Coupling of cleaner production with a day-ahead electricity market: a hypothetical case study

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Abstract

During the last 25 years day-ahead electricity markets are continuously expanding and the amount of energy being traded through them is increasing. Moreover, there is a possibility for production facilities to act directly on a day-ahead market as independent market players. The aim of this paper is to analyse the potential for reduction of variable costs of an arbitrary production facility consisting of high-efficient combined heat and power (CHP), grid connection and production unit, thermal and products storage and photovoltaic (PV) panels. Costs are reduced by offsetting the expensive electricity with the use of thermal and products storage and optimization of power flows. Variable costs are, together with the costs of a raw material, directly related to input costs of energy in the form of a fossil fuel derivatives and/or electricity. Two hypothetical cases will be analysed: (1) production facility with installed PV acting as a prosumer and (2) production facility without the installed PV acting only as a consumer from the market point of view. Mathematical model consists of two sub-models

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which are solved in a coupled manner: the optimization of cost-reduction by retaining the output product distribution and model for obtaining the day-ahead market clearing price of electricity. The results show that coupling of market modelling with optimization of running costs for an arbitrary production facility can be used for estimation of market clearing price and optimization of power flows within the production facility.

Keywords: Day-ahead electricity market; Integer programming; Market clearing price; Renewable energy sources; Thermal storage

Nomenclature

A	area [m^2]
e	energy [kWh]
E	energy content in thermal storage [kWh]
$\overline{E}$	maximum energy content in thermal storage [kWh]
I	integer programming variable [-]
n	number of products [-]
$\overline{n}$	maximum productivity in one hour [-]
p	price per unit energy [eur/kWh]
$\overline{P}$	maximum power capacity [kW]
$\underline{P}$	minimum power capacity [kW]
q	energy from market players [kWh]
X	productivity per unit of energy [n/kWh]
η	efficiency [-]

List of subscripts

id	unit "i" of demand side
is	unit "i" of supply side
t	hour "t"

List of superscripts

fuel	relates to the fuel
el,imp/exp	relates to the import/export at the electricity hub
th,CHP	thermal output from CHP unit
el,CHP	electric output from CHP unit
el	relates to electric energy flow
el,prod	relates to electric energy demand for productivity
th,prod	relates to thermal energy demand for productivity
prod	relates to productivity
prod,dem	relates to products demand rate
imp/exp	relates to import/export from the market
iter	iteration
iter-1	previous iteration

List of abbreviations

CHP Combined Heat and Power

MCP	Market Clearing Price
MM	Market Model
PF	Production Facility
PFM	Production Facility Model
PTH	Power to heat
PV	Photovoltaic
URF	Under-relaxation factor

1. Introduction

Due to the increase in greenhouse gas concentrations in the atmosphere, reduction of greenhouse gas emissions has become major technological, societal, and political imperative worldwide (Klemeš et al., 2010). The reduction of greenhouse gas emissions can be achieved by transforming fossil-oriented energy systems into more sustainable ones. The integration of renewable energy sources in existing energy systems has been recognised as a first step for this (Kostevšek et al., 2014). The penetration of various renewable energy sources in the overall power generation reduces the environmental impact caused by fossil fuel generation systems (Zare Oskouei and Sadeghi Yazdankhah, 2015). In this context, ensuring cleaner energy is also a milestone for cleaner production, especially for reducing the greenhouse gases emissions and emissions of other pollutants, which are directly related to the types and loads of the energy sources used (Yong et al., 2015).

Due to increased environmental awareness, cleaner and more efficient production is gaining on importance in all industrial sectors (Klemeš et al., 2012). In order to achieve this aim, the industry players need to change the traditional ways of their production (Chofreh et al., 2014). They need to start acting as prosumers, meaning that they need to act as customers that can both produce and consume electricity (Brand et al., 2014). The prosumers additionally increases the complexity of the commercial relationship between utilities and entities generating energy for self-consumption because they can also sell their excess capacity to the utility company (Cardenas et al., 2014). To avoid blackouts, electricity systems require a perfect balance between supply and demand at all times (Ochoa and van Ackere, 2015). This has been well presented in the study by Ho et al. (2014). The study showed that a renewable energy based distributed energy generation system for a small community in Malaysia is technically feasible and economically viable.

The electrical balancing in a prosumer way, that is to increase economic benefits for the customers, was already analysed by different authors on different type of systems. Verleden et al. (2011) analysed the electrical balancing for residential installations. The study showed that a self –efficient system can be achieved by balancing supply and demand on a local level, from which benefit both the distribution grid operator and the prosumer. Alahäivälä et al. (2015) analysed the optimal control strategy for a residential micro-CHP system with a power sink. The study showed that the presence of the intermittent generation in a power system occasionally causes surplus in electricity production, and that in such a case, it may be profitable to use electricity for heat production in a micro-CHP system. Laveyne et al. (2014) analysed the load-shifting of electrical heat pumps, showing that the heat can be stored much more cost efficiently than electricity, by the load shifting ability of heat pumps. Salpakari and Lund (2016) studied the cost-optimal and rule-based control for buildings with PV, employing a heat pump, thermal and electrical storage. The study showed that for a low-energy house in Southern Finland, the most cost-optimal measure was a PV with a thermal storage, a heat pump and a battery. Perković et al. (2016) in their study showed that coupling of desalination and renewables increases the system stability by utilizing the brine and fresh water storage. Novosel et al. (2015a) showed that introduction of electric vehicles can allow larger penetration of renewables.

