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Economic and Environmental Analysis of an Operation of a Residential Microgrid

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Abstract

Aggregating consumers and distributed generation on the same location with coupled centralized control is the main advantage of a microgrid concept. If these consumers do not have the ability to balance the variability of the renewable energy sources (RES) production the microgrid can be perceived from the distribution system point of view as a potential imbalance source. Evaluating the potential flexibility benefits of different units in the microgrid provides a valuable step towards a successful integration of renewable energy sources.

This paper presents results obtained from the simulations conducted on a developed mixed integer linear (MILP) model. The model is described in short and the most important equations are listed. The impact on the microgrid flexibility indicators, wasted heat and curtailed wind, of different microgrid components installed capacity (battery storage, heat storage, micro combined heat and power units (μCHP)) and their efficiency factors is presented. Finally, the interaction of the microgrid with the distribution system through the point of common coupling in an hourly operation controlled by the rolling horizon unit commitment strategy is shortly described.

Keywords: microgrid; energy storage; flexibility; rolling horizon unit commitment

1. Introduction

Integration of renewable energy sources is today in a large share driven by incentives [1] and is a general goal of the European Union to increase the share of zero emission generation [2]. Investments and improvements on the distribution grid level will be needed to reduce the impact and balance the system with large shares of variable and unpredictable production from renewable energy sources [3].

The current “fit and forget” approach will therefore need to be replaced with a “smart grid” approach since the first requires large investments and leads to loses increase [5]. The second approach can postpone the capital investments but requires installation of control and monitoring equipment which can enable integration of RES on the local level, e.g. microgrid level [5]. Traditionally all the imbalance

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between the production and consumption had to be compensated on centralized units whereas now the negative effect can be compensated for on local level. The idea of a virtual power plant [6], [7] is well known but still there is a lack of integral microgrid level models that can show the interaction between the microgrid and the rest of the distribution system, unit commitment among the microgrids distributed generators and enable flexible and robust response to all the possible fluctuations. In order to integrate all the requests optimal sizing of microgrid elements and efficient central control strategy is needed.

This paper presents main characteristics of the microgrid and problems that occur when dimensioning its elements. Furthermore, the operational flexibility term is defined and described and the possible flexibility services microgrids can provide to the system are mentioned. The developed MILP (Mixed Integer Liner Program) model and the developed rolling horizon unit commitment strategy bases on model predictive control (MPC) are described and simulation results are presented.

Nomenclature

$E_{chp}(t,i)$	Heat production of a µCHP unit [kWh]
$E_{ehp}(t,i)$	Heat production of a EHP unit [kWh]
$H_{hs}(t,i)$	Heat flow through heat storage [kWh]
$C_{hs}(t,i)$	Capacity of a heat storage [kWh]
$E_{bat}(t,i)$	Battery charge/discharge energy [kWh]
$C_{bat}(t,i)$	Capacity of a battery storage [kWh]
$C_{batMAX}(t,i)$	Maximum capacity of battery storage [kWh]
$E_{flex}(t,i)$	Flexible demand [kWh]
τ	Duration of time step [kW]
$E_{imp}(t)$, $E_{\exp}(t)$	Imported electricity from the distribution grid [kWh] , Exported electricity [kWh]
$E_d(t,i)$	Electric demand of *i-th* household [kWh_e]
$E_{wind}(t)$	Wind turbine production [kWh]
$E_{PV}(t)$	PV production [kWh]
$c_{imp}(t)$, $c_{\exp}(t)$	Import electricity price[€/kWh] /export electricity price [€/kWh]
$Fuel(t)$	Total fuel used (CHP units and auxiliary boilers)
$H_{waste}(t)$	Wasted heat [kWh]
$E_{wind\_curt}(t)$	Curtailed wind energy [kWh]

2. Microgrid concept

Microgrid can be defined as a set of consumers, distributed generation and energy storages controlled in a coordinated manner with the aim of achieving reliable and predefined exchange with the rest of the distribution system through a point of common coupling (PCC) [8]. If possible all the imbalances are compensated on the microgrid level and the upstream system has no negative effects and the microgrid can be considered to be fully flexible energy node (Fig. 1). The benefits microgrid concept can bring includes losses reduction, emissions reduction, and reliability of supply improvement, ancillary services support and easier integration of RES [9], [10].

