General framework for optimization of pipeless plant with integrated production scheduling and energy constraints

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Abstract

A pipeless batch processing production system uses mobile vessels to transfer the material between the processing stations. The plant performance depends on hardware of equipment and software of operation. The plant includes many design factors such as number of vessels, stations and AGVs, layout of stations, vessel moving rules, job scheduling. In this work, a general framework for optimization of pipeless plants with integrated production scheduling and energy constraints was proposed. Its goal is to define pipeless plant scheduling with energy management for demand response programmes. A methodology for the model is based on State Task Network and Mixed Integer Linear Programming problem formulation. The integrated problem formulation has been illustrated on one case study example drawn from the literature with different scenarios, considering electricity market integration, electrical energy storage integration as well as on – site renewable energy system integration. **Key Words:** flexible process, day – ahead electricity price, pipeless batch plant, energy constraints, smart grid, energy management, mixed integer linear programming, renewable energy, electrical energy storage, demand side management.

1. Introduction

The manufacturing trend nowadays is facing towards a sustainability and flexibility in production because of the higher demand of tailor-made products. The quick adaptability to the market changes is of a big interest of many manufacturing utilities, due to potential of improving the productiveness of a batch plant, and this reason led to increased popularity of multipurpose batch plants. However, the flexibility of the batch plants can be limited due to the need of pipe network cleaning, especially in the fine chemical industry (Schiffelers et al. 2002) and therefore the concept of pipeless batch plants was introduced.

The decreasing price of the on – site renewable energy generation systems and attractive financial plans has made it reasonable for bigger scale utilities to install renewable energy generators and produce the electricity or heat from RES. In the modern EG, the prosumers can also sell the excess of energy to the grid or store it in the EES (Avancini et al 2019). The big amount of electricity produced from Photovoltaic (PV) panels that is injected in grid can however produce a voltage disturbances or fluctuations and possibly destabilize the grid (Conteh et al 2017). These reasons among others has made it urgent to establish the Demand Response (DR) programs in the industrial sector in order to help Distribution System Operators (DSO's) stabilize the electrical grid as well as help industrial facilities make the energy costs reduction. Based on that, in the presence of DR programs, Industrial Customers (IC) can buy and sell energy with various bidding systems available on various spot electricity markets such as Nord Pool, which is currently one of the main leading day – ahead power markets in Europe (Nord Pool 2019). The main challenge of DR for IC is the higher priority of industrial facilities to sustain a reliable production. Thus, the appropriate integer models need to be investigated in order to see how the allocation of the machinery could be shifted in time from peak periods to off-peak periods in order to minimize the total production cost associated with energy consumption and what is extremely important - to meet the external requirements of the production.

The mathematical formulation model for short - term production scheduling of the discrete pipeless batch plant with energy constraints based on State Task Network (STN), Smart Grid (SG) and Demand Response (DR), considering Renewable Energy Sources (RES), Electrical Energy Storage (EES) and day-ahead electricity market was developed, and the comprehensive and generic Mixed Integer Linear Programming (MILP) formulation model was investigated.

1.1 Problem statement

The optimal production, Electrical Energy Storage (EES) and electricity market schedule can be obtained by solving the following problem.

Given:

1. Operating information of the pipeless plant:
   - The State Task Network of the industrial process
   - The illustrative plant topology
   - The stations' suitability to perform the process tasks
   - Processing time of each task
   - Initial amount of raw materials available
   - Operating points of each task
   - Amount of material produced and consumed by each task associated with operating point
   - Vessel types
   - The number and capacity of each vessel type
   - Unit price for a delivered product
2. Operating information of energy demand:
   - Tasks' electricity demand
3. Operating information of electrical energy storage unit:
   - Maximum Storage Capacity
   - Maximum Charging Rate
   - Maximum Discharging Rate
   - Charging Efficiency
   - Discharging Efficiency
4. Operating information of on-site electricity generation unit:
5. Forecasted within 24hour range electricity generated from PV panels
6. Operating information of electricity market integration:
   - Forecasted within 24hour range buying and selling price of electricity from and to the electrical grid.

