EINDHOVEN UNIVERSITY OF TECHNOLOGY

Towards Renewable Energy Systems: A Design Framework for a Low Grid-Dependent Residential District

Citation for published version (APA):
Farrokhifar, M., Havinga, L. C., & Hoes, P.-J. (2023). Towards Renewable Energy Systems: A Design Framework for a Low Grid-Dependent Residential District. In *2023 IEEE Conference on Technologies for Sustainability, SusTech 2023* (pp. 151-156). IEEE Press. https://doi.org/10.1109/SusTech57309.2023.10129565

DOI:
10.1109/SusTech57309.2023.10129565

Document status and date:
Published: 01/04/2023

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.

Download date: 12. Feb. 2025

Towards Renewable Energy Systems: A Design Framework for a Low Grid-Dependent Residential District

Meisam Farrokhifar, Lisanne Havinga, Pieter-Jan Hoes
Department of the Built Environment
Eindhoven University of Technology
Eindhoven, The Netherlands
{m.farrokhifar, l.c.havinga, p.hoes}@ tue.nl

***Abstract*— The transition from fossil fuels to renewable energy generation is imperative to limit global warming and meet international climate targets. However, energy production from uncertain and intermittent renewable sources results in various energy management challenges. In this research, we propose an efficient computational design framework for the conceptual design of the energy system of a residential district, which includes energy generation, storage, demand, and distribution on building and district levels. Our approach is demonstrated using a Dutch residential district (the Brainport Smart District; BSD) as a case study. The proposed computational design framework can be used to model and evaluate the performance of various energy systems configurations, such as the enhanced use of photovoltaic (PV) systems and energy storage devices. In this paper, we present the results for various generation and storage scenarios with the purpose of supporting decision-making.**

Keywords*— *renewable generation; energy management; building performance; energy storage; heating demand.

I. Introduction

The construction and built environment sectors in the EU are responsible for 40% of ultimate energy consumption and 33% of CO_2 emissions. The operation of existing buildings requires approximately 75% of this energy consumption and CO_2 emissions [1]. The energy transition of the built environment is necessary to reduce the energy consumption and CO_2 emissions of the built environment. It entails huge investments in the sustainable renovation of current buildings, the introduction of renewable energy sources, the strengthening of the electricity network, and the introduction of the infrastructure of new energy systems such as district heating grids [2].

The use of renewable energy sources can solve existing problems in the field of energy and the environment. Moreover, decarbonization and transit to renewable energy sources reduce environmental pollutants resulting in great economic advantages in terms of preventing health expenses from diseases around the world [3]. In this regard, governmental plans are of high importance. For example, the Swedish government aims at reaching 100% renewable-based electricity generation by 2040 [4]. From another viewpoint, the electricity grid is not available for millions of households in the world. Therefore, areas without an electricity grid can benefit from renewable power production [5].

PV systems for public and agricultural applications can be operated as independent power sources of the grid or connected ones with low power to supply the electrical energy needed from small houses to large complexes [6]. Several applications of PV systems for energizing buildings were studied in the literature. The authors of [7], introduced a design framework for an independent renewable microgrid to feed a rural community load demand in China. A large-scale building-applied PV system was studied in [8] through economic, technical, and environmental analyses. The planning of distributed PV systems and energy storage devices linked to a distribution grid considering carbon emission reduction impact was investigated in [9]. Besides, the authors of [10] included the cost analysis in addition to the reliability assessment for a large-scale PV system in their research.

In the same context, the concept of Positive Energy Districts gained interest in recent years in order to accelerate the implementation of renewables in the built environment. According to a definition in [11], Positive Energy Districts are districts 'that can not only generate more energy than consumed but are flexible enough to respond to all the variety of the available energy in the market'. Recently the International Energy Agency (IEA) started the Annex 83 project 'Positive energy districts' in the Energy in Buildings and Communities (EBC) Program.

