

Modeling the allocation and economic evaluation of PV panels and wind turbines in urban areas

Citation for published version (APA):

Mohammadi, S., Vries, de, B., & Schaefer, W. F. (2014). Modeling the allocation and economic evaluation of PV panels and wind turbines in urban areas. In H. Timmermans (Ed.), *Proceedings of the 12th International Conference on Design & Decision Support Systems in Architecture and Urban Planning (DDSS2014)*, 24-27 August 2014, Eindhoven, The Netherlands (pp. 333-351). (Procedia Environmental Sciences; Vol. 22). Elsevier. <https://doi.org/10.1016/j.proenv.2014.11.032>

DOI:

[10.1016/j.proenv.2014.11.032](https://doi.org/10.1016/j.proenv.2014.11.032)

Document status and date:

Published: 01/01/2014

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

12th International Conference on Design and Decision Support Systems in Architecture and Urban Planning, DDSS 2014

Modeling the allocation and economic evaluation of PV panels and wind turbines in urban areas

Saleh Mohammadi^{a*}, Bauke de Vries^a, Wim Schaefer^a

^a*Eindhoven University of Technology, Department of Built Environment, Vertigo 9.09, P.O. Box 513, 5600MB Eindhoven, The Netherlands*

Abstract

A model for allocating PV panels and wind turbines in urban areas is developed. Firstly, it examines the spatial and technical requirements for the installation of PV panels and wind turbines and then evaluates their economic feasibilities in order to generate the cost effective electricity neutral plan. The model is applied on a residential district in the municipality of Eindhoven, the Netherlands and simulates the electricity generation of allocated renewable energy technologies to satisfy the demand of the area in hourly time-steps over a one year. The allocation model runs for different combinations of PV panels and wind turbines. Accordingly, four scenarios based on the different technical and economic assumptions are conducted and energy and economic indicators are compared. Results show that in the current situation without subsidies, PV panels are not economic, compared with wind turbines, but if appropriate subsidies are devised, they become comparable. The analyses also show that the allocation model help planners and policy makers to examine the influence of different energy policy tools for the promotion of renewable energy technologies in urban areas.

© 2014 The Authors. Published by Elsevier B.V This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Peer-review under responsibility of the Eindhoven University of Technology, Faculty of the Built Environment, Urban Planning Group

Keywords: Allocation model; spatial and economic evaluation; PV panels; wind turbines

1. Introduction

Electricity generation from renewable resources is progressively being recognized as an important option in the supply side of energy systems and future energy policies of many countries. Therefore, identifying the potential of

* Corresponding author. Tel.: +31-040-247-4969 ; fax: +31-040-245-0328.
E-mail address: s.mohammadi@tue.nl

renewable energy resources has become a key area of interest within urban and energy planning domains. Coherent analyses of how renewable energy technologies can be implemented, what spatial and energetic effects they have on the current energy system and urban layout and what their financial implications will be are crucial elements that should be comprehensively considered¹. Such analyses require tools and models that can provide answers for these issues by modeling defined energy systems.

This paper presents an allocation model, which is utilised to allocate PV panels and wind turbines in urban areas up to what is spatially and technically feasible and aimed at generating electricity neutral plan. The allocation model evaluates the spatial, technical and economic feasibility of PV panels and wind turbines, while considering spatial specifications and resource availability. Allocation of PV panels and wind turbines is established upon the interaction between renewables and the spatial conditions that exist at the locations where these technologies are installed and their mutual interactions. The renewables spatial range of influence is also different in different land uses. Besides technical and spatial conditions, economic analysis is considered as well. Capital and annual operation and maintenance costs are the main considered cost components.

The model allocates renewables and simulates the system operation to satisfy the total electricity demands. The simulation is operated in hourly time-steps over a one-year time-period. The configuration of the generation setup, which consists of PV panels, wind turbines and combination of them, is fully selectable. The geographical scale of the model can range from a neighbourhood to urban district and a spatial data structure based on parcels is adopted. For demonstration purposes, the model is applied to the residential area in the municipality of Eindhoven in the Netherlands. Four scenarios based on the different technological, technical and economic assumptions and settings will be presented and compared. These analyses help planners and policy makers to examine the influence of different promotion schemes and energy policies on the penetration of renewable energy technologies in the electricity sector for the given area.

The paper is structured as follows; section 2 and 3 describe the renewable energy technologies that are implemented in the allocation model. In section 4 the spatial data structure of the model is presented and the parcel attributes are described. The economic evaluation and financial indicators are examined in section 5. Allocation process as a backbone of the model is presented in sections 6 and 7. Section 8 explains the implementation of the allocation model. In section 9 the case study area and datasets that use in the allocation are described. Scenarios are introduced and discussed in the section 10 and section 11 explains conclusions and future extensions to the current model.

2. Wind turbines

Wind turbine is a sustainable energy technology that contributes to the sustainable energy system and converts the kinetic energy of wind into electricity². The overall wind turbine features are described under three headings: resource availability, power output determination and spatial and technical requirements for installation of wind turbines. These are described below.

2.1. Wind resource availability

To estimate the output of wind turbines, the main variable that affects their performance is a wind speed on the hub height of the wind turbines^{2,4}. The required wind speed data is a set of 8,760 values representing the average wind speed, expressed in meters per second for each hour of the year. This data is utilised to calculate the output of wind turbines each hour of the year. Wind speed tends to increase with height above ground, so if the wind turbine hub height is not the same as the anemometer height, wind speed data are adjusted accordingly^{5,6}. The wind turbine hub height is the height above ground at which the rotor sits. Hub heights typically range between 25 m (for smaller wind turbines, 50 kW or less) and 100 m (for large, multi-megawatt wind turbines). Ground-level obstacles such as vegetation, buildings, and topographic features tend to slow the wind near the surface. Since the effect of these obstacles decreases with height above ground, wind speeds tend to increase with height above ground⁷. Wind speed is proportional to the logarithm of the height above ground. Following equation gives the ratio of the wind speed at hub height to the wind speed at anemometer height^{2,6}:

$$v_j(z_{hub}) = \left(\ln \left(\frac{z_{hub,j}}{z_j} \right) \right) / \left(\ln \left(\frac{z_{anem,j}}{z_j} \right) \right) v_j(z_{anem}) \quad (1)$$

where $z_{hub,j}$ is the hub height at parcel j , $z_{anem,j}$ is the anemometer height, z° is the surface roughness length, $v_j(z_{hub})$ is the wind speed at the hub height at parcel j and $v_j(z_{anem})$ is a wind speed at anemometer height.

The surface roughness length or roughness coefficient is a parameter that characterizes the roughness of the surrounding terrain^{2,6}. Table 1 contains representative surface roughness lengths for different terrains⁸.

