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Implementation of energy recovery and storage systems in cranes in the Port of Gävle

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Abstract

Container traffic in seaports around the world in constantly increasing, with energy costs being a significant part of the total costs. The container terminal (CT) of the Port of Gävle, the largest in the east coast of Sweden, is not an exception to this. With traffic growing annually, a new terminal will be opened in the following years, adding three more ship-to-shore (STS) cranes to the two existing ones, and six electric rubber tyred gantry (eRTG) cranes. Therefore, it is highly important to strengthen energy efficiency measures, reducing the energy consumption and the costs associated with it. This is why the aim of this report is to analyse whether implementing energy storage systems in the cranes of the container terminal Port of Gävle can contribute to reduce electricity costs by recovering energy when braking lowering containers, and by *shaving* power peaks. After a literature review of current energy recovery and storage options, this work presents three solutions: two alternatives for the current situation with two ship-to-shore (STS) cranes, and a third solution to be implemented in the three future STS cranes to be installed, which can also be beneficial for any other crane in the terminal. According to the made calculations, the three alternatives can reduce considerable energy consumption, and they are highly profitable. However, those solutions are a preliminary study and more work needs to be done to determine the exact profitability and technical system details. This work has been done in collaboration with the Port of Gävle and Yilport, the company operating the container terminal.

Keywords: Port of Gävle, container terminal, energy storage system (ESS), energy recovery, power peak shaving, port crane, STS crane, RTG crane.

Preface

I would first like to thank my thesis supervisor, Arman, for his support during the realisation of this work. I also want to express my gratitude to Henrik, from the Port of Gävle, who has been very helpful during the whole work. I am also grateful to the personnel from Yilport Gävle, who have provided me with the necessary technical information.

A big thanks as well to my fellow students from the University of Gävle, for making this academic year especially enjoyable.

Finally, this year being probably the last of my studies, I am very grateful to my family and friends back home for their continuous support during these years.

Nomenclature

Abbreviations and acronyms

Letters	Description
AC	Alternating current
CT	Container terminal
DC	Direct current
GBP	Pound sterling
eRTG	Electric rubber tyred gantry
ESS	Energy storage system
FES	Flywheel energy storage
QC	Quay crane
RTE	Round trip efficiency
RTG	Rubber tyred gantry
SC	Supercapacitor
STS	Ship-to-Shore
SEK	Swedish krona
TEU	Twenty-foot equivalent unit (normal container = 2 TEU)
USD	United States dollar

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1 Introduction

1.1 Background

Freight traffic in container terminals (CTs) around the world is increasing every year, and the associated energy demand is growing consequently [1], [2]. Nowadays, around 75% of all goods traded in and out of the EU are moved by ports [3]; and 85% of world's cargo traffic is transported by sea [2]. Of which, more than 60% is moved in containers, reaching up to 100% in some routes [4].

The container terminal of Port of Gävle, operated by Yilport, is the largest in the east coast of Sweden, and as such, it is following the same growing tendency, and it has experienced a large increase in traffic the last years. This is why a new CT is under construction, with which the Port of Gävle will soon double its capacity [5].

Seaports are big energy and power consumers, with electrical systems that can demand several megawatts of power and consume hundreds of thousands of MWh [6]. In addition, fossil fuels are also consumed in large amounts in ports [7]. As freight traffic incessantly increases, energy and power demand are raising as well [6].

A large part of costs in CTs are associated with energy costs [2]. Therefore, energy efficiency measures are crucial to make ports more efficient and economically profitable. In addition, energy efficiency measures also contribute to reduce the environmental impact of ports, which is usually high [7], [8].

Several measures to increase energy efficiency and to reduce costs in ports exist, and they are being implemented in ports around the world [2]. Those measures vary in form and complexity, from making operational changes to reduce peak power and energy consumption [2], [9] to implementing new technologies that allow, for example, to connect ships to the electrical grid (*cold ironing*) or to set energy storage systems (ESS) to recover and store energy from cranes and thus make them more efficient [2].

This last technology will be explored in this work, for the case of the Port of Gävle. Currently, its container terminal has two ship-to-shore (STS) cranes, and because of its extension, it will soon get three more STS cranes, and six electric RTG cranes.

Those cranes use electric motors to handle the containers. A large amount of power is needed to lift them. In addition, when lowering the containers, the motors act in a regenerative way, producing power peaks that are sent back and wasted. Recovering and storing this energy could make the cranes more efficient and reduce the overall operation costs of cranes.

This thesis is part of the Energy Systems course in the University of Gävle, and it has been carried out in collaboration and contact with the Port of Gävle, and Yilport, the company operating the container terminal. Its main objective is to determine if implementing energy storage systems in the container terminal of the Port of Gävle is feasible and profitable.

1.2 Literature review

This section will explore the state-of-the-art of energy storage systems in container port cranes, based on published literature. Firstly, a general overview of the functioning of container terminals will be given, to then explore in more detail the different technologies available for this purpose. Two application examples will close the section.

1.2.1 Container terminals

Many different types of container terminals exist [4]; therefore, this subsection will give a general overview of container ports, and it must be taken into consideration that some container terminals could not match exactly with the ones described below.

Container terminals are generally composed by three subsystems, consisting on the berth – where ships dock –, the container yard, and the gate – where containers are taken in and out the terminal by trucks or trains [4] –. Four operations are done between the mentioned subsystems: loading/unloading the ship, transfer, storage and delivery/receiving [10]. The former operation, loading/unloading, is achieved by quay cranes (QC), which are usually ship-to-shore cranes (STS) [11], [12]. STS cranes are connected to the electric grid, as they are installed in a fixed position and their movement is limited [11], [13]. The transfer and delivery/receiving operations are usually done by vehicles like tractors, trucks, automated guided vehicles or straddle carriers [4], [10], [11]; but in the case of trains, gantry cranes are also used for loading and unloading [4]. For storage, stacking and handling the stored containers, straddle carriers, rubber-tyred gantry (RTG) or rail-mounted gantry (RMG) cranes are commonly used [4], [11].

STS and RTG cranes will be explained in more detail in the following pages.

1.2.1.1 STS cranes

Quay cranes (QC) load and unload container ships, the most common type mentioned in the literature being ship-to-shore (STS) cranes [2], [12], [14]. STS cranes are situated on the dockside, and can move along it, as they are mounted on rails [12]. This means the movement of STS cranes is limited, and thus they can be connected to the electrical grid without difficulty. Therefore they are usually electric cranes [11].

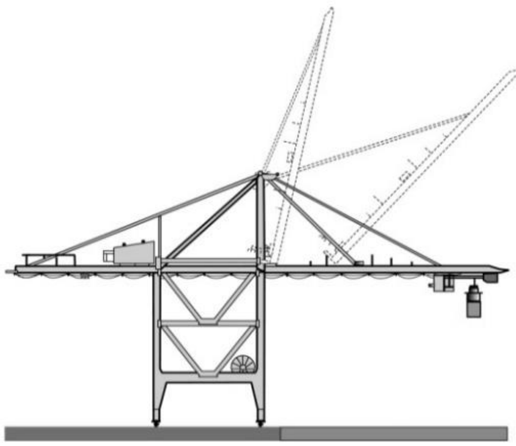

FIGURE 1. EXAMPLE OF AN STS CRANE. SOURCE: [15]

One possible classification of QCs is according to the size of the ship they serve [12], [15]. *Panamax* cranes can load and unload vessels that are able to cross the Panama Canal (30-40 m width, or 11-13 container rows). *Post-Panamax* cranes can serve 45-55 m width ships (17-19 containers). Finally, *Super Post-Panamax* cranes reach 60-70 m (21-23 containers) [15]. Smaller cranes than Panamax also exist, even if they are not part of this classification [16].

STS cranes have three general types of movement: hoist, trolley and travel (or gantry) [14], [16], [17]. The boom movement is also counted as a main movement by Jo and Kim [17].

- Hoist is the vertical movement for lifting containers, and it requires the highest power of all movements [14], as a large mass must be lifted in a limited amount of time. Typical speeds are 50-90 m/min without load, and 125-180 m/min when hoisting a container [15], [16].

- The trolley is the mobile element that moves along the main beam, and its movement takes its name. Consequently, the trolley movement is perpendicular to the quayside, and it moves from the shore to the ship, and vice-versa. Depending on the size of the crane, trolley speed varies from 50 m/min to 240 m/min [15], [16].

- Finally, the movement of the whole crane along its dockside rail is called the gantry movement, or travel. Therefore, this movement is parallel to the dockside and the served vessel. Usual speeds range from 45 m/min to 70 m/min [15], [16], reached after some seconds of acceleration [15].

In order to be handled, containers are held by an element called spreader, which in its simple form typically weights around 10-12 tonnes, but can weigh more than 20 tonnes [7], [18]. This weight must be considered in calculations.

When a container is handled, the cycle is completed in six main steps: hoisting, trolley and lowering (hoist down), followed by the same steps without load [19], [20] (Figure 2). The cycle is completed in roughly two minutes, depending on the crane and conditions. During a cycle power demand is variable with high peaks, mainly during hoist [20]. The power demand for a rated load cycle of the new STS cranes to be acquired by the Port of Gävle is shown in Figure 3 as an example. During lowering, STS cranes can regenerate up to 90% of the hoisting energy. If this energy is not used or stored, it is sent back to grid, causing disturbances on it [19].

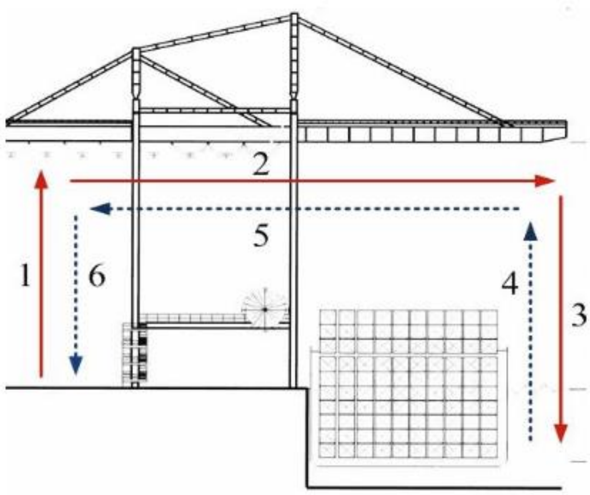

Figure 2. Cycle steps in container cranes. (1, 4) hoist, (2, 5) trolley, (3, 6) lowering. Source: Parise and Honorati [20].

The cranes' electrical bus can be DC [14] or AC[1], which do not necessarily match with the motors' current type. Electronic converters are used to connect both systems[1] [14].