Designing the energy system of (positive energy) districts is a complex task since many aspects need to be considered, e.g., from the technical perspective (electricity production, energy storage, energy management, etc.), but also from the social perspective. Appropriate tools can support decision-makers in their decision-making process [12]. Depending on the type of decision maker, such tools might require the modeling of various energy carriers, various market behavior, and social aspects. Moreover, the modeling requires adequate detail of the techno-economic structure [13]. In order to establish decision-making, the requirements and preferences per stakeholder as well as for the system as a whole have to be incorporated into the tools [14]. In summary, principles for modeling district energy systems in the built environment should consider: energy demand, energy potential, system costs and benefits, end-user characteristics,

979-8-3503-4548-3/23/$31.00 ©2023 IEEE

infrastructure and energy storage, system boundaries, interface, energy saving measures, and flexibility of measures [13].

Despite the complexity of designing the future energy systems for districts, it was observed that district energy planners in the Netherlands do not often make use of the existing models in the scientific area [13]. Therefore, in this paper, we propose an efficient computational design framework for the conceptual design of the energy system of residential districts that can be used by these designers.

The design framework is demonstrated for the development of the energy system for the Brainport Smart District in the Netherlands. The Brainport Smart District is a residential district of ca. 2500 houses that will be built in the coming years. The district has ambitious (sustainability) goals [15], e.g., reducing the dependency on national electricity by using local renewable generation as much as possible locally within the district. In this paper, we use the computational design framework to evaluate the performance of various design options for the future district energy system. Different key performance indicators are assessed to support the decision-making. In order to maximize the on-site energy matching, a simple and efficient method is introduced for managing the energy storage system.

This paper is arranged in the following sections. The problem description and the computational design framework are explained in Sections II and III. The paper is followed by describing the case study and datasets as well as results in Sections IV and V. The last section contains the conclusion.

II. Problem Description

This research aims at energizing a residential district utilizing local renewable energy generation as much as possible. In order to assess and compare various design solutions, the following key performance indicators (KPIs) are adopted.

A. *On-site Energy Matching (OEM) [16]*

This indicator demonstrates the ratio of on-site produced energy that is consumed by the load. In (1), P(t) and D(t) are the on-site produced power and load demand at an instantaneous interval. Moreover, dt shows the calculation time-step, whereas t1 and t2 show the beginning and finishing points of the time interval.

$$OEM = \frac{\int_{t1}^{t2} Min[P(t); D(t)]dt}{\int_{t1}^{t2} P(t)dt} \tag{1}$$

B. *On-site Energy Fraction (OEF) [16]*

This indicator shows the ratio of the load fed by on-site produced energy.

$$OEF = \frac{\int_{t1}^{t2} Min[P(t); D(t)]dt}{\int_{t1}^{t2} D(t)dt} \tag{2}$$

The OEM and OEF can be calculated for time intervals like a specific day, month, season or year by adjusting the beginning and finishing points. It is also possible to adjust the timestep, but in order to adequately assess the demand-matching, the timestep needs to be relatively small. In this research, the OEM and OEF are evaluated on a yearly time interval, and hourly time-steps are used. The graphical description for the calculation of OEM and OEF is shown in Fig. 1. Both OEM and OEF could vary between 0 and 1, including both boundaries. An appropriate on-site energy matching takes place when OEM and OEF take higher values simultaneously. In the ideal case, both OEM and OEF are equal to 1, meaning that all on-site produced power is consumed by and completely covers the on-site load demand [16].

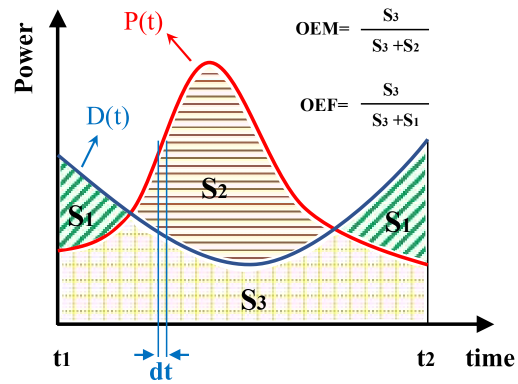


Figure 1. Visualization of OEM and OEF [16].