2.2. Wind turbines power determination

A wind turbine is characterized by its power curve and it is the most important property of the wind turbine. The power curve is a graph that indicates how large the electrical power output will be for the wind turbine at different wind speeds. For a specific wind turbine power curve considers all aspects including blade aerodynamics and auto-furling effects, electrical generator, any gearing and the power electronics associated with turbine itself^{4,7,9}. Fig.1 displays FL 100 wind turbine power curve¹⁰.

All wind turbines share certain operating characteristics, such as cut-in, rated and cut-out wind speeds:

- Cut-in speed is the minimum wind speed at which the wind turbine will generate usable power.
- The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power.
- At very high wind speeds, typically between 45 and 80 mph, most wind turbines cease power generation and shut down. The wind speed at which shut down occurs is called the cut-out speed.

To calculate the output of the wind turbine in a particular hour, the model takes that hour wind speed from the wind resource data, adjusts it to the wind turbine hub height using the logarithmic profile and then apply it to the wind turbine power curve to calculate the power output under standard conditions of temperature and pressure. Finally multiplies it by the air density correction for the real conditions.

Table 1. Surface roughness length for terrain type.

Terrain Description	Roughness coefficient (z°)
Lawn grass	0.008 m
Rough pasture	0.010 m
Fallow field	0.03 m
Crops	0.05 m
Few trees	0.10 m
Many trees, few buildings	0.25 m
Forest and woodlands	0.5 m
Suburbs	1.5 m
City center, tall buildings	3.0 m

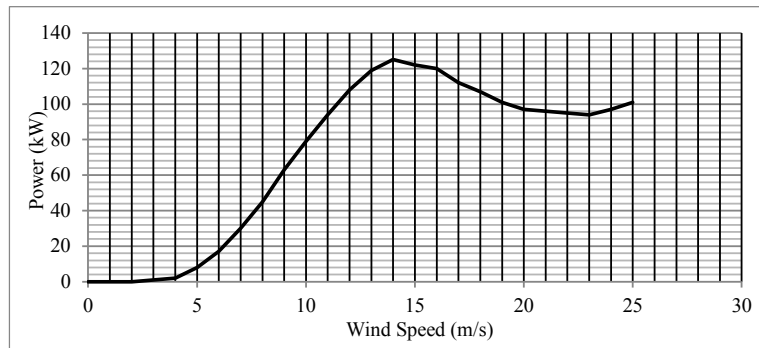


Fig. 1. FL 100 wind turbine power curve.

Wind power varies linearly with the air density sweeping the blades¹¹. The quantity that is used is the air density ratio, which is the actual air density divided by the air density under standard conditions (The air density at sea level at 1 atm and 60°F is 1.225 kg/m³). Using this as a reference, ρ is corrected for the site-specific pressure. When the output of the wind turbine is calculated at the specified altitude, the power output obtained from the wind turbine power curve is multiplied by the air density ratio^{6,11}. The air density is given by the following equation(2), which is valid up to 6,000 m of site elevation above sea level¹¹:

$$\rho = \rho_0 - (1.194 \times 10^{-4} H_m) \quad (2)$$

where H_m is the site elevation in meters. The power output of the wind turbine is a total of 8760 hourly power outputs generated for a wind turbine during one year.

2.3. Spatial and technical requirements for installation of wind turbines

Installation of wind turbines specifically in urban areas requires considering multiple conditions, constraints and spatial requirements such as safety, inconvenience and a minimum damage to the environment. There are detailed requirements and conditions that affect the allocation of wind turbines in the environment. In general the spatial requirements and installation regulations of wind turbines are strongly depend on the hub height and the length of rotor blades^{2,11}. The following requirements apply to wind turbines in our model:

- Roof top mounted wind turbines are not considered.
- The wind turbine and any infrastructure required to support it must not be attached to the any building.
- Wind turbines must be installed on the parcels of over 1000 square meters in size.
- Residential areas are sensitive to the installation of wind turbines. Wind turbines have nuisance of noise, visual, shadow, glare and safety risks. Minimum distances for each of the conditions have to be considered.
- Wind turbines are allowed to be installed on industrial and agriculture areas.
- In urban areas it is desirable to install micro wind turbines close enough to the built-up areas.
- Minimum distance between wind turbines to prevent negative effects on their performance is desirable. The average distance is six times the diameter.
- The annual average of noise level as result of wind turbines must not be greater than 47 dB in a day. During the night the average noise level can't be greater than 41 dB as measured from the closest inhabited area.
- All wind turbines are to be constructed of non-reflective materials, and fitted with some form of automatic breaking, manual breaking and speed protection.

In each location if wind turbines do not fulfil each of the abovementioned requirements, it is not allowed to be installed.

3. PV panels

PV panels convert solar energy into electricity. A solar cell is a basic photovoltaic device that generates direct current (DC) when exposing to the light. Solar cells are combined to form modules to obtain the desired voltage and current. Modules are put together to shape the array and meet the required power load. The overall PV panel features are described under the following headings.

3.1. Solar resource availability

The amount of solar radiation available to the PV panel throughout the year is utilised as a raw input data to the model. PV panel power outputs are calculated each hour of the year through this data. Solar radiation data is the set of 8,760 values representing the average global solar radiation on the horizontal surface, expressed in kWh/m², for each hour of the year. Solar radiation is not a constant. It depends on the weather and time of the year and changes continuously during the day^{2,11,12}. It is also varies from a region to region, for instance the tropics receive more radiation than the subtropics.

3.2. PV panel power determination

The following formula is applied to determine the output of the PV panel in time t at parcel j ^{6,12}:

$$P_{pv,t,j} = P_{pv,STC} l_{pv} R_{t,j} (1 + \alpha_p (T_{cell,t} - T_{cell,STC})) \cos \theta_{t,j} \quad (3)$$

where $P_{pv,STC}$ (kW) is the rated capacity of the PV panel under standard test conditions (STC or standard test conditions define PV panel performance at an incident sunlight of 1000 W/m², a cell temperature of 25°C and an air mass of 1.5), l_{pv} (%) is the power loss factor, $R_{t,j}$ (kW/m²) is the solar radiation incident on the PV panel at parcel j in time step t , α_p (%/°C) is a temperature coefficient of power regarding solar cell temperature, $T_{cell,t}$ (°C) is the PV cell temperature in time step t , $T_{cell,STC}$ (25°C) is the PV cell temperature under standard test conditions and θ_t is the angle of incidence between the solar beam and the PV surface at parcel j at time step t .

Based on the equation (3) two important variables specify the output of the PV panels, the ambient temperature at the installation location of PV panels and the angle of incidence between the solar beam and collectors^{7,12}. The solar cell temperature is a parameter that has a great influence on the behaviour of PV panels¹³. During the night it is the same as the ambient temperature, but in full sun the cell temperature exceeds the ambient temperature¹². The operating temperature of a PV module is determined by the equilibrium between the cell temperature (T_{cell}) and ambient temperature ($T_{ambient}$). The solar cell temperature is calculated by ambient temperature and solar radiation¹⁴.

$$T_{cell,j,t} = T_{ambient,j,t} (1 + 1.25 R_{j,t}) \quad (4)$$

where, $R_{j,t}$ (kW/m²) is the solar irradiance that strikes the solar cell surface in time step t at parcel j .

