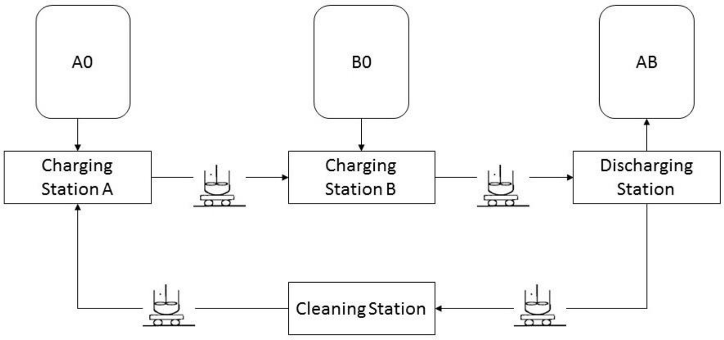

General framework for optimization of pipeless plant with integrated production scheduling and energy constraints

Mixed Integer Linear Programming Model

Hubert Bolesta

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisor: Prof. Tânia Rute Xavier de Matos Pinto Varela

Examination Committee

Chairperson: Prof. Duarte de Mesquita e Sousa

Supervisor: Prof. Tânia Rute Xavier de Matos Pinto Varela

Member of the Committee: Prof. Nelson Chibeles Martins

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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 program, renewable energy, electrical energy storage, demand side management.

Um sistema de produção de processamento em lote sem tubulação utiliza embarcações móveis para transferir o material entre as estações de processamento. O desempenho da planta depende do hardware do equipamento e do software de operação. A planta inclui muitos fatores de projeto, como número de embarcações, estações e AGVs, layout das estações, regras de movimentação de embarcações, programação de tarefas. Neste trabalho, foi proposta uma estrutura geral para otimização de plantas sem tubulação com programação de produção integrada e restrições de energia. Seu objetivo é definir a programação da planta sem tubulação com gerenciamento de energia para programas de resposta à demanda. Uma metodologia para o modelo é baseada na formulação de problemas de "State Task Network" e Programação Linear Inteira Mista. A formulação integrada do problema foi ilustrada em um exemplo de estudo de caso retirado da literatura com diferentes cenários, considerando a integração no mercado de eletricidade, a integração do armazenamento de energia elétrica e a integração do sistema de energia renovável no local. Palavras-chave: processo flexível, preço da eletricidade no dia seguinte, planta em lotes sem tubulação, restrições de energia, rede inteligente, gerenciamento de energia, programa linear inteiro misto, energia renovável, armazenamento de energia elétrica, gerenciamento do lado da demanda.

Palavras-chave: processo flexível, preço da eletricidade no dia seguinte, planta em lotes sem tubulação, restrições de energia, rede inteligente, gerenciamento de energia, programa linear inteiro misto, energia renovável, armazenamento de energia elétrica, gerenciamento do lado da demanda.

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Nomenclature

AGV	Automated Guided Vehicle
CCHP	Combined Cooling Heat and Power
DER	Distributed Energy Resources
DOP	Determined Operating Point
DR	Demand Response
DSO	Distribution System Operator
EG	Electrical Grid
EGS	Energy Generation System
EMS	Energy Management System
ESS	Energy Storage System
h	Hour
IC	Industrial Consumer
IDSM	Integrated Demand Side Management
IEMS	Industrial Energy Management System
IP	Industrial Process
IS	Industrial Sector
M	Smart Meter
MILP	Mixed Integer Linear Program
NEGS	Non – Schedulable Energy Generation System
PV	Photovoltaic
RES	Renewable Energy Sources
SEH	Smart Energy Hub
SG	Smart Grid
SSN	State Sequence Network
STN	State Task Network
TED	Total Electricity Demand

1 Introduction

In this chapter the background and context to help understand the problem was presented. In the Section 1.1 the problem statement with all the inputs and outputs for the developed formulation was presented. In the section 1.2 the main project goals were outlined. Finally, in the section 1.3 the chapters in this thesis were introduced.

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 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.

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.

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 STN of 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:
   - Forecasted within 24hour range electricity generated from PV panels
5. 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.

1.2 Objective of the thesis

The purpose of this thesis is to develop a general formulation for pipeless plants, using a State Task Network representation and Mixed Integer linear Programming for integrated production scheduling with energy constraints of a pipeless batch processing plant. The aim is to understand the benefits and obstacles of demand response program as well as the influence of on-site renewable energy systems and electrical energy storage for the final production costs in this type of plants.

1.3 Thesis outline

This project is composed of five major chapters.

- The first chapter describes the background and context of the problem under study, striving to set the baseline for this work. It includes the characterization of the problem including the connection between several different aspects such as renewable energy, pipeless plant and electricity markets.
- Second chapter provides a state of the art regarding:
    - batch process characterization
    - pipeless plants
    - energy efficiency in the industrial sector

  Pipeless plants' characteristics were studied. Literature review regarding scheduling of the pipeless plants as well as the existing pipeless plants and industries that used pipeless plants were found. The pipeless adaptability to Demand Response programmes based on similarities with batch processes in the context of cement plant and textile plant was studied. Possible technologies for the energy integration for pipeless plants were discussed. Based on that research, the further work development was set, in order to meet the objectives set in the first chapter.
- Third chapter explains the methodology used to develop this thesis. The general approaches for recipe representation - State Task Network – was introduced. The developed system under study was explained and the approach for Integrated Demand Side Management was shown.
- Chapter four outlines the developed mathematical model. The formulation was developed and adapted based on the assumptions of the methodologies described in the chapter 3 and two literature examples of :
    - Scheduling of pipeless plant (Pantelides, 1995)
    - A Demand Response Energy Management Scheme for Industrial Facilities in Smart Grid (Ding, 2014).
- In the chapter 5 the case study was developed to prove the model applicability. The example of the pipeless plant scheduling problem with on – site Photovoltaic system, electrical energy storage unit and day-ahead electricity market was solved and the results were discussed and analysed.
- Finally, in the last chapter 6 the main conclusions were presented, and future work discussed.

2 State of the art

The research about the pipeless plants and batch processes was conducted and in the section 2.1 its results were presented. Based on the research, there has never been done any integrated production scheduling with energy constraints for pipeless plant. The next topic of the research was based on the literature review regarding energy efficiency in the industrial sector and its results were presented in the section 2.2. Finally, based on the two main research areas, in the section 2.3 the conclusions regarding the energy integration in the pipeless plant were presented and the further work development areas were defined.

2.1 Pipeless and batch process characterization

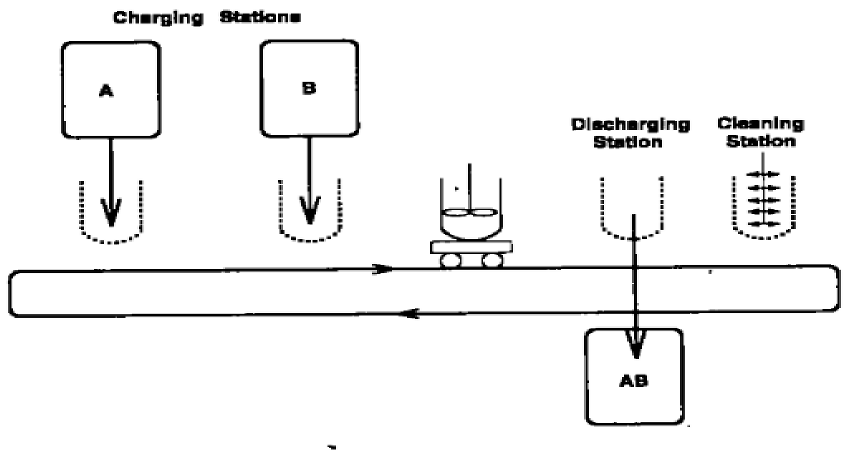

Figure 1 - Pipeless plant example (Realff, 1996).

Batch process is any process which is the result of discrete tasks that must track a predefined sequence from raw materials to final products – a recipe (Majozi, 2010). A comprehensive recipe consists of the information about quantities of materials that must be processed by individual tasks as well as duration of each task within the recipe together with various operating conditions of different tasks. There are several ways of presenting the recipe of batch products. The most common – State Task Network (STN) - was presented by Kondili et al. (1993). The method constitutes of 2 types of nodes, namely state nodes and task nodes. State nodes such as feeds, intermediates or final products represent all the processed materials in the plant and are usually depicted in circles. Task nodes are usually represented as rectangles and represent the unit operations or tasks that are made with the use of equipment in the plant. There are also other available recipe representations in the literature. Majozi and Zhu (2001) proposed State Sequence Network (SSN) that is very similar to State Task Network but with the difference that the tasks are not explicitly declared but rather indirectly inferred by the state changes.

There are two main types of batch plants: multiproduct and multipurpose batch plants (Majozi, 2010). In a multiproduct batch plant, each produced batch follows the same sequence of unit operations from raw materials to final products. This way of producing is perfect for products with identical and fixed recipes. For the recipes of products which may vary along the production line, the better design choice is multipurpose batch plant. Multipurpose batch facilities are more appropriate in the manufacture of products that vary in recipes – it is worth noting, that the same product can have various recipes. Usually, the multipurpose batch facilities are more complex not only from an operational perspective but also from mathematical formulation that describes the multipurpose batch processing system. The way the time is handled in the design process of a batch plant is a crucial design assumption. Fixed time approach assumes that the time intervals are known a priori, and the time horizon is discretized evenly (Majozi, 2010). This approach is a simplification if the processing times and are not dependent on the batch size.

In the Figure 1 the pipeless plant that consists of 4 processing stations, three dedicated storage tanks and one movable Automated Guided Vehicle (AGV) was illustrated (Reallf, 1996). 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 stations are used for several different types of operations, for example: filling, blending, heating, cooling, discharging and vessel cleaning at the end of the process. Their internal adaptability to sudden changes, suitability to share common equipment units and the products that can be characterized by the common recipes, together with their high flexibility, trigger that these kind of plants are well suited for low volume and high value-added products and could make them processes of choice in a volatile and changing conditions of a current global markets.

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 and in 1993 the Eastman Kodak Company released a patent for producing photographic film or paper which used the movable vessels for propulsion preparation (US Patent no. 5.339.875, 1993).

To illustrate it more conveniently, the actual pipeless plant can be equated to a chemical laboratory where chemists move around a stationary equipment such as beakers or flasks in which complicated procedures of for example synthesizing a product are performed – in this case the chemists can be compared to movable vessels. Units of the plant need to be precisely positioned because layout of the plant determines the transfer times between the stations (Dimitrios et al. 2005). Several examples of different possible layouts can include herringbone, linear or circular layouts.

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.

- What is more, pipeless plants reduce the problem of cross-contamination as well as contamination by previously used substances (Ciprian, 2003).
- By minimizing the amount of pipework's, the flexibility of the production process efficiency can be increased, and the complexity of cleaning equipment can be reduced (Liu, 1996).
- Pipeless plants can find an application whenever the transport of the substances through pipes can be difficult.

Some works described the use of pipeless plants as a substitute for one step in the whole chemical process (Niwa, 1993). There has not been too many examples of potential commercial use and only low complexity processes has been carried in pipeless plants due to several reasons:

- Technical difficulties related to the safety operation of reactions that needed to be carried out in closed containers and under pressure (Ciprian, 2003).
- 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.

The automation level of pipeless plants makes the use of production planning and process control systems very useful. Vessels which are equipped with control computers can exchange the information between each other. The control algorithm defines the vessels' routing paths in order to meet the final production requirements as well as to avoid the collisions. Production process can be described using STN introduced by Kondili et al. (1993) which can be then translated into a MILP problem.

In the literature, there are several works for scheduling the operation of pipeless plants. Short Term Scheduling of Pipeless Batch Plants introduced by Pantelides et al. (1995) was one of the first attempts to address this problem. Authors of this work developed a scheduling algorithm based on the STN and general algorithm for short term scheduling of batch operations. The process and transportation times in this work were fixed and known a priori and the time horizon was divided into equal length intervals. The work was concerned about the design of the pipeless plant in order to maintain necessary levels of the different resources in such a plant. The objective function sought to optimize the economic plant performance by maximizing the net present value of the investment, which was a subject to fulfill the production requirements for one or several products considered. That work did not take the design of the plant into consideration. In the work of Realff et al. (1996) a simultaneous approach for the design, layout and scheduling of the pipeless plant was discussed. Authors assumed the general geometry by defining the shape of the available space. Another assumption was made for the processing times to be fixed and known before. All the previously mentioned scheduling algorithms were predictive i.e. the times of the transfer between the stations or processing times were fixed and known a priori. However, there could be unexpected events or stochastic variations of the processing or transport times between the processing stations. Schiffelers et al. (2002) presented an approach for a dynamic scheduling in a pipeless plant with feedback information on the state of reactions, where the times were treated as variables depending on the state of the reaction. In his work, the copolymerization production process was used as a case study for the layout study of the pipeless plant. More recent work regarding scheduling of pipeless plants found was the work of Shaik et al. (2018) in which authors developed a general framework for optimization of pipeless plant with integrated production scheduling and routing vessels. So far, there was no energy constraint integration in the scope of scheduling a pipeless batch plant.