Over the years, the rising cost of energy encouraged manufacturing facilities decision-makers to tackle the energy cost problem in different manners (Shrouf et al., 2014). The potential to reduce energy costs can lie in the integration of different production industries and day-ahead electricity markets. This energy cost reduction potential and optimal production scheduling was recently studied by Hadera and Harjunkoski (2013). The study showed that the steel plant production that is assumed to participate in a day-ahead electricity market with hourly varying electricity prices, may lead to significant savings in the electricity bill. Hadera et al. (2015) studied the process flexibility of a steel production plant. The study show that the potential impact of high prices in the day-ahead markets of electricity can be mitigated by jointly optimizing the production schedule and the associated net electricity consumption cost. Ferruzzi et al. (2016) presented a decision making model for optimal bidding in the day-ahead energy market of a grid-connected residential microgrid, acting as an prosumer, under forecast uncertainty. Bidding and scheduling in electricity markets between the aggregator and the prosumer with the use of stochastic programming is investigated by the Ottesen et al. (2016) The difference between the two common control strategies, the cost-optimal and rule-based control, for a building-integrated PV is analysed in study of Salpakari and Lund (2016), where thermal storage with heat pumps and batteries performed better than the demand shift measures in cost reduction. This study also stressed out the importance of having grid-connected system for improved performance and increased flexibility of a prosumer microgrid.

However, when it comes to the electrical balancing of a production of any kind of a manufacturing facility with a day-ahead electricity market when production facility can influence the market clearing price, this has till now not been reported.

Therefore the novelty of this work is a new model that couples the calculation of predicted market clearing price of electricity with optimal scheduling of production with the aim of better resource management, cleaner production and reduction of costs. Moreover, the production facility can be considered as a grid-connected microgrid, having possibility of renewable and conventional supply, as well as thermal storage and warehouse capacity for offsetting the production in times of high cost of power supply and selling own surplus in the day-ahead market.

1.1. Problem formulation

The configuration under the investigation, shown in Fig.1, is consisting of the day-ahead electricity market and the production facility. Production facility is connected to the market through the interconnecting power flow cable which connects production facility to the grid and enables the production facility to act as a market player. One of the assumptions of the model is that the production facility can sell or purchase electricity only with the electricity market. Production facility can supply electricity from the market, CHP unit at the cost of fuel and PV unit at zero marginal cost. Moreover, the production facility has a strict hourly-based delivery schedule for the number of products that have to be delivered in each hour of the day, and each product requires the predefined amount of thermal and electrical energy. The main task of this work is to provide the coupling of the day-ahead market model (MM) and production facility model (PFM) with the objective for minimizing the production cost and maximizing the production facility income from the interplay with the MM. In order to offset the high price of electricity, production facility can use capabilities of thermal storage and warehouse (storage for products) and produce its products during the periods of low price of electricity or high solar irradiation, i.e. from it's own production at PV unit. There is also a possibility to completely bypass the CHP unit with the use of production facility's power-to-heat capability (PTH). In that case, all electric and thermal demand can be served from the PV unit and the grid connection to the electricity market that are supplying the electricity bus. Additional income can be gained for the production facility from selling the excess of electricity directly on the day-ahead market. In order to explore the influence of solar irradiation between the winter and summer, and to investigate the impact of PV unit has on the cost reduction, four different cases have been simulated: summer and winter week, with and without the PV unit.

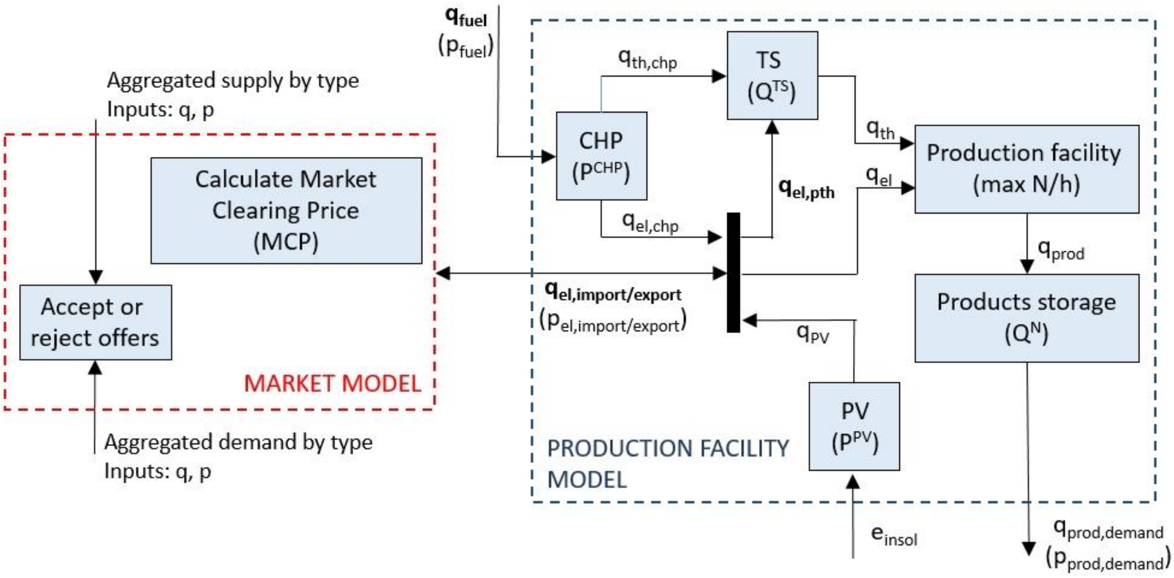

Fig. 1. Problem formulation: coupling of the market and the production facility model.

In this work it is assumed that all environmental variables, such as solar irradiation and demand schedule are fully known in advance, making this problem mathematically deterministic.

2. Methodology

2.1. Market model (MM)

Day-ahead electricity market aims to find a market clearing price (MCP) of electricity that maximizes the social welfare, i.e. the profit for market bidders: the producers (supply) and the consumers (demand).

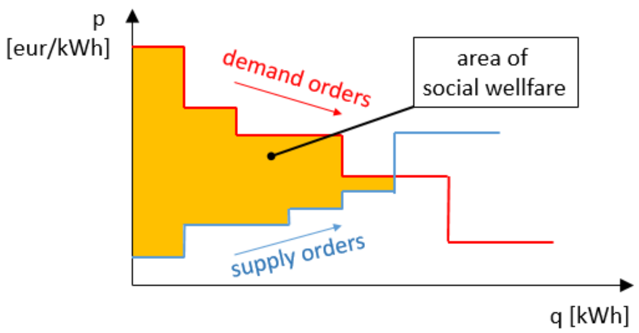

Fig. 2. Demand and supply orders for one hour in the day-ahead electricity market.