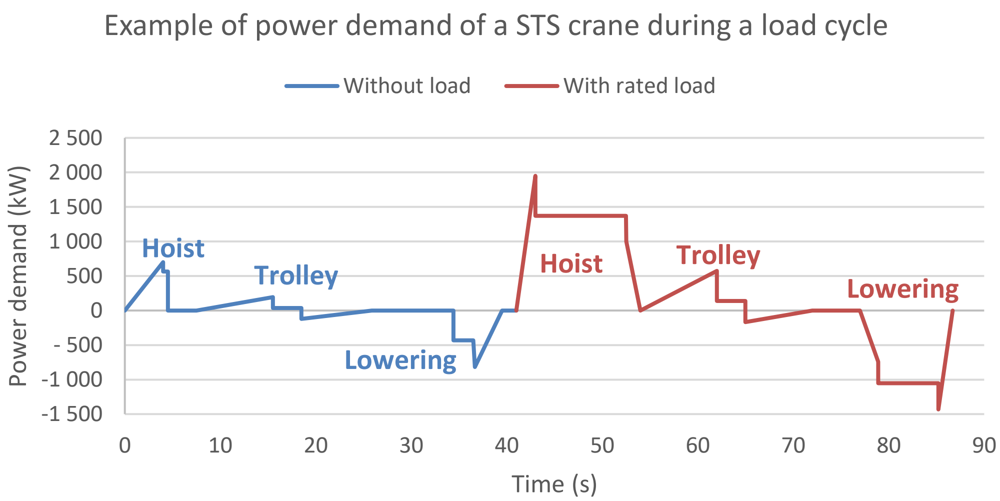

Figure 3. Power demand during a cycle of the new STS cranes to be acquired in the Port of Gävle. Information provided by Mitsui E&S via Yilport.

[1] This is the case for the STS cranes in the port of Gävle, according to the documents provided by Yilport.

1.2.1.2 RTG cranes

Rubber tyred gantry cranes, or RTG, are a common type of crane used to handle and stack containers [1], [11]. They have the advantage of being able to move freely around the terminal, since they are not mounted on rails [11], as Figure 4 shows. The drawback of this is the fact that their freedom of movement usually prevents them of being continuously connected to the electrical grid [11]. Therefore, common RTG cranes are powered by diesel engines, which feed an electrical generator; and consequently are a considerable source of pollution, often accounting for half of emissions of container terminals [10]. However, ports are starting to use more sustainable alternatives, for instance finding solutions to electrify the RTG cranes [21], [22].

FIGURE 4. RTG CRANE. SOURCE: CORVUS ENERGY [23].

Fuel efficiency of diesel RTG cranes is not very high, as kinetic energy is usually dissipated in dump resistors in order to brake lowering containers [8], [11]. In addition, engines in conventional RTG cranes are designed to deal with containers as heavy as 40 t. A lift of such a container can have a peak power demand of 410 kW. Thus, the engine must be designed to provide such power, in order to maintain stability during power peaks [24]. However, conventional port containers commonly weight significantly less. Furthermore, container lifts take less than 20% of the total crane operation time, and power peaks usually last no more than 2 seconds [25]. This means that diesel engines in RTG cranes are oversized and almost always work out of the optimal point. As a consequence, they are operated in non-efficient manner [24].

This problem has been taken into consideration in the recent years, and manufacturers are starting to take measures [21], [26]. RTG cranes can considerably reduce their emissions and maintenance costs if they are connected to the electric grid [22], [27], and using auxiliary diesel engines only when it is not possible to keep the crane connected to the grid [10]. The electrical connection is usually achieved using a bus bar situated next to the crane, or through a cable [27]. Those cranes are often abbreviated as eRTG [26]. Other ways of reducing RTG emissions are using a hybrid system composed of lithium batteries and a downsized engine [23], [27], [28], or using fuel cells [29].

Recovering and storing the energy generated by means of different ESS when hoisting down containers have also shown to be interesting methods to substantially reduce fuel consumption, and therefore pollutant emissions [7], [25]. These ESS will be explored further on.

1.2.2 Energy storage systems (ESSs)

Cranes use a significant amount of power and energy for hoist, and part of it is regenerated when braking during hoist-down. But this regenerated electricity is not habitually used, and it is sent back to the grid or dissipated in resistors [25]. Therefore, there is a potential to make cranes more efficient and profitable reusing this energy.

In addition, crane movements, specially hoist, create power peaks that can cause disturbances in the electrical grid. Therefore, electrical companies make customers pay for the maximum amount of power demanded during a specific period. Furthermore, ports acquiring new electric cranes can suffer overload problems in their grids, which can result in blackouts or high costs for reinforcing the grid [21].

Finding a way to compensate those power peaks using previously stored energy can help *shaving* those power peaks, and thus reducing operation costs and avoiding investments for grid reinforcement [21]. In addition, if this stored energy is obtained recovering the braking energy, the overall energy consumption – and cost – will also decrease.

Literature suggests three ESS candidates for cranes, which will be studied in the following lines: supercapacitors, flywheels and batteries.

1.2.2.1 Supercapacitors

Supercapacitors (SCs), also called ultracapacitors [30], are high-capacity electrochemical capacitors. They have a considerably higher energy density than usual electrolytic capacitors [31]. Compared to batteries, they have higher power density [31] and efficiency [20], [32] (RTE[2] of 92-98% [33]), as well as a longer lifetime (10-16 years [33], and even more than 20 in some cases [33]). SCs also have a much faster dynamic response than batteries [34]; they can charge almost instantly, in contrast with batteries, which usually need hours [35]. In addition, supercapacitors require almost no maintenance [29], [35], [36], to the point that maintenance costs can be considered negligible [33].

[2] RTE, round-trip efficiency, is the ratio between input and output energy in an ESS.

However, supercapacitors have lower energy densities than batteries [31], [32]. Moreover, they need to be connected to a DC-DC converter which regulates its charge [20], since, unlike batteries, the state of charge of supercapacitors is very dependent on the applied voltage [31].

Supercapacitors are still under development [32], which will reduce their costs [37], although they have already been in use for some years [33], [38]; and they have a promising future in the electricity storage domain [32]. Some of the main application areas of SCs are renewable energy generation, and energy recovery in lifts [39], cranes [14], [31], [39], and electric vehicles and railways [31], [38], [40].

Using supercapacitors on diesel RTG cranes has the advantage of using the engine only as a constant power source, while supercapacitors supply power peaks when needed [24]. Therefore, the engine's power supply becomes smoother. Kim and Sul [25] concluded that using SC technology on RTG cranes can downsize the engine to a third of the conventional size, and reduce fuel consumption by 35% and emissions by more than 40% [25]. This technology is already being used in ports [38].

Cranes connected to the electric grid like STSs and electric RTGs can also benefit from supercapacitors [21], [41], as they can contribute to reduce costs, by reducing the peak power demand and the overall energy consumption [33].

The capital costs of supercapacitor systems are range from 100 USD/kW to around 400 USD/kW [14], [33], depending on the energy storage capacity. A 2019 report from the US Department of Energy [33] mentions the system costs of three real projects using supercapacitors, which are shown in Table 1.

Table 1. Examples of costs of projects using supercapacitors. Source: US Department of Energy [33]

Provider	System power (kW)	Energy storage capacity (kWh)	System cost (USD)	Cost per unit of power (USD/kW)	Cost per unit of energy (USD/kWh)
Ioxus Energy	250	[*unknown*]	40 000	160	-
Maxwell	1 000	7.43	241 000	241	32 565
Maxwell	1 000	12.39	401 000	401	32 365

1.2.2.2 Flywheels

Flywheels store energy as rotational kinetic energy. They are made of a rotating mass – the rotor – coupled to an electric machine that acts like a motor or generator [7]. When the motor accelerates the rotor, it accumulates energy, which can be released braking the mass using the electric machine as a generator.

In low-speed flywheels (< 10 000 rpm) the rotor is usually made of metal; while in high-speed applications (> 10 000 rpm) fibre composite rotors are used [42], [43]. Low-speed systems have been in use for a long time mostly to improve power quality in electrical grids. High-speed flywheels, although they exist commercially, are still mostly object of research [43].

Electric machines commonly used in flywheel systems are induction machines, permanent magnet synchronous machines, switched reluctance machines and synchronous homopolar machines [43].

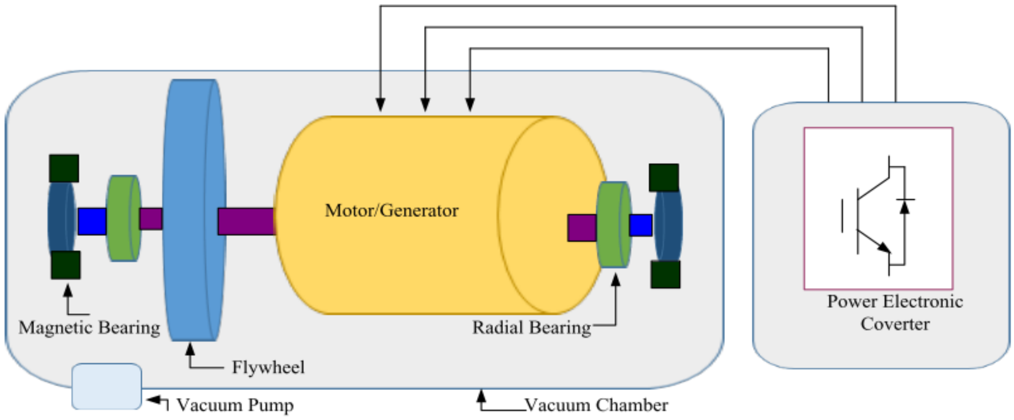

FIGURE 5. STRUCTURE OF A FLYWHEEL ENERGY STORAGE SYSTEM. SOURCE: M. KHODAPARASTAN AND A. MOHAMED [43]

Flywheels rotate in a vacuum, and usually have magnetic bearings to reduce friction [7], although some of them use common ball bearings [44]. However, not even magnetic bearings can avoid high losses [44]. Consequently, energy can be stored from 1 to 30 minutes [33]. Yet, as long-term energy storage is not required in port cranes, flywheel technology is an interesting option.

Flywheel systems are connected to a bus by means of a power electronic converter [42], [43], or to a higher voltage grid using a transformer [14]. Several flywheels can be paralleled in order to get a higher power [14].

Flywheels can provide high power peaks for a short time, usually some seconds, for many consecutive cycles. They also have a long lifespan of around one million cycles [42], or 20 years [14]. According to a report from the US Department of Energy, flywheels can be used to provide power peaks up to 20 MW, and store up to 5 MWh of energy, and they have a RTE ranging from 70 to 98%, with most sources giving a number near to 85% [33].

A drawback of flywheel systems is that they have higher maintenance costs than SCs [14], although they remain small (around 5.6 USD/kW/year [33]). They also have a complex installation process [14]. In addition, as said, their high losses prevent them from storing energy for a long period of time.

TABLE 2. EXAMPLES OF COSTS FOR PROJECTS USING FLYWHEEL ENERGY STORAGE. SOURCE: US DEPARTMENT OF ENERGY [33]

Provider	System power (kW)	Energy storage capacity (kWh)	System cost (USD)	Cost per unit of power (USD/kW)	Cost per unit of energy (USD/kWh)
Beacon Power[a]	20 000	5 000	50 M	2 400	10 000
Kinetic Traction	999	4.5	599 400[b]	600[b]	133 333[b]
Helix Power	1 000	7.4	1.05 M	1 050	141 892
Piller	2 700	[*unknown*]	1.62 M	600	-

[a] Information of a large flywheel power plant in the US
[b] Installation costs not included

Apart from their traditional use for stabilising power grids [42], flywheels are potentially suitable options for applications needing short, high power peaks like uninterruptable power supply (UPS), electric vehicles and trains and trams. Flywheels can also be very beneficial in diesel RTG cranes reducing considerably fuel consumption and emissions [7]; and also in electric cranes like STS [14].

