research area. The third adjustment is the downgrade of the wind speeds to a local level of the parcels. Using this method the wind energy potential per parcel can be determined.

These adjusted wind speeds are subsequently used to calculate the wind energy generation. Therefore, the method as proposed by Tina et. al. (2006) is integrated into the energy production model. This method calculates the hourly energy generation using the adjusted wind speeds from the wind atlas methodology. The method incorporates the properties of the wind turbines, namely; cut-in wind speed, rated wind speed, cut-out wind speed, and rated power of the wind turbines. If the wind speed is lower than the cut-in wind speed no energy is generated. When wind speeds are between cut-in wind speed, and rated wind speed a linear curve describes the increase of power output of the wind turbines. If the wind speed is higher than the rated wind speed, and lower than the cut-out wind speed than the rated power output is generated.

For the energy generation of solar PV generation also the model as proposed by Tina et. al. (2006). This method uses the meteorological data as collected by the Royal Dutch Meteorological Institute. This method also combines the properties of the PV modules namely; module size, and module efficiency.

The economic evaluation of the energy configuration consists of two major components. First, the capital costs of the constructed configuration is calculated. This are the combined costs to purchase, transport, and install the renewable energy technology. Second, the O&M costs are calculated over the proposed lifetime of the system. This is done using the discount cash flow methodology, which is often used to evaluate the feasibility of investments.

The configuration are evaluated on the overall costs per produced kWh over the complete lifetime of the system. The energy model aims to find ever lower values for the costs per produced kWh, using the simulated annealing algorithm.

The energy model is tested using a case-study. The research area in this case-study is the business premises of “de Brand”. “de Brand” is a business premises in the periphery of the city ‘s-Hertogenbosch, and has the ambition to become energy neutral.

The model is run using different variables to assess the operation of the model, and with the variables set as they would when truly analysing the potential of renewable energy technologies on the research area. To provide the properties of the wind turbines, and PV modules producers where addressed. For the wind turbine the WES 50 wind turbine is chosen, this is a medium size wind turbines which is able to be allocated on business premises. For the solar generation a Benq mono-crystalline PV modules are chosen, these mono-crystalline modules have a high energy efficiency.

The results of the energy model show that wind turbines are not feasible to be used for the generation of electricity for the use of business premises. The PV modules shown much lower values for the costs per produced kWh over the complete lifetime. However, the results show that there is no configuration of renewable energy technologies which can compete with the costs per kWh produced by fossil fuel based electricity stations.

Furthermore, the allocation of the renewable energy technologies some restrictions are implied for a fact only one wind turbine can be allocated within a parcel, while this parcel can in fact harbour more wind turbines. Additionally, the allocation of PV modules use the whole roof surface of a building, while installations are neglected, as well as the geometry of the buildings.

For the further development of this model the focus can lie on; further elaboration of the wind turbines allocation model, so multiple wind turbines can be allocated on one parcel, and the safety check will no longer be solely from the centre of the parcel, the integration of the orientation, and geometry of the buildings in the research area. This will provide a more accurate allocation of PV-modules, further elaborate the possible renewable energy technologies such as, Geothermal, PV-T, or Biomass, integrate the possibility of energy storage, to simulate the operations of a local energy grid, and thereby creating an autarkic district.

1. Introduction

The energy system is transforming towards a distributed renewable energy system were energy is locally produced, and consumed. However, the implementation of distributed renewable energy resources in the built environment is complicated for decision makers due to the complex, and diffuse nature of the built environment, and the restrictions for implementing renewable energy technologies in this urban fabric.

Furthermore, experts in the field of electrical engineering (Clastres, 2011; Hermans, 2014; Lasseter, 2011; Roberts & Sandberg, 2011) are jointly agree that the future of the electrical systems will compose of a multitude of micro-grids, which together compose a smart-grid. A micro-grids/smart-grids are characterized by the coupling of energy generation, storage, and loads on a local level, and therewith adjust supply, and demand. A challenge for developing smart-grids/micro-grids is to consider al spatial, and legal constraints, and deal with conflicting objectives for the allocation, and optimization of the renewable energy generation technologies on a local urban level.

To implement renewable energy technologies on the local urban scale, comprehensive energy models can be utilized to capture the aspects of the urban environment to support decision makers. Several renewable energy models are developed to aid decision makers developing sustainable blocks, district or cities, or to assess the potential of renewable energy technologies in the built environment (Bernal-Agustin & Dufo-Lopez, 2009; Borowy & Salameh, 1996; Deshmukh & Deshmukh, 2008; Maclay et al., 2007; Mohammadi et al., 2012). However, the models do not regularly integrate the built environment, on a district level. For example, the studies of Dufo-Lopez et. al. (2009) neglects the influence of the spatial environment, and solely focus on the optimization of an stand-alone renewable energy system based on multiple loads. The main focus of these energy models is to find a set of renewable energy technologies, which can provide the research area with sufficient energy, without considering the spatial constraints. Furthermore, models which integrate the spatial environment mostly do not focus on district-scales, but rather focus on the geographical scale of a whole region, or even a state (Aydin, Kentel, & Duzgun, 2010; Ramachandra, Rajeev, Krishna, & Shruthi, 2011). Additionally, the focus often lies on the generation of electricity for residential areas, were industrial, and business premises are the major consumer of electricity in the built environment.

In fact, according to Timmerman et. al. (2013) no examples of renewable energy modelling for business premises can be found in the current literature. Moreover, often the literature neglects the impact of the urban environment on the composition of renewable energy systems, and focus solely on the optimization of renewable energy technologies.

In this study, the aim is to develop an energy model which can be used on district-level, with the focus on energy consumption in business premises, while considering spatial constraints. To do so the current literature is analysed on often used methods, and assumptions. Furthermore, a techno-economic energy model is proposed, and tested on a case-study.

1.1. Problem Definition

The above stated problem analysis leads to the following problem definition; *"There is no evidence found in current literature of the existence of an energy model to determine the optimal combination of energy technologies composing a renewable energy system for business premises".*

1.2. Research Questions

The problem definition leads to the following research questions. The main research question will be: *''Can a decision support tool be developed which can produce a "most optimal" combination of renewable energy conversion technologies based on the energy demand of business premises, and spatial constraints? And, what would the optimal combination be for a specific business premises?"*

With the following sub questions;

1) What is the current state of energy systems models? In what degree are they applicable for the built environment?
2) What is the current state of spatial decision support system for the development of renewable energy systems?
3) What are the spatial, and legal constraints which influence the composition of a renewable energy system?
4) What would be the composition of a renewable energy system?

1.3. Research Design

For this research several succeeding steps are followed, this is shown in **Figure 1**. The aim of this research is to develop an energy optimization model for the use on business premises. In advance of doing so a comprehensive literature review has to be composed. This literature review focusses on the existing spatial decision support systems, and energy optimization/simulation models. Here major components, and approaches of energy modelling will be identified, and conditions, and constraints are defined. All together, the literature review will provide a substructure for the development of the energy optimization model.

After all data, and methods are gathered an energy optimization model will be constructed, and tested on a case-study. In conclusion this, it will be possible to advice decision makers in the development of an energy system on business premises.

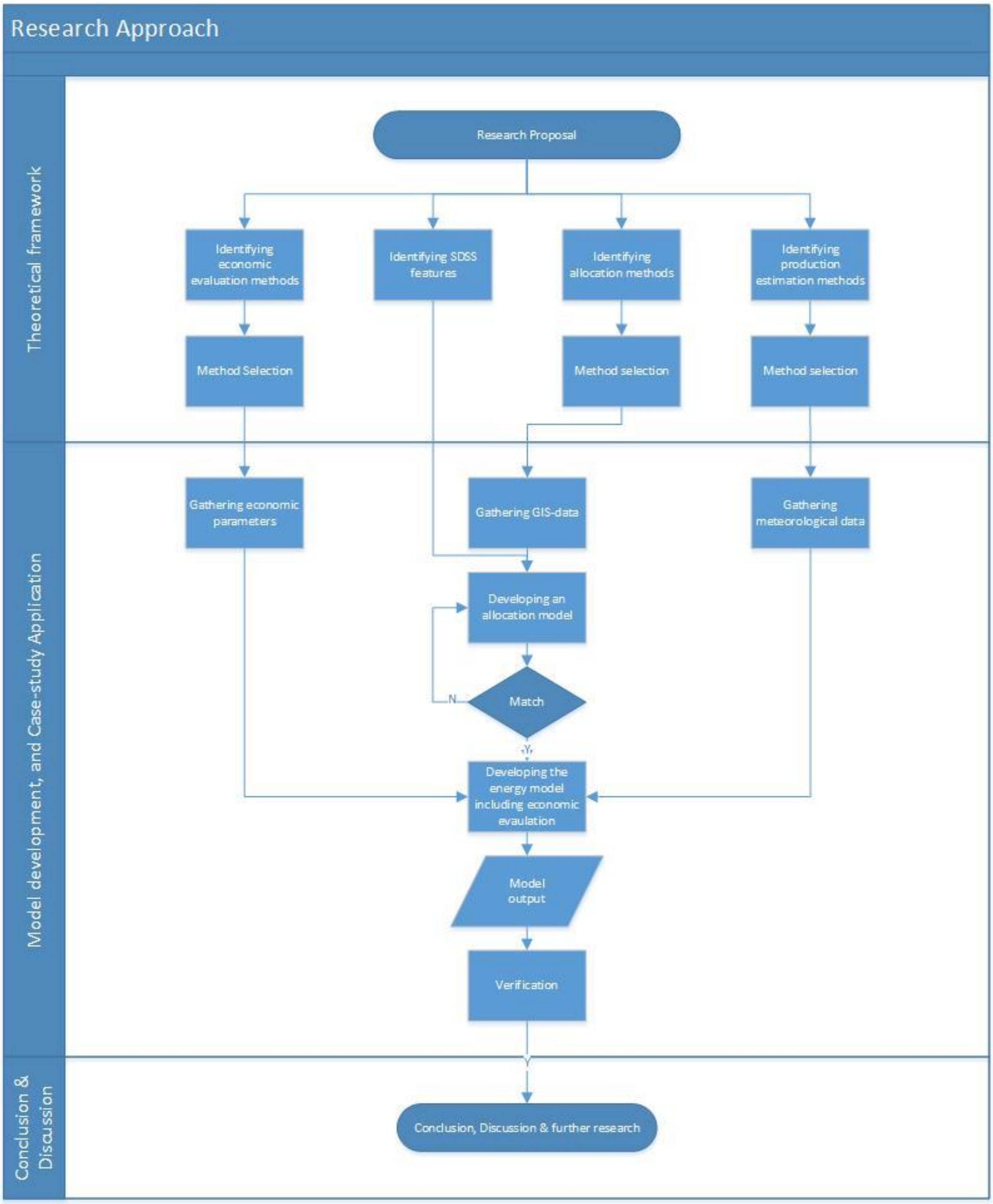

Figure 1. Research Design

1.4. Expected Results

This research will result in the development of a comprehensive energy optimization model for the development of renewable energy technologies on business premises to provide the research area with sufficient energy to become self-sufficient. The model should distribute the renewable energy technologies on the basis of safety, and energy production, using a GIS-map. Furthermore, the model focuses on size optimization to provide the best configuration for the business premises, and its occupants, aiming to minimize the costs of electricity. While incorporating spatial constraints for the development of certain energy technologies, and considering the local meteorological characteristics.

The results produced by the energy model will provide insight in the feasibility of an energy system on the research location, the configuration, and location of energy technologies within the urban environment.

2. Sustainable Energy Modelling

This study is done in as an extension of the concept of energy planning. Energy planning is the endeavour of finding a set of sources, and conversion devices so as to meet the energy requirements/demands of all tasks in an "optimal" manner (Hiremath, Shikha, & Ravindranath, 2007).Within, this concept multiple energy planning tools/ models are used to assist decision makers in the development of sustainable spatial plans. Energy models are carried out at a centralized level using computer-based modelling and, are valuable mathematical tools based on the systems approach (Timmerman et al., 2013).

These models are developed as decision support system, and spatial decision support systems. Where, decision support systems is the area of the information systems discipline that is focused on supporting and improving managerial decision-making (Arnott & Pervan, 2005). And, spatial decision support systems are designed to provide the user with a decision-making environment by coupling analytical multi criteria evaluation models used for selecting, and rating decision criteria, and alternatives in combination with geographical information systems (Densham, 1991; Gorsevski et al., 2013).

Geographical Information Systems, or GIS, is a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world (Maguire, 1991). GIS-map can be further specified into vector-, and raster map representation. Where, vector consist of a combination of polygons, lines, and points. In raster map is the geographical setting presented in a tiles with the size set by the user. In both maps, features data is represented in tables, and linked to the GIS-map. In this research, a vector-map representation is used to provide the geographical boundaries. The GIS-map in this research consist of multiple features to complete the analyses for the logical test to allocate renewable energy technologies, these data sets are presented in **Table 11**. The file is converted into a shapefile (.shp) to allow the modelling program to upload the GIS-map.

Furthermore, the energy models can also be subdivided in simulation, optimization models, hybrid models, and others. However, in this research the focus lies on the first two. The models diver in the operation of the systems. Simulation models use a pre-defined technological setups including one or multiple loads to simulate the operation of an energy system over a fixed period of time (Timmerman et al., 2014). Optimization models are used to compare alternative system configurations, and to evaluate different operation strategies in terms of energetic, economic, and environmental performance (Keirstead, Jennings, & Sivakumar, 2012).

In these models several renewable energy technologies are used, however in this research the distinction is made between wind energy, and solar PV energy. Wind energy is the energy produced by transforming the kinetic energy from the wind, into a mechanic motion used to produce electricity (Patel, 2006). Solar PV energy is the energy produces by converting the direct, and indirect solar irradiation into electricity, using photovoltaic cells (Patel, 2006).

To calculate the energy production multiple methods are proposed, and used by researchers. In this research, measured meteorological data is used to calculate the energy production by the renewable energy technology. However, the measured wind speeds have to be adjusted from the measured height to the hub height of a wind turbine. Therefore, the wind atlas methodology (Millward-Hopkins et al., 2013a) is used, moreover with this methodology it is possible to estimate the wind potential per parcel. The wind atlas methodology is a method with uses the logarithm properties of wind speeds in relation to the ground surface to estimate the wind speed at a different height, than the measured height. It uses three steps to calculate the estimate wind speed at a different height as presented in **Figure 2**. The equations with are used are presented in Eq. 6, Eq. 7, and Eq. 8. Where, z_{0fetch} is the roughness length of the fetch area, and d_{fetch} is the displacement height of the fetch area. The roughness length, and displacement height are variables to estimate the effect of the built environment on the logarithmic function of the wind speed. The measured wind speed height is set on the standard 10m. In the first step, the method uses the concept of urban boundary layer (UBL_{height}) which is the height where the urban environment does not have any influence on the wind speed. This is often set on a standard of 200m (Eq. 6). In the second step, the blending height (BL_{height}) of the wind speed is used, this is the height where the fetch-area has its influence on the wind speeds. This height is often set on twice to five times the average building height. Finally, the wind speed at hub height (HUB_{height}) is estimated. This height is predetermined by the height of the hub of the wind turbine. Furthermore, al calculations use predetermined values for the roughness length, and the displacement height of the surface area, these are presented in **Table 9**. The displacement height is the height in meters above the ground at which zero wind speed is achieved as a result of flow obstacles such as trees, and buildings. The roughness length is a corrective measure to account for the effect of the roughness of a surface on wind flow. These values can be set either with the aid of height data, or by visual analysis. In this research no height data is available therefore, the values of roughness length, and displacement height determined on basis of visual analyses. This method is used by several researchers to calculate the wind potential within the built environment, using measured wind speed data from the national meteorological institute.

This research uses meteorological data collected by the Dutch Royal Meteorological Institute. Using several weather station throughout the Netherlands they collect all meteorological data on an hourly bases (KNMI, 2015). The data collected by a weather station nearby the research area is used to simulate the hourly wind, and solar energy production. The data source provided by the KNMI contains numerous measurements of the weather. Most of this is redundant for this research. In fact, only two data streams are used in this research, which are the average wind speed per hour, and the average solar irradiation per hour. The data is freely available for everyone who wants to work with the data.

The energy production is calculate using this estimated hourly wind speed, therefore the method of Tina et. al. (2006) is used. This method uses the cut-in wind speed (v_c), rated wind speed (v_R), cut-out wind speed (v_F), and rated power (P_R) of the wind turbines set by the modeller. When the wind speed is higher than but not equal to the rated wind speed, the wind turbine will have a power output which is a fraction of the rated power of the wind turbine. If the wind spee d is equal, or higher than the rated wind speed, but lower than the cut-out wind speed, then the wind turbine will produce energy equal to the rated power of the wind turbine. The methodology is presented in Eq. 9. However, according to the producer of the used wind turbine the power output of the wind turbine is much higher than the rated power of the wind turbine. Therefore, it has to be noted that the outcome of the wind turbine are slightly more negative.

For the energy production of solar PV modules using meteorological data, no method to adjust measured irradiation data can be found in the existing literature. Therefore, no adjustments are used for the solar irradiation data. The energy production is calculated on an hourly bases using the methodology as proposed by Tina et. al. (2006) in this method the surface area of the PV module (A_c), the efficiency (η),and the hourly solar irradiation (I_β) is used. The power output of the PV modules is the product of these three variables. The equation is shown in Eq. 4.

The energy produced per hour of wind, and solar technologies are aggregated to calculate the total production of electricity in a year, this is defined in Eq. 12. Furthermore, to calculate the produced energy over the lifetime, the yearly produced energy (Eq. 12) is multiplied with the number of years the system is estimated to operate.

Furthermore, the demand profiles can be used to estimate the outage, and surplus in the system, in order to design a storage system for the renewable energy system. This could make the whole system with loads, and generation completely autarkic.

The allocation of the renewable energy technologies on a parcel is done on the bases of a number of logical test, provided by the regulations set by the Dutch Government, and system requirements. These logical test use the GIS-dataset presented in **Table 11**, to determine the possibility of allocating a renewable energy technology on that parcel. The test consist for wind turbines consist of; check if there are no vulnerable building in the vicinity, if there are wind turbine within the vicinity, and is there sufficient free area available to be able to install a wind turbine. For the allocation of PV module the only requirement is that there is a roof available to install the modules on. Because, for the installation of PV modules on rooftops, no legal restrictions, or permits are required. However, for the determination of the amount of available module on a roof is calculated by dividing the surface area of the roof by the required surface area for one PV module (Eq. 2). The required surface area calculated using the methodology proposed by Notenbomer (2014), and is depicted in Appendix 4) Method of Notenbomer. This method uses the length of the PV module, and the angle in which it will be installed to calculate the possible shading, and thereby the required distance between the PV-modules.

The objective of the energy model is to minimize the costs of produced electricity. To do so an economic evaluation is integrated. In this research a Levelized Unit Electricity Costs (LUEC) method is used. This method calculates the costs of energy over the whole operations of the system, and integrates the time-value of money, this is defined in Eq. 15. To integrate the time value of money, the discounted cash flow method is used. The discounted cash flow method is used to calculate the present value of all operation & Maintenance costs over the lifetime of the system, this is presented in Eq. 18. The lifetime of the system can be set by the user, by simple sliding a slider, and increase or decrease the time period per year. Additionally, the total capital costs have to be calculated, this is defined by in Eq. 16. The capital costs are calculate the amount of installed energy technologies times the price of purchase, and installation. The amount of energy technologies is given by the model, the price per technology can be set by the user in the Interface. The capital costs in this research are defined as the costs for purchasing, transporting, and installing the technology on the given location. The cash flow that is calculated using the discounted cash flow method is the O&M-costs with recur every year Eq. 18. The user can also set the amount of O&M-costs per technology per year.

To calculate the Levelized Unit Electricity Costs of proposed system, the total costs of the O&M over the lifetime of the system, and the total capital costs of the system are added, and divided by the total produced energy over the life time, this is presented in Eq. 12.

In the existing literature, there is an abundance of optimization algorithms, which can be used when trying to find optimal solution given one- or multiple constraints. The dominant optimization algorithms are heuristic. This is an approach to problem solving, learning, or discovery that employs a practical methodology not guaranteed to be optimal or perfect, but sufficient for the immediate goals (Pearl, 1984). In this study, the simulated annealing algorithm is used to be the optimization algorithm. The SA algorithm is a general optimization technique for solving combinatorial optimization problems (Erdinc & Uzunoglu, 2012). It is derived from the chemical process of heating a metal in a heat bath, and then cooled down by lowering the temperature in the heat bath (Erdinc & Uzunoglu, 2012).

The simulated annealing process consists of 7 steps (Jayaraman & Ross, 2003). The first step is the initialization, step 2 check feasibility, step 3 is Generate a feasible neighbouring solution, step 4 is the evaluation incumbent solution with neighbouring solution, step 5 is examining Metropolis condition, step 6 Increment counters. Step 7 adjust the temperature. The algorithm stops when no improved solution can be found, and/or the stopping criteria for the simulation is met.

The model itself is constructed in the software package Netlogo, which is a multi-agent programming language, and modelling environment for simulating complex behaviour (Tisue & Wilensky, 2004). The model consists of three major components, the interface, the code, and the input data. The interface of the model consists of the representation of the research area, and all variables that can be set by the modeller. The variables set in the interface are subdivided into multiple groups to which the variable consist.

First, of all there are three input windows for uploading the GIS-map, the meteorological data, and hourly demand data. These consist of the data types described earlier. Second, there are the settings for the optimization algorithm, which are the "temperature", which is a control value, the amount of iterations per cooling-down sequence, and cooling down rate, also the total energy demand of the research area can be set. Third, there are two economic variables which are the lifetime analysis, and discount-rate for the discounted cash flow. Fourth, the variables for the wind atlas methodology are integrated. These consist of the urban boundary height (z_{UBL}), and the roughness length of the urban boundary layer ($z_{0\text{-}ref}$), this is most often set on 0.14m. Furthermore, the roughness length of the fetch area ($z_{0\text{-}ref}$), and the displacement height (d_{fetch}) are integrated. Also, the urban blending height (z_{UBL}) is depicted as a variable. For the final step in this method the values for the local roughness length, and displacement height are not variable, and are derived from the GIS-map. Only the value of the hub height (z_{bl}) can be changed by the user. Fifth, the variables which are specific for the wind turbines can be set. These consist of the safety zoning regarding vulnerable buildings, and the interference with neighbouring wind turbines. Furthermore, the variables for calculating the power output of the wind turbine are variable, which are the cut-in wind speed (v_C), rated wind speed (v_R), cut-out wind speed (v_F), and rated power (P_R). Also, the economic variables of the wind turbine can be set, these are the capital costs of the wind turbine, defined by purchase, transportation and installation, and the O&M-costs which is a percentage of the capital costs. Finally, the variables for the PV modules can be set by the user these are the investment costs per PV-module, the O&M costs per module. Additionally, the modules efficiency can be set by the user, and the required surface area can be set.

These variables are all presented in **Table 14** till **Table 18**, and in Appendix 4) Variables of the Energy Model. The variables that can be set by the modeller correlate with the values that are required to assess the potential of renewable energy systems on the business premises.

Besides the input variables, the model also produces several outputs. These are also integrated in the interface of the model. Furthermore, the interface also depicts the output of the simulations, these are descripted in **Table 19** till **Table 21**, and also shown in Appendix 4) Variables of the Energy Model. The output which is generated, can be used for evaluating the potential of renewable energy on business premises.

The code described the behaviour of the "agents" in the model, and provides all boundaries set by the Dutch legislation, and modeller. Furthermore, the input is vital for the operations of the energy model. The input windows provide in the interface enables the possibility for the modeller to simple integrate the input data as described before.

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3. Spatial Decision Support Systems for Energy Integration

Abstract

The energy sector is going through a transition towards an energy system composed of distributed renewable energy technologies. The integration of these renewable energy technologies within the urban fabric involves multiple difficulties due to the complex, and diffuse nature of the built environment.

Spatial Decision Support System (SDSS) for the integration of renewable energy technologies within the urban fabric can offer the solution to deal with these multi-objective problems. The development of sizing optimization, and simulation for stand-alone renewable energy systems is a well research topic. In this chapter an attempt has been made to understand and review the various methodologies, objective and issues related to energy modelling.

Different SDSS for energy integration are described, as well as sizing optimization models, simulation models, hybrid models, and specific wind and solar energy models. Also proposed optimization algorithms are reviewed, and described. This review will provide insights for the development of a new renewable energy model for the use on business premises.

3.1. Introduction

The built environment, as a major consumer of fossil fuels, is at the start of the transition towards a decentralized, renewable energy system. To assist planners, and policymakers in their decision making regarding energy planning, comprehensive energy models can offer a solution to capture the different aspects of transforming the energy system towards a renewable based energy system. These decision support systems already exist in a wide variety (Fleiter, Worrell, & Eichhammer, 2011; Jebaraj & Iniyan, 2006; Keirstead et al., 2012; Rylatt, Gadsden, & Lomas, 2001; Timmerman et al., 2014).

Furthermore, researchers and decision makers are convinced that the future energy system consist of small-scale renewable energy system which produces, stores, and consumes its electricity on a local level. For the design of a local renewable systems comprehensive energy models can offer some structure. However, in this research the focus will lie on the integration of renewable energy technologies in the built environment, and no literature regarding energy storage will be elaborated.

Therefore, in this literature review the existing literature on decision support systems, and energy modelling will be examined, and general structure will be proposed for the development of a decision support energy model for the use on business premises.

The aim of this literature review is to develop an understanding about energy models for the optimisation of unit sizing of a wind/solar hybrid energy system for the use on business premises, with the aim to meet the energy demand of the area. The scope of this literature review will be limited to wind, and solar, and hybrid energy modelling. Wind, and solar energy are the most common renewable energy technologies at this moment. Furthermore, in this study the focus will lie on electricity generation. Technologies which produce both will be left out of the scope, due to the fact that they will also shift the focus towards heat. Also, possible optimisation algorithms will be elaborated.

In chapter 3.3.1 is to identify existing energy models, with their scope, level of analysis, and type of modelling. In chapter 3.3.2 is to identify multiple wind energy models, their aim, restrictions, allocation restrictions, economic, and energy calculation. Following, in chapter 3.3.3 the focus will lie on solar energy modelling (PV). In chapter 3.4 the economic evaluation which have been used in their studies will be discussed. Finally, in chapter 3.5 a conclusion is drafted analysing the most important features of a renewable energy model.

3.2. Spatial Decision Support Tools for allocating Wind & Solar PV

Spatial Decision Support System are derived from the broader concept of Decision Support Systems. Decision support systems (DSS) is the area of the information systems discipline that is focused on supporting and improving managerial decision-making (Arnott & Pervan, 2005). DSS is an interactive, computer-based system that aids users in judgment, and choice activities of provides for not only data storage, and retrieval, but also enhances the traditional information access, and retrieval functions with support for model building, and model based reasoning (Bandamutha, 2006). During the short history of DSS, it has moved from a radical movement, towards a mainstream commercial IT movement that all organizations engage.

Furthermore, Decision Support Systems are increasingly used in the development of sustainable land-use plans. Thereby, decision makers increasingly use Geographical Information Systems (GIS) to assist them in solving complex spatial problems (Densham, 1991). So forth, spatial decision support systems are on the rise, to assist decision makers with complex spatial problems. SDSS are designed to provide the user with a decision-making environment by coupling analytical multi-criteria evaluation models used for selecting, and rating decision criteria, and alternatives in combination with geographical information systems (Densham, 1991; Gorsevski et al., 2013), and assist in strategic decision-making activities considering spatial, and temporal variables, which help in regional planning.

Gorsevski (2013) demonstrated the benefits of applying a spatial decision support system framework for evaluating the suitability of wind farm siting in Northwest Ohio. Furthermore, in the research of Aydin (2010), a GIS-based environmental assessment of wind energy systems is proposed using fuzzy sets, including the legal restrictions, regarding noise, safety, natural reserves, bird habitats, and aesthetics. Ramachandra et al. (2011) proposed a GIS-based assessment of wind potential on district level. Janke (2010) also proposed a multi-criteria GIS model in order to be able to make spatial analysis for the allocation of wind farms. However, the proposed methods all evaluate the possibility of wind farms in a regional, or state level, and do not evaluate regional, or local scale allocation problems. Therefore, miss the specific problems concerning allocation of wind turbines within the urban environment. The constraints in above mentioned research can provide insight in the development of a new renewable energy allocation model.

The allocation of PV modules in the built environment is a well-researched topic. Amado et. al. (2012) proposed a model which connects the energy demand of buildings, with their ability to produce energy from solar resource integrating solar analysis. This model incorporates the geometry of the urban environment to determine the solar energy potential on the roof surfaces. Charabi et. al. (2011) proposed a model to assess the land suitability to allocate large PV-farms in Oman. Gadsden et. al. (2003) describe some aspects of a prototype software designed to assist local authority planners, and energy advisers in their efforts to increase the uptake of solar hot water systems. Rylatt et. al. (2001) described the development of a solar energy planning system, consisting of a methodology, and decision support software for planners, and energy advisers. Massimo et. al. (2014) developed a energy model which evaluates the availability of land, the productive potential, the estimation of residential energy consumptions, and the integration of PV arrays. Gagliano et. al. (2013) illustrate the capabilities of GIS to determine the available rooftop area for PV deployment for an urban area. For the allocation of PV modules no specific problem arises for the allocation within the urban environment. The spatial decision support system for analysing renewable technologies in the urban environment, and the suitability for installing wind turbines, and PV modules in the urban environment, are summarized in **Table 1**.

Analysing the literature it can be stated that the use of spatial decision support system for analysing renewable energy technology potential is a well research topic. However, the wind turbine allocation models focus on a greater scale, mostly on a regional scale. On the other hand, the PV allocation models do focus on the district level. Allocation models which feature both technologies are more scares, however the interest in this topic is growing. These allocation models can be used as a basis to develop a new renewable energy allocation model for the use on business premises.