In this work a very simple model is applied for modelling of the electricity market, meaning that only simple hourly-based orders are taken into account and there is no market coupling with external markets. The model consists from two separate sub-models with the following objectives:

- maximization of social welfare by finding the optimal configurations
- finding the MCP which results in maximum social welfare within the optimal configuration

Mathematically, the first sub-model searches for optimal configuration with binary integer programming. The objective function represents the maximization of social welfare for each hour:

$$\max\left(\sum_{id=1}^{Nd} I_{id}\, p_{id}\, q_{id} - \sum_{is=1}^{Ns} I_{is}\, p_{is}\, q_{is}\right)_t \tag{1}$$

The above equation represents the basic objective of the market model as presented in Fig. 2. Variables I_{id} and I_{is} represent binary decision variables and can be only zero or one. They are including or excluding the market bids, represented by multiple of demand/supply specific price p and quantity q. The only constraint in the modelling is that supply has to be larger or equal to demand, which allows the model to result with a small amount of surplus in supply:

$$\left(\sum_{is=1}^{Ns} I_{is}\, q_{is} \geq \sum_{id=1}^{Nd} I_{id}\, q_{id}\right)_t \tag{2}$$

Variables I_{id} and I_{is} are binary integers, meaning that they can include or exclude the bids, represented by the multiplication of the price and quantity pairs (p, q), which result in the largest social welfare, represented by the shaded surface in Fig. 2.

The second sub-model searches the optimal MCP p_t^{MCP} within the optimal configuration. The objective function can be expressed as:

$$\max\left(\sum_{id=1}^{Nd} I_{id}\left(p_{id} - p_t^{MCP}\right)q_{id} + \sum_{is=1}^{Ns} I_{is}\left(p_t^{MCP} - p_{is}\right)q_{is}\right) \quad (3)$$

Inputs for market model presented in this work are price-quantity pairs for the each market player.

2.2. Production facility model (PFM)

The aim of the production facility model is to minimize the running cost of the production facility without violating the delivery schedule and physical constraints for each modelled unit within the production facility, like capacities of thermal storage, products storage, cable capacity towards the market and nominal power of the CHP plant. Each unit can be expressed by a set of simple relations that take into account only the power flows q and the associated cost p. Fig. 1 shows that the production facility running cost is associated to imports of fuel q^{fuel} and import/export of the power flow in exchange with the market $q^{el,imp/\exp}$.

The CHP unit gives the thermal and electrical power on the output that is directly related to the input fuel and the respective efficiencies:

$$q_t^{th.,CHP} = \eta^{th,CHP} q_t^{fuel} \quad (4)$$

$$q_t^{el.,CHP} = \eta^{el,CHP} q_t^{fuel} \quad (5)$$

The electricity bus balances the electrical power flows within the production facility and allows no direct storage of electric energy.

$$q_t^{el.,imp/\exp} + q_t^{el.CHP} - q_t^{el} - q_t^{PTH} + e_t^{PV} = 0 \quad (6)$$

The supply/demand from the input/output of electric energy, supply from the CHP unit and the PV plant is balanced with electrical demands from the production unit and power-to-heat. Electrical energy can be converted to heat and stored in thermal storage. This power-to-heat is governed by the separate power flow q_t^{PTH} which also needs to be optimized, but without the associated cost, except the one related to the loss of energy due to efficiency related to converting power into heat.

Thermal storage can (TS) be modelled by the inputs and outputs of power flows that have to satisfy the available capacity of the TS. The inputs from CHP unit and power-to-heat are balanced with the state from previous hour and production unit demand

$$0 \le E_{t-1} + q_t^{th.,CHP} + \eta^{PTH} q_t^{PTH} - q_t^{th} \le \overline{E} \quad (7)$$

The electric energy and the quantity of products being produced inside the production plant is related through the productivity per unit of energy $X^{el.,prod}$:

$$X^{el.,prod} q_t^{el} = n_t^{prod} \quad (8)$$

Electric and thermal demand for production unit are directly related and thermal demand can be expressed as a function of electric demand:

$$X^{el.,prod} q_t^{el} = X^{th.,prod} q_t^{th} \rightarrow q_t^{th} = \frac{X^{el.,prod}}{X^{th.,prod}} q_t^{el} \quad (9)$$

Moreover, the number of units being produced cannot exceed the production unit capacity:

$$n_t^{prod} \le \overline{n} \quad (10)$$

Products storage balances the inputs of newly produced products from the production facility and outputs of products given by the hourly schedule (demand for products). Number of products cannot exceed the warehouse capacity.

$$0 \le N_{t-1} + n_t^{prod} - n_t^{prod,dem} \le \overline{N} \tag{11}$$

From the equations above the objective function for minimizing the PFM running cost and associated constraints can be derived:

$$\min\left(C = \sum_{t=1}^{24} \left(p_t^{MCP} q_t^{el.,imp/\exp} + p_t^{fuel} q_t^{fuel} + p_t^{PTH} q_t^{PTH} \right) \right) \tag{12}$$