2.2 Energy efficiency in the industrial sector

The increased popularity of batch processes together with the new environment regulations increased the need of energy optimization for discrete manufacturing systems. In general, batch processes were thought to be less energy intensive than counterpart continuous processes. However, some of the batch operations like for example brewery or dairy 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)

1. Technical and technological improvements in batch processes

Technical and technological improvement methods can increase dramatically the efficiency of the industrial plant. 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).

Process Integration techniques for energy optimization in continuous processes have been known and applied successfully for more than 3 decades (Majozi, 2010). Some of the typical graphical methods are Pinch Analysis, Mass Exchanger Network Analysis or Water Pinch. In the Batch Processes these methodologies however cannot be accurately used because of the time dimension that is overridden in the beforementioned methodologies. In fact, the most challenging aspect of the process integration is to capture the essence of the time, because of the discrete nature of the tasks. For the discrete type of manufacturing facilities, several works have been done in the area of technical and technological improvements of the discrete manufacturing processes. Very early attempt to characterize heat integration in Batch Processing was introduced by Vaselenak et al. (1986). The article addressed the problem of predicting the maximum heat integration in batch processes with co-current, countercurrent and mixed cases of heat exchange in batch processing vessels. The maximum heat transfer was obtained for countercurrent case. When there was no possibility of countercurrent exchange, the mixed case was preferred rather than concurrent heat exchange. The reasoning presented has shown how important is the trade-off between the cost of a spare tank and energy savings. The heuristic approach provided a tool to evaluate scheduling and heat integration in various combinations of heat exchange between vessels in batch plants. The direct and indirect heat integration was introduced by Papageorgiou et al. (1994). In his work, the operation of multipurpose batch plants was investigated inside the framework of general scheduling formulation with both types of heat integration. The conclusion was that both, direct and indirect heat integrations can coexist inside the same plant. In the work of Pinto et al. (2003) the problem of heat integration in multipurpose batch facilities was investigated and the MILP problem was formulated. In this work, the optimal plant topology was obtained as well as optimal heat transfer policies and heat transfer auxiliary equipment associated areas. Majozi (2009) proposed a mathematical technique for optimization of energy use in the multipurpose batch plants with the predefined size thermal energy storage units. The technique implemented in the agrochemical facility for the case study has shown savings of more than 75(%) in external utility steam consumption.

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.

In the pipeless plants, there were mentioned the problems with fixed electrical wiring structures (Ciprian, 2003). Nowadays, it is very possible to adapt the technologies that are being currently used and developed in other sectors such as Electric Vehicles and Wireless Power Transfer. Based on this assumption, the stations and vessels would use more electrical loads rather than heating loads. This gives a wide range of possibilities to integrate Renewable Energy Sources (RES) inside the pipeless plant. The electricity generated by Photovoltaic (PV) panels could be used for powering the pumps, stations, vessels, blenders etc. On the same hand, the Wireless Power Transmission could be used for powering the vessels in the real time, by using the dynamic inductive charging technology as described in Panchal et al. (2018). By utilizing PV panels in the pipeless plant the amount of electricity bought from the grid could be reduced. By further implementing Smart Grids and Demand Response programs, the production schedule of pipeless plant could be adapted in order to minimize the energy costs.

2. Policies and behavioural 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). In the industrial case however, it is more difficult than in the residential sector because of the different various energies utilization, triggering the use of an integrated management system to coordinate various technologies and their optimal operation. Demand Side Management and integration of RES was reported to be the most saving method for improving the efficiency of the industrial facility (Mohammad, 2018).

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). In the cement industry, the typical process consists of raw material grinding that constitutes over 70 % of the electricity demand. The grinding process can be considered DR-friendly because of its batch characteristics, large storage capacity for its' output and bottleneck of the production. Similarly, in the textile sector, the most common yarn production process can be considered highly suitable for DR purposes. The spinning process that uses different machines for putting the material on the roll can be considered batch process and a bottleneck process because the intermediate processes can be shifted in time to wait before the next processing task. Finally in the Wetprocessing plants which include tasks such as preparation or dying exist many batch processes that work on several different orders and products. To take advantage of DR there must be a high level of coordination between different departments within a plant who oversee production planning, energy management, utility bills paying, etc.

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. The potential of Combined Cooling & Heat & Power (CCHP) generation with Renewable Energy Sources (RES) integration has been studied in Gazda et al. (2016). The results showed the decrease of emission and energy savings. The wind turbines to supply electricity into the industrial sector have been studied in Finn et al. (2014) and the results has shown a significant reduction in energy costs and increase of the wind energy share in the total energy mix as a result of DR programme. In Ding et al. (2014) the DR energy management scheme for an industrial process based on Mixed Integer Linear Programming (MILP) and STN was proposed. The work divided processing task of an industrial facility into schedulable and non–schedulable tasks. In the proposed work, the day – ahead hourly electricity prices were determined in order to schedule the production process and minimize the cost of energy. In another work of Ding et al. (2013) there was proposed a steel manufacturing process as a case study for the model.

2.3 Conclusions

In the following chapter the main characteristics and features of pipeless plants in the scope of batch processes and energy efficiency were discussed and analysed based on examples from the brewery, cement and textile industry. Pipeless plants exist already, mostly in Japan. They have a wide range of benefits over the typical batch plants in terms of multi – product flexibility. The areas of research that had been already identified consisted of scheduling and routing in the scope of hazardous situations. The possible technological improvements including heat integration on the process level are possible, however this is already well investigated field in the batch plants. In the pipeless plants most of the loads could be considered electrical and thus Photovoltaic (PV) system integration with Electrical Energy Storage (EES) was suggested as a main research area of this work. Moreover, 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

In this section the main assumptions and methodologies used for the purpose of this thesis development were described. State Task Network (STN) is a process representation by using rectangles – tasks – and circles - states. The multipurpose and multiproduct plants definitions were mentiond in order to understand the similarities and differences between these two kinds of plants. What is more, the integrated demand side management concept was presented, and the work achievements were highlighted in the Figure 4. Finally, the system under consideration was explained in detail and presented in the Figure 5.

State-task -network characterization

The State Task Network representation introduced by Kondilini et al. (1993) was applied. To illustrate the STN representation an illustrative example is used, Figure 2. 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.

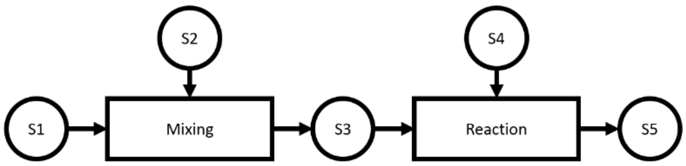

Figure 2 – STN representation.

In the Figure 3 the general idea of multiproduct and multipurpose batch plants was shown (Majozi, 2010). The arrows depicted the main difference between those two types of plant – the tasks in the multiproduct plant must be performed in the same order when in the multipurpose plants the products can have different routes and thus require different sequences of tasks. In the Case Study the tasks must follow specified sequence of tasks as has been shown in the multiproduct case in the picture 2 (Majozi, 2010).

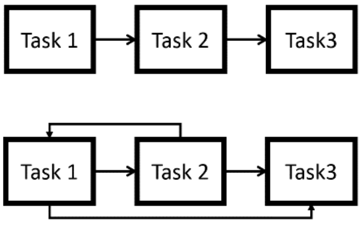

Figure 3 - Multiproduct and multipurpose plant(Majozi, 2010).

Integrated demand side management system

Demand Response (DR) is the definition used for describing adjustment of electricity usage in response to system or market conditions. The DR programmes are often proposed in order to reduce peak electricity demand as well as a mean of mitigating the challenges of integrating variable renewable generation, by reducing demand of the facility (Lynch, 2019). Demand Side Management (DSM) define all the necessary methods such as financial incentives or process integration techniques in order to better manage the electrical consumption of the industrial customer (Open Electricity Market). Integrated Demand Side Management (IDSM) is the concept that integrates the DSM, DR and energy efficiency techniques to better manage multiple energy carriers' systems (Navigant Search). In the Figure 4 an IDSM approach for heat and electricity integration in the energy system is presented. Two levels of integration were defined: process level and market level. Process heat or electricity can be integrated at the process level, through technical and technological improvements. Market level integration requires additional mechanisms and policies such as Smart Grid (SG) and Demand Response (DR) programmes, that link the final energy user with the utility grid. Moreover, there are the on – site energy generation units: RES or gas turbines, as well as energy storage units (thermal or electrical). Smart Energy Hub (SEH) is the physical place where two forms of energy : electrical energy from RES and SG, as well as, thermal energy from indirect heat integration from the process can be stored and used later in the process. The SEH allows market integration with utility network where IC can buy electricity, gas or heat, as well as, sell the excess to the grid. The use of SEH allows for a constant and reliable energy demand balancing (Mohammad, 2018). In this work, orange areas are explored and implemented in the model. The use of PV panels with EES and the electricity market was investigated in the case study.

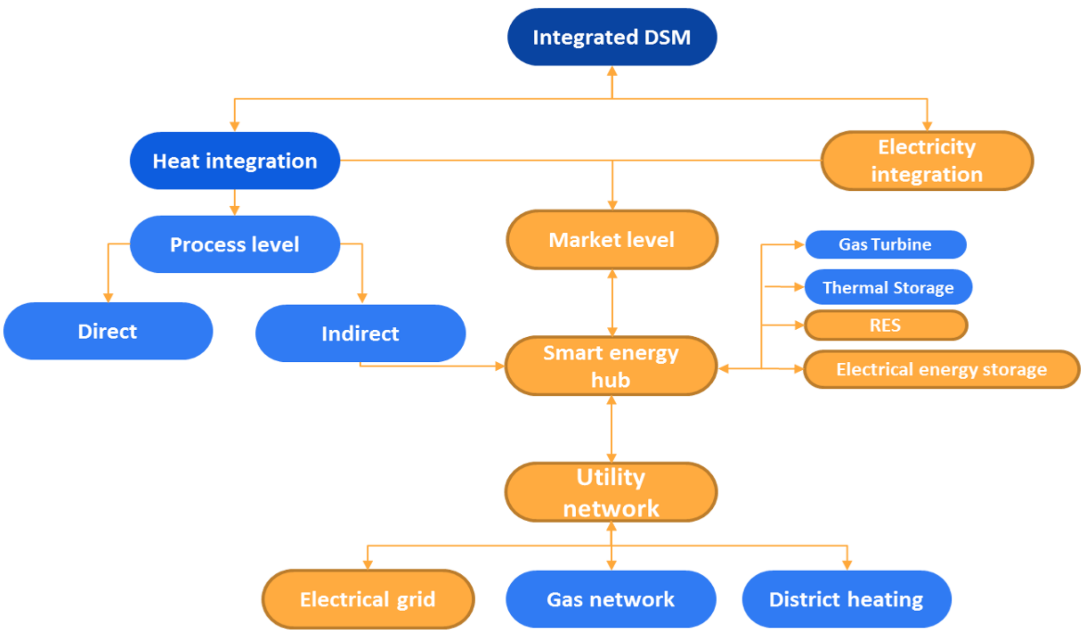

Figure 4 - Indegrated DSM explained

Characterization of system under study

In the Figure 5 the system under study is presented. The physical pipeless plant is considered inside the black rectangle. Inside that rectangule, there is the whole production plant inside the red frame (pipeless STN plant representation) which corresponds to physical appliances such as vessels and stations. Moreover, inside the plant, there is energy management system (EMS), energy generation system (EGS) and electrical energy storage system (ESS). EMS is connected to the utility database, IP, EGS and ESS through internet, as well as electrical grid through 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 which was defined as a Non – Schedulable Energy Generator (NEGS) due to the uncertainty connected with every renewable energy source. Electrical Energy Storage system (EES) is a physical place where there is a storage unit installed.

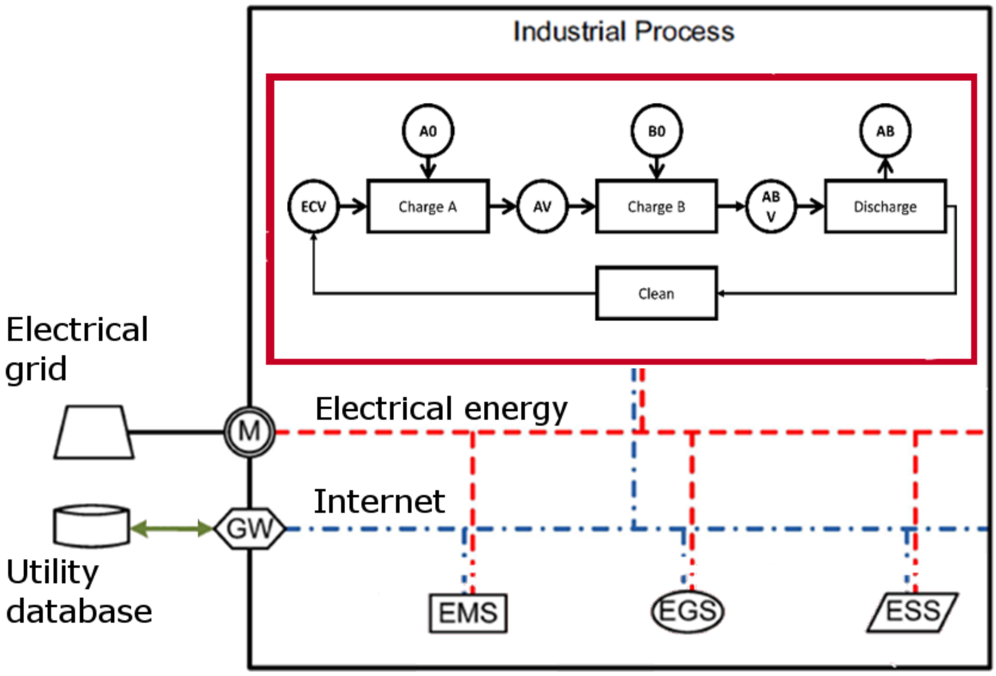

Figure 5 - System under study

4 Mathematical formulation.

The following chapter describes the mathematical formulation which is the core of the present work. In the subsection 4.1 Sets, parameters and variables necessary for the description of the model were presented. In subsection 4.2 the model constraints were explained.

