Distributed energy resources for a zero-energy neighbourhood

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Distributed Energy Resources for a Zero-Energy Neighborhood

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Abstract—Zero energy buildings are on the increasing trend. They are perceived as appropriate technology to reducing CO₂ emissions, improving energy efficiency and alleviating energy poverty. The main goal is that a grid-connected building produces enough energy on site to equal or exceed its annual energy requirement while using the grid as a buffer. Many municipalities see this concept as a prospective solution for developing future neighborhoods and thereby aim to develop a neighborhood with net zero energy concept. This paper proposes passive designs measures and distributed power generations required in designing such a neighborhood.

Index Terms— Distributed power generation, Green buildings, Energy management, Sustainable development, Power system planning.

I. INTRODUCTION

With approximately 40% of the total primary energy demand of the EU being consumed in buildings [1], the building sector should be a key player in Europe’s energy transition goals towards a highly energy-efficient, low carbon economy by 2030 [2]. In this context, the concept of zero-energy buildings (ZEB) is increasingly being perceived as a viable pathway for reducing energy use in the building sector to achieve these policy ambitions and alleviate the current worldwide energy challenges of rising prices, climate change and security of supply [3], [4]. By “zero energy”, it is meant that the building delivers as much energy to the supply grids as it draws from them on a yearly basis. The proposed steps to achieve a zero energy balance are reducing site energy demand by using low-energy building technologies and other energy efficient measures, and utilizing on-site distributed energy resources (DER) to supply the remaining energy demand [3]-[5].

This paper reports the findings of a case study of a grid-connected zero-energy neighborhood of 400 houses that will be built in a small city of the province Overijssel, in the Netherlands. The design of the system is for the year 2030. On a yearly basis, the DER of the neighborhood will produce as much thermal and electrical energy as they draw from the supply grids. The scope of the project further included the design of the low-voltage distribution network servicing the neighborhood. The grid, in addition to supporting DER, should withstand increasing household electricity demands over time, including a fleet of plug-in electric vehicles (EVs).

II. CASE STUDY

A. The Neighborhood

In line with Dutch and European energy policy, the municipality of Steenwijkerland, in the Netherlands, has outlined a sustainability roadmap to 2030 in which energy savings in the built environment play an important role. The aim is to construct energy efficient/neural buildings in the framework of pilot programs and strategic partnerships with the local electricity and natural gas distribution system operator (DSO), housing corporations, architects, contractors and surrounding municipalities [6]. The master plan for the project of the new neighborhood of Steenwijkerland calls for 153 terraced, 90 semi-detached, and 85 detached houses; and 72 apartments. The breakdown is graphically depicted in Fig. 1.

The municipality advocates the combination of passive and active technical solutions for the built environment to achieve energy neutrality. Passive solutions include improved construction materials and solar design. Active solutions for electricity generation consist of roof-integrated PV systems and on-site wind turbines. For domestic hot water, thermo-solar systems are viewed as the most appropriate solution. Finally, for heating applications, ground-source heat pumps or biogas-fed cogeneration units are proposed to be used in combination with highly efficient, low temperature terminal systems [7].

B. System design process

This project is focused on the interrelationships among the building envelope, the grid and occupant consumption profiles in order to devise inclusive solutions for the dwelling and distribution network designs. This is carried out by taking local
III. DESIGN PROPOSAL

A. Building envelope

Passive and active design measures that were examined for the project are detailed in the following paragraphs:

1) Physical components

The south-facing glazing areas of each type of house were optimally designed with respect to the climate characterization of the building site. This design, in conjunction with the use of high-transmission, low emissivity glazing, maximizes solar heat gains in the winter without causing overheating in the summer. User-controllable window shades further limit unwanted heat gains during the summer months.