Flywheel systems are quite expensive, with prices ranging from 600 USD/kW to 2 400 USD/kW, according to a report from the US Department of Energy [33]. According to Parise et al., flywheels have a significantly lower cost of 200-350 USD/kWh [14].

1.2.2.3 Batteries

Lithium batteries have been used profusely in many areas, and they are a suitable option for diesel RTG crane hybridization, giving those cranes independence while reducing the use of the diesel engine, making them more efficient [23], [24]. Diesel-battery hybrid systems allow replacing the original engine by one a third in size [45] and emission can be reduced by 50-60% [45]. Such hybrid systems have been implemented by different crane manufacturers around the world [23], [27], [28].

However, having worse power and dynamic characteristics than other ESSs [29], they are not the best option for peak-shaving and energy recovery in electric cranes, making SCs or FES more appropriate [7].

1.2.3 Application cases

ESSs have been widely used for diesel RTG cranes [27], as they provide a clear improvement and an important reduction both in emissions and costs. However, less literature is available about the use of energy storage systems in electric cranes, as being electric they have a smaller ecological impact. But since electric cranes also cause problems like a high and irregular power demand that can affect the grid and energy costs, ESS are also a suitable solution for electric RTG and STS cranes, as this chapter will show.

1.2.3.1 Port of Long Beach, California, United States

Parise et al. and Kermani et al. [14], [19], [41] suggest a hybrid FES-SC system to recover potential energy of lowering containers, while reducing power peaks in large STS cranes on the Pier E in the Port of Long Beach, in California.

During hoist, those cranes have a maximum steady power demand of approximately 2 000-2 450 kW for around 20 seconds, with initial peaks arriving almost to 4 000 kW for around 5 seconds. Consequently, the authors decided that the best solution was to set two different ESS working in coordination with each other. Supercapacitors would provide a 2 000 kW compensation for the first high peak and around 500 kW for almost 10 seconds, and they would be situated in each crane's bus. About the flywheel system, one would be set for all the cranes, occupying an area of 7.5 by 18 m [19]. It would provide a constant power of around 1 800 kW for 20 seconds, thanks to the higher capacity of FES to store energy [14], [41].

The authors combine the ESS with a power optimization tool, aiming to avoid several cranes demanding a high power at the same time [14], [19].

According to the authors, the proposed system can reduce the maximum power demand in 7 600 kW (74%), while also reducing the overall energy consumption, and it may be "extremely profitable", with a payback of less than seven years [14].

1.2.3.2 Port of Felixstowe, England, United Kingdom

Studies from Alasali et al. [21], [46] and Luque et al. [1] examine the opportunities for ESS systems in a system formed by two eRTG cranes, based on data from the Port of Felixstowe, England; which has 85 eRTGs [21]. They also study the possibilities of reinjecting the recovered energy to the grid.

The studied ESS is a 150 kW and 1 kWh flywheel system sized to lift the average weight of containers (27 tonnes in that case) instead of the maximum (40 tonnes), as this way capital costs are reduced considerably. The rated power of hoist motors is 250 kW. Each crane would incorporate one of these systems [1].

The authors conclude that applying that ESS system in electric RTG cranes in the Port of Felixstowe can reduce the annual electricity consumption in 30%, saving 6 300 GBP per each pair of eRTG cranes in the port [21], which means an energy cost saving of 267 750 GBP a year, excluding power cost reduction.

Pietrosanti et al. [44] also study the case of the Port of Felixstowe, in this case to optimise the power management of an eRTG equipped with a flywheel system, in order to reduce ESS costs. Both energy consumption and power demand are reduced using the proposed system.

1.3 Aims and limitations

The goal of this work is to find suitable and profitable energy recovery and storage systems for the different present and future cranes in the container terminal of the Port of Gävle. This way, the terminal's energy and power peak demand is expected to decrease, improving its energy and economic performance.

The main study objects will be the two currently installed STS cranes in the Port of Gävle, as well as the new STS cranes to be installed with the opening of the new CT. A general overview about ESS applications for the new eRTGs to be acquired by the port will also be given.

This work is a preliminary study to explore the possibilities of implementing such technologies in the Port of Gävle, based on costs of other projects publicly available, and using the data provided by the Port of Gävle and Yilport. Due to the limited amount of time, equipment and data available, this report will not delve into precise technical implementation details. Therefore, this study should be considered as a first overview on the different ESS options more than a detailed technical installation description.

1.4 Approach

Using the available information provided and obtained from literature, different ESS will be suggested for the CT of the Port of Gävle. Two suggestions will be made for the current situation with two STS cranes, and another one for the future situation with the new STS and eRTG cranes. Energy and power demand savings will be calculated for each of the suggested solutions. The calculated savings will be compared to the costs and lifetimes of such solutions to determine their profitability.

2 Method

2.1 Study object

2.1.1 The Port of Gävle

The data for this section has been obtained primarily from conversations with Henrik Rosengren, from the Port of Gävle; and with Ulf Muhr and Fredrik Ronnqvist, from Yilport, who have provided information and several documents. Information has also been obtained in part from the Port's website [5], [47], and the literature review in the Introduction chapter.

The Port of Gävle is formed by three main sea terminals: the Energy Port, for oil and chemical products; the bulk terminal, for materials for primary industries and large pieces like wind turbines; and the container terminal[3].

The container terminal is the largest in the East Coast of Sweden, handling approximately 300 000 TEU[4] annually and it is currently under extension works to multiply its capacity [5], which are expected to end in Spring 2021 [47]. The owner of the Port is Gävle Hamn AB, the Port of Gävle, a municipal company, while the container terminal is operated by Yilport.

According to the data given by the Port and Yilport, currently cranes in the Port of Gävle make 11 000 hoists per month, or 132 000 per year. This number is expected to grow by 5-8% per year.

The weights of the containers handled in the Port of Gävle, Yilport states, range from 2 to 45 tonnes, although most of them are divided into two groups, depending on their average weight:

- 3-tonne containers, which account for around 45% of the containers.
- 25-tonne containers, which are approximately the remaining 55%.

For the calculations in this report, this distribution of only two types of containers will be assumed.

According to Yilport, this distribution is not expected to change with the opening of the new terminal.

The CT has at present two STS cranes, which allow to serve ships up to 190 m long and with a capacity of 1 500 containers [47]. No other gantry cranes are used currently to handle and stack containers in the port. After the expansion of the terminal, three larger STS cranes will be added, as well as six RTG cranes. The terminal will be able

[3] Source: visit to the Port the 14th April 2020.

[4] TEU is a unit to measure the number of containers. 1 TEU is equivalent to 6.1 metres. A normal container is equivalent to 2 TEU, or 12.2 metres [5].

then to receive ships up to 366 meters long and with a maximum capacity of 14 000 containers [47]. Figure 6 shows the future container terminal in the Port of Gävle.

FIGURE 6. THE PORT OF GÄVLE, WITH THE FUTURE NEW CONTAINER TERMINAL IN FRONT. THE FIVE CRANES ON THE DOCKSIDE ARE STS CRANES, WHILE THE SIX RTGS CAN BE SEEN ON THE CONTAINER STACKING ZONE. SOURCE: PORT OF GÄVLE [48]

2.1.1.1 Current STS cranes

The container terminal has at present two Liebherr P115L(MT) *Super* STS cranes, with an outreach of 35 m over the ships, being able to serve vessels with 11 rows of containers; and a portal structure, which makes them able to store containers on the deck under the crane.

According to information provided by the Port and Yilport, the height of containers hoists ranges from 20 to 30 m. The average value, 25 m, will be considered for calculations.

Currently, the two STS cranes handle 11 000 containers per month. It will be assumed that each of the two cranes handle half of them: 5 500 containers. As said, those containers are divided in two main groups: 45% weight about 3 tonnes, and 55% weight about 25 tonnes. In addition, the weight of the spreader is unknown, but it will be assumed to weigh 11 tonnes, as this is a typical value [18].

The cranes are fed at 10.4 kV AC, and an onboard transformer reduces the voltage to 520 V AC, which feeds the bus on the crane.

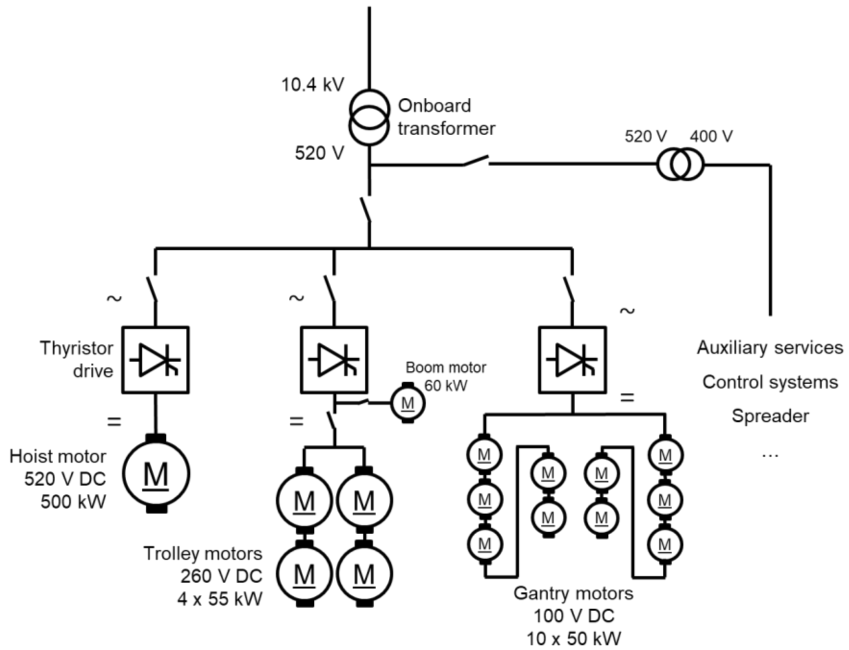

FIGURE 7. ONE-LINE DIAGRAM OF THE CURRENTLY PRESENT STS CRANES. SOURCE: OWN WORK; INFORMATION PROVIDED BY YILPORT

Each of the cranes is equipped with a 500 kW DC motor for hoist, four 55 kW motors for the trolley, and ten 50 kW DC motors for the gantry movement. Each of the movement units (hoist, trolley and gantry/travel) have a thyristor drive to connect the DC motors to a 520 V AC grid. The connection of the motors to the bus is shown in Figure 7.

Yilport has provided technical information about the speeds of the different main movements of the cranes. They are shown in Table 3.

TABLE 3. CHARACTERISTICS OF THE CURRENT STS CRANES IN THE PORT OF GÄVLE. INFORMATION SOURCE: DOCUMENTS PROVIDED BY YILPORT

Movement unit	Motors	Min speed (m/min)	Max speed (m/min)	Acceleration time (s)	Deceleration time (s)
Hoist	1 x 500 kW	50 (56 t)	120 (11 t)	3	1.5-2.3 depending on mass
Trolley	4 x 55 kW	180		5-10 depending on wind	*[no data]*
Gantry	10 x 50 kW	105		7-10 depending on wind	6

The power and energy consumption of each motor is not known, but the electricity invoice of the two cranes of the month of April 2019 has been provided. It contains the energy and maximum power consumption for the months of January, February, March and April 2019, which is useful to have an idea of the average consumption during the year.