The mathematical formulation was based on work of Pantelides et al. (1994) and Ding et al. (2014). Original sets, parameters, variables and constraints from these two papers were modified and adapted for the purpose of this work. Several equations were developed independently.

4.1 Sets, parameters and variables

Sets:

I	set of processing tasks
J	set of processing stations
V	set of vessel types
T	set of time periods
OP	index of operating point for schedulable task
RW_s	subset of raw material states
PRD_s	subset of final products states
$STORE_s$	subset of fixed storage states
$IJ_{i,j}$	task-station pairs allocation
$IJV_{i,j,v}$	task-station-vessel allocation
$ICS_{i,s}$	states consumed by task i
$IPS_{i,s}$	states produced by task i
$SBJ_{s,j}$	states before station j
$SAJ_{s,j}$	states after station j
$SJK_{j,k}$	processing station sequence

Parameters:

Not	notional value of Empty Clean Vessels at the end of the time horizon (€/vessel)
totV	total number of vessels
$tr_{j,k,v}$	transfer time between stations
$pt_{i,j,v}$	processing time for task i at station j for vessel of type v
$pt_{s,i,j,v}$	processing time for task i at station j in the vessel of type v for state s
$Nb^{max}_{j,v}$	maximum number of vessels of type v allowed to wait before station j at any given time
$Na^{max}_{j,v}$	maximum number of vessels of type v allowed to wait after station j at any given time
Nb^{max}_{j}	maximum total number of vessels of all types allowed to wait before station j at any given time
Na^{max}_{j}	maximum total number of vessels of all types allowed to wait after station j at any given time
Cap_v	capacity of a vessel of type v
$rhp_{i,op,s}$	quantity of state s produced by task i operating at point op expressed as fraction of capacity of a vessel of type v
$rhc_{i,op,s}$	quantity of state s consumed by task i operating at point op expressed as fraction of capacity of a vessel of type v
$uv_{s,t}$	1 unit value of the final product in state s delivered to external clients at time t (€/m^3)
$Nb^{ini}_{s,j,v}$	initial number of vessels of type v holding state s waiting to be processed by station j at t = 0
$Na^{ini}_{s,j,v}$	initial number of vessels of type v holding state s waiting after station j at t = 0

St^{ini}_s	initial amount of state s in dedicated storage at t = 0
$e_{i,op}$	electricity demand of schedulable task i that operates at point op
$E_{NEGS,t}$	total quantity of electricity generated by the NEGS during time interval (t, t+1) by the non-schedulable generator

Energy storage parameters:

α	charging efficiency
β	discharging efficiency.
C_{SE}	maximum storage capacity (kWh).
CH_{SE}	maximum charging rate (kWh)
DCH_{SE}	maximum discharging rate (kWh)
$S_{ESS}{}^{ini}{}_{,t}$	initial amount of energy stored at time t = 0

Electricity market parameters:

BM	large positive number
pp_t	electricity purchasing price over time
ps_t	electricity selling price over time

Continous variables:

$Nb_{s,j,v,t}$	number of vessels of type v holding state s waiting to be processed by station j over interval t
$Na_{s,j,v,t}$	number of vessels of type v holding state s after station j at time t
$M_{s,j,k,v,t}$	number of vessels of type v carrying material in state s that start moving from station j to station k at time t

$R_{s,t}$	amount of material in state s received from external sources at time t
$S_{s,t}$	amount of material in state s in fixed storage at time t
$De_{s,t}$	amount of material delivered to external clients at time t
$Pa_{s,i,t}$	amount of state s produced by task i at time t
$Ca_{s,i,t}$	amount of state s consumed by task i at time t
TR	total revenue
TP	total profit
TEC	total energy cost
E_t	total electricity demand of the plant at time t
$e_{i,t}$	electricity demand of task i at time t
$E_{CESS,t}$	amount of electricity charged by ESS at time t
$E_{DESS,t}$	amount of electricity discharged by ESS at time (t, t+1)
$S_{ESS,t}$	amount of stored energy by ESS at time interval (t, t+1)
$E_{EGS,t}$	total quantity of electricity generated by the EGS during time interval (t, t+1)
$E_{DM,t}$	electricity demand, when positive indicates purchasing of electricity, when negative indicates selling electricity to the grid
ES_t	electricity sold to the grid
EP_t	electricity bought from the grid

Binary variables:

$z_{i,j,op,t}$	binary variable that takes value 1 if station j operates a schedulable task i at operating point op at time t
$z_{c,t}$	binary variable that is assigned the value 1 when charging energy storage and 0 otherwise
$z_{d,t}$	binary variable that is assigned the value 1 when discharging energy storage and 0 otherwise
$z_{p,t}$	binary variable that is assigned the value 1 when the pipeless plant energy management system is buying electricity, 0 otherwise
$z_{s,t}$	binary variable that is assigned the value 1 when the pipeless plant energy management system is selling electricity, 0 otherwise

4.2 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).

4.2.1 Pipeless plant operation constraints.

The Figure 6 illustrate the STN applicability in energy consumption over operating points. The task i consumes s1 and can hold up to M operating. For each operating point (op) the consumed quantity of state s1 ($rhc_{i,op,s}$) and produced quantity of state s2 ($rhp_{i,op,s}$) as well as electricity demand of the task i ($e_{i.op}$) had different values and were known a priori – the stations use variable motor speed pumps. The flexibility of the production with different operating points makes the use of stations more sustainable and allows for economical savings.

The Operating Point 1 (op_1) was assumed to be a stand-by-mode where the stations were not processing any material, so the quantities of the material consumed and produced ($rhc_{i,op,s}$, $rhp_{i,op,s}$) were 0 for that operating point and $e_{i.op}$ values were also 0 (kWh). For the stand-by-mode there was no vessel at the station being processed at that time.

The Operating Point 2 (op_2) was assumed to be a medium-mode where the stations were prcessing material, so the quantities of the material consumed and produced ($rhc_{i,op,s}$, $rhp_{i,op,s}$) as well as $e_{i.op}$ values were higher than 0 and there was a vessel processed at the station at that time. The Operating Point 3 (op_3) was assumed to be a maximum-mode where the stations were prcessing material, so the quantities of the material consumed and produced ($rhc_{i,op,s}$, $rhp_{i,op,s}$) as well as $e_{i.op}$ values were higher than 0 and higher than for Operating Point 2 and there was a vessel processed at the station at that time.

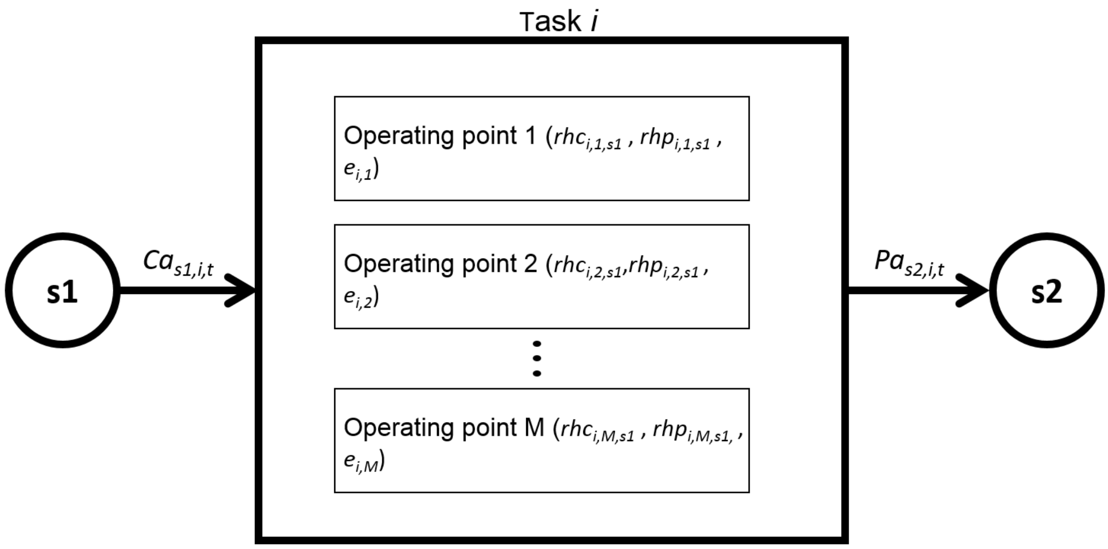

Figure 6 - Operating points scheme for the task i

Processing station allocation. The constraint 1 assures that any station j that is suitable for processing task i is operating at only one operating point op at time t. The constraint 2 and 3 express the quantity of state s produced and consumed by task i as a percentage fraction of a vessel capacity respectively. (Defined in the equations 1, 2, 3).

$$\sum_{op} z_{i,j,op,t} = 1 \; ; \; \forall \left(i,j \; \in IJ_{ij}\right) \wedge \forall t \geq 0 \tag{1}$$

$$PA_{s,i,t} = \sum_{op} z_{i,j,op,t} * rhp_{i,op,s} \, ; \; \forall \left(s \in \; IPS_{i,s}\right), \left(i,j \; \in IJ_{ij}\right) \wedge \; \forall t > 0 \tag{2}$$

$$CA_{s,i,t} = \sum_{op} z_{i,j,op,t} * rhc_{i,op,s} \;\; ; \forall \left(s \in \; ICS_{i,s}\right), \left(i,j \; \in IJ_{ij}\right) \wedge \; \forall t > 0 \tag{3}$$

Mass balance held in dedicated storage. The amount of material in state s at time t ,$S_{s,t}$, is given by the amount of state s held in the in previous instan,t $S_{s,t-1}$, plus the amount of material produced $Pa_{s,i,t}$ at time t, minus the amount of material consumed $Ca_{s,i,t}$ at time t, plus the amount of material $R_{s,t}$ added from external sources at time t, minus the amount delivered $De_{s,t}$ to external clients at time t. (Defined in the equation 4).

$$S_{s,t} = S_{s,t-1} + \sum_{i,j,v \, \in \left(IPS_{I,S} \, \cap \, IJV_{I,J,V}\right)} PA_{s,i,t-pts_{s,i,j,v}} * CapV_v \; - \sum_{i,j,v \, \in \left(ICS_{I,S} \, \wedge \, IJV_{I,J,V}\right)} CA_{s,i,t} * CapV_v \tag{4}$$

$$+R_{s,t} - D_{s,t}; \; \forall s \in S, \forall t > 0$$

Balance on vessels waiting before processing stations. The number of vessels waiting before the processing station j (left hand side of the equation 5), holding state s at time t, in a vessel of type v, is equal to:

- the number of such vessels waiting before the processing station j at time instant t-1,
- plus the number of such vessels arriving to this station from other processing stations,
- minus the number of vessels that are processed by station j.