C. *One-Percent Peak Power (OPP) [17]*

The OPP (in kW) shows the net swapped peak power with the network. This indicator provides the average of the 1% highest swapped power.

$$OPP = \frac{W1\%_{peak}}{\Delta t/100} \tag{3}$$

In (3), the numerator shows the energy in the one-percent highest peaks, and the denominator demonstrates the entire studied time.

D. *Unused Energy Production (UEP)*

The UEP (in MWh) represents the amount of the on-site produced energy which is not consumed by the load during a certain time interval. This indicator shows the amount of energy that can be exported to the grid.

$$UEP = \int_{t1}^{t2} P(t)dt - \int_{t1}^{t2} Min[P(t); D(t)]dt \tag{4}$$

E. *Uncovered Load Demand (ULD)*

The ULD (in MWh) shows the amount of the load in terms of energy that is not fed by on-site produced energy during a certain time interval. This indicator demonstrates the amount of energy that should be imported from the grid or stored in a potential seasonal energy storage device.

$$ULD = \int_{t1}^{t2} D(t)dt - \int_{t1}^{t2} Min[P(t); D(t)]dt \tag{5}$$

III. Computational Design Framework

The design process starts with the analysis of the generation and demand datasets. Based on the given load demand, the OPP is calculated. Moreover, different PV and battery sizes should be defined for further analysis based on load demand. Having the generation and demand data, the OEM and OEF are determined over different periods in the presence of an energy storage device. The greater the concurrent OEM and OEF values the less energy is imported from the grid. For example, if both annual OEM and OEF values are greater than 0.5 the district will need less than 50% of its demand to be imported from the grid while at least 50% of on-site produced power is consumed internally.

It is worth mentioning that, any type of renewable energy source or a mixture of sources can be used in the modeling based on the topography of a district. In this paper, we utilize PV systems as the energy source. Besides, this research proposes different potential solutions; however, the final decision for selecting the PV and battery sizes is made by the project holders based on their criteria like available areas for installing PV systems, investment budget, long-term plans, etc. The flowchart of the proposed computational design framework is presented in Fig. 2.

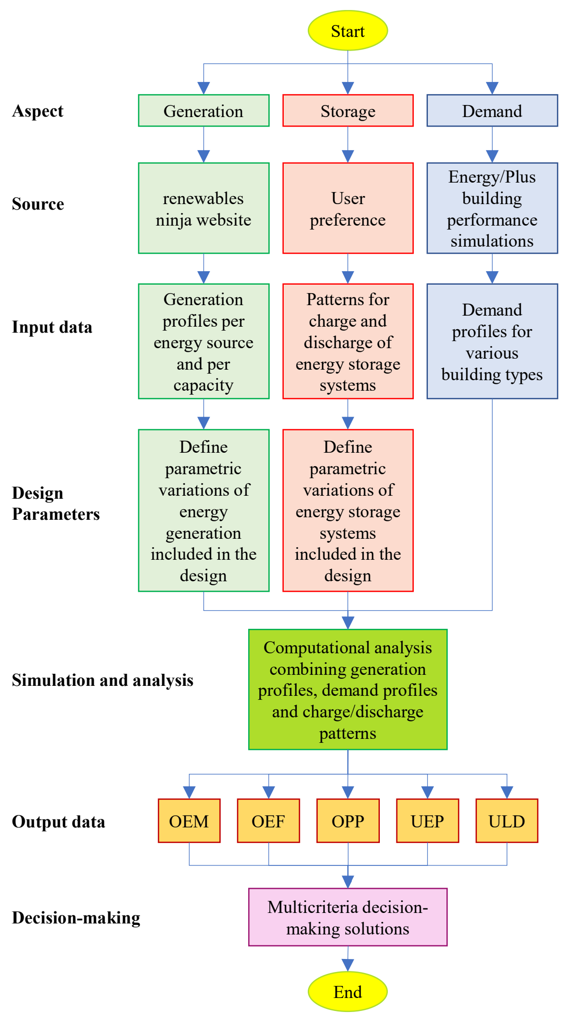


Figure 2. Flowchart of the proposed computational design framework.