The electricity of the two cranes is billed together by the company Gävle Energi. In the month of April 2019, 199 144 kWh were consumed by the two cranes, and the annual estimation in the invoice is 2 400 422 kWh. It is important to note that this energy does not only correspond to the container handling operations, and an important part of it can be also to feed auxiliary systems like air-conditioning, heating or lighting.

Conversely, the peak power consumption is a better indicator of the container handling, as hoisting is the operation that consumes the largest amount of power. The maximum monthly power consumption is shown in Table 4. It is not clear if this power is a sum of both cranes hoisting simultaneously, or if it is only from one, or any other alternative. But the numbers are close to the maximum power of a single hoist motor, which suggests that it could be due to one individual hoist.

TABLE 4. PEAK POWER BILLED BY THE ELECTRICITY COMPANY FOR THE CURRENT TWO STS CRANES. HIGH LOAD PEAK POWER IS EMPTY FOR APRIL AS THE ELECTRICITY COMPANY CONSIDERS THE HIGH LOAD PERIOD TO BE WEEKDAYS 7:00-21:00 FROM NOVEMBER TO MARCH, AND BILLS IT SEPARATELY. SOURCE: ELECTRICITY INVOICE PROVIDED BY YILPORT

Month	Low load period peak power (kW)	High load period peak power (kW)
January 2019	504	497
February 2019	477	480
March 2019	513	490
April 2019	488	-

2.1.1.2 New STS cranes

The new STS cranes will be provided by Mitsui Engineering and Shipbuilding Ltd. They will be *Super Post Panamax* cranes, capable of serving ships with 22 rows of containers [48].

The range of hoisting heights will be slightly larger than in the current STS cranes, varying from 20 to 35 m. The average value, 27.5 m, will be considered for calculations.

The available data about the motors is not so comprehensive as for the currently present STS cranes. However, it is known that they will have AC drives; and information about power consumption and hoisting and trolley speed of the new cranes during a working cycle has been obtained; provided by Mitsui via Yilport. The following data and conclusions can be extracted from the provided information:

- Spreader-only hoisting and lowering speeds are 3 m/s, with an acceleration phase of 4 seconds and deceleration phase of 3.5 seconds for both hoisting and lowering.

- Spreader-only hoisting consumes 563 kW at steady state, with an initial peak of 700 kW. Spreader-only lowering produces 400 kW of power. Using expression (5) in Appendix A, it can be concluded that the mass of the spreader must be between 14.7 and 19.1 tonnes. If a similar efficiency is assumed for generation and consumption of electric power, the mass of the spreader will be around 17 tonnes. This mass will be assumed for calculations related to the new STS cranes in this report.

- The rated load is hoisted and lowered at 1.5 m/s. The acceleration phase lasts 2 seconds for both hoisting and lowering. Deceleration phase lasts 1.5 s for both.

- Hoisting the rated load consumes 1 372 kW during the phase of constant speed, with an initial peak of 1 950 kW. Lowering the rated load produces 1 055 kW during the phase of constant speed. Using expression (5) in Appendix A, it can be concluded that the rated load must be a weight between 71.7 and 93.1 tonnes. Assuming the motor/generator efficiency is similar when producing and consuming electric power, the rated load is 82 tonnes. As the spreader weighs 17 tonnes, this type of crane can hoist containers up to 65 tonnes.

- Comparing the potential energies of the obtained masses (spreader and rated load) with the consumed and produced power, the efficiency of the motor/generator (and of its possible converter) can be obtained. This value is near to 88% in all cases. When doing calculations related to those STS cranes this efficiency will be used.

- The initial power peak when hoisting is between 1.24 and 1.42 times higher than the steady power demand.

- Trolley, without load, consumes 38 kW during constant speed, with power increasing from zero to a 195-kW peak during acceleration, which lasts 8 seconds. During its deceleration it produces 123 kW, that decreases to zero in 7 seconds.

- Trolley, with rated load, consumes 138 kW during constant speed, with power increasing from zero to a 572-kW power peak during acceleration, which lasts 8 seconds. When decelerating, it produces 166 kW, that decrease to zero in 7 seconds.

2.1.1.3 New eRTG cranes

Yilport will purchase 6 automated electric RTG cranes from Konecranes [49], [50] for Gävle's container terminal. The RTG cranes to be acquired will be electric and connected to a busbar, but they will have a generator to feed the cranes while not being connected to the grid.

As no specific data has been provided about the power consumption and number of containers handled by these RTG cranes, as well as for power demand, general suggestions will be given concerning them, based on consulted literature.

2.1.2 Electricity costs

Electricity is provided to the Port by the municipal company Gävle Energi. Its electricity comes entirely from four renewable sources: wind power, hydropower, biomass and solar energy [51].

The electricity prices to be used in this report will be the average price for the last nine years in mid-southern Sweden (SE3 zone) [52], while electricity fees will be based on the prices of an invoice of the current two STS cranes from April 2019, provided by Yilport. Power fees are updated to 2020 prices according to the pricing information published by Gävle Energi, the electricity company, on its website [53].

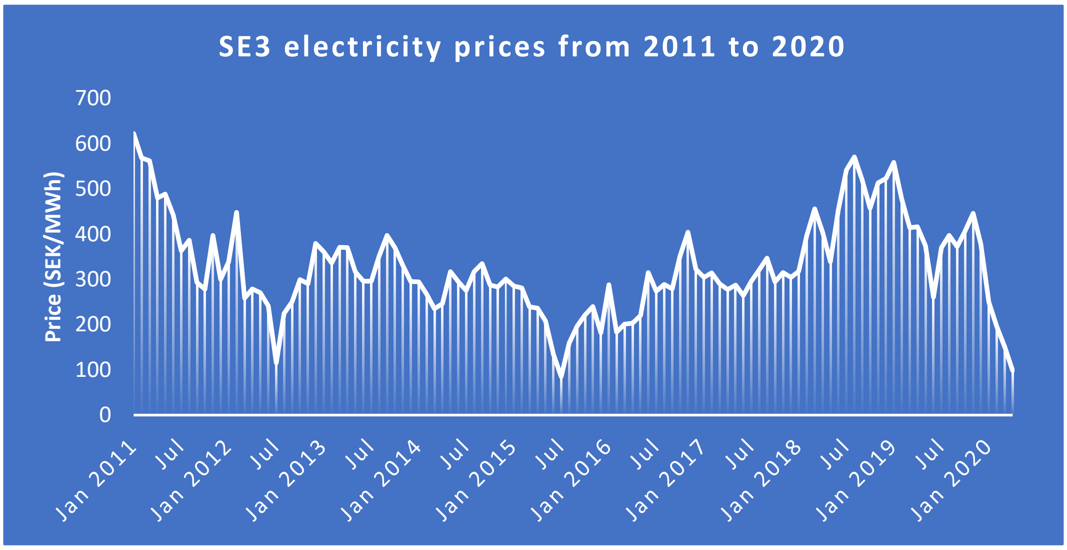

FIGURE 8. ELECTRICITY PRICES IN THE SE3 ZONE (MID-SOUTHERN SWEDEN) FROM 2011 TO 2020. DATA: NORDPOOL VIA BIXIA [52]

Electricity price, taxes and fees from the month of April 2019 are shown in Table 5. Electricity price was 0.4216 SEK/kWh, and the total amount to pay with taxes and fees was 1.0546 SEK/kWh. The electricity price (excluding other fees) is always fluctuating and therefore is difficult to predict. During the 2011-2020 period the average electricity price was 0.3323 SEK/kWh [52]. Electricity prices for this period are shown in Figure 8. The average price, maintaining the rest of the fees and taxes constant, will be used for the calculations in this report, which gives a total electric energy cost of 0.9429 SEK/kWh.

TABLE 5. ELECTRICITY PRICES FROM GÄVLE ENERGI FOR APRIL 2019. SOURCE: INVOICE PROVIDED BY YILPORT

Cost type	Concept	Price (SEK/kWh)
Energy supplier	Electricity price	0.4216
Energy supplier	Grid company fee	0.0057
Energy supplier	Electricity certificates	0.0295
Energy supplier	Energy warranty fees	0.0098
Tax (energy supplier)	VAT	0.1167 (25%)
Network	Transmission charge	0.0300
Network	Energy tax	0.3470
Tax (for network costs)	VAT	0.0943 (25%)
TOTAL		**1.0546**

Power fees are shown in Table 6. They are paid for the maximum power consumed during a specific period. There are two power fees, one to be paid for power consumed from November to March, during high load hours (7:00-21:00 on weekdays). This fee is 66 SEK/kW/month in 2020. The other fee is the one to be paid during the low load period, which is all the time except for the high load period. This fee is 19 SEK/kW/month and is paid every month. This means that from November to March both fees are paid.

TABLE 6. GÄVLE ENERGI'S POWER FEES FOR 2020. SOURCE: GÄVLE ENERGI [53]

Concept	Price (SEK/kW)	Notes
Monthly peak power; low load period	19	Billed every month. Low load period is all year except high load period.
Monthly peak power; high load period	66	Billed from November to March. High load period: weekdays Nov-Mar, from 7:00 to 21:00

During the first 4 months of 2019, electricity costs accounted for 1 282 987 SEK, which extrapolated to the whole year give an annual cost of 3 848 962 SEK.

2.1.3 Energy storage system requirements

2.1.3.1 Requirements for current STS cranes

As said, current STS cranes are assumed to lift 5 500 containers per month each, 45% of them weigh around 3 tonnes, and 55% weigh around 25 tonnes. In all cases, the mass of the spreader must be added: 11 tonnes.

The exact power demand for each container type is unknown, but as the hoisting velocities and weights are known, it is possible to calculate the minimal power value needed to lift a container using the time derivatives of potential and kinetic energy expressions, as shown in (5) and (7) in Appendix A.

The maximum possible recoverable energy is obtained by the potential energy of a container, given by expression (3) in Appendix A.

The demand of electrical power and energy will be higher than the calculated one for a real hoist, as the motor and its drive have efficiencies lower than 1. For the same reason, the recovered energy will be less than the maximum recoverable energy. The efficiencies for motors in these cranes are unknown, but it is reasonable to assume an efficiency of 0.9 for the motor and its converter [41], [54].

Moreover, electrical motors can have high power peaks when starting, in addition to the minimal required physical power. Those initial peaks can be up to around 40% higher than the required power, according to Parise et al. [14] and the information provided by Yilport about the new cranes' power consumption. However, other publications don't show any initial power peaks [21]. Looking at the invoice from the current STS cranes, those peaks, present or not, seem to not have a big effect on the power consumption, as the maximum billed power corresponds approximately to the physical lifting power needs.

A simulation of the minimum needed mechanical energy and power has been made for the containers weighting 45 t, 25 t, 3 t and for the empty spreader (loads of 56 t, 36 t, 14 t and 11 t, respectively) using the expressions in Appendix A to calculate the hoisting situation every 0.2 seconds. This has been done in Microsoft Excel.