Determine:

1. The production schedule making use of selected resources to achieve the production requirements, minimize the energy cost and

assure the appropriate station allocation sequence.
2. Total profit dependent on the product delivery price and the energy cost.
3. EES unit schedule based on defined characteristics.
4. Electricity market integration schedule.

In order to optimize the economic performance of the plant, measured in terms of energy consumption.

2. State of art

There is currently no paper available with integrated pipeless plant scheduling with energy constraints. About the pipeless plants there were found several articles regarding scheduling. Energy efficiency and batch plants can have a lot in common and that has never been confirmed, which this work gives its attention – to check the suitability of pipeless plant for DR programme.

2.1 Pipeless and batch process characterization

Pipeless batch plants main characteristics consist in the use of movable vessels that move on dedicated tracks and transfer the processing material between various processing stations (Majozi, 2010). The concept of the pipeless plant is not new and had been incorporated in the early 80's in the coating factories, lubrication oil or adhesives factories (Ciprian, 2003). It had been developed further by Japanese engineering firms: Asahi Engineering, Toyo Engineering or Mitsui Toatsu Chemicals (Cybulski, 2001). According to Ciprian et. al. there could be around 20 pipeless plants under operation in Japan. Pipeless plants were also used in the photographic film or paper production.

Mobility of pipeless batch plant is a very important aspect and has several advantages:

- The process operation order can be easily modified by changing the path between different processing stations which increases the speed of product and process development through less complicated pipeworks.
- Pipeless plants can find an application whenever the transport of the substances through pipes can be difficult.

There are also several concerns regarding pipeless plants:

- The needs of fixed electrical wiring structures that power the stations and vessels.
- The initial capital costs can be potentially higher and dependent on the transport system.
- Safety requirements specifications related with hazardous materials.

2.2 Energy efficiency in the industrial sector

Some of the batch operations like for example brewery or diary are as much energy intensive as continuous processes (Migon, 1993).

In general, methods of improving the energy efficiency in the industrial sector can be divided into three categories (Mohammad, 2018): Technical and technological improvements, Policy making and behavioural training; Industry Energy Management System (IEMS) are three main methods of improving the energy efficiency in the industrial sector (Mohammad, 2018).

1. Technical and technological improvements in batch processes

Those include energy audits or waste heat recovery at the process level through a heat exchanger between two reaction stations (direct) or an energy storage medium (indirect).

In the context of pipeless plant, there has never been done any investigation regarding the energy optimization of these kind of plants – this is due to rather small amount of actual plants under operation There could be a possibility for heat integration inside the pipeless plant through heat exchanger network, but this area has been already well researched in the context of batch plants.

2. Policies and behavioral training

Policies can encourage the industrial management facilities to decrease their environmental impact by for example providing subsidies for the integration of RES or implying penalties such as carbon taxes. What is more, DR programmes can be implemented further to increase the attention of industrial facilities and shift the peak demand (Dranka, 2019).

The DR potential implementation in the industry is highly recommended for batch processes with large storage capacities and bottleneck processes i.e. the processes that cause the entire process and the production rate to slow down. (Hasanbeigi, 2017).

The pipeless plants are very well suited for integration with DR programmes because of their flexibility in the production of several different products through batch processes. Their internal capacity for storing the material together with the bottleneck in production process are another main characteristic that make pipeless plants suitable for integrating with DR policies.

3. Industry Energy Management System (IEMS)

Abovementioned areas of interest need a common system that connects every operational aspect of an industrial plant and is necessary to take advantage of Distributed Energy Resources (DER) and DR - Industrial Energy Management System (IEMS). IEMS refer to any system that contributes to the integration of every energy generation and storage unit inside the policy framework such as DR.