A simple but efficient strategy for charging and discharging the energy storage device is presented in this research. The energy storage device starts for a charge or discharge while amounts of on-site produced power and load are different during the studied time-step. In the charge period, the amount of on-site produced power is greater than the load demand and there is a charge capacity. On the other hand, in the discharge period, the amount of on-site produced power is lower than the load demand and there is a discharge capacity. The details of the charge and discharge strategy for the energy storage device are explained in Fig. 3.

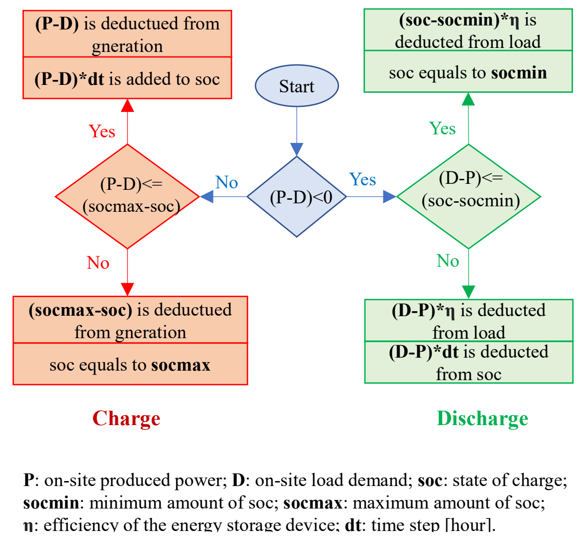


Figure 3. Charge and discharge strategy of the energy storage device for each time-step.

Having the proposed strategy, we need to define different sizes for PV and energy storage systems. A simple approach was introduced in [18] to calculate the size of a PV system for Dutch houses. Undoubtedly, this method is not based on exact optimization formulas; however, it provides a simple assumption for calculating the PV system's size. In this research, we use a 4 kW solar system as an initial value for the size of each PV in a house. This size could be smaller at the district level because of the reduced amount of demand in the connected loads. Moreover, in addition to the initially selected size, we examine other sizes including smaller and greater than to make a fair comparison among the KPIs.

Based on the defined PV sizes, we can examine also different energy storage sizes. In the next sections, the KPIs will be analyzed through a heat map that includes various PV and battery sizes in a graph.

IV. Case Study And Datasets

In this paper, energizing Brainport Smart District (BSD) is investigated. The following design requirements of BSD are defined by the BSD design team: the annual OEM and OEF of the district should be around 0.5; the OPP should be lower than 4 kW per house.

The district will be built in different phases. The share of different households in phase 1 is reported in Table I. It is worth mentioning that phase 1 consists of 21 projects (building plots) which each contain 60 houses, so in total 1260 houses. In the next section, we will analyze the KPIs related to each type of house in one project. Later, the combinations of different house types will be investigated for the given number of projects.

TABLE I. THE SHARE OF DIFFERENT HOUSEHOLDS IN PHASE 1.

Type of house	Apartment	Terraced	Detached	Total
Number	600	540	120	1260
Number of projects	10	9	2	21
Share (%)	47.6	42.8	9.6	100

The hourly load profiles over the period of a year are taken from [19]. This reference also provides the details of the surface for each type of house. Besides, our analysis is based on the electricity supply for all devices, including heating. Therefore, domestic hot water (DHW) and space heating will require heat pumps. The used values for the coefficient of performance (COP) for heat pumps are reported in Table II. For the space heating demand data, the current thermal insulation package according to the Dutch building code is employed. The details of insulation parameters are provided in Table III.