Table 1. Spatial Decision Support Systems for allocating renewable energy technologies

Objective	Geographical Scale	Technology	Type of data	Source
Asses the wind potential in rural areas	Regional	Wind	Vector	(Ramachandra et al., 2011)
Environmental assessment of wind energy system	Regional	Wind	Vector	(Aydin et al., 2010)
Wind farm site selection	State	Wind	Vector	(Gorsevski et al., 2013)
Asses area potential for wind, and solar technologies	State	Wind / solar PV	Vector	(Janke, 2010)

Assess the best solar potential in the urban environment	District	Solar PV	Vector	(Amado & Poggi, 2012)
To predict, and realise the potential of solar energy	District	Solar PV	Vector	(Rylatt et al., 2001)
Predict the potential of PV	District	Solar PV, Solar Heat	Vector	(Hisarligil, 2013)
Evaluate PV potential	Regional	Solar PV	Vector	(Massimo et al., 2014)

3.3. Energy Modelling: a brief review

Energy modelling is derived from the broader concept of energy planning. Which according to Hiremath et. al. (2007), is the energy-planning endeavour involves finding a set of sources, and conversion devices so as to meet the energy requirements/demands of all tasks in an "optimal" manner.

Energy modelling is carried out at a centralized level using computer-based modelling and, are valuable mathematical tools based on the systems approach. These models can offer a solution as they identify the configuration, and operation that provide an optimal trade-off between economic and environmental performances (Timmerman et al., 2013).

To identify major approaches in the operations of energy models, the models will be reviewed based on multiple characteristics. The discussed models will be subdivided according to their approach. Furthermore, the models will be discussed on characteristics, which include, geographical scale, level of analyses, and temporal or static. In the existing literature a characterisation based on methodology is a common way subdivide the existing energy models. Multiple researchers (Baños et al., 2011; Bazmi & Zahedi, 2011; Fleiter et al., 2011; Keirstead et al., 2012; Timmerman et al., 2014) classified the energy models in the following division simulation models, and Optimization models.

Furthermore, existing wind, and solar energy models are investigated in order to find key characteristics. These models often neglect the effect of the built environment, however they do propose an economic evaluation, and energy optimization techniques. These two types will be described based on several characteristics. Namely; methodology, geographical scale, energy calculation, economic calculations, and temporal, or static.

3.3.1. Simulation models vs. optimization models

To develop a new energy optimization model, the current state of the simulation, and optimization models has to be analysed, to find gaps, opportunities, and existing approaches in developing energy models, and the operation of energy models. In this chapter, the characteristics of optimization, and simulation models will be described. The main difference between these models is that the simulation models use a predefined setup, and evaluate the performance by simulating the differences between supply, and demand. Optimization models are designed to find an optimal configuration within a predefined set of constraints. Most of the time the optimal configuration is defined by economic features.

Simulation models

Simulations models use a pre-defined technological setups including one or multiple loads to simulate the operation of an energy system over a fixed period of time. Simulation models are used to compare alternative system configurations, and to evaluate different operation strategies in terms of energetic, economic, and environmental performance (Timmerman et al., 2014), or also to test different policies(Chen, Duan, Cai, Liu, & Hu, 2011). However, simulation models show a greater variety of different approaches and modelling philosophies, which makes it difficult to clearly define this type of models (Fleiter et al., 2011). In **Table 2** several known simulation models are summarized with their characteristics.

Table 2. Existing energy simulation models

Energy tool	Geographical scale	Temporal / Static	Focus	Source
EnergyPLAN	Regional/national	Hourly Time	Heating, cooling, electricity, hydrogen, Natural gas	(Lund, Munster, & Tambjerg, 2004; Timmerman et al., 2013)
Homer	Local/ community	User defined time steps	Electricity One predefined heat load	US. NREL (Connolly, Lund, Mathiesen, & Leahy, 2010; Manfren, Caputo, & Costa, 2011; Timmerman et al., 2013)
TRNSYS	Local	Seconds	Building HVAC and micro generation	(Manfren et al., 2011)
HYDROGEMS	Single-project investigation	One minute time steps/ Hourly time steps	Library of hydrogen systems	(Connolly et al., 2010; Manfren et al., 2011)

EnergyPLAN (Lund et al., 2004) has been developed, and expanded on a continuous basis since 1999 at Aalborg University, Denmark. The main purpose of the tool is to assist the design of national or regional energy planning strategies by simulating the entire energy system, including heat, and electricity supplies as well as the transport and industrial sectors. EnergyPLAN optimises the operation of a given system as opposed to tools which optimise investments in the system.

HOMER (Lambert, Gilman, & Lilienthal, 2006) is a micro power design tool developed by the national renewable energy laboratory in the USA. HOMER simulates stand-alone and grid-connected power systems with any combination of wind turbines, PV arrays, run-of-river hydro power, biomass power, internal combustion engine generators, micro turbines, fuel cells, batteries, and hydrogen storage, serving both electric and thermal loads (Connolly et al., 2010).

TRNSYS (Manfren et al., 2011) is a transient systems simulation program that has been commercially available since 1975. This model has an open modular structure with open source code which simulates the electricity and heat sectors of an energy system(Connolly et al., 2010). It can simulate all thermal and renewable generation except nuclear, wave, tidal and hydro power. The tool uses a user-defined time-step, which can range from .01 seconds to 1 hour.

HYDROGEMS (Connolly et al., 2010; Manfren et al., 2011) is a set of hydrogen energy tools suitable for the simulation of integrated hydrogen energy-systems. It is particularly for stand-alone power systems(Connolly et al., 2010). The HYDROGEMS-tools can be used to analyse the performance of hydrogen energy-systems. The tools are particularly designed to simulate hydrogen mass flows, electrical consumption, and electrical production, but can also be used to simulate the thermal performance of integrated hydrogen systems. The HYDROGEMS-library consist of the following components, wind energy conversion, photovoltaic systems, water electrolyses, fuel cells, hydrogen gas storage, metal hydride, hydrogen storage, hydrogen compressor, secondary batteries, power conditioning equipment, and diesel engine generators.

Optimization models

Optimization models aim to find a best solution for a given objective function, within the set constraints. Classical optimization models minimize the total system costs across all time periods and assume equilibrium on energy markets, thus allowing for interactions between demand and supply (Fleiter et al., 2011). Timmerman et. al. (2014) also describe these models as evolution models, with the purpose of finding the least-cost investment paths. These models can be based on multiple optimization algorithms, as suggested by Erdinc et. al. (2012), Keirstead et. al. (2012), and Zhou et. al. (2010). Multiple optimization models exist, in **Table 3** multiple of these models are summarized based on scale, objective, technology, and optimization algorithm, etc.

The models start from a base year, and develops the configuration, and regulates the operation of the energy service demands at minimum costs, while complying with technologic, economic, and environmental limits. Every time slices the optimisation algorithm computes the values of the decision variables for the objective function, which is subject to a number of constraints.

Optimisation constraints are given by mathematical formulations that discount and accumulate costs, model the operation of technologies, keep track of capacity extension, describe commodity balances, and impose bounds to decision variables. Multiple existing modelling frameworks carry the label of an optimisation energy model, some examples are the MARKAL, TIMES, ETEM and OSeMOSYS, furthermore several optimization models are proposed by researchers.

Furthermore, hybrid energy optimization systems are a popular field of study for researchers. Kanase-Patil et. al (2011) proposed a sizing tool for a stand-alone PV/wind hybrid energy system based on load profiles. Borowy et. al. (1996) proposed a methodology for sizing the combination a battery bank and PV array in a hybrid energy system. Furthermore, there are several researchers proposed methods to optimize, or simulate the interaction between PV, wind, and in some cases batteries (Akiki, Eng, & Avenue, 1998; Deshmukh & Deshmukh, 2008; Nelson, Nehrir, & Wang, 2006; Tina et al., 2006; Wang & Yang, 2013). In **Table 3** the methods are summarized with their used optimization algorithms, objectives, input data, and used technologies.

Table 3. Existing energy optimization models

Energy Tool	Objective	Geographical Scale	Technology	Optimisation logarithm	Input	Source
MARKAL	-	National/ state/ regional	-	Linear Programming	Hourly/ daily	(Connolly et al., 2010)
TIMES	-	National/ state/ regional	-	Linear Programming	Hourly/ daily	(Connolly et al., 2010)
ETEM-SG	-	Regional	-	Linear Programming	Seasonal	(Babonneau, 2015)
OSeMOSYS	-	-	-	Linear Programming	-	(Howells et al., 2011)
-	Minimize costs and emission, and maximize system reliability	-	Wind, solar	-	Hourly meteorological data	(Akiki et al., 1998)
-	Minimize Cost of Electricity	-	Wind/PV and fuel cells	-	Hourly meteorological data	(Nelson et al., 2006)
-		-	Wind/solar battery power system	Particle swarm optimization	-	(Wang & Yang, 2013)

-	Capital costs	-	-	-	-	(Kanase-Patil et al., 2011)
-	Capital costs	-	Wind, solar and batteries	-	Probability density function for wind, and solar	(Borowy & Salameh, 1996)
-	-	-	Wind, and solar	-	Probability density function for wind, and solar	(Tina et al., 2006)
-	Maximize the Net Present worth of the system	-	Wind and solar energy	Particle swarm optimization	-	(Mohammad i et al., 2012)
-	Minimize diesel generator output, minimize total cost of energy	-	Wind, solar, diesel and batteries	Strength Pareto Evolutionary Algorithm	Average daily irradiation, and hourly wind speed	(Dufo-López et al., 2011)
-	Deficiency of Power Supply Probability	-	Wind, solar	DPSP technique	Hourly wind speed, and irradiation	(Kaabeche, Belhamel, & Ibtiouen, 2011)
-	Minimize total capital costs	-	Wind, solar and batteries	Branch-and-Bound	Hourly wind speeds, and irradiation	(Geem, 2012)

The MARKAL (Smekens, 2005) and TIMES (Loulou, Lehtila, Kanudia, Remne, & Goldstein, 2005) models are general purpose model generators tailored by the input data to represent the evolution over a period of usually 20-50 years or 100 years, of a specific energy-environment system at the global, multi-regional, national, state/province, or community level (Connolly et al., 2010). The modeller can set the options that minimises total discounted system cost or the total discounted surplus over the entire planning horizon.

OSeMOSYS (Howells et al., 2011) is a full-fledged systems optimization model for long-run energy planning unlike long established energy systems models. In the current version of OSeMOSYS the lowest net present cost of an energy system to meet given demands for energy carriers, energy services, or their proxies.

ETEM-SG (Babonneau, 2015) is a modelling tool tailored to represent a regional energy system. ETEM-SG is an extension of ETEM, a model which is developed and maintained by ORDECSYS, an which belongs to the MARKAL/TIMES family of models (Babonneau, 2015). ETEM-SG takes into account the intermittency of electricity produced by renewables. The objective is to find the energy system with the minimum total discounted cost over the horizon.

The models as presented in **Table 3** all consider the time value of money, and aiming to find the financially most optimal solution. However, only the MARKAL/TIMES model considered the community scale energy optimization. Unfortunately, it is unclear if these models consider the spatial influences on the development of a renewable energy system.

The optimum design of renewable energy system is a popular topic, and there is sufficient literature dedicated to this topic. The design problems are related to the determination of the optimal configuration of the power system, and optimal location, type and sizing of generation units installed in certain nodes, so that the system meets load requirements at minimum cost (Erdinc & Uzunoglu, 2012). To acquire such a solution multiple optimisation techniques are used by researchers, from linear programming, to particle swarm optimization. Uzunoglu (2012) described multiple optimization algorithms, and programs which have been used for energy modelling, also Keirstead (2012) mentioned multiple optimization algorithms. Zhou et. al. (2010), also described multiple optimization approaches, and subdivided these into optimization approaches, which consist of Artificial intelligence methods, iterative technique, probabilistic approaches, and graphic construction method. In **Table 4** summary of used optimization algorithms is depicted.

Table 4. Optimization algorithms

Optimization approach	Optimization algorithms	Advantages	Disadvantages	Sources
Artificial Intelligence	Genetic Algorithm	Efficient performance Sufficient examples	Harder to code	(Fadaee & Radzi, 2012; Gandomkar, Vakilian, & Ehsan, 2009)
Artificial Intelligence	Particle Swarm Optimization	Easy to code Sufficient examples	Lower performance for finding global optimum	(Mohammadi et al., 2012)
Iterative technique	Linear Programming	Easy to code	Computational time inefficiency	(Howells et al., 2011; Loulou et al., 2005; Smekens, 2005)
Iterative technique	Simulated Annealing	Easy to code, Sufficient examples	Relatively lower performance	(Busetti, 2013; Dowsland & Thompson, 2012; Gandomkar et al., 2009)
Artificial Intelligence	Ant Colony Algorithm	Easy to code	Lower performance for finding global optimum	(Erdinc & Uzunoglu, 2012)

3.3.2. Wind energy modelling

The optimal location and configuration of wind turbines in city centres is a problem multiple researchers have tried to solve (Drew, Barlow, & Cockerill, 2013; McWilliam, van Kooten, & Crawford, 2012; Millward-Hopkins et al., 2013a; Ozturk & Norman, 2004; Sunderland, Mills, & Conlon, 2013; Toja-Silva, Colmenar-Santos, & Castro-Gil, 2013). For wind turbine allocation multiple research tools are available, with the focus on the urban, or rural area. Main difference between the research tools, is the methodology between the models. The methodology ranges from the use of CFD (Computational fluid Dynamics) models (Toja-Silva et al., 2013) with a high level of detail, to lower detailed estimations of local wind speeds (McWilliam et al., 2012; Millward-Hopkins, Tomlin, Ma, Ingham, & Pourkashanian, 2013b; Sunderland et al., 2013) . Sunderland et. al (2013) use a log wind profile method to extrapolate measured wind speeds from a non-urban environment to an urban environment. Millward et. al. (2013a) use the same method for their assessment of wind potential in the city of London. Also, the purpose of these models differ. McWilliam et. al. (2012) uses the power law to extrapolate the measured wind at height x, usually 10 meters, to the height of the wind turbines hub height.

Schallenberg et. al. (2013 identified three methods to extrapolate wind data in the current literature, including the logarithmic method of Sunderland, and Millward, and the power law of McWilliam. The third method is the log-linear law (Log LL), which is based on the Monin-Obukhov similarity theory. The Log-LL, and the Log-L methods make use of the roughness of the urban area to calculate the effect on the differentiation of the wind speed over the height.

The roughness length is a parameter which characterizes the influence of surface irregularities on the vertical wind speed profile. This means, the rougher the terrain the thicker will be the affected layer of air, and the more gradual will be the velocity increase with height. In the absence of experimental data, the roughness length has to be selected on the basis of visual inspection of the terrain (Schallenberg-Rodriguez, 2013).

The displacement height is a parameter which characterizes the height in meters above the ground at which zero wind speed is achieved as a result of obstacles such as trees, and/or buildings. This adjustment can be set using the values set in **Table 9**.

The power-law depends on the Hellmann exponent, which depends on the atmospheric stability, wind speed, temperature, land features, and the height interval (Schallenberg-Rodriguez, 2013). This implies that a single parameters that describes the wind profile at a particular location. The geographical scale on which the methods are used do not differ much. However, the CFD-method is primarily used for the estimation of wind energy around a single building, and is characterized by its relatively high amount of details (Toja-Silva et al., 2013). This is not relevant for a district evaluation of wind potential in the urban environment. In **Table 5** several methods which have been used in previous research are summarized.

Table 5. Wind profile methods

Method	Level of Analysis	Temporal or static	Source
CFD	Building	-	(Blocken & Persoon, 2009; Toja-Silva et al., 2013)
Log wind profile	City, district Grid of 100 by 100	Static or Temporal	(Millward-Hopkins et al., 2013a; Schallenberg-Rodriguez, 2013; Sunderland et al., 2013)
Power Law	Regional, District Grid 100 by 100	Static or Temporal	(Schallenberg-Rodriguez, 2013; Sunderland et al., 2013)
Log-Linear Law	Regional, district	Static or Temporal	(Schallenberg-Rodriguez, 2013)

When the potential wind velocity in the urban area is estimated, the next step is to evaluate the wind production of a wind turbine, given the previously determined wind speeds. For the calculation of the wind energy production several approaches are discussed in the literature. Patel (2006) proposes a method with which the annual energy potential of the area can be quickly estimated, using the average wind speed per year. Tina et. al. (2006) proposed a method which also includes some properties of a wind turbines, such as the rated power output, cut-in wind speed, rated wind speed, and cut-out wind speed. Billinton (2004) also proposed such a method, however the calculation for the wind production are slightly different. The calculations as proposed by Giorsetto (1983) to calculate the energy production when wind speed are below the rated wind speed of the turbine. Both, use the cut-in, current wind velocity and rated wind velocity to calculate the fraction of rated power output, in order to calculate the electricity production at time t. Several methods to calculate the wind profiles are summarized in **Table 6**.

Table 6. Wind energy production methods

Method	Temporal or static	Input	Source
Mean	Static	Mean yearly windspeed	(Patel, 2006)
Hourly	Temporal	Hourly windspeed	(Tina et al., 2006; Yang, Lu, & Zhou, 2007)
Hourly	Temporal	Hourly windspeed	(Billinton & Bai, 2004; Giorsetto & Utsurogi, 1983)

Besides, wind speed adjustment, and energy production of wind turbines, there is an allocation issue for developing larger scale wind turbines in the built environment. For safety reason several distance regulation are in effect, when developing wind turbines near, or in the built environment (AgentschapNL, 2012). Furthermore, to minimize the interference between multiple wind turbines certain distances have to be considered (McWilliam et al., 2012; Patel, 2006). AgentschapNL (2012) defined two safety zones, the first one is the size of a rotor blade, and forbids the presents of limited vulnerable objects within this zone. The second, is about the size of the height of the wind turbine plus the rotor size, and forbids the presents of vulnerable objects within this contour.

When installing a cluster of wind turbines within a small area, certain spacing between the wind tower must be maintained to optimize the energy crop over the year(Patel, 2006). This depends on the terrain, wind direction, speed, and turbine size. According to Patel (2006), the optimum spacing is found in rows of 8 – 12 rotor diameters down wind, and 2 – 4 rotor diameters in the crosswind direction. However, Mcwilliam et. al. (2012) proposed a micro-sitting model to allocate wind turbines which depends on wind turbine spacing and the location of sensitive noise receptors, such as dwellings. However, in this research the population density is used to estimate the noise receptors. The scale of this analysis is based on the development of wind turbines within a large region, instead of a city district.

3.3.3. Solar (PV) energy modelling

In the existing literature, examples of solely solar energy modelling, and allocation are not frequently found. However, sizing optimization is a frequently researched topic, however this is mostly done in combination with another energy technology this topic will be discussed in chapter 0. For this reason, we will limit the scope of this chapter to energy generation, and allocation of PV-panels.

An explanation for the limited research in solar energy modelling can be the fact that the allocation for PV-technology is rarely restricted by safety, nuisance regulations, or other environmental aspects. In fact, the development of PV-panels on a roof is only restricted by the fact that there needs to be enough distance from the roof edge to the installation in order to safely walk around the installation, and to limit the visibility of the installation (Notenbomer, 2014).

In the existing literature multiple methods for the calculation of energy generation for PV panels are proposed. Patel (2006) proposed a method which includes the hourly solar radiation, and also the effect of temperature on the efficiency of the PV panels. While Deshmukh et. al. (2008), Borowy et. al. (1996),and Wang et. al. (2013), also include the indirect irradiation into the hourly production equation. Nelson et. al. (2006), Akiki et. al. (1998), and Tina et. al. (2006) proposes a simpler which only focuses on the hourly insolation data, surface area of the PV array, and the overall efficiency of the panels. This methods assumes that the PV system has a maximum power point tracking, and it ignores the temperature effect on the PV panels. The only difference between the last three studies is that Tina et. al. (2006) correct the irradiation data from a horizontal surface to the inclination of the PV panels. Besides, these methods there exist another even more simplified method to calculate the power production of a solar PV array per year. It uses the Watt peak, Wp , performance of the array, and multiply that with a constant, which varies according to the geographical location. In the Netherlands this constant is 0.85 however, this is not a very accurate, and trustworthy method. **Table 7** gives a quick summary of the methods.

Table 7. Solar energy production methods

Temporal or static	Input	Source
Temporal	Temperature Irradiation data Efficiency panels Surface area	(Patel, 2006)
Temporal	Temperature Irradiation data (Direct/ Indirect) Efficiency panels Surface area	(Borowy & Salameh, 1996; Deshmukh & Deshmukh, 2008)
Temporal	Hourly Irradiation Efficiency panels Surface area	(Akiki et al., 1998; Nelson et al., 2006; Tina et al., 2006)
Static	Efficiency panels Constant	-

3.4. Economic Evaluation

It is evident that an economic analysis is required, when dealing with an optimization problem. In the current literature of energy modelling, multiple objective are proposed in order to find a best solution for a given problem. As can be seen in **Table 8** researchers use different objective in order to find an optimal solution for their problem. However, in a major part of the found literature economic evaluation of solar/wind energy systems is a crucial part in the optimization of energy systems. However, as with the objective, different approaches are used in order to find the economic evaluation.

As researchers solely focus on the capital costs of the energy systems, they neglect the influence of Operation and Maintenance costs throughout the life time of the system (Borowy & Salameh, 1996; Geem, 2012). This is also the case when the focus lies on the Cost of Energy, where the capital costs are divided by the amount of electricity is generated in a year (Dufo-López et al., 2011; Nelson et al., 2006). This focus limits itself to the evaluation of an energy system in one single year. Mohammadi (2012) integrated the time-value of money according to the capital recovery factor method. This incorporate the effect of inflation on the value of money over time. This enables the researcher to evaluate the effect of operation and maintenance costs on the feasibility of the proposed energy system. Moreover, the economic value of the system can be calculated over a period of time, which is equal to the life expectance of the system. Kaabeche et. al. (2011) also uses the capital recovery method to calculate the present value of money. Furthermore, the discounted cash flow can also be integrated to calculate the future value of money, this is a common method to evaluate investment decision.

Table 8. Economic evaluation of energy system

Method	Time-value of money	Description	Source
LUEC method (Capital recovery factor)	Yes	LUEC is defined as the total cost of the whole hybrid system divided by the energy supplied from the hybrid system. The capital recovery factor is the ratio used to calculate the present value of any annuity.	(Kaabeche et al., 2011)
Total costs of the system (Capital recovery factor)	Yes	The capital recovery factor is the ratio used to calculate the present value of any annuity.	(Mohammadi et al., 2012)
Levelized cost of energy (capital recovery factor)	Yes	Is similar to the method as the LUEC method.	(Dufo-López et al., 2011; Nelson et al., 2006)
Discounted cash flow	Yes	Is a comprehensive method to estimate the present value of all incoming, and outgoing cash streams.	(Metrick & Yasuda, 2011)

3.5. Conclusion

Major approaches, and methods have been identified in the existing literature concerning spatial decision support systems, and urban energy modelling.

To incorporate the spatial constraints of the built environment a GIS approach is proposed in this research. In the reviewed literature there is a clear preference for the use of vector GIS maps. However, it has to be noted that the research area in these articles are of a grander scale than the intended research area in this study. Though with the focus developing a local energy allocation a vector map represents the research area in a realistic manner. The vector-map gives a very detailed, and clear view of the research area. Furthermore, this provides a comprehensive way to incorporate individual consumers for future use of the model. The GIS-map not only consist of a vector-map, but also a feature lists containing all valuable data-required this data is further elaborated in chapter 4.3.1.

Technology incorporated in this research are the PV-modules, and wind turbines. These technologies are restricted to a number of legal regulations. The PV-modules are in the Netherlands restricted to two regulations when installed on a flat roof. First, there needs to be sufficient space available for a mechanic to safely walk around the installation. Second, the PV-modules have to be limited visible from the street surface. These restrictions will be incorporated in the allocation model of the PV-modules. In this research the assumption is made that PV modules will only be installed on roofs. Therefore, the only required GIS data required is the amount of roof surface is available on any particular parcel.

For the allocation of wind turbine multiple restrictions are in effect, due to safety a minimal distance is required between dwellings and the wind turbine, and other installations and wind turbines. In this research the distance requirements regarding vulnerable, and limited-vulnerable buildings will be integrated, as well as distance requirements in relation to other wind turbines. Safety demand for the allocation in relations to roads, and railways are neglected. The allocation of wind turbine on parcels requires more elaborated spatial data. The following parameters are required to allocate a wind turbine, available free surface, vulnerability of surrounding buildings, and others.

The energy production can be calculated using average wind speeds, and solar irradiation, however average values for energy calculation can lead to too optimistic values. Moreover, this energy model will be developed with the intention to eventually enhanced it with a storage component. In order to do so a dynamic energy production calculation is required. Therefore, the energy production of the renewable energy technologies will be calculated with the use of hourly meteorological data. This approach enables a realistic view of the potential energy generation at the research area. Furthermore, to calculate the energy generation of the technologies present at the research area, the method as proposed by Tina et. al. (2006) are used.

However, to fully incorporate this data in the model an adjustment has to be made to coop with the roughness, and the characteristics of the surrounding area. To deal with the height, and urban surface adjustment the method proposed by Millward et. al. (2013a). This approach uses three steps to adjust the measured wind speed at 10m, to an estimated wind speeds at the Hub height. This method will be further elaborated in Part 2.

For the optimization of the energy technologies in the research area an optimization algorithm is used to find the optimal configuration. In this model the simulated annealing approach is used to find, and improve the configuration of the energy technologies and propose a best fit solution, within the set objective, and constraints. The simulated annealing optimization algorithm is designed to be able to “climb” out of local minima, and find the global optimum solution. Furthermore, this is a very comprehensive method, and is easily coded.

The aim of this model is to find an optimal configuration of renewable energy technologies on business premises. The optimum solution for the configuration of renewable energy technologies is to minimize the overall costs per produced kWh. In this manner, the system capital costs, operation and maintenance costs, and the total produced energy is combined in one value, which can be easily tested, and provides a clear view on the feasibility of the system over a pre-determined lifespan. For this method the time-value of money will be by aggregating the discounted-cash-flow methodology. This method incorporates the time value of money, and is a comprehensive, and often used method to calculate the feasibility of investment, and business decisions.

Finally, the model must be able to assist decision makers with the development of energy system within the built environment. For this reason all variables of importance are integrated in the Interface of the model.

Furthermore, the outputs are also visualized in the Interface to give a clear view of the configuration of the model. The output generated by the model gives the modeller insight in the potential of the research area. The location, energy production per technology, number of technologies, capital costs, O&M-costs, and overall Costs per produced kWh.

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4. Development of a Spatial Decision Support Energy Model

Abstract

The allocation of renewable energy technologies within the urban environment, where a trade-off has to be made between multiple objectives present a major challenge for planners, and system developers. It can be stated that there are no straightforward solutions, to find an "optimal" solution to provide the research area with sufficient energy, without administrating major changes to the urban environment, due to the complexity, and diffused nature of this urban environment.

For this reason, a spatial decision energy support tool is develop to find an "optimal" configuration to supply the research area with sufficient energy. The aim of the model is to find an "optimal" solution, with the least costs per produced kWh in order to provide users with affordable electricity. The focus lies on the integration of two major renewable energy technologies namely, wind and solar power in the urban environment. The spatial environment is represented by a GIS-map consisting of individual parcels of the research area. The parcels provide the boundaries, and also the spatial constraints of the research area.

In order to incorporate the wind potential in the urban environment of a business area the wind atlas methodology is integrated to assess the wind potential per parcel, in relation to its build surface. Furthermore, meteorological data from a weather station in the vicinity of the research area is integrated, to generate an accurate estimation of the amount of energy produced on a yearly bases. For the optimization of the configuration the optimization algorithm simulated annealing is used.

The model is tested on a case-study in the Netherlands on a business premises near 's-Hertogenbosch, called "de Brand". Three scenarios are tested on this case. First, the scenarios, a 50 kW case, is tested where the meteorological data represent the geographical location of the business premises near Den Bosch. Second, a scenario is proposed where a larger wind turbine is introduced in the model. Third, a scenario is proposed where the capital costs of the PV modules decrease with 10% of its original value.

In all case a configuration is proposed solely consisting of PV modules. This can be explained by the low average velocity of the research area. However, all proposed configuration only have small differences, implying that the model always finds approximately the same configuration for when only small changes are made in the configuration of the variables.

4.1. Introduction

The allocation of renewable energy technologies within the urban fabric is a complex problem for the sustainable redevelopment of urban districts. This problem arises due to the complex, and diffuse nature of the urban fabric. The problem decision makers are facing is finding an "optimal" solution to provide the research area with sufficient energy, without administering major changes to the urban environment.

The allocation of services, and facilities in the existing fabric of the urban environment requires the ability to balance numerous variables, constraints, and conflicting objectives, to find a realistic, and appropriate solution for any given spatial problem. SDSS models can assist decision makers with the automated process of problem solving, and can offer a solution, to identify the configuration, and operation that provide an optimal trade-off between economic, and environmental aspects.

Researchers have developed comprehensive energy models to aid decision makers in the development of redevelopment plans. Multiple methods have been developed to find the optimal sizing of renewable energy technologies to provide an area with sufficient energy (Borowy & Salameh, 1996; Kaabeche et al., 2011; Nelson et al., 2006; Zhou et al., 2010). However, in many of the research spatial constraints are hardly considered. In the research of Millward et. al. (2013b) the urban fabric is integrated to take into account the urban fabric on the wind potential in the city. However, the scope of Millward et. al. (2013b) doesn't incorporate the allocation of wind turbines in the urban environment.