The second factor is the angle between beam and collector i.e. the angle between solar beam and PV panel surface normal. The raw solar resource data for each time step is the amount of solar radiation striking the horizontal surface on the earth. But the power output of the PV panel depends on the amount of radiation striking the surface of the panel which is not normally horizontal. As a result, in each time step, the solar irradiation incident on the PV panel surface should be estimated. θ is calculated using the following formula²:

$$\cos \theta = (A - B) \sin \delta + [C \sin \omega + (D + E) \cos \omega] \cos \delta \quad (5)$$

where,

$$A = \sin \varphi \cos \beta$$

$$B = \cos \varphi \sin \beta \cos \gamma$$

$$C = \sin \beta \sin \gamma$$

$$D = \cos \varphi \cos \beta$$

$$E = \sin \varphi \sin \beta \cos \gamma$$

ϕ is the solar panel latitude, β is the collector slope, γ is the surface azimuth angle, ω is the solar hour angle and δ is the solar declination.

The solar declination is the angle between the equator and a line drawn from the centre of the earth to the centre of the sun calculated using equation (6)²:

$$\delta = \delta_0 \sin \left[\frac{360(284+n)}{365} \right] \quad (6)$$

where n is the day in the year ($n = 1$ on 1 January) and $\delta_0 = 23.45^\circ$.

The solar hour angle is the angle through which the earth has rotated since solar noon (highest position of sun) and the solar declination is the angle between the sun's direction and the equatorial plane¹⁵. The solar hour angle is the angle through which the earth has rotated since solar noon. Since the earth rotates at $360^\circ / 24 \text{ h} = 15^\circ \text{ h}^{-1}$, the hour angle is given by the following equation²:

$$\omega = (15^\circ \text{ h}^{-1})(t_{\text{solar}} - 12\text{h}) \quad (7)$$

where t_{solar} (h) is the local solar. ω is positive in the evening and negative in the morning.

3.3. Spatial and technical requirements for installation of PV panels

Spatial requirements influence the installation of PV panels in urban areas. Potential solar irradiation as a main factor in the PV panel generation is the main determinant of these characteristics. In the built environment, potential solar irradiation is a function of building orientation, roof area, roof slope and interaction between buildings and urban vegetation. The following conditions apply to PV panels:

- Only solar roof panels are considered, since they can be installed directly on the roofs and do not require additional land.
- In the PV panel allocation process only the built-up area of parcels is taken into account.
- The generation of PV panels in parcels depends on the built-up area specifications such as area, orientation, slope, shadow and solar radiation intensity.

Each of the aforementioned characteristics must satisfy the minimum thresholds that are determined in the model assumptions. In general, the model allocates PV panels to the rooftops that have the best performance for the given conditions.

4. Spatial data structure of the allocation model

Two main approaches in spatial data modeling are grid cells and parcels and fundamental differences are between them. Most of the spatial applications have used a spatial data model based on the grid cells, but several limitations drive to the adoption of the parcel-based data model¹⁶. Superimposing an entirely regular shape on a polygonal layer of parcels that are different in size and shape leads to the splitting of parcels in a way that generates inaccurate representation of the reality. But on the other hand, cell based applications are rather computationally efficient. The reason is the adaptation of raster processing approach in analyses that is the main motivation for using this approach

to modeling the spatial environment¹⁶. Parcels contrary to cells that are homogenous in terms of size and geometry and can be treated in a same way, are heterogeneous and these differences should be taken into account. In this research the spatial data model and geographic unit of analysis established upon parcels has been adopted for representation of the spatial environment. This indicates that urban areas are composed of parcels which each parcel has its own features and characteristics. Parcel is fundamentally a piece of land meant to be owned by an owner(s) and may come in different size, shapes and geometry. The parcel-based data model takes advantage of a data model that exploits parcel as a basic object and unit of spatial analysis. Each building or piece of land is associated with a specific parcel. Parcel-based data model reduces urban areas into parcel features and provides a relaxed representation of the reality. In this paper the allocation and distance analysis are carried out based on the parcels and gravity centre of parcels. Accordingly renewable energy technologies are allocated to the gravity centre of parcels. The parcel features determine the allocation type of renewable energy technologies. Features that vary continuously over the space are allowed to be recorded in parcels discretely. Parcel state can represent any spatially distributed variable and can be adjusted by the user. Table 2 shows the list of parcel features. In the allocation process for evaluating the possibility of allocating renewable energy technology options in parcels, different spatial data layers are required. The type of spatial data layers depends on the renewable energy technology option.

5. Economic analysis

To determine the cost efficient configuration plan of renewables to supply the electricity demand of urban areas, the economic analysis is performed. For each of the renewable energy technologies, two main cost components, including initial capital cost and operating and maintenance (O&M) cost are taken into consideration. The capital cost of a renewable energy technology is the total installed cost of the technology at the beginning. The operating and maintenance cost is the lifetime operation and maintenance cost of the renewable energy technology. In this research the operating and maintenance cost regarded as a regular annual cost. The economic analysis is performed based on the initial and operating cost of technologies since it provides an appropriate cost comparison between renewable energy technologies with low initial investment cost and high operating cost with technologies with high investment cost and low operating cost. Annual interest rate and renewable energy technology lifetime are the main economic input variables that are used in the allocation process.

Table 2. Parcels attributes.

Attributes	
1	Address
2	Area
3	Function
4	Built-up area
5	Roof area
6	Roof slope
7	Roof orientation
8	Built year
9	Building type
10	Electricity connection type
11	Average yearly electricity demand
12	Yearly demand load profile
13	Surface roughness
14	Land value
16	Solar radiation
17	Wind speed

Net present cost (NPC) and cost of energy production (COEP) are considered as the main economic performance metrics for the assessment and comparison of different renewable options. After running the model renewable energy technologies are ranked according to their COEP. The lower the COEP is the better the renewable energy technology is. The NPC is the present value of all the cost components of the technology over its lifetime⁶. It is also represents the lifecycle cost. The NPC cost components comprises capital cost and operating and maintenance cost. NPC calculate using the following equation (8):

$$C_{NPC,t} = \frac{(C_{cap,t} + C_{o\&m,t})}{CRF(i, N_t)} \quad (8)$$

where $C_{NPC,t,j}$ is the net present cost of technology t at parcel j , $C_{cap,t,j}$ is the capital cost of technology t at parcel j , $C_{o\&m,t,j}$ is the annual operating and maintenance cost of technology t at parcel j , CRF is the capital recovery factor, i is the interest rate and N_t is the lifetime of the technology t . The capital recovery factor is a ratio used to calculate the present value of a series of equal annual cash flows. The equation for the capital recovery factor is (9):

$$CRF_{i,N} = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (9)$$

where i is the annual interest rate and N is the technology lifetime. The prominent economic indicator for economic evaluation of renewable energy technologies is the COEP. COEP (\$/kWh) is the cost per kilowatt hour of electricity generates by renewable energy technologies. The equation for COEP is as follows (10):

$$COEP_{t,j} = \frac{C_{NPC,t,j}}{S_{t,j}} \quad (10)$$

where $COEP_{t,j}$ is the COEP of technology t in the parcel j , $C_{NPC,t,j}$ is the NPC of technology t in the parcel j and $S_{t,j}$ is the electricity supply of technology t in the parcel j . COEP or cost per kilowatt is a common way to compare the production costs of different forms of electricity production.