2.3 Conclusions

Pipeless plants exist already, mostly in Japan. They have a wide range of benefits over the typical batch plants in terms of flexibility. There are several common characteristics that pipeless plants processes have similar with other industries, so the DR programs are recommended to be applied. Based on that, the further work will fulfil the literature gap by investigating the DR program applied to pipeless batch plant with RES, EES and day ahead electricity price market integration.

3. Methodology

State Task Network (STN) is a process representation by using rectangles – tasks – and circles - states. To illustrate the STN representation an illustrative example is used, Figure 1. The task denoted by mixing and reaction are depicted in the rectangles. Circles represent the all the states that raw materials obtain before they were processed or after. In the illustrative example, State 1 (S1) was mixed with State 2 (S2) and State 3 (S3) was obtained. After the "Mixing" Task completed, State 3 (S3) was produced. During the reaction, State 4 (S4) and S3 were added into the reactor so at the end, the State 5 (S5) was produced.

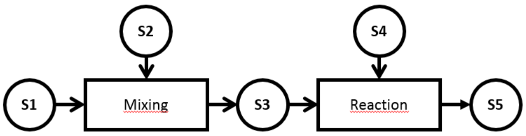

Figure 1 - STN

The physical pipeless plant is considered inside the black rectangular as shown in the Figure 2. Inside that rectangular, there is the whole production plant inside the red frame (pipeless process State Task Network). Inside the plant, there is an energy management system (EMS), energy generation system (EGS) and electrical energy storage system (ESS). EMS is connected to the utility database, Industrial Process(IP), EGS and ESS through internet, as well as electrical grid through Smart Meter (M). This allows for constant monitoring and information exchange about the energy consumption of the plant, energy generated, energy stored. energy purchased or sold back to the grid. Based on that, the electricity can be bought or sold to the grid and the performance of the plant can be optimized in order to reduce the energy cost. EGS is a physical place which contains a PV System. Electrical Energy Storage system (EES) is a physical place where there is a storage unit installed.

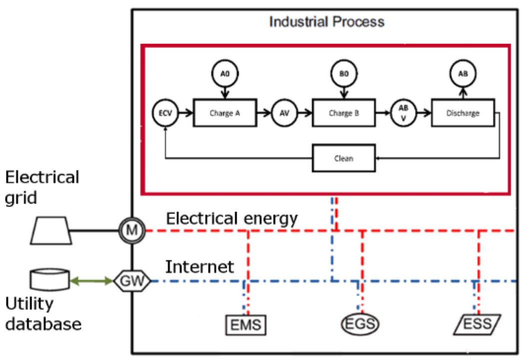

Figure 2 - System under study

4. Mathematical Formulation

The simultaneous production schedule with renewable energy, electrical energy storage and electricity market integration for discrete – time pipeless batch plant was modelled as a MILP problem with different sets of operational (Pantelides, 1995) and energy constraints (Ding, 2014).

The Figure 3 illustrate the STN applicability in energy consumption over operating points. The task i consumes s1 and have electricity demand associated with the amount of material transferred. It can hold up to M operating points.

Operating Point 1(op_1) does not consume or produce any material and has 0(kWh) electricity demand. Op_2 consumes or produces 20 percentage of the total vessel capacity (totV) and consumes 55 (kWh) of energy. Op_3 consumes or produces more than Op_2 and consumes 550 (kWh).

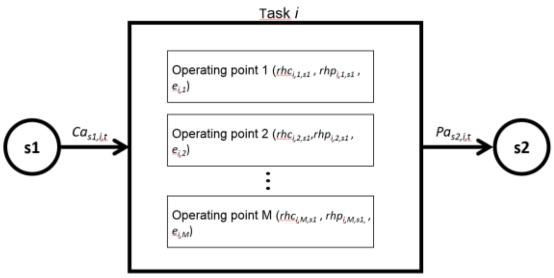

Figure 3- Operating points scheme

Electrical Energy Storage (EES) stores electricity when the price is and supply electricity to industrial processes or sells electricity back to the grid when the price is high. α is a charging efficiency and β is a discharging efficiency, Figure 4.

