OPTIMAL PLANNING TOOL FOR NEARLY ZERO ENERGY DISTRICT

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ABSTRACT

This approach has the potential to increase energy efficiency, renewable and local resource application. This research work describes the development of optimal planning tool with on-site energy management model and the analysis of case study existing campus building stocks. This research focuses on the boundary of the building, thereby not being limited to only a single building but spanning over a cluster of buildings, so called "Zero Energy District". Using the developed methodology, the optimal CHP capacity for each building, optimal capacity distribution in the boundary for minimizing annual primary energy consumption was simulated. The series of results in case study show that the on-site energy generation has potential to reduce primary energy consumption and it is more effective by integrating buildings. Moreover, the proposed model makes it possible to utilize the measured database of existing building stocks for planning energy efficiency improvement in the campus.

INTRODUCTION

Zero Energy District

In the energy used for heating, the energy efficiency of buildings is a key factor. The European Energy Performance of Buildings Directive (EPBD) requires all new buildings to be nearly zero energy buildings (nZEB) by 31.12.2020, in the context of energy challenges in Europe (EPBD 2010/31, EPBD 2012/27), and two years prior to that for public buildings. The Finnish ZEB project "FinZEB" aims to meet the EPBD requirement. An nZEB is a building that has a very high-energy performance and is cost effective. However, achieving the energy balance status in ZEB without the support of the electrical and thermal grids will be quite difficult. The research work, thus, focuses on the boundary of the building, thereby not being limited to only a single building but spanning over a cluster of buildings; a so-called "Nearby Energy District". The key motivation of ZEB is to utilize distributed energy resources as well as energy-efficient systems. To further increase energy efficiency, approaches that are not only limited to a single building but also consider groups of buildings might enable reaching of an almost zero energy situation in a zero energy district. This approach has the potential to increase energy efficiency, renewable and local resource application and promote energy resilience and security. The Distributed Energy Systems (DESY) project, which was a R&D program for local energy systems in Finland, defined local district energy as "sustainable hybrid energy production using local renewable energy sources". DESY also took into account that energy production in several countries is nowadays too dependent on external factors. B.J.A. Walker explored whether the provision of community benefit was associated with increased local support for a hypothetical, future offshore wind farm in Exmouth, UK, using an experimental methodology (B.J.A. Walker *et al*, 2014).

The previous studies by the authors (G. Kayo *et al*, 2014) clarified that energy sharing has the potential to reduce primary energy consumption when considering building combinations and CHP operations. However, the CHP capacity of each building in the boundary was fixed in the study. Thus, the case study in this research work developed the methodology, which makes possible to find CHP capacity distribution within the boundary, to examine building cases that connect to a district heating network and to analyse the impact of on-site energy distribution and integration by simulating various possible combinations of CHP capacities in the boundary.

Objectives

This study was carried out to find the potential of on-site energy management in a cluster of existing campus building stock. The following three research questions were set: 1) How much benefit of primary energy reduction is expected by on-site energy generation with CHP? 2) How the on-site generation capacity should be distributed and integrated among buildings? and 3) Which is better for primary energy reduction: buildings with on-site generation integrated or separated? This research work describes the methodology development of an on-site energy distribution model by combining with the optimisation method (Multi-Objective Building Performance Optimization Software, MOBO). The developed methodology was proposed as energy planning tool for studying nearly zero energy district by utilizing available big database in terms of energy use. Moreover, the research work carries out the methodology application on a case study in Finland. In the case study, this research work focuses on energy in campuses, especially energy-management possibilities at the building and district levels.

SIMULATION

Description of Cases

In order to investigate the impact of on-site energy generation and sharing, three cases were prepared. Case 1 is the base case, which is the measured result in 2012. Case 2 is the separated case, which means that on-site energy management was at every building individually. Case 3 is the shared case for on-site energy management with energy sharing (both electricity and heat) among buildings if some energy deficits and surpluses occur (Figure 1). Case 1 as a "base case" means the current situation, in which the buildings don't have any on-site generation technology such as CHP, so that all electricity demand is covered by the grid supply and all heat demand is covered by the district heating network. In Case 2, the building is able to have on-site CHP and generate both electricity and heat. Surplus electricity can be sold to the grid but surplus heat is accessed to the air. Deficit electricity is covered by the grid and deficit heat is covered by the district heating network. In Case 3, energy deficits are also covered by the grid and district heating network, but if surplus energy is available from neighbouring buildings, surplus energies transfer first in order to cover the deficit situation.