Decision variables are hourly values of: input/output of the power flow exchanged with the market $q_t^{el,imp/\exp}$, amount of power-to-heat q_t^{PTH} and power flow from the CHP unit q_t^{fuel}. The optimization is constrained with the following constraints:

$$\begin{aligned} &\left(\eta^{TS,in} \eta^{th,CHP} - \frac{1}{\eta^{TS,out}} \frac{X^{el.,prod}}{X^{th.,prod}} \eta^{el,CHP} \right) q_t^{fuel} - \\ &- \frac{1}{\eta^{TS,out}} \frac{X^{el.,prod}}{X^{th.,prod}} q_t^{el.,imp/\exp} + \\ &+ \left(\eta^{PTH} + \frac{1}{\eta^{TS,out}} \frac{X^{el.,prod}}{X^{th.,prod}} \right) q_t^{PTH} \le \overline{E} - E_{t-1} + \frac{1}{\eta^{TS,out}} \frac{X^{el.,prod}}{X^{th.,prod}} e_t^{PV} \end{aligned} \tag{13}$$

$$\begin{aligned} &-\left(\eta^{TS,in} \eta^{th,CHP} - \frac{1}{\eta^{TS,out}} \frac{X^{el.,prod}}{X^{th.,prod}} \eta^{el,CHP} \right) q_t^{fuel} + \\ &+ \frac{1}{\eta^{TS,out}} \frac{X^{el.,prod}}{X^{th.,prod}} q_t^{el.,imp/\exp} - \\ &- \left(\eta^{PTH} + \frac{1}{\eta^{TS,out}} \frac{X^{el.,prod}}{X^{th.,prod}} \right) q_t^{PTH} \le E_{t-1} - \frac{1}{\eta^{TS,out}} \frac{X^{el.,prod}}{X^{th.,prod}} e_t^{PV} \end{aligned} \tag{14}$$

$$X^{el.,prod} \eta^{el,CHP} q_t^{fuel} + X^{el.,prod} q_t^{el.,imp/\exp} - X^{el.,prod} q_t^{PTH} \le \overline{N} - N_{t-1} + n_t^{prod,dem} - X^{el.,prod} e_t^{PV} \tag{15}$$

$$- X^{el.,prod} \eta^{el,CHP} q_t^{fuel} - X^{el.,prod} q_t^{el.,imp/\exp} + X^{el.,prod} q_t^{PTH} \le +N_{t-1} - n_t^{prod,dem} + X^{el.,prod} e_t^{PV} \tag{16}$$

$$X^{el.,prod} \eta^{el,CHP} q_t^{fuel} + X^{el.,prod} q_t^{el.,imp/\exp} - X^{el.,prod} q_t^{PTH} \le \overline{n} - X^{el.,prod} e_t^{PV} \tag{17}$$

$$- X^{el.,prod} \eta^{el,CHP} q_t^{fuel} - X^{el.,prod} q_t^{el.,imp/\exp} + X^{el.,prod} q_t^{PTH} \le X^{el.,prod} e_t^{PV} \tag{18}$$

$$\underline{P^{imp/\exp}} \le q_t^{el.,imp/\exp} \le \overline{P^{imp/ep}} \tag{19}$$

$$0 \le q_t^{fuel} \le \overline{P^{CHP}} \tag{20}$$

$$0 \le q_t^{PTH} \le \overline{P^{PTH}} \tag{21}$$

Equations (13) and (14) are limiting the input and output of energy in or out of the thermal storage. Equations (15) and (16) are limiting the input and output of products into or out of the warehouse. Equations (18) and (19) are balancing the electric energy on the electricity bus. Equation (20) and (21) are limiting the energy rate of CHP unit and PTH link to be less or equal to their installed capacity. The minimization problem presented in Equations (12 - 21) can be minimized with non-linear programming.

2.3. Coupling the MM and PFM

Two models are coupled sequentially, meaning that they are executed independently from each other, but are coupled with the decision variables p_t^{MCP} and $q_t^{el.,imp/\exp}$ in consecutive iterations. The MCP p_t^{MCP} is output from MM and input to PFM, while $q_t^{el.,imp/\exp}$ is output from PFM and input to MM. Price at which $q_t^{el.,imp/\exp}$ is offered in MM also has to be provided. The decision variable $q_t^{el.,imp/\exp}$ has to be divided into two variables that serve as demand or supply from the MM point of view:

$$q_{id}^{PF} = \max\left(q_t^{el,imp/\exp},0\right) \tag{22}$$

$$q_{is}^{PF} = \min(q_t^{el.,imp/\exp},0) \tag{23}$$

Above equations state that input of electricity into the factory is seen as additional demand in the MM, while export of electricity in the PFM is seen as additional supply bid in the MM. The scheme of the coupling is given in Fig. 3.

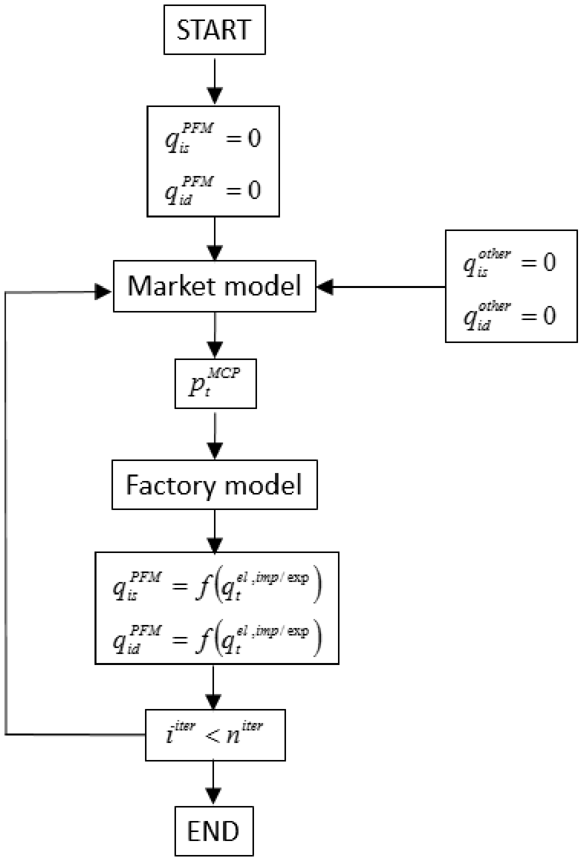

Fig. 3. Coupling scheme between MM and PFM.