Insulation with high heat resistance values were selected for the wall, floor and roof of each type of house. In order to increase the thermal mass of the building envelope and stabilize daily indoor temperatures during the heating season, short-term thermal energy storage capabilities were added to each house. This was done by applying a 30 mm-thick plaster layer to the walls, containing microencapsulated phase-change materials (PCM).

2) Terminal systems

The thermal mass of the building and an increase in indoor temperature stability enable low temperature floor heating systems for each dwelling instead of using high temperature radiators. Additionally, air quality is maintained at comfortable and healthy levels by a heat recovery balanced ventilation system with a heat recovery efficiency of 90% during the heating season, and a bypass damper for the heat exchanger during the summer months.

B. Distributed energy resources for electricity and heating

1) Electricity system

Typical electricity demands for each type of household for the year 2009 and their projections toward 2030 are depicted in Table I below. Figures were calculated based on data from [9], [10], and [11]. The yearly electricity demand of the entire neighborhood in 2030 amounts to 1.84 GWh.

<table>
<thead>
<tr>
<th>Type of dwelling</th>
<th>Electricity Demand [kWh/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009</td>
</tr>
<tr>
<td>Detached house</td>
<td>5116</td>
</tr>
<tr>
<td>Semi-detached house</td>
<td>4458</td>
</tr>
<tr>
<td>Terraced house</td>
<td>3751</td>
</tr>
<tr>
<td>Apartment</td>
<td>2466</td>
</tr>
</tbody>
</table>

The yearly electricity demands of the neighborhood can be covered with roof-integrated photovoltaic cells (PV) with a total installed capacity of 2MWp. The proposed neighborhood PV system will yield 1.9 GWh per year. The modules for the apartments are connected to the inverter in a single string, whilst the modules for the terraced, semi-detached and detached houses are arranged into two strings to keep the input voltages and currents of the inverter within its operational ranges. Wind energy was not considered for this project due to lack of public support for on-site wind turbines.

The houses are interconnected by the LV grid, which also acts as a buffer to compensate for the mismatch between the energy supply and demand. Without having the need for electricity storage, it is possible for each dwelling to draw electricity from the grid during periods of low or no production, whilst any excess production during the daytime is fed into the grid. However, autonomy from the grid brought about by installing a battery bank would be a desirable attribute in case of power outages. The availability of electricity storage would also enable the decoupling of production and demand during the day-to-day on-peak periods.

In the Netherlands, power outages occur approximately once every three years on the LV grid, and power is usually restored within four hours [12]. With such a reliable grid, it is not only beneficial, but rather necessary to use the battery banks as a peak shifting mechanism in order to justify the considerable investment costs for this piece of equipment.

The design concept of the storage system consists of communal sealed lead-acid battery banks for every branch in the distribution system. The storage capacity, calculated at 1.6 MWh, will support the critical loads of the neighborhood until power is restored in the event of an outage. Additionally, the battery banks will enable a load shift of up to 400 kW during the peak periods. Calculations were made under the assumptions that the discharge rate of the battery capacity will be kept at 50% to preserve battery life, and that the energy conversion efficiency of the battery system is 90%.

2) Heating system

Heating demands for the neighborhood are divided into domestic hot water (DHW) and space heating. DHW consumption is occupant-driven and not expected to change significantly in the coming years [13]. DWH demands are set at 2833 kWh/a per household, or 1.13 GWh/a for the entire neighborhood. DHW demands will be supplied by roof-integrated solar thermal systems. Each module consists of glazed flat-plate absorbers coated with a spectrally-selective black chrome coating, and a drain-back system to avoid problems associated with freezing pipes during winter. The modules are sized to supply 100% of the DHW demand during summer, based on a system
efficiency of 35% [14]. The aggregated annual energy yield totals 0.63 GWh/a, or 56% of the yearly DHW demand. Space heating demands for 2009 and their projections toward 2030 are depicted in Table II. Figures for 2009 were based on data from [15]; those for 2030 are obtained after implementation of the building envelope design in section A of this chapter.

