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Discrete event simulation of distributed energy supply systems

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Abstract. The paper presents a Discrete Event Simulation (DES) model to analyse the Distributed Energy Supply Systems (DESS) in order to increase the overall system efficiency. DES is used for assessing the energy demand at each participating source and overall energy demand for the entire system. The energy-flow through the network of energy suppliers, consumers, heating and cooling storage facilities, and power transmission lines is considered as a flow of goods known from the material logistics. In the DES model different tariffs of purchasing and selling the energy in case of energy deficit or surplus are applied. The model considers different tariffs for the different time-frames during a particular day. To increase the DESS cost efficiency, the energy distribution is adapted to the energy demand, demand-meeting and cost depending on time-frames. The model is calibrated based on historical data and gives promising results for identifying the optimal time-frame for the various components operating in the energy supply network.

Keywords: Co-generation, Discrete event simulation, Distributed energy supply system

Simulacija diskretnih dogodkov sistemov razpršene oskrbe z energijo

V članku predstavljamo analizo sistemov razpršene oskrbe z energijo s pristopom simulacije diskretnih dogodkov. Simulacijo uporabimo za oceno energetskih obremenitev vsakega vira in skupne potrebe celotnega sistema. Na energetske tokove skozi omrežje virov, potrošnikov, hladilnih in ogrevalnih sistemov ter električnega omrežja gledamo iz vidika logistične oskrbe. Simulacijski model upošteva različne nabavne in prodajne tarife, ki pridejo v poštev tako pri presežkih kot tudi pri energetskih primanjkljajih. Analiziran model upošteva različne tarife v časovnih okvirih tekom dneva. Za izboljšanje stroškovne učinkovitosti energetskega sistema se porazdelitve obremenitev prilagodijo potrebam, stroškom in porabam posameznih virov glede na časovne okvirje. Simulacijski model smo kalibrirali na podlagi dolgotrajnih meritev, kar s čimer je omogočena identifikacija optimalnih časovnih okvirjev za upravljanje gradnikov omrežja energetske oskrbe.

1 INTRODUCTION

Distributed generation can play an important role for future energy systems. It can provide economically effective reduction of the greenhouse gas emissions of an energy supply and possible diversification of the primary energy sources where alternative fuels, such as natural gas or even solar and wind energy, are utilised [1]. Co-generation of electricity, heat and cooling power represents an established option for development of highly efficient and cost-effective integrated energy systems [2]. The multi-energy customer demand-meeting also promotes the multi-energy systems integration for energy supply and utilisation of renewable energy hybrid systems by the distributed energy sources [3]. One of the critical factors that affect the energy saving, economic and environmental performance of such a combined cooling, heating and power systems (CCHP) are operation strategies [4]. The operation strategies tend to reach a twofold objective: minimizing the total operational cost and finding the optimal size of a CCHP system. So, a rational method for determining the size and operation strategy of CCHP system has to be developed [5] in the near future.

Since the typical co-generation users are commercial malls, hospitals, office buildings and other public facilities, it is not always possible to use same tools for optimizing energy utilizations as at the production facilities. Usually raw data from production planning and control systems can be used to perform the energy load prediction in production facilities. In those cases, the historical data of the energy demand-meeting are the only source of data. The paper presents a DES model for analysing the energy workload requirements for a particular time of the day and a particular exterior temperature.

2 LITERATURE REVIEW

In the recent years, distributed generation of electricity, heat and cooling power has become an interesting topic