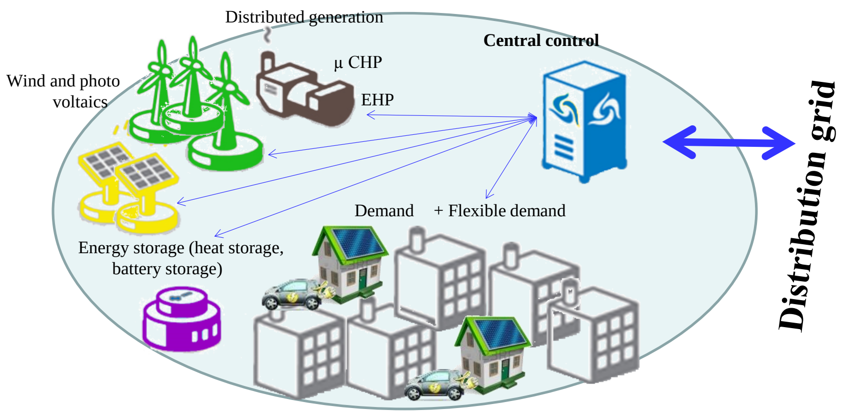


Fig. 1. Microgrid elements and the potential of connection of a microgrid as a flexible multi energy node through a PCC

The microgrid integrates various flows of energy, electricity, heat and gas. The coupled control of all energy vector unlocks additional potential, in the first place a flexible response to all the fluctuations. Therefore the developed microgrid model (Fig 2.) includes all abovementioned energy vectors and enables additional flexibility benefits of coupled µCHP and EHP operation enhanced with heat and battery storage.

3. Operational flexibility

In future power system flexibility is becoming a key characteristic as an answer to an increasing share of variable generation. It can be defined as an ability to respond to changes is demand/generation equilibrium [11]. If market behavior of a certain entity is observed the flexibility can be defined as a capability to quickly adjust to most current market situation and follow the scheduled plan of exchange [12]. All power systems inherently have a certain flexibility level which was satisfactory until the unpredictability and variability of generation increased due a large share of RES. In that circumstances it is a question how will an additional amount of RES effect the operation, how much of variable production current system can integrate and what are the changes needed to keep the present level of reliability. Lack of system flexibility can be manifested in frequency deviations which can lead to load shedding, deviations from contracted exchanges, wind curtailment, higher price volatility. The current system wide flexibility requirements prediction mostly base itself on deterministic calculation which increases the system costs and does not include the variables that stretch through several time periods (intertemporal constraints) [13]. With the advent of new technologies (µCHP, electric vehicles, flexible demand, electric heat pumps etc.) new flexibility potential can be unlocked on the local, distribution level [14]. Inclusion of all the units on the distribution level in the unit commitment problem requires formulation of new control concepts. Therefore the evaluation how much of an impact different technologies have is a valuable information when dimensioning a microgrid system. This paper provides an insight how for example microgrid capabilities to provide flexible response change in dependence on the size of battery storage device.

4. Microgrid control

Microgrid control can be observed as a hierarchical structure (Fig 2.) [15], [16]. The lowest level is directly connected with the characteristics of the generator. The second level ensures the stabilization of frequency after the fluctuations. The second level keeps the frequency