In this research, an energy optimization model is proposed for the redevelopment of business premises, which will size the distribution between solar PV, and wind energy in an "optimal" manner, while considering the spatial constraint given by the research area, and providing enough renewable energy to make the research area self-sufficient. For this research, methods, used by several researchers, are used for the calculation of renewable energy production. (Ekren & Ekren, 2010; Kaabeche et al., 2011; Nelson et al., 2006; Tina et al., 2006).

In chapter 4.2.1, the proposed energy model is further elaborated with its objective function, constraints, and methods. In chapter 4.3, the required data is described for operating the model. In chapter 4.4, the user interface is presented using a case-study of a business area in the Netherlands. Furthermore, the results of this case-study are presented under different scenarios. In chapter 5, the operations of the energy model are discussed in retrospect.

4.2. Model Design

The optimization energy model proposed in this research, aims to find the best configuration of renewable energy technologies within the built environment, and more specifically on business premises.

In this chapter the setup of the model is further elaborated. For the optimization an objective function is defined in chapter 4.2.1. In chapter 4.2.2, and 4.2.3 the methods are proposed for allocating, and calculating the energy production of PV arrays, and wind turbines. The optimization algorithm used is discussed in chapter 4.2.4. Finally, in chapter 4.2.5 an economic evaluation is defined to check the economic variables to the decision parameters.

4.2.1. Objective function

In this research, an optimization energy model is proposed for the use on business premises in the Netherlands. The objective of the proposed method is to optimize the least costs per produced unit of electricity (kWh). This results in the following objective function;

Minimize Costs/$kWh_{production}$ (€/kWh; COE) (Eq. 15)

Subject to safety, and spatial constraints are met (Chapter 4.3, 4.2.2, 4.2.3)

Capacity constraint $E_G \geq E_D$

The objective function is subject to spatial constraints as given by the built environment, legal restriction defined by national governments (chapter 4.2.2 & 4.2.3), and the produced electricity over a year has to be equal to, or larger than the yearly energy demand.

4.2.2. Mathematical model for PV systems

The amount of solar radiation that reaches the ground depends on the geographical location, and climatic conditions. In this chapter, a PV array allocation method is proposed. Furthermore, the method for estimating hourly energy production is defined, and specified.

Allocation of PV panels

For the allocation of PV arrays on a flat roof of buildings only two restrictions are applied, which are the requirement that a mechanic can safely, and easily walk around the PV arrays, and that the PV array are limited visible from the ground floor (Notenbomer, 2014). This restriction implies that there needs to be sufficient space between the roofs edge, and the PV modules. The value of required surface area per PV module can be adjusted by the modeller in the interface, this will be further elaborated in chapter 4.4.

Before allocating PV modules on a specific parcel a number of conditional statements (Eq. 1) have to be completed. For the allocation of PV modules this implies the following statement;

$$\varphi \rightarrow \psi \quad (1)$$

Where, φ is the conditional statement verifying a parcel if it complies with the condition for installing PV modules. In this case, this results in verifying the parcel if it has a roof surface large enough to utilize PV modules. ψ is the procedure following if φ is true. This procedure results in the allocation of a number of PV modules using Eq. 2.

Furthermore, in this research, we assume that when PV panels are installed, the whole roof is installed with PV panels. This results in Eq. 2, as shown here below.

$$N_{pv\,(N)} = \frac{RS_{building\,(N)}}{SA_{PV}} \quad (2)$$

Where, N_{pv} is the number of panels that can be installed on the roof in question, and $RS_{building\ n}$ is the roof surface which is retrieved from the GIS-map. The SA_{pv} is the required square meters a PV module needs when installed on a flat roof in a 35° angle.

The required square meters to install one PV module on a flat roof is calculated using the method proposed by Notenbomer (2014) (Eq. 3), this method calculates the minimum distance required between PV module to minimize the shadow effect of succeeding PV module , and is further elaborated in Appendix 5) Method of Notenbomer. This method is uses an inclination conversion value, which is depend on the angle of the installed PV module, to calculate the distance required between PV modules.

$$SA_{PV} = (LPV * ic) * WPV \tag{3}$$

Where, SA_{PV} is the required square meters a PV module requires to be installed on a flat roof, *LPV* is the length of the PV module, *ic* is the conversion value which is related to the angle of the PV module, and *WPV* is the total width of the PV module.

It has to be noted that in the allocation of PV modules the geometry, and orientation of the buildings are neglected. Additionally, it is assumed that the roof is completely covered with PV modules. This limits the possible outcomes for the model, and therefore limits the simulation time of the model.

PV Energy Generation

For the hourly energy generation of the pv-panels, the method of Tina et. al. (2006) is used shown in Eq. 4. This method uses hourly meteorological data to calculate the hourly power output of the PV array. The hourly solar irradiation is provided by the KNMI database (chapter 4.3.2).

$$P_{PV} = A_C * \eta * \mathrm{I}_\beta \tag{4}$$

Where, P_{pv} is the power output of the PV module in a hour, A_C is the total square surface of the PV array, which is determined by the model, and only indicates the active surface of the PV module, and η is the efficiency of the PV module in percentages, and can be set by the user (chapter 4.4.2). I_β is the hourly solar irradiation given by the meteorological data.

The total energy production of the PV modules is calculated by summarizing all values of Eq. 4 into one number using Eq. 5.

$$P_{pv(t)} = \sum_{i=1}^{i=8760} P_{pv} \tag{5}$$

Where, $P_{pv(t)}$ is the total energy production of PV modules in one year, and P_{pv} is the energy production per hour. With this approach, it is assumed that the PV panels have maximum power tracking. The summation runs from 1 to 8760 due to the amount of hours in a year. The method uses the total active surface of the PV array, and combine the module efficiency, and transformer efficiency into one percentage of total converted irradiation.

4.2.3. Mathematical model for Wind turbines

The allocation, and energy production for wind turbines in the built environment, requires more extensive planning then that of PV arrays. This is mainly due to the safety restriction, and the possible interference of the built environment on the local wind speed. Therefore, comprehensive modelling for the allocation of wind turbines is required, in order to find the location with the highest wind energy potential, while being subject to legal restrictions. The wind speeds measured by the KNMI (chapter 4.3.2) have to be adjusted to the local level of the research area, using the wind atlas methodology. Furthermore, the legal restrictions of allocating wind turbines will be discussed.

Wind Atlas Methodology

The regional wind climate is used as the starting point of the model is the freely available KNMI database (KNMI, 2015). To estimate the wind speeds at a parcel level, the Wind Atlas Methodology as proposed by Millward et. al. (2013a) is used. This methodology enables the user to correct the measured wind speeds to a different height at a location nearby. It involves applying a number of adaptations to a wind speed database to account for the effects of the urban area upon wind profiles. It relies on knowledge of the regional wind climate in the city, and also the aerodynamics properties of the urban surface, which are typically quantified using the parameters roughness length (z_0), and displacement height (d), these are shown in **Table 9**. The general concept of this method is represented in **Figure 2**.

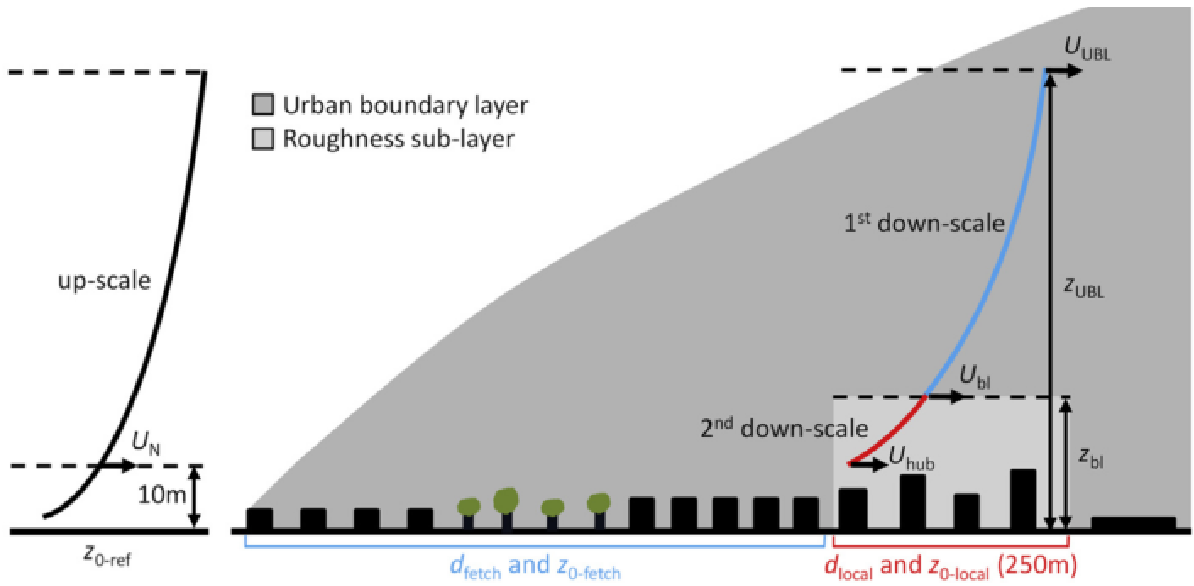

Figure 2. Schematic representation of the Wind Atlas Methodology (Millward-Hopkins et al., 2013a)

The 'wind atlas methodology' uses therefore three scaling procedures. The first scaling procedure, involves scaling the wind speeds up towards the top of the urban boundary layer (UBL), at height z_{UBL} (Eq. 6). This is usually set as a constant of 200 m, at this height the influence of the urban surface is assumed to be absent (Millward-Hopkins et al., 2013b). The wind speed at this height is calculated using the standard logarithmic wind profile, with a reference 'open country' roughness length (Z_{0-ref}) of 0.14m.

This results in the following equation;

$$U_{UBL} = U_N \frac{\ln(z_{UBL}/z_{0-ref})}{\ln(10/z_{0-ref})} \tag{6}$$

Where, U_N is the hourly wind speed at the measured height of 10m. The roughness length is donated as $z_{0-ref,}$ and is a fixed value. z_{UBL} is the height of at the top of the Urban boundary Layer. And, U_{UBL} is the corrected hourly wind speed at UBL height.

In the remaining procedure of the methodology, the wind speed at the top of the UBL is down-scales to the hub height of the wind turbine, in two stages, using aerodynamic parameters appropriate for the urban area. These parameters can be estimated based upon detailed data describing the geometry of all buildings and major vegetation in the city. In the absence of this data these parameters can be estimated on visual inspections (Schallenberg-Rodriguez, 2013).

The second procedure of the methodology (Eq. 7) is used to estimate the wind speed at the blending height (z_{BL}). The blending height is considered to be the top of the 'roughness sub layer', below this height the wind profile is considered to be determined by the local geometry. The blending height is mostly set on a height of 2 – 5 times the average building height. The wind profile above the z_{BL} is assumed to be affected by the area directly upwind of the prediction location, extending to a distance of 5 km, the area can be referred to as "upwind fetch". To obtain the U_{BL}, aerodynamic parameters appropriate for this fetch are used in the logarithmic profile;

$$U_{BL} = U_{UBL} \frac{\ln[(z_{bl} - d_{fetch})/z_{0-fetch}]}{\ln[(z_{UBL} - d_{fetch})/z_{0-fetch}]} \tag{7}$$

Where, U_{bl} is the adjusted wind speed at blending height. z_{0-ref} and d_{fetch} are the fetch roughness length and displacement height respectively, as shown in **Table 9**. z_{UBL} is the height at the top of the Urban boundary Layer. And, U_{UBL} the adjusted wind speed as calculated in Eq. 6. For the estimation of roughness length, and displacement height of the "upwind fetch" the dominant wind direction is used.

The third procedure (Eq. 6), is down-scaling the wind speed at blending height to the turbine hub height (z_{HUB}). The assumption is now made that the wind profile is adapted to the local area, and the aerodynamic parameters are estimated for this local area. The local area in this model will be the individual parcels, therefore the displacement height, and roughness length of the parcels have to be integrated in the GIS-map, as stated in chapter 4.3.1.

These parameters will be the input of the logarithmic profile;

$$U_{hub} = U_{bl} \frac{\ln[(z_{hub} - d_{local})/z_{0-local}]}{\ln[(z_{bl} - d_{local})/z_{0-local}]} \quad (8)$$

Where, U_{bl} is the adjusted wind speed as calculated in Eq. 7. $z_{0\text{-}local}$, and d_{local} are the roughness length, and the displacement height of the local area. z_{bl} is the blending height, and U_{hub} is the estimated wind speed at the hub height. The wind speed at the hub height will be used to calculate the energy production of the wind turbine. Note that in this research the wind direction is neglected, due to the fact that we assume that the wind turbines hub will always rotate towards the wind direction.

Table 9. Roughness length and Displacement Height

Terrain description	Roughness Length (Z_0) **(Wieringa, 1992)**	Displacement Height (d) (Best et al., 2008)
Open Sea	≈ 0.0002	0
Concrete, flat desert, tidal flat	0.0002 – 0.0005	0
Flat snow field	0.0001 – 0.0007	0
Rough ice field	0.001 – 0.012	0
Fallow ground	0.001 – 0.004	0
Short grass and moss	0.008 – 0.03	0
Long grass and heather	0.02 – 0.06	0
Low mature agricultural crops	0.04 – 0.09	0
High mature crops	0.12 – 0.18	0
Regularly-built large town	0.7 – 1.5	3.10
Tropical forest	1.7 – 2.3	7.00
Continuous bush land	0.35 – 0.45	19*2/3
Mature pine forest	0.8 – 1.6	20*2/3
Dense low buildings	0.4 – 0.7	20*2/3

Wind Energy Generation

For the calculation of hourly power output of the wind turbines, the method as proposed by Tina et. al. (2006) is used, as shown in Eq. 8. For a typical wind turbine, the power output characteristics can be assumed in such a way that it starts at the so called, cut-in wind speed v_C, it is assumed that the power output increases linearly as the wind speed increases from v_C to the rated wind speed v_R. The rated power P_R is produced when the wind speed varies from v_R to the cut-out wind speed v_F, at which the wind turbine will shut down. The wind speed "v" is calculate with the above mentioned 'wind atlas methodology', using hourly meteorological data from the KNMI. This results into the following equations;

$$P_W(v) = \begin{cases} \left(\frac{P_R}{v_R - v_C}\right) * (v - v_C) & v_c \leq v \leq v_R \\ P_R & v_R \leq v \leq v_F \\ 0 & Otherwise \end{cases} \tag{9}$$

Where, P_w is the power output of the wind turbine at wind speed (v). v_C is the cut-in wind speed , v_R is the rated wind speed, and v_F is the cut-out wind speed of the wind turbine. Furthermore, the P_R is the rated power output of the wind turbine, which is produced when the wind speed is equal or higher than the rated wind speed, and lower than the cut-out wind speed.

The total energy production over the year is calculated using the Eq. 10.

$$P_{w(t)} = \sum_{i=1}^{i=8760} P_w(v) \tag{10}$$

Where, $P_{w(t)}$ is the total energy production of one specific wind turbine, and $P_w(v)$ is the energy production calculated using Eq. 9. The summation suns from 1 to 8760 due to the amount of hours in a year.

All variables in this equation are adjustable in the interface of the model, except for, the hourly wind speeds which are derived from the KNMI dataset. The possibility to adjust these parameters is further described in chapter 4.4.2.

Allocation of Wind Turbines

The allocation of wind turbines within the urban environment require the aggregation of multiple safety regulations. The Dutch government (Faasen, Franck, & Taris, 2013) have defined two safety zones regarding, vulnerable, and limited vulnerable buildings, as seen in **Figure 3**.

The most inner circle, also donated as the 10^{-5} contour, is where no buildings, or installation are allowed. The safety range of this safety zone is often equal to the rotor radius of the wind turbine. The outer circle, also donated as 10^{-6} contour, is the safety zone wherein no vulnerable buildings are authorized. Vulnerable buildings are defined as, dwellings, hospitals, offices with a higher floor surface then 1500 m^2, etc. Within this contour it is authorized to have limited vulnerable buildings such as, office smaller than 1500 m^2, warehouses, and so on. The distinction between vulnerable, and limited vulnerable buildings are made on the basis of the GIS-maps, and visual analysis as stated in chapter 4.3.1. This contour is often set on the radius of the rotor plus the hub height of the wind turbine , and therefore dependent on the size of the wind turbine (Faasen et al., 2013).

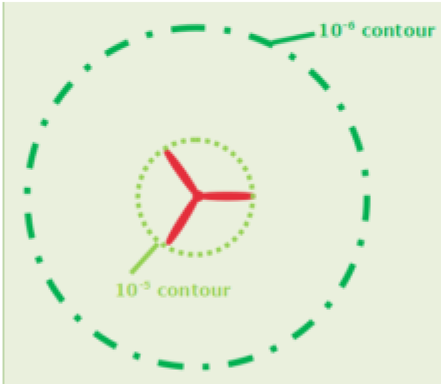

Figure 3. Safety zoning for wind turbines

Furthermore, for the allocation of wind turbines it is also required to consider the interference caused by surrounding wind turbines (Aydin et al., 2010; Ozturk & Norman, 2004; Patel, 2006). The wind speed after a wind turbine is significantly less than up wind, this reduction has a negative influence on the wind production of wind turbines installed downwind of other wind turbines. The distance requirements differ between the upwind positioning, and cross wind positioning. However, in this research there is no distinction between wind directions, therefore, in the positioning of wind turbines, there is no distinction between upwind, and crosswind positioning.

When analyzing the outcomes of the optimization model, this restriction have to be considered, before undertaking further steps. All distance regulation are shown in **Table 10**.

In the model the safety checks, and safety zoning checks all originate from the centre of the parcel, this is done to limit the amount of possible location for the model, and however this can create some errors when allocating neighbouring wind turbines resulting in Eq. 11. These conditions result into the following conditional statement for allocating a wind turbine on a parcel;

$$(\alpha \cap \beta \cap \gamma \rightarrow \delta) \tag{11}$$

Where, α is condition that a parcel have sufficient available square surface, β is the condition that there is no vulnerable object within the 10^{-6} contour of the wind turbine, and γ is the condition that there is no wind turbine within the vicinity of the proposed wind turbine. If all conditions are met the procedure δ will commence, which results in the development of a wind turbine on a parcel. If one or all condition are false, than the procedure δ will not commence.

Table 10. Distance Restriction for allocating Wind Turbines

Regulations[1]	Distance requirements(m)
Distance regulation regarding buildings Limited vulnerable objects (Hotel, shops, office<1500 m²) (10^{-5} contour)	radius of the rotor blades
Vulnerable objects (dwellings, hospitals, schools, offices >1500m²) (10^{-6} contour)	Height of the wind turbine + radius of the rotor blades
Distance regarding surrounding Wind turbines	2 – 4 radius of rotor blades

4.2.4. Optimization algorithm for the distribution of Wind Turbines & Solar PV

The optimization algorithm used in this energy model is the simulated annealing (SA) algorithm. The simulated Annealing is a general optimization technique for solving combinatorial optimization problems (Erdinc & Uzunoglu, 2012). It is derived from the chemical process of heating a metal in a heat bath, and then cooled down by lowering the temperature in the heat bath(Erdinc & Uzunoglu, 2012).

The simulated annealing process consists of 7 steps (Jayaraman & Ross, 2003). The first step is the initialization, step 2 check feasibility, step 3 is generate a feasible neighbouring solution, step 4 is the evaluation incumbent solution with neighbouring solution, step 5 is examining Metropolis condition, step 6 Increment counters. Step 7 adjust the temperature.

At each iteration, a candidate mode is randomly selected and this mode is accepted if it leads to a solution with a better objective function value than the current solution. Otherwise, the move is accepted with a probability that depends on the deterioration of the objective function value based on “Metropolis Criteria”, Eq. 12.

The annealing procedure depending on the temperature decrement allows for wide area searches by a faster temperature decrement at the beginning of the iterative process, then local area searches around the best solutions in the wide area search steps with slower temperature in the next steps of the algorithm (Erdinc & Uzunoglu, 2012). In SA the cost of a solution is equivalent to the energy of the physical state, and the temperature, although it has no physical meaning, can be seen as controlling the entropy of the system. At high temperature, all solutions the optimization problem are equally likely while, at low temperature only the minimal cost solutions are accepted. The initial temperature (Eq. 12) is set in such a manner, that the worst possible solution is accepted with a change of 80%. Resulting the following equation;

$$T_0 = \frac{-\delta f^+}{\ln(0.8)} \quad (12)$$

[1] Handbook Risk zoning Wind turbines was used (Faasen et al., 2013)

Where, T_0 is the temperature at time zero, and $-\delta f^+$is the greatest difference between options. This implies that the value of the initial temperature is dependent on the scaling of the objective function, and therefore is problem specific. Following an appropriate cooling schedule, SA has the potential to avoid local minima and converges to the global optimal solutions within a reasonable computing time (Gandomkar et al., 2009).

Solutions which are not of a better value than the previous is accepted with the probability (Eq. 13);

$$P = \begin{cases} 1 & if\ \dot{\int} \leq \int \\ \exp\left(\frac{\int - \dot{\int}}{T}\right) & if\ \dot{\int} > \int \end{cases} \tag{13}$$

Where, $\int$ is the costs current configuration, $\dot{\int}$ is the costs proposed configuration, and T is the temperature of the system. The algorithm is run until a stopping condition is reached, typically a minimum temperature value, specified as part of the annealing schedule. The end temperature can be determined by two conditions, one, there are no more improvements, and two the acceptance ratio is falling below a given value. The overall code of the system which is used to find new solution, and provide the initial setup is represented in Appendix 6) Netlogo Code.

Initial Setup

The energy model is started by pressing the "setup" button in the interface. This procedure initiates several components of the energy model. First, of all the procedure starts for uploading the GIS-vector map with all required features. Second, for each parcel a "turtle" is generated which stores all features of the parcel on which it's located, this "turtle" is used in a future step. These "turtles" also contain the values of energy production potential per parcel per year. These values are calculated with the methods proposed in chapter 4.2.2, and 4.2.3. Finally, a random configuration is generated. This configuration only serves as a starting point for the optimization procedure, and will not have an effect on the outcome of the energy system.

The starting configuration is obliged to a certain set of constraints as stated in chapter 4.2.2 and 4.2.3. The starting configuration is generated by selecting at each iteration a random parcel, and allocate either a wind turbine, or PV modules. This division is done on a 50/50 bases, if the parcel complies with all constraint. If a renewable energy technology is allocated the model chooses a new random parcel, and allocates another technology, continuing this process until the energy demand is met. This process is shown in the flowchart as presented in **Figure 4**, and the continuation is shown in **Figure 5**.

When the random configuration is completed all required values are calculated, and the configuration is stored in an internal memory of the system. From this point new configuration will be generated in order to find the "best" solution for the research area.

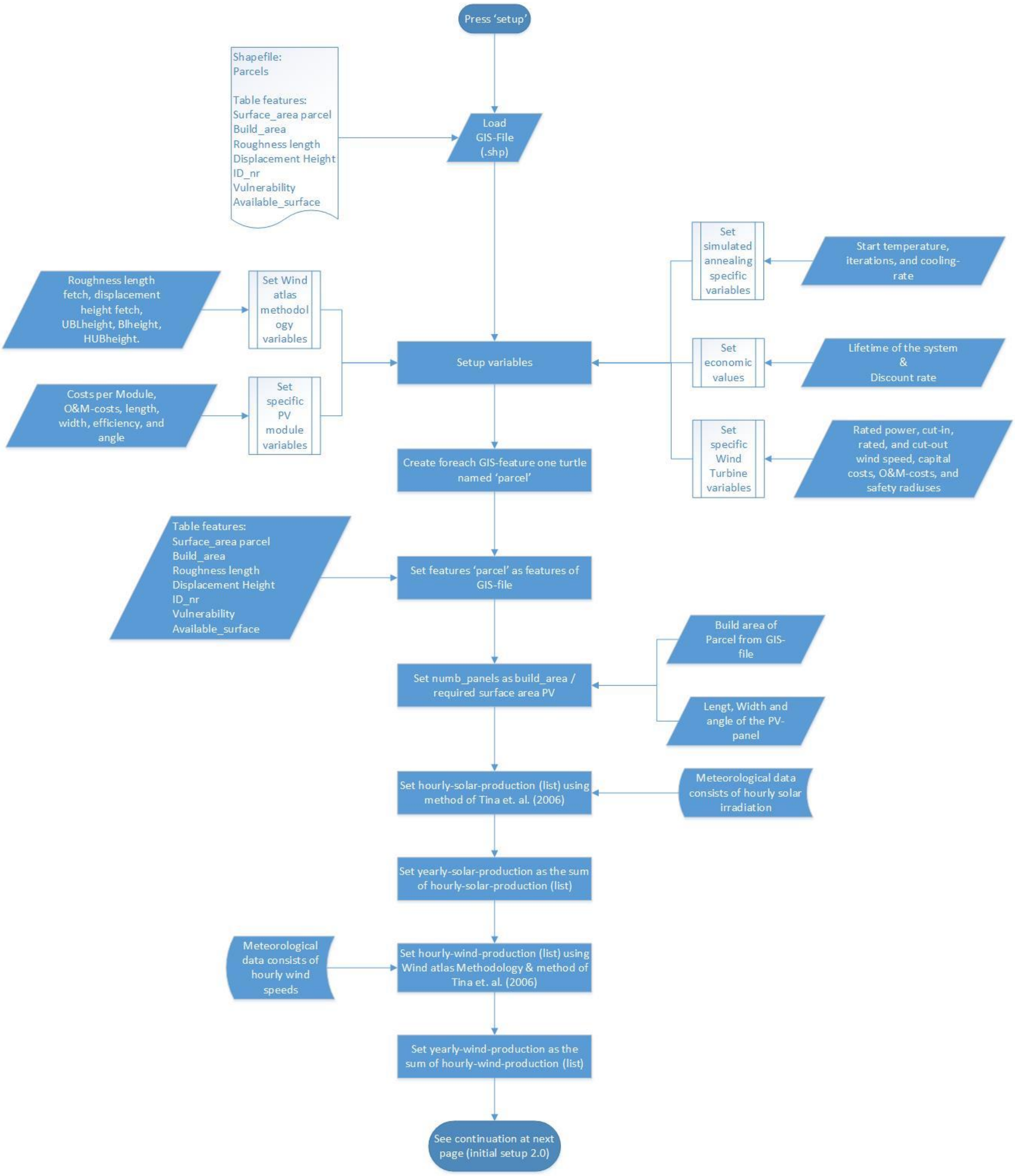

Figure 4. Flowchart for initial setup of the model

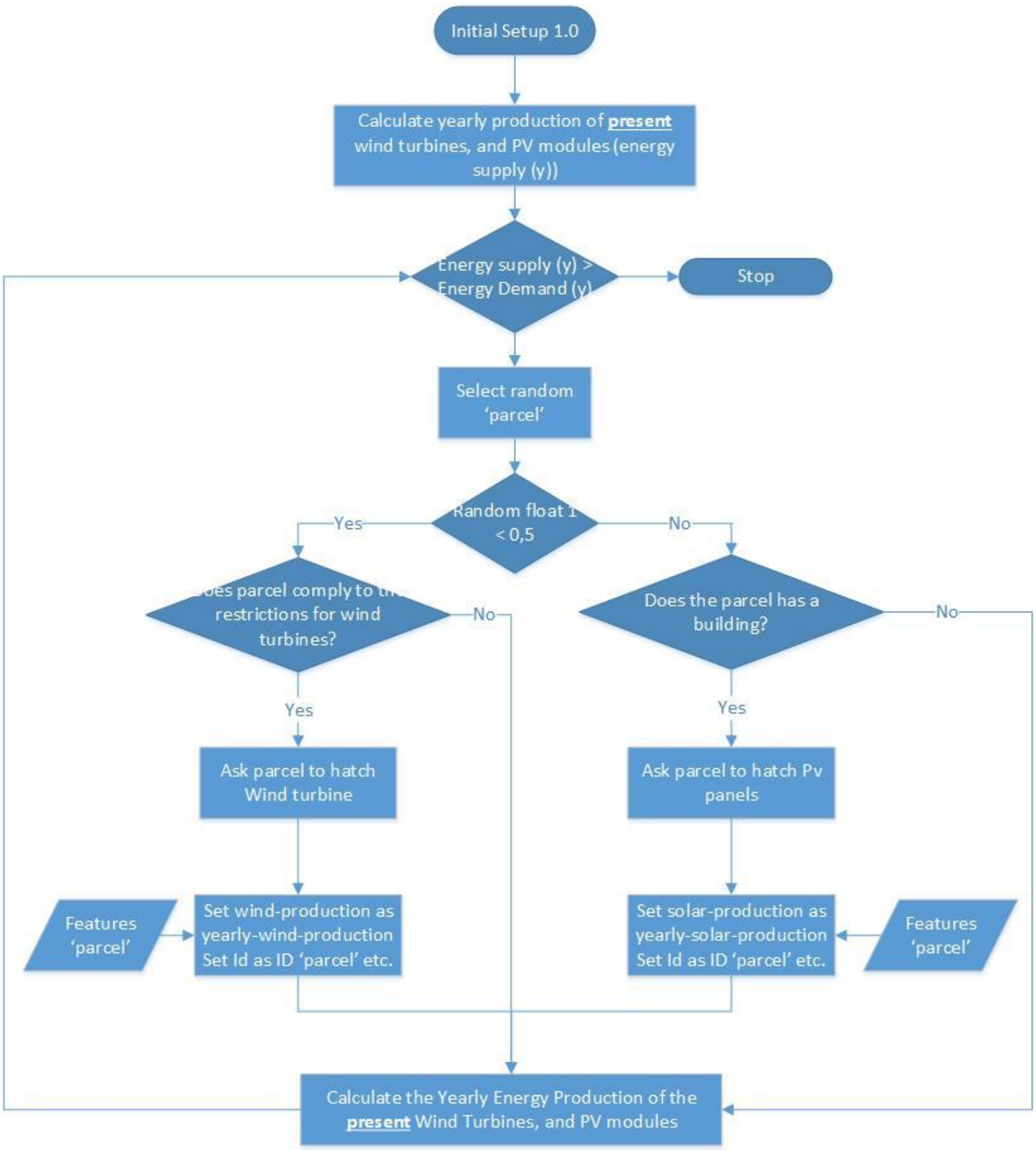

Figure 5. Continuation of the flowchart in figure 4 (Initial setup 2.0)

Changing the configuration

In order to optimize the distribution of renewable energy technologies on the research area an algorithm is develop which finds a new configuration at each iteration. The algorithm is drafted in such a fashion that at each iteration only one small change is made to the existing configuration of renewable energy technologies. This implies that at the end of the algorithm only five possible outcomes are present. The model either installs, or removes a wind turbines, either installs, or remove PV modules, or does nothing.