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for researchers. Mathematical programming as such has been the most widely applied tool in energy planning applications. Mavrotas et al. introduce an energy planning framework combining Mathematical Programming and Monte Carlo Simulation. It can be applied in buildings of the Services Sector like hospitals, hotels, sport centres, universities and elsewhere where the uncertainty in the cost parameters is expressed by probability distributions [6]. Simulations are widely employed to provide a means for optimization for the distributed energy resource management [7]. Wu et al. [8] present an approach to simulate the CHP operations and to verify simulation results through an experiment, while Farmani et al. [9] propose a conceptual CCHP simulation model. An optimized schedule for generators and other resources is investigated by Hawkes et.al [1]. They use a deterministic linear formulation of the problem and system design. A linear programming cost-minimization problem for the system design and corresponding unit commitment of generators and storage within a micro-grid is introduced. A two-stage decomposition-based solution strategy to solve the optimisation problem using a genetic algorithm performing the search in the first stage and a Monte Carlo simulation dealing with uncertainty in the second stage are introduced by Zhou and co-authors [10]. They claim that an optimal design under the uncertainty does not deviate from the deterministic one. The preferred deterministic model is due to its computational efficiency. On the other hand, a comprehensive input-output matrix approach for modelling of co-generation equipment, which takes into account the interactions between the plant components and external energy network, was presented by Chicco et al. [2]. The results obtained from a numerical example show the modelling effectiveness of the proposed formulation. The study performed by Li et al. [4] analyses five different operational strategies such as: following the electric load, the thermal load, a hybrid electric–thermal load, the seasonal operation strategy, and the electric–thermal load. The authors claim that the redundant energy is not the best criterion to evaluate the CCHP systems under the current configuration. Understanding the different energy demands during the day is analysed in [11] where the authors observe short-term and long-term loads of an airport CCHP and use linear optimisation to reduce the operation cost, with the demand-meeting monitored on an hourly basis and the data used for the demand-meeting forecasting. Among the other simulation techniques Kohl et al. [12] present a DES approach for a production-based energy demand-meeting.

3 METHODOLOGY

The aim of our paper is to build a hybrid DESS model capable of predicting and showing the energy load of each component of the given DESS for any selected time window throughout the year, depending on the external temperature. The proposed hybrid model consists of a discrete event simulation (DES) model of the DESS system which models the system functioning and a statistical regression to calculate the dependence of the energy demand on the external temperature.

3.1 *DES model*

When dealing with the energy load prediction in production facilities, the data used in production planning and control systems are employed. But in facilities like hospitals, schools and other public facilities, such data are not available. In those cases, historical energy demand-meeting data are the only source available. In our investigation this problem is addressed using a DES methodology. We propose an approach where the energy is presented by logistic packages, with every package presenting a unit of energy. The simulation data input presents the DESS-produced and consumed packages. Discrete events present any changes in the energy production output and demand-meeting at different time-frames.

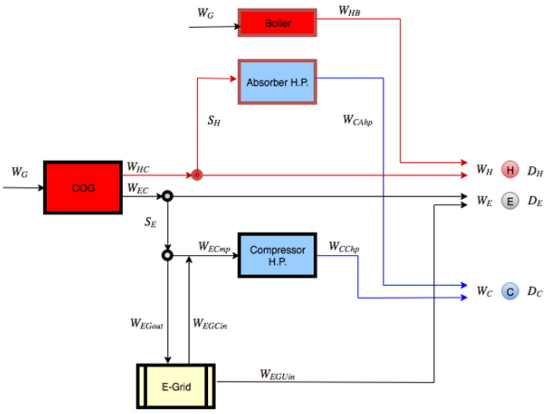

Figure 1. DESS configuration

In the DES model (Figure 1) the inputs present the CHHP heat and electricity production and energy demand for heating, cooling, and electricity. The grid electricity supply or heating using the a gas-fired boiler is determined depending on the deficit or surplus of the CCHP energy production based on demand-meeting. While the system energy demand requires constant heating for technological services, the cooling demand-meeting mainly depends on the external temperature.

Heating demand (D_H) presents a combined demand for hot water for heating purposes and technological services. A high-efficiency gas-fired boiler (W_HB) is used only when the CHP heating, (W_HC) does not meet the heating demands, with the CHP running at a constant load to meet the electricity demand. Heating surplus (S_H) is used for cooling purposes. The consumed heating energy (W_H) is then:

$$W_H = \begin{cases} W_{HC} - S_H; & W_{HC} \geq D_H \\ W_{HC} + W_{HB}; & W_{HC} < D_H \end{cases} \quad (1)$$

It is obvious that when $W_{HC} \geq D_H$, $W_{HB} = 0$ and $S_H = D_H - W_{HC}$. But when $W_{HC} < D_H$, $W_{HB} = D_H - W_{HC}$ and $S_H = 0$.