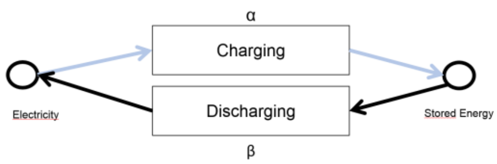

Figure 4 - Energy Storage scheme

5. Case study

The following case study example was drawn from literature (Pantelides, 1995) in order to show the model applicability. Three scenarios were explored with delivery requirements specified in the Table 1.

Table 1 - Deliveries Requirements

Deliveries Requirements	
Minimum amount of delivery within time interval	10 (m^3)
Maximum amount of delivery within time interval	350 (m^3)
Unit price of product AB	1500 (€ / m^3)

Table 2 - Scenarios comparison

Scenario	*Grid Connected*	*EES Unit*	*PV System*
Baseline	X	-	-
a)	X	X	-
b)	X	X	X

A pipeless plant is to be designed at a maximum profit to produce product AB from two raw materials A0 and B0 as shown in the STN as in the Figure 5.

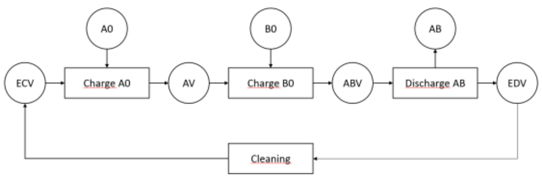

Figure 5 - STN of the process

In the Figure 6 the illustrative plant topology with vessel movement sequence was shown.

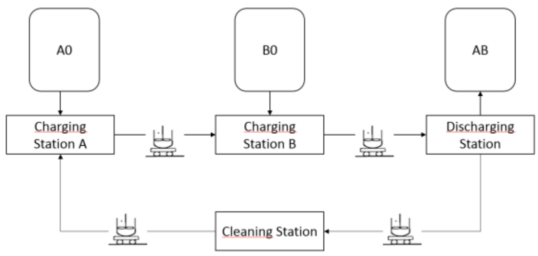

Figure 6 - Illustrative plant topology

Each processing station was equipped with various rotor speed pumps to transfer the different amount of the material expressed as a fraction of the total vessel capacity ($rhp_{i,op,s}$/ $rhc_{i,op,s}$) between the vessel and the corresponding processing station. The electricity demand was dependent on the different rotor pumps speed and associated with their operating points' electricity demands that were listed in the Table 3 and 4.

Table 3 - Operating points electricity demands

Station (j)	***Operating Point (op)***	***Electricity Demand ($e_{i,op}$ kWh)***
Charging station A	1	0
	2	55
	3	500
Charging station B	1	0
	2	55
	3	500
Discharging station	1	0
	2	55
	3	500
Cleaning station	1	0
	2	55

Table 4 - Operating points amount of material consumed and produced

Station (j)	***Operating Point (op)***	***Amount of state consumed / produced ($rhc_{i,op,s}$ / $rhp_{i,op,s}$)***
Charging Station A	1	*0*, 0 / 0
	2	*0*, 0.2/ 0.2
	3	*0*, 0.3/ 0.3
Charging Station B	1	0, 0/ 0
	2	0.2, 0.2/ 0.4
	3	0.3, 0.3/ 0.6
Discharging Station	1	0 / 0
	2	0.4 / 0.4
	3	0.6 / 0.6
Cleaning Station	1	*0 / 0*
	2	*0 / 0*

The information of the forecasted prices is a necessary for the model in order to find the cheapest possible patterns of the production schemes, Figure 5. Solar energy generation was forecasted throughout the day, Figure 6. The electrical energy storage parameters were listed in the Table 5.