The speed and acceleration information for the maximum and minimum load has been provided (shown in Table 3), but not the intermediate values. To get that information, speeds have been interpolated depending on the load. It is important to note that as power is derived from the hoisting velocity, it could not correspond exactly to the real value. In fact, if maximum and minimum powers would have been interpolated instead, the power demand for an intermediate load would be slightly lower. However, the calculated power in this document will be derived from the interpolated velocities, as this way calculations will be more conservative with respect to maximum power demand. This is also one of the reasons why billed maximum power does not correspond exactly with the calculated maximum power, although the values are close.

As the current STS cranes in the Port of Gävle work with heights between 20 and 30 metres, an average height of 25 m will be used to calculate the total energy savings. But to calculate the maximum power demand, which determines the price to pay for power, the highest possible heights and weights have also been considered: a 56-tonne load (45-tonne container and the spreader) in a 30-m hoist.

Figure 9 represents the minimum mechanical power needed to make a 25-m hoist complying with those conditions for three different loads: 36 tonnes (25-tonne container and spreader), 14 tonnes (3-tonne container and spreader), and 11 tonnes (only spreader). Those hoists last from 15 to 20 seconds, for which a minimum amount of energy is needed. Those values are shown on the figure, and are equivalent to the potential energy of the corresponding containers at 25 m. Therefore, they are a reference of the maximum energy that potentially could be recovered, without accounting for efficiencies.

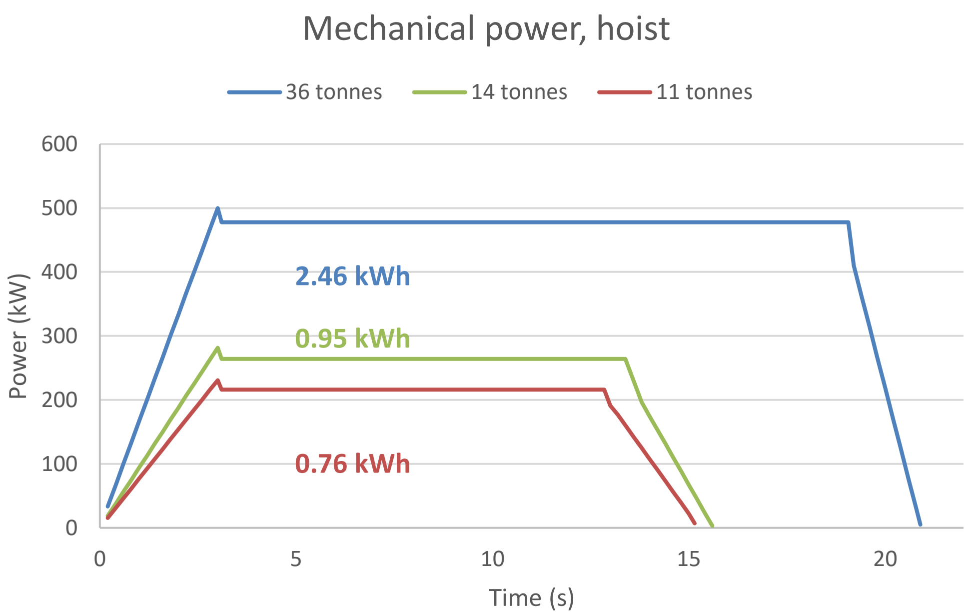

FIGURE 9. MECHANICAL POWER NEEDED TO COMPLY WITH THE GIVEN SPEEDS AND ACCELERATIONS IN THE CURRENTLY PRESENT STS CRANES FOR AN AVERAGE HOIST. THE 36 TONNES LINE REPRESENT THE HOIST OF 25-TONNE CONTAINERS, AND THE 14 TONNES LINE REPRESENT THE 3-TONNE CONTAINERS, AS THE SPREADER WEIGHTS AROUND 11 TONNES. THEREFORE, THE 11-TONNES LINE CORRESPONDS TO A HOIST OF AN EMPTY SPREADER. THE CONSIDERED HEIGHT IS 25 M IN ALL CASES.

Assuming an efficiency of 0.9 for the motor and the rectifier, the maximum constant electrical power demand for lifting a 25-tonne container is 531 kW, slightly over the rated motor power[5]. And if the regenerated power curve during hoist-down is assumed to be the same in shape as the hoist curve (which is reasonable, as it happens

[5] As said earlier, this power value is obtained indirectly, and therefore the value may not correspond exactly to the measured value.

with the provided information for the other STS cranes), with also the same efficiency, the maximum constant regenerated power will be 430.1 kW. This is the maximum power that an ESS would need to be able to absorb. Interestingly, as heavier loads are hoisted at lower speeds, the needed power remains approximately constant for heavier containers, and even decreases for very heavy loads. This is true assuming that speed varies linearly with weight, which, as it has been explained before, could not correspond exactly to the real behaviour.

However, and even if most of the handled containers weigh approximately 3 or 25 tonnes, some containers may weigh as much as 45 tonnes, meaning the crane will lift a load of 56 tonnes. As said, the required power will be approximately the same; but the needed energy will be higher. Therefore, an ESS would need to store enough energy to provide a certain constant power during the whole lift, so that a higher power peak does not appear (since that peak would be billed). Expression (3) in Appendix A can be used to get this maximum potential energy, which is 4.58 kWh for a 30 m height. Assuming the motor/generator and drive efficiency to be 0.9, the regenerated electric energy is 4.12 kWh.

Nevertheless, this amount of energy will rarely need to be stored, since, as it has been explained before, most of the time only two types of containers are handled by the STS cranes: containers with a weight around 25 tonnes, and containers with around 3 tonnes, which require much less energy to be stored. This means that if another solution were found for heavy containers, like hoisting them slower to limit the peak power demand, it would be more interesting to use an ESS with a smaller capacity, since this would considerably reduce costs. This measure is also taken in the second application example shown in the literature review.

If such a solution can be found, the maximum energy to be stored will be the energy needed to provide a certain power during the maximum height hoist (30 m) of a 25-tonne container. Calculating that potential energy, and using the efficiencies of the motor/generator and converter system considered earlier (0.9), the maximum energy to be stored is 2.65 kWh. Figure 10 shows the electrical and mechanical power needed for that scenario, as well the regenerated power curve in a hoist-down.

In short, the requirements for an ESS for the currently present STS cranes is to be able to store 2.65 kWh of energy, and to absorb and provide around 430.1 kW of power.

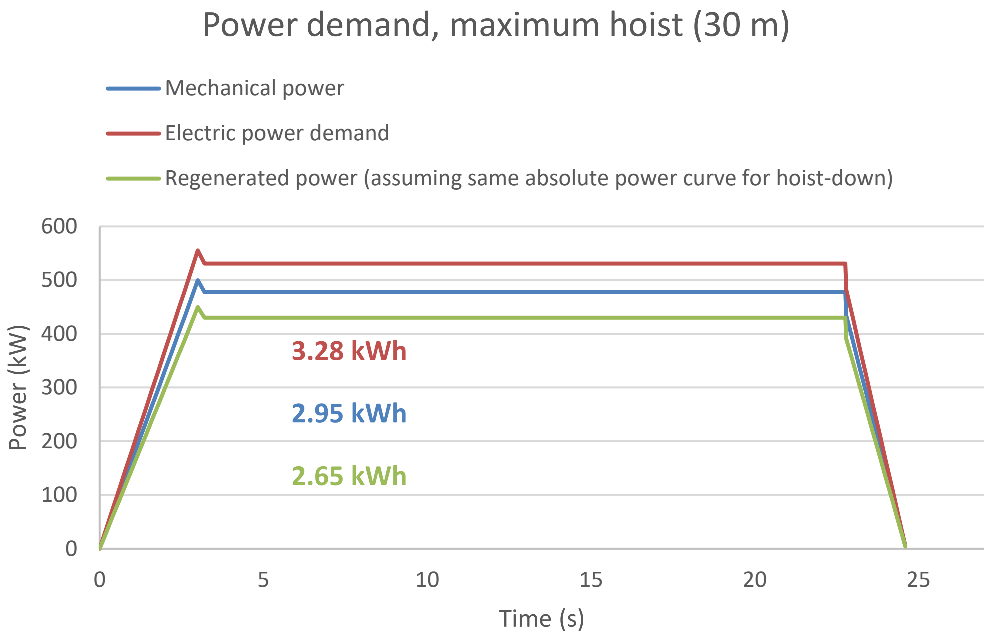

FIGURE 10. IN RED, ELECTRIC POWER DEMAND TO HOIST A 25-T CONTAINER 30 M HIGH, ASSUMING AN EFFICIENCY OF 0.9. IN BLUE, THEORETICAL MECHANICAL POWER NEEDED FOR THAT HOIST. IN GREEN, ABSOLUTE VALUE OF POTENTIALLY MAXIMUM RECOVERABLE POWER ASSUMING THE SAME EFFICIENCY AND THE SAME CURVE SHAPE FOR A HOIST-DOWN. ENERGY NEEDED/PRODUCED SHOWN OVER THE CURVES.

Table 7 shows the potentially recoverable electric power and energy for different loads and heights. Knowing that 11 000 containers are hoisted per month at an average height of 25 m, 45% of approximately 3 tonnes, and 55% of approximately 25 tonnes; and that for each cycle the empty spreader will also hoist, the potentially recoverable energy would be around 25 100 kWh per month, which is a considerable amount. The reusable energy will be slightly less than that amount, considering the ESS efficiency.

It is important to note that it will only be interesting to set an ESS on the currently present cranes if the amount of the containers they handle stays similar once the new STS cranes are installed. Evidently, if all the traffic is diverted to them, an ESS would only be interesting on those new cranes. Systems for both options will be analysed.

Table 7. Recoverable power and energy for different loads in currently present STS cranes, assuming a motor-generator and converter efficiency of 0.9 and identical power curves for hoist and lowering

Load	Recoverable max. constant power with eff. 0.9 (kW)	Recoverable energy, with eff. 0.9 and 25 m height hoist-down (kWh)	Recoverable energy, with eff. 0.9 and 30 m height hoist-down (kWh)	Notes
11 t (spreader)	194.4	0.68	0.81	Hoisted every cycle
14 t (spreader + 3 t)	237.9	0.86	1.03	45% of containers
36 t (spreader + 25 t)	430.1	2.21	2.65	55% of containers
56 t (spreader + 45 t)	412.4*	3.44	4.12	Maximum load, not usual
*Because speeds have been obtained interpolating the given max. and min. speeds, they increase linearly with the weight, and therefore the maximum power does not correspond to the maximum load. It is possible that actual speeds increase in a manner where power is more constant.				

2.1.3.2 Requirements for new STS cranes

The future three STS cranes will be larger than the old ones, and they will have the capacity to lift heavier containers. However, according to Yilport, the weight distribution of containers will not change in the next years. On the other hand, as mentioned before, the spreader will weigh 17 tonnes in these cranes.

Therefore, the requirements for the ESS will be related to the maximum usual hoisting load (25 t + 17 t), instead of the absolute maximum (65 t + 17 t).

The hoisting height will range from 20 to 35 m; therefore, the average height considered in this case for energy saving calculations will be 27.5 m.