To arrive at one of these five possibilities, the algorithm starts with the selection of a random parcel in the research area. For the selected parcel the technology with the least costs per kWh is selected. Before installing the selected technology a set of conditional statements have to be met. The results of the conditional statements determine which of the five possibilities is utilized. If the possibility arise that the model decides that nothing will be change in the configuration the steps of calculating the overall costs, production and costs/kWh is skipped, and a new parcel is randomly selected.

When a new configuration is composed the overall production, and costs is calculated to determine the overall costs of energy (COE). The new configuration is accepted according to the statements as described in Eq. 10. If the new configuration is accepted, the new configuration becomes the best configuration, and the model continues searching for another solution. This process is continued until the stopping procedure is met, or no better solution is found by the energy model. The whole procedure is shown in **Figure 6**.

Limitations of the energy model

There are several limitations implies in this energy optimization model. This limitations mainly relate to the allocation of the renewable energy technologies, and amount of allocated renewable energy technologies.

First of all, the allocation of wind turbines is limited to one turbine per parcel. This is done because of the inability to incorporate the interference of wind turbines on a parcel level. Thus, the possibility that multiple wind turbines are allocate on one parcel, and provide the research area with sufficient energy is not incorporated. Second, the allocation of PV modules is done on the complete roof surface. The methodology neglects the effect of installations, or other constraints that can imply on a roof of a building. Third, the constraints regarding highways, canals, and other limitations for allocating wind turbines are neglected. In this study, only the vulnerability of the surrounding buildings are incorporated.

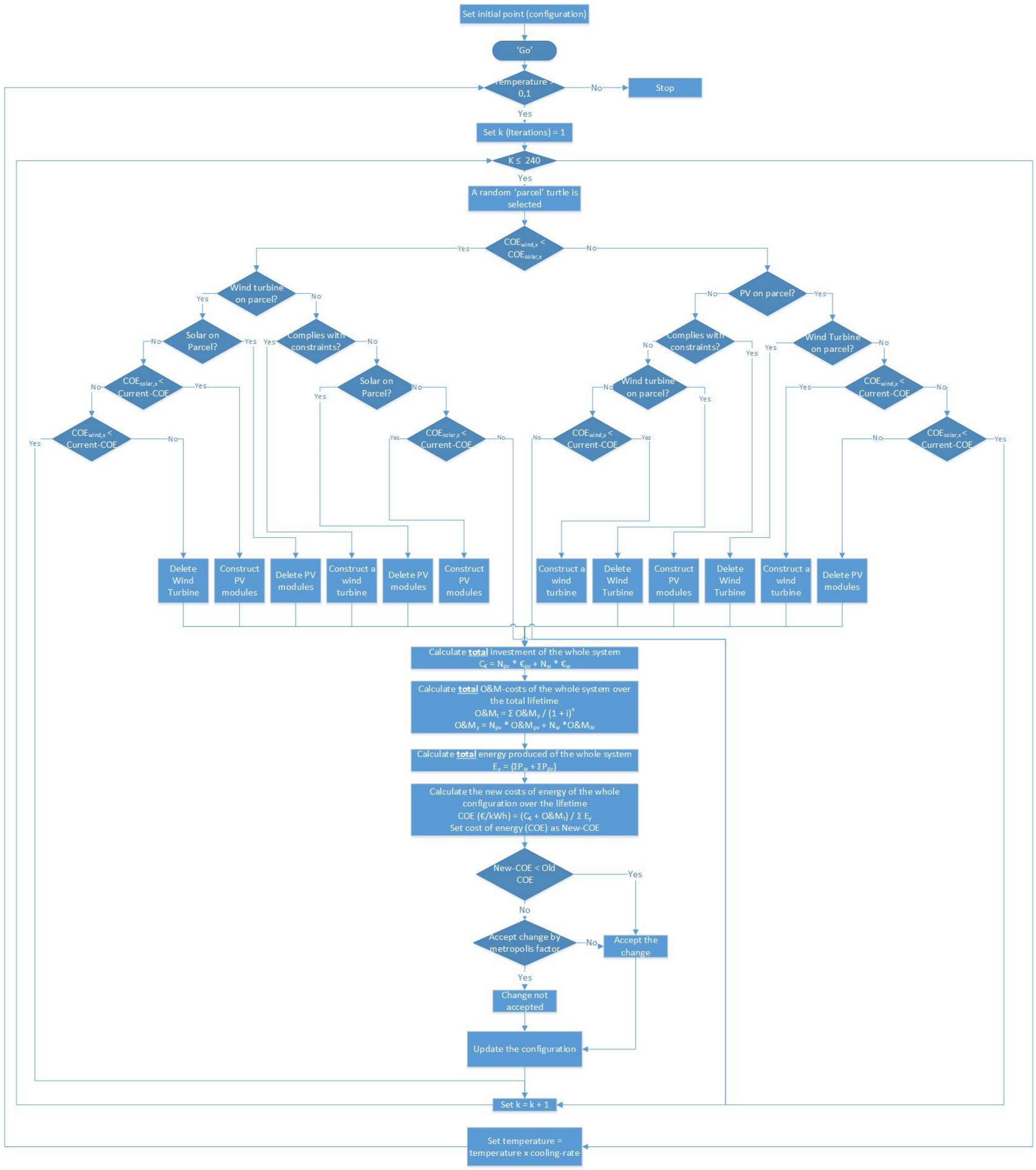

Figure 6. Flowchart for finding new configurations

4.2.5. Economic Analysis

It is necessary to have an economic analysis, when attempting to optimize the costs per produced kWh. As stated in chapter 4.2.1, the objective function of the energy model is to minimize the costs per produced kWh over the lifetime of the system. The expected costs of the system over the lifetime will consist of the capital costs, spend at the start of the year, and the yearly O&M-costs of the renewable energy technologies. The expected energy production over a lifetime is calculated using the total yearly energy production, by aggregating Eq. 4 & Eq. 9, and multiplied with the lifetime of the system. This implies that the total energy production is equal for each year. The costs per kWh (Eq. 15) is defined a following;

$$€/_{kWh} = \frac{(C_{(€)} + O\&M_T)}{\sum_{y=1}^{y=lifetime} E_y} \tag{14}$$

Where, *€/kWh* is the costs in Euro's per produced kWh over the complete lifetime. *C (€)* is the capital costs of the system, as donated in Eq. 16. $O\&M_T$ is the operation and maintenance costs over the complete life time calculated with Eq. 17, and E_y is the total produced electricity over the complete lifetime as calculated in Eq. 12. The user is able to adjust several variables in this equation, this enables the modeller to make simple analysis of the performance of the system with various settings this is elaborated in chapter 4.4.2.

The total yearly energy production of the allocated renewable energy technologies is calculated for two reasons. First of all for the check if the overall energy generation is sufficient to provide the research area with sufficient renewable energy. Second, to use it to calculate the overall costs of energy for the whole system. The total yearly energy production is easily calculated by adding the energy produced by the wind turbines, with that of the PV panels the total energy production is calculated per year. This results in the following function;

$$E_Y(t) = \sum_{i=0}^{i=n} P_{w(t)} + \sum_{i=0}^{i=n} P_{pv(t)} \tag{15}$$

Where, E_Y *(t)* is the total generated electricity in kWh. $P_w(t)$ is the electricity production by wind turbines over the year, and $P_{pv}(t)$ is the electricity production by PV array over the year. The energy generation of the PV-arrays, and wind turbines are calculated using the equation as defined in Eq. 4, and Eq. 9.

Furthermore, the capital costs are the costs for purchasing, transportation, and installation of the system. The capital costs are assumed to be spend in the first year. The capital costs consist of the combined costs for the PV panels, and the wind turbines. The total capital costs are defined by;

$$C\ (€)_{P,W} = N_{PV} * €_{pv} + N_w * €_W \tag{16}$$

Where, $C\ (€)_{pv,w,}$ is the capital costs of the system, N_{pv} is the total number of pv-modules in the system, $€_{pv}$ are the costs for installing an pv-module on a flat roof, N_w is the total number of wind turbines installed in the system, and $€_w$ is the costs for designing, and installing and wind turbine on the premises.

Additionally, the Operation and Maintenance costs (O&M-costs) are calculated over the lifetime of the system. The costs for operation and maintaining the system can be adjusted per renewable energy technology. In the case of the wind turbine the O&M-cost is a percentage of the capital costs. For the

PV-array the O&M-costs are a given number, both adjustable by the modeller (chapter 4.4). The O&M-costs per year are defined by the following equation;

$$O\&M_{(y)} = \sum_{i=0}^{i=n} O\&M_w(y) + \sum_{i=0}^{i=n} O\&M_S(y) \tag{17}$$

Where, $O\&M_{(y)}$ is the total O&M costs for the system for a year, $O\&M_w(y)$ is the O&M costs per wind turbine per year, $\&M_s(y)$ is the O&M costs per PV panel per year, and n is the number of wind turbines, and PV modules on the research area.

Before the O&M-costs can be integrated in the objective function, the costs of O&M have to be added over the years. To calculate the current value of future cash flows the discounted cash flow is used to aggregate the O&M-costs over the lifetime of the system (Metrick & Yasuda, 2011). It is a commonly used method to assess the feasibility of a project, asset or business. The discounted cash flow is defined in the following equation;

$$O\&M_T = \sum_{n=1}^{\mathrm{n=lifetime}} \frac{O\&M_y}{(1+i)^n} \tag{18}$$

Where, $O\&M_T$ is the discounted present value of the O&M costs over the set lifetime. i is the discount rate (%), n the year for which is calculated, and $O\&M_y$ is the O&M cost per year as calculated in Eq. 17.

The user can set multiple variables within the economic evaluation, this is further discussed in chapter 4.4.2.

4.3. Required data input

For the user to successfully operate the energy model multiple data sources are required to make a valid estimation. First, of all a GIS-map has to be uploaded providing all necessary data per parcel in order to make an analysis. Second, the meteorological data have to be adjusted collected by the KNMI (Dutch Royal Meteorological Institute), and integrated in the model. Third, the hourly demand data from the EDSN can be integrated, however this is optional the description of this data source is further elaborated in Appendix 2) EDSN Demand Profiles. The GIS-map, and the meteorological data provide the most important input for the optimization model.

4.3.1. GIS-mapping

To incorporate spatial constraints in the optimization of renewable energy technologies a GIS-vector map is integrated in the optimization. The GIS-maps are made available by the land register (Kadaster, 2015). The GIS-maps are downloaded as shape-files (.shp) so it is compatible with the Netlogo environment. Additionally, the GIS-maps also contain information about the occupation, size and address of the parcels.

Before uploading the GIS-maps in the Netlogo model some additions have to be made, this can easily been done with GIS software packages such as FME workbench, and QGIS. First, the researchers has to be sure that only the research are is presented in the map, and delete all other parcels. This can be done using FME workbench. Second, for the calculation of energy potential of renewable energy technologies some variables have to be integrated in the GIS-map, which consists of; the available roof surface, available free surface, vulnerable building, local roughness length, and local displacement height as described in the wind atlas methodology. This variable can be easily be added using the QGIS software package.

Furthermore, **Table 11** presents the required information, and table names in order for the model to successfully extract the data from the shapefiles.

Table 11. Attributes of the per parcel in the GIS-map

Nr	Variable	Type	Example
1	ID number	Integer	0, 1, 2,..,N
2	Total surface area parcel	Integer	2000 m^2
3	Roof surface	Integer	1500 m^2
4	Available free space	Integer	500 m^2
5	Vulnerable building	Boolean	0 or 1
6	Local roughness length	Integer	**Table 9**
7	Local displacement height	Integer	**Table 9**

4.3.2. Meteorological data

The meteorological data is used to estimate the energy production of the selected renewable energy technologies. The data is obtained from the Dutch Royal Meteorological Institute (KNMI), and is freely available. The dataset consist of a text-file (.txt), before uploading some adjustments are required. Redundant data needs to be removed from the file, with the purpose to keep the model clear. For the energy production calculates only the average wind speeds per hour, and average solar irradiation per hour are required. These datasets need to be organized in two columns in a text-file before uploaded in the Netlogo model, as presented in **Table 12**. Another overview of this data, and the sources of this data are represented in Appendix 1) KNMI database.

Table 12. Example of the meteorologische data

Windspeed (0.1 m/s)	Irradiation
40	0
40	0
50	0
…	…..

4.4. User Interface

The interface is the representation of the research area, variables, and output, of the renewable energy system. The most important variables are integrated in the Interface, so the user can set the model. In this chapter, the Interface will be elaborated using a case study.

4.4.1. Overview

The interface, shown in **Figure 7**, is structured according to the relation to the model. The groups are defined as; the input section for data sources, the simulated annealing section, economic, technologic, Wind Atlas Method, and output section. These groups divided using letters, and are elaborated in chapter 4.4.2. The groups consist of variables which are from importance for these technologies, or methods. The interface will be discussed using a case study. All variables are individually shown in Appendix 4) Variables of the Energy Model.

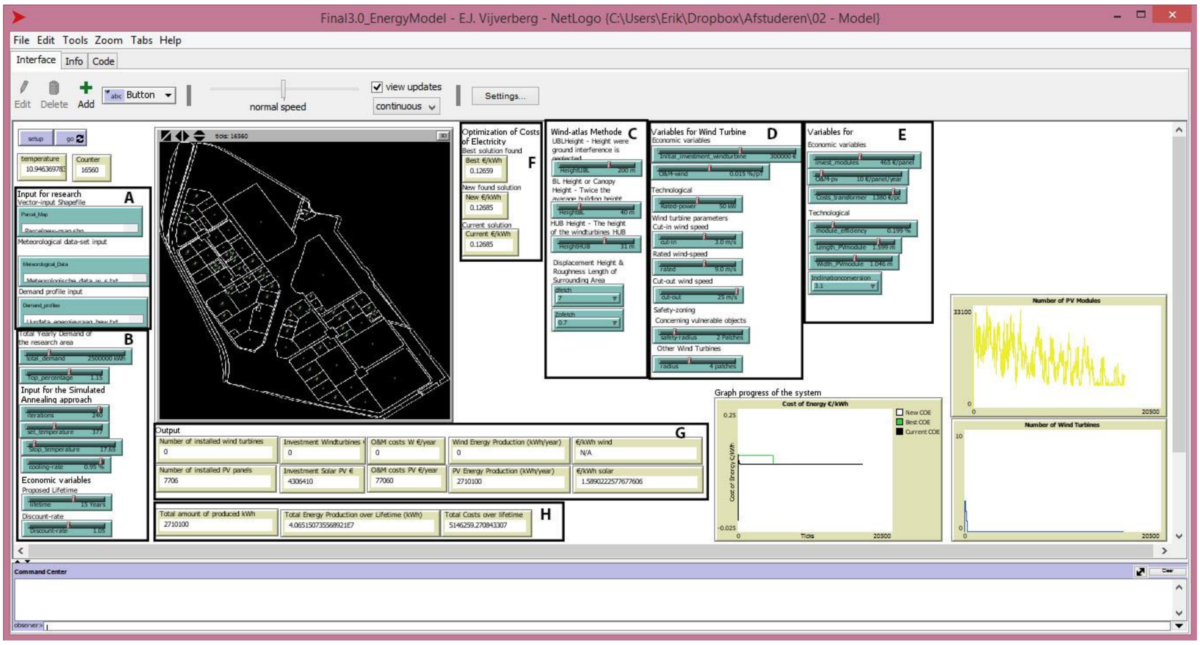

Figure 7. Overview of the models Interface

4.4.2. Variables

The user can modify the settings of the model in order to influence the possible outcomes of the optimization model. As stated in chapter 4.4.1 all variables are clustered in multiple groups. In this chapter all groups of variables are shown with the given value for a realistic analysis of the case-study "de Brand". This is a business park located near the highways A2, and N279 in the municipality of Den Bosch. The development is done with the help of a clear urban development concept. The large scale business are located at the outer edges, and the medium and small scale are concentrated at the centre.

In **Table 13** the variables corresponding with group A are described. These input windows are for uploading the GIS-map (chapter 4.3.1), and meteorological data input (chapter 4.3.2) into the model. Demand data is optional, but will not affect the optimization process.

Table 13. Input monitors for the required data (A)

Variable	Description	Type
Parcel_map	This is the input window for the shapefile (.shp) containing the research area	Input window
Meteorological_data	Input window for the text file containing two columns. First the wind speed, and second the solar radiation.	Input window
Demand_profiles	Input window for the demand profiles as provided by EDSN. (OPTIONAL)	Input window

In **Table 14** the variables corresponding with group B are described. These include essential variables for the simulated annealing procedure, total demand of the research area, and economic evaluation.

The amount of iterations is set so that every parcel can change its status in one cooling-down procedure. The cooling rate is set on a regular percentage of 5%. The start temperature is set on 360, and stop temperature on 60. The economic lifespan of the system is set on the estimated lifespan of the system, and the discount rate on 5%, which is a common number for the discount-rate is no specific data is available.

Table 14. Variables and values for total demand & simulated annealing algorithm (B)

Variable	Description	Type
Total demand	Slider to set the total electricity demand of the area in kWh.	Slider
Top percentage	Slider to set the percentage of which the supply may exceed the energy demand	Slider
Iterations	Slider to set the amount of iterations per cooling period in the simulated annealing procedure	Slider

Set_temperature	Setting to set-up the starting temperature of the simulated annealing procedure	Slider
Stop_temperature	Stop criteria for the simulated annealing	Slider
Cooling-rate	The percentage of cooling the temperature has each cooling down period (%)	Slider
Lifetime	The amount of years over which the energy production, and costs are calculated	Slider
Discount-rate	The interest rate for depreciation of money	Slider

In **Table 16** the variables corresponding with group C are shown. These variables are set using literature research, visual observations, and producer's documentation. The height of the urban boundary layer is set on 200 meters (Millward-Hopkins et al., 2013a). The blending height is set on twice the average building height, due to a lack of data regarding buildings height, this value is set on 40 meters based on visual observations. The hub height is set based on the producer's information of the WES 50 wind turbine. The dfetch, and $z_0$fetch are set on small build surface as described in **Table 9**.

Table 15. Variables and values for the Wind Atlas Methodology (C)

Variable	Description	Type
Height UBL	The height of the Urban boundary layer often set on 200 m	Slider
HeightBL	The height of the blending height set 2 x average building height	Slider
HeightHUB	The height of the wind turbines hub	Slider
Dfetch	The displacement height of the fetch area	Chooser
Z_0fetch	The roughness length of the fetch area	Chooser

In **Table 16** the variables are shown which correspond with group D. These variables are set based on the producer's documentation, and contact with the supplier. More detailed specification can be found in Appendix 5) Specifications of Energy Technologies. According, to the supplier the costs of this wind turbine for purchasing, installation, and transportation is around €300.000,-, and the yearly O&M-costs are around 1.5% of the CAPEX. For the safety zoning the values as set in **Table 10** are used. In the case of the WES 50 this is 45 m, and 90 meters, which results in 1.5 patch, and 3 patches.

Table 16. Variables, and values for the Wind turbine setup (D)

Variable	Description	Type
Initial_investment_ windturbine	The costs per wind turbine for purchase, transport, and placement	Slider
O&M-wind	O&M costs per wind turbine per year in % of initial investment	Slider
Rated power	The rated power of the wind turbine	Slider

Cut-in wind speed	The cut-in speed of the wind turbine	Slider
Rated wind speed	The rated wind speed of the wind turbine	Slider
Cut-out wind speed	The cut-out wind speed of the wind turbine	Slider
Safety zoning (vulnerable build.)	The safety zoning regarding vulnerable buildings	Slider
Safety zone wind turbines	Safety zoning to reduce interference between wind turbines	Slider

In **Table 17** the variables are shown which related to group E. These variables are set based on producer's documentation. More detailed information is shown in Appendix 5) Specifications of Energy Technologies. According to the supplier, a Benq PV-module costs around €465,- for purchasing, and installation on a flat roof. For the O&M-costs no specific amount is specified, although the modules have to be cleaned, for this reason a value of €10,- is set for cleaning, and other maintenance. For the required surface the method of Notenbomer (2014) is used, which resulted in a square surface of 5.05 m^2.

Table 17. Variables, and values for the setup of the PV modules (E)

Variable	Description	Type
Invest_modules	The investment costs per PV module	Slider
O&M-pv	O&M costs per module per year	Slider
Module-efficiency	Module efficiency given in %	Slider
Length of the PV module	Length of the module given in meters	Slider
Width of the PV module	Width of the module given in meters	Slider
Inclination conversion	Gives the conversion value to calculate the minimum distance between modules	Chooser

4.4.3. Output

The generated output is shown in multiple windows, and graphs shown in the Interface of the model. These are shown as group F, G, and H in **Figure 7**. The generated output is from importance for the modeller to estimate the feasibility of the proposed configuration. In **Table 18** the monitors are shown which correspond with group F. The monitors shown the current state of the system, and its best state ever found. These states are based on the costs per produced kWh.

The model minimizes the costs of electricity for the whole area, and considering the operation lifetime as shown in. The outputs for wind turbines are summarized in, and the outputs generated for PV array are summarized in **Table 20**. The visualization of the output monitors are represented in Appendix 4) Variables of the Energy Model.

Table 18. Monitors for output generation overall costs of energy per configuration (F)

Monitor	Description	Value
Best-COE	Displays the lowest cost of energy of the entire system over the lifetime found	€/kWh
New-COE	Displays the COE for the new found configuration over the lifetime	€/kWh
Current-COE	Displays the COE of the latest accepted configuration of the energy system	€/kWh

In **Table 19** the monitors are shown which correlate with group G, also the graphs are part of these outputs. These monitors shown the amount of technologies installed, O&M cost per technology, and energy produced per technology per year, and per lifetime.

Table 19. Monitors for output generation per renewable energy technology (G)

Monitor	Description	Value
Number of wind turbines/ PV modules	Depicts the number of installed renewable energy technologies on the research area	Pieces
Investment wind turbines	Displays the total investment costs for the renewable energy technologies	€
O&M costs wind turbine	Displays the total O&M costs of the renewable energy technologies in one year	€/year
Wind energy production	Displays the total energy produced by renewable energy technology per year	kWh/year
Costs per kWh wind	Displays the costs per produced kWh over one year	€/kWh

In **Table 20** the total values are represented, these correspond with group H in **Figure 7**. These monitors shown the total costs, and electricity production of the proposed configuration of renewable energy technologies.

Table 20. Monitors of the total costs, and production of proposed configuration (H)

Monitor	Description	Value
Total production	Displays the total production of the configuration on a yearly bases.	kWh
Total production over lifetime	Displays the total production of the configuration over the total proposed lifetime	kWh
Total Costs over lifetime	Displays the total costs of the configuration of	€

Besides these output monitors also a text-file is composed from the final configuration consisting of the locational data, production, capital-costs, O&M-costs per allocated renewable energy technology. These tables are represented in Appendix 8) Output simulations.

4.5. Scenarios design

For the case “de Brand” multiple scenarios are developed to evaluate the operations of the energy model. For this reason three scenarios are developed based on realistic options for future events or designers decisions.

First, the 50 kW is tested. The variables in this scenario are set to find a most likely result for the renewable energy configuration on “de Brand”. The second scenario consist of an alteration in the choice for wind turbine type. In this scenario a larger wind turbine is proposed with a higher rated power output, and also a higher rated wind speed. In the third scenario the assumption is made that the costs for a PV module strongly drops over the next few years, and a decrease in capital costs for PV modules is made.

The models is tested using three different scenarios, which could happen in the near future. A basic description of the scenarios is given in **Table 21**.

Table 21. Basic description of scenarios

Nr	Name Scenario	Basic description
1	50 kW	Consist of a 50 kW wind turbine, and a PV module with 19% efficiency
2	100 kW Wind Turbine	The 50 kW wind turbine is replaced with a 100 kW wind turbine which costs nearly the same
3	Drop in Capital Costs PV	The capital costs of PV panels drop with 15% due to increase in production efficiency

The results of this analysis will provide insight in the feasibility, and configuration of an energy system on the business premises “De Brand”, and the operation of the energy model.

4.5.1. Simulations Results

The same type of data output is generated for each scenario, described in the previous chapter. The outputs of the scenarios will be discussed in this chapter.

The scenarios do not interfere with the operation of energy model, and the process of finding new solution. The proof of this can be seen in **Figure 8**. The process of finding new solution show a comparable lines, and also show the acceptance of worse solution, to avoid getting stuck in local minima.

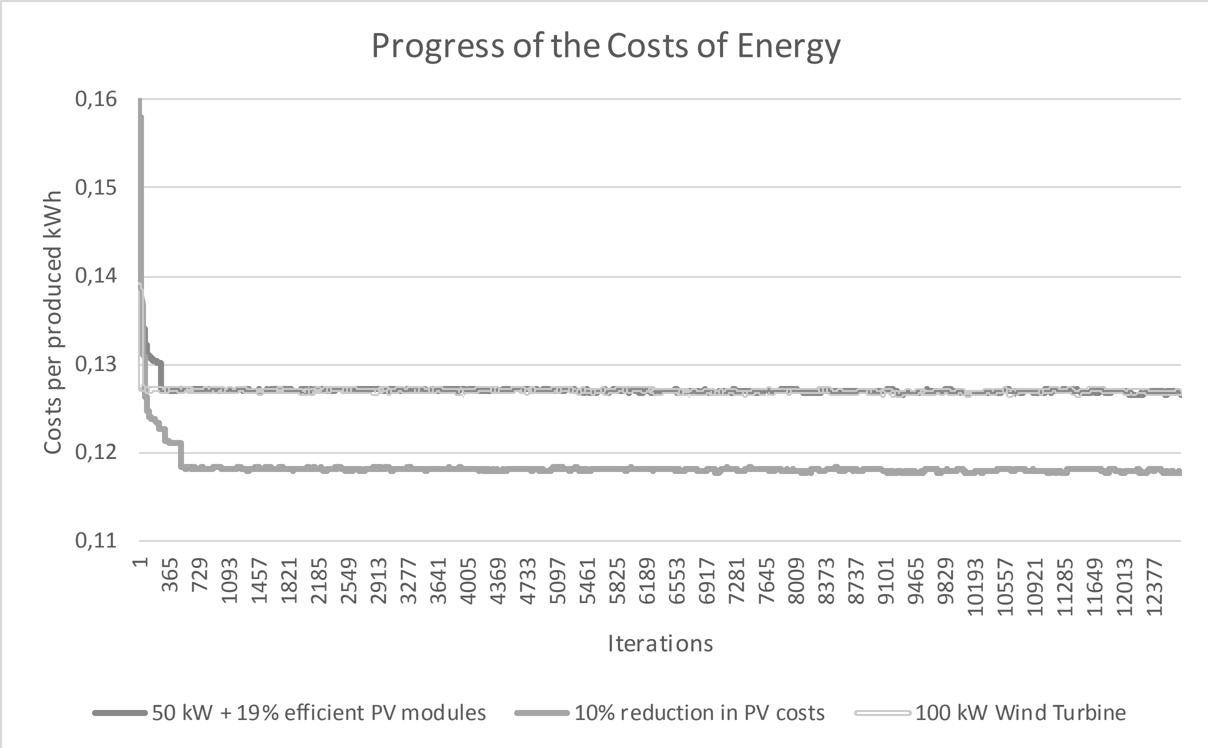

Figure 8. The progress of the Costs of Energy per configuration

The rapid decrease in COE can be explained by the design of the algorithm. When a technology does not contribute to lowering the overall costs per produced energy, it will be deleted from the configuration. Furthermore, **Figure 8** shows use that the model accepts configuration which do not result in a lowering of the COE. For finding a new configuration no cap on the energy production is implied. A cap is implied however, for finding the “best” configuration. The process of finding the “best” solution is presented in **Figure 9**. This prevents the possibility that a system is proposed which produces an overload of electricity.