6. Allocation process

This part describes how the allocation model works. As mentioned the main objective of the model is evaluating the technical and economic feasibility of PV panels and wind turbines for allocation in urban areas, while considering spatial specifications and resource availability. Allocation models in general refer to the algorithms used to determine an optimal location for one or more facilities that will service specific demands. The algorithm assigns demands to facilities while considering factors such as the number of facilities available, cost and the maximum impedance from the facility to the demand points¹⁷. In this research, allocation process as a core of the model allocates PV panels and wind turbines based on the spatial, technical and economic requirements and the aim is generating a cost-effective electricity neutral plan. Accordingly the area is populated with renewable energy technologies to the extent it becomes electricity neutral. Renewable energy technologies are installed on the gravity centre of parcels based on their installation spatial conditions. Figure 2 depicts the flowchart of the allocation process. The flowchart illustrates the main steps of the allocation model. Below steps are described in detail.

The allocation environment is constructed of parcels. Each parcel has its own features. The parcel features determine the allocation type of renewable energy technologies. Different spatial data layers are utilised to set up the environment (Table 2).

The allocation analyses are performed based on the average annual electricity demand. Each parcel has an average electricity demand. In parcels that more than one electricity connection are located, the aggregation of connections is considered as a parcel demand. To calculate the total electricity demand of the area (T(d)), average annual electricity demand of parcels are aggregated. Following aspects determine the allocation conditions of renewable energy technologies:

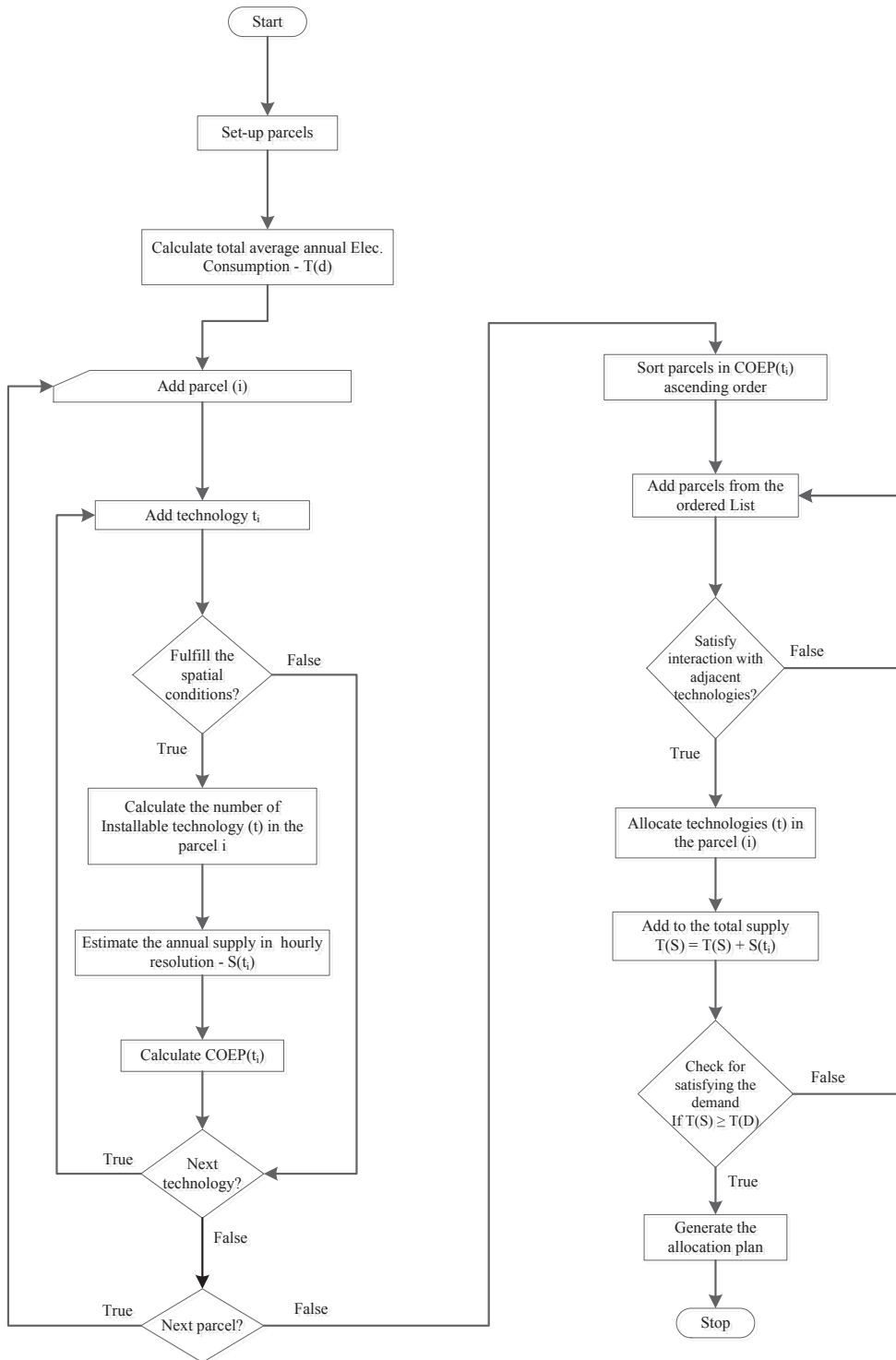


Fig. 2. Allocation process flowchart.

- Interaction between renewable energy technologies and spatial conditions of installation locations.
- Mutual interaction of renewable energy technologies and their spatial range of influence

Each renewable energy technology has specific requirements for installation that these conditions must be satisfied.