TABLE II. THE COEFFICIENT OF PERFORMANCE (COP) FOR THE HEAT PUMPS (AIR-WATER).

Load type	DHW	Space Heating
COP	2	3.5

TABLE III. THE THERMAL INSULATION PARAMETERS [19].

Insulation package	Current
Rc-floor, [m^2k/W]	3.5
Rc-wall, [m^2k/W]	4.5
Rc-roof, [m^2k/W]	6

Each load profile consists of the following categories of plugged loads, heating/cooling loads, and DHW loads. For heating/cooling loads, EnergyPlus simulations were conducted in [19]. For plugged and DHW loads, measured datasets from Dutch households over the period of a year are used. The average annual load demand values per house in a project are expressed in Table IV. To have an appropriate design framework, different kinds of households such as couples and families are used to form the total load. In this table, SP stands for the set point, whereas, the high SP equals 24 °C and the low SP equals 20 °C. Each project consists of 60 plugged loads, 15 space heating demands for high SP-Couple, 15 space heating demands for low SP-Couple, 30 DHW demands for Couple, 15 space heating demands for high SP-Family, 15 space heating demands for low SP-Family, and 30 DHW demands for Family. Having different types of demands, we can form the mixture demand. The average values for the annual mixture demands in each project (60 houses) are shown in Table V.

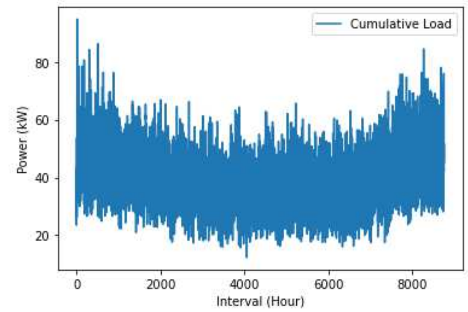
TABLE IV. THE AVERAGE ANNUAL LOAD DEMAND BY CATEGORY.

Category	Apartment	Terraced	Detached
Plugged loads [kWh]	3038.35	3038.35	3038.35
Space heating (High SP-Couple) [kWh]	591.95	1629.25	1960.39
Space heating (Low SP-Couple) [kWh]	366.25	1060.16	1235.89
DHW (Couple) [kWh]	1348.86	1348.86	1348.86
Space heating (High SP-Family) [kWh]	636.02	1578.48	1865.34
Space heating (Low SP-Family) [kWh]	395.79	922.01	1143.01
DHW (Family) [kWh]	2950.32	2950.32	2950.32

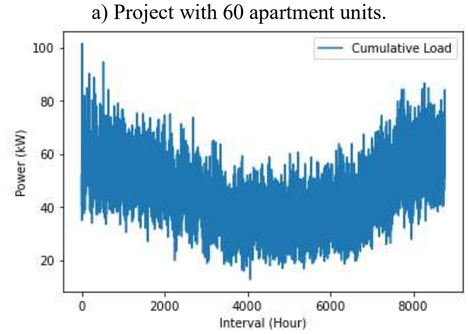
TABLE V. THE AVERAGE ANNUAL MIXTURE DEMAND PER PROJECT (60 HOUSES).

Project type	Apartment	Terraced	Detached
Total mixture demand [kWh]	5685.44	6485.42	6739.09

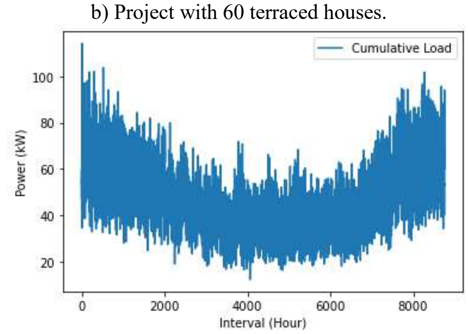
The cumulative load demand for each type of house in one project is shown in Fig. 4.



a) Project with 60 apartment units.



b) Project with 60 terraced houses.



c) Project with 60 detached houses.