<table>
<thead>
<tr>
<th>Type of dwelling</th>
<th>Space Heating Demand [kWh/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009</td>
</tr>
<tr>
<td>Detached house</td>
<td>7612</td>
</tr>
<tr>
<td>Semi-detached house</td>
<td>10796</td>
</tr>
<tr>
<td>Terraced house</td>
<td>13342</td>
</tr>
<tr>
<td>Apartment</td>
<td>4656</td>
</tr>
</tbody>
</table>

For the year 2030, the neighborhood has a space heating demand of 1.64 GWh every year, significantly lower compared with 3.61 GWh/a for 2009. This reduction is attributable to the energy efficiency measures within the building envelope. Two possible solutions were considered for supplying the neighborhood’s space heating energy needs: ground-source heat pumps and district heating CHP running on 80% natural gas and 20% green (bio) gas. Primary energy requirements for each solution were calculated using the expense numbers and primary energy factors of their heat generation according to German norm DIN 4701-10. The comparison of primary energy demands for each type of heating system for the whole neighborhood can be found in Table III.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Primary Energy Demand for Heating [GWh/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geothermal heat pump</td>
<td>1.86</td>
</tr>
<tr>
<td>District heating CHP</td>
<td>1.39</td>
</tr>
<tr>
<td>80% natural gas + 20% bio gas</td>
<td></td>
</tr>
</tbody>
</table>

The calculated primary energy demand for district heating CHP is lower than the actual heating energy demand of the neighborhood because bio gas is given a primary energy factor of zero in the DIN 4701-10 due to its renewable character. In addition to being the solution that requires the least amount of primary energy, district heating CHP was preferred over ground-source heat pumps because of potential adverse impacts on the LV network. Simulations show overloading of the feeding transformer and feeder cables, and voltage deviations more than the 10% limit set by the Dutch grid code. These issues are further discussed in detail in the simulations chapter.

IV. SIMULATIONS

1) Building Envelope

The building envelopes are designed and simulated with CASAnova software which uses a one-zone thermal model to perform heat flow analysis, depicted by Fig. 2. Four geometrically different types of energy-efficient buildings were simulated and compared to a “business-as-usual” scenario. The comparison is based on assumption that energy for “business-as-usual” buildings is supplied solely by fossil fuels and standard building materials were used.

2) LV Network

The selected topology of the LV network servicing the neighborhood is radial. This choice is based on the ease of operation and economic feasibility of this configuration compared to other morphologies. The radial network choice is also backed by the inherent high reliability of the grid components and the standby power provided by the communal battery storage systems. A simplified schematic of the system is depicted in Fig. 3. Note that, in reality, the lengths of the cables are not homogeneous and thus are not drawn to scale.

V. RESULTS AND ANALYSIS

A. Building performance

The passive and active redesign of the building envelope had a very positive impact on the energy demands of the space heating system. That is, the energy efficiency measures taken resulted in higher time lapses in which the indoor temperatures are at a comfortable level without the need for the heating or cooling systems to be running, as can be seen in Table IV.
### TABLE IV

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Heating hours [%]</th>
<th>Zero-energy hours [%]</th>
<th>Cooling hours [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>56</td>
<td>29</td>
<td>15</td>
</tr>
<tr>
<td>Proposed system</td>
<td>43</td>
<td>49</td>
<td>8</td>
</tr>
</tbody>
</table>

Apart from fostering a comfortable indoor environment for the inhabitants, the reduction in heating hours—and ergo, heater operation time—also translates into considerable energy savings, as depicted in Fig. 4. Thanks to a better selection of materials and more efficient terminal systems, the building losses kept low and the total primary energy demand for heating was reduced by almost half.