On-site Energy Distribution Model

In order to study the energy balance among buildings in a cluster, on-site energy distribution model was developed (Figure 2). The model consists of two part, data input part by user (energy demand profiles, primary energy factors, and technology performance information) and energy balance calculation part written by R language. Energy balance is calculated hourly and summed up total as monthly and annually. Energy demand types are distinguished as electricity (E_{dem}) and heat (H_{dem}). CHP in every building supplies electricity (E_{chp}) and heat (H_{chp}) for the demand of the building first based on operation modes. Energy production by CHP (E_{chp} and H_{chp}) are describe as following equations,

$$E_{chp} = P_{chp.e} \cdot PL \cdot \eta^{e} \quad PL \in [0, 1] \quad \text{(Eq.1)}$$

$$H_{chp} = P_{chp.h} \cdot PL \cdot \eta^{h} \quad PL \in [0, 1] \quad \text{(Eq.2)}$$

where $P_{chp.e}$ is the constant power of CHP, PL is the partial load, and (η^{e} =0.336) is the efficiency of electricity generation and (η^{h} =0.507) is that of heat generation. The efficiency is based on the manufacturer's catalogue value (IBEC, 2001). After calculating CHP generation, energy balance of each building is calculated, such as production (E_{prod}, H_{prod}), self-consumption (E_{self}, H_{self}), surplus (E_{sur}, H_{sur}) and deficit (E_{def}, H_{def}). In Cases 1 and 2, deficit of energy are covered by imported electricity from the grid (E_{import}) and imported heat from district heating network (H_{import}). In Case 3, if some bulging has surplus energy generation ($E_{surplus}$, $H_{surplus}$) and also other building had deficit situation, energy transfer from suplus side to deficit side is allowed. After considering energy share, the deificit energy is covered by imported energy.

In terms of primary energy factors, the following values are used (Table 1). Renewable energy in this study was simply assumed to be biomass-based energy, such as biofuels. In this study, the effect of selling the surplus electricity to the grid was not taken into account in the calculations of the net primary energy according to the the current Finnish Building Code. Also, the surplus heat from CHP, which doesn't meet the requirement from other buildings at the moment, was wasted. The storage effect and energy losses by distribution are not considered in this study.

Table 1: Primary energy factors (FIN3 building code D3, 2012)

	kWh/kWh
Electricity from the grid	1.7
Heat from district heating	0.7
Renewable fuels used in the building	0.5