The first part of the evaluation process is the spatial and technical examination of parcels. In determining conditions for installation, each parcel will be examined for all conditions for all renewable energy technologies. Conditions such as function, area, built-up area, visual and noise nuisance and resource availability are considered. Parcels with functions including transportation, water, wetlands and flood-ways are left out from the allocation. Spatial conditions for the allocation of PV panels and wind turbines are explained in sections 2.3 and 3.3. Conditions and constraints specify the boundary of the allocation problem and determine the preliminary allocation locations. If the spatial conditions of the parcel satisfy the requirements of the renewable energy technology, afterwards the energy potential of the technology and its COEP in the given parcel are calculated. Detailed procedures for the calculation of the energy potential of PV panels and wind turbines in parcels are elaborated in the sections 2 and 3. In addition the required formulas for cost analysis and calculation of COEP of technologies are presented in section 5. In the economic analysis, COEP is the main factor for the allocation of renewable energy technologies.

Allocation of technologies based on their COEP is the second part of the allocation model. All parcels are sorted in an ascending list based on their COEP. The length of the given list is equal to the number of technologies multiplies by the number of parcels that means each parcel for each technology comes in the list separately. The allocation starts from the first item of the list, i.e. parcel with the lowest COEP. Before the installation of the energy technology on the parcel, the interaction of technology in the given parcel with the other technologies in that parcel and adjacent parcels are examined. The mutual interaction of renewable energy technologies is different. This indicates that for installation of renewable energy technologies certain specific requirements in addition to the local conditions have to be realized. PV panels can be installed in each parcel with suitable roof area and have no effect on the other type of technologies in that parcel or adjacent parcels. The wind turbine installation depends on the parcel function and adequate available square meter for installation. To prevent a wind turbine influences the other wind turbine efficiency; a minimum distance between them is desirable. The distance depends on the wind turbine specifications such as swept area, rotor diameter and tower height. While the total supply of the allocated technologies is less than the total electricity demand of the area, the allocation of renewable energy technologies are proceeding. Whenever the total supply of allocated technologies fulfils the total electricity demand of the area, the allocation process is stopped and the cost-effective electricity neutral plan is generated. The allocation algorithm generates the plan that minimizes total cost and maximizes the electricity generation of renewable.

As demonstrated above, the allocation model is independent of the type of renewable energy technology and operates for all renewable energy technology options. Depend on the user preferences, new technologies can be added to the model. The installation conditions and settings of technologies are also adjustable and help the users investigate how the results are affected by changes in the model settings. The adjustable settings provide deep insight to the users about substantial relationship between the performance of renewable energy technologies and the spatial condition of parcels.

Finally, the model helps planners and policy makers to make appropriate decisions about the allocation of different type of renewable energy technologies. Later the model will be extended to examine the effect of different energy policy tools and schemes on the allocation of renewable energy technologies from spatial, energetic and economic perspectives.

7. Evaluating the performance of the generated plan

Equations (11) and (12) are applied to calculate the total energy generation and total cost of the generated plans. The total energy supply of the plan is equal to the aggregation of supply of all technologies in parcels in the generated plan. The total supply and demand functions are (11-12):

$$S_{total} = \sum_{j=1}^n P_{pv,j} + P_{wt,j} \quad (11)$$

$$D_{total} = \sum_{j=1}^n D_j \quad (12)$$

where S_{total} (kWh/year) is the total electricity generation of the generated plan, D_{total} (kWh/year) is the total demand of the area, D_j (kWh/year) is the yearly average demand of the parcel j and n is the number of parcels. The total implementation cost of technologies in the generated plan is equal to the aggregation of total net present cost of technologies in each parcel (13).

$$C_{total} = \sum_{j=1}^n \sum_{t=1}^m C_{NPC,t,j} \quad (13)$$

where C_{total} is the total net present cost of all technologies in the generated plan and $C_{NPC,t,j}$ is the total net present cost of technology t in the parcel j and m is the number of renewable energy technologies.

8. Implementation of the simulation model

For the implementation of the model, Netlogo is used. Netlogo is a software application that provides comprehensive facilities to programmers for software development. It is a programmable modeling environment for simulating natural and social phenomena and particularly well suited for modeling complex systems¹⁸. Netlogo provides a reliable platform for the design, implementation and visualization of spatial models and allowing modelers to focus on building models, rather than building basic tools and procedures necessary to set up a computer simulation model^{19–21}.

All GIS operations are carried out with the vector-based spatial analysis tools, FME[®] Version 2014-build 14235 and QGIS version 2.0.1. FME is utilized to spatial data transformation and translation and QGIS is applied to store, retrieve, manage, display and rather preliminary analyses of geographical and spatial data. Fig. 3 shows the Graphical user interface (GUI) of the model and embedded sliders, switches, choosers and input boxes to adjustment of the input variables and running the model and the list of adjustable user inputs and outputs of the model are presented in Table 3.

9. Case study and datasets

For the demonstration purposes, the allocation model is applied to a residential district in the municipality of Eindhoven in the Netherlands. Eindhoven is located on the geographic coordinates of 51° 26' 0" N latitude and 5° 29' 0" E longitude at an average altitude of 22 meters. The case study surface area is approximately 1038757m² that is divided into 1359 parcels. The majority of the parcels have residential function. The total yearly electricity demand of the area is 8605254 kWh/year.

The meteorological data of the case study area is obtained from the Koninklijk Nederlands Meteorologisch Instituut²². The descriptions of the datasets that are used to run the model are as follows:

The solar irradiation data is in hourly resolution scale (8760 data values, one for each hour of the year) expressed in kWh/m² and representing the average solar irradiation on the horizontal surface. The annual average solar irradiation for the case study area is 2.819 kWh/m²/day. The ambient temperature values that are used to calculate the cell temperature at each time step are also in an hourly resolution scale.

The wind speed dataset is the wind speed at a height of 10 meters and representing the average wind speed in meters per second, for each hour of the year. The annual average wind speed for the case study area is 4.831 m/s.

The annual electricity use per connection is calculated from the available invoicing data. The invoicing data are obtained from Endinet Company. Endinet is a company which is active in providing energy in the Noordbrabant area²³. Endinet has 111,410 electricity connections in Eindhoven area for which for each connection the invoicing system contains the yearly electric consumption, yearly gas consumption, postal code, tariff system, connection type, bill type, ground area and building type. From Endinet database the average yearly electricity usage of parcels are acquired.

Table 3. Adjustable inputs variables and outputs of the model.