#### B. Network performance

##### a) Base case

The base case refers to the network performance with no DG or special loads connected. The voltage bands at every node are as shown in Fig. 5. The upper and lower boundaries for acceptable voltage levels according to the Dutch grid code are represented by dotted red and blue lines respectively. It is evident from the diagram that the voltage drops experienced in all nodes falls well within the ±10% range. The nodes most sensitive to voltage drop are R and S, as they have the longest cable connection and connect the largest number of loads. Figure 6 shows the branch currents, expressed as load percentage, of all cables and transformers.

While all branches are able to cope with the loads to which they are subjected, it is possible that, when connecting DG and special loads, transformer 3 and branches 18 and 19 might not be able to withstand the additional stress to the system.

##### b) Impact of PV

A worst-case scenario of maximum PV production and minimum load, occurring in the summer, will be used to evaluate the effects of PV production on the network. PV output was modeled in Gaia as a negative load divided symmetrically among the three phases of the conductors. The installed capacity per node is depicted in Fig. 7. The voltage levels at every node are graphed in Fig. 8. It can be observed that although there is considerable voltage rise in the nodes, the levels fall within the allowed limits. Branch loads for this scenario are as shown in Fig. 9.
Under these circumstances, the transformer and cable loads are again within the acceptable limits.

c) Electric vehicle adoption impact on the network

The electric vehicle (EV) fleet for the neighborhood is modeled in Gaia as a constant-current load on each of the end nodes. Two charging scenarios were used for the simulations and modeled as normal probability distribution functions:

- car owners will charge their vehicles upon their return from work; and
- they will charge them before going to sleep.

For the first scenario, it is posited that most people will arrive home from work at 18.00h and start charging at that time; for the second scenario, the charging will begin at 23.00h. The standard deviation in both cases is 30min. The magnitude of the loads in each node is set at 3.3 kW per vehicle, assuming a 40% adoption level among the households. For both scenarios, minimum PV production and maximum load are assumed. Figure 10 shows the voltage levels at every node.

The voltage drops significantly as a result of the additional stress of connecting the EVs, but the node voltages are still within acceptable limits. Additionally, it can be seen from Fig. 11 that the transformers and cables are very heavily loaded due to the fact that the EVs are charging during the peak period of electricity use in the household, adding to the peak load. Once more, transformer T3 and cables 18 and 19 are the weak points of the network, although the branch currents are still lower than their rated short-circuit currents, and could therefore be theoretically acceptable.

If the communal battery system in each branch is used to shift the peak created around 18.00h (~400kW during 4 hours) for four hours, it is possible to reduce cable loadings by approximately 5%. Using the battery banks is also beneficial in the sense that peak electricity prices are avoided in great measure; cost savings could be significant. The voltage bands at every node for the charging after work scenario are graphed in Fig. 12. Note that voltage drops fall within the allowance, and are significantly much less than in the previous case. Branch loads for this scenario are shown in Fig. 13.
Because the EVs started charging at the end of the peak period or the beginning of the off-peak period, the network branches are not as heavily loaded as in the previous scenario. This charging scheme is by far superior to the previous scenario, as it takes better care of the network components.

1) **PV, 40% electric vehicles and 100% heat pumps**

The objective of these simulations was to determine whether heat pumps could be implemented as the individual heating system for each house without exceeding the peak capacity of the network. A worst-case scenario of maximum electrical household loads with maximum heat pump operation to cope with the houses’ heating loads is used. Such a situation presents itself in the month of January, in which between 28-30% of the yearly heating demand is consumed. The heat pump loads were modeled at the end nodes of each cable, and their magnitudes are in proportion with the number and types of houses connected to each feeder and symmetrically distributed over the three phases of the conductors. The heat pump loads were added to the previous wintertime scenario of minimum PV production, maximum load, and 40% penetration level of EVs recharging at 11 p.m.