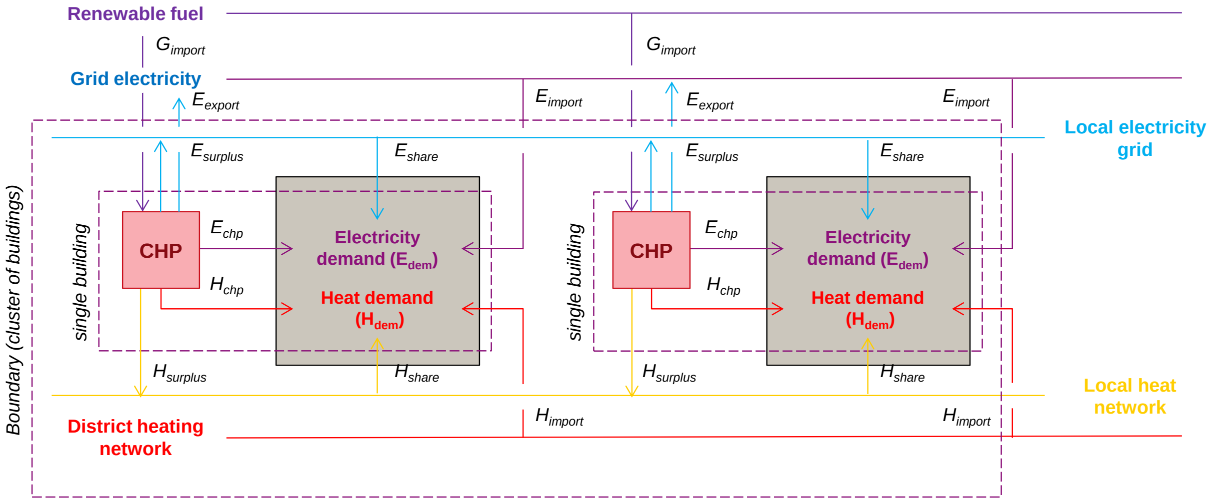

Figure 1: Energy flow in Case 3 (Energy transfer from surplus side to deficit side is allowed.)

Optimisation

It is clear that the optimisation methodology, especially Genetic Algorithms are feasible for energy engineering or building engineering since there are plenty number of practical use (A. Nguyen *et al*, 2014). In order to find the optimal CHP capacity distribution and integration patterns among the four buildings, the optimisation method used the Multi-Objective Building Performance Optimization Software (MOBO). MOBO is generic free software developed by one of the co-authors, A. Hasan, and his research group (M. Palonen, 2013). MOBO has been globally recognized as "the major optimization engine in the coming years" as indicated by Nguyen *et al*. It is able to handle single- and multi-objective optimisation problems with continuous and discrete variables and constraint functions. It is also able to handle multi-modal functions and have automatic constraint handling. The user can write the input by algebraic formulas using standard symbols. Figure 2 shows the coupling with the on-site energy distribution model and MOBO as optimiser. The user prepares the energy demand dataset and sets the primary energy factor, performance information of energy systems and cost information. MOBO creates the input file with system capacity combinations, and the on-site energy distribution model loads it and starts calculation. The parameters of Optimisation are 50 for population and 100 for generation, resulting in 5000 iterations. The objective of the optimisation is to minimize the annual total primary energy consumption (in kWh) of all four buildings (*TPEC*, Eq.3). Design variables are the CHP capacity (in kWe) for each building; the design variables are prepared from 21 discrete values (0, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950 and 1000) (Eq.4). When the value for the design variable is 0, it means the building has no CHP; then all energy demands are covered by the grid electricity and district heating network in Case 2. In Case 3, transferring surplus energy from neighbouring buildings that have their own CHPs is possible.

$$Min \sum_{i=1}^{N} TPEC^{i} \quad \text{(Eq.3)}$$

$$s.t.\ P_{chp.e}^{i} \in [0, 50, 100, \dots, 1000] \quad \text{(Eq.4)}$$

Where *i* is the building number, and *N* is the total number of campus buildings, in this study *N*=4.