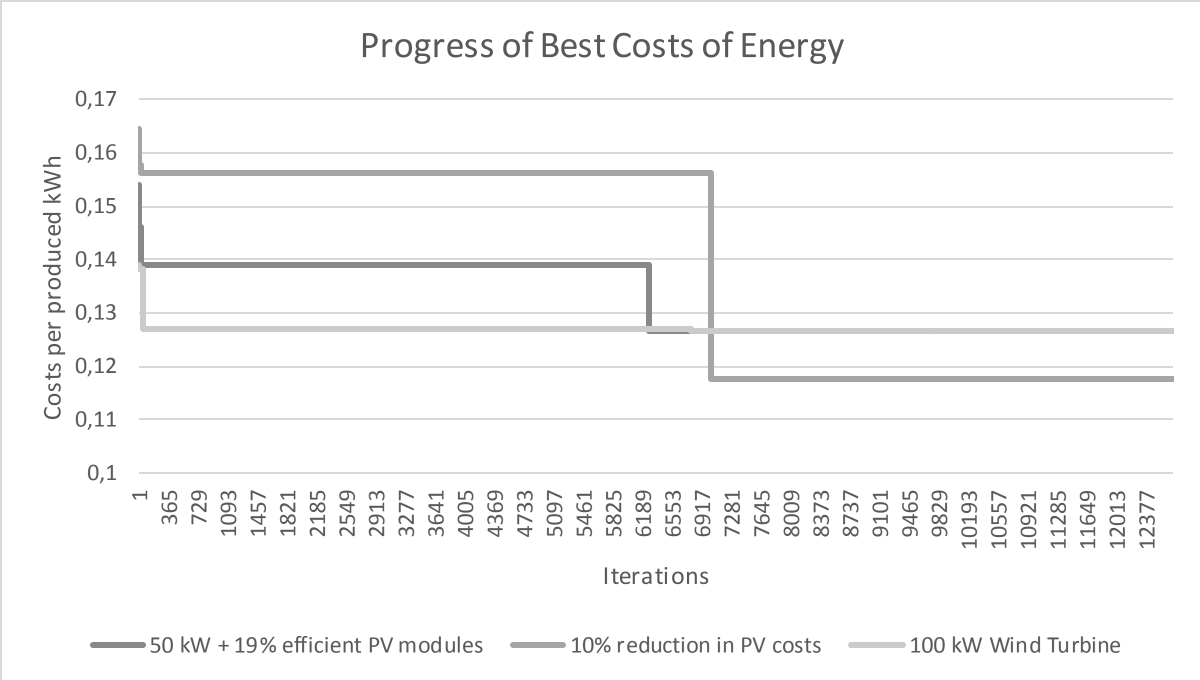

Figure 9. The progress of the acceptance of a new best configuration

In **Figure 9** it can be seen that a great number of iteration before finding a solution which complies with all constrains. The found configuration for the three scenarios are represented in **Table 22**. Each of these results are more detailed represented in Appendix 8) Output simulations.

Table 22. Results of the three scenarios

Variables	50 kW	100 kW wind turbine	PV module costs drop with 10%
€/kWh over lifetime	€ 0,1265	€ 0,1265	€ 0,1176
Number of wind turbines installed	-	-	-
Capital costs Wind turbines	-	-	-
O&M costs Wind turbines per year	-	-	-
Wind energy production (kWh/Year)	-	-	-
Number of Solar PV modules installed	7136	7168	7132
Capital costs PV modules	€ 3.987.540,-	€ 4.003.800,-	€3.649.096,-
O&M-costs PV modules per year	€ 777.727,02	€ 781.214,60	€777.291,07
Energy production PV modules	2.509.639 kWh	2.520.893 kWh	2.508.232 kWh
Energy production per PV module	352 kWh	352 kWh	352 kWh
Total costs over lifetime	€4.765.267,02	€4.785.014,58	€ 4.426.387,07
Total produced energy over total lifetime	37.644.582 kWh	37.813.392 kWh	37.623.481 kWh
Allocation Output	Appendix 7) Output simulations	Appendix 7) Output simulations	Appendix 7) Output simulations

Analysing the results it becomes clear that the feasibility of wind turbines on the business premises are not feasible according to this energy model. This can be explained by the low average wind velocity on the business premises of “de Brand”. The feasibility of wind turbines will be better in a more wind rich environment.

The found results for the 50 kW wind turbine, and the 100 kW wind Turbine case are almost the same due the fact that Wind Turbines are rejected in this configuration, and there were no changes which affect the performance of the PV modules.

Furthermore, the drop of 10% of the PV module overall costs has only limited effect on the overall costs per produced kWh over the lifetime of the system. This can also be seen in the process of finding a new configuration for the business premises represented in, where all process of the three scenarios are represented. It can be clearly seen that the values for the 50 kW, and 100 kW wind turbine case do not differ much.

Businesses on business premises are donated as large consumers, and thereby can purchase electricity for around €0,08 per kWh. The lowest costs of the scenarios found a configuration of around €0,11 per produced kWh, which cannot compete with the current electricity delivery.

The model can also generate visual output which shows the location of the technology on the business premises. An example is shown in **Figure 10** where the green squares represent the PV modules, unfortunately no Wind Turbines are allocated in this example. Furthermore, additional output is generated this includes the location, number, production, capital costs, O&M costs, and overall costs per installed technology. These outputs can be found in Appendix 8) Output simulations.

Figure 10. Visualization of the outcome of the 50 kW case scenario

5. Discussion & Recommendation

In this study a Spatial Decision Support Tool is developed for the allocation of renewable energy technologies on business premises, in order to provide the research area with sufficient electricity, at a minimum costs. In this chapter, the research, and outcomes will be discussed, and recommendation will be made to further elaborate this tool.

5.1. Discussion

The energy model developed in this research is able to find an “optimal” solution for the given research area. However, it is apparent that the user verifies the results of the energy model by visiting the site, and otherwise.

Analysing the three scenarios it can be stated that the found “best” configuration cannot compete with the existing fossil fuel based energy system. Businesses on business premises are donated as large consumers of electricity, and therefore are able to purchase cheap electricity for around 7 to 8 euro cent (CBS, 2015). However, the difference between the fossil fuel kWh prices, is only slightly lower than the found costs of energy in the cases presented in chapter 4.5.1. This could imply that only a small contribution given by governments can stimulate the development of renewable energy systems, for example with SDE subsidies.

Additionally, the configuration of the results was noteworthy. What is striking is the lack of wind turbines installed in each scenario, and the small differences between the 50 kW case, and the case of the 10% of the PV costs. This can be explained by the fact that the reduction of 10% is just a fraction of the total costs of energy system. Additionally, the lack of wind turbines in the 100 kW case can be explained by the increase in required wind speed to reach the rated power output. This would mean that in the majority of the time the wind turbine only produces a fraction of its maximum capacity. This is a direct result of the low average wind velocity in the research area.

The develop energy model is subjected to a number of limitations, in order to deal with the problem of allocation, and optimizing renewable energy technologies. First, of all the allocation of PV modules is done by positioning them on roof tops. The assumption is made that when PV modules are allocated the maximum amount of PV modules are positioned on the roof top. This prevents the possibility that a roof is only partially covered. Furthermore, the geometry, and orientation of the buildings are left out of the scope of this research. This limitation has an effect on the number of installed PV modules per building. This could result in optimistic numbers for the allocation of PV modules. In addition, the calculation for energy production is quite optimistic. Second, the allocation of wind turbines on the parcel surface does not account for the presence of roads, waterways, and other infrastructure, and therefore only consider the proximity of vulnerable, or limited vulnerable building. In addition, for the distance requirements of between wind turbines only one value is checked. This implies that there is no distinction between down-wind, and cross-wind positioning. Furthermore, the lay-out of the parcel is also neglected. This implies that the position of the present building on the parcel is not considered in this research. Therefore, the possibility exists that a wind turbine can be allocate on the parcel within the model, but not in reality. Additionally, the checks if the possibility exist for allocating a wind turbine all originate from the centre of the parcel, this implies that the possibility to allocate a wind turbine in the corner of the parcel is not possible in this energy model. Third, in the economic evaluation of system the possibility of major maintenance issues, where production of wind turbines or PV module completely stops, are not incorporated in this research. For the economic evaluation the assumption is made that energy production never stops for maintenance related issues. Fourth, in this model it is only possible to allocate one wind turbine on each parcel, even when a parcel has a sufficient space to allocate two or more wind turbines on its surface.

5.2. Valorisation

The proposed energy model in this research has to be seen as a first step towards a more accurate, and realistic energy model for business premises. The energy model can allocate, and optimize the distribution of renewable energy technologies on business premises with a fairly primitive method. Therefore, for a realistic attempt to enter the private sector the model is still too simplistic.

However, almost all data, and software used in this research is available for private, and public parties. Only the GIS-map, which can be downloaded from the Kadaster, costs around 80 Euro cents per parcel (Kadaster, 2015). All other datasets, and software packages are freely available on the internet, or can be requested at the municipality. This property makes it a useful tool for first time exploration of the possibility of installing renewable energy technologies on business premises. Furthermore, Netlogo is a fairly easy to learn software package which enables users to adjust the specification of the model to their liking.

However, in order to be fully applicable, and from added value for the market in general, several adjustments, and enhancements have to be made in the allocation model, and energy generation calculations to provide a more realistic, and reliable outcome.

5.3. Recommendations

The proposed model in this research is the first step towards, new part of spatial energy modelling, and energy planning. For this model some recommendations are applied, such as;

- The further elaboration of the wind turbines allocation model, so multiple wind turbines can be allocated on one parcel, and the safety check will no longer be solely from the centre of the parcel.
- The integration of the orientation, and geometry of the buildings in the research area. This will provide a more accurate allocation of PV-modules.
- Further elaborate the possible renewable energy technologies such as, Geothermal, PV-T, or Biomass.
- Integrate the possibility of energy storage, to simulate the operations of a local energy grid, and thereby creating an autarkic district.

These are the main recommendation for the further development of this energy model.

6. Conclusion

A techno-economic energy model for the use on business premises has been developed, and it proved that is able to allocate wind, and solar energy within the built environment using GIS-maps, and therewith find a least costs solution to provide the research area with sufficient energy.

However, the simulation time of the energy model, which is developed within Netlogo, is a down side which need to be addressed, the simulation takes around 30 minutes, however the model is intended to give a fast, and reliable method to calculate the least costs per kWh configuration.

Furthermore, the accuracy of the proposed energy model is a component that could be improved, to generate even more realistic results. This is also the case for the integration of more safety regulations regarding roads, railways, etc.

Despite the limitations of the proposed energy model it is able to find a least costs per kWh configuration using a GIS base to incorporate the urban fabric. This model can be used to analyse the possibility, and configuration of a future renewable energy grid within the built environment. Thereby, reduce the change that major changes to the urban environment have to be made.

However, when decision makers, or system designers analyse the results of the energy model, they always need to keep in mind the limitations of the energy model, and check if the results are valid for their research area.

The proposed renewable energy model can be seen as a start for the further development of a spatial renewable energy optimization model which can allocate, and optimize renewable energy technologies within the urban environment. Furthermore, the energy model can be further elaborated by integrating more renewable energy technologies besides, solar, and wind energy.

However, for the integration of renewable energy technologies on business premises a reduction of investment, O&M-costs, and/or efficiency of the renewable energy technologies have to be made in order to be able to compete with fossil fuel based energy system. Or, investors do not mind to pay more for their energy as long as it is locally produced with the help of renewable energy technologies.

6.1. Societal relevance

The energy system is transitioning towards a distributed renewable energy systems, with renewable energy generation within the built environment. This model can be used to evaluate the possibility of renewable energy technologies within the built environment, and thereby be used to convince investors, or other stakeholders to invest in renewable energy systems. Furthermore, this energy model can be used to determine where renewable energy system can be installed to find the least costs per produced kWh configuration.

6.2. Scientific relevance

Renewable energy optimization is a frequent researched topic, however the combination between GIS-systems, and renewable energy generation is only seldom been made. This research proposes a new approach to help integrated renewable energy technologies while considering the spatial constraints on a parcel bases. This model can be used as a first step towards new renewable energy optimization systems.

6.3. Beneficiary relevance

A company/ organisation can utilize this energy model to assess the possibility of renewable energy technologies on business premises. The model provides insight in the possible location of renewable energy technologies. But foremost, this energy model has to be seen as a first step towards a more accurate, and a more realistic energy model which can aid decision makers with the development of renewable energy technologies.

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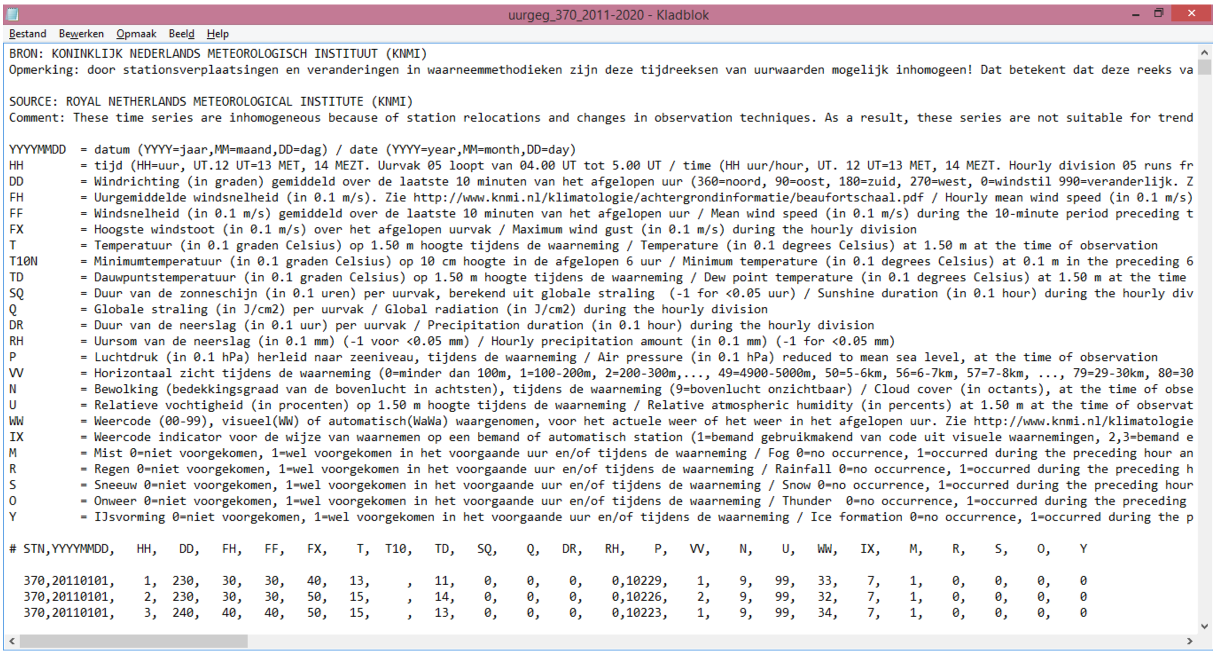
Appendixes

Appendix 1) KNMI database

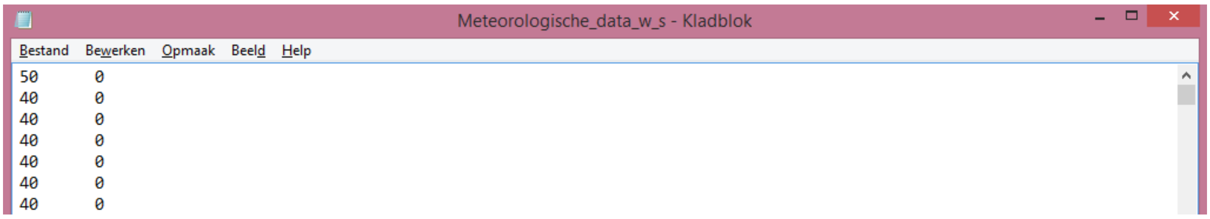
The meteorological data is freely available on the website of the KNMI, and presented in a text-file. A example of this text-file is represented in Figure 1.



```
uurgeg_370_2011-2020 - Kladblok
Bestand  Bewerken  Opmaak  Beeld  Help
BRON: KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT (KNMI)
Opmerking: door stationsverplaatsingen en veranderingen in waarneemmethodieken zijn deze tijdreeksen van uurwaarden mogelijk inhomogeen! Dat betekent dat deze reeks va

SOURCE: ROYAL NETHERLANDS METEOROLOGICAL INSTITUTE (KNMI)
Comment: These time series are inhomogeneous because of station relocations and changes in observation techniques. As a result, these series are not suitable for trend

YYYYMMDD  = datum (YYYY=jaar,MM=maand,DD=dag) / date (YYYY=year,MM=month,DD=day)
HH        = tijd (HH=uur, UT.12 UT=13 MET, 14 MEZT. Uurvak 05 loopt van 04.00 UT tot 5.00 UT / time (HH uur/hour, UT. 12 UT=13 MET, 14 MEZT. Hourly division 05 runs fr
DD        = Windrichting (in graden) gemiddeld over de laatste 10 minuten van het afgelopen uur (360=noord, 90=oost, 180=zuid, 270=west, 0=windstil 990=veranderlijk. Z
FH        = Uurgemiddelde windsnelheid (in 0.1 m/s). Zie http://www.knmi.nl/klimatologie/achtergrondinformatie/beaufortschaal.pdf / Hourly mean wind speed (in 0.1 m/s)
FF        = Windsnelheid (in 0.1 m/s) gemiddeld over de laatste 10 minuten van het afgelopen uur / Mean wind speed (in 0.1 m/s) during the 10-minute period preceding t
FX        = Hoogste windstoot (in 0.1 m/s) over het afgelopen uurvak / Maximum wind gust (in 0.1 m/s) during the hourly division
T         = Temperatuur (in 0.1 graden Celsius) op 1.50 m hoogte tijdens de waarneming / Temperature (in 0.1 degrees Celsius) at 1.50 m at the time of observation
T10N      = Minimumtemperatuur (in 0.1 graden Celsius) op 10 cm hoogte in de afgelopen 6 uur / Minimum temperature (in 0.1 degrees Celsius) at 0.1 m in the preceding 6
TD        = Dauwpuntstemperatuur (in 0.1 graden Celsius) op 1.50 m hoogte tijdens de waarneming / Dew point temperature (in 0.1 degrees Celsius) at 1.50 m at the time
SQ        = Duur van de zonneschijn (in 0.1 uren) per uurvak, berekend uit globale straling  (-1 for <0.05 uur) / Sunshine duration (in 0.1 hour) during the hourly div
Q         = Globale straling (in J/cm2) per uurvak / Global radiation (in J/cm2) during the hourly division
DR        = Duur van de neerslag (in 0.1 uur) per uurvak / Precipitation duration (in 0.1 hour) during the hourly division
RH        = Uursom van de neerslag (in 0.1 mm) (-1 voor <0.05 mm) / Hourly precipitation amount (in 0.1 mm) (-1 for <0.05 mm)
P         = Luchtdruk (in 0.1 hPa) herleid naar zeeniveau, tijdens de waarneming / Air pressure (in 0.1 hPa) reduced to mean sea level, at the time of observation
VV        = Horizontaal zicht tijdens de waarneming (0=minder dan 100m, 1=100-200m, 2=200-300m,..., 49=4900-5000m, 50=5-6km, 56=6-7km, 57=7-8km, ..., 79=29-30km, 80=30
N         = Bewolking (bedekkingsgraad van de bovenlucht in achtsten), tijdens de waarneming (9=bovenlucht onzichtbaar) / Cloud cover (in octants), at the time of obse
U         = Relatieve vochtigheid (in procenten) op 1.50 m hoogte tijdens de waarneming / Relative atmospheric humidity (in percents) at 1.50 m at the time of observat
WW        = Weercode (00-99), visueel(WW) of automatisch(WaWa) waargenomen, voor het actuele weer of het weer in het afgelopen uur. Zie http://www.knmi.nl/klimatologie
IX        = Weercode indicator voor de wijze van waarnemen op een bemand of automatisch station (1=bemand gebruikmakend van code uit visuele waarnemingen, 2,3=bemand e
M         = Mist 0=niet voorgekomen, 1=wel voorgekomen in het voorgaande uur en/of tijdens de waarneming / Fog 0=no occurrence, 1=occurred during the preceding hour an
R         = Regen 0=niet voorgekomen, 1=wel voorgekomen in het voorgaande uur en/of tijdens de waarneming / Rainfall 0=no occurrence, 1=occurred during the preceding h
S         = Sneeuw 0=niet voorgekomen, 1=wel voorgekomen in het voorgaande uur en/of tijdens de waarneming / Snow 0=no occurrence, 1=occurred during the preceding hour
O         = Onweer 0=niet voorgekomen, 1=wel voorgekomen in het voorgaande uur en/of tijdens de waarneming / Thunder  0=no occurrence, 1=occurred during the preceding
Y         = IJsvorming 0=niet voorgekomen, 1=wel voorgekomen in het voorgaande uur en/of tijdens de waarneming / Ice formation 0=no occurrence, 1=occurred during the p

# STN,YYYYMMDD,   HH,   DD,   FH,   FF,   FX,    T,  T10,   TD,   SQ,    Q,   DR,   RH,    P,   VV,    N,    U,   WW,   IX,    M,    R,    S,    O,    Y

  370,20110101,    1,  230,   30,   30,   40,   13,     ,   11,    0,    0,    0,    0,10229,    1,    9,   99,   33,    7,    1,    0,    0,    0,    0
  370,20110101,    2,  230,   30,   30,   50,   15,     ,   14,    0,    0,    0,    0,10226,    2,    9,   99,   32,    7,    1,    0,    0,    0,    0
  370,20110101,    3,  240,   40,   40,   50,   15,     ,   13,    0,    0,    0,    0,10223,    1,    9,   99,   34,    7,    1,    0,    0,    0,    0
```

Figure 1. Example text file meteorological data

A lot of data presented in this file is not necessary for the energy model proposed in this research. So only the columns of Q, and FH are kept in the text-file, and all other data is deleted. This results in the text-file as shown in Figure 2.



```
Meteorologische_data_w_s - Kladblok
Bestand  Bewerken  Opmaak  Beeld  Help
50      0
40      0
40      0
40      0
40      0
40      0
40      0
```

Figure 2. Text file meteorological data

Where the first column is the average wind speed in m/s, and the second column is the global irradiation per hour. The text file presented in figure 2 can be integrated in the Netlogo file.

Appendix 2) EDSN Demand Profiles

The demand profiles are provide by the EDSN, Energie Data Service Nederland. These demand profiles consist of a data set with the percentage of total yearly energy use per quartile. In the table below the set-up of the demand data can be seen. Before, being able to integrate the demand data in the energy model, the data has to be aggregated as seen in the figure below a representation is given of the text-file which can be imported in the energy model.

Versie nr			1.00_E1A	1.00_E1B	1.00_E1C	1.00_E2A	1.00_E2B	1.00_E3A	1.00_E3B	1.00_E3C	1.00_E3D	1.00_E4A
Toepassingsjaar			2014	2014	2014	2014	2014	2014	2014	2014	2014	2014
Categoriecode			E1A	E1B	E1C	E2A	E2B	E3A	E3B	E3C	E3D	E4A
UTC+1	CET van	tot										
1-1-2014 00:15	1-1-2014 00:00	1-1-2014 00:15	0.00003990	0.00004084	0.00003660	0.00002273	0.00002498	0.00002018	0.00002051	0.00002051	0.00002519	0.00006024
1-1-2014 00:30	1-1-2014 00:15	1-1-2014 00:30	0.00003876	0.00003950	0.00003476	0.00002230	0.00002521	0.00001941	0.00002117	0.00002117	0.00002502	0.00006024
1-1-2014 00:45	1-1-2014 00:30	1-1-2014 00:45	0.00003713	0.00003822	0.00003415	0.00002225	0.00002527	0.00001916	0.00002147	0.00002147	0.00002484	0.00006024
1-1-2014 01:00	1-1-2014 00:45	1-1-2014 01:00	0.00003573	0.00003705	0.00003554	0.00002221	0.00002534	0.00001965	0.00002131	0.00002131	0.00002476	0.00006024
...	....	....	.....	...	...	..	...	...	...	...	...	...

Connection	Description
E1A	<= 3x 25 Ampere, enkel telwerk
E1B	<= 3x 25 Ampere, dubbel telwerk nachttarief
E1C	<= 3x 25 Ampere, dubbel telwerk avond actief tarief
E2A	> 3x25 Ampere <= 3x80A, enkel telwerk
E2B	> 3x25 Ampere <= 3x80A, dubbel telwerk
E3A	> 3x80 Ampere, < 100 kW, BT <= 2000 uur
E3B	> 3x80 Ampere, < 100 kW, BT > 2000 uur, BT <= 3000 uur
E3C	> 3x80 Ampere, < 100 kW, BT > 3000 uur, BT < 5000 uur
E3D	> 3x80 Ampere, < 100 kW, BT >= 5000 uur
E4A	Alle gemeten aansluitingen geschakeld op het stuursignaal openbare verlichting met een aangesloten vermogen van minder dan 100 kW

Appendix 3) Settings of the energy model in the multiple scenarios

Table 1. Specific variables for "de Brand"

Variable	50 Kw	100 kW Windturbine	15% drop in PV costs
Total demand	2.500.000	2.500.000	2.500.000[2]
Top percentage	1,15 (115%)	1,15 (115%)	1,15 (115%)
Iterations	240	240	240
Set_temperature	360	360	360
Stop_temperature	60	60	60
Cooling-rate	5%	5%	5%
Lifetime	15 years	15 years	15 years
Discount-rate	5%	5%	5%

Table 2. Variables for the wind-atlas-methodology

Variable	50 Kw	100 kW Windturbine	15% drop in PV costs
Height UBL	200	200	200
HeightBL	40	40	40
HeightHUB	31	31	31
Dfetch	3.1	3.1	3.1
Z_0fetch	0.7	0.7	0.7

Table 3. Variables for the wind turbines

Variable	50 Kw	100 kW Windturbine	15% drop in PV costs
Initial_investment_ windturbine	€300.000,-	€300.000,-	€300.000,-
O&M-wind	€4.500,- (1,5%)	€4.500,- (1,5%)	€4.500,- (1,5%)
Rated power	50 kW	100 kW	50 kW
Cut-in wind speed	< 3 m/sec	< 3 m/sec	< 3 m/sec
Rated wind speed	9,5 m/sec	12 m/sec	9,5 m/sec
Cut-out wind speed	25 m/sec	25 m/sec	25 m/sec
Safety zoning (vulnerable build.)	2 patch (30m per patch)	2 patch (30m per patch)	2 patch (30m per patch)
Safety zone wind turbines	4 patches (30m per patch)	5 patches (30m per patch)	4 patches (30m per patch)

[2] Data from the municipality of Den Bosch

Table 4. Variables for the PV modules

Variable	50 Kw	100 kW Windturbine	15% drop in PV costs
Invest_modules	€465,-	€465,-	€395,-
O&M-pv	€10,- per panel	€10,- per panel	€10,- per panel
Module-efficiency	19.9%	19.9%	19.9%
Length of the PV module	1,559	1,559	1,559
Width of the PV module	1,046	1,046	1,046
Inclination conversion	3,1	3,1	3,1

Appendix 4) Variables of the Energy Model

In this appendix all variables as shown in the interface are shown.