Because, ideally, the whole neighborhood should run on a single heating system to minimize costs related to infrastructure, a 100% penetration level of geothermal heat pumps was analyzed. The voltage bands at every node are given in Fig. 13. Nodes R and S, the weakest points in the network, experience a voltage drop of approximately 15%, a value that infringes upon the accepted voltage tolerances. Branch loads for this scenario are shown in Fig. 15. The combination of heat pumps and EVs causes an overload of the network in general:

- The transformers, if not overloaded (as is the case of T3), are operating at nearly full capacity, much to the detriment of the equipment’s lifetime.
- Cables 2, 3, 9, 16 and 18, which had not been the source of problems in the previous cases, are now approaching their loading limits.
- Cables 18 and 19 are overloaded by almost 50% more than normal.

Removing the EV fleet in order to accommodate for 100% penetration of heat pumps does not solve the network problems altogether. Even though the loads on the branches emanating from transformers T1 and T2 are now within operable limits, and the voltages on their end nodes fall also within the grid code tolerances, transformer T3 and its branches are still overloaded, and nodes R and S still experience under-voltages. Further studies reveal that a 20% adoption of heat pumps can be achieved and combined with EVs and PV systems without overloading the network. A higher penetration rate could be possible if the weakest points of the network are addressed, either by relocating the transformer stations for a more equitable load distribution (T3 is responsible for supplying over 40% of the neighborhood’s energy demand), or by adding a fourth transformer station.

However, since it is more practical to have a single collective heating system for the whole neighborhood in terms of infrastructure, it is a better option to discard the geothermal heat pumps altogether, and go with the option of bio gas-powered CHP with district heating, as it was the heating system with the greatest energy savings.
VI. FINAL SYSTEM DESIGN

Fig. 16 shows the schematic of the final design proposed for the municipality of Steenwijk erland. According to simulation results, the neighborhood’s thermal demands are fulfilled by the district heating CHP system, running on a mixture of natural and bio gas, and the solar water collector systems. PV electricity production covers the households’ electricity needs, while CHP electricity production is more than enough to offset EV demands. In this scenario, the electricity distribution grid is used as a buffer during times of low or zero production, and each branch is equipped with a battery storage system that enables load shifting of up to 400 kW during peak periods, and autonomous operation of four hours in case of unexpected interruptions of service. Excess electricity production are fed back into the grid for a slight profit, depending on the available government policies regarding feed-in tariffs or other pricing mechanisms and/or financial incentives. In the future, this excess production could even be traded across other DG networks, with all transactions centrally managed at an aggregate level by a virtual power plant (VPP) operator. Who owns, manages and operates this VPP is an extremely interesting question for further research; the answers will be without a doubt driven by new opportunities brought about by the transition to the Smart Grids concept, namely the changing role of the distribution system operator (DSO) and the increasing participation of the consumer within the framework of DER.

The proposed distribution network design is suitable for a high adoption level of PV and EVs. It is necessary, however, to devise an energy management strategy —most likely with the aid of a smart energy management control system— for load/production peak-shaving during times of maximum PV production and minimum load, and the charging times of EVs during on-peak winter periods.

For the network to accommodate heat pumps without exceeding its capacities, additional feeder branches and an extra transformer need to be installed for a more equitable division of the loads.

Table IV shows the global energy balance of the neighborhood in Steenwijkerland, in which it can be seen that it can be a positive energy neighborhood in terms of electricity production and usage in a period of one year. This positive balance could be used to offset almost half of the primary energy demand for heating being supplied by natural gas. In this case, only 20% percent of the total energy demand of the neighborhood is not covered by RES.