In first iteration q_{id}^{PF} and q_{is}^{PF} are assumed to be equal to zero, meaning that there is no interaction between the PFM and the MM. Then the MM provides the MCP without the influence of PFM. In all consecutive iterations the MM takes into account bids and offers from the PFM, represented by the (q_{id}^{PF} , p_{id}^{PF}) and (q_{is}^{PF} , p_{is}^{PF}) pairs. The overall coupling algorithm is terminated when iteration count reaches the iteration limit number, which has to be set in advance. There is a possibility that convergence of results, which can be monitored for MCP, solution variables, or values of objective function, will not be stable, but oscillating. In order to reduce these oscillations, the under-relaxation of results has been introduced between the iterations for damping the abrupt changes in MCP:

$$p_t^{MCP} = URF p_t^{MCP,iter} + (1 - URF) p_t^{MCP,iter-1}$$

The value of under-relaxation factor in this work is set to 0.5 and the number of iterations is set to 20.

2.4. Hypothetical case study setup

A hypothetical case study is used in this work to demonstrate the applicability of the presented methodology. Four cases will be analysed, as presented in Table 1.

Table 1 Description of cases within the hypothetical case study.

Case	*Week no.*	*Installed PV unit capacity as a percentage of total annual electricity demand*	*Allowed export to market*
WiPV00	1^{st}	0%	no
WiPV50	1^{st}	50%	yes
SuPV00	25^{th}	0%	no
SuPV50	25^{th}	50%	yes

Cases WiPV00 and SuPV00 have with zero percent of installed capacity as a percentage of the total electricity demand and production facility is not allowed to offer the excess of electricity to the market. Therefore, from the market point of view, in these cases production facility is only a consumer. It can still have an influence on the price of electricity via the demand bids. On the other hand, in the cases WiPV50 and SuPV50, production facility acts like a prosumer (producer and consumer) from the market point of view. In these cases the installed capacity of the PV unit is chosen in such way that it produces 50% of the total annual electricity demand of the production facility.

Daily schedule for the production facility delivery is given in the following pattern:

$$n^{prod,dem} = [6 \quad 6 \quad 6 \quad 6 \quad 6 \quad 6 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 6 \quad 6 \quad 6 \quad 6 \quad 6 \quad 6] \times 10^3 \tag{24}$$

The amount of power from the PV unit is directly linked to solar insolation for a given location and can be expressed as

$$e_t^{PV} = A^{PV} \eta^{PV} e_t^{insol,m2} \tag{25}$$

The insolation per square meter is obtained from the Meteonorm Software (2015), and corresponds to average of four Croatian major cities: Zagreb, Split, Rijeka and Osijek. The case study assumption is that the CHP unit runs on gas and that the price of gas is constant for a simulated period. The price of gas is given on the basis of energy content. All model parameters for the PFM are given in Table 2.

Table 2 Inputs for the PFM.

Parameter	*Unit*	*Value*	*Parameter*	*Unit*	*Value*
p_t^{fuel}	[eur/kWh]	0.05	$X^{el.,prod}$	[1/kWh]	0.01
$\eta^{th,CHP}$	[-]	0.50	$X^{th.,prod}$	[1/kWh]	0.02
$\eta^{el,CHP}$	[-]	0.35	p^{PTH}	[eur/kWh]	0.0
η^{PTH}	[-]	0.95	$\underline{P^{imp/\exp}}$	[kW]	3 e5
$\overline{E}$	[kWh]	$\overline{P^{CHP}}\eta^{th,CHP}3h$	$\overline{P^{imp/\exp}}$	[kW]	5 e5
$\overline{n}$	[1/h]	8.0e3	$\overline{P^{CHP}}$	[kW]	1.00e6
$\overline{N}$	[-]	12.0e3	$\overline{P^{PTH}}$	[kW]	$\overline{P^{CHP}}\eta^{th,CHP}$
η^{PV}	[-]	0.15	p_t^{MCP}	[eur/kWh]	from the MM
A^{PV}	[m^2]	calculated	$\eta^{TS,in}$, $\eta^{el,CHP}$	[-]	0.95

From the objective function, Eq. (12), it can be seen that the cost of PTH over the direct offer of electricity to the market has to be defined. In this work it is defined as a cost resulting from the price difference between the MCP and the price of fuel needed for the same thermal input to thermal storage.

$$p_t^{PTH} = p_t^{MCP} - \frac{1}{\eta^{CHP,th}} p_t^{fuel} \tag{26}$$

Aggregated supply and demand by type, which serve as an inputs for the MM, are obtained from the simulation of Croatia's energy sector obtained in EnergyPLAN (Conolly et al., 2012) and downscaled to 25%, in order to enable the production facility to have comparable energy volumes as the rest of the energy system and to make the influence of production facility interplay with the market more visible. EnergyPLAN provides demand and supply by type in hourly resolution (Novosel et al., 2015b). The inputs are summarized in Table 3.

Table 3 Inputs by type for the MM, as obtained from the EnergyPLAN.

Supply		*Demand*	
Type	*Marginal cost* p_{is} [eur/kWh]	*Type*	*Offered price* p_{id} [eur/kWh]
Wind	0.00	Electricity	0.10
PV	0.00	Export (fixed)	0.02
River Hydro	0.005	Export	0.65
Dam Hydro	0.01	Production facility (q_{id}^{FM})	0.15
CHP	0.055		
Power plants	0.055		
Nuclear	0.025		
Import (fixed)	0.02		

Import	0.07		
Production facility (q_{is}^{PF})	0.00		

Production facility interacts with the MM through the q_{is}^{PF} and q_{id}^{PF}. These flows have the associated prices of 0.0 eur/kWh for supply and 0.15 eur/kWh for the demand bids. In that way it is ensured that bids and offers from the production facility will be taken into account for calculation of MCP. The inputs for the marginal costs on the supply and the offered price on the demand side are chosen arbitrary, but following the logic that inputs from renewables have zero marginal cost. Both the marginal costs and the offered prices are not changed between the hours of simulation.