Table 5 – EES parameters

Electrical Energy Storage Parameters

Maximum storage capacity (kWh)	6000
Maximum charging rate (kWh)	1500
Charging efficiency (-)	0.9
Maximum discharging rate (kWh)	1500
Discharging efficiency	0.9

Day-ahead hourly prices for buying and selling electricity

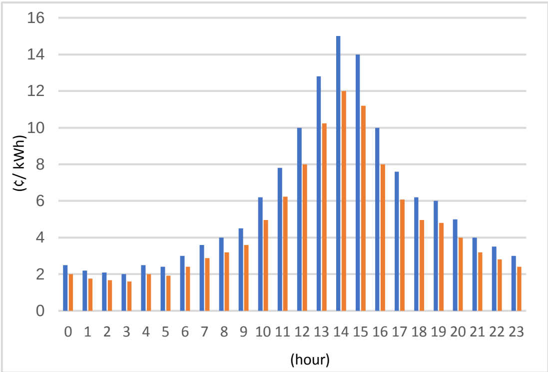

Figure 7 – day ahead prices for buying and selling electricity

Solar electricity generated

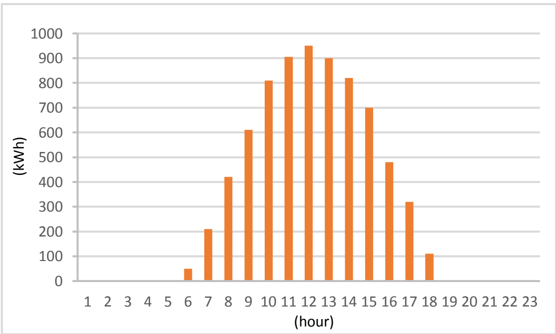

Figure 8 - Solar electricity generated

5.1 Case study results

The Gannt chart was presented in the Figure 9, from which it is possible to analyse the processing stations allocation during the whole-time horizon and vessel tracking – each vessel has its own colour, Table 6.

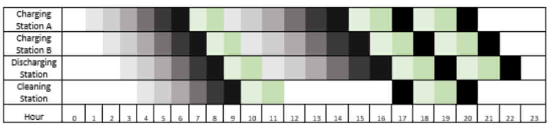

Figure 9 - Gannt chart

Table 6 - vessels colors

	Vessel no. 1		Vessel no. 5
	Vessel no. 2		Vessel no. 6
	Vessel no. 3		Vessel no. 7
	Vessel no. 4		Vessel no. 8

Figure 10 shows the total electricity demand and the buying price for electricity for the baseline case. The demand was shifted from peak hour price period to the lower price period.