This means the maximum energy to be stored will be given by a 25-tonne container (42 t load) hoisted 35 m. The potential energy needed for that is 4 kWh. On the other hand, the trolley movement regenerates from 0.12 to 0.16 kWh in each braking. Considering the efficiency of the new STS cranes, 0.88, 3.68 kWh will be the minimum storage needed in the ESS.

For each of the new STS cranes, the electrical power consumption ranges from 563 kW to 1 950 kW for the maximum load. Interpolating the hoisting speeds, the maximum power peak for 25-tonne containers (load of 42 tonnes, including the spreader) is around 1 476 kW. If power is interpolated instead, 1 142 kW is the maximum. The first case will be selected to make more conservative calculations. This peak happens at the beginning of the hoist and lasts about one or two seconds.

The power demand during constant speed hoist is lower, around 1 136 kW; 340 kW less.

The provided power curves of the new STS cranes show that the regenerated power curves are identical to the demand ones, but smaller by a factor of around the square of the motor/generator and converter efficiency, or 0.77 times. This makes sense, as the losses come from that energy conversion. Therefore, a 25-tonne container will regenerate a transient peak of 1 143 kW, followed by a constant maximum power of 880 kW. Since the first peak does almost not contain energy, it is enough if the system can absorb 880 kW.

Therefore, the minimum rating for an ESS on the new cranes will be 880 kW of power absorption capacity and 3.68 kWh of storage. However, as it will be shown in the Results chapter, a higher rated system that could serve several cranes could be interesting to consider.

In addition, even if the initial peak is not interesting to be reabsorbed when lowering a container, the equivalent peak when hoisting is important, as it sets the maximum power to pay for. Therefore, a different system absorbing a minimum amount of energy but able to provide a high peak that could compensate the additional 340 kW can also be desirable.

2.1.3.3 Requirements for new RTG cranes

As no data is available about the power consumption and the number of handled containers for the new RTG cranes, no special requirements are set, and the given suggestions will be based on literature.

2.2 Procedure

This work has been conducted in six main steps:

1. Literature review about container terminals and energy storage systems, in general and in ports. Analysis of the current situation and application cases.
2. Gathering of data from the Port of Gävle in several ways: visit to the Port, communication via internet with personnel of Gävle Hamn and Yilport, internet research. Based on this, the CT has been described and data has been collected for calculations.
3. Calculation of requirements, based on the obtained data, for implementing ESS systems in the current and future cranes in the Port of Gävle.
4. ESS system calculations and comparison, to choose the most appropriate one. Energy and power consumption have been compared and calculated based on

the obtained data. Calculations have been made simulating position, velocity, acceleration, energy and power for every 0.2 seconds using Microsoft Excel.

5. Economic analysis, comparing savings with the costs of implementing energy storage technologies, also in Microsoft Excel.

6. Discussion and conclusion drawing based on the obtained results.

3 Process and Results

3.1 General assumptions

Three different energy storage solutions are presented in this chapter. The two first solutions are focused on the currently present cranes and container traffic. This means they could be implemented nowadays. The third solution is proposed for the new container terminal, and it is aimed at the three future STS cranes. However, that solution could also be useful for the two current cranes and the eRTG cranes, as it will be explained.

Some assumptions have been made for all the calculations. Those assumptions have been taken in accordance with given data and consulted literature, in order to maintain realistic values:

- Motor/generator and drive efficiency of 0.9 in the current STS cranes, based on literature; and of 0.88 in the new STS cranes, based on given power demand data for those specific cranes.
- RTE of 0.92 for supercapacitors,
- RTE of 0.85 for flywheel systems.
- Converter efficiency of 0.9 for ESS, when RTE is not used.
- The calculations made in this chapter only consider the efficiency of the motor/generator and converter system and the ESS. Therefore, to account for any not considered efficiency or other unexpected factors that could reduce the calculated savings, all the calculated savings have been multiplied by a 0.75 factor, in order to make calculations more conservative.
- A SC life of 10 years.
- A FES life of 20 years.
- USD/SEK change of 9.8.
- An electricity cost of 0.9429 SEK/kWh, including all fees and taxes. It is considered constant. Power costs are assumed to be constant; they are shown in Table 6, in the Electricity costs section.

3.2 Previous considerations for existing STS cranes

As said in the Method chapter, the highest handled load sets the maximum size for an energy storage system. For the current STS cranes in the Port of Gävle, these maximum requirements are to store 4.12 kWh multiplied by the ESS converter efficiency, and to provide 430.1 kW of power, which are needed to reduce the maximum power demand during the whole lift of a 45-tonne container (a 56-tonne load, including the spreader).

However, as explained in the previous section, since very heavy loads (56 tonnes) are rare, it is probably a better option to downsize the ESS and take other maximum power reduction measures for when hoisting heavy containers is necessary. An example could be to reduce the hoisting speed more than usual, thus reducing the power, while using the ESS to help reducing the power demand. The required time would increase, but if those containers are not common this solution may be acceptable.

Therefore, the maximum needed storage is 2.65 kWh, as determined in the previous chapter, multiplied by the ESS converter efficiency (2.39 kWh). This is the minimum value needed to store the usual maximum energy, but it can be a good idea to dimension the ESS slightly larger to be sure it will store the necessary energy. The power absorption rating is 430.1 kW multiplied by the minimum ESS converter efficiency: 387 kW.

It is important to note that this is the maximum storage capacity if the ESS is charged with recovered energy. If the ESS is also charged directly at a lower power from the grid more than the strictly necessary to compensate losses, the storage capacity could be higher. But this possibility is not considered in this solution, as more unknown factors need to be considered.

Therefore, knowing that the ESS will have a power rating of 387.1 kW and 2.39 kWh of storage, the first decision to make is to choose a suitable EES. The three main possibilities are batteries, flywheels or supercapacitors. As mentioned in the Introduction chapter, batteries are not the best option to provide a high power load and to be charged rapidly. Consequently, SCs and FES systems are best options, as they have a much faster response and function well at high power levels [41].

A cost analysis can help deciding which of them is a better solution for the Port of Gävle.

3.3 Solution 1: Supercapacitors for existing STS cranes

According to literature, supercapacitors are usually connected to the DC buses of the cranes, so that they only need a DC-DC converter and they avoid the AC-DC converter, thus reducing costs.

The current STS cranes in the container terminal of Gävle function with DC motors, but their internal grid is in AC. Therefore, the best solution economically speaking would be to set the supercapacitors in the DC part, which in this case would mean between the motor converter and the motor itself. Further analysis is needed to determine if this solution is technically feasible. In the case it is not, the supercapacitors could be installed in the cranes' internal AC bus, but an additional AC-DC converter would be needed, possibly increasing costs.

The solution presented here considers that a group of SCs are installed on each crane, as it is done in consulted literature. This way, each crane will have the ability to store and use its energy independently.

As said, a 387.1 kW-system is needed, at least. Assuming the input and output rated power values are the same, such a system would provide 348.5 kW, considering the converter losses.

To be conservative and to allow possible excesses, the system to design will have a power rating of 400 kW and 3 kWh, on each of the two cranes.

3.3.1 ESS costs

The cost of such system has been based on the consulted literature. As it has been said, SC costs range from 100 to 400 USD/kW. This price varies depending on the energy storage capacity. Table 1 in the Introduction chapter shows the cost for three real SC systems. The closest to this case was the was project with 1 000 kW and 7.43 kWh system, with a cost of 241 000 USD, giving a cost by power unit of 241 USD/kW, and a cost by energy storage unit of 32 565 USD/kWh.

Using these costs to calculate the cost of each of the two SC systems for the current STS cranes in the Port of Gävle, the cost would be between 96 400 USD (calculated using power), and 97 695 USD (calculated using energy storage), for each of the SC systems. Therefore, and considering the higher cost in order to keep the calculations conservative, the two SC systems would have a total cost of 195 390 USD, or 1 914 822 SEK.

As mentioned in the Introduction chapter, maintenance costs are negligible in supercapacitors.

3.3.2 Energy cost savings

As it has been said, the container traffic is assumed to remain constant on the two cranes during the system lifetime for the profitability calculations. This assumption should be taken with caution depending on how traffic will be diverted with the opening of the new terminal. The minimum required number of containers to keep the system profitable is studied at the end of the section.

The distribution of the handled containers is considered to be formed by 45% 3-tonne containers (4 950 per month), and 55% 25-tonne containers (6 050 per month), plus the 11 tonnes of the spreader in all cases. For each container hoist, there will be an empty spreader hoist, to complete the cycle (11 000 hoists per month). Calculations are made considering the average height of 25 m. Finally, energy from the braking of trolley and gantry movements can also be recovered and therefore reduce still more costs, but as it is difficult to determine exactly how much energy is used for each of those movements with different loads, those calculations assume that this energy is not recovered.

Table 7 showed different recoverable electric energies for different hoist-downs (generator and drive efficiency included), among which are the recovered energy of the three above-mentioned loads. 0.68 kWh, 0.86 kWh and 2.21 kWh can be recovered respectively from the empty spreader, the 3-tonne containers and the 25-tonne containers, respectively.

Multiplying those values by the supercapacitors' round-trip efficiency (RTE), 0.92; 0.62 kWh, 0.79 kWh and 2.03 kWh are obtained, respectively. These energies will be the real recoverable energy from each of the hoist-downs. Considering that 4 950 light and 6 050 heavy containers are handled per month, and that the spreader is lifted and downed for each of those cases, total monthly energy saving of 23 043 kWh is obtained, or 276 520 kWh per year. This represents the 12% of the cranes' total energy consumption.

This is the maximum reusable energy. However, in order to consider other possible losses and any unforeseen circumstances, it will be considered that only 75% of this energy is actually reused. Therefore, the reused energy will be 207 390 kWh.

Economically, this represents an annual energy cost decrease of 195 548 SEK.

3.3.3 Power cost savings

A supercapacitor system with a maximum power output of 400 kW, can provide up to 360 kW, accounting for its converter efficiency.

The maximum steady power calculated to hoist a 25-tonne container (and it is similar for heavier one) is 477.9 kW of mechanical power, or 531 kW of electricity, with a peak of around 500 kW of mechanical power, or 555 kW of electricity, at the beginning due to the increase of kinetic energy. The maximum power demand sets the price to pay to the electricity company.

The difference between the power provided by the SC system and the actual electricity demand is the power demand to the grid, and thus the power to pay for. In this case, the maximum power demand decreases in 360 kW. For this to be true, supercapacitors must provide this power each time such a high power is needed. Therefore, as gantry movement, with its ten 50 kW motors, also requires a high power, supercapacitors must provide it too. The needed energy is unknown, but in case recovered energy is not enough to fulfil this, supercapacitors could be recharged at a lower power rate from the grid.

Nevertheless, a 75% of this power reduction is considered, the profitability calculations to be conservative. Therefore, the maximum power demand reduction will be 270 kW.

Figure 11 shows the electrical power demand curve to lift a 25-tonne container the average height, and the part of this power provided by the supercapacitor system.

Recalling the power fees mentioned earlier, 150 660 SEK will be saved annually using the SC system.