When station j operates at Operating Point 2 (op_2) or higher, at time t it means that the vessel is currently processed. When processing station is operating at a stand-by mode: Operating Point 1 (op_1) – it means there is no vessel being processed by the processing station. (Defined in the equation 5).

$$N^{before}_{s,j,v,t} = N^{before}_{s,j,v,t-1} + \sum_{k} M_{s,k,j,v,t} \; - \sum_{\left(i \epsilon IJV_{I,J,V} \, \cap \, ICS_{I,S}\right),} \; \sum_{op>1} z_{i,j,op,t} \, ; \tag{5}$$

$$\forall \left(s,j \in SBJ_{S,J} \wedge s, j \sim RW_S \wedge s, j \sim PRD_S\right), \forall v \in V, \forall t \geq 0$$

Limit on number of vessels of type v waiting before processing station j. The number of vessels of type v waiting before the processing station j at time t may be limited – when there are several types of vessels in the system that have for example different capacity. (Defined in the equation 6).

$$\sum_{s \in SBJ_{S,J} \wedge s\sim RW_S \wedge s\sim PRD_S;\ i \in IJV_{I,J,V}} \sum N_{s,j,v,t}^{before} \leq Nb_{j,v}^{max};\ \forall j \in J, \forall v \in V, \forall t \geq 0 \tag{6}$$

Limit on the total number of vessels of all types waiting before processing station j. The number of vessels of all types waiting before the processing station *j* may be limited. The need of this constraint can be related with the available space of the floor (Defined in the equation 7).

$$\sum_{s \in SBJ_{S,J} \wedge s\sim RW_S \wedge s\sim prd_s;\ i,v \in IJV_{I,J,V} \cap ICS_{I,S}} \sum N_{s,j,v,t}^{before} \leq Nb_{j}^{max};\ \forall j \in J, \forall v \in V, \forall t \geq 0 \tag{7}$$

Balance on vessels waiting after processing stations. The number of vessels waiting after the processing station j, holding state s, at the time t, in a vessel of type v (left hand side of the equation 8) is equal to:

- the number of such vessels in time t-1
- minus the number of such vessels that start moving towards other stations
- plus the number of vessels that finish being processed at station j at time t - i.e. when station j operates at point 2 or higher. (Defined in the equation 8).

$$N_{s,j,v,t}^{after} = N_{sjv,t-1}^{after} - \sum_{jj} M_{s,j,k,v,t} + \sum_{(i \epsilon IJV_{I,J,V} \cap ICS_{I,S})} \sum_{op>1} z_{i,j,op,t} \tag{8}$$

$$\forall (s, j \in SAJ_{S,J} \wedge s, j\sim RW_s \wedge s, j\sim PRD_s)\ \forall v \in V, \forall t \geq 0$$

Limit on number of vessels of type v waiting after processing station j. The number of vessels of type v waiting after the processing station j at time t may be limited - when there are several types of vessels in the system that have for example different capacity. (Defined in the equation 9).

$$\sum_{s \in SAJ_{S,J} \wedge s\sim PRD_S;\ i \in IJV_{I,J,V}} \sum N_{s,j,v,t}^{after} \leq Na_{j,v}^{max};\ \forall j \in J, \forall v \in V, \forall t \geq 0 \tag{9}$$

Limit on the total number of vessels of all types waiting after processing station j. The number of vessels of all types waiting after the processing station j may be limited. The need of this constraint can be related with the available space of the floor (Defined in equation 10).

$$\sum_{s \in SAJ_{S,J} \wedge s\sim PRD_S;\ i,v \in IJV_{I,J,V} \cap ICS_{i,s}} \sum N_{s,j,v,t}^{after} \leq Na_{j}^{max};\ \forall j \in J, \forall v \in V, \forall t \geq 0 \tag{10}$$

Balance on vessels waiting at processing stations. The number of vessels waiting at the processing station j, holding state s, at time t, in a vessel of type v is equal to:

- the number of such vessels in time t-1,

- plus the number of such vessels that arrive at this station,
- minus the number of vessels that finish processing at time t, and move towards another station j. (Defined in equation 11).

$$N_{s,j,v,t}^{before} = N_{s,j,v,t-1}^{before} + \sum_{k \in SJK_{k,j}} M_{s,k,j,v,t} - \sum_{k \in SJK_{j,k}} M_{s,j,k,v,t} \tag{11}$$

$$\forall (s, j \in SBJ_{S,J} \vee SAJ_{S,J} \wedge s, j \sim RW_S \wedge s, j \sim PRD_S), \forall v \in V, \forall t > 0$$

Limit on number of vessels of type v waiting at processing station j. The number of vessels of type v waiting at the processing station j in time t may be limited. (Defined in equation 12).

$$\sum_{s \in SAJ_{S,J} \vee SBJ_{S,J} \wedge s \sim rw_s \wedge s \sim prd_s} N_{s,j,v,t}^{before} \leq Nb_{j,v}^{max} \; ; \; \forall j \in J, \forall v \in V, \forall t \geq 0 \tag{12}$$

Limit on the total number of vessels of all types at processing station j. The number of vessels of all types waiting at the processing station j may be limited. (Defined in equation 13).

$$\sum_{s \in SAJ_{S,J} \vee SBJ_{S,J} \wedge s \sim rw_s \wedge s \sim prd_s ; \; i,v \in IJV_{i,j,v} \cap ICS_{i,s}} \sum N_{s,j,v,t}^{before} \leq Nb_j^{max} ; \; \forall j \in J, \forall v \in V, \forall t \geq 0 \tag{13}$$

Limit on the total number of vessels of all types in the system. The total amount of vessels in the system holding any state s before or after or at the station must be restricted and always equal to the initial number of vessels (totV) at any time t. (Defined in the equations 14, 15, 16).

$$\sum_{s \in SBJ_{S,J} \wedge s \sim rw_s ;} \sum_{j,v} N_{s,j,v,t}^{before} \leq totV ; \; \forall t > 0 \tag{14}$$

$$\sum_{s \in SAJ_{S,J} \wedge s \sim rw_s ;} \sum_{j,v} N_{s,j,v,t}^{after} \leq totV ; \; \forall t > 0 \tag{15}$$

$$\sum_{s \in SAJ_{S,J} ;} \sum_{j,v} N_{s,j,v,t}^{after} + \sum_{s \in SBJ_{S,J} \wedge s \sim rw_s ;} \sum_{j,v} N_{s,j,v,t}^{before} \leq totV ; \; \forall t > 0 \tag{16}$$

Production requirements. In order to meet the production goals the total amount of a product delivered to the external clients must be set between the minimum and maximum amount required. (Defined in the equations 17, 18).

$$\sum_{t} De_{s,t} \geq Dmin_{s,t} \; ; \; \forall s \in PRD_S, \forall t \geq 0 \tag{17}$$

$$\sum_{t} De_{s,t} \leq Dmax_{s,t} \; ; \; \forall s \in PRD_S, \forall t \geq 0 \tag{18}$$

4.2.2 Energy constraints

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

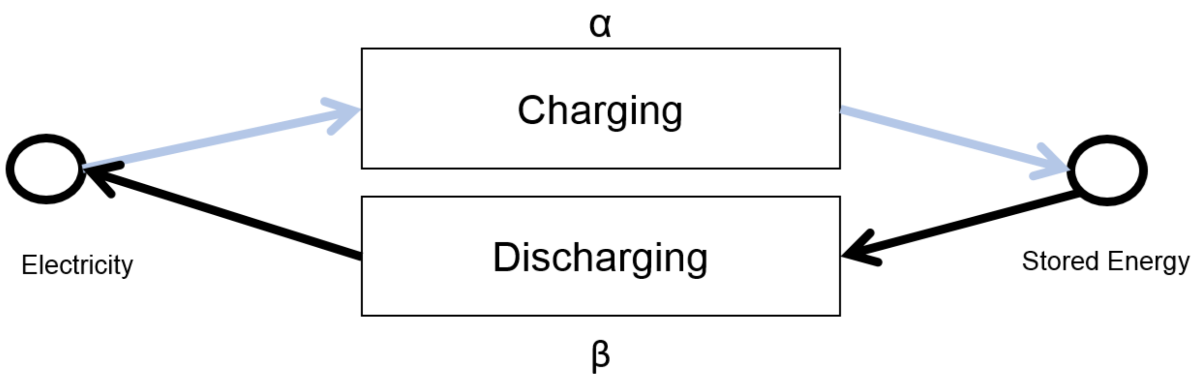

Figure 7 -ESS representation (Ding, 2014)

Total electricity Demand . The total electricity demand Et during time interval (t, t + 1) for a given production process is equal to the sum of the electricity demand of each task $e_{i,t}$ within time interval (t, t + 1). (Defined in equation 19).

$$E_t = \sum_i e_{i,t} ; \forall t \geq 0 \tag{19}$$

Electricity Demand. Electricity demand of task i at any time t is dependent on the binary variable $z_{i,j,op,t}$ and the parameter electricity demand at the operating point op ($e_{i,m}$). (Defined in the equation 20).

$$e_{i,t} = \sum_{op} z_{i,j,op,t} * e_{i,m} \; ; \; \forall i, j \in IJ_{i,j} \tag{20}$$

Electrical energy storage balance. The amount of electricity stored at time t is equal to the amount of electricity stored at time t-1, plus the amount of electricity added to the storage unit during the time interval (t-1, t) multiplied by charging efficiency, minus the amount of electricity discharged during the time interval (t-1, t) divided by the discharging efficiency. (Defined in the equation 21).

$$S_{ESS,t} = S_{ESS,t-1} + E_{CESS,t-1} * \alpha - \frac{E_{DESS,t-1}}{\beta} ; \; \forall t > 0 \tag{21}$$

Charging & Discharging constraints. By introducing the binary variables $z_{c,t}$ and $z_{d,t}$ the constraint 22 assures that there is only charging or discharging of the electrical energy storage system occurring at instance t. The amount of electricity charged and discharged is limited by constraints 23 and 24 by the maximum charging and discharging rate CH_{SE}, DCH_{SE} . The quantity of stored electricity is limited by equation 25 with maximum storage capacity C_{SE}. (Defined in the equations 21, 22, 23, 24, 25).

$$z_{c,t} + z_{d,t} \leq 1;\ \forall t \geq 0 \tag{22}$$

$$0 \leq E_{CESS,t} \leq CH_{SE} * z_{c,t} \tag{23}$$

$$0 \leq E_{DESS,t} \leq DCH_{SE} * z_{d,t} \tag{24}$$

$$S_{ESS,t} \leq\ C_{SE};\ \ \forall t > 0 \tag{25}$$

Energy Generation System constraints. The total energy generated is given by one type of non-schedulable generator – in this example, PV panels. The amount of electricity generated by PV panels is known a priori based on predicted 24hour forecast – Figure 10. (Defined in the equation 26).

$$E_{EGS,t} = E_{NEGS,t};\ \forall\ t \geq 0 \tag{26}$$

Electricity market integration constraints. Energy generated from PV supplies electricity to the process or charges the EES and, can be stored or sold when there is a surplus to the Electrical Grid (EG). The variable $E_{DM,t}$ which is present in the constraint 27 identifies if the electricity is being bought from the grid or sold to the grid. The positive value indicates purchasing electricity from the grid. The negative value indicates the selling of electricity back to the EG. Other variables present in the constraint 27 are E_t which is a total electricity demand at time t, $E_{CESS,t}$ which is a total electricity charged to EES at time t, $E_{DESS,t}$ which is electricity discharged from EES at time t and finally, $E_{EGS,t}$ which is the electricity generated by PV. Moreover, the electricity can be bought and stored in the EES when the price is low and used in the process or sold back to the grid when the price of electricity is high, which is a consequence of the equation 30 and 34. When the electricity supplied by PV is insufficient to meet the demand, the variable $E_{DM,t}$ is positive so due to the equation 28 $z_{p,t}$ is assigned the value of 1. When there is a surplus of electricity in the system at time t, the variable $E_{DM,t}$ is assigned a negative value so then equation 29 forces the variable $z_{s,t}$ to have assigned the value of 1 which is the situation when the electricity is sold back to the electrical grid. What is more, the relationship between $E_{p,t}$ $E_{s,t}$ and $E_{DM,t}$ is characterized by equation 30. $E_{p,t}$ and $E_{s,t}$ are non-negative values defined with equation 31 and 32 and lower than the multiplication of the binary variables $z_{p,t}$ or $z_{s,t}$ and any sufficient large number BM. With equation 30, the $E_{p,t} = E_{DM,t}$ when the $E_{DM,t}$ is positive and $E_{s,t} = 0$ – no energy was sold, only purchased. When $E_{DM,t}$ is negative, from equation 30 $E_{p,t} = 0$ and $E_{s,t} = -E_{DM,t}$ which indicates that the energy was sold to the grid. (Defined in the equations 26, 27, 28, 29, 30).

$$E_{DM,t} = E_t + E_{CESS,t} - E_{DESS,t} - E_{EGS,t};\ \ \forall t \geq 0 \tag{27}$$

$$E_{DM,t} \leq z_{p,t} * BM;\ \forall t \geq 0 \tag{28}$$

$$E_{DM,t} \geq z_{s,t} * (-BM);\ \ \forall t \geq 0 \tag{29}$$

$$E_{p,t} - E_{s,t} = E_{DM,t};\ \ \forall t \geq 0 \tag{30}$$

$$0 \leq E_{p,t} \leq z_{p,t} * BM \tag{31}$$

$$0 \leq E_{s,t} \leq z_{s,t} * BM \tag{32}$$

Total revenue. Revenue (€) is dependent on the amount of product delivered to the external client and corresponding unit value $uv_{s,t}$ (€/m^3) of the product. Additionally, the number of the Empty Clean Vessels (ECV) at the end of horizon has a notional value (parameter Not) of 1 (€). Total revenue is the sum of all the deliveries $De_{s,t}$ (m^3) added over the time horizon and the total number of Empty Clean Vessels at the end of the time horizon. (Defined in the equation 33).

$$TR = \sum_{s}\sum_{t} uv_{s,t} * De_{s,t} + \sum_{j}\sum_{v}\sum_{t=24} (N^{before}_{ECV,j,v,t} + N^{after}_{ECV,j,v,t}) * Not \tag{33}$$

Total energy cost. Energy cost is dependent on the total amount of energy bought from the grid EP_t (kWh) and sold back to the grid ES_t (kWh) as well as the price of buying pp_t (€) and selling the electricity back to the electrical grid (€). (Defined in the equation 34).

$$TEC = \sum_{t} pp_t * EP_t - \sum_{t} ps_t * ES_t \tag{34}$$

Objective Function(€). The objective of the optimization is to maximize the total profit. (Defined in equation 35).

$$Max\ TP = (TR - TEC) \tag{35}$$

5 Case study

The following case study example was drawn from literature (Pantelides, 1995) in order to show the model applicability. The pipeless plant must deliver the final product AB to external clients between the minimum ranges specified in the table 1 over the time horizon of 24 hours which was divided into 24 equal intervals of 1 hour each and maximize the Total Profit. The simulation was made for three different scenarios. In the base scenario – Grid - the plant was assumed to be connected to the electrical grid neither without electrical energy storage unit nor photovoltaic unit. In the scenario a) – Grid & EES - the pipeless plant was connected to the electrical grid and had an electrical energy storage unit installed. In the third scenario – Grid & EES & PV- the plant was connected to the grid and had installed the electrical energy storage unit as well as photovoltaic system. The summary with information about each scenario is included in the Table 2.