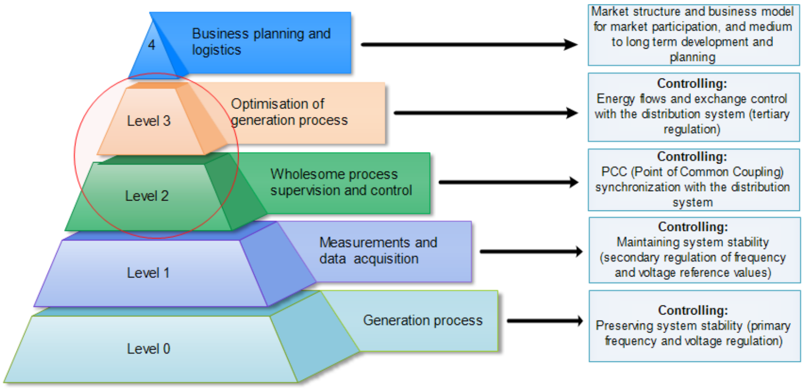


Fig. 2. IEC/ISA 95 standard hierarchy control adjusted for the observed microgrid concept

The developed model utilizes a central control system of higher level (Fig 2. – primarily level) with the assumption that the lower level control is efficiently implemented. The controller for the rolling horizon unit commitment uses model predictive control scheme (MPC). The basic idea of MPC control is shown on figure below (Fig. 3.).

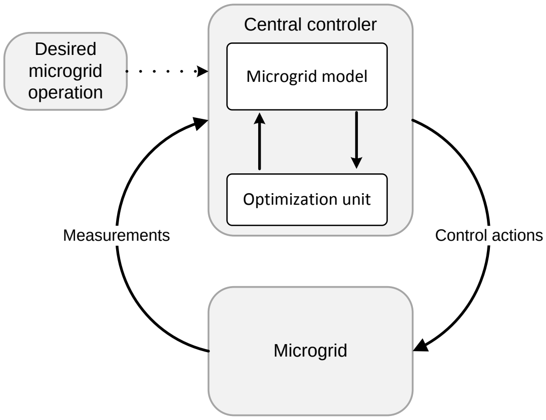


Fig. 3. Model predictive control concept applied to the developed microgrid model

For every simulation step *t* the control algorithm estimates the system state for the whole observed planning horizon. On the basis of the present state and forecasts for the planning horizon the optimal state is determined. This way both the current state and the future forecast errors are included in the scheduling. More detailed description of the iterative optimization process can be found in [17]. For the next simulation step the process is repeated. In this paper used planning horizon for the rolling unit commitment model is 24 hours since it is assumed the microgrid participates on the day-ahead market.

5. Microgrid simulation model

The developed MILP model described in details in [17] that represents a residential microgrid with 300 households of different load types was expanded further. This paper presents results from a more detailed model that includes more precise μCHP unit model with different efficiencies and has a battery storage included.

The battery storage was modeled in two different ways:

1. Central battery storage– assumed that the investment into such battery could be done by the distribution system operator (DSO). The battery coordination is done together with distributed generation resources of the microgrid. The sensitivity analysis that shows how the flexibility indicators (wasted heat and curtailed wind) change for the different combinations of installed capacities of RES and battery storage.
2. Distributed battery storage– assumed a percentage of households that have an EHP have a battery storage that enables even better utilization of coupled operation of μCHP units and EHP units. The sensitivity analysis was performed again. Additionally, since this is the more probable scenario the microgrid containing distributed battery storage governed by the adaptive rolling horizon unit commitment was simulated to operate on a day ahead market. The results showing the reduction in environmental impact, e.g. less need for the usage of gas for μCHP units, are presented.

The battery for a central model is incorporated with the following equations. Maximum value of energy flow through battery (charge/discharge) at any given time step is limited and connected with the maximum capacity of the battery (Eq. 1)). It is assumed that, for example, in a time simulation step of a half an hour the battery can be charged to one eight of its capacity.

$$-C_{batMAX} / (\tau \cdot 4) \cdot \eta_{dsc} \leq E_{bat\_tot}(t) \leq C_{batMAX} / (\tau \cdot 4) \cdot \eta_{charge} \quad (1)$$

$E_{bat}(t)$ is positive for battery charging and negative for battery discharging. The information about the total capacity of battery at every time step is modelled with continuous decision variable. $C_{bat}(t)$ is intertemporal variable that holds the information of the central capacity.