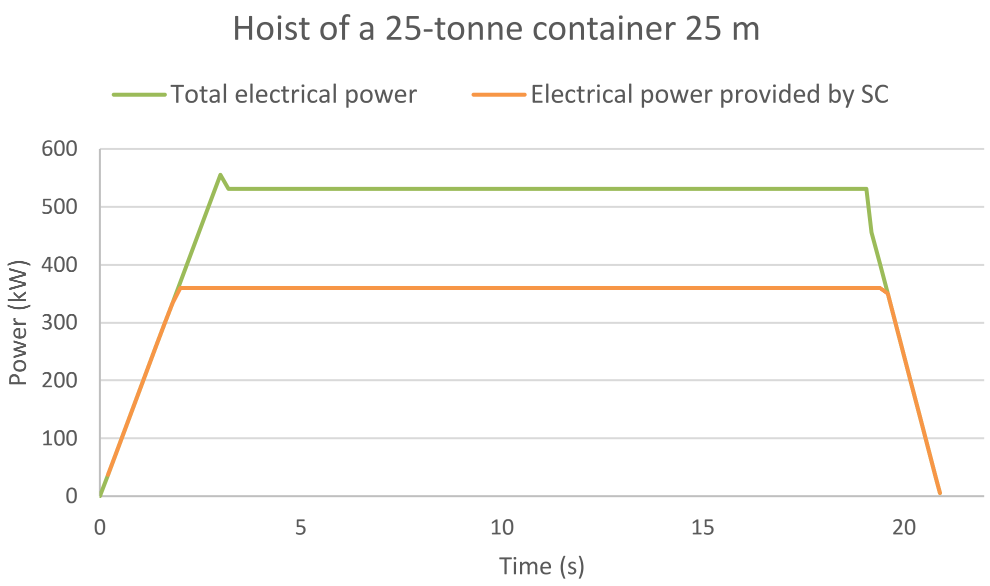

FIGURE 11. ELECTRICAL POWER DEMAND TO HOIST 25 M A 25-TONNE CONTAINER, AND ELECTRIC POWER PROVIDED BY THE SUPERCAPACITOR SYSTEM IN ORDER TO REDUCE THE MAXIMUM POWER DEMAND.

3.3.4 Benefits and payback

In short, implementing a supercapacitor ESS in each crane, has a cost of 1 914 822 SEK, and the annual savings are 346 208 SEK. Therefore, electricity costs are reduced by 9%.

Therefore, the payback period is 5.5 years. This means the system is profitable, as SCs are expected to have a lifetime of 10 years.

After recovering the investment, benefits for the rest of the system's lifetime are 1 547 261 SEK; the annual benefits are therefore 154 726 SEK.

One of the assumptions made for the calculation of this profitability was that the current STS cranes maintain the container traffic they had once the new terminal is open. If this is not the case, these STS cranes would need to keep at least the 21% of their current container traffic to keep the SC systems profitable.

3.4 Solution 2: Flywheels for existing STS cranes

Due to the higher costs of a FES system, it is advisable to set a single system for all the cranes in the container terminal, instead of an individual system for each.

3.4.1 ESS costs

Recalling the literature review in the Introduction chapter, costs for FES systems vary from 200 to 2 400 USD/kW, and from 133 to 142 thousand USD/kWh for small systems. Therefore, setting a system with the same power and energy storage capabilities than the SC system explained above – a 400 kW and 3 kWh system – would cost from 80 000 USD to 960 000 USD based on power costs, or from 399 000 USD to 426 000 USD based on energy storage costs.

An intermediate cost of 410 000 USD, or 4 018 000 SEK is considered. At the end of this section, the maximum cost for the system to be profitable is specified.

Maintenance costs are around 5.6 USD/kW per year in flywheels, which gives an annual maintenance cost of 2 240 USD or 21 952 SEK.

3.4.2 Energy and power cost savings

Repeating the calculations made for the SC system, but with an RTE of 0.85, the annual energy savings are 191 611 kWh, and the maximum power demand is reduced in 270 kW. In economic terms, the energy savings account for 180 670 SEK, and maximum power reduction for 150 660 SEK. Therefore, the total savings are 331 330 SEK per year.

3.4.3 Benefits and payback

The saved amount corresponds to 8.6% of the annual electricity bill for the two STS cranes.

The payback is achieved in 13 years. Therefore, this project is also profitable, as lifetime for flywheel systems is 20 years. The total benefits from the payback time until the end of life of the system would be 2 159 552 SEK, which, divided into the system lifetime years accounts for 107 978 SEK annually.

About the uncertainty of the initial FES system cost, a cost of around 4 million SEK has been assumed, but this system would be profitable for any cost under 6 million SEK. Evidently, the higher is the cost, the lower will be the obtained benefit. On the other hand, a total system cost of less than 3 million SEK would make the annual benefit of this system higher than the SC system described above.

3.5 Previous considerations for future STS cranes

Predictions for container traffic growth in Port of Gävle after the opening of the new terminal vary from 5% to 8% annually, according to Yilport. Consequently, the first years after the opening the container to STS crane ratio will decrease, since there will be five STS cranes instead of two for a similar number of containers. The mentioned estimation of traffic growth is shown in Figure 12.

In any case, according to Yilport, the distribution of container types (45% of 3-tonne containers; 55% of 25-tonne containers) will remain invariable.

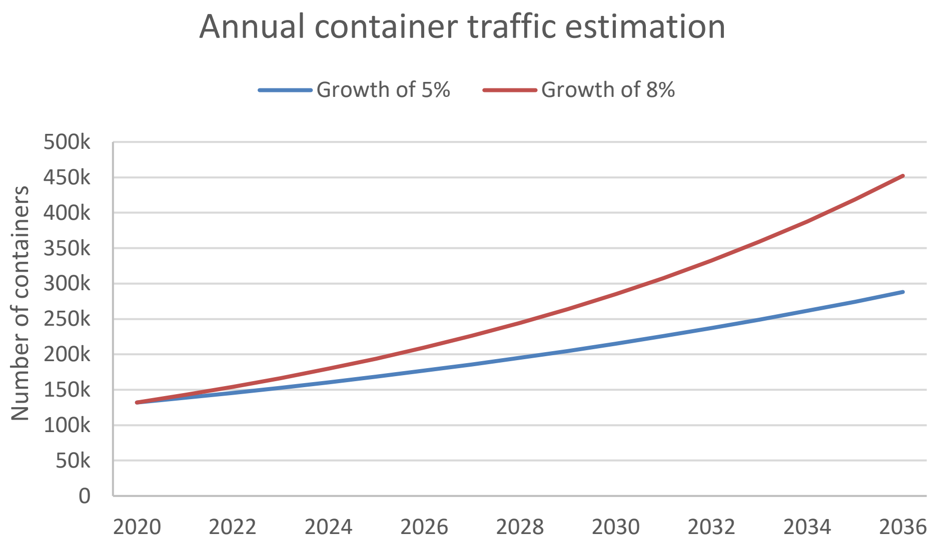

FIGURE 12. ESTIMATION OF INCREASE OF CONTAINER TRAFFIC IN THE PORT OF GÄVLE. SOURCE: YILPORT.

Therefore, individual ESS for each crane would pose problems if the number of containers handled is lower than the predicted one.

A centralised system, like the flywheel system described earlier, would not have this problem, since it can work with any number of cranes connected to the same grid, although its size should be increased to cope with the power and energy demand of the new cranes.

Independently of the number of containers, if the cranes are used, the peak power demand must be paid.

The power consumption of these cranes is considerably higher than the old STS cranes, so it can be very interesting to reduce these values using ESS. Even trolley movement uses a considerable amount of power; therefore, it would be convenient to use ESS to flatten both curves.

The ESS requirements analysed in the Method chapter defined the minimum power and energy settings. These were 880 kW of capability to absorb power and 3.52 kWh of storage. In addition, a system that could compensate fast additional 340 kW peaks is also desirable.

3.6 Solution 3: FES-SC system for future STS cranes

Based on the idea of Parise et al. [14] mentioned in the Introduction chapter, it could be interesting to use a small supercapacitor system (about 400 kW and 0.2 kWh) installed on each crane to shave the highest peaks, while having a centralised flywheel system for all the cranes to reduce steadier high power demands. This would allow to optimise the use of available storage and would not depend so much on the number of containers handled on each individual crane to be profitable. An example of operation of this system is shown in Figure 13.

Coordinating the cranes not to have the highest peak power at the same time, a centralised 1 500-kW and 5-kWh flywheel system (approximate values, depending on how simultaneous is the crane use) could be enough for all the cranes in the container terminal, and the possibility to use this system for other systems demanding high peak powers of energy in the port should be studied.

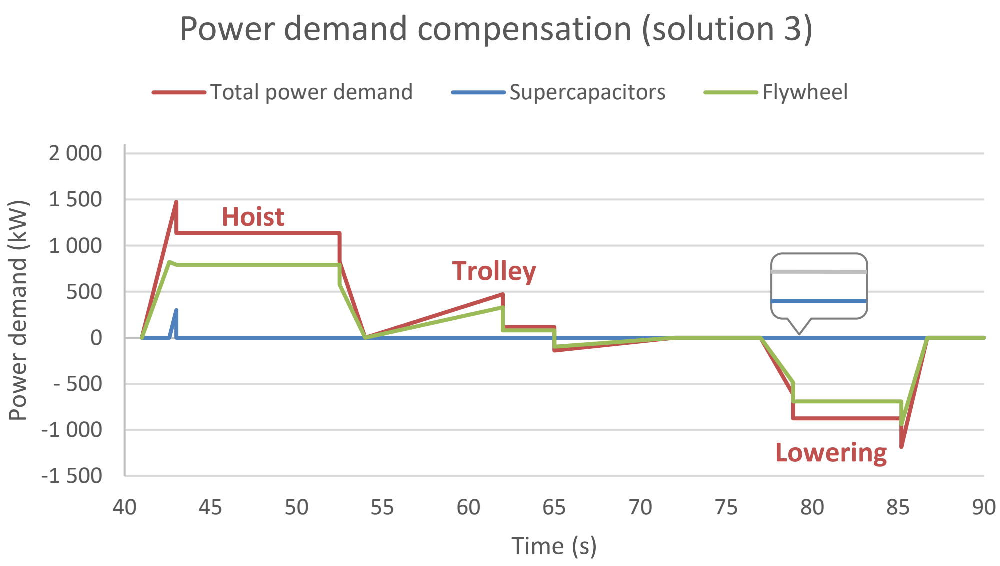

FIGURE 13. OPERATION EXAMPLE OF "SOLUTION 3", WITH AN EXAMPLE OF LOADED HOIST, TROLLEY AND LOWERING. THE POWER GRID COMPENSATES THE DIFFERENCE BETWEEN THE DEMAND AND THE POWER PROVIDED BY THE ESS. IT CAN ALSO CHARGE THE ESS AT A LOWER POWER TO GIVE IT ENERGY FOR THE NEXT HOIST. THE DETAIL IN THE LOWERING PHASE SHOWS THAT THE SC ALSO CHARGE DURING THAT PHASE. THE DEMAND CURVE IS BASED ON THE INFORMATION PROVIDED BY MITSU E&S VIA YILPORT.