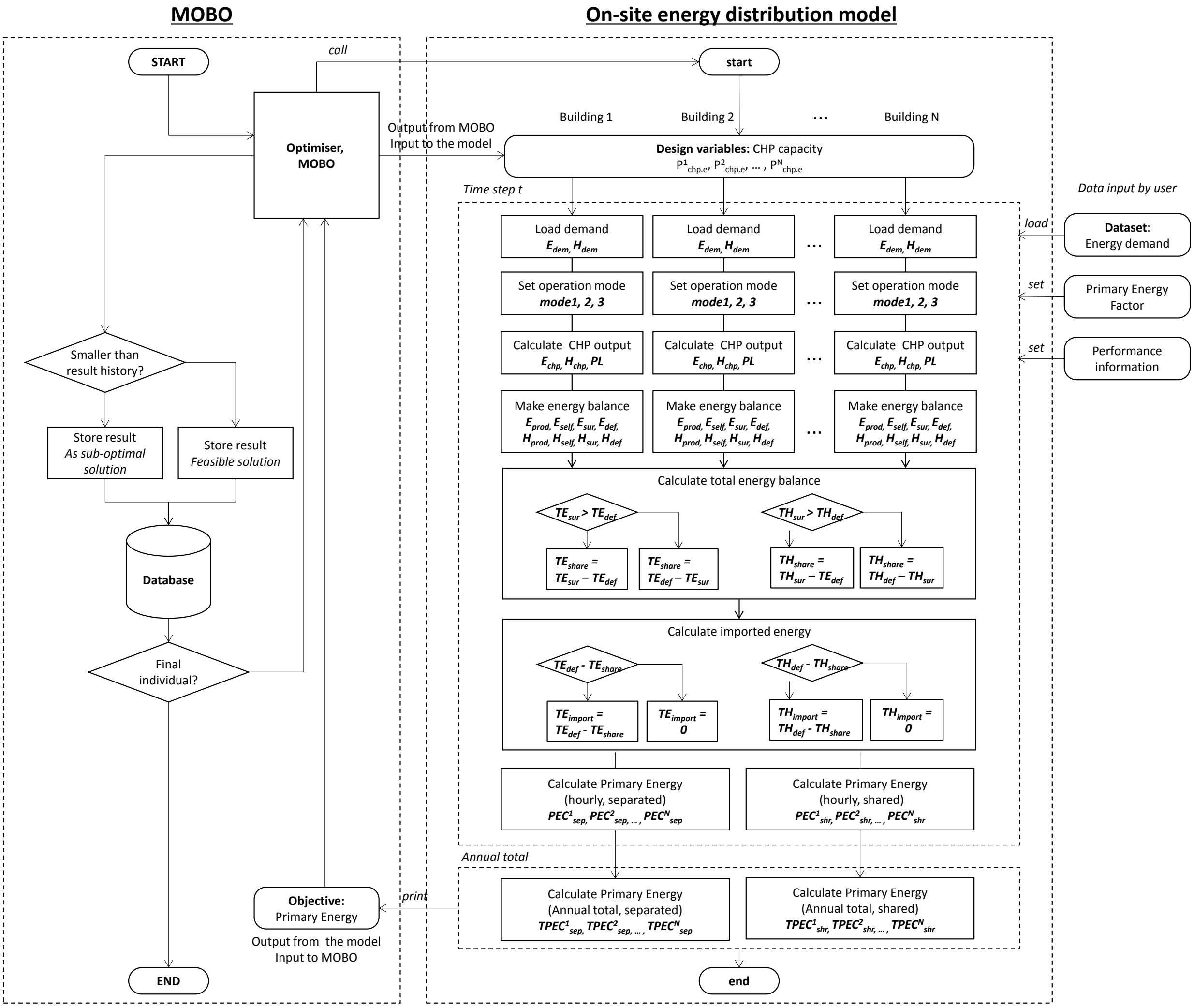

Figure 2: Coupling of MOBO and On-site Distribution Model

CASE STUDY

Campus Building Management

Nowadays, universities, especially through the campus activities, take a role in developing and demonstrating various pilot projects towards sustainable development. Sustainable campus development is connected to both academic and educational activities. To share the knowledge and experience, and carry out physical activities towards these achievements, some platform is created. For example, The International Sustainable Campus Network (ISCN) created a global consortium to enhance communication among universities from around the world, for achieving sustainable campus operations and integrating sustainability in research and teaching. Improving energy efficiency of existing building stocks in campus area is one of the essential factors when a university tries to promote sustainable campus development. Therefore, this study focuses on energy in campuses, especially energy-management possibilities at the building and district levels. Moreover, the Green Guide for Universities, which is published by International Alliance of Research Universities (IARU), clearly says that energy consumption of campus buildings can be the main target for campus sustainability and establishing energy measures by installing effective metering technology is key to identify infrastructure and effective operation strategy to improve energy efficiency of campus buildings. The series of these researches suggest that new energy planning methodologies for existing campus building stocks are highly demanded.

Building

Considering the possibility of integration with the local energy grid, four campus buildings (K1, K2, K3 and K4) in the same block were selected for case study (Table 2). Both electricity and heat in the campus are supplied by a private energy company through commercial grid and district heating networks. The existing buildings in the campus were mainly built in the 1960s, and therefore it is time to perform renovation work (T. Sekki *et al*, 2015). In connection with renovations, the aim is to improve the energy efficiency of the buildings and to develop the functionality of the properties to meet the current requirements.