Input variables	Descriptions	Outputs
Show-roofs?	Display roof maps	Total area (m ²)
Show-parcels?	Display parcels	Number of parcels
Altitude (m)		Allocated parcels
Latitude and longitude		Total roof area (m ²)
Temperature (C°)		Wind turbine number
Solar radiation data (kWh/m ²)		PV panel number
PV?	Inclusion of PV panels in the allocation process	Total net present cost (\$)
PV power (W)	PV panel rated power	PV panel COEP (\$/kWh)
PV losses (%)	PV panel energy losses	Wind turbine COEP (\$/kWh)
PV panel cost per square meter (\$/m ²)		Renewable fraction (%)
PV O&M cost (\$)	PV panel operating and maintenance cost	PV panel electrical production (kWh/year)
PV panel installation area coefficient (%)		Wind turbine electrical production (kWh/year)
Wind speed data (m/s)		Total electrical production (kWh/year)
WT?	Inclusion of wind turbines in the allocation process	Electrical consumption (kWh/year)
WT power (kW)	Wind turbine rated power	Fraction of total demand (%)
WT capacity factor (%)	Wind turbine capacity factor	Excess electricity (kWh/year)
WT capital cost (\$)	Wind turbine capital cost	Unmet electricity load (kWh/year)
WT O&M cost (\$)	Wind turbine operating and maintenance cost	PV panel supply profile
WT swept area (m ²)	Wind turbine swept area	
Electricity price (\$/kWh)		
Life-cycle (years)		
Interest rate (%/year)		

10. Results and Discussion

Two renewable energy technologies are implemented in the allocation model; PV panel and wind turbine. The model runs for different combinations of these technologies to determine the most cost efficient plan. Four different scenarios are constructed and the energy and economic analyses are performed. For each scenario, the energy and economic indicators are calculated and compared.

The following technical specifications for each of the renewable energy technologies are applied to supply the energy requirement of the area. Detailed descriptions of the selected technologies are presented in Tables 4 and 5.

Table 4 displays the detailed specifications of the selected PV panel module that are used in the allocation model. The proposed module has a rated power of 245W and 30 V power voltages. The estimated capital cost is 550 \$/m², including mounting, control system, wiring and installation costs. 1% of the capital cost is considered as the operating and maintenance cost and its lifetime is assumed to be 25 years.

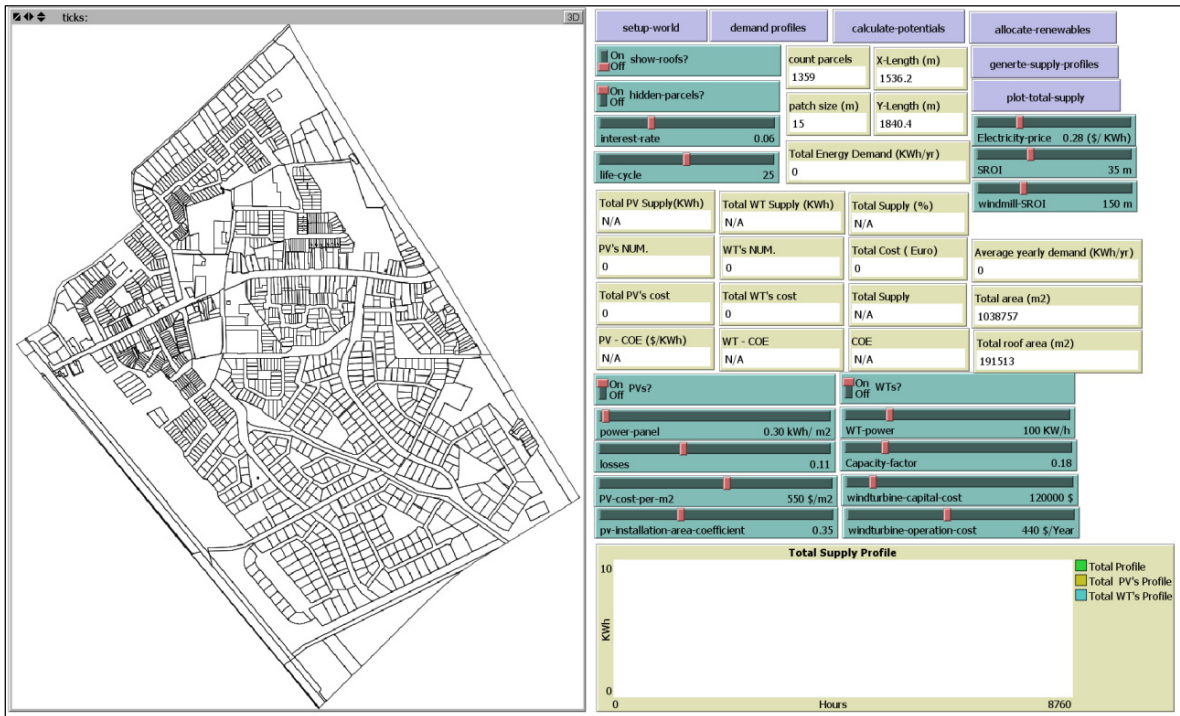


Fig. 3. Graphical user interface (GUI) and embedded sliders, switches, choosers and input boxes.

Table 4. YL245P-29b PV module specifications.

Description	Specification
Manufacturer	Yingli Green Energy
PV model type	YL245P-29b
Nominal efficiency	15.0%
PV module rating	245 W
Maximum power voltage	30.2 V
Maximum power current	8.11 A
Open circuit voltage	37.8 V
Dimensions	1650 × 990 × 40 mm
Weight	19.1 kg
Life time	25 years
Capital cost	550 per m ²
Operating and maintenance cost	1% of capital cost

A FL 100 wind turbine is adopted in the allocation model. Table 5 shows the detailed technical characteristics of the wind turbine. The FL 100 is a three-bladed wind turbine. The diameter of a rotor is 21 meters and the rotor swept area is 346 square meters. The rated power output is 100 kW. At a wind speed of 2.5 m/s the FL 100 turbine joins the supply system. The rated actual power output is at a wind speed of 13.0 m/s. The connection to the energy system cuts at a wind speed of 25.0 m/s. The FL 100 turbine is designed up to a maximum wind speed of 67.0 m/s. The FL 100 has a steel tube tower with a height of 35 meters and the lifetime is assumed to be 25 years. The capital

cost of a wind turbine is considered as 1200 \$/kW with an annual operating and maintenance cost of 3% of the capital cost. Fig. 1 displays the power curve of the FL 100 wind turbine.

As mentioned, four scenarios are conducted based on the technical and economic assumptions of PV panels and wind turbines. The results are presented in Figs. 4 and 5, and Tables 6, 7, 8, 9 and 10.

In scenario 1, it is assumed that the electricity demand of the whole area is supplied only by PV panels. The total potential of the area to generate electricity by PV panels are investigated in this scenario. The technical and economic assumptions for running the model to this scenario are presented in Tables 4 and 6. 0.6% is considered as an annual interest rate and the COEP are calculated based on the PV panels' life time.

Based on the results in Table 6 the total electricity production of PV panels in the area is 8607840 kWh/year. It implies that PV panels fulfil the whole electricity demand of the area. Subsidies are not considered in this scenario and the total average COEP is 0.166 \$/kWh.

In scenario 2 it is assumed that the production of electricity in the area is entirely based on the wind turbines. In this scenario, wind turbines are allocated to the parcels. Table 7 shows the result of the allocation. As shown in table 7, the total production of the wind turbines in the case study area is about 10927570 kWh/year. Compared to the total demand of the area, it shows that the total demand is satisfied and 26.66% of the total supply is considered as surplus energy that can be stored in energy storage technologies or sold to the electricity grid. Average COEP (0.128 \$/kWh) of the scenario 2 shows that the production cost of electricity with wind turbines is cheaper than the scenario 1 and implies the economic feasibility of wind turbines in their lifetimes. In this scenario subsidies are not considered.