Figure 4. Cumulative load demand for three projects each with 60 houses.

The PV generation profiles for the city of Helmond (Latitude: 51.5 and Longitude: 5.4) over the period of a year are taken from [20].

V. RESULTS

In this section, the OPP values related to each type of house in one project are calculated. After that, the whole district including 10 apartment projects, 9 terraced house projects, and 2 detached house projects will be analyzed. It is worth mentioning that different scenarios for the size of PV and energy storage devices will be considered in our analysis. The district energy operator will have the freedom to choose the final solution among the proposed ones based on investment costs, the area given for PVs, and the inclusion of other generation/storage units.

The numerical analysis was done using Python codes. It is important to note all calculations are made based on hourly intervals. Moreover, the parameters related to the energy storage device are provided in Table VI.

TABLE VI. THE PARAMETERS USED FOR THE BATTERY.

Parameter	Efficiency of the battery	socmin	socmax
Value	90%	10% rated capacity	100% rated capacity

A. *Individual Projects*

Each project contains 60 different load profiles which were discussed in Table IV. Therefore, 3 different types of projects are considered, consisting of apartment houses, terraced houses, and detached houses, respectively. The OPP values are reported in Table VII for each type of building at house and project levels.

TABLE VII. THE OPP VALUES FOR EACH HOUSE TYPE.

House type	Apartment	Terraced	Detached
One project [kW]	69.94	77.91	88.57
One house [kW]	1.16	1.29	1.47

B. *The BSD Level (The Whole District)*

Phase 1 of BSD contains 1260 houses which are analyzed through 21 projects. The details related to the number of buildings by house type were provided in Table I. The cumulative load demand for 21 projects is illustrated in Fig. 5.

The PV size calculation is accomplished based on the descriptions supplied in Section III. The PV sizes are 1.2, 2.4, 4.8, 7.2, and 9.6 all in MW. Also, the battery sizes are 0, 4.8, 9.6, 14.4, and 19.2 all in MWh.

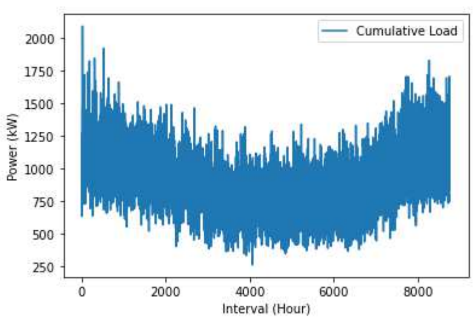
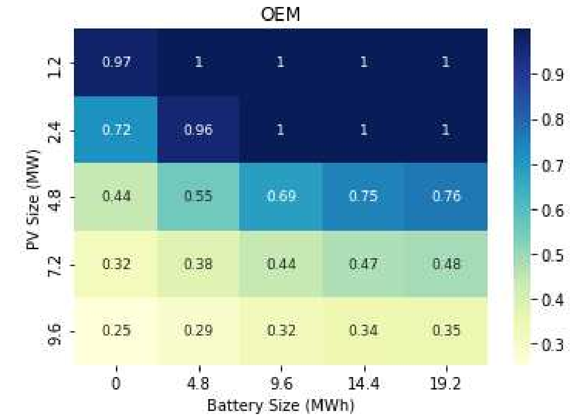


Figure 5. Cumulative load demand for 21 projects (1260 houses).

1) *OEM and OEF analysis*

Following the proposed approach for the individual projects, different PV and battery sizes are considered for the calculation of the annual OEM and OEF in Fig. 6. According to Fig. 6, for the PV size equal to 7.2 MW and the battery size equal to 9.6 MWh, OEM and OEF are equal to 0.44 and 0.48, respectively. These values are close to the requirements mentioned in Section IV and can be considered acceptable. This specific design solution is investigated in more detail below by investigating the daily OEM and OEF values.



a) Heat map for the OEM.