The cooling demands (D_C) can be met by either the absorption heat pump (W_{CAhp}) or from additional cooling energy from the compression heat pump (W_{CChp}). The cooling surplus (S_C) may be generated by a sufficient thermal or electrical surplus directed to the compression heat pump. The consumed cooling energy (W_C) is:

$$W_C = \begin{cases} W_{CAhp} - S_C; & W_{CAhp} \geq D_C \\ W_{CAhp} + W_{CChp}; & W_{CAhp} < D_C \end{cases} \quad (2)$$

$$W_{CAhp} = S_E * k_{Ap} \quad (3)$$

When $W_{CAhp} \geq D_C$, $S_C = D_C - W_{CAhp}$. But when $W_{CAhp} < D_H$, $W_{CChp} = D_C - W_{CAhp}$ and $S_C = 0$. The efficiency coefficient of the absorption cooler is $k_{Ahp} = 0.72$.

The electricity demand (D_E) depends on both the cooling as well as on the service demand. An insufficient thermal surplus to meet the cooling demand requires utilization of the compression heat pump. A sufficient electricity surplus (S_E) from the CHP facility may cover a possible compression heat-pump energy demand-meeting, however, a deficit requires an additional electricity from the power grid. The electrical demand-meeting is then:

$$W_E = \begin{cases} W_{EC} - S_E; & W_{EC} \geq D_E, \\ & W_{CChp} \leq D_C - W_{CAhp} \\ W_{EC} + W_{EGin}; & W_{EC} < D_E \end{cases} \quad (4)$$

$$W_{EChp} = W_{CChlp}/k_{Chp} \quad (5)$$

Also, when $W_{EC} \geq D_E, W_{CChp} \leq D_C - W_{CAhp}$, $S_E = D_E - W_{EChp}$ and when $W_{EC} < D_E$, $W_{WGin} = D_E - W_{EChp}, S_E = 0$. The compressor heat-pump efficiency is $k_{Chp} = 4$.

As seen in Figure 1, W_{EGCin}presents the required electricity for the compression heat pump and W_{EEUin} required power for other electricity workload. The electricity surplus that is not used for the cooling purpose is returned to the grid ($W_{EGout} = S_E - WEChp$).

3.2 Regression model

The inputs for the DES model presented above are the values of demand for an individual energy (D_H, D_C, D_E) during 24 hours of a particular day. As the energy demand-meeting is assumed to be correlated with external temperature it is necessary such an assumption is checked. First the correlation between the series of measured external temperatures (T) and the measured total energy loads within the selected time window is checked. Next, the linear and polynomial correlation are checked and the latter is used due to its greater r^2. The total individual energy loads is assumed to equal the total individual energy demand. When the correlation is sufficient, the regression curve is calculated:

$$D_H = f(T), D_C = f(T), D_E = f(T) \quad (6)$$

At that point DES model inputs can be evaluated. Using a set of 24 temperatures (T) measured each hour of a particular day as an input of the regression model provides the demands of an individual energy demand distribution (D_H, D_C, D_E) during the 24 hours of a particular day.

3.3 Hybrid model

Both the DES and the regression model are combined in order to provide a workload simulation based on historical demand-meeting data (Figure 2).

Input: External temperatures T in Celsius for each hour within a particular time window.

Output: Energy load of each component of DESS for each hour within a particular time window.

i. The regression model calculates the demands (D_H, D_C, D_E);
ii. The DES model calculates the energy loads of the DESS components according to the input demands;
iii. Both calculations are repeated for each hour within a particular time window.