Total Electricity Demand. Case study: baseline scenario

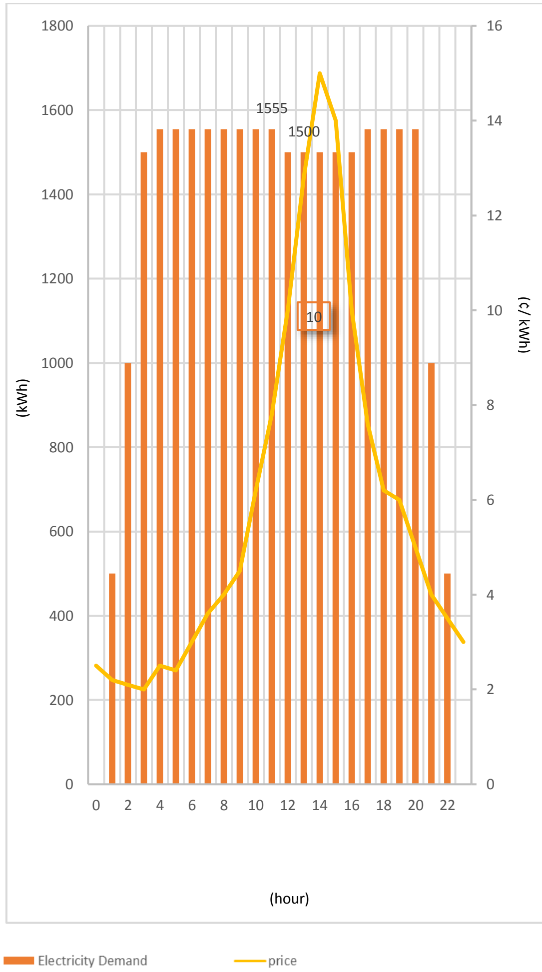

Figure 10 - Total electricity demand: baseline scenario

In the Figure 11 the energy flow analysis for case b) was presented. During the whole horizon the total energy demand was fulfilled by trading the energy with EES. Energy flow analysis for scenario c) which includes a PV and EES was shown in the Figure 12. Scenarios comparison was shown in the Figure 13.

Energy flow analysis: scenario b)

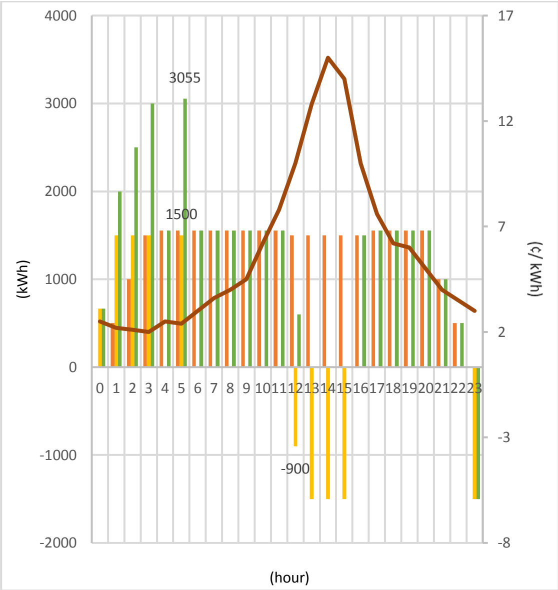

Figure 11 - energy flow scenario b)

Energy flow analysis: scenario c)

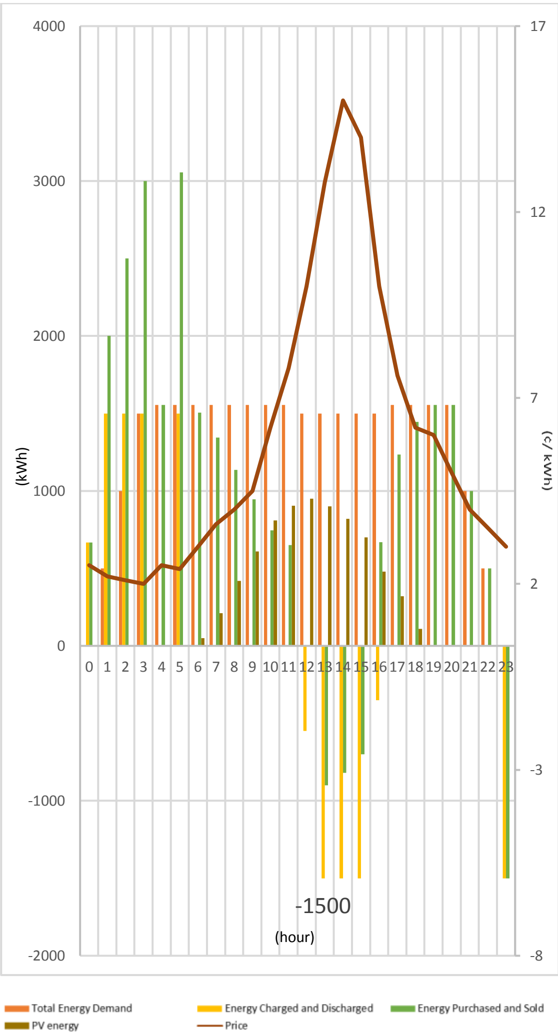

Figure 12 - energy flow analysis: scenario c)

In the Figure 12 the EES' energy charged, and discharged schedule was presented. Positive values represent the situation when EES was charged and negative values when EES was discharged during the time horizon. In the table 7 the optimization results were shown.