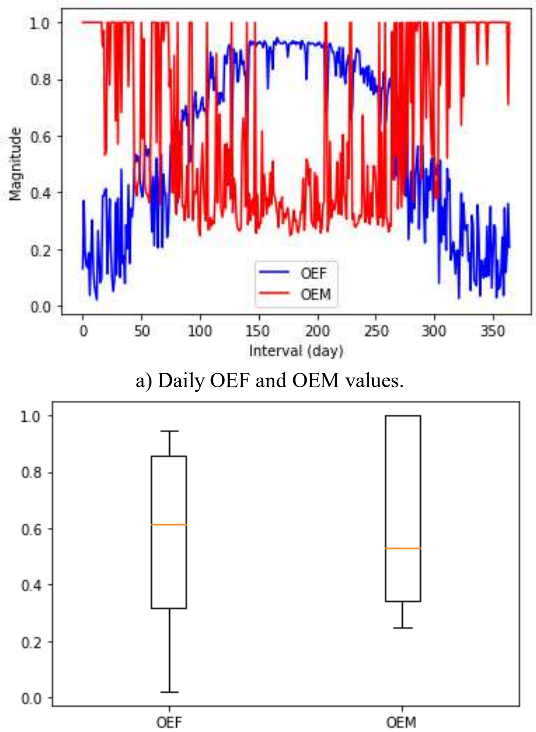
b) Heat map for the OEF.

Figure 6. Annual OEM and OEF values for the BSD.

Fig. 7 shows daily OEM and OEF analysis for the district. The components of this figure show the variety of OEM and OEF based on daily intervals over a year (365 days). Under Fig. 7, the OEM takes values between 0.28 and 1 in which the winter days are greater. Also, the OEF takes values between 0.05 and 0.95 in which the summer days are greater.

2) *OPP and energy balance analysis*

The amount of the OPP in the BSD level equals 1.5 MW. Also, the annual energy balance values are reported in Table VIII for the whole district. These meet the requirements as defined in Section IV.



a) Daily OEF and OEM values.

b) Box plots of daily OEF and OEM.

Figure 7. Daily OEM and OEF analysis for the BSD (PV= 7.2 MW and battery= 9.6 MWh).

TABLE VIII. THE ANNUAL SUMMARY OF THE ENERGY BALANCE.

Item	Amount of energy [MWh]
Initial Generation	5584
Initial Load Demand	7722
UEP	1127
ULD	3265

VI. CONCLUSION

This paper offers an efficient computational design framework for the conceptual design of district energy systems of residential districts with low dependency on the grid. Renewable energy systems are considered the main source of electricity generation for the district. Therefore, optimal design and operation of energy storage systems are important to increase the self-consumption of the district. The framework allows the assessment of the relevant KPIs for the solutions. Besides, the framework is demonstrated for the Brainport Smart District in the Netherlands; it provides valuable insights to the design team regarding the various design solutions (the optimal capacity of storage and PV production).

Future developments still are open in the following categories. For the generation, other renewable sources could be considered. For storage systems, heat storage is an advantageous option for research. For the demand, including different factors such as housing types, user types, and insulation levels result in a more accurate decision-making tool. Finally, different district heating networks can be investigated to provide further potential solutions.

REFERENCES

[1] "www.commission.europa.eu/," [Online]. [Accessed 2023].

[2] P. Lopion, P. Markewitz, M. Robinius, and D. Stolten, "A review of current challenges and trends in energy systems modeling," *Renewable and Sustainable Energy Reviews,* vol. 96, pp. 156-166, 2018.