3. Result and discussion

3.1. Coupling intensity between MM and PFM

Convergence of MCP over the iterations for four chosen hours is presented in Fig. 4. The convergence is clearly visible in the case of winter, and oscillation of results occur in summer hours. Probable cause of oscillations is non-linear dependence of MM and PFM through the variable p_t^{MCP}. Oscillations are more visible in the summer hours, where significant amount of cheap power from the PV unit is present, and the production facility is in the producer mode influencing the MCP in the next iteration. Despite the oscillations, a trend of MCP convergence is clearly visible, meaning that in winter hours increased demand from the production facility increases the MCP, while in summer week in the case of SuPV50 the MCP drops down by half. This is valid for the daytime at noon, since during the night there is no PV source of exporting energy and curves for WiPV50 and WiP00 overlap. Convergence of the MCP varies across the hours of simulation.

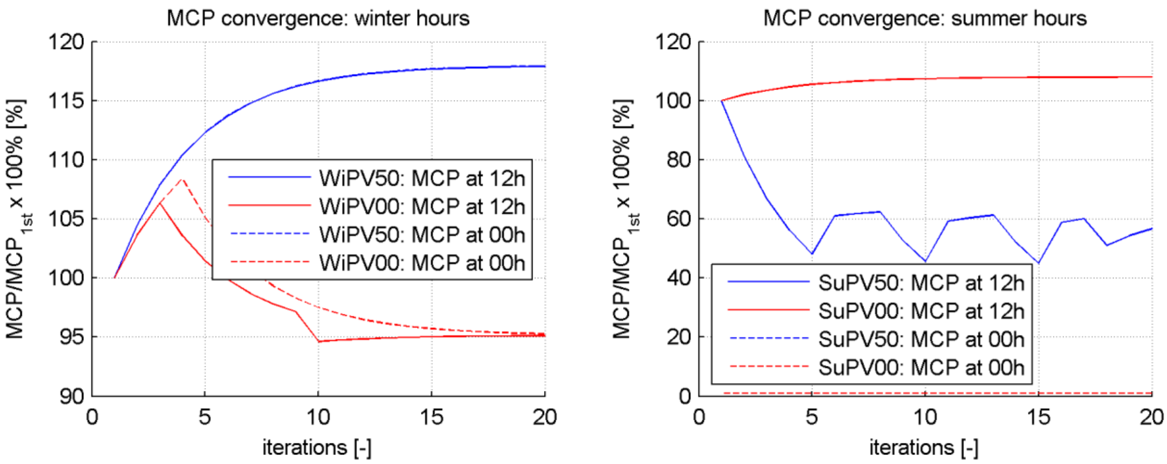

Fig. 4. Convergence of MCP for Monday at midnight and noon for winter and summer week; convergence is presented as a relative change with respect to the values at the first iteration

Coupling of the production facility (PFM) with the market (MM) model is illustrated in Table 4, which represents the ratio between production facility electricity supply and total market supply, as well as the ratio between the production facility electricity demand and the total market demand. The last column represents the ratio between the production facility supply to the market and total PV produced by the production facility. It can be seen that the demand share of PFM on the market, the second column, varies between one third of the total demand, except in the summer, where this ratio drops below one quarter. The drop of the ratio in second column shows the influence of the PV unit on reduction of overall demand on the market. Consequently, MCP is also reduced, since PV unit is offered at low *p*. Supply share of PFM on the market, the first column, is visible only for the case SuPV50, where supply holds a share of less than 10%., enough to reduce the MCP, Fig. 5. The small share can be explained by the fact that majority of the power from the PV unit is used directly for the PFM thermal and electric supply, while only quarter of the PV unit supply has been put to the market.

Table 4 Aggregated coupling ratio between MM and PFM.

Case	$\sum_{t=1}^{T} q_{is,t}^{PF} \Big/ \sum_{t=1}^{T} q_t^{\sup,MM} \times 100\%$ [%]	$\sum_{t=1}^{T} q_{id,t}^{PF} \Big/ \sum_{t=1}^{T} q_t^{dem,MM} \times 100\%$ [%]	$\sum_{t=1}^{T} q_{is,t}^{PF} \Big/ \sum_{t=1}^{T} e_t^{PV} \times 100\%$ [%]
WiPV00	0	34.21	0
WiPV50	0	34.21	0
SuPV00	0	33.54	0
SuPV50	8.14	22.09	22.54

Influence of the PFM on the MCP can also be estimated, since production facility in the prosumer mode is offering its energy, produces in the PV unit, at the zero price, thus reducing the MCP of the market. The magnitudes of MCP reduction are different in winter and summer weeks, as it can be seen in Fig. 5.

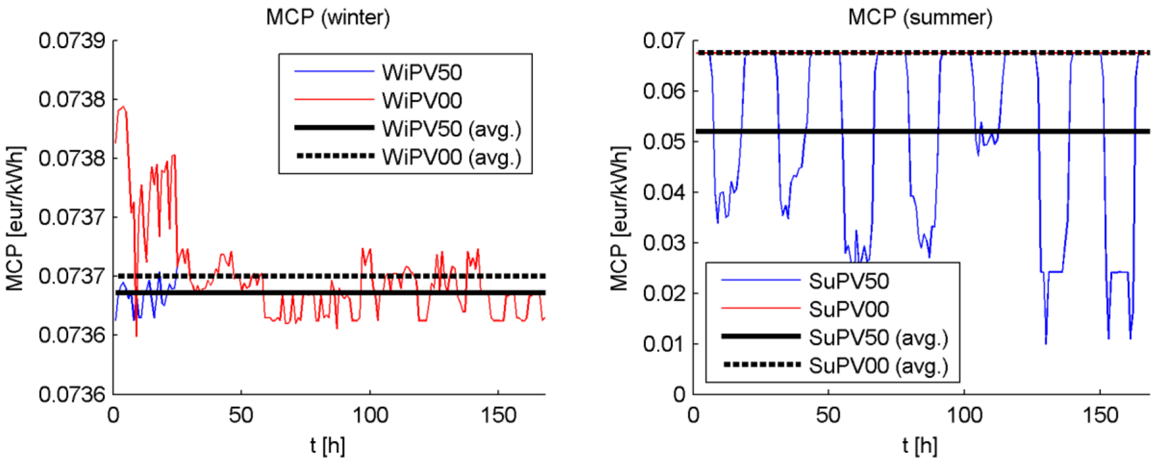

Fig. 5. MCP in winter and summer week.