The results for each scenario as well as the comparison between them were presented in the chapter 5.2. The conclusions were presented in the chapter 5.3

Table 1 – Deliveries Requirements

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

Table 2 - Scenarios comparison

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

In the Figure 8 the illustrative plant topology with vessel movement sequence was shown. The plant equipment consists of four fixed processing stations depicted in four rectangles, as well as three Dedicated Storage Tanks depicted in the three rounded rectangles. It is important to mention that the stations location in the space was not considered in the design of this plant. Charging Station A and Charging Station B are responsible for filling the raw materials A0 and B0 into the vessel, that come from Storage Tanks A0 and B0, respectively. At the Discharging Station the final product AB is released into the fixed dedicated storage tank from the vessel. The Cleaning Station is responsible for the washing of the vessel. All the plant equipment is listed in the Table 3.

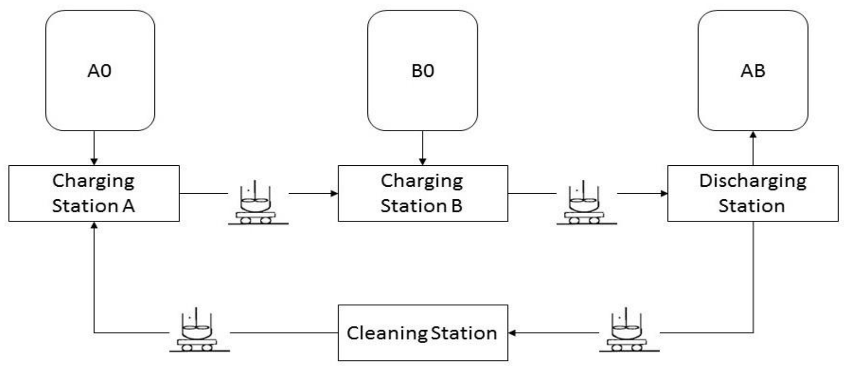

Figure 8 - Pipeless plant topology with vessel movement sequence

Table 3 - pipeless plant equipment

Equipment	***Amount***
Charging Stations	2
Discharging Station	1
Cleaning Station	1
Dedicated Storage Tanks	3
Transferrable Vessels	8

- The recipe represented using STN and the plant topology was presented in the Figure 9. A pipeless plant is to be designed at a maximum profit to produce product AB from two raw materials A0 and B0. Four different tasks are considered. Task Charge A0 transforms state Empty Clean Vessel (ECV) into A in Vessel (AV) by simultaneously adding raw material A0. Task Charge B transforms state AV by simultaneously adding raw material B0 into state AB in Vessel (ABV). The task Discharge AB transforms state ABV into final product AB and state Empty Dirty Vessel (EDV) is produced. Finally, the task Cleaning is transforming state EDV into ECV and the process can be repeated. It is important to mention, that each task can consume only the corresponding states which are linked with the tasks by the arrows. Each task could have consumed or produced the corresponding states listed in the Table 4.

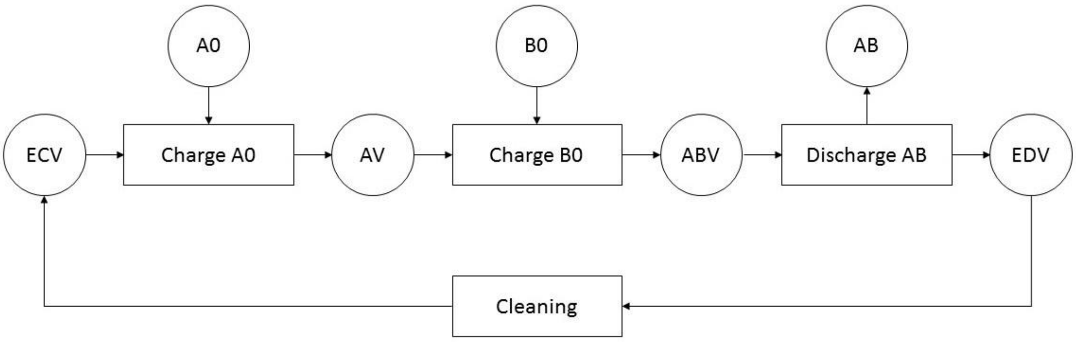

Figure 9 - STN of the process

Table 4 - Tasks' corresponding states

Task	***States Consumed***	***State Produced***
Charge A0	ECV, A0	AV
Charge B0	AV, B0	ABV
Discharge AB	ABV	AB, EDV
Cleaning	EDV	ECV

The main assumptions were listed below:

- There is only one type of transferrable vessels that have capacity of 10 (m^3).
- The Dedicated Storage Tanks have unlimited capacity.
- In the beginning of the process there was unlimited amount of raw materials A0, B0.
- In the beginning of the process all the transferrable vessels are placed before the Charging Station A.
- The station can process only one vessel at time instant t.
- The plant topology is illustrative and the distances between processing stations and their allocation around the floor were not considered during the design process.
- The transfer times between processing stations were neglected.

- Each task could have been performed only at the restricted processing station- Table 5 - and must have followed the station sequence as depicted with arrows in the Figure 8.

Table 5 - Processing times and task suitability

Task (i)	***Station (j)***	***Processing Time (h)***
Charge A0	Charging Station A	1
Charge B0	Charging Station B	1
Discharge AB	Discharging Station	1
Cleaning	Cleaning Station	1

- 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 angular velocities and associated with their operating points' electricity demands that were listed in the Table 6.

Table 6 - Station j electricity demands associated with their operating points

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

- Each station, despite the Cleaning Station, could have operated at three different Operating Points (OP) that corresponded to various speeds of rotor pumps. The OP_1 meant that the station was neither consuming nor producing any amount of material – so the station was considered to work in a stand – by - mode. The OP_2 was considered as a medium Operating Point where the amount of material produced or consumed was lower than in the case of OP_3. For the Cleaning Station, there were only 2 Operating Points defined, since the cleaning does not required transfer of the material. The Charging Station A as well as Cleaning Station consumed Empty Clean Vessel (ECV) and Empty Dirty Vessel (EDV) that had been assigned a notional value of *0*. When Charging Station A operates at OP_1 the corresponding values of states consumed and produced are equal to 0. At OP_2 the corresponding values of states consumed are 0 (ECV) and 0.2 (A0). The corresponding value of state (AV) produced by Charging Station A for OP_2 is 0.2. Similar reasoning could be applied for OP_3.

Table 7 - Operating Points

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 forecasted quantity of electricity generated by the solar energy generation system were presented in the Figure 11 (Ding, 2014). The maximum electricity generated from the PV panels was forecasted to be 950 (kWh) at noon. During the night between 19th - 5th (hours) the PV panels did not produce any energy.
- The information of the forecasted prices is a necessary for the model in order to find the cheapest possible patterns of the production schemes. The day-ahead hourly electricity prices forecasted within a 24 (hour) (Ding, 2014) forecasting range were shown in the Figure 10. The prices were the lowest at 3rd (h) with the value observed at the level of 2. Then they started to increase reaching the highest price of 15 (¢/ kWh) observed at 14th (h). The prices started to fall and reached 3 (¢/ kWh) at the end of the 24 h period. The price for selling the electricity back was assumed to be 20 (%) lower than the purchasing price based on the assumption of prosumer market in which from 1 (kWh) put into the grid the consumer obtains 0.8 (kWh) of energy from the grid.
- The electrical energy storage parameters were listed in the Table 8. The Maximum storage capacity was assumed to be four times higher than the maximum charging rate, equal 6000 (kWh). Maximum discharging rate was assumed to be equal with the maximum charging rate at the level of 1500(kWh). Similarly, charging and discharging efficiencies were assumed to be equal to 0.9.

Table 8 - EES Parameters (Ding, 2014)

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

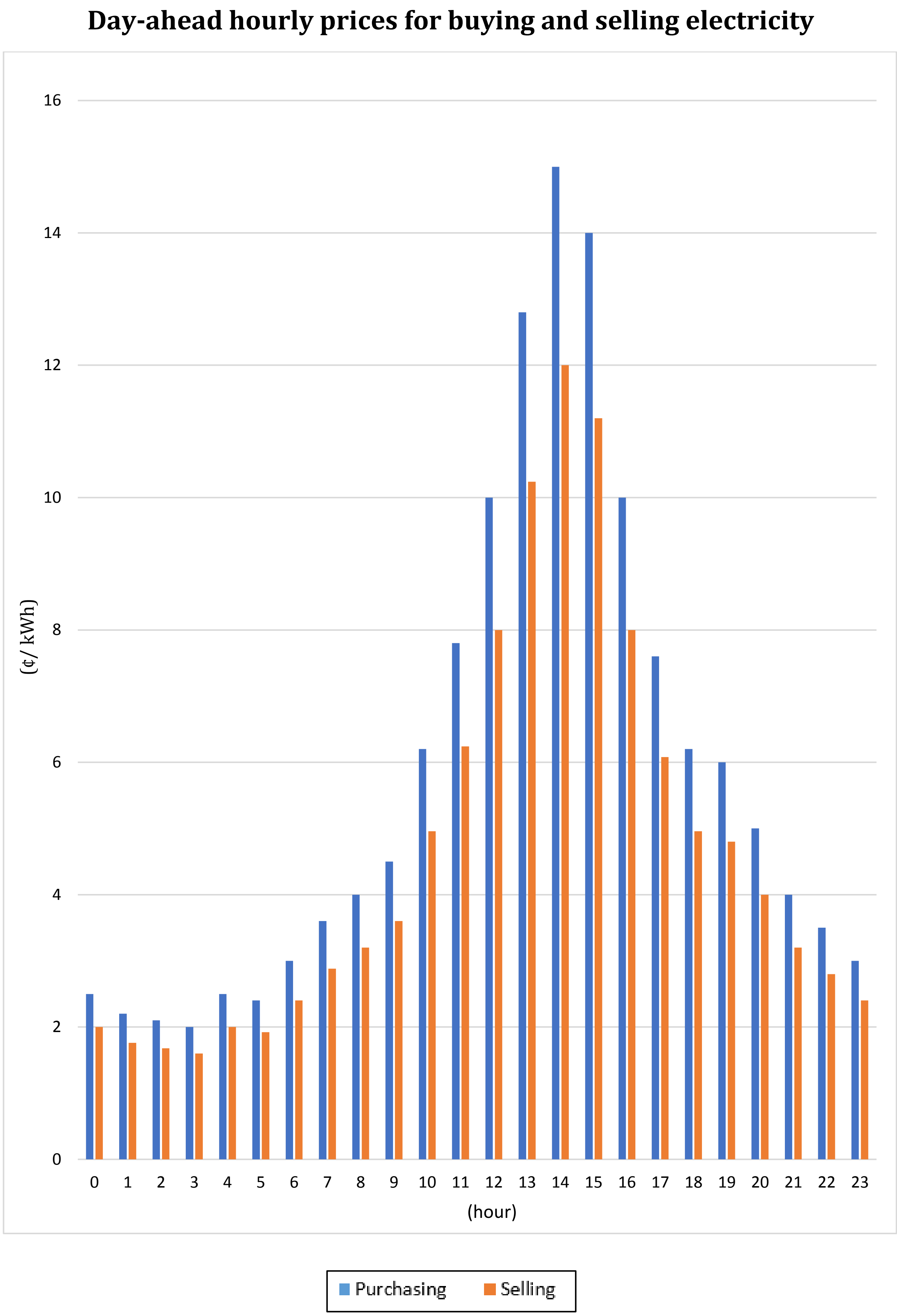

Figure 10 - Day-ahead hourly prices for buying and selling the electricity (Ding, 2014).