Input data

Input GIS-map

Figure 1. Input window for the GIS-map (Shapefile)

Input Meteorological data

Figure 2. Input window for the meteorological data

Input EDSN Demand Profile

Figure 3. Input window for the demand profiles

Total Yearly Energy Demand

Figure 4. Total yearly demand of the total research area

Cap Energy Supply

Figure 5. Cap for the energy supply

Simulated Annealing input

Iterations

Figure 6. Number of iterations per cooling schedule

Set-up temperature

Figure 7. Start temperature for the simulated annealing procedure

Stop temperature

Figure 8. Stop temperature for the simulated annealing procedure

Cooling rate

Figure 9. Cooling rate of the simulated annealing procedure

Economic Variables

Proposed Lifetime

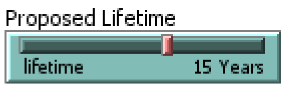


Figure 10. Proposed lifetime of the renewable energy technologies

Discount-rate

Figure 11. Discount rate for the DCF-method

Wind Atlas variables

HeightUBL

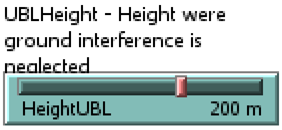


Figure 12. Height of the urban boundary layer

HeightBL

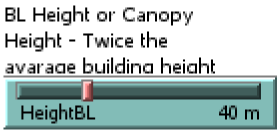


Figure 13. height of the boundary layer

HeightHUB

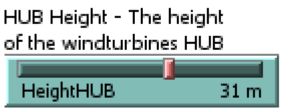


Figure 14. Height of the wind turbines hub

Dfetch & Z_0fetch

Figure 15. Displacement height, and Roughness length of the fetch area

Variables for wind turbines

Investment Wind turbine

Figure 16. Capital costs of the wind turbine

O&M costs of wind turbine

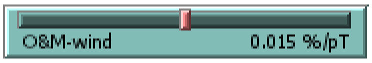


Figure 17. O&M-costs of a wind turbine

Rated power of wind turbine

Figure 18. Rated power of the wind power

Cut-in wind speed

Figure 19. Cut in wind speed of the wind turbine

Rated wind speed

Figure 20. Rated wind speed of the wind turbine

Cut-out wind speed

Figure 21. Cut out wind speed of the wind turbine

Safety radius vulnerable buildings

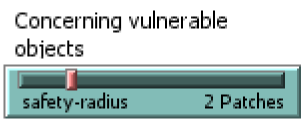


Figure 22. Safety zone between wind turbines, and vulnerable objects

Radius other wind turbines

Figure 23. Safety zoning between wind turbines

Variables for PV modules

Investment PV modules

Figure 24. Investment costs per PV module

O&M-PV

Figure 25. O&M costs per PV module

Costs Transformer

Figure 26. Costs per transformer

Module efficiency

Figure 27. Efficiency of the PV module

Length PV module

Figure 28. Length of the PV module

Width PV module

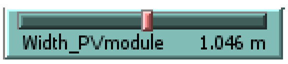


Figure 29. Width of the PV module

Inclination conversion

Figure 30. Inclination conversion for the Notenbomer method

Output

Graph costs of energy

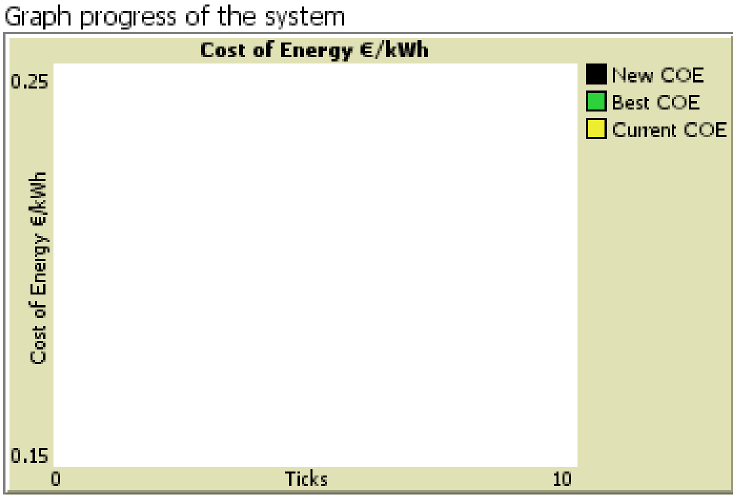


Figure 31. Graph shows the progress of the found COE

Number of PV panels

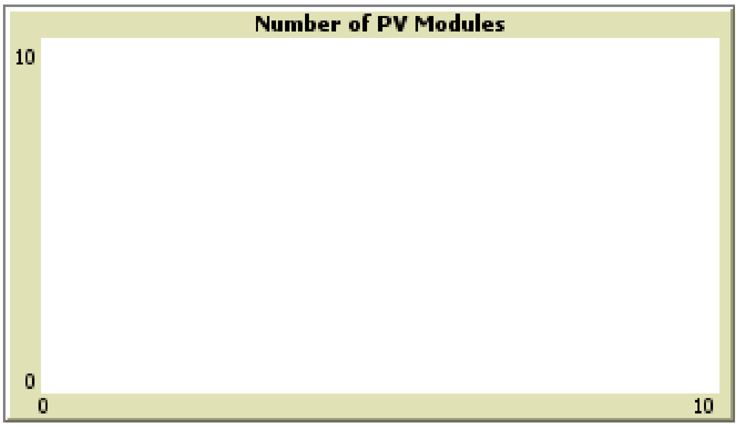


Figure 32. Graph of the number of PV module installed

Number of Wind turbines

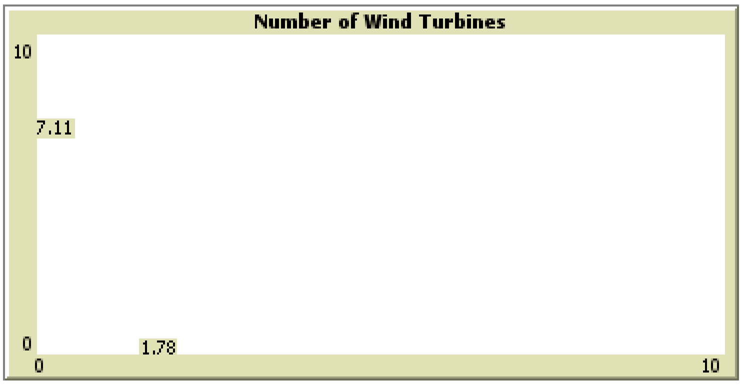


Figure 33. Graph of the number of wind turbines installed

Total investment Wind

Figure 34. Total investment of installed wind turbines

Total investment PV

Figure 35. Total investment of installed PV modules

Yearly production Wind

Figure 36. Total wind energy production

Yearly production PV

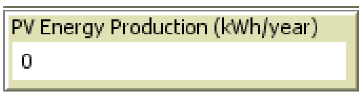


Figure 37. Total PV energy production

Best COE

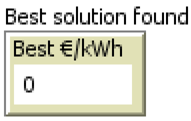


Figure 38. Value of the best found COE configuration

Current COE

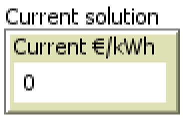


Figure 39. Value of the current found COE configuration

Appendix 5) Method of Notenbomer

To calculate the array-distance a calculation is in effect, in corporation with a conversion table, shown as Table 1. To determine the distance requirements the equation as shown in Eq. 1 is used to calculated this relation.

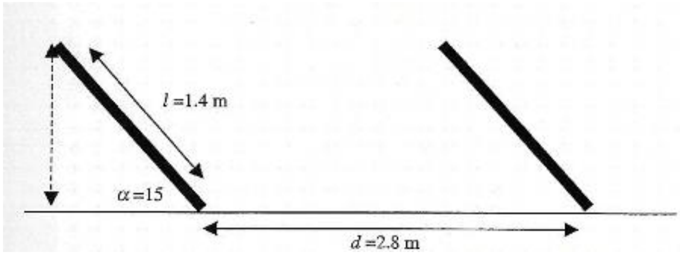


Figure 1. Visualization of distance requirements

Ideal distance between pv-arrays	
Inclination	Conversion (a)
0	1
5	1.3
10	1.7
15	2.0
20	2.3
25	2.6
30	2.9
35	3.1
40	3.4
45	3.5
50	3.7
55	3.9
60	4.0
65	4.1
70	4.1
75	4.1
80	4.1
85	4.1
90	4.1

Table 1. Conversion table to determine distance requirements

The distance between the pv panels can then be determined by the following formula:

$$Distance = Conversion(a) * panel\ length \quad (1)$$

Where *a* is the inclination of the pv-panel, and conversion stands for the calculation value, given in table above. Where, *distance* is the required distance between the feet of the PV module, and *panel length* is the total length of the PV modules.

Appendix 6) Specifications of Energy Technologies

The PV-modules selected in this case are the mono-crystalline modules from Benq. These panels have one of the highest capacities available on the market today. The specification are shown in Table 1.

Table 1. Specification of the PV modules (Benq, 2011)

PV specifications	Values[3]
Productnr	PM0096B00-330
Supplier	Benq
Type	Mono-crystalline
Lifespan guarantee	10 Year
Capacity (Wp)	320 – 330
Costs per panel	€465,-
Efficiency (%)	19.9%
Measurements (LxHxD) (mm)	1559 x 1046 x 46
Production area	1559 x 1046
Required surface at 35° (m^2)	5,05
O&M-costs	€10,- per panel

A medium sized wind turbine is selected in this case, due to the fact the smaller wind turbines are often not profitable, and large wind turbines require a large safety zone making them less likely to be able to install in, or near the built environment. The wind turbine selected is a 50 kW wind turbine produced by WES, and has a hub height of 31 meters. Further specifications are shown in table 2.

Table 2. Specification of the used wind turbines (WES BV., 2015)

Specification	WES50[4]
Supplier	WES BV.
Life Expectancy	20 year
Service/maintenance	Twice a year
Rated Power	50 kW
Cut in wind speed	< 3 m/sec
Cut out wind speed	25 m/sec
Nominal wind speed	9,5 m/sec
Number of blades	2
Rotor diameter	20,3 m

[3] From Benq website
[4] WES website, and email contact with the supplier

Direction	Clockwise
Swept Area	327 m^2
Tower Height	31 m
Costs	€300.000,-
O&M Costs	€4.500,-
Safety radius	2 patch (30m per patch)
radius	4 patches (30m per patch)

Appendix 7) Netlogo Code

```
extensions [ gis ]

globals [
  boundaries               ;; global variable for boundaries drawn in the GIS-file
  windspeedUBL             ;; Global list of the windspeed on UBL height (200 m)
  windspeedBL              ;; Global list of the windspeed on BL height
  Wind_production          ;; Total wind production of all installed wind turbines
  total_wind_investment ;; total wind investment of all installed wind turbines
  cost/kWh                 ;; Overall costs per produced kWh of whole system
  temperature              ;; Control parameter for the simulated annealing
  counter
  maintenance-costs        ;; Total maintenance costs of the whole system
  DCF                      ;; Global list of Discounted Cash Flow of the whole system
  NPV                      ;; Net present value of whole system over lifetime
  total_costs              ;; Sum of O&M costs + capital costs
  parcelx                  ;; The number of the random parcel which is chosen each time
  new-COE                  ;; The costs per produced kWh of the new found configuration
  new-state-w              ;; A list of the allocated wind turbines in the new found configuration
  new-state-s              ;; A list of the allocated PV panels in the new found configuration
  current-COE              ;; The costs per produced kWh of the previous accepted configuration
  current-state-w          ;; A list of the allocated wind turbines in the previous found configuration
  current-state-s          ;; A list of the allocated PV modules in the previous found configuration
  best-COE                 ;; The lowest found costs per produced kWh ever
  best-state-w             ;; A list of the allocated wind turbines in the best found configuration
  best-state-s             ;; A list of the allocated PV modules in the previous found configuration
  new-totalproduction      ;; The total energy production of the new found configuration
  current-totalproduction ;; The total energy production of the previous accepted configuration
  solar_production         ;; Total wind productio of all installed PV modules
  total_production         ;; Total production of wind and solar technologies combined over one year
  total-production         ;; Total production of wind and solar technologies over the whole lifetime

  number                   ;; Control parameter
  balance_final_state      ;; Difference between production, and demand
  production_final_state ;; Total production of the best found configuration
  numb                     ;; Control parameter
  investment_solar         ;; Total investment of PV modules
  numb_modules             ;; Number of installed PV modules
  maint_cost_pv            ;; Maintenance costs of the PV modules over a lifetime

  hourly-wind-production ;; A list of the wind production of a wind turbine calculated for every hour
  hourly-solar-production ;; A list of the solar production of PV modules calculated for every hour
  CFpv                     ;; Cash flow of the PV modules
  CFw                      ;; Cash flow of the Wind turbines

  measured_irradiation     ;; Measured solar irradiation for KNMI dataset
  measured_windspeed       ; Measured wind speeds from KNMI dataset
```

```
  pro                          ;;  Control parameter
  solar_pro                    ;;  Control parameter

  demand_profile_a
  demand_profile_b
  demand_profile_c
  demand_profile_d
  demand_profile_e
  demand_profile_f
  demand_profile_g
  demand_profile_h
  demand_profile_i
  demand_profile_j

]

breed [ windturbines windturbine ]
breed [ panels panel ]
breed [ parcels parcel ]

windturbines-own [
  Roughness               ;;  Roughness length which applies to this wind turbine
  displace                ;;  Displacement height which applies to this wind turbine
  WindspeedHUB            ;;  Wind speed at HUB height
  production              ;;  Yearly energy production
  wind_investment         ;;  Wind investment
  efficiency              ;;
  id                      ;;  ID number identical as the ID number of the parcel
  O&M-wind-costs          ;;  Yearly O&M costs of the wind turbine
  O&Mw                    ;;  O&M costs over the wholle lifetime
]

parcels-own [
  Avail_surf              ;;  The amount of available surface on a parcel
  Roughness               ;;  The roughness length set for this specific parcel
  Displace                ;;  Displacement height set for a specific parcel
  Opp_perc                ;;  Total surface area of a parcel
  Opp_build               ;;  Build surface of a parcel
  vulnerable              ;;  Vulnerability type of the construction on the parcel
  id                      ;;  ID number
  production_wind         ;;  Production of a wind turbine on a parcel
  production_solar        ;;  Production of a solar PV modules on a parcel
  O&M_costs_PV            ;;  O&M costs of the PV modules on this parcel
  O&M_costs_Wind          ;;  O&M costs of the wind turbines on this parcel
  COE_wind                ;;  Costs of Energy of a wind turbine on this parcel
  COE_solar               ;;  Costs of Energy of PV modules on this parcel
  numb_panels             ;;  Number of panels possible on this parcel
  DCFpv                   ;;  Discounted Cash Flow (NPV) of a PV system
  DCFw                    ;;  Discounted Cash Flow (NPV) of a Wind turbines
```

```
]

panels-own [
  id                    ;; ID number identical to that of the parcel
  solar-production      ;; Solar energy production over one year
  roof_surface          ;; Total amount of roof surface
  amount-panels         ;; Number of installed panels on one roof
  required-surface      ;; Minimum required surface for one PV module
  O&M-PV-costs          ;; O&M costs for PV modules over one year
  capacity              ;; Capacity of the PV modules
  costs-panel           ;; Costs per PV module
  lengthpv              ;; Length of the PV module
  widthpv               ;; Width of the PV module
  investmentpv          ;; Total investment of the PV modules
  O&Mpv                 ;; Total O&M costs over the lifetime
]

;; sets-up the whole system, containing the parcels, initial configuration, initial temperature, etc.
to setup
  clear-all
  reset-ticks
  set boundaries gis:load-dataset          Parcel_map
  gis:set-world-envelope-ds gis:envelope-of boundaries
  gis:set-drawing-color                    white
  gis:draw boundaries                      1

  let lists_dem split-into-n-listsx 10 read-file-into-listx Demand_profiles
  set demand_profile_a          item 0 lists_dem
  set demand_profile_b          item 1 lists_dem
  set demand_profile_c          item 2 lists_dem
  set demand_profile_d          item 3 lists_dem
  set demand_profile_e          item 4 lists_dem
  set demand_profile_f          item 5 lists_dem
  set demand_profile_g          item 6 lists_dem
  set demand_profile_h          item 7 lists_dem
  set demand_profile_i          item 8 lists_dem
  set demand_profile_j          item 9 lists_dem

  let lists_meteo split-into-n-lists 2 read-file-into-list Meteorological_Data
  set measured_windspeed        item 0 lists_meteo
  set measured_irradiation      item 1 lists_meteo
  set counter                   0

  set windspeedUBL              Av_windspeed * ( (ln ( HeightUBL / 0.0002 )) / ( ln ( 10 / 0.0002 ) ) )
  set windspeedBL               windspeedUBL * ( (ln ( ( heightBL - dfetch ) / Zofetch ) ) / (ln ( (
HeightUBL - dfetch ) / Zofetch ) ) )

  setup-parcels
  calculate-hourly-adjusted-windspeed
  calculate-hourly-windproduction
```

```
  calculate-hourly-solarproduction
  calculate_O&Mcosts_PV
  calculate_O&Mcosts_wind
  calculate-COEw
  calculate-COEpv
  setup-configuration
  setup-values

  set temperature              set_temperature
  set best-state-w             [ id ] of windturbines
  set best-state-s             [ id ] of panels
  set best-COE                 cost/kWh
  set current-state-w          [ id ] of windturbines
  set current-state-s          [ id ] of panels
  set current-COE              cost/kWh
  set new-state-w              current-state-w
  set new-state-s              current-state-s
  set new-COE                  current-COE

end
```

;; *sets-up the boundaries of the parcels, and uploads its properties*

```
to setup-parcels
   foreach gis:feature-list-of boundaries [
    let feature ?
    let center gis:location-of gis:centroid-of feature
          create-parcels 1 [
           setxy               item 0 center item 1 center
           set color           grey
           set shape           "dot"
           set size            0.5
           set avail_surf      gis:property-value feature "Avail_surf"
           set roughness       gis:property-value feature "Roughness"
           set displace        gis:property-value feature "displace"
           set opp_build       gis:property-value feature "opp_build"
           set vulnerable      gis:property-value feature "vulnerable"
           set id              gis:property-value feature "id"
           set numb_panels     int ( opp_build / ( ( length_PVmodule * inclinationconversion ) *
        width_PVmodule ) )
          ]
   ]
end
```

;; sets-up the initial configuration. This is done by a pure randomization

;; *radius has to be defined further depending on size of the parcelmap*

```
to setup-configuration

 repeat 1000  [

  let w_production     sum [ production ] of windturbines
```

```
  let s_production     sum [ solar-production ] of panels
  let t_production     w_production + s_production

  if t_production > total_demand [ stop ]

  ifelse random-float 1 < 0.5 [
   ask one-of parcels [
     let anywindturbinenearby any? [ windturbines in-radius radius ] of self
     let anyvulnerablebuildingnearby any? [ parcels with [ vulnerable = 1 ]  in-radius safety-radius ] of
self
     let surf [ Avail_surf ] of self

      if not anywindturbinenearby and not anyvulnerablebuildingnearby and surf > 15 [
       hatch-windturbines 1 [
         set xcor                [ xcor ] of myself - .1
         set ycor                [ ycor ] of myself - .1
         set shape               "windmill"
         set color               white
         set size                1.5
         set roughness           [ roughness ] of myself
         set displace            [ displace ] of myself
         set production          [ production_wind ] of myself
         set wind_investment     Initial_investment_windturbine
         set efficiency          wind_investment / production
         set id                  [ id ] of myself
         set O&M-wind-costs      wind_investment * O&M-wind
         set O&Mw                [ DCFw ] of myself
         ]
      ]
     ]
   ]  [
     ask one-of parcels [
       let build_surf [ Opp_build ] of self
       let anypanelnearby any? [ panels in-radius 1 ] of self
        if build_surf > 10 and not anypanelnearby [
         hatch-panels 1 [
           set xcor              [ xcor ] of myself + .1
          set ycor               [ ycor ] of myself + .1
          set shape              "pvpanels"
          set size               1.5
          set color              yellow
          set id                 [ id ] of myself
          set O&M-PV-costs       O&M-pv
          set lengthpv           Length_PVmodule
          set widthpv            Width_PVmodule
          set roof_surface       [ Opp_build ] of myself
         set required-surface     ( ( length_PVmodule * inclinationconversion ) * width_PVmodule )
         set amount-panels        [ numb_panels ] of myself
         set investmentpv         ( amount-panels * invest_modules) + (( int ( amount-panels / 14 ) ) *
Costs_transformer)
```

```
          set capacity              200
          set solar-production    [ production_solar ] of myself
          set O&Mpv                 [ DCFpv ] of myself
         ]
       ]
      ]
    ]
  ]
end
```

;; The id numbers of the windturbines are saved in the current-state, these numbers are identical to the parcel id
;; This procedure has to find the parcel with the same "id" number and retrive all necesarry data from that

```
to display-state-w [ solution solution-color ]
 set number 0 - 1

 repeat length solution [
  set number number + 1

  ask parcels with [ id = item number solution ] [
    hatch-windturbines 1 [
      set xcor                    [ xcor ] of myself - .1
      set ycor                    [ ycor ] of myself - .1
      set shape                   "windmill"
      set color                   solution-color
      set size                    1.5
      set roughness               [ roughness ] of myself
      set displace                [ displace ] of myself
      set production              production_wind ] of myself
      set wind_investment    Initial_investment_windturbine
      set id                      [ id ] of myself
      set O&M-wind-costs     wind_investment * O&M-wind
      set O&Mw                    [ DCFw ] of myself
      ]
   ]
  ]
end

to display-state-s [ solution solution-color ]
  set number        0 - 1

 repeat length solution [
    set number number + 1

  ask parcels with [ id = item number solution ] [
    hatch-panels 1 [
      set xcor                    [ xcor ] of myself + .1
      set ycor                    [ ycor ] of myself + .1
```

```
        set shape                  "pvpanels"
        set size                   1.5
        set color                  solution-color
        set id                     [ id ] of myself
        set lengthpv               Length_PVmodule
        set widthpv                width_PVmodule
        set O&M-PV-costs           O&M-pv
        set roof_surface           [ Opp_build ] of myself
        set required-surface       ( ( length_PVmodule * inclinationconversion ) * width_PVmodule )
        set amount-panels          [ numb_panels ] of myself
        set investmentpv           ( amount-panels * invest_modules) + (( int ( amount-panels / 14 ) ) *
Costs_transformer)
       set capacity                200
       set solar-production        [ production_solar ] of myself
       set O&Mpv                   [ DCFpv ] of myself
      ]
    ]
  ]
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

;; 'go' procedure initiates the running of the energy model
to go

  if temperature <= Stop_temperature [
    ask windturbines        [ die ]
    ask panels              [ die ]

    display-state-w best-state-w green
    display-state-s best-state-s green

    set production_final_state          sum [ production ] of windturbines + sum [ solar-production ]
of panels
   set balance_final_state              production_final_state - total_demand

   setup-values
   print-values
 ;; currently only stops the simulation, and also asks all windturbines to die
   stop

 ;; there is no best-solution being generated yet, this is dependent on the memory of the system
  ]

  repeat iterations [
    tick
   set counter counter + 1
```

```
    change-configuration

if new-COE < best-COE and total_demand < new-totalproduction and ( total_demand *
Top_percentage ) > new-totalproduction [
    set best-COE           new-COE
    set best-state-w       new-state-w
    set best-state-s       new-state-s

  ]

  if new-COE < current-COE and total_demand < new-totalproduction [
     set current-COE                    new-COE
     set current-state-w                new-state-w
     set current-state-s                new-state-s
     set current-totalproduction      new-totalproduction
  ]

  if random-float set_temperature < temperature and total_demand < new-totalproduction [
     set current-COE                    new-COE
     set current-state-w                new-state-w
     set current-state-s                new-state-s
     set current-totalproduction      new-totalproduction
  ]

  ask windturbines      [ die ]
  ask panels                [ die ]

 display-state-w current-state-w white
 display-state-s current-state-s white

 ]
set temperature    temperature * cooling-rate

end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
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;; one parcel is randomly selected in order to find another neighboring solution to the current one
;;
to select_parcels
    set parcelx one-of parcels
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```

```
;; This procedure initiates the process of finding a new solution while confoming to the constraints
;; It consists of two major if-then-else function
;; Patches zijn +_ 30 meter per stuk dit is van belang voor de afstandsbepaling van de windturbines.
to change-configuration

  select_parcels

  let avail_surfx           [ avail_surf ] of parcelx
  let opp_buildx            [ opp_build ] of parcelx
  let idx                   [ id ] of parcelx
  let xx                    [ xcor ] of parcelx
  let xy                    [ ycor ] of parcelx
  let anywindturbinenearby_x          any? [ windturbines in-radius radius ] of patch xx xy
  let anywindturbineonparcel          any?  windturbines with [ id = idx ]
  let anymoduleonparcel               any? panels with [ id = idx ]
  let anyvulnerablebuildingnearby_x  any? [ parcels with [ vulnerable = 1 ]  in-radius safety-radius ] of
patch xx xy
  let coew                  [ COE_wind ] of parcelx
  let coes                  [ COE_solar ]  of parcelx

  if coew < coes [
    ifelse not anywindturbineonparcel [
      ifelse avail_surfx > 15 and not anywindturbinenearby_x and not anyvulnerablebuildingnearby_x [
       develop_wind ][
        ifelse anymoduleonparcel [
         if coes > current-COE [
          delete_PV
          ]
         ] [
          if coes < current-COE and opp_buildx > 10 [
             develop_PV
             ]
           ]
        ]
      ]  [
      ifelse anymoduleonparcel [
       delete_PV ][
        ifelse coes < current-COE [
          if opp_buildx > 10 [
           develop_PV
          ]
         ]  [
          if coew > current-COE [
           delete_wind
           ]
          ]
       ]
     ]
  ]
```

```
  if coes < coew [
    ifelse not anymoduleonparcel[
     ifelse opp_buildx > 10 [
       develop_PV
        ] [
        ifelse anywindturbineonparcel [
         if coew > current-COE [
          delete_wind
          ]
         ] [
          if coew < current-COE and avail_surfx > 15 and not anywindturbinenearby_x and not
anyvulnerablebuildingnearby_x [
           develop_wind
           ]
         ]
       ]
     ]  [
     ifelse anywindturbineonparcel [
       delete_wind
       ]  [
        ifelse coew < current-COE [
         if avail_surfx > 15 and not anywindturbinenearby_x and not anyvulnerablebuildingnearby_x [
          develop_wind
          ]
        ]  [
         if coes > current-COE [
          delete_PV
          ]
         ]
       ]
     ]
   ]
end

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;; Is initiated by the procedure above.  It ensures the development of PV modules on a randomly
selected parcel
to develop_PV ;; generate PV

  let idx [ id ] of parcelx

  ask parcels with [ id = idx ] [
    hatch-panels 1 [
     set xcor              [ xcor ] of myself + .1
     set ycor              [ ycor ] of myself + .1
     set shape             "pvpanels"
     set size              1.5
```

```
      set color                   yellow
      set id                      [ id ] of myself
      set lengthpv                Length_PVmodule
      set widthpv                 width_PVmodule
      set O&M-PV-costs            O&M-pv
      set roof_surface            [ Opp_build ] of myself
      set required-surface        ( ( length_PVmodule * inclinationconversion ) * width_PVmodule )
      set amount-panels           [ numb_panels ] of myself
      set investmentpv            ( amount-panels * invest_modules) + (( int ( amount-panels / 14 ) ) *
Costs_transformer)
      set capacity                200
      set solar-production        [ production_solar ] of myself
      set O&Mpv                   [ DCFpv ] of myself
    ]
  ]

  setup-values

  set new-totalproduction        total_production
  set new-COE                    cost/kWh
  set new-state-w                [ id ] of windturbines
  set new-state-s                [ id ] of panels

end

;; Is initiated by the procedure above.  It ensures the development of Wind turbine on a randomly
selected parcel
to develop_wind

  let idx [ id ] of parcelx

  ask parcels with [ id = idx ] [
    hatch-windturbines 1 [
      set xcor                    [ xcor ] of myself - .1
      set ycor                    [ ycor ] of myself - .1
      set shape                   "windmill"
      set color                   white
      set size                    1.5
      set roughness               [ roughness ] of myself
      set displace                [ displace ] of myself
      set production              [ production_wind ] of myself
      set wind_investment         Initial_investment_windturbine
      set id                      [ id ] of myself
      set O&M-wind-costs          wind_investment * O&M-wind
     set O&Mw                     [ DCFw ] of myself
     ]

   ]

  setup-values
```

```
  set new-totalproduction              total_production
  set new-COE                          cost/kWh
  set new-state-w                      [ id ] of windturbines
  set new-state-s                      [ id ] of panels

end

;; Deletes the PV modules from the randomly selected parcel

to delete_PV
  let idx [ id ] of parcelx

 ask panels with [ id = idx ] [
   die
  ]

  setup-values

  set new-totalproduction              total_production
  set new-COE                          cost/kWh
  set new-state-w                      [ id ] of windturbines
  set new-state-s                      [ id ] of panels

end

;; Deletes the Wind turbine from the randomly selected parcel
to delete_wind
  let idx [ id ] of parcelx

  ask windturbines with [ id = idx ] [
    die
  ]

  setup-values

  set new-totalproduction              total_production
  set new-COE                          cost/kWh
  set new-state-w                      [ id ] of windturbines
  set new-state-s                      [ id ] of panels

end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
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;; Calculate the feasibility (cost of energy) has to be elaborated
;; Discounted cash flow has to be integrated for a lifetime of 15 years
;; Meteorological data has to be integrated
```

```
to setup-values

  set wind_production              sum [ production ] of windturbines
  set solar_production             sum [ solar-production ] of panels
  set total-production             ( wind_production + solar_production ) * lifetime
  set total_production             wind_production + solar_production
  set maintenance-costs            sum [ O&M-wind-costs ]  of windturbines
  set numb_modules                 sum [ amount-panels ] of panels
  set investment_solar             sum [ investmentpv ] of panels
  set maint_cost_pv                numb_modules * O&M-pv
  discounted-cf
  set NPV                          sum DCF
  set total_wind_investment        sum [ wind_investment ] of windturbines
  set total_costs                  total_wind_investment + investment_solar + NPV
  set cost/kWh                     total_costs / total-production
end

;; This procedure calculates the discounted cash flow of the whole energy system over the lifetime
to Discounted-CF

    let life         n-values lifetime [?]
    set numb       0
    set DCF         ( list )

  repeat lifetime [
     let costs       (maintenance-costs + maint_cost_pv) / ( discount-rate ^ item numb life )
     set DCF         lput costs DCF
     set numb      numb + 1
  ]
end

;; This procedure calculates the O&M costs of all PV modules over the lifetime using DCF-method
to calculate_O&Mcosts_PV

 ask parcels [
   let n n-values lifetime [?]
     set CFpv       ( list )
     set numb       0

     repeat length n [
        let costs       ( O&M-pv * numb_panels  ) / (discount-rate ^ item numb n)
        set CFpv       lput costs CFpv
        set numb      numb + 1
     ]

   set DCFpv       ( sum CFpv )
  ]
end
```

```
;; This procedure calculates the O&M costs of all wind turbines over the lifetime using DCF-method

to calculate_O&Mcosts_wind
  ask parcels [
    let n             n-values lifetime [?]
    set numb      0
    set CFw         ( list)

     repeat length n [
       let costs      ( Initial_investment_windturbine * O&M-wind ) / (discount-rate ^ item numb n)
       set CFw        lput costs CFw
       set numb     numb + 1
     ]
   set DCFw         ( sum CFw )
   ]
end

;; This procedure calculates for every parcel the costs of energy for a wind turbine

to calculate-COEw
  ask parcels [
      set O&M_costs_Wind     DCFw
      set COE_wind                 ( Initial_investment_windturbine + O&M_costs_Wind ) / (
production_wind * lifetime )
  ]
end

;; This procedure calculates for every parcel the costs of energy of PV modules
to calculate-COEpv

  ask parcels [
     if numb_panels > 1 [
        set O&M_costs_PV         DCFpv
        set COE_solar                ((numb_panels * invest_modules ) + (( int ( numb_panels / 14 ) ) *
Costs_transformer ) + O&M_costs_PV ) / ( production_solar * lifetime )
    ]
  ]

end

;; This procedure usess the wind-atlas-methodology to calculate the adjusted wind speed per parcel
using the displacement height, and roughness length
to calculate-hourly-adjusted-windspeed
   let x 0 - 1
   set windspeedUBL (list)

  repeat length measured_windspeed [
     set x                          x + 1
     let w_speed               item x measured_windspeed
     let UBL                      ((w_speed * 0.1) * ( (ln ( HeightUBL / 0.0002 )) / ( ln ( 10 / 0.0002 ) ) ) )
```

```
    set windspeedUBL       lput UBL windspeedUBL
  ]

  let y 0 - 1
  set windspeedBL ( list )

  repeat length windspeedUBL [
    set y                    y + 1
    let w_speed              item y windspeedUBL
    let WBL                  ( w_speed * ( (ln ( ( heightBL - dfetch ) / Zofetch ) ) / (ln ( ( HeightUBL -
dfetch ) / Zofetch ) ) )  )
    set windspeedBL        lput WBL windspeedBL
  ]
end
```

;; *This method uses the previous calculated values to calculate the energy prodution of a wind turbine on a specific parcel.*