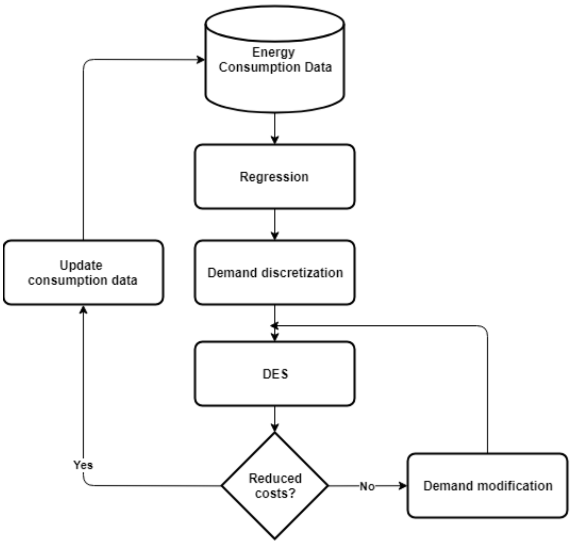

Figure 2. Hybrid simulation model.

4 RESULTS

4.1 Regression model results

The hourly temperature readings taken in June 2015 are examined. This term is selected for being typical for an early summer month. The input data are hourly temperatures for each single day. Based on these data mean temperature for each hour throughout the month is calculated. The monthly mean hourly temperatures are given in table 1.

Table 1. The calculated mean monthly temperatures in $^{\circ}C$

Hour	Mean temp	Hour	Mean temp.
0	17,3	12	23.5
1	16,8	13	24.1
2	16,3	14	24.5
3	15,8	15	24.9
4	15,3	16	25.1
5	15,0	17	24.7
6	15,2	18	23.9
7	16,3	19	22.7
8	20,1	20	21.5
9	23,9	21	19.8
10	22,8	22	18.7
11	23,3	23	17.9

A sample of the total individual energy demands (D_H, D_C, D_E) is taken. The Mean hourly energy demands are given in table 2.

The energy units are given in kilowatt hours for each different energy type (cooling, heating, and electricity). After performing a correlation and regression analysis for each pair $(T^{\circ}C, D_E), (T^{\circ}C, D_C), (T^{\circ}C, D_H)$ the energy demand based on exterior temperatures is calculated as:

$$(T^{\circ}C, D_E) \rightarrow y = 40,8x + 42,1; R^2 = 0,6804 \quad (7)$$

$$(T^{\circ}C, D_C) \rightarrow y = 42,7x - 236,7; R^2 = 0,7413 \quad (8)$$

$$(T^{\circ}C, D_H) \rightarrow y = -0,83x^3 + 48,73x^2 - 920,48x + 6410 \quad (9)$$

Figure 3 shows the demands obtained with the comparison between the regression model and the measured demand-meeting.

4.2 DES model

Values D_H, D_C, D_E, used as an input in the DES model and shown in Figure 3 present a typical thermal, cooling and electricity demand for an early summer working day. The result of applying the DES model for 24 hours are given in Figure 4. While the regression model uses the data for one month, the simulation model follows the modelled hourly temperature and the temperature-based demands. The CCHP unit workload is constant, because the installed CCHP unit has the best efficiency maximum power, which is a constant load of 1100 kWh. Using the data of the early summer month i.e. June, the heat demand (D_H) (Figure 4) is not high enough to engage the gas-fired boiler. Therefore the produced energy (W_{HB}) is constantly zero. Hence, there is the possibility to use it as additional energy to

Table 2. Calculated monthly energy demands in kWh

Hour	Mean D_H	Mean Dc	Mean D_H
0	679.0	513.7	740.1
1	652.4	481.0	717.8
2	639.3	450.7	690.1
3	626.5	440.2	646.2
4	622.1	407.5	704.0
5	642.8	381.3	725.8
6	743.4	397.7	787.0
7	934.9	385.5	851.1
8	1053.9	435.3	860.5
9	1113.7	507.2	842.5
10	1147.0	670.7	876.0
11	1148.6	722.7	860.5
12	1149.1	803.7	839.9
13	1138.5	818.2	800.1
14	1076.5	841.5	732.3
15	1032.1	862.0	707.7
16	969.8	836.2	723.5
17	917.1	845.0	726.7
18	949.3	930.7	735.3
19	919.8	901.7	745.0
20	860.8	853.0	741.9
21	770.6	735.8	728.7
22	742.4	678.7	742.5
23	707.0	585.0	748.6