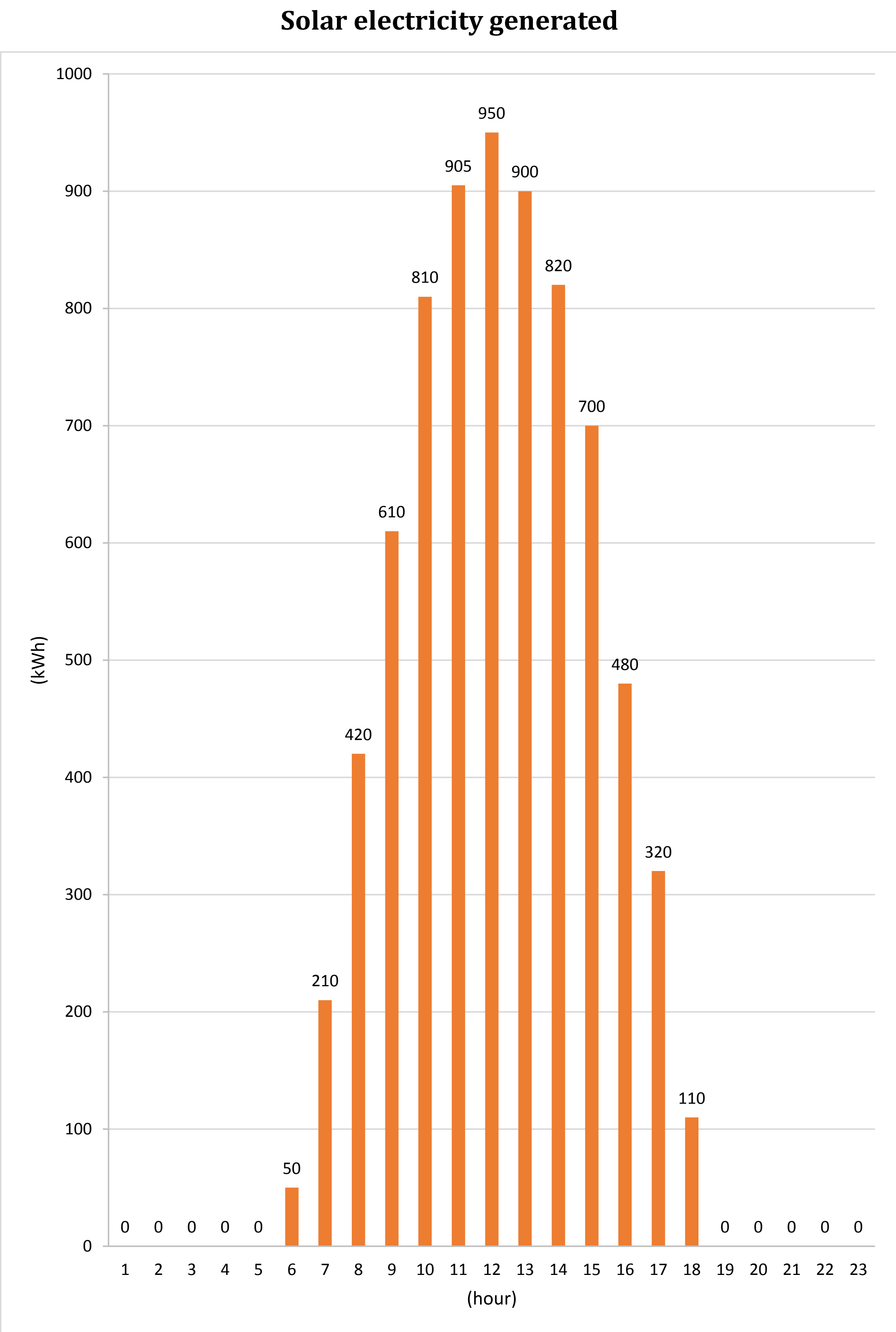

Figure 11 - Solar electricity generated.

5.1 Case study results

The MILP problem was solved using CPLEX which is a commercially available solver. The calculations were held on the personal computer Dell XPS 12 with Intel® Core ™ @1.6 GHz with 4 GB RAM and Windows 8 x64. The model was implemented in GAMS 25.03 and solved using IBM ILOG CPLEX 25.03. The solution was obtained after 0.02 seconds for every scenario and the relative and absolute gap was reported to be 0.

In the Table 9 the Determined Operating Points for the Case study were presented. For every scenario, the schedule result based on DOP was obtained the same. The Gannt chart was presented in the Figure 13, from which it is possible to analyse the processing stations allocation during the whole-time horizon. Additional information about the number of vessels before and after station allows for a detailed vessel tracking depicted also in the Figure 13, with every different colour corresponding to one of eight vessels of the same type v_1 as described in the Figure 12. The operating points were assigned to every task / station combination. The fact that the price for electricity was the highest between 12 and 16 hours made the scheduling algorithm assign the operating point 1 for cleaning operation.

Table 9 - Determined Operating Points

	Task	***Charging A0***	***Charging B0***	***Discharging***	***Cleaning***
Hour	**Station**	Charging Station A	Charging Station B	Discharging Station	Cleaning Station
0		1	1	1	1
1		3	1	1	1
2		3	3	1	1
3		3	3	3	1
4		3	3	3	2
5		3	3	3	2
6		3	3	3	2
7		3	3	3	2
8		3	3	3	2
9		3	3	3	2
10		3	3	3	2
11		3	3	3	2
12		3	3	3	1
13		3	3	3	1
14		3	3	3	1
15		3	3	3	1
16		3	3	3	1
17		3	3	3	2
18		3	3	3	2
19		3	3	3	2
20		3	3	3	2
21		1	3	3	1
22		1	1	3	1
23		1	1	1	1

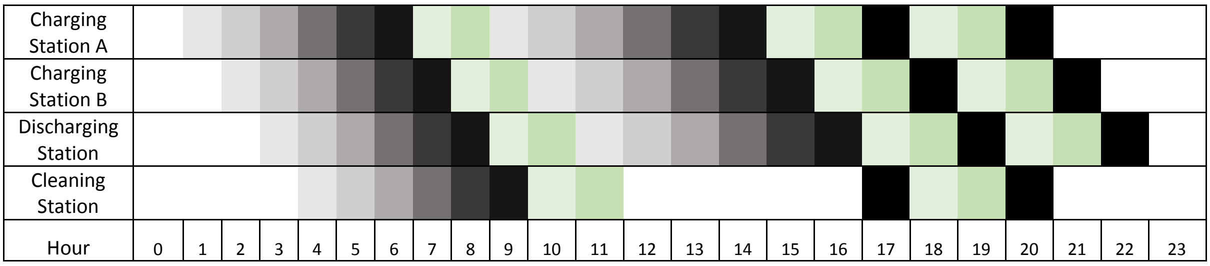

Figure 12 - Gannt Chart

	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 13 - Vessels and their corresponding colours

Figure 14 shows the total electricity demand and the buying price for electricity for the baseline case. At time period 0 (h) the electricity demand was equal to 0 (kWh) – the process started at time instance 1(h). Between the time 1 (h) and 4 (h) there was observed a rapid growth of electricity demand reaching its' peak at time 4 of 1555 (kWh). It could have been observed that when the price of electricity reached 10 (¢/ kWh), the total electricity demand was shifted from peak hours between 12 and 16 to the hours when the electricity price was lower and so, decreased from 1555 (kWh) to 1550 (kWh) between 12th (h) and 16th (h). Between the hours 17 and 20 the electricity demand was again observed to be 1555(kWh) and the price of electricity was observed to be lower than in the peak hours 12th (h) – 16th (h). The electricity demand started to decrease from the hour 21 till 23 where it reached the value of 0 (kWh) – the processing stations were not operating, and the process was stopped. It is important to mention that total electricity demand values were obtained the same for all the three scenarios. In the Figure 15 the energy flow analysis for baseline case was presented. During the whole horizon the total energy demand had to be fulfilled with the electricity bought from the grid in the baseline scenario.

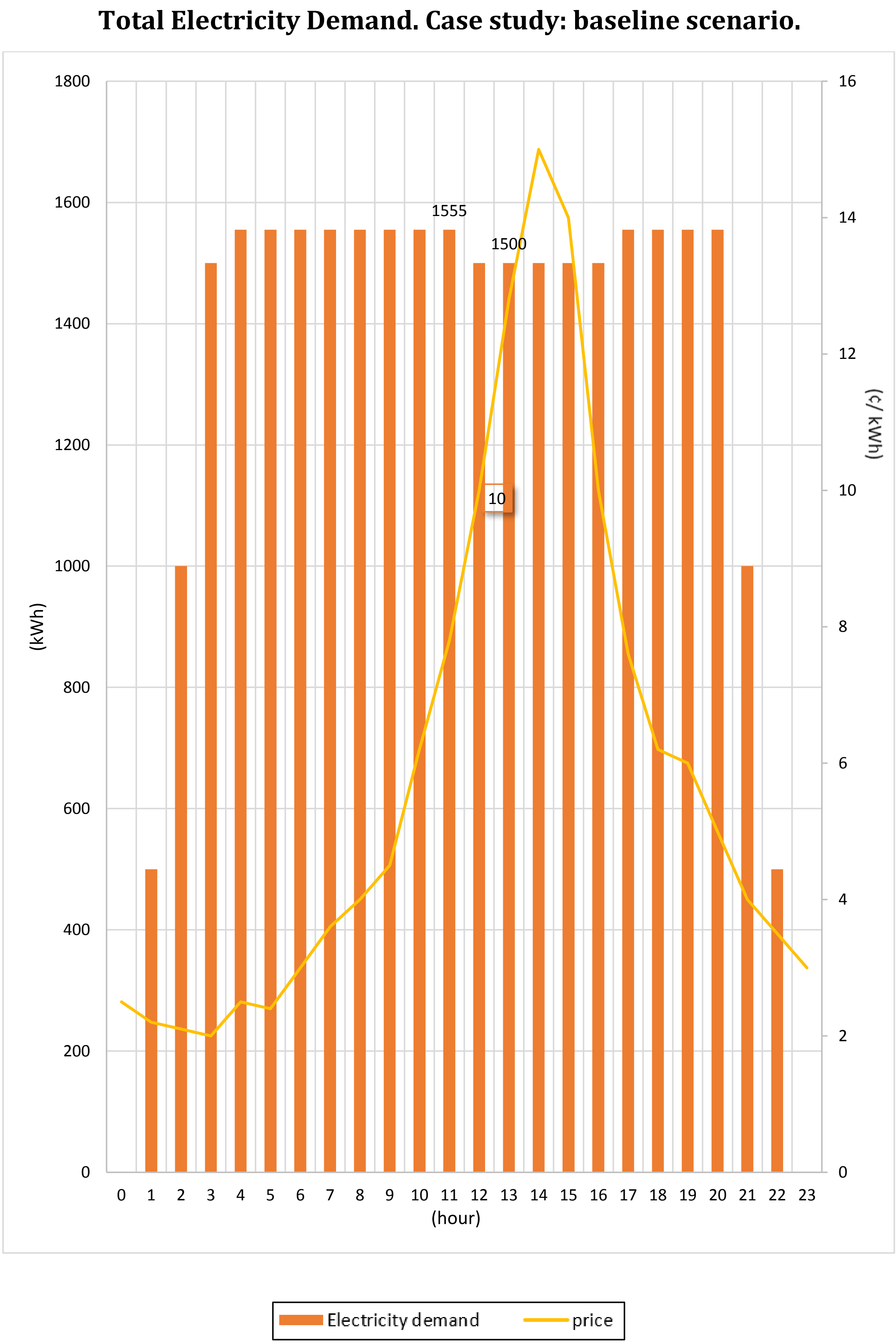

Figure 14 – Total electricity demand and the electricity buying price.

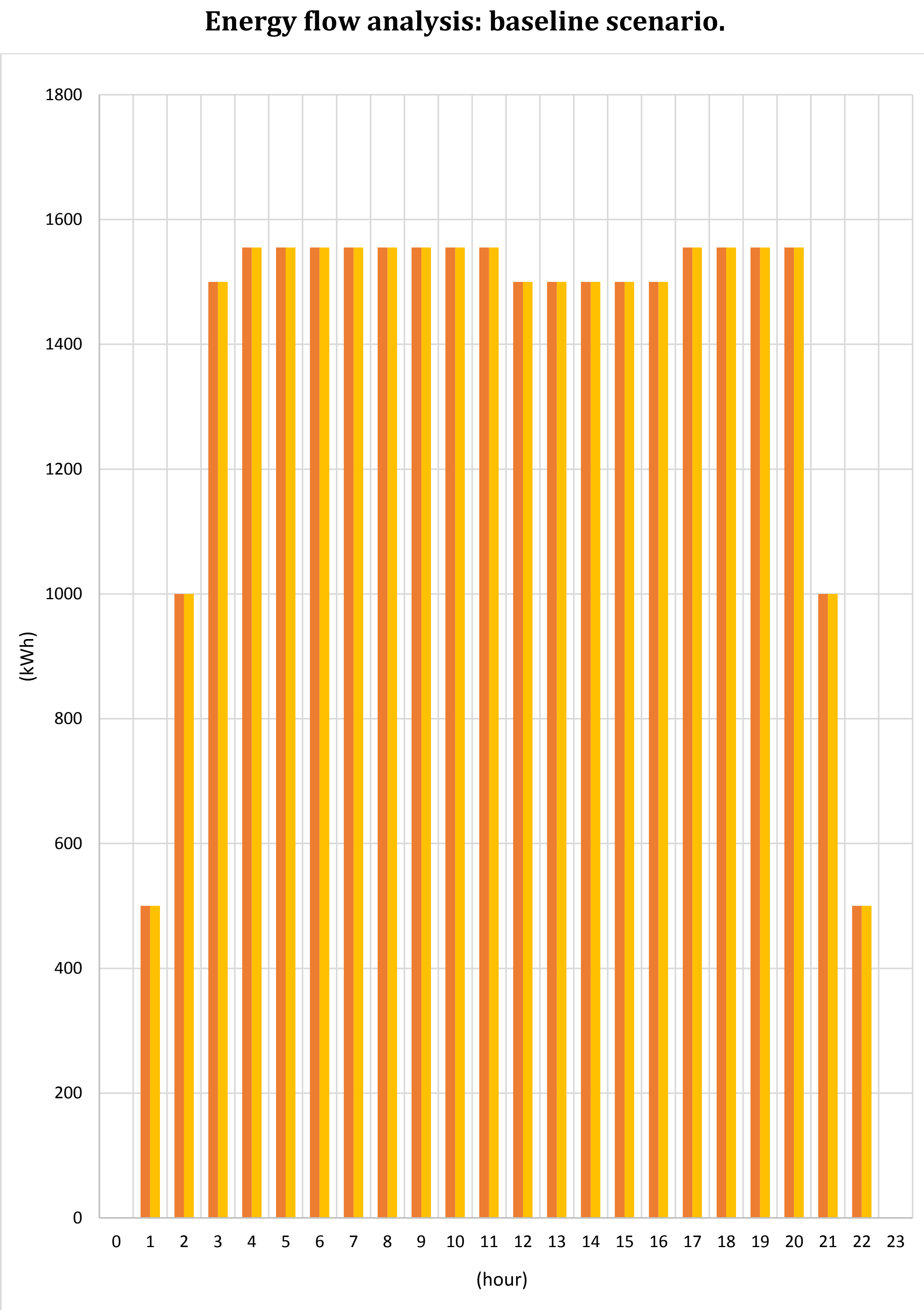

Figure 15 - Energy flow analysis : baseline scenario.