Table 2: Specifications of the buildings (openenergy.fi)

	K1	K2	K3	K4
Year (completion)	1966	1965	1968	1967
Total area [m^2]	8 616	3 235	7 229	9 165
Energy sources	District heating			
Facility functions	Teaching, research and office			
Energy class	D	G	F	E
Electricity [MWh/a]	764.2	383.8	945.7	643.3
Heat [MWh/a]	817	862	1,581	1,760

Energy Demand Profile

The basic utility consumption (electricity from the grid, heat supply from district heating system and water) for every building in the campus was measured. These data are summarized in the database (www.enerkey.com), so that a property manager can browse the current energy consumption and past records. This study used the energy data, which were the measured results in 2012 (Figures 3).

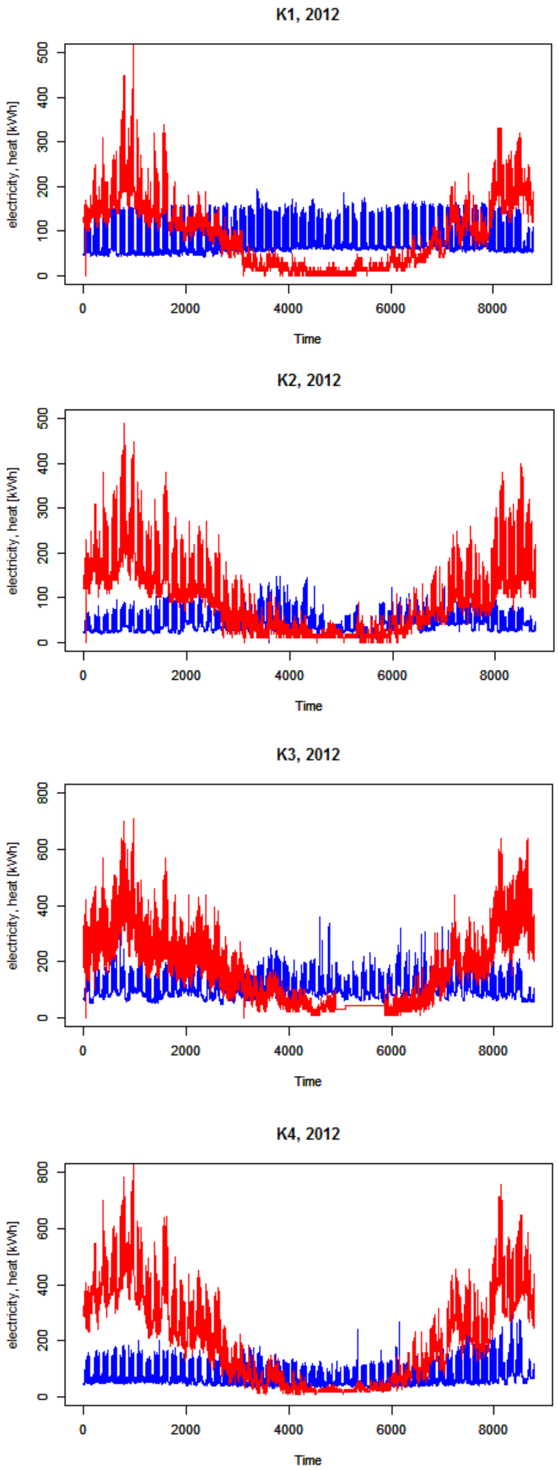

Figure 3. Electricity demand (blue) and Heat demand (red)

According to the difference in the use of space for each building, the demand profiles are different. During the summer season, from the end of June to the beginning of September, the activity in the campus buildings is almost nothing. However, there is some basic energy use in summer, especially use of electricity. Generally, it is important how the property manager utilizes measured energy data for implementing further energy efficiency improvements. Thus, another motivation of this study is to develop an energy analysis model that can support decision-making in energy planning or renovation phases with a limited energy dataset. In this study, neither additional measurements nor investigations were done.