The lowering of the MCP is more visible in the summer than in the winter week, since during the summer there is more solar irradiation and consequently more power production from the PV unit.

3.2. Influence of PV on production running costs

Results presented in Fig. 6 show that running costs are substantially lower if PV unit is part of the production facility.

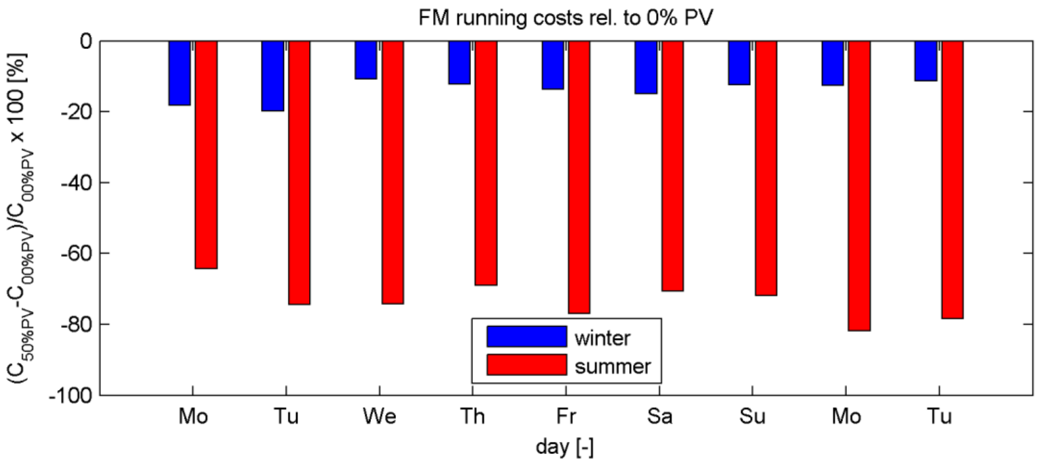

Fig. 6. Relative running costs between cases 50PV and 00PV.

The influence of the production from the PV unit is substantial, since in combination with market exchange it reduces the need for imports and enables extra income with market sales. The aggregated power flows for all cases is presented in Fig. 7. Comparison between the cases PV00 and PV50 for both the summer and winter week shows that power produced from the PV unit is rather used for reduction of external supply, like import from the market (q_d^{FM}) and CHP unit ($q^{el,CHP}$), than for direct sale to the market (q_s^{FM}.). Aggregated demand for products (q^{el}) is the same for all cases, since it does not depend on supply mix.

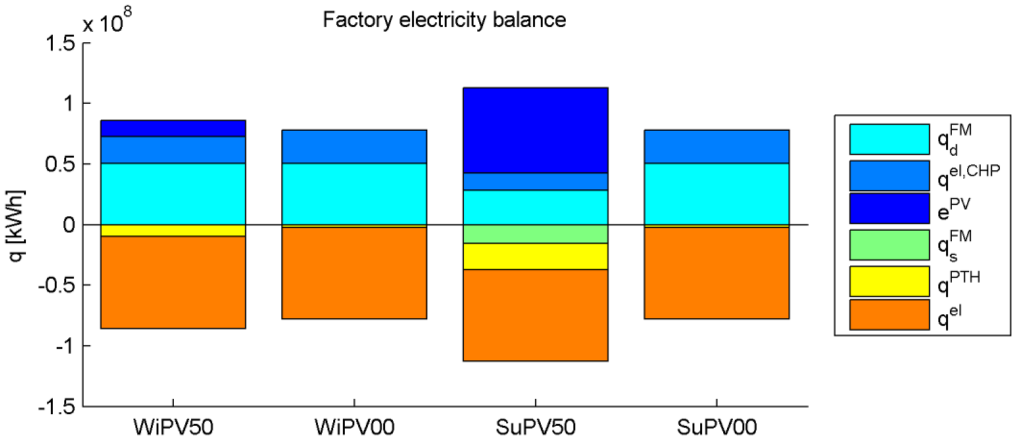

Fig. 7. Production facility electricity balance; values above the zero line are directing towards the bus; values below the zero line are directing away from the bus.

Fig. 8 shows running costs of the production facility, as well as sells to the market, expressed in monetary units. It can also be seen that net savings in production facility running costs is directly related to the amount of energy from the PV unit, indicating that for the current configuration majority of PV energy at zero marginal cost was used directly in the production facility, instead of being placed on the market. On the other hand, magnitude of savings between the cases WiPV50 and WiPV00 is lower than the ones between SuPV50 and SuPV00, which is directly proportional to the amount of irradiation collected by the PV unit, which is larger during the summer week.

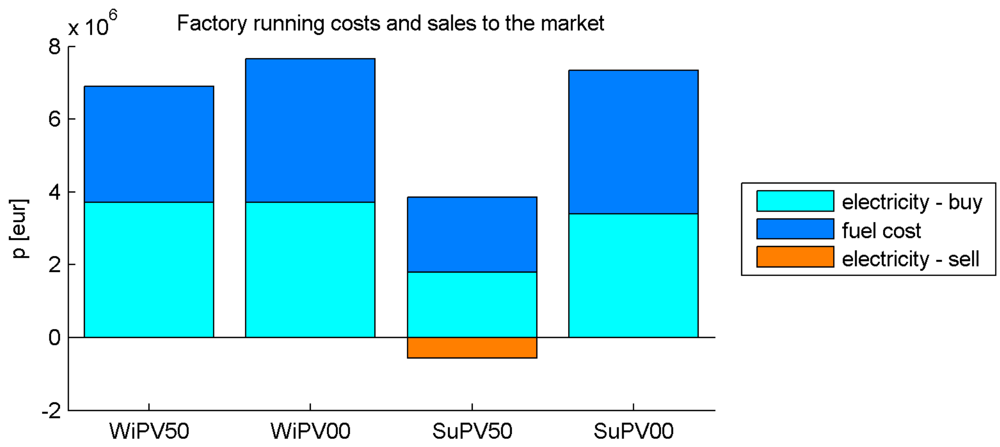

Fig. 8. Production facility running costs (above the zero line) and sales to the market (below the zero line).