In the figure 16 the energy flow analysis for scenario b) was presented. The Figure presents Total Energy Demand in comparison with the energy charged and discharged to EES and from EES. The third column represents energy bought and sold to the grid. Additionally, the price of the energy was shown on the separate axis. From the analysis it is possible to conclude how much electrical energy from the grid was fed directly to the process and how much of the electricity bought is stored in the EES. For example, in the 5th (h) the Total energy purchased was calculated to be 3055 (kWh) from which 1500 (kWh) was charged into EES and 1555 (kWh) was used in the process.

At 12th there was a situation where 60 (%) of the total energy demand was covered with the previously stored energy in the EES and 40 (%) of the total energy demand was covered with the energy from the grid. In the price – peak periods, between 13th and 15th (h) all the previously charged energy was discharged in order to make energy savings.

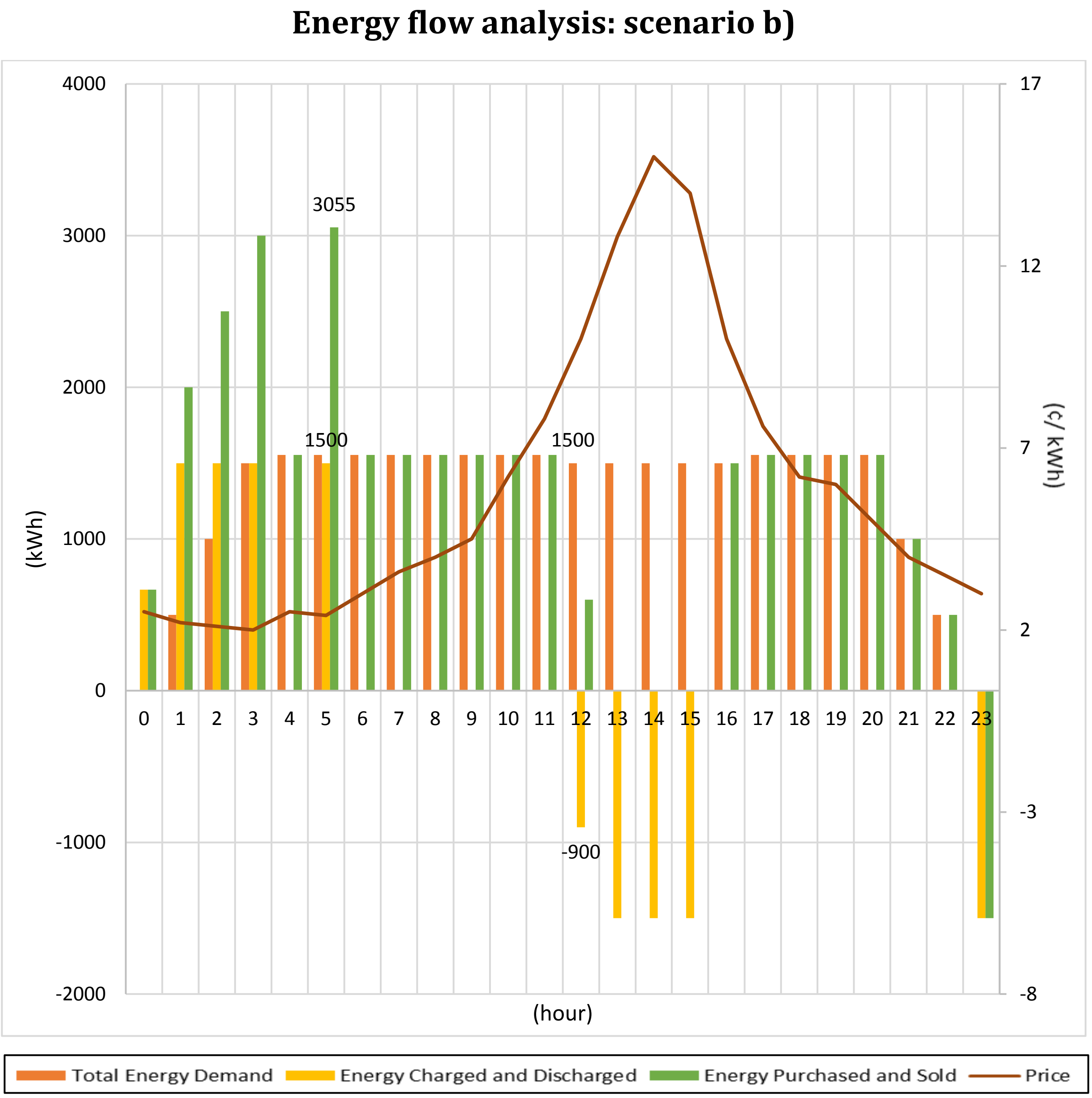

Figure 16 - Energy flow analysis - scenario b)

In the figure 17 the energy flow analysis for scenario c) was presented. The Figure presents also a PV energy generated shown in the fourth column. From the analysis it is possible to conclude how much electrical energy from the grid was fed directly to the process and how much of the electricity bought was stored in the EES as well as how the energy generated from the PV affected the total energy bought or sold. For example, in the 11th (h) the Total energy purchased was calculated to be 650 (kWh) and the total energy demand of 1555 (kWh) was fulfilled with PV energy – 905 (kWh). At 13th (h) total energy generated from PV was used in the process, together with the energy discharged from EES. The surplus was sold back to the grid.

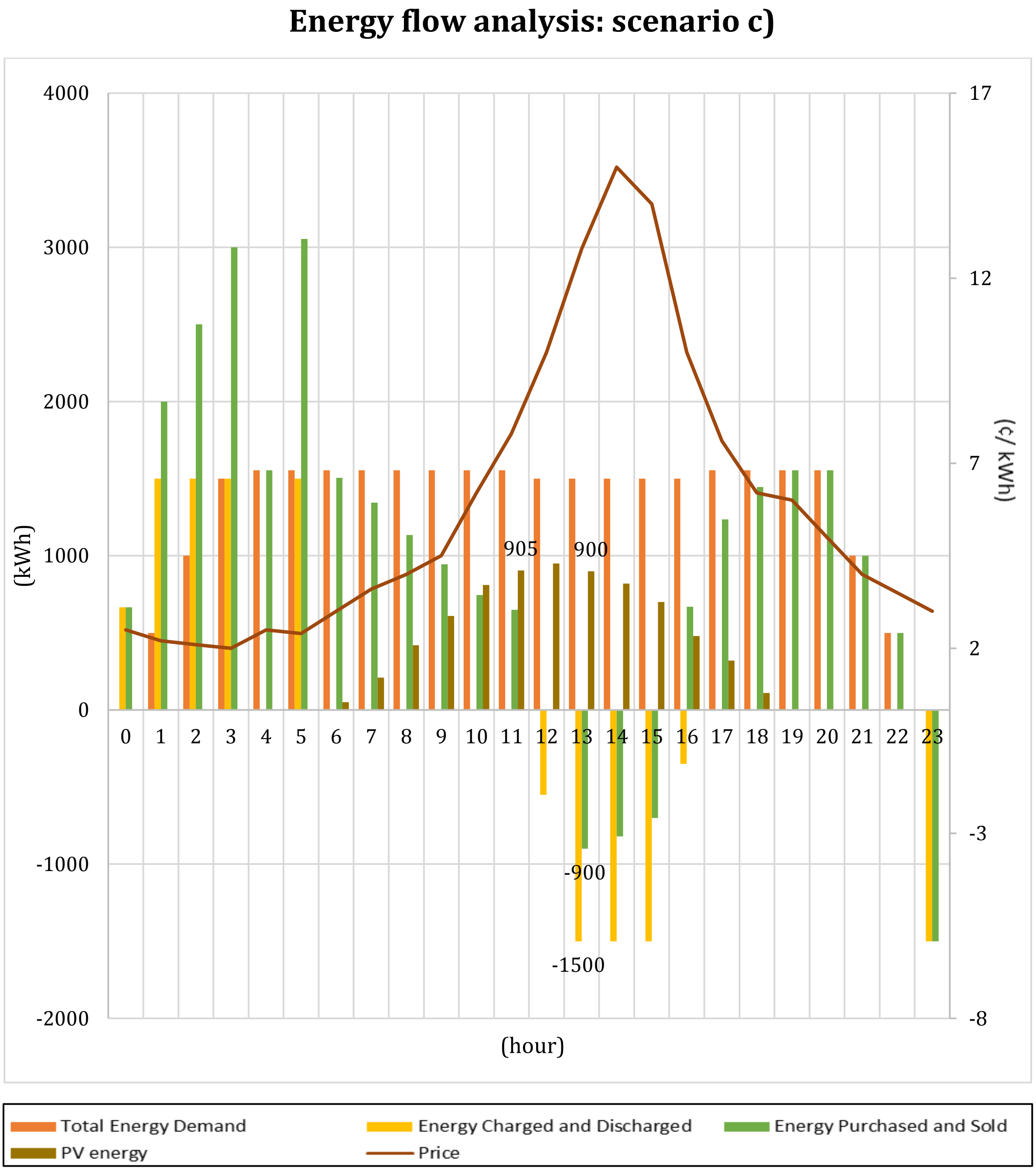

Figure 17 - Energy flow analysis : scenario c)

In the Figure 18 the purchased and sold electrical energy to the grid was presented for all three scenarios. At the time 0 (hour) for the base scenario, there was no electricity bought from the grid while for scenario b) and c) there was 667.67 (kWh) bought from the grid and stored in the EES at the price of 2.5 (¢/ kWh).

Between the 1st (h) and 3rd (h) the amount of electricity bought from the grid for all scenarios increased as the energy demand increased. However, for Scenario b) and c) the amount of electricity bought from the grid was 4 times higher than electricity bought for the base scenario at 1st (h). Similar trend could have been seen for time instances 2 and 3 where the electricity bought from the grid was around 2 times higher for the scenarios b) and c). The breaking point was observed at the time instance 4 when there was a local maximum for the price observed at the level of 2.5 (¢/ kWh). For that time the electricity bought for all the scenarios was equal to the energy demand of the pipeless plant.

At time instance 5 there was a local minimum for the price observed so the energy bought from the grid for scenarios b) and c) was at its' peak value. From the time instance 5, the electricity price was constantly increasing to reach its' global peak at time instant 14. For the base scenario and scenario b) the electricity bought from the grid was equal between the 6th (hour) and 11th (hour). For the Scenario c) in between 6th (h) and 11th (h) the constant decrease of electricity bought from the grid was observed.

For example, at 11th (h) the total energy bought from the grid for scenario c) was around 42 (%) lower for case c) in comparison with case b) and the baseline case – due to the PV system installed.

At 12th (h) the electricity bought from the grid for the base scenario was equal to the total energy demand, while for scenario b) was 40 (%) lower. Moreover, for scenario c), at 12th (h) it was observed that total electricity bought from the grid was 0 (kWh). In between the 13th (h) and 15th (h) for the base scenario, the electricity bought from the grid was still equal to the total energy demand while for scenario b) it was equal to 0 (kWh). It is worth mention that during the period of 13th (h) and 15th(h) there was a peak buying electricity price observed. In the same period, pipeless plant in scenario c) was selling electricity back to the grid. From16th (h) till 22nd (h) the amount of electricity bought from the grid was in equilibrium for base scenario and scenario b) and was rising constantly for scenario c) till 19th (h) where it reached equilibrium with the total electricity demand of the pipeless plant.

At 23rd (h) pipeless plant in the base scenario was not buying electricity from the grid while in scenario b) and c) was selling the excess amount of electricity back to the grid at the price of 3 (¢/ kWh).

Figure 18 - Purchased and sold energy. Case study : scenarios comparison.

In the Figure 19 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. Between the 0 (h) and 5th(h) the amount of electricity charged into the EES raised from around 667.67 (kWh) to 1500 (kWh) – which is a maximum charging rate of the EES - and stayed constant till the 3rd hour. At the 5th (h) there was also charging occurring at the maximum charging rate. Between 6th (hour) and 11th (h) there was no charging or discharging occurring for both scenarios. At 12th (h) the amount of electrical energy discharged at scenario 2 was higher by 350 (kWh) in comparison with the scenario 3. From 13th (h) till 15th (h) the discharge was occurring at the maximum discharge rate for both scenarios. at 16th (h) there was discharging occurring for scenario 3. At 23rd (h) there was discharging occurring for both scenarios.