$$C_{bat}(t) \leq C_{batMAX} \quad (2)$$

$$C_{bat}(t) = L \cdot C_{bat}(t-1) + E_{bat\_tot}(t) \quad (3)$$

On the other hand the battery model for the batteries distributed among households (K is the number of households) is described with the following constraints:

$$E_{bat}(\mathrm{t,i}) \leq C_{batMAX\_dist}(t,i) / (4 \cdot \tau) \quad (4)$$

$$E_{bat\_tot}(t) = \sum_{i=1}^{K} E_{bat}(t,i) \quad (5)$$

$$C_{bat\_dist}(t) \leq C_{batMAX\_dist} \quad (6)$$

Equilibrium between electricity production and consumption must be achieved at every time step:

$$E_d(t,i) + E_{\exp}(t) + \sum_{i=1}^{K} E_{ehp}(t,i) = E_{imp}(t) + E_{pv\_r}(t) + E_{wind\_gen}(t) + \sum_{i=1}^{K} E_{chp}(t,i) + \sum_{i=1}^{K} E_{flex}(t,i) + E_{bat\_tot}(t) \quad (7)$$

The objective function for the simulations that generated sensitivity analysis calculates the yearly operational costs (17520 half an hour time steps). In the yearly simulation no stochastic error of forecast is used. Penalty factor P is used to highlight the importance to use all the available energy and avoid the waste of heat and wind curtailment. Factor L highlights the importance of efficient use of energy It discourages cycling of energy of the battery with an introduction of a small amount of losses (0.05%).

$$COST = \sum_{t=1}^{T_{\max}} \begin{pmatrix} Fuel(t) \cdot c_{ng}(t) + E_{imp}(t) \cdot c_{imp}(t) - E_{\exp}(t) \cdot c_{\exp}(t) \\ +P \cdot E_{wind\_curt}(t) + P \cdot H_{waste}(t) + L \cdot E_{bat\_tot}(t) \end{pmatrix} \quad (8)$$

6. Results

Conducted analysis of the impact battery storage and distributed generation efficiency has on an operation of a microgrid shows that specific elements have higher impact. The results from a set of simulations for different µCHP technologies [18] are shown in Table 1. The total share of µCHP units in households is set to be 50%, share of EHP units 20% and the rest of the households had only auxiliary boiler as ah heating source. The off-grid operation mode was used, export and import not allowed. It can be seen that the capability of a microgrid to integrate RES is highly dependent on the technology used for the µCHP units that represent a most important heat source in the microgrid. Additionally since there is a possibility to shed the wind with the addition of battery storage the PV installed capacity rises.

Table 1. Dependence of the microgrid capability to integrate RES on the µCHP technology used

µCHP technology	Efficiency [%]		Optimal PV installed capacity [kW]		Optimal WIND installed capacity [kW]		Wasted energy		Total emissions [tons]	Percent of el. demand met from RES
	Elec.	Therm.	No bat.	Battery	No bat.	Battery	Heat[1]	Wind[2]		
Fuel cell	30	55	72	82	72	68	1,04%	4,37%	813	36,93%
Stirling engine	20	77	60	69	188	178	0,84%	27,19%	783	61,84%
Comb. engine	26	64	60	71	109	102	2,86%	9,57%	794	45,48%
Steam engine	24	70	58	67	137	130	4,75%	15,33%	778	51,71%
µ gas turbine	25	58	62	75	99	91	2,33%	7,73%	833	43,11%

[1]*In percent to total heat used* || [2]*In percent to total wind production*

If the wasted energy share is observed for all the µCHP technology types the addition of battery storage in all cases reduces the unused energy amounts (Fig. 5).