The storage activity difference between the PV50 and PV00 cases is presented in Fig. 9, where qualitatively different behaviour between the cases can be observed.

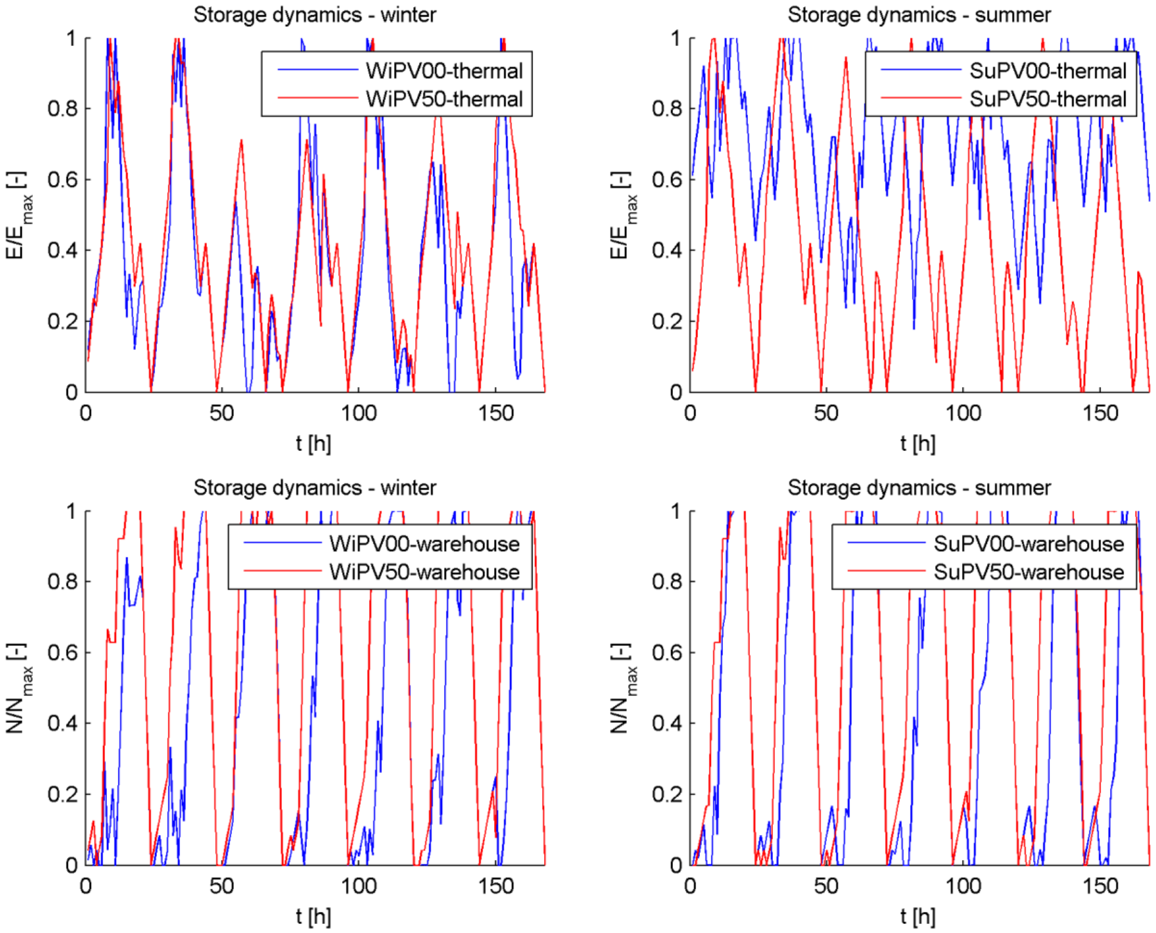

Fig. 9. Products and storage dynamics, PV50 vs. PV00.

It can be seen that for both cases storage levels for both the thermal storage and the warehouse are filled from zero to 100%, emptying during the night when MCP is lower and filling in during the day, when MCP is higher.

4. Conclusion

This work presents the coupled modelling approach for optimization of production facility running costs and maximization of social welfare through the MCP in the market modelling. The hypothetical case study has been presented, in which production facility demand was a combination of thermal and electric with presence of PV unit and market model was based on electrical energy balance for Croatia obtained from EnergyPLAN. Results show that the methodology presented in this work can capture the interplay between the two models, providing an estimation on expected running costs if production facility acts on a market as the prosumer or only as the consumer. It is shown that both the MCP of electricity and production facility running costs can be lowered if PV unit is a part of the production facility energy supply. Storage dynamics is also different if PV is present, meaning that both the thermal and products storage activity is also responsible for offsetting the higher values of MCP. However, convergence of the results has to be improved, since oscillations of the resulting MCP is present over the iterations. Oscillations are most likely a result of non-linear relation between the MM and the PFM and should be regulated only with under-relaxation factor and number of iterations.

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Figure and Table captions

Fig. 1. Problem formulation: coupling of the market and the production facility model.

Fig. 2. Demand and supply orders for one hour in the day-ahead electricity market.

Fig. 3. Coupling scheme between MM and PFM.

Fig. 10. Convergence of MCP for Monday at midnight and noon for winter and summer week.

Fig. 11. MCP in winter and summer week.

Fig. 12. Relative running costs between cases 50PV and 00PV.

Fig. 13. Production facility electricity balance; values above zero line are directing towards the bus; values below the zero line are directing away from the bus.

Fig. 14. Production facility running costs (above the zero line) and sales to the market (below the zero line).

Fig. 15. Products and storage dynamics, PV50 vs. PV00.

Table 1 Description of cases within the hypothetical case study.

Table 2 Inputs for the PFM.

Table 3 Inputs by type for the MM, as obtained from the EnergyPLAN.

Table 4 Aggregated coupling ratio between MM and PFM.