[3] T. Galimova, M. Ram and C. Breyer, "Mitigation of air pollution and corresponding impacts during a global energy transition towards 100% renewable energy system by 2050," *Energy Reports,* vol. 8, pp. 14124-14143, 2022.

[4] J. Zhong, M. Bollen, and S. Ronnberg, "Towards a 100% renewable energy electricity generation system in Sweden," *Renewable Energy,* vol. 171, pp. 812-824, 2021.

[5] S. Wang, "Current status of PV in China and its future forecast," *CSEE Journal of Power and Energy Systems,* vol. 6, no. 1, pp. 72-82, 2020.

[6] A. Desai, I. Mukhopadhyay, and A. Ray, "Techno-economic-environment analysis of solar PV smart microgrid for sustainable rural electrification in agriculture community," in *IEEE 48th Photovoltaic Specialists Conference (PVSC)*, 2021.

[7] J. Zhou and Z. Xu, "Optimal sizing design and integrated cost-benefit assessment of stand-alone microgrid system with different energy storage employing chameleon swarm algorithm: A rural case in Northeast China," *Renewable Energy,* vol. 202, pp. 1110-1137, 2023.

[8] A. Alazazmeh, A. Ahmed, M. Siddiqui, and M. Asif, "Real-time data-based performance analysis of a large-scale building applied PV system," *Energy Reports,* vol. 8, pp. 15408-15420, 2022.

[9] S. Yang, X. Wang, Y. Yang, and J. Li, "Bi-level planning model of distributed PV-energy storage system connected to distribution network under the coordinated operation of electricity-carbon market," *Sustainable Cities and Society,* vol. 89, p. 104347, 2023.

[10] M. Nageh, M. P. Abdullah, and B. Yousef, "Reliability evaluation and cost analysis for optimized large scale solar PV system," in *IEEE Industrial Electronics and Applications Conference (IEACon)*, 2021.

[11] A. Hedman, H. Rehman, A. Gabaldón, A. Bisello, V. Albert-Seifried, X. Zhang, F. Guarino, S. Grynning, U. Eicker, H.-M. Neumann, P. Tuominen, and F. Reda, "IEA EBC Annex83 Positive Energy Districts," *Buildings,* vol. 11, no. 3, p. 130, 2021.

[12] M. Farrokhifar, F. Hamzeh Aghdam, A. Alahyari, A. Monavari, and A. Safari, "Optimal energy management and sizing of renewable energy and battery systems in residential sectors via a stochastic MILP model," *Electric Power Systems Research,* vol. 187, p. 106483, 2020.

[13] K. Bouw, K. Noorman, C. Wiekens, and A. Faaij, "Local energy planning in the built environment: An analysis of model characteristics.," *Renewable and Sustainable Energy Reviews,* vol. 144, p. 111030, 2021.

[14] D. Connolly, H. Lund, B. Mathiesen, and M. Leahy, "A review of computer tools for analysing the integration of renewable energy into various energy systems," *Applied Energy,* vol. 87, no. 4, pp. 1059-1082, 2010.

[15] "www.brainportsmartdistrict.nl/en/," [Online]. [Accessed 2022].

[16] S. Cao, A. Hasan, and K. Siren, "On-site energy matching indices for buildings with energy conversion, storage and hybrid grid connections," *Energy and Buildings,* vol. 64, pp. 423-438, 2013.

[17] Z. Mohammadi, P.-J. Hoes, and J. L. Hensen, "Simulation-based design optimization of houses with low grid dependency," *Renewable Energy,* vol. 157, pp. 1185-1202, 2020.

[18] "www.settledownsupport.nl/solar-panels-on-a-dutch-house/," [Online]. [Accessed 2022].

[19] S. Wang, P.-J. Hoes, J. L. Hensen, O. C. Adan, and P. A. Donkers, "Identifying promising use cases for a novel heat battery in Dutch residential buildings," in *CLIMA Conference*, 2022.

[20] "www.renewables.ninja," [Online]. [Accessed 2022].