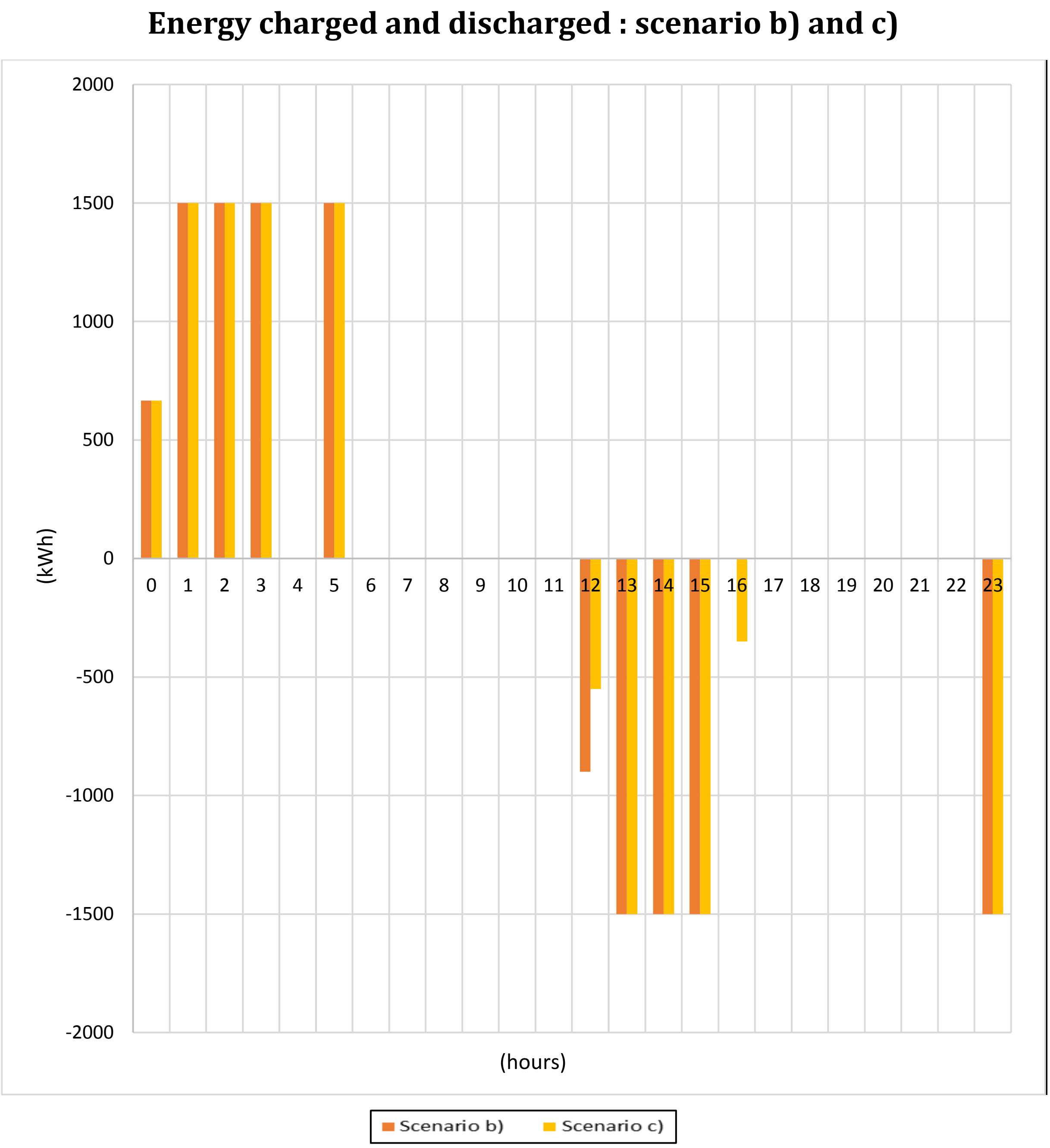

Figure 19 - EES schedule : scenario b) and c)

In the Figure 20 the quantity of electrical energy stored (kWh) was shown over the time horizon. The charging started with 40 (%) of maximum charging rate. The charged amount of electricity stored raised from 600 (kWh) at 1st (h) and was charged for 3 (h) till it reached 75 (%) of maximum charging capacity at 4th (h). There was no charging occurring at 4th (h). At 5th hour there was last charging occurring with maximum discharging rate and the EES was fully charged. From 12th (h) till 15th (h) there was discharging occurring for both scenarios. For the scenario 3 there was also discharging occurring at 16th (h).

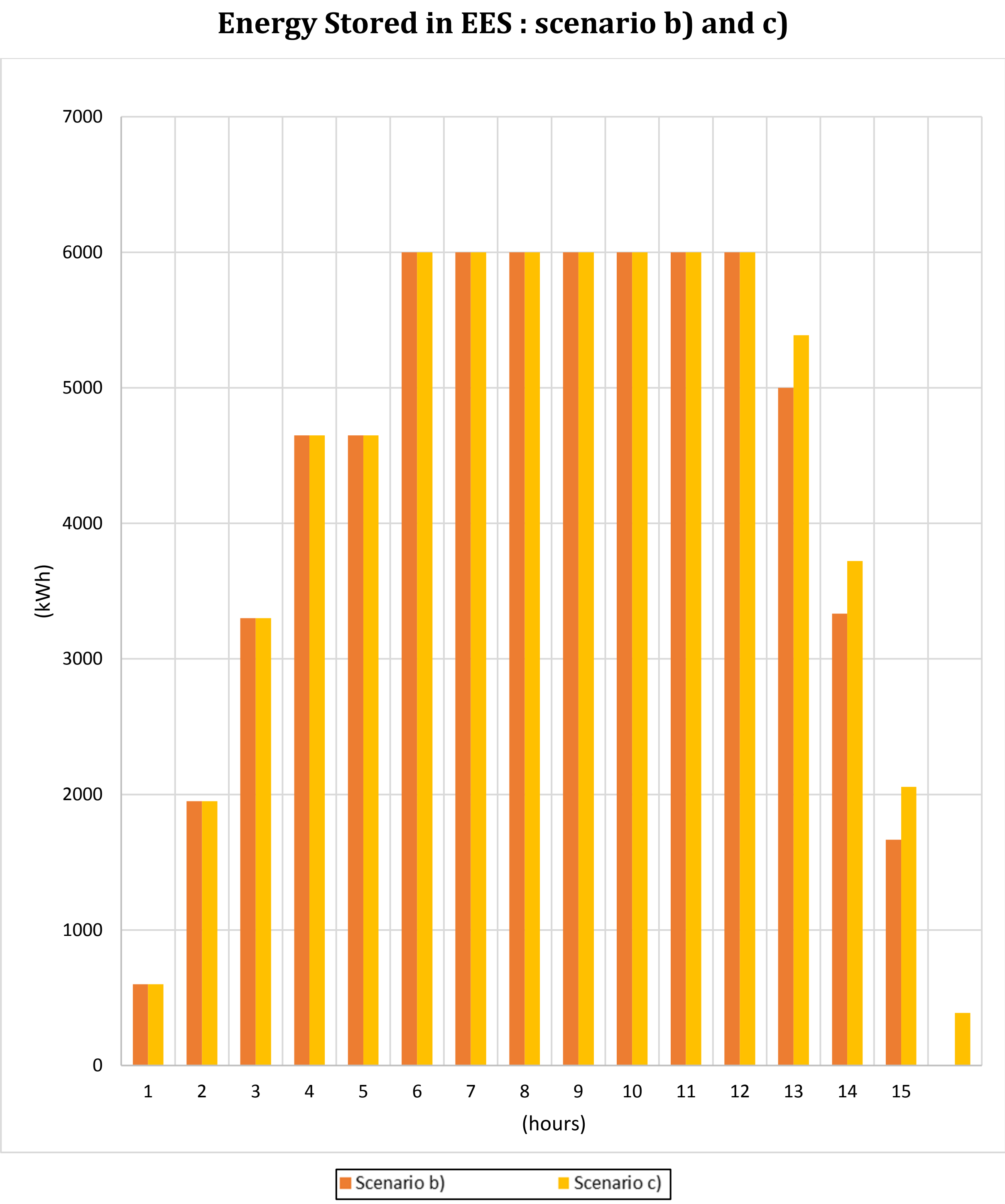

Figure 20 - Energy stored in EES : scenario b) and c)

In the Table 10 the optimization results were presented. The highest Total Profit was obtained for the scenario c) with both EES and PV installed. Moreover for the same scenario the Total Energy Cost was the lowest. Total amount of deliveries equal to 120 (m^3) for all the scenarios.

Table 10 - Optimization results

Variable	***Baseline scenario***	***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 (m^3)		120	

5.2 Case study – conclusions

Based on the assumptions for the case study, the optimization results of the MILP model determined:

- Production schedule Gannt Chart (Figure 13) based on Determined Operating Point (Table 8) for each task during the whole-time horizon.
- Total electricity demand at each interval during the time horizon.
- Market integration – electricity trading schedule.
- EES charging and discharging schedule.

In the production schedule (Table 9) the sequence of performing each task after another was obtained following the assumed STN and plant topology (shown in the Figure 8 and Figure 9) and allowed for an analysis of the station utilization and vessel movement for every hour during the time horizon shown in the Gannt Chart (Figure 13). It is worth notice, that pipeless plant schedule can be analysed also by looking at the Total Electricity Demand (Figure 14). Since there can only be one vessel utilized by each station and every vessel needs to follow the same sequence of operation, it was noticed the rising electricity demand at the beginning of the process - which is related to the number of vessels being processed at every time instance. Due to the high range of the delivery requirements (Table 1) and low values of products that were consumed and produced by each task (Table 6), the results of the DOP (Table 8) 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) – which was the most energy demanding Operating Point (Table 6). There was no shifted process' schedule for those operations – Charging A0, Charging B0, Discharging - because the objective function goal was to maximize the total profit (equation 35). However, the production schedule was shifted from peak electricity price to the lower electricity price areas for the Cleaning tasks which took place at Cleaning Station. The results showed also, that all the 8 vessels were left Empty and Dirty at the end of the horizon, because of too low notional value assigned to Empty Clean Vessel when running the optimization. These were the reasons why the demand for cleaning operations could have been shifted from peak to off – peak hours for the cleaning operation.

The electricity market integration is a valuable tool for energy management scheme creation. From three different scenarios comparison it was noticed that for different situations, the different amount of electricity can be bought or sold to the electrical grid.

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 shown in the Table 10 - 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. Comprehensive literature review of pipeless plants and industrial demand side management was studied and the conclusions were followed with the recommendation for the future path of the thesis development. Pipeless plants topic is not well investigated. There are however several examples of existing pipeless plants in several different areas such as photography and film industry. The companies such as Mitsubishi Heavy Industries or Toyo Engineering has released several demonstrational multiproduct – small volume pipeless plants in the past. The problems of pipeless plants issues were reported to be the possible capital costs as well as technical issues related with the electrical wirings, so 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 scheduling of the EES 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.

Pipeless plants reveal similarities between the textile and cement plants such as bottlenecks in production and batch product delivery characteristics. Based on these similarities of pipeless plants to the cement or textile plants, the strategy for energy management scheme in the Demand Response programme was investigated because of the cement and textile plants have a very high suitability for Demand Response programmes that was already well investigated, but not in the pipeless plants. The results of the production confirm the adaptability of pipeless plants, because the Deliveries Requirements goals were reached and in the same time it was possible to shift the electricity demand of the cleaning operation as shown in the Gannt Chart (Figure 12).

The new electricity markets such as Nord Pool, give the possibility to buy the electricity on the day-ahead basis and thus, the pipeless plant with on-site renewable energy system and electrical energy storage unit was also investigated in the context of the market integration. The integrated production and energy management system was developed as a MILP formulation and implemented in GAMS. 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.

The process schedule in the form of DOP and Gannt Chart was obtained from which it is possible to track the vessel movement and asses the processing station utilization during the whole-time horizon which can help to avoid hazardous situations when designing the plant at an early stage.

Three scenarios were investigated. In the baseline scenario, all the energy had to be bought from the grid because of lack of EES and PV. For the scenario b) with EES the operating strategies for charging and discharging EES, based on predefined assumptions and mechanisms of modern electricity markets were optimized and the charging schedules during the time horizon were validated. The results for this scenario showed that by charging the storage unit when the prices of electricity are lower the operational costs can be decreased by around 31(%) which corresponded to 605 (€) per day.

The energy flow analysis has shown the best results for the scenario c) with PV and EES where the lowest amount of electricity had to be bought from the grid. The total profit of the pipeless plant was the highest for this scenario with the savings of around 63 (%) per day, which corresponds to 1223 (€) per day in the followed case study.

The results of the work are very promising and show the high level of the model applicability. The developed and presented model is a solid operation management tool that helps to define operating decisions for industrial customer. 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 detailed stations characteristics are required for more accurate case studies. Based on the specific case study future work could also involve expanding the model into implementing several renewable energy sources and electrical energy storage units. What is more, the future analysis could involve also fossil fuel generators such as diesel engines in order to implement the full example of integrated demand side management scheme for pipeless plant. Further work can be developed also to assess the performance of this approach for more complex STN and pipeless plant topologies. Finally, a user-friendly interface could be developed to take advantage of the framework in a more comfortable way.

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