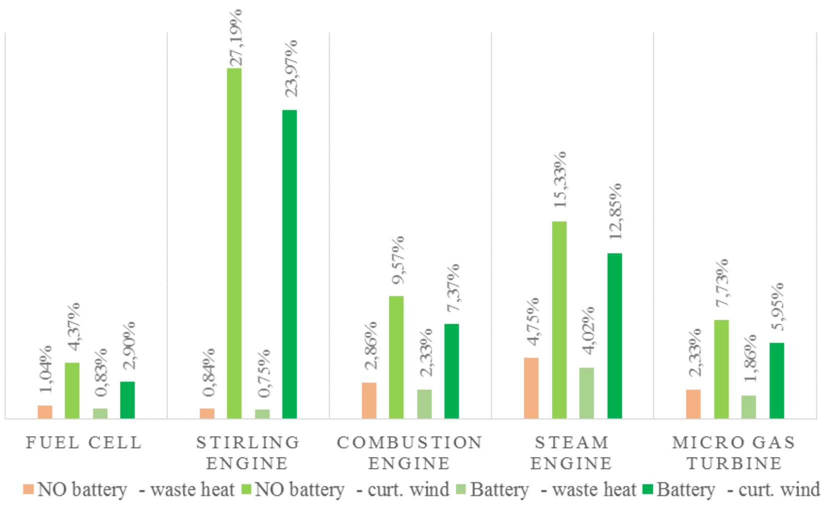
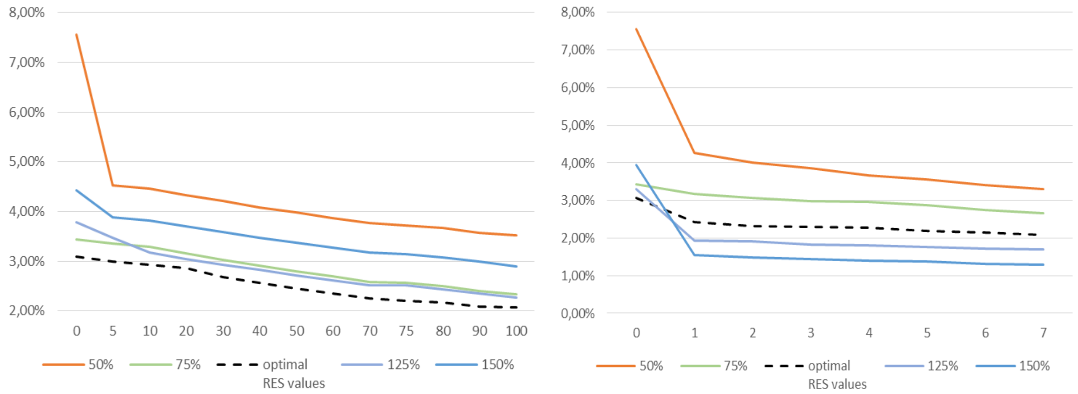


Fig. 5. Unused energy amounts for microgrid with and without the battery storage (in percent to total heat used || total wind energy production)

The optimal capacity of total installed RES with the addition of battery storage changes. So does the amounts of wasted energy which are reduced. The sensitivity analysis is performed for both central battery and distributed battery storage. The observed wasted energy for different installed capacities of

RES is shown on Fig. 4. All other parameters are kept unchanged during these simulations. Optimal RES values for a case without any storage are 109 kW of installed wind power and 60 kW of installed PV.



a) *b)*

Fig. 6. Sensitivity analysis for battery storage size and unused energy amount
(a) Central battery storage; (b) Distributed battery storage

It can be seen that the slowly decreasing trend is present in both cases with the biggest additional value of battery is observable at the first addition of battery capacity. It is interesting to observe that battery has a greater effect for smaller capacity of RES because it enables the better utilization of μCHP unit electricity production which is forced to produce more electricity. Since electrical and thermal output are connected at certain simulation periods waste of energy occurs. Additionally the distributed battery storage enables higher level of RES integration but also altogether all the households distributed batteries have a bigger total capacity and total investment costs. The optimal installed values for a series of small 3 kWh batteries increases to a total 300 kW of installed wind and 138 kW installed PV. This is the reason why the sensitivity analysis for higher installed capacities returns better operation indicators since the control algorithm has even more resources it can use to avoid the waste of heat and totally eliminate curtailment of wind and cover almost 100% of electricity demand from the RES.