```
to calculate-hourly-windproduction
  ask parcels [
      let x                          0 - 1
      set hourly-wind-production ( list )

repeat length windspeedBL [
   set x             x + 1

   let w_speed      item x windspeedBL
   let speed         w_speed * ( (ln ( ( heightHUB - displace) / roughness ) ) / (ln ( ( HeightBL -
displace ) / roughness ) ) )

   if speed < cut-in [
     set pro       0
    ]

   if speed > cut-in and speed < rated [
     set pro      (rated-power / (rated - cut-in)) * ( speed - cut-in )
   ]

   if speed > rated and speed < cut-out [
     set pro      rated-power
   ]

   if speed > cut-out [
    set pro     0
   ]
   set hourly-wind-production          lput pro hourly-wind-production
  ]
   set production_wind                  ( sum hourly-wind-production )
  ]
end
```

```
;; This procedure calculates the hourly solar energy production for the PV modules
to calculate-hourly-solarproduction

  ask parcels [
    set hourly-solar-production ( list )
    let x                    0 - 1
    let array_surface        numb_panels * ( Length_PVmodule * width_PVmodule )

   repeat length measured_irradiation [
     set x                          x + 1
     let hourly_irradiation/m2      (( item x measured_irradiation / 3600 ) * 10 )
     set solar_pro                  ( array_surface * module_efficiency * hourly_irradiation/m2 )
     set hourly-solar-production    lput solar_pro hourly-solar-production
   ]
     set production_solar           ( sum hourly-solar-production )
]
end

;; This procedure reads, and imports the dataset from the KNMI
to-report read-file-into-list [ Meteorologische_data_w_s.txt ]
   file-open Meteorological_Data
   let xs []
   while [ not file-at-end? ] [
      set xs lput file-read xs
  ]
  file-close
  report xs
end

;; This procedure splits the data set in proper lists
to-report split-into-n-lists [ n xs ]
   let lists n-values n [[]]
   while [not empty? xs] [
      let items []

 repeat n [
     if not empty? xs [
      set items lput (first xs) items
      set xs but-first xs
     ]
   ]

   foreach (n-values length items [ ? ]) [
     set lists replace-item ? lists (lput (item ? items) (item ? lists))
   ]
  ]

  report lists
end
```

```
;; This procedure reads, and imports the dataset from EDSN
to-report read-file-into-listx [ Uurdata_energievraag_bew.txt ]
   file-open Demand_profiles
   let xs []
   while [ not file-at-end? ] [
     set xs lput file-read xs
  ]
  file-close
  report xs
end

;; This procedure splits the data set in proper lists
to-report split-into-n-listsx [ n xs ]
   let lists n-values n [[]]
   while [not empty? xs] [
     let items []
     repeat n [
       if not empty? xs [
         set items lput (first xs) items
         set xs but-first xs
       ]
   ]
   foreach (n-values length items [ ? ]) [
       set lists replace-item ? lists (lput (item ? items) (item ? lists))
   ]
  ]
  report lists
end

;; This procedure prints the outcome of the energy model
to print-values
  file-open "test.txt"

  ask windturbines [
     file-show      id
     file-show     production
     file-show     wind_investment
     file-show     O&M-wind-costs
     file-show     O&Mw
  ]

  ask panels [
     file-show     id
     file-show     solar-production
     file-show     amount-panels
     file-show     investmentpv
     file-show     O&M-PV-costs
     file-show     O&Mpv
```

```
  ]