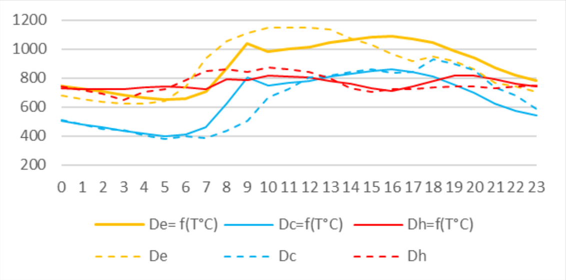

Figure 3. Comparison between the calculated demands and measured energy demand-meeting.

drive the absorber heat pump. Its workload (W_{CAhp}) is between 100 and 300 kWh. Since the cooling demand is the highest between noon and 8 p.m., the workload of the compressor heat pump (W_{Cchp}) is also the highest. As at that time window the CCHP does not produce enough electricity to meet all the electricity demand (D_E) and still produces enough surplus to drive compressor heat pump to produce W_{CChp}, electricity has to be bought from the grid as shown in Figure 5. On the other hand, in the morning and through the night, the demand-meeting for electricity is so low, that the energy is constantly sold to the grid.

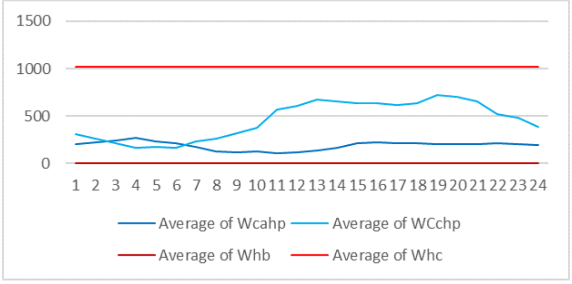

Figure 4. Calculated energy workload of the DESS components.

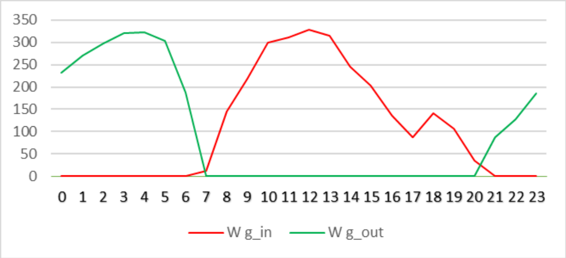

Figure 5. Purchased (red) and sold (green) electricity in kWh.

4.3 Discussion

Using the presented DES model provides a tool capable of modelling the energy flow through the network. It shows the difference between the electricity bought and sold from or to the grid. Since the balance between the bought and sold electricity depends entirely on energy demand-meeting within a certain time window during the day, the best option of changing the balance is changing the demand. The model shows the workload of individual DESS components and the total electricity balance when an individual energy needs are changed (Figure 5), and when it is only the cooling demands that is taken into account. The system cooling demand-meeting depends on the external temperature and on the desired internal temperature. So, the higher is the external temperature, and the lower is the inside temperatures, the higher is the energy demand-meeting.

Assuming that the electricity surplus is sold to the grid between 21 p.m. and 8 a.m. of the next morning, to cool down a building more than usual, by the internal temperature staying on a still comfortable level a little longer, meaning that less cooling is needed between 8 a.m. and 11 a.m., when electricity is bought from the grid. In the afternoon, the desired temperature is simply raised for 1 or 2 degrees. The variation with the cooling demand is presented as a dotted line in Figure 6.

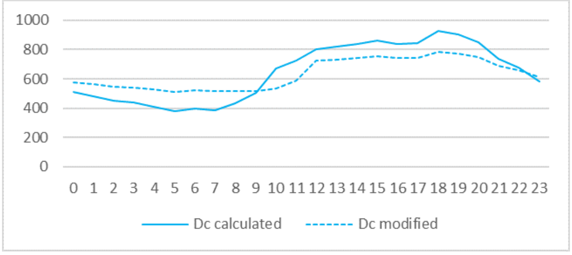

Figure 6. Calculated and modified cooling demand-meeting.