Scenario 3 is a mixed configuration of PV panels and wind turbines. In this scenario the PV panels and wind turbines are allocated to the parcels based on their spatial and technical requirements and their mutual interactions. Table 8 displays the results of the allocation. As table 8 shows, the mixed scenario of renewable energy technologies satisfies the whole electricity demand of the area. As expected, only wind turbines are allocated to the parcels. The reason is the average COEP of wind turbines is much less than the average COEP of PV panels and it is more economical to meet the demand only with wind turbines.

Table 5. Technical characteristics of the FL 100 wind turbine

Description	Specification
Type of wind turbine	FL 100 astOs
Manufacturer	Fuhrlander AG
Cut-in wind speed	2.5 m/s
Cut-out wind speed	25.0 m/s
Rated wind speed	13.0 m/s
Rated power	100.0 kW
Maximum design wind speed	67.0 m/s
Number of rotor blades	3
Swept area	346.0 m ²
Rotor diameter	21.0 m
Hub heights	35m
Capital cost	1200 \$/kW
Operating and maintenance cost	3% of capital cost
Lifetime	25 years



Fig. 4. Electricity neutral plans generated for the study area (a) scenario 1; (b) scenario 4.

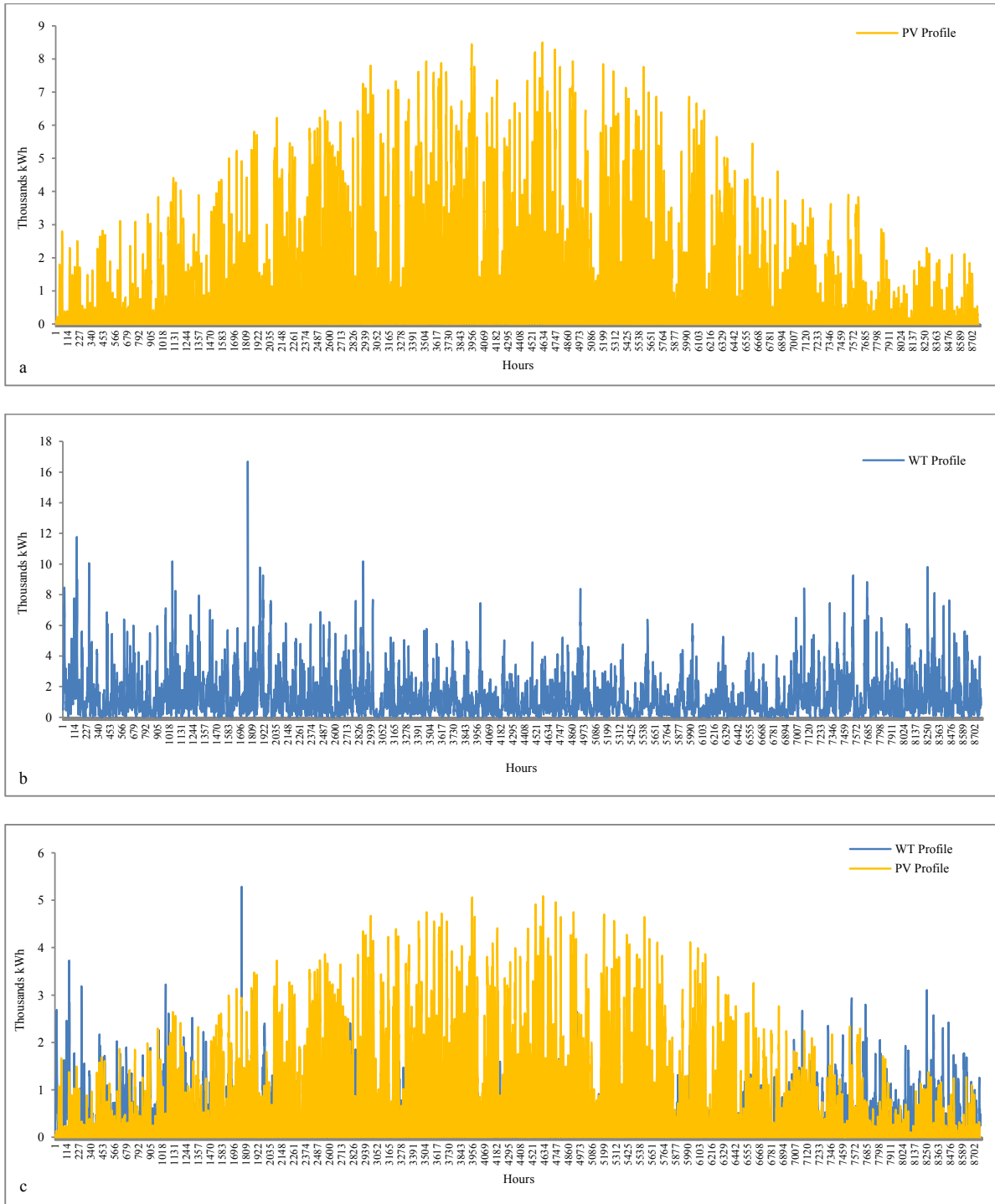


Fig. 5. Yearly electricity generation profiles in an hourly resolution scale (a) scenario 1; (b) scenario 2 & 3; (c) scenario 4

In scenario 4 also a mixed configuration of PV panels and wind turbines are considered, but in this scenario the subsidy of 100 \$/m² is allocated to the PV panels. Owing to the subsidies, both PV panels and wind turbines are allocated to the generated plan. As seen in the table 9, 59.91 % of the total demand is satisfied by PV panels and 40.09 % of the demand is supplied by wind turbines. With the given subsidy the average COEP of PV panels is 0.131 \$/kWh that is much less than the COEP of PV panels without subsidy. The COEP of scenarios are compared in Table 10.

Fig. 4 displays generated electricity neutral plans for the study area. In each plan based on the scenario settings and technology options, the renewable energy technologies are allocated to the parcels. PV panels are allocated to the parcels with suitable roof areas, whereas wind turbines are allocated to the non-residential parcels with determined minimum distance to the residential parcels.

Yearly electricity generation profiles of scenarios in an hourly resolution scales are shown in Fig. 5. The graphs show their compatibility with the availability of renewable resources, including solar radiation and wind power during the generation period. The daily and yearly fluctuations of the renewable electricity production are demonstrated in the graphs (Fig. 5).

Table 6. Allocation results for scenario 1.