Results of the model incorporating rolling horizon predictive control are demonstrated for one winter day (24 hours). The simulations include demand and renewable energy resources forecast error. The control algorithm in every time step gathers the most recent forecasts and based on them, current state of the microgrid and announced day-ahead exchanges optimizes the microgrid operation. The goal is to follow the contracted day ahead exchanges while at the same time balancing and alleviating the impact of the unpredictable RES production. For a μCHP unit dispatch for an observed winter day is depicted on Figure 6. The results are presented for operation with and without storage. In case no storage is available it can be seen that μCHP units are following the heat demand which shows that EE price was high enough to justify the use of cogeneration. If storage is available bigger production in periods of high EE prices can be observed while it is less costly to burn natural gas. This reduces total emissions and costs. On the other hand when the electricity is cheap it is used to produce and store heat and electricity for upcoming periods. As it was already shown on the yearly operation the storage capacities enable the microgrid to utilize its resources more efficiently.

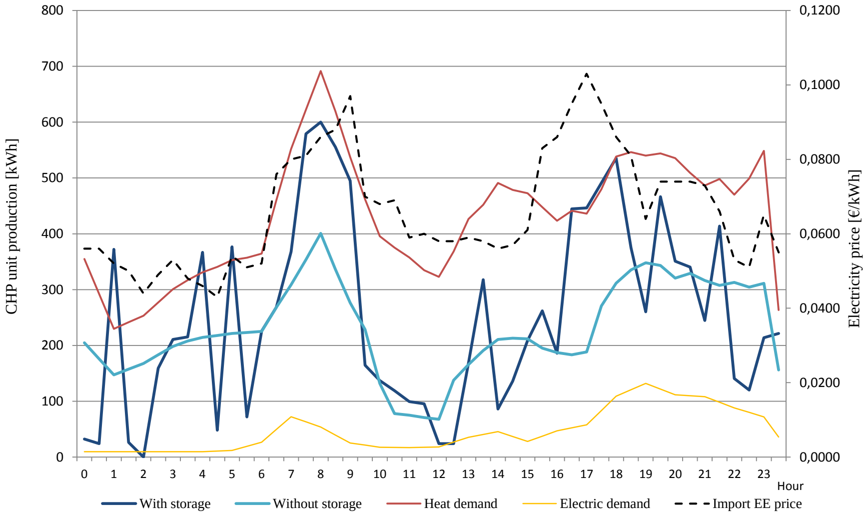


Fig. 7. µCHP unit operation in the daily simulation governed by the adaptive rolling horizon unit commitment algorithm

7. Conclusion

This paper presents a possibility to deal with the RES integration problem on a local level, inside the microgrid system. The prerequisite for that is a design of a satisfactory control algorithm that can provide enough flexibility. In accordance, the paper presents the detailed MILP model of a residential microgrid consisting of 300 households and that has included all the important distributed generation technologies, µCHP, EHP; RES and with special highlight how storage technologies effect the operation. The paper differentiates two different simulation types. The first that was explained in more detail is the yearly operation simulation that is used for the dimensioning of microgird elements and for general evaluation what an impact they have on microgrid flexibility. The paper proposes waste of energy to be an indicator of operation that shows how flexible microgrid is in responding to fluctuations in RES production. The second series of simulations give a glimpse of results obtained from the daily operation of microgrid entity that participated on the day-ahead market and is governed by the adaptive rolling horizon control algorithm. It is shown that the usage of proposed algorithm increases efficiency of the distributed generation utilization.

8. Copyright

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Biography

Ninoslav Holjevac is a PhD student at the University of Zagreb Faculty of Electrical Engineering and Computing. He is working at the Department of Energy and Power Systems as a research and teaching assistant. Professional interests include microgrid operation optimization, distribution network reliability and planning and multi energy systems.