Performing the DESS simulation provides the energy values of the surplus heating and electricity energy, purchased electricity and used natural gas for heating by the gas-fired boiler in order to harmonize the energy demand-meeting and production output by selling and buying less energy to and from the grid. Balancing between the bought and sold electricity presented in Figure 7 shows that a small change on the demand side causes a change on the demand-meeting side. While less cheaper energy is sold during the night, so is less cheaper energy is purchased during the day, resulting in a lower total cost.

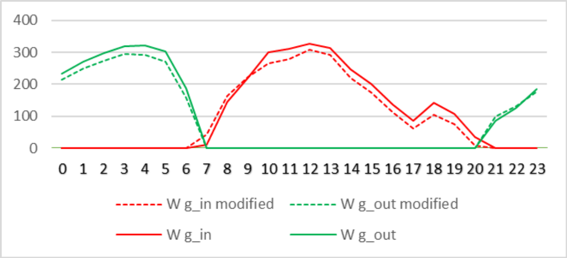

Figure 7. Expected electricity demand-meeting of the calculated and modified demand-meeting.

The workloads of appliances given in Figure 8 shows that by modifying only the cooling demands, the workload of the absorption heat-pump that relies on the heating surplus remains the same when the cooling demand changes. As expected, the only change is seen in the workload of the compressor heat pump (W_{CChp}), and the electricity surplus is entirely used to run the compressor heat pump.

Comparing the cooling demand from Table 2 and the external temperature from Table 1 shows that they are linearly correlated.

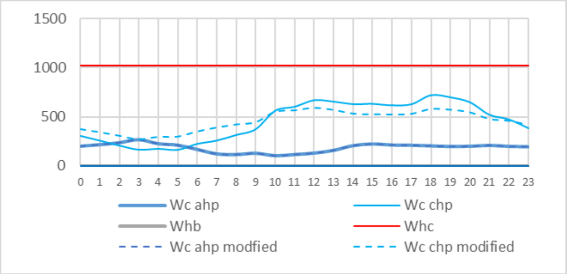

Figure 8. Expected electricity demand-meeting of calculated and modified demands-meeting.

A similar effect can be observed when shifting the heat demand. When a facility requires heating for its service as well as for the temperature maintenance, shifting the service demand-meeting into a later time i.e. postponing the service requiring heat into later hours (Figure 9) when the external temperature is lower, provides a heating surplus that can be used for the absorption heat pump, thus reducing the electricity load of the compressor heat pump. However, due to a lower efficiency of the absorption cooler, such shifting of the heat demand provides an insignificant cost difference for the electricity supply.

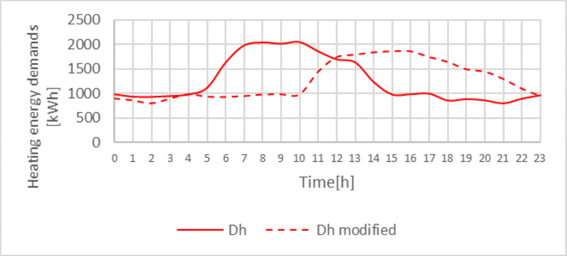

Figure 9. Expected demand of the calculated and modified heating demand-meeting.

Similarly, any service that requires electricity can be postponed into a lower tariff hour, thus providing lower electricity cost. As the facilities benefiting from DESS generally require services for their personnel and customers, demand-meeting should not be viewed only from the cost point of view but also in terms of personnel comfort and, moreover, postponing services may raise other facility operating costs.

4.4 Conclusion

The presented DES model provides a means to analyse the required load of each system component and can be adapted to variations in a particular heating, cooling, or electricity demand-meeting or in an external temperature. Depending on the CHP production, time of the day, and external temperature, the model identifies electricity, cooling, and heating deficits or surpluses at any node. With the gas-fired boiler and CHP running on the natural gas, the operating costs can be directly expressed by the cost of either the natural gas or electricity, while the latter needs to be adapted to a particular time of the day. Cost optimization can be performed by observing both the energy surpluses and deficits and by comparing the cost of acquiring either the grid electricity or increasing the gas-fired boiler output. The model can be further modified to include the use of ice banks and batteries for storing the energy surpluses and for cost-benefit analysis by comparing the cost of any possible system variation.

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