  file-close
end
```

Appendix 8) Output simulations

Alongside the generation of a least costs configuration, and number of installed renewable energy technologies the model also generated other output data which included the location of the renewable energy technologies, and there characteristics.

Output three scenarios

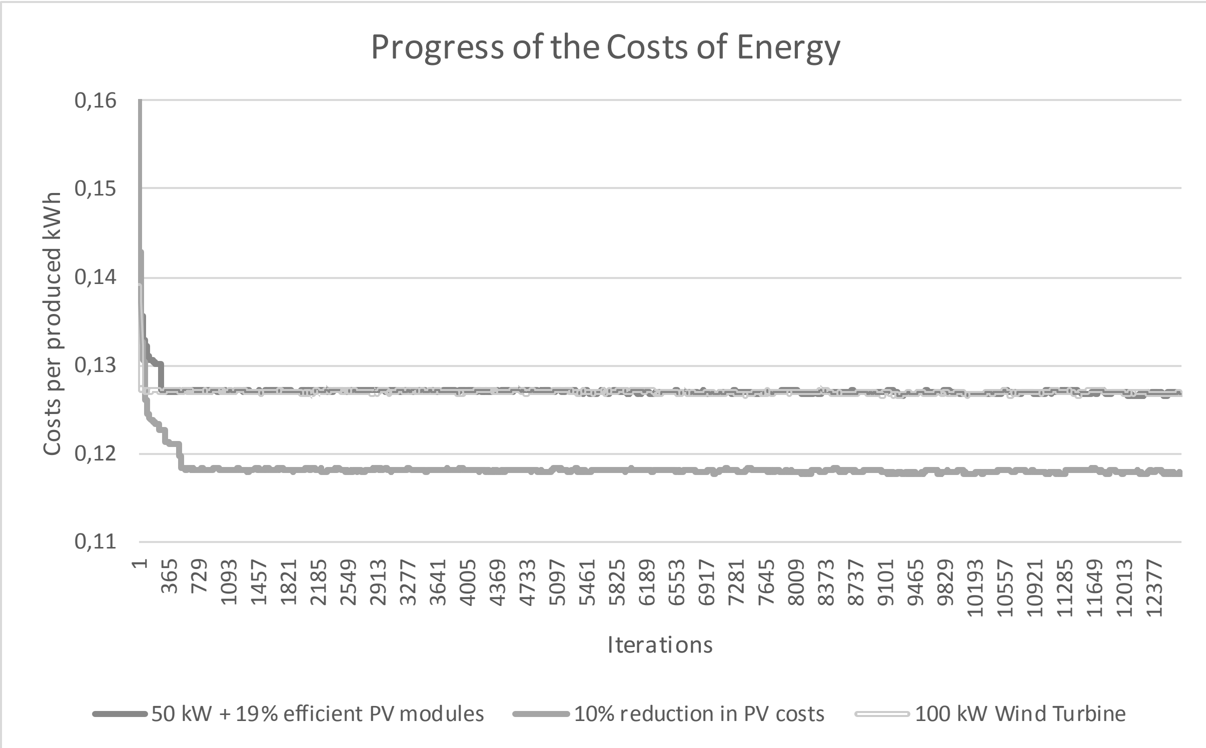

Figure 1. Current Cost of energy configuration

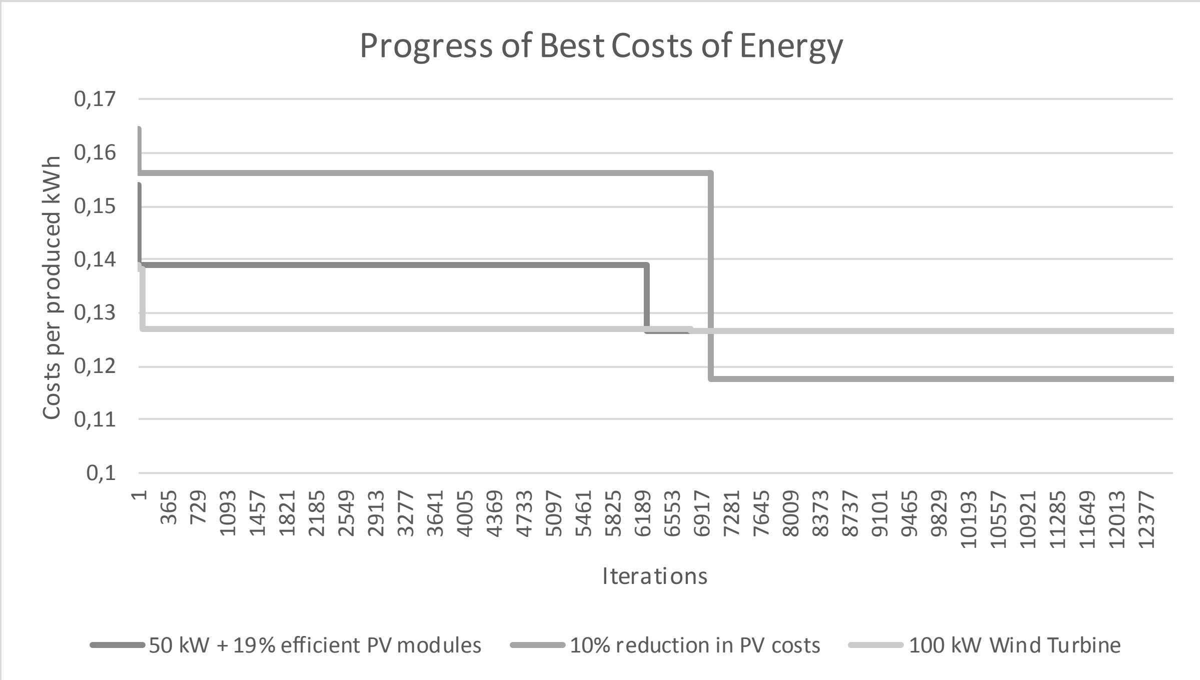

Figure 2. Best Cost of Energy configuration

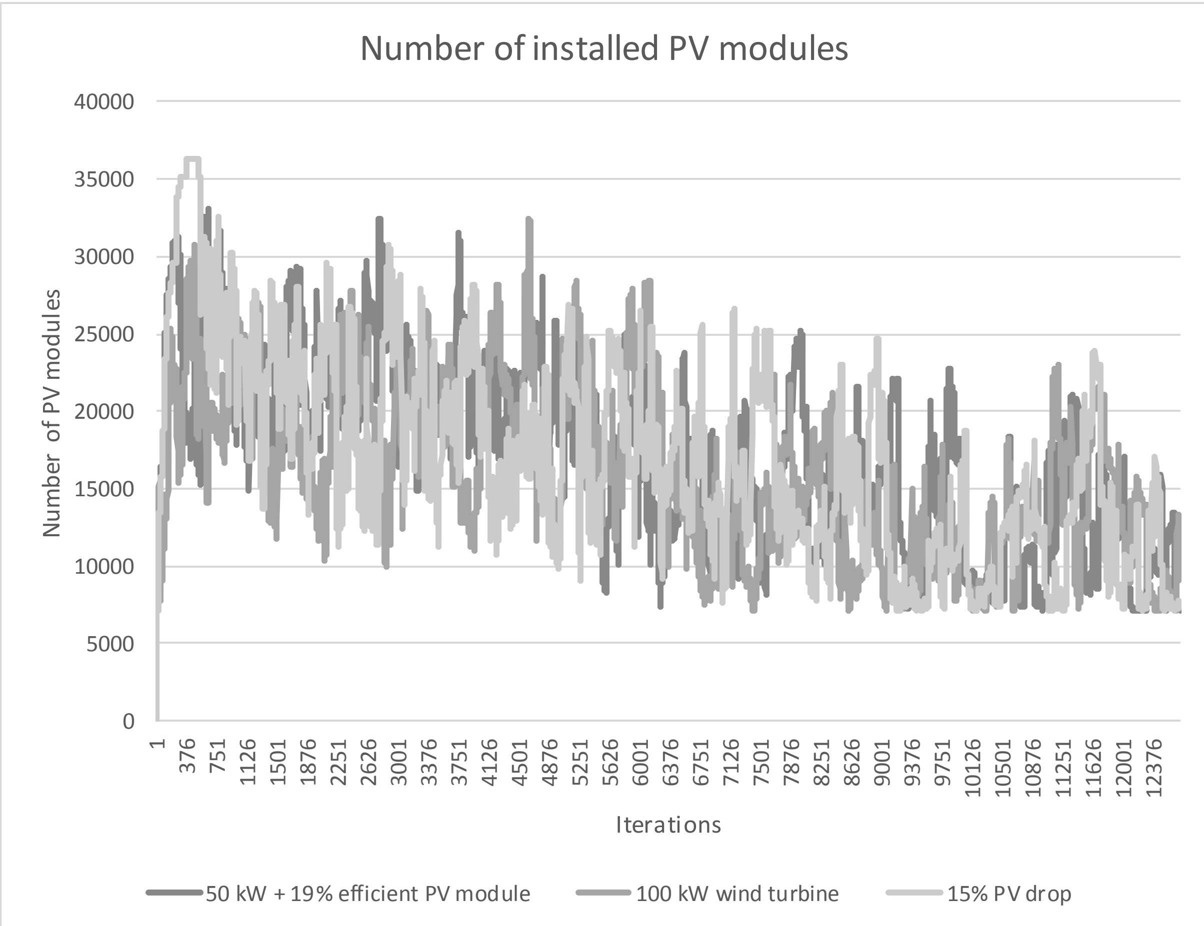

Figure 3. Number of PV modules installed per iteration

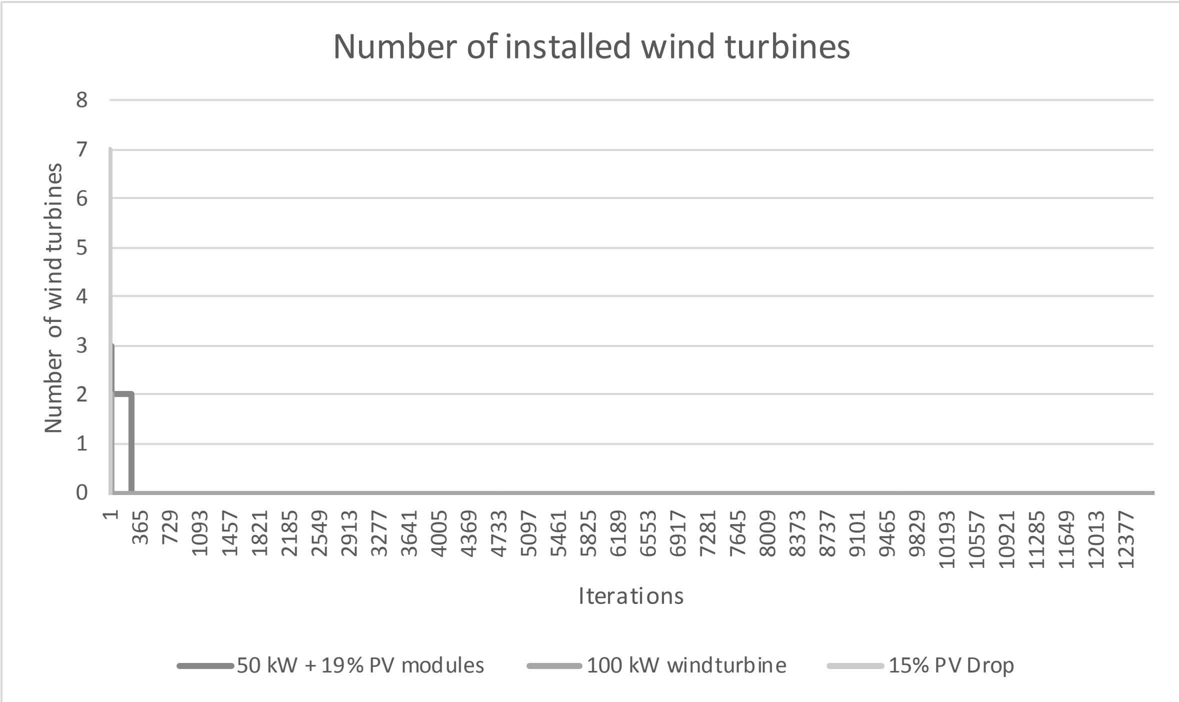

Figure 4. Number of wind turbines installed per iteration

Table 1. Summation of each installed Renewable Energy Technology 50 kW

RET Nr	Parcel ID	Yearly Production (kWh)	Number of Panels	Investment	O&M-costs over lifetime
(panel 674715)	98	4.572	13	€ 6.045,00	€ 1.416,82
(panel 674735)	95	61.897	176	€ 98.400,00	€ 19.181,61
(panel 674709)	69	48.885	139	€ 77.055,00	€ 15.149,11
(panel 674734)	97	40.796	116	€ 64.980,00	€ 12.642,42
(panel 674729)	25	73.503	209	€ 116.505,00	€ 22.778,16
(panel 674724)	7	62.249	177	€ 98.865,00	€ 19.290,59
(panel 674701)	46	77.371	220	€ 123.000,00	€ 23.977,01
(panel 674707)	73	92.142	262	€ 146.670,00	€ 28.554,44
(panel 674728)	63	38.334	109	€ 60.345,00	€ 11.879,52
(panel 674700)	102	146.654	417	€ 233.925,00	€ 45.447,33
(panel 674704)	55	71.392	203	€ 113.715,00	€ 22.124,24
(panel 674731)	47	36.927	105	€ 58.485,00	€ 11.443,57
(panel 674710)	115	107.265	305	€ 170.805,00	€ 33.240,85
(panel 674717)	62	78.426	223	€ 124.395,00	€ 24.303,97
(panel 674726)	103	86.515	246	€ 137.850,00	€ 26.810,66
(panel 674720)	44	78.426	223	€ 124.395,00	€ 24.303,97
(panel 674732)	96	52.050	148	€ 82.620,00	€ 16.129,99
(panel 674706)	59	62.952	179	€ 99.795,00	€ 19.508,57
(panel 674718)	52	48.181	137	€ 76.125,00	€ 14.931,14
(panel 674719)	48	36.927	105	€ 58.485,00	€ 11.443,57
(panel 674698)	20	28.135	80	€ 44.100,00	€ 8.718,91
(panel 674736)	28	55.918	159	€ 89.115,00	€ 17.328,84
(panel 674705)	93	50.995	145	€ 81.225,00	€ 15.803,03
(panel 674727)	114	274.316	780	€ 438.600,00	€ 85.009,40
(panel 674725)	70	1.407	4	€ 1.860,00	€ 435,95
(panel 674703)	110	88.273	251	€ 140.175,00	€ 27.355,59
(panel 674730)	84	30.597	87	€ 48.735,00	€ 9.481,82
(panel 674713)	104	51.698	147	€ 82.155,00	€ 16.021,00
(panel 674711)	42	92.142	262	€ 146.670,00	€ 28.554,44
(panel 674722)	113	82.646	235	€ 131.355,00	€ 25.611,81
(panel 674723)	106	72.096	205	€ 114.645,00	€ 22.342,21
(panel 674716)	26	15.826	45	€ 25.065,00	€ 4.904,39
(panel 674702)	107	41.147	117	€ 65.445,00	€ 12.751,41
(panel 674708)	61	117.112	333	€ 186.585,00	€ 36.292,47
(panel 674712)	12	37.631	107	€ 59.415,00	€ 11.661,55
(panel 674733)	27	14.067	40	€ 21.360,00	€ 4.359,46
(panel 674714)	74	74.558	212	€ 119.280,00	€ 23.105,12
(panel 674721)	100	32.355	92	€ 51.060,00	€ 10.026,75
(panel 674699)	94	43.258	123	€ 68.235,00	€ 13.405,33
Total		**2.509.641**	**7136**	**€ 3.987.540,00**	**€ 777.727,02**

Table 2. Summation of each installed Renewable Energy Technology 100 kW wind turbine

RET Nr	Parcel ID	Yearly Production (kWh)	Number of Panels	Investment	O&M-costs over lifetime
(panel 947115)	72	101.286	288	€ 161.520,00	€ 31.388,09
(panel 947110)	76	127.311	362	€ 202.830,00	€ 39.453,08
(panel 947142)	66	117.815	335	€ 187.515,00	€ 36.510,45
(panel 947119)	50	92.494	263	€ 147.135,00	€ 28.663,43
(panel 947131)	69	48.885	139	€ 77.055,00	€ 15.149,11
(panel 947136)	44	78.426	223	€ 124.395,00	€ 24.303,97
(panel 947106)	26	15.826	45	€ 25.065,00	€ 4.904,39
(panel 947109)	104	51.698	147	€ 82.155,00	€ 16.021,00
(panel 947113)	61	117.112	333	€ 186.585,00	€ 36.292,47
(panel 947130)	113	82.646	235	€ 131.355,00	€ 25.611,81
(panel 947120)	52	48.181	137	€ 76.125,00	€ 14.931,14
(panel 947112)	96	52.050	148	€ 82.620,00	€ 16.129,99
(panel 947117)	62	78.426	223	€ 124.395,00	€ 24.303,97
(panel 947124)	27	14.067	40	€ 21.360,00	€ 4.359,46
(panel 947143)	55	71.392	203	€ 113.715,00	€ 22.124,24
(panel 947139)	84	30.597	87	€ 48.735,00	€ 9.481,82
(panel 947129)	115	107.265	305	€ 170.805,00	€ 33.240,85
(panel 947114)	73	92.142	262	€ 146.670,00	€ 28.554,44
(panel 947132)	110	88.273	251	€ 140.175,00	€ 27.355,59
(panel 947133)	100	32.355	92	€ 51.060,00	€ 10.026,75
(panel 947116)	59	62.952	179	€ 99.795,00	€ 19.508,57
(panel 947105)	20	28.135	80	€ 44.100,00	€ 8.718,91
(panel 947126)	46	77.371	220	€ 123.000,00	€ 23.977,01
(panel 947128)	48	36.927	105	€ 58.485,00	€ 11.443,57
(panel 947111)	94	43.258	123	€ 68.235,00	€ 13.405,33
(panel 947135)	12	37.631	107	€ 59.415,00	€ 11.661,55
(panel 947140)	8	34.817	99	€ 55.695,00	€ 10.789,65
(panel 947121)	103	86.515	246	€ 137.850,00	€ 26.810,66
(panel 947107)	99	34.465	98	€ 55.230,00	€ 10.680,67
(panel 947138)	98	4.572	13	€ 6.045,00	€ 1.416,82
(panel 947118)	25	73.503	209	€ 116.505,00	€ 22.778,16
(panel 947108)	42	92.142	262	€ 146.670,00	€ 28.554,44
(panel 947134)	7	62.249	177	€ 98.865,00	€ 19.290,59
(panel 947141)	97	40.796	116	€ 64.980,00	€ 12.642,42
(panel 947144)	47	36.927	105	€ 58.485,00	€ 11.443,57
(panel 947122)	63	38.334	109	€ 60.345,00	€ 11.879,52
(panel 947127)	106	72.096	205	€ 114.645,00	€ 22.342,21
(panel 947123)	102	146.654	417	€ 233.925,00	€ 45.447,33
(panel 947137)	70	1.407	4	€ 1.860,00	€ 435,95
(panel 947125)	95	61.897	176	€ 98.400,00	€ 19.181,61
Total		**2.520.895**	**7168**	**€ 4.003.800,00**	**€ 781.214,59**

Table 3. Summation of each installed Renewable Energy Technology 15% PV drop

RET Nr	Parcel ID	Yearly Production (kWh)	Number of Panels	Investment	O&M-costs over lifetime
(panel 975765)	66	117.815	335	€ 171.770,00	€ 36.510,45
(panel 975762)	113	82.646	235	€ 120.310,00	€ 25.611,81
(panel 975764)	103	86.515	246	€ 126.288,00	€ 26.810,66
(panel 975786)	63	38.334	109	€ 55.222,00	€ 11.879,52
(panel 975757)	96	52.050	148	€ 75.664,00	€ 16.129,99
(panel 975767)	94	43.258	123	€ 62.454,00	€ 13.405,33
(panel 975769)	76	127.311	362	€ 185.816,00	€ 39.453,08
(panel 975793)	48	36.927	105	€ 53.550,00	€ 11.443,57
(panel 975788)	16	196.241	558	€ 287.064,00	€ 60.814,42
(panel 975758)	98	4.572	13	€ 5.434,00	€ 1.416,82
(panel 975775)	27	14.067	40	€ 19.480,00	€ 4.359,46
(panel 975772)	26	15.826	45	€ 22.950,00	€ 4.904,39
(panel 975773)	55	71.392	203	€ 104.174,00	€ 22.124,24
(panel 975785)	52	48.181	137	€ 69.686,00	€ 14.931,14
(panel 975770)	70	1.407	4	€ 1.672,00	€ 435,95
(panel 975784)	100	32.355	92	€ 46.736,00	€ 10.026,75
(panel 975760)	53	45.016	128	€ 65.924,00	€ 13.950,26
(panel 975774)	93	50.995	145	€ 74.410,00	€ 15.803,03
(panel 975780)	7	62.249	177	€ 90.546,00	€ 19.290,59
(panel 975795)	46	77.371	220	€ 112.660,00	€ 23.977,01
(panel 975781)	59	62.952	179	€ 91.382,00	€ 19.508,57
(panel 975768)	104	51.698	147	€ 75.246,00	€ 16.021,00
(panel 975787)	97	40.796	116	€ 59.528,00	€ 12.642,42
(panel 975771)	20	28.135	80	€ 40.340,00	€ 8.718,91
(panel 975778)	73	92.142	262	€ 134.356,00	€ 28.554,44
(panel 975759)	44	78.426	223	€ 113.914,00	€ 24.303,97
(panel 975790)	25	73.503	209	€ 106.682,00	€ 22.778,16
(panel 975792)	110	88.273	251	€ 128.378,00	€ 27.355,59
(panel 975763)	95	61.897	176	€ 90.128,00	€ 19.181,61
(panel 975761)	47	36.927	105	€ 53.550,00	€ 11.443,57
(panel 975789)	62	78.426	223	€ 113.914,00	€ 24.303,97
(panel 975783)	28	55.918	159	€ 81.642,00	€ 17.328,84
(panel 975777)	89	104.099	296	€ 152.708,00	€ 32.259,98
(panel 975794)	115	107.265	305	€ 156.470,00	€ 33.240,85
(panel 975766)	69	48.885	139	€ 70.522,00	€ 15.149,11
(panel 975779)	42	92.142	262	€ 134.356,00	€ 28.554,44
(panel 975782)	50	92.494	263	€ 134.774,00	€ 28.663,43
(panel 975791)	106	72.096	205	€ 105.010,00	€ 22.342,21
(panel 975776)	12	37.631	107	€ 54.386,00	€ 11.661,55
Total		**2.508.233**	**7132**	**€ 3.649.096,00**	**€ 777.291,09**

Output HvH scenario

The high renewable energy potential is set up to evaluate the configuration, and costs of the renewable energy system if it were allocated in an area with a higher renewable energy potential. Besides integrating other meteorological dataset no changes were made. This implies, that in this case-study the assumption is made that the fetch area for the wind atlas methodology is the same as in the base-case. Furthermore, the assumption is made that all safety zoning, and regulations are identical to the base-case. In this case, the meteorological data from the weather station in 'Hoek van Holland' is used, which is located in the south of the province South-Holland, and nearby the North Sea. It has a yearly average wind speed of around 7.5 m/s, and an average of 1600 solar hours per year which si significant higher than in 's-Hertogenbosch.

The progress of the energy model can be seen in Figure 9, where the value of the cost of energy is shown for each found configuration. The more preferable meteorological location increases the energy output of the renewable energy technologies, which in turns decreases the differences of the costs of energy between the renewable energy technologies. This becomes clear in Figure 9, where the found changes are small, and in Figure 6 is seen that the "best" configuration is found rapidly.

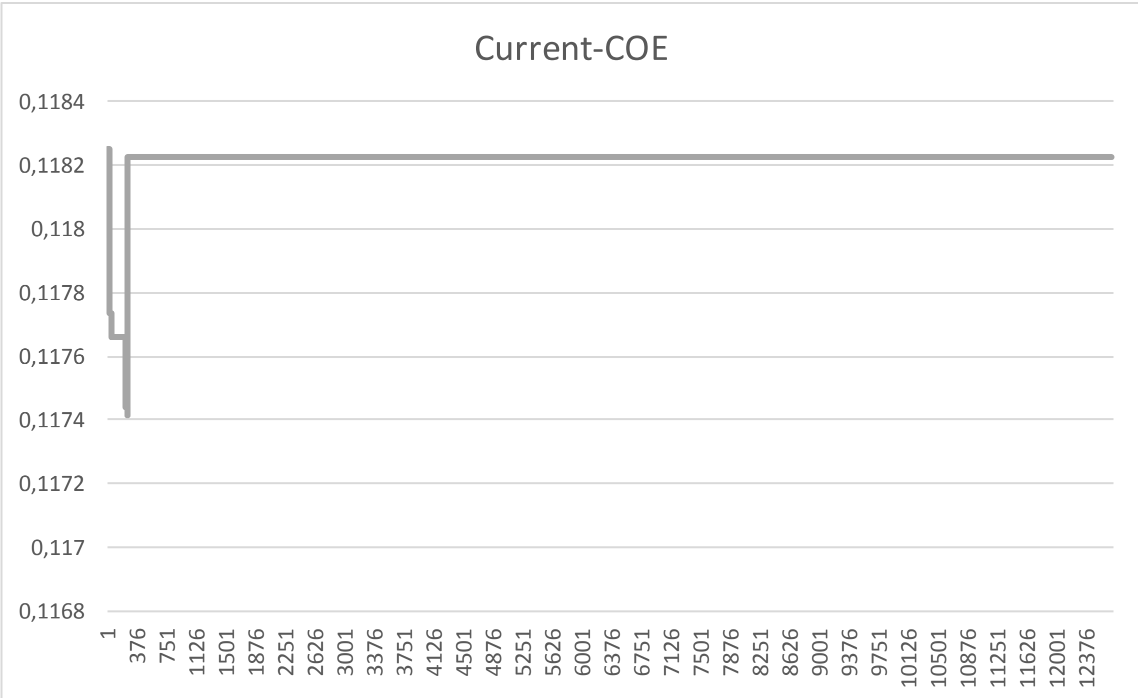

Figure 9. The progress of the COE

In Figure 10 the progress of the found "best" configuration is presented. It can be seen that the lowest Costs per kWh after almost 450 iterations, and no better solution is found afterwards, which fits all constraints. This can be a result of the small differences between the costs of energy of the renewable energy technologies on the business premises. The overall results are represented in Table 3.

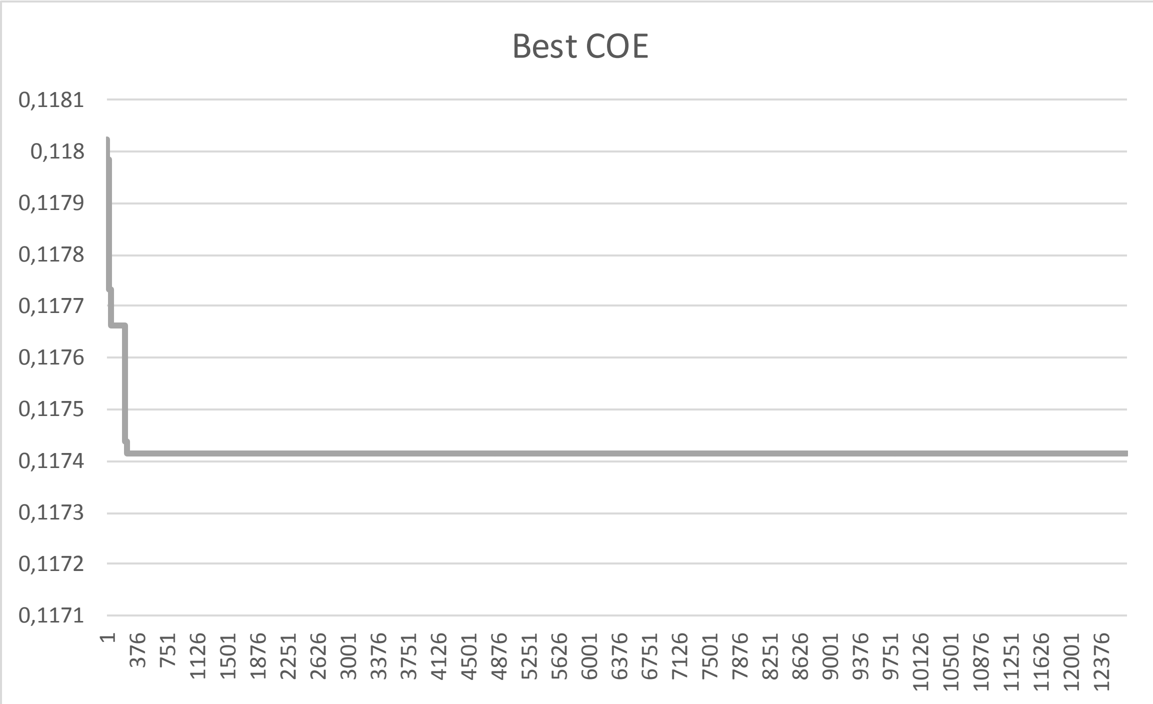

Figure 10. The progress of the acceptance of a new best configuration

Figure 11. Visualization of the "best" found configuration

In contrast to the results of the base-case, in this case a number of wind turbines are installed to contribute to the renewable energy production. This is due to the higher average wind speeds in the meteorological data. Furthermore, the overall costs per produced kWh is also lower than the base-case this can also be explained by the used meteorological data.

However, the found renewable energy configuration is still not feasible for the use on business premises, because companies are noted as large consumers, and thereby pay a kWh price of around €0,07 - € 0,08.

Table 3. Results energy model case-study HvH

Variables	Values
€/kWh over lifetime	€0,1174
Number of wind turbines installed	5
Capital costs Wind turbines	€1.500.000,-
O&M costs Wind turbines per year	€245.219,42
Wind energy production (kWh/Year)	1.053.213 kWh
Number of Solar PV modules installed	4609
Capital costs PV modules	€2.588.925,-
O&M-costs PV modules	€502.318,36
Energy production PV modules	1.692.881
Total costs over lifetime	€4.836.462,78
Total produced energy over lifetime	41.191.410 kWh

Also for the Hvh case multiple outputs are generated, as in the base case the graph of the coe progress (figure 9), and the best Coe (figure 10) is generated.

Figure 11, and Figure 12 shown the constantly shifting configuration of renewable energy technologies on the research area. And the values shown in figure 9 is the corresponding cost of energy for each configuration. In figure 11 the number of PV modules per iterations, figure 12 shows the number of wind turbines installed per configuration.

Furthermore, the location of the installed PV modules, and Wind turbines is from importance when investors, and decision makers want to install renewable energy technologies on business premises in a safe, and feasible manner. Therefore, a text file is created by the Netlogo model with information about the location, number, investment, maintenance costs, and the production of the renewable energy technology, this information is presented in table 4.

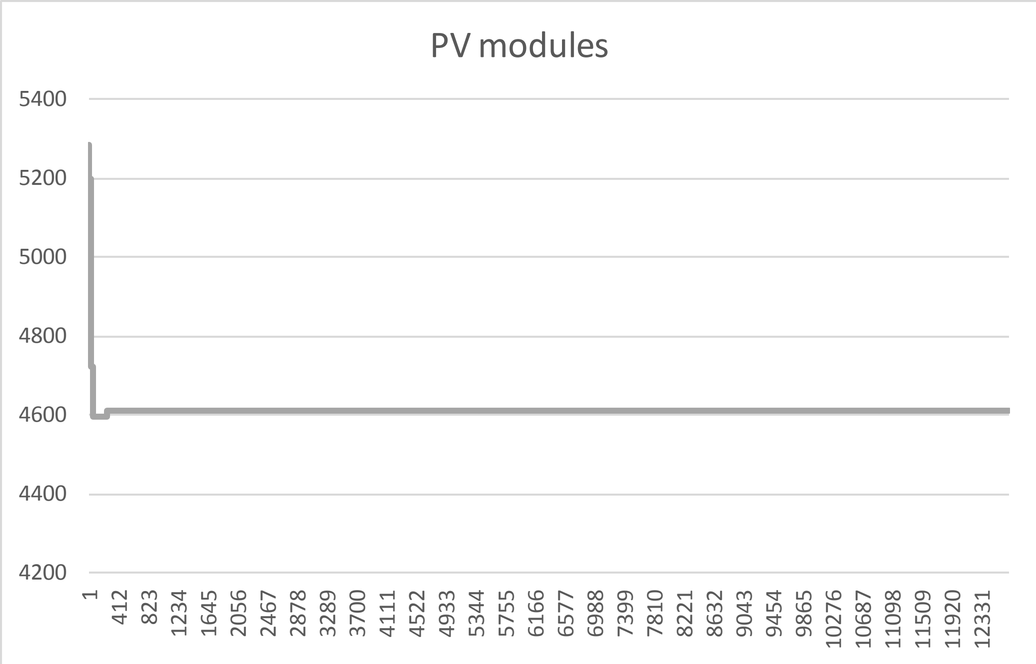

Figure 11. Number of PV modules installed on the research area

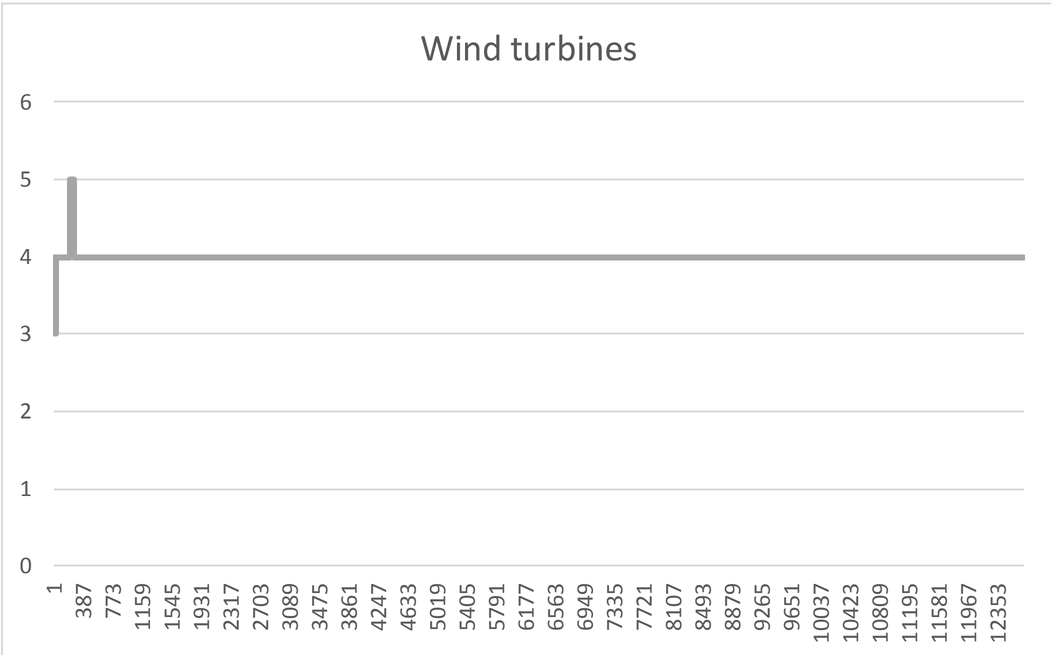

Figure 12. Number of wind turbines installed on the research area

Table 4. Location, and values of installed renewable energy technologies

RET NR	Parcel ID	Energy production kWh/year	Number of Technologies	Investment	O&M-costs
(windturbine 190813)	22	202992	1	€ 300.000,00	€ 49.043,88
(windturbine 190817)	48	202992	1	€ 300.000,00	€ 49.043,88
(windturbine 190815)	78	215743	1	€ 300.000,00	€ 49.043,88
(windturbine 190814)	34	215743	1	€ 300.000,00	€ 49.043,88
(windturbine 190816)	2	215743	1	€ 300.000,00	€ 49.043,88
(panel 190820)	53	47014	128	€ 71.940,00	€ 13.950,26
(panel 190822)	25	76765	209	€ 116.505,00	€ 22.778,16
(panel 190824)	107	42973	117	€ 65.445,00	€ 12.751,41
(panel 190823)	29	892536	2430	€ 1.368.690,00	€ 264.836,97
(panel 190818)	70	1469	4	€ 1.860,00	€ 435,95
(panel 190828)	86	208993	569	€ 319.785,00	€ 62.013,27
(panel 190825)	103	90355	246	€ 137.850,00	€ 26.810,66
(panel 190819)	98	4774	13	€ 6.045,00	€ 1.416,82
(panel 190826)	16	204952	558	€ 313.290,00	€ 60.814,42
(panel 190827)	62	81907	223	€ 124.395,00	€ 24.303,97
(panel 190821)	65	41137	112	€ 63.120,00	€ 12.206,48
Total		**2.746.088**	**4.614**	**€ 4.088.925,00**	**€ 747.537,77**

Appendix 9) English Summary

A Techno-Economic Energy Model for Business Premises

The creation of a spatial optimization model for the allocation, and optimization of renewable energy technologies in the urban fabric

Graduation Program:

Construction Management & Engineering 2014 -2015

Graduation Committee:

Prof. Dr. Ir. B. (Bauke) de Vries

Dr. Ir. B. (Brano) Glumac

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Date of graduation:

15-7-2015

Abstract

The energy system is changing towards a more distributed renewable energy systems with locally produced, and consumed energy. This implies the integration of renewable energy technologies within the complex, and diffuse nature of the built environment. This creates a challenging problem for system designers, and urban planners. Energy modelling can aid decision makers in the development of renewable energy systems within the built environment without administrating major changes to the built environment.

For this reason a spatial energy decision support system is created to aid decision makers with the development of renewable energy systems. This model incorporate a GIS-map to represent the spatial environment. Furthermore, the model incorporates a method for allocating wind, and solar energy technologies, and energy production calculation. The energy systems are evaluated using an economic evaluation based on costs per kWh. The model is tested on "de Brand" in 's-Hertogenbosch.

Keywords: Energy Planning, Energy modelling, Renewable energy technologies, Wind Atlas Methodology, Spatial Decision Support Systems

Introduction

The energy system is transforming towards a distributed renewable energy system were energy is locally produced, and consumed. However, the implementation of distributed renewable energy resources in the built environment is complicated for decision makers due to the complex, and diffuse nature of the built environment, and the restrictions for implementing renewable energy technologies in this urban fabric.

To implement renewable energy technologies on the local urban scale, comprehensive energy models can be utilized to capture the aspects of the urban environment to support decision makers. Several renewable energy models are developed to aid decision makers developing sustainable blocks, district or cities, or to assess the potential of renewable energy technologies in the built environment (Bernal-Agustin & Dufo-Lopez, 2009; Borowy & Salameh, 1996; Deshmukh & Deshmukh, 2008; Maclay et al., 2007; Mohammadi et al., 2012).

The focus often lies on the generation of electricity for residential areas, were industrial, and business premises are the major consumer of electricity in the built environment. In fact, according to Timmerman et. al. (2013) no examples of renewable energy modelling for business premises can be found in the current literature. Moreover, often the literature neglects the impact of the urban environment on the composition of renewable energy systems, and focus solely on the optimization of renewable energy technologies.

In this study, the aim is to develop an energy model which can be used on district-level, with the focus on energy consumption in business premises, while considering spatial constraints. To do so the current literature is analysed on often used methods, and assumptions. Furthermore, a techno-economic energy model is proposed, and tested on a case-study.

Problem definition

The above stated problem analysis leads to the following problem definition; *"There is no evidence found in current literature of the existence of an energy model to determine the optimal combination of energy technologies composing a renewable energy system for business premises".*

Research Question

The problem definition leads to the following research questions. The main research question will be: *''Can a decision support tool been developed which can produce a "most optimal" combination of renewable energy conversion technologies based on the energy footprint of business premises, and spatial constraints? And, what would the optimal combination be for a specific business premises?"*

With the following sub questions;

1) What is the current state of energy systems models? In what degree are they applicable for the built environment?
2) What is the current state of spatial decision support system for the development of renewable energy systems?

3) What are the spatial, and legal constraints which influence the composition of a renewable energy system?
4) What would be the composition of a renewable energy system? And, what would be the potential energy savings of this systems?

Spatial Decision Support Systems for Energy Integration

Spatial Decision Support System are derived from the broader concept of Decision Support Systems. Decision support systems (DSS) is the area of the information systems discipline that is focused on supporting and improving managerial decision-making (Arnott & Pervan, 2005). DSS is an interactive, computer-based system that aids users in judgment, and choice activities of provides for not only data storage, and retrieval, but also enhances the traditional information access, and retrieval functions with support for model building, and model based reasoning (Bandamutha, 2006).

Spatial decision support systems are on the rise, to assist decision makers with complex spatial problems. SDSS are designed to provide the user with a decision-making environment by coupling analytical multi-criteria evaluation models used for selecting, and rating decision criteria, and alternatives in combination with geographical information systems (Densham, 1991; Gorsevski et al., 2013), and assist in strategic decision-making activities considering spatial, and temporal variables, which help in regional planning.

Wind and solar allocation

Energy modelling is derived from the broader concept of energy planning. Which according to Hiremath et. al. (2007), is the energy-planning endeavour involves finding a set of sources, and conversion devices so as to meet the energy requirements/demands of all tasks in an "optimal" manner.

Energy modelling is carried out at a centralized level using computer-based modelling and, are valuable mathematical tools based on the systems approach. These models can offer a solution as they identify the configuration, and operation that provide an optimal trade-off between economic and environmental performances (Timmerman et al., 2013).

Simulations models use a pre-defined technological setups including one or multiple loads to simulate the operation of an energy system over a fixed period of time. Simulation models are used to compare alternative system configurations, and to evaluate different operation strategies in terms of energetic, economic, and environmental performance (Timmerman et al., 2014), or also to test different policies(Chen et al., 2011).

Optimization models aim to find a best solution for a given objective function, within the set constraints. Classical optimization models minimize the total system costs across all time periods and assume equilibrium on energy markets, thus allowing for interactions between demand and supply (Fleiter et al., 2011). Timmerman et. al. (2014) also describe these models as evolution models, with the purpose of finding the least-cost investment paths. These models can be based on multiple optimization algorithms, as suggested by Erdinc et. al. (2012), Keirstead et. al. (2012), and Zhou et. al. (2010).

To acquire such a solution multiple optimisation techniques are used by researchers, from linear programming, to particle swarm optimization. Uzunoglu (2012) described multiple optimization algorithms, and programs which have been used for energy modelling, also Keirstead (2012) mentioned multiple optimization algorithms. Zhou et. al. (2010), also described multiple optimization approaches, and subdivided these into optimization approaches, which consist of Artificial intelligence methods, iterative technique, probabilistic approaches, and graphic construction method.

It is evident that an economic analysis is required, when dealing with an optimization problem. In the current literature of energy modelling, multiple objective are proposed in order to find a best solution for a given problem. As researchers solely focus on the capital costs of the energy systems, they neglect the influence of Operation and Maintenance costs throughout the life time of the system (Borowy & Salameh, 1996; Geem, 2012). This is also the case when the focus lies on the Cost of Energy, where the capital costs are divided by the amount of electricity is generated in a year (Dufo-López et al., 2011; Nelson et al., 2006). This focus limits itself to the evaluation of an energy system in one single year. Mohammadi (2012) integrated the time-value of money according to the capital recovery factor method. Moreover, the economic value of the system can be calculated over a period of time, which is equal to the life expectance of the system.

Spatial Decision Support Energy Model

In this research, an energy optimization model is proposed for the redevelopment of business premises, which will size the distribution between solar PV, and wind energy in an "optimal" manner, while considering the spatial constraint given by the research area, and providing enough renewable energy to make the research area self-sufficient. For this research, methods, used by several researchers, are used for the calculation of renewable energy production. (Ekren & Ekren, 2010; Kaabeche et al., 2011; Nelson et al., 2006; Tina et al., 2006).

Model Design

The optimization energy model proposed in this research, aims to find the best configuration of renewable energy technologies within the built environment, and more specifically on business premises.

Objective function

The objective of the proposed method is to optimize the least costs per produced unit of electricity (kWh). This results in the following objective function;

Minimize	$Costs/kWh_{production}$ (€/kWh; COE) (Eq. 5)
Subject to	safety, and spatial constraints are met

Capacity constraint $E_G \geq E_D$

Allocation PV modules

For the allocation of PV arrays on a flat roof of buildings only two restrictions are applied, which are the requirement that a mechanic can safely, and easily walk around the PV arrays, and that the PV array are limited visible from the ground floor (Notenbomer, 2014). This restriction implies that there needs to be sufficient space between the roofs edge, and the PV modules.

Before allocating PV modules on a specific parcel a number of conditional statements (Eq. 1) have to be completed. For the allocation of PV modules this implies the following statement;

$$\varphi \rightarrow \psi \wedge -\varphi \rightarrow \dagger \quad (1)$$

Where, φ is the conditional statement verifying a parcel if it complies with the condition for installing PV modules. In this case, this results in verifying the parcel if it has a roof surface large enough to utilize PV modules. ψ is the procedure following if φ is true. This procedure results in the allocation of a number of PV modules using Eq. 2. ¬φ is the presentation of the conditional statement when false, and † is the procedure when the conditional statement is false.

PV Energy generation

For the hourly energy generation of the pv-panels, the method of Tina et. al. (2006) is used shown in Eq. 2. This method uses hourly meteorological data to calculate the hourly power output of the PV array. The hourly solar irradiation is provided by the KNMI database.

$$P_{PV} = A_C * \eta * \mathrm{I}_\beta \quad (2)$$

Where, P_{pv} is the power output of the PV module in a hour, A_C is the total square surface of the PV array, which is determined by the model, and only indicates the active surface of the PV module, and η is the efficiency of the PV module in percentages, and can be set by the user. I_β is the hourly solar irradiation given by the meteorological data.

Allocation of Wind turbines

The allocation of wind turbines within the urban environment require the aggregation of multiple safety regulations. The Dutch government (Faasen et al., 2013) have defined two safety zones regarding, vulnerable, and limited vulnerable buildings.

Furthermore, for the allocation of wind turbines it is also required to consider the interference caused by surrounding wind turbines (Aydin et al., 2010; Ozturk & Norman, 2004; Patel, 2006). The wind speed after a wind turbine is significantly less than up wind, this reduction has a negative influence on the wind production of wind turbines installed downwind of other wind turbines.

In the model the safety checks, and safety zoning checks all originate from the centre of the parcel, this is done to limit the amount of possible location for the model, and however this can create some errors when allocating neighbouring wind turbines resulting in Eq. 3. These conditions result into the following conditional statement for allocating a wind turbine on a parcel;

$$(\varphi \ \& \ \psi \ \& \ \beta \rightarrow \dagger) \wedge (-\delta \rightarrow -\dagger) \quad (3)$$

Where, φ is condition that a parcel have sufficient available square surface, ψ is the condition that there is no vulnerable object within the 10^{-6} contour of the wind turbine, and β is the condition that there is no wind turbine within the vicinity of the proposed wind turbine. If all conditions are met the procedure † will commence, which results in the development of a wind turbine on a parcel. If one or all condition is false, donated as –δ, the procedure † will not commence, donated as –†.

Wind Energy Generation

The regional wind climate is used as the starting point of the model is the freely available KNMI database (KNMI, 2015). To estimate the wind speeds at a parcel level, the Wind Atlas Methodology as proposed by Millward et. al. (2013a) is used. This methodology enables the user to correct the measured wind speeds to a different height at a location nearby. It involves applying a number of adaptations to a wind speed database to account for the effects of the urban area upon wind profiles. It relies on knowledge of the regional wind climate in the city, and also the aerodynamics properties of the urban surface, which are typically quantified using the parameters roughness length (z_0), and displacement height (d). The results of this adjustment are used to calculated the energy production of the wind turbines.

For the calculation of hourly power output of the wind turbines, the method as proposed by Tina et. al. (2006) is used, as shown in Eq. 4. For a typical wind turbine, the power output characteristics can be assumed in such a way that it starts at the so called, cut-in wind speed v_C, it is assumed that the power output increases linearly as the wind speed increases from v_C to the rated wind speed v_R. The rated power P_R is produced when the wind speed varies from v_R to the cut-out wind speed v_F, at which the wind turbine will shut down. The wind speed "v" is calculate with the above mentioned 'wind atlas methodology', using hourly meteorological data from the KNMI. This results into the following equations;

$$P_W(v) = \begin{cases} \left(\dfrac{P_R}{v_R - v_C}\right) * (v - v_C) & v_c \le v \le v_R \\ P_R & v_R \le v \le v_F \\ 0 & Otherwise \end{cases} \quad (4)$$

Where, P_w is the power output of the wind turbine at wind speed (v). v_C is the cut-in wind speed , v_R is the rated wind speed, and v_F is the cut-out wind speed of the wind turbine. Furthermore, the P_R is the rated power output of the wind turbine, which is produced when the wind speed is equal or higher than the rated wind speed, and lower than the cut-out wind speed.

Economic analysis

It is necessary to have an economic analysis, when attempting to optimize the costs per produced kWh. The objective function of the energy model is to minimize the costs per produced kWh over the lifetime of the system. The expected costs of the system over the lifetime will consist of the capital costs, spend at the start of the year, and the yearly O&M-costs of the renewable energy technologies. The expected energy production over a lifetime is calculated using the total yearly energy production, and multiplied with the lifetime of the system. This implies that the total energy production is equal for each year. The costs per kWh (Eq. 5) is defined a following;

$$€/_{kWh} = \frac{(C_{(€)} + O\&M_T)}{\sum_{y=1}^{y=lifetime} E_y} \tag{5}$$

Where, *€/kWh* is the costs in Euro's per produced kWh over the complete lifetime. *C (€)* is the capital costs of the system, as donated in Eq. 6. $O\&M_T$ is the operation and maintenance costs over the complete life time calculated with Eq. 7, and E_y is the total produced electricity over the complete lifetime as calculated.

The capital costs are the costs for purchasing, transportation, and installation of the system. The capital costs are assumed to be spend in the first year. The capital costs consist of the combined costs for the PV panels, and the wind turbines. The total capital costs are defined by;

$$C\,(€)_{P,W} = N_{PV} * €_{pv} + N_w * €_W \tag{6}$$

Where, $C\,(€)_{pv,w,}$ is the capital costs of the system, N_{pv} is the total number of pv-modules in the system, $€_{pv}$ are the costs for installing an pv-module on a flat roof, N_w is the total number of wind turbines installed in the system, and $€_w$ is the costs for designing, and installing and wind turbine on the premises.

The Operation and Maintenance costs (O&M-costs) are calculated over the lifetime of the system. The costs for operation and maintaining the system can be adjusted per renewable energy technology. In the case of the wind turbine the O&M-cost is a percentage of the capital costs. For the PV-array the O&M-costs are a given number, both adjustable by the modeller. The O&M-costs per year are defined by the following equation;

$$O\&M_{(y)} = \sum_{i=0}^{i=n} O\&M_w(y) + \sum_{i=0}^{i=n} O\&M_s(y) \tag{7}$$

Where, $O\&M_{(y)}$ is the total O&M costs for the system for a year, $O\&M_w(y)$ is the O&M costs per wind turbine per year, $\&M_s(y)$ is the O&M costs per PV panel per year, and n is the number of wind turbines, and PV modules on the research area.

Before the O&M-costs can be integrated in the objective function, the costs of O&M have to be added over the years. To calculate the current value of future cash flows the discounted cash flow is used to aggregate the O&M-costs over the lifetime of the system (Metrick & Yasuda, 2011). It is a commonly used method to assess the feasibility of a project, asset or business. The discounted cash flow is defined in the following equation;

$$O\&M_T = \sum_{n=1}^{\text{n=lifetime}} \frac{O\&M_y}{(1+i)^n} \quad (8)$$

Where, $O\&M_T$ is the discounted present value of the O&M costs over the set lifetime. i is the discount rate (%), n the year for which is calculated, and $O\&M_y$ is the O&M cost per year as calculated in Eq. 7.

Case-study 'De Brand'

"De Brand" is a business park located near the highways A2, and N279 in the municipality of Den Bosch. The development is done with the help of a clear urban development concept. The large scale business are located at the outer edges, and the medium and small scale are concentrated at the centre.

Results

Notable is the fact that no wind turbines are allocated on the research area, when using the meteorological data from the weather station nearby. This is a result of the very low average wind speeds in the region of 's-Hertogenbosch, and thereby resulting in a high average costs per produced kWh. For this reason the PV modules are preferable to produce the required renewable energy.

However, for the use on business premises the renewable energy configuration are still not feasible without government support. Because, businesses on business premises are donated are large consumers, an thereby can purchase kWh for around €0,08. While, the result of the energy model finds a least cost per kWh of €0,12. The location output is represented in Appendix 7) Output simulations.

Table 1. Results of the three scenarios

Variables	50 kW	100 kW wind turbine	PV module costs drop with 10%
€/kWh over lifetime	€ 0,1265	€ 0,1265	€ 0,1176
Number of wind turbines installed	-	-	-
Capital costs Wind turbines	-	-	-
O&M costs Wind turbines per year	-	-	-
Wind energy production (kWh/Year)	-	-	-
Number of Solar PV modules installed	7136	7168	7132

Capital costs PV modules	€ 3.987.540,-	€ 4.003.800,-	€3.649.096,-
O&M-costs PV modules per year	€ 777.727,02	€ 781.214,60	€777.291,07
Energy production PV modules	2.509.639 kWh	2.520.893 kWh	2.508.232 kWh
Energy production per PV module	352 kWh	352 kWh	352 kWh
Total costs over lifetime	€4.765.267,02	€4.785.014,58	€ 4.426.387,07
Total produced energy over total lifetime	37.644.582 kWh	37.813.392 kWh	37.623.481 kWh
Allocation Output	Appendix 7) Output simulations	Appendix 7) Output simulations	Appendix 7) Output simulations

Conclusion & Recommendation

A techno-economic energy model for the use on business premises has been developed, and it proved that is able to allocate wind, and solar energy within the built environment using GIS-maps, and therewith find a least costs solution to provide the research area with sufficient energy.

However, the simulation time of the energy model, which is developed within Netlogo, is a down side which need to be addressed, the simulation takes around 30 minutes, however the model is intended to give a fast, and reliable method to calculate the least costs per kWh configuration.

Furthermore, the accuracy of the proposed energy model is a component that could be improved, to generate even more realistic results. This is also the case for the integration of more safety regulations regarding roads, railways, etc.

Despite the limitations of the proposed energy model it is able to find a least costs per kWh configuration using a GIS base to incorporate the urban fabric. This model can be used to analyse the possibility, and configuration of a future renewable energy grid within the built environment. Thereby, reduce the change that major changes to the urban environment have to be made.

The proposed model in this research is the first step towards, new part of spatial energy modelling, and energy planning. When models are further developed they can provide a reliable tool in the development of sustainable spatial plans. However, for this model some recommendations are applied, such as;

- The further elaboration of the wind turbines allocation model, so multiple wind turbines can be allocated on one parcel, and the safety check will no longer be solely from the centre of the parcel.
- The integration of the orientation, and geometry of the buildings in the research area. This will provide a more accurate allocation of PV-modules.
- Further elaborate the possible renewable energy technologies such as, Geothermal, PV-T, or Biomass.
- Integrate the possibility of energy storage, to simulate the operations of a local energy grid, and thereby creating an autarkic district.

Ir. Ing. E.J. (Erik) Vijverberg

This thesis is the result of more than a half year work. It was a turbulent process writing this graduation project, however I am pleased with the result. My hope is that other students will further developed this model.

Educational CV

2011 – 2015 Mastertrack Construction Management and Engineering
2014 – 2015 Internship at Heijmans
2007 – 2011 Bachelor of Built Environment (University of The Hague)
2005 – 2007 HAVO (N&G)