RESULT AND DISCUSSION

Primary Energy Consumption

Table 3 shows the results of the optimisations. The optimisation result for the separated case (*op.sep*) shows that the primary energy consumption is 77% of the base case (*base*) by distributing on-site CHPs in every building. Moreover, by sharing energy within the four buildings, the primary energy is 65% of the base case. This means that the balances of surplus and deficit of electricity and heat are managed, and reduce the reliance on the energy infrastructure of the grid. Thus, the on-site energy management has positive potential to reduce primary energy consumption within the boundary.

Table 3. Results of optimal CHP combinations and annual primary energy consumption

	CHP capacity [kWe]				Primary Energy [GWh]	
	K1	K2	K3	K4	separated	shared
base	---	---	---	---	246.9	
op.sep	100	50	100	100	189.8	160.3
op.shr	0	500	0	0	299.9	125.3

The result of sharing optimisation (*op.shr*) is 500 kWe CHP at building K2, so that the primary energy can be reduced 49% by sharing. However, the same solutions for separated case, does not have any positive advantage in reducing primary energy consumption. The local energy management without transferring surplus electricity and heat generated by CHP is not effective. The primary energy consumption increases 21% compared to the base case. It means that both CHP capacity distribution and integration are strongly related each other in on-site energy management. The results suggest that on-site energy generation has potential, and it is made more effective by sharing energy. Therefore, sharing can be one of the possible key issues when on-site energy systems are planned.

Advantage of Energy Sharing

Figure 4 shows the resulting distribution of the history of the candidate solutions during the optimisation process. The X-axis indicates the expected reduction ratio for the separated case (Case 2) compared with the base case, and the Y-axis is that of the shared case (Case 3). The value 1.0 indicates the primary energy of the base case. Candidates solutions are located in the first and fourth quadrants (I, IV) more than in the second and third quadrants (II, III). This means that on-site energy generation does not always have positive advantages in terms of reducing primary energy consumption. The distribution layout shows that the best solution for the sharing optimisation case (*op.shr*) is located in the fourth quadrant (IV). The on-site energy generation has the advantage by integrating buildings and sharing energy, but acquires a disadvantage by separating buildings and not sharing. Some solutions are located in the first quadrant (I), which means all on-site energy generation of these candidates cannot be expected. Since most of the solutions are located in the third and fourth quadrants (III, IV), energy sharing is effective for on-site energy systems.

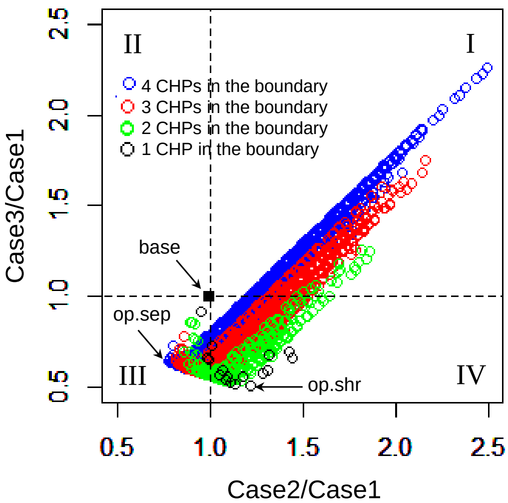

Figure 4. Distributions of the candidate solutions, primary energy reduction in Case2 and Case3 compared with the base case (Case 1)

Capacity Distribution

Figure 4 also shows the influence of capacity distribution and primary energy reduction. The black circles indicate the results of one CHP in the boundary, green circles show those of two CHPs, red circles show those of three CHPs, and blue circles indicate those of four CHPs, which means each building has its own CHP. The candidate layout in the third quadrant (III) shows that a larger number of CHPs results in the smaller primary energy consumption in separated cases (Case 2). On the other hand, the information in the fourth quadrant (IV) shows that the smaller number of CHPs results in the smaller primary energy consumption in shared cases (Case 3). Capacity distribution is one of the influential factors for primary energy consumption by on-site energy generation and integration. Moreover, in Case 2, if the number of CHPs is less than the number of buildings, it means that some buildings are supplied energy from the grid and district heating network. Thus, in the case of a single-building boundary, on-site generation has the potential to reduce primary energy consumption. This is because the primary energy factor of CHP operation is less than the grid electricity and district heating network.