Energy Purchased and Sold: scenarios comparison.

Figure 13 - Energy Purchased and Sold

Energy charged and discharged: scenario b) and c)

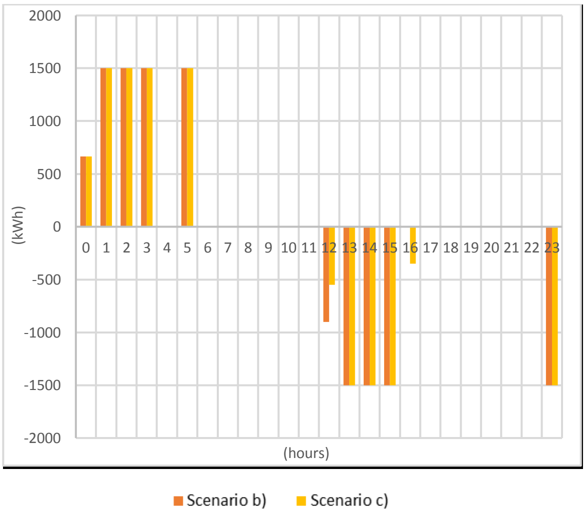

Figure 14 - EES schedule

Table 7 - Optimization results

Variable	*Baseline*	*Scenario b)*	*Scenario c)*
Total profit (€)	178039,31	178645,14	179262,36
Total energy cost (€)	1960,84	1355,01	737,78
Total amount of deliveries (m³)		120	

5.2 Case study conclusions

The Gannt Chart (Figure 7) showed that Charging Station A0, Charging Station B0 and Discharging Station were operating through around 83 (%) of the whole-time horizon at the Operating Point 3 (op_3) Cleaning tasks which took place at Cleaning Station were shifted in time to the off-peak hours. For the base scenario, 100 (%) of all the electricity demand needed to be covered by only buying the electricity from the grid at every time interval, due to lack of EES and PV system installed. For the scenario b) it was noticed, that more energy could have been bought in the lower price periods and then used when the buying electricity price was higher. The scenario b) with only EES takes the whole advantage of DR programme. What is more interesting, for the scenario c) with EES and PV system installed, the renewable energy source allowed not only for reducing the electrical consumption from the grid during the sunlight hours, but also for selling the excess of the energy back to the grid when the price was the highest and thus obtaining the best operational results. The objective function values for each scenario – a final comparison, Table 7 - showed that just by installing EES the operational cost of energy could be decreased by around 31(%) which in the case study corresponded to savings of around 605 (€) per day. Adding the on – site renewable energy system such as PV can further decrease the primary cost of energy by around 63 (%) which corresponded to the savings of around 1223 (€) per day in the case study.

6. Conclusions and future work

The following work contains a general framework for optimization of pipeless plant with integrated production scheduling and energy constraints. Pipeless plants topic is not well investigated – there are only several examples of existing pipeless plants in several different areas such as photography and film industry. The integration of PV panels and electrical energy storage system together with energy management system was suggested, in thought of making operational savings to decrease the payback time of the capital invested. Therefore a MILP model resolves the issues of production scheduling and EES scheduling integrated with the day-ahead electricity market. The optimized schedule of EES together with PV and DR decreases the operational costs of the pipeless plant related with energy use. The method gives significant advantages in the energy systems management and helps to implement the production management patterns that will reduce the operating cost of the pipeless plant. From the results obtained, it was concluded that it is highly recommended to be participant of DR programme for industrial customer who owns a pipeless plant and it would not affect the required production goals. By integrating on – site renewable energy systems together with EES in the pipeless plant, the operational profits could be further optimized. In this work the layout of the plant was not investigated. The future work would explore the more detailed analysis in the context of the pipeless layouts with integrated energy constraints. The future analysis could involve also fossil fuel generators such as diesel engines. The work can be developed also to assess the performance of this approach for more complex STN and pipeless plant topologies.

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