Table IV

<table>
<thead>
<tr>
<th>Application</th>
<th>Yearly energy demand/production [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total heating demand</td>
<td>-2.87</td>
</tr>
<tr>
<td>Total electricity demand</td>
<td>-2.39</td>
</tr>
<tr>
<td>Solar thermal DHW</td>
<td>0.63</td>
</tr>
<tr>
<td>CHP production, bio gas</td>
<td>0.33</td>
</tr>
<tr>
<td>CHP production, electricity</td>
<td>1.32</td>
</tr>
<tr>
<td>PV production</td>
<td>1.89</td>
</tr>
<tr>
<td>Total balance</td>
<td>-1.09</td>
</tr>
</tbody>
</table>

VII. CONCLUSIONS

The proposed solution for Steenwijkerland neighborhood reduces the primary energy demand for heating by almost 50% without sacrificing occupant comfort. These energy savings are attributable, in a great measure, to passive solar design and upgraded building materials, which help stabilize indoor climate regardless of the weather conditions. In this scenario, approximately one third of the total primary energy for heating comes from renewable energy sources. Electricity-wise, the neighborhood is energy positive, as it produces more than what is needed to power the households and EV fleet. At a global level, the energy balance of the neighborhood is near zero energy: 80% of the primary energy needs are met by renewable energy sources.

In summary this paper shows that:

a. Zero energy concepts are useful for the built-environment.
b. Designing energy neutral neighborhoods harvest the collective benefits of individual buildings.
c. Passive designs are necessary pre-requisite to reduce the energy demands of buildings.
d. The case of Steenwijkerland demonstrates that with passive solutions and good choice of DER, zero-energy neighborhoods can be realized.
VIII. REFERENCES


IX. BIOGRAPHIES

**Rosa Maria Morales González** (S’2012) received her BSc in Mechatronics Engineering from the Universidad Panamericana in Mexico City and her MSc in Sustainable Energy Technology from Eindhoven University of Technology in The Netherlands. Currently, she is a PDEng researcher at the Energy Systems Group of the Faculty of Electrical Engineering in Eindhoven University of Technology. Her research is focused on developing smart energy buildings and cities.

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He is a PhD researcher at the Energy Systems Group of the Faculty of Electrical Engineering in Eindhoven University of Technology. His research is focused on energy management solutions for the built environment.

**Sjef Cobben** was born in Nuth, The Netherlands, in 1956. In 2002 he received the Masters degree in Electrical Engineering from Eindhoven University of Technology. From 2003 to 2007 he worked part time on a PhD project about “intelligent grids”, specializing in Power Quality. Sjef Cobben is in Alliander, grid operator in the Netherlands, research scientist and specialized in safety of the LV- and MV-networks, Power Quality and safety of installations connected to the networks. He is member of several national and international standardization committees about requirements for low and high voltage installations and characteristics of the supply voltage. He is author of several books about low voltage installations and Power Quality. He is part-time professor at Eindhoven University of Technology, with research area Intelligent grids, Power Quality.

**Wil L. Kling** (M’95) was born in Heesch, The Netherlands in 1950. He received the M.Sc. degree in electrical engineering from the Eindhoven University of Technology, The Netherlands, in 1978. From 1978 to 1983 he worked with Kema and from 1983 to 1998 with Sep. Since then up till the end of 2008 he was with TenneT, the Dutch Transmission System Operator, as senior engineer for network planning and network strategy. Since 1993 he was a part-time Professor at the Delft University of Technology and since 2000 also a part-time Professor in the Electric Power Systems Group at the Eindhoven University of Technology. He is a PhD researcher at the Energy Systems Group of the Faculty of Electrical Engineering in Eindhoven University of Technology. His research is focused on energy management solutions for the built environment, integration of wind power, network concepts and reliability.

Mr. Kling is involved in scientific organizations such as Cigre and IEEE. He is the Dutch Representative in the Cigre Study Committee C6 Distribution Systems and Dispersed Generation.

**Gerrit Scharrenberg** was born in Deventer, The Netherlands, in 1965. He received the Bachelors degree in Electrical Engineering from the Technical University of Groningen in 2005. In 2007 he received the Masters degree in Energy Systems at the Delft University of Technology. In 1984 he started his career in the energy distribution. From 1984 to 2004 he worked for different energy distribution companies in Holland. At this moment he is working for NV RENDO one of the eight grid operators in Holland, where he is engaged as Asset Manager Elektra.