Iteration Process

Figure 5 shows the record of the optimal solution search in *op.shr*. The black circle plots are sub-optimal solutions through the optimisation process, the white circle plot is the final optimal solution and cross plots are the results of minimum solutions in each generation. The calculation detected the sub-optimal solutions effectively in the first 10 generations, and the final optimal solution was detected after 3500 calculations, which is in the 70th generation. Since various possibilities were calculated in every generation, the settings of MOBO are eligible and the calculation results are therefore validated.

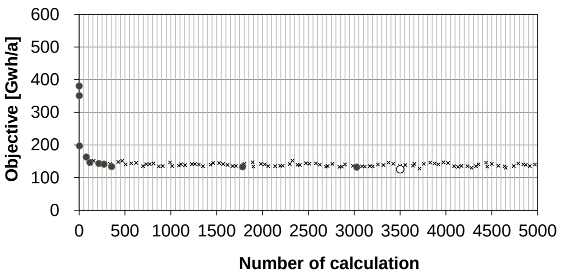

Figure 5. The record of the optimal solution search in op.shr

Verification of the Optimisation Results

To check the validity of the optimisation result, the calculations were carried out using the method of Brute Force Search. As there are four sets of design variables with 21 discrete values, the total calculation number reached 194,481 (=214). Figure 6 shows the resulting distributions of the Brute Force Search andthe optimisation. Comparing the results by the optimisation, the same optimal solutions for *op.sep* and *op.shr* are detected, as all results by the optimisation are. Thus, the results by the optimisation are reliable and the optimal solution can be detected effectively with 2.5% of the calculation numbers (=5,000/194,481). The accuracy of the optimisation results is checked by the Brute Force Search. Since one of the objectives of this research is to develop optimal planning tools for distributed energy systems by integrating on-site energy technology, the Brute Force Search can be used to check the optimization solution. In the next following studies, the number of variables will be increased by including on-site renewable energy technologies (e.g., geothermal heat pumps, photovoltaic panels or solar collectors, etc.), energy demands reduction by building renovations, consideration of distribution losses, and storage effects. Brute Force Search will consume an enormous amount of time because the problem will be very complicated. Therefore, the methodologies of multi-objective optimisation, such as genetic algorithms will be used to planning tool development.

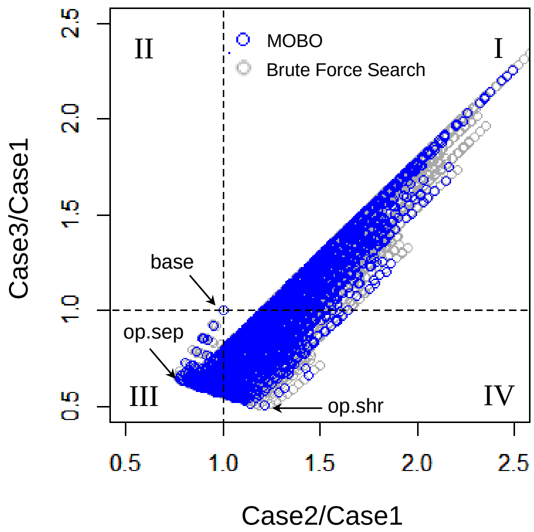

Figure 6. Result distributions (dark blue; MOBO, light grey: Brute Force Search)

CONCLUSION

This research work focuses on the boundary of the building, thereby not being limited to only a single building but spanning over a cluster of buildings, so called "Zero Energy District", and the potentials of on-site energy generation and sharing in a cluster of campus building in Finland were studied as one of the possible actions. Using an on-site energy distribution model and optimisation method, the optimal CHP capacity for each building, optimal capacity distribution within the boundary and operation mode for minimizing annual primary energy consumption were simulated. The main findings are as follows:

1. The optimisation result for the separated case (*op.sep*) shows that primary energy consumption is 77% of the base case (*base*) by distributing on-site CHPs in every building. Moreover, by sharing energy within four buildings, the primary energy is 65% of the base case. This result shows that on-site energy generation has potential and more effective impact by sharing energy is expected. Therefore, the sharing possibility can be one of the key options toward reducing primary energy consumption when on-site energy systems are planned.
2. Capacity distribution is one of the influential factors for primary energy consumption by on-

site energy generation and integration. Optimisation results also show that on-site energy generation does not always have a positive advantage in terms of primary energy consumption. In the case of a single-building boundary, on-site generation has the potential to reduce primary energy consumption. This is because the primary energy factor of the renewable fule used in the CHP operation is less than that of the grid electricity and district heating network. Thus, the distribution of the CHP capacities is one of the key factors for energy efficiency within the community.

3. One of the objectives of this study is to develop optimal planning tools for distributed energy systems by integrating on-site energy technology. The study in this research work clarified that optimal CHP capacity distribution and operation can be simulated if energy demand profiles are available. Thus, this tool can be used for sustainable campus planning or distributed energy systems to improve energy efficiency of existing building stocks. After checking the accuracy of the results from the model, a more complicated case study will be simulated during the subsequent steps. For example, involving on-site renewable energy technologies (e.g., geothermal heat pumps, photovoltaic panels or solar collectors, etc.), energy demands reduction by building renovations, consideration of distribution losses, and storage effects. Furthermore, the efficiency of the district heating networks is one of the related factors for total energy efficiency. The influence and benefit of on-site energy systems for the district heating network will be a part of the upcoming research questions. Also, the impact of energy export, in case surplus energy is produced, should be studied. Moreover, the multi-objective optimisation with respect to primary energy, life-cycle cost, or environmental impact should be considered in the future research.

NAMENCLATURE

base	Current energy system in the campus
CHP	Combined heat and power generator
E_{chp}	Electricity production by CHP (hourly) [kWh]
E_{def}	Amount of electricity deficit (hourly) [kWh]
E_{dem}	Total electricity demand (hourly) [kWh]
E_{import}	Electricity import from the grid (hourly) [kWh]
E_{self}	Amount of electricity directly consumed where the CHP is located (hourly) [kWh]
E_{share}	Shared electricity among buildings (hourly) [kWh]
E_{sur}	Amount of electricity surplus (hourly) [kWh]
G_{import}	Renewable fuel import (hourly) [kWh]
H_{chp}	Heat production by CHP (hourly) [kWh]
H_{def}	Amount of heat deficit (hourly) [kWh]
H_{dem}	Total heat demand (hourly) [kWh]
H_{import}	Heat import from district heating network (hourly) [kWh]
H_{self}	Amount of heat directly consumed where the CHP is located (hourly) [kWh]
H_{share}	Shared heat among buildings (hourly) [kWh]
H_{sur}	Amount of heat surplus (hourly) [kWh]
i	building number [-]
MOBO	Multi-Objective Building Performance Optimization Software
N	Total number of buildings [-]
op.sep	Optimal solution with the on-site CHPs separated
op.shr	Optimal solution with the on-site CHPs integrated and shared
TE_{def}	Total deficit electricity [GWh]
TE_{excess}	Total excessed electricity [GWh]
TE_{import}	Total electricity import from the grid [GWh]
TE_{shr}	Total shared electricity among buildings [GWh]
TE_{sur}	Total surplus electricity [GWh]
TH_{def}	Total deficit heat [GWh]
TH_{excess}	Total excess heat [GWh]
TH_{import}	Total heat import from district heating network (hourly) [kWh]
TH_{shr}	Total shared heat among buildings [GWh]
TH_{sur}	Total surplus heat [GWh]
TPEC.sep	Annual primary energy consumption in the boundary in separated case (annual) [GWh]
TPEC.shr	Annual primary energy consumption in the boundary in shared case (annual) [GWh]
TPE_{prod}	Total primary energy production in the boundary [GWh]
PL	Partial load of CHP [-]
PEC.sep	Primary energy consumption of the building in separated case (hourly) [GWh]
PEC.shr	Primary energy consumption of the building in shared case (hourly) [GWh]

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