Indicators	PV panels	Wind turbines	Total
Renewable energy technology	***		
Allocated parcels	1300		
PV power (kW)	245W		
Wind turbine power			
Total net present cost (\$)	35812796		35812796
Average Cost of Energy Production (COEP) (\$/kWh)	0.166		0.166
Renewable fraction (%)	100		100
Electricity production (kWh/year)	8607840		8607840
Fraction of total demand (%)	100.3		100.03
Excess electricity (kWh/year)			2586
Unmet electricity load (kWh/year)			0.000
Subsidy (\$)	0.000		0.000

Table 7. Allocation results for scenario 2.

Indicators	PV panels	Wind turbines	Total
Renewable energy technology		***	
Allocated parcels		6	
PV power (kW)			
Wind turbine power		100	
Total net present cost (\$)		34926384	75585277
Average Cost of Energy Production (COEP) (\$/kWh)		0.128	0.128
Renewable fraction (%)		100%	100%
Electricity production (kWh/year)		10927570	10927570
Fraction of total demand (%)			126.99%
Excess electricity (kWh/year)			2322316
Unmet electricity load (kWh/year)		0.000	0.000
Subsidy (\$)		0.000	0.000

Table 8. Allocation results for scenario 3.

Indicators	PV panels	Wind Turbines	Total
Renewable energy technology	***	***	
Allocated parcels	0	6	
PV power (kW)	245W		
Wind turbine power		100	
Total net present cost (\$)	0.000	34926384	34926384
Average Cost of Energy Production (COEP) (\$/kWh)	0.000	0.128	0.128
Renewable fraction (%)	0.000	100%	100%
Electricity production (kWh/year)	0.000	10927570	10927570
Fraction of total demand (%)	126.99%	126.99%	126.99%
Excess electricity (kWh/year)			2322316
Unmet electricity load (kWh/year)			0.000
Subsidy (\$)	0.000	0.000	0.000

Table 9. Allocation results for scenario 4.

Indicators	PV panels	Wind Turbines	Total
Renewable energy technology	***	***	
Allocated parcels	746	2	
PV power (kW)	245W		
Wind turbine power		100	
Total net present cost (\$)	16869958	8553400	25423358
Average Cost of Energy Production (COEP) (\$/kWh)	0.131	0.099	0.118
Renewable fraction (%)	59.91	40.09	100
Electricity production (kWh/year)	5155424	3459917	8615340
Fraction of total demand (%)	59.91	40.09	100.12
Excess electricity (kWh/year)			10086
Unmet electricity load (kWh/year)			0.0000
Subsidy (\$)	100(\$/m2)	0.000	

Table 10. Average COEP of scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Average Cost of Energy Production (COEP) (\$/kWh)	0.166	0.128	0.128	0.118

11. Conclusions

As we look at the COEP's of scenarios, it is evident that the difference between scenario 1 with other scenarios are significant. In the current situation, without subsidies, PV panels compared with other renewable energy technologies are not economic. But if proper subsidies are devised, as shown in scenario 4, it becomes comparable with other technologies. As shown, the scenarios help planners and policy makers to examine the influence of different energy policy schemes on the promotion of renewable energy technologies in the electricity sector of urban areas. As a result of the allocation, the cost efficient configuration plans are generated and the effects of energy policies are examined. In this paper the energy storage technologies are not included in the simulation model, but in

the future publications, the effect of introducing energy storage technologies as a balancing buffer to the renewable electricity network will be investigated thoroughly.

References

1. Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Appl Energy* 2010;**87**(4):1059-82.
2. Twidell J, Weir T. *Renewable energy resources*. Abingdon, UK: Taylor & Francis; 1986.
3. Cace J, Horst E, Syngellakis K. *Guidelines for small wind turbines in the built environment*. Bristol, UK; 2007. Available at: <http://www.urbanwind.net>.
4. Li Z, Boyle F, Reynolds A. Domestic application of micro wind turbines in Ireland: Investigation of their economic viability. *Renew Energy* 2012;**41**:64-74.
5. Hafez O, Bhattacharya K. Optimal planning and design of a renewable energy based supply system for microgrids. *Renew Energy* 2012;**45**:7-15.
6. NREL (National Renewable Energy Laboratory). *HOMER computer software Version 2.68 beta*. 2011. Online Available at: <http://www.homerenergy.com/software.html>.
7. Kelleher J, Ringwood JV. A computational tool for evaluating the economics of solar and wind microgeneration of electricity. *Energy* 2009;**34**(4):401-9.
8. Manwell JF, McGowan JG, Rogers AL. *Wind energy explained: theory, design and application*. West Sussex, UK: John Wiley & Sons; 2010.
9. Masters GM. *Renewable and Efficient Electric Power Systems*. New Jersey: Wiley; 2005.
10. Resort A. *Fuhrlander Wind Turbine Overview*. 2004. Available at: <http://www.fuhrlander.de/en>.
11. Breu F, Guggenbichler S, Wollmann J. *Wind and solar power systems: design, analysis, and operation*. Boca Raton, FL: CRC Press; 2008.
12. Duffie JA, Beckman WA. *Solar Engineering of Thermal Processes*. New Jersey: Wiley; 2013.
13. Alonso García MC, Balenzategui JL. Estimation of photovoltaic module yearly temperature and performance based on nominal operation cell temperature calculations. *Renew Energy* 2004;**29**(12):1997-2010.
14. Shen WX. Optimally sizing of solar array and battery in a standalone photovoltaic system in Malaysia. *Renew Energy* 2009;**34**(1):348-52.
15. Cooper PI. The absorption of radiation in solar stills. *Sol Energy*. 1969;**12**(3):333-46.
16. Waddell P. *The open platform for urban simulation and urbanSim users guide and reference manual*. University of California Berkeley: Berkeley, CA; 2011. Online Available at: <http://www.urbansim.org>.
17. Wade T, Sommer S. *A to Z GIS: an illustrated dictionary of geographic information systems*. Redlands, California: ESRI Press; 2006.
18. Wilensky U, Stroup W. *NetLogo*, Retrieved from Center for Connected Learning and Computer-Based Modeling. Northwestern University: Evanston, IL; 1999. Online Available at: <http://ccl.northwestern.edu/netlogo>.
19. Railsback SF, Lytinen SL, Jackson SK. Agent-based simulation platforms: review and development recommendations. *Simul* 2006;**82**(9):609-23.
20. Tobias R, Hofmann C. Evaluation of free Java-libraries for social-scientific agent based simulation. *J Artif Soc Soc Simul* 2004;**7**(1).
21. Crooks A, Castle C, Batty M. Key challenges in agent-based modelling for geo-spatial simulation. *Comput Environ Urban Syst* 2008;**32**(6):417-30.
22. KNMI. *Koninklijk Nederlands Meteorologisch Instituut - Daily weather data for the Netherlands*. 2013. Online Available at: <http://www.knmi.nl>.
23. Blokhuis E, Brouwers B, Van der Putten E, Schaefer W. Peak loads and network investments in sustainable energy transitions. *Energy Policy* 2011;**39**(10):6220-33.