3.6.1 ESS costs

The supercapacitor system would have about 400 kW of power output and 0.2 kWh of storage capacity. Based on the costs per unit of energy mentioned earlier, 32 565 USD/kW, each system would cost 6 513 USD, or 63 827.4 SEK. The costs per unit of power mentioned in the previous pages would give a disproportionated cost for such a small system, since the cost per unit of power increases with the storage capacity [33].

A SC system would be installed in each crane, which would mean that the total cost for SC systems will be 191 482 SEK.

The flywheel system would be able to provide 1 500 kW and store 5 kWh. As mentioned before, costs for FES systems vary from 200 to 2 400 USD/kW, and from 133 to 142 thousand USD/kWh for similar systems. Using the same cost per unit of energy as for the *solution 2*, a total system cost of around 683 300 USD is obtained, or 6 696 340 SEK. This is a similar cost to the one that would be obtained using the cost per unit of power of a similar case studied in the Introduction chapter and shown in Table 2.

The maintenance costs (5.6 USD/kW/year) will account for 8 400 USD/year, or 82 320 SEK.

3.6.2 Energy savings

The supercapacitors' energy savings are not considered, since they store a very small amount of energy compared to the flywheel system.

The energy savings on the FES system depend on the total number of containers. Assuming every crane is connected to this ESS, the number of containers handled nowadays can be assumed for the calculations. This number is presumed to stay constant in this first calculation.

A hoist height of 27.5 m is considered, as this is the average value for the new cranes. The spreader is supposed to weigh 17 tonnes, as mentioned before. Therefore, for one hoist, the needed potential energies for the empty spreader, a 3-tonne container, and a 25-tonne container are 1.28 kWh, 1.5 kWh and 3.15 kWh, respectively. Multiplying these values by the generator efficiency and by the ESS' RTE, the following values are obtained, respectively: 0.95 kWh, 1.12 kWh and 2.36 kWh.

In addition, according to the information provided, these cranes can also recover energy during trolley braking. This energy varies between 0.12 kWh and 0.16 kWh depending on the carried load. The conservative value of 0.12 kWh is used on the following calculations.

As said, the handled container quantity is assumed to be 11 000 per month, which is all the current traffic, with the weight distribution explained earlier.

Multiplying the number of containers by the reusable energy, a total monthly saved energy of 32 280 kWh is obtained, or 387 359 kWh per year. As for the previous calculations, this is multiplied by 0.75 to account for other unexpected factors or not considered efficiencies. This gives 290 519 kWh.

This saved energy corresponds to 273 931 SEK per year.

As traffic is expected to increase, the same calculations have been repeated for an annual traffic growth of 6.5% (average prevision), that stabilises when the traffic has doubled. In this case 12 924 MWh are saved in 20 years, an average of 646 191 kWh per year. Using the 0.75 factor, those values are 9 693 MWh and 484 643 kWh, respectively. In economic terms, this means a 20-year saving of 9.1 million SEK, which gives an average saving of 456 970 SEK per year, ranging from 273 931 SEK the first year, to 547 629 SEK during the last 8 years of system life.

3.6.3 Power cost savings

The supercapacitor system *shaves* the high and brief power peaks during the acceleration phase of hoist, making them disappear from the electric power demand. Therefore, the peak power demand decreases by 360 kW, considering the 0.9 efficiency of the SC converter. Similarly, as done before, a 0.75 factor will be imposed to consider any unexpected factor and make these calculations more conservative.

This means that the peak reduction is 270 kW, which in economic terms means an annual saving of 200 880 SEK.

On the other hand, the flywheel system reduces the maximum constant power demand, which happens when hoisting heavy containers, in 1 350 kW (having the efficiency of the ESS converter into consideration). The factor of 0.75 is also imposed in this case, to consider any factor that could reduce the efficiency of the system. So, the power reduction is 1 012.5 kW. This reduction means an annual saving of 753 300 SEK.

3.6.4 Benefits and payback

The SC system investment is recovered rapidly during the first year of use, giving a total benefit of 1 817 318 SEK from the investment recovery until the end of its lifetime.

The FES system takes longer to recover, 7.1 years, if the container traffic is maintained constant, with a total benefit of 12.2 million SEK after the investment recovery. The payback is also around 7 years if the traffic is considered to grow at 6.5% per year until it doubles, in this case giving a net benefit of 15.9 million SEK.

3.7 New eRTG cranes

No exact data about the number of containers that these cranes will handle is available, as well as the power to be consumed by them. Thus, only a general overview of ESSs in those cranes is given.

According to consulted literature, RTG hoist motors can have a power of 250 kW [1], which is considerably lower than the present and future STS cranes. Therefore, their peak power demand should not be a big issue if they are connected to the same grid as the STS cranes, and they are not used simultaneously.

As explained in the literature review, individual flywheel systems have been studied to be used in electric RTG cranes. However, being connected to a single bus, the possibility of using a single centralised flywheel can also be analysed. In that case the possibility of using the flywheel system proposed in *solution 3* can be considered; oversizing it, if needed.

4 Discussion

Results show that implementing energy storage systems in the cranes of the container terminal of Gävle can largely reduce electricity costs and energy consumption. In addition, the power demand is flattened, which is beneficial for the electrical grid.

Moreover, although the CT in the Port of Gävle uses 100% renewable electricity, the implementation of such systems can have the extra benefit of reducing CO_2 emissions by using the saved electricity in places where the used electricity comes from fossil fuels.

4.1 ESS choice and profitability

Three ESSs have been proposed for the current and new STS cranes, and it should be noted that the suggested systems are not complementary, but different alternatives. The two first solutions are suitable to be installed nowadays in the present cranes. The third solution could be implemented once the new container terminal is constructed and working, as it is focused on the three new STS cranes to be installed.

Firstly, the two solutions for the existing cranes will be compared. An individual supercapacitor system (*solution 1*) has been proposed for each existing STS crane. These systems reduce in 9% the annual electricity bill, and they have an annual net benefit of around 155 000 SEK, and a payback of 5.5 years. With the FES system (*solution 2*), common for both cranes, electricity costs are reduced in 8.6%, having an annual net benefit of 108 000 SEK, slightly lower than with SCs; and the payback is achieved in 13 years. The benefit is very dependent on the initial cost, which varies significantly from one source to another. In fact, if the initial system cost of the FES system is made lower than 3 million SEK, this system will become more profitable.

With the chosen costs, however, the individual SC systems seem to be more profitable. In addition, they give more independence to each crane, being able to demand power peaks simultaneously. Therefore, they would probably be the best solution if the container terminal were to remain the same size.

But, as the terminal will grow, getting three new cranes, a system useful for all the cranes could be more beneficial. This leads to *solution 3*, with a considerably higher initial cost, but also with greater benefits. This solution includes small individual SC systems to *shave* the highest power peaks, while using a centralised flywheel system to compensate longer high power peaks in the tree new STS cranes. With a total investment cost of around 6.9 million SEK, and 82 320 SEK/year of maintenance, around 1 million SEK could be saved per year in terms of saved energy and reduced power peaks. This means that after recovering the investment, net benefits from savings would range from 14 to 18 million SEK for the combined SC-FES system, during its lifetime. It is important to note that these benefits are much higher than *solutions 1* and *2*, because the costs of operating three new more consuming cranes will be higher, due to the greater power demand of those cranes, and the extra energy needed to lift the heavier spreader.

The ESS cost will be highly influenced by the power rating and energy storage capacity chosen for the flywheel system. This must be chosen depending on the simultaneity the cranes are used. If a high power demand of only one of the cranes at a time can be guaranteed, the ESS size can be lower than the chosen one. If, on the other hand, the intention is to use several cranes at a time, or to add new cranes to they system (the eRTG cranes, for instance), the chosen size or a greater one can be appropriate. A more detailed analysis is necessary to determine this point.

Indeed, even if this system is thought and has been calculated for the three new STS cranes, the system can be used to reduce other power peak demands, as for the electric RTG cranes. Furthermore, once the installation is made, increasing the system size should be simpler, as the transformer/converter and other equipment are already installed. Thanks to this, the system could adapt to future new cranes, or other high and intermittent power demands.

If several cranes are connected to the ESS, it is advisable to set a program to coordinate the crane operation, delaying each crane's power peak with respect to the others, as it was mentioned in the literature review.

An additional benefit of this system is that it avoids the need of increasing the Port's electric grid capability if new cranes are installed in the future. This could already be applied for the eRTG cranes to be installed.

Saving energy and reducing power demand using ESSs is also helpful to make the port more resilient to fluctuations in electricity prices and power fees, which is important considering that those prices are difficult to predict and can suffer sudden changes that can strongly affect the incomes of a company.

4.2 Limitations

Several assumptions have been made for profitability calculations. Although an effort has been made those assumptions to be the most accurate as possible, calculations should be considered merely illustrative. More specifically, due to limited data and resources, electricity consumption profiles were based on simplifications or were theoretically calculated. In addition, the handled containers distribution was also simplified and divided into two main weight groups. Evidently, reality is much more complex. This is why the 0.75 factor has been used to not overestimate the profitability possibilities. However, further and more precise analysis should be carried out in order to estimate more accurately the profitability of such systems.

However, calculations showed that the benefits of ESS implementation were large, not at the limit of profitability. Consequently, it is safe to affirm that energy storage systems are profitable and advantageous in container cranes, in accordance with the consulted literature.

4.3 Future

Supercapacitors and flywheels are examples of ESSs that have a great potential to reduce energy consumption by reutilisation, and to flatten power demand. They are young technologies still under development, even if they are already being used in many sectors. Therefore, their costs can be expected to decrease as their use becomes more widespread.

This combined with the increasing traffic and thus electricity demand of the CT of Gävle makes ESSs potentially highly beneficial and suitable in it, and profitability can be expected to increase, as ESS costs lower and electricity demand becomes greater.

5 Conclusions

5.1 Study results

This work showed how implementing energy storage systems in the Port of Gävle can considerably reduce energy-related costs, as well as energy consumption.

Setting an ESS in the current situation, with only two STS cranes, would be profitable, being a system based either on supercapacitors or flywheels. The former option appears more profitable, reducing electricity costs in 9% and with a shorter payback. However, assuming the new terminal will open soon, setting a combined SC-flywheel system for the future three STS cranes is a more interesting option, as this system would be more profitable and the FES system could be also used by other cranes in the port connected to the same grid, like the old STS cranes, and the eRTG cranes to be installed.

Such a system could save from 290 MWh to more than 480 MWh annually, depending on the container traffic, which translated in economic savings ranging from 274 thousand to 457 thousand SEK only in energy. Additionally, this system would reduce maximum power demand costs in 753 000 SEK per year. Therefore, net benefits would be around 14-18 million SEK in the system's lifetime (10 years for SCs, 20 years for FES).

It is important to note that this has been a preliminary study based on many assumptions, and that therefore further research is needed to specify the exact profitability of such a project, as well as the technical implementation details.

5.2 Outlook

Energy storage systems like supercapacitors and flywheels are young technologies that are still under research, even if they are already in use in many applications. This, added to the fact that container traffic in the Port of Gävle will considerably increase with the opening of the new terminal, gives ESS a huge potential to increase their profitability in the upcoming years.

Therefore, a more extensive investigation could be of great interest to determine to what extent can such systems benefit the Port, considering the time of implementation as well, focusing on factors like ESS cost reduction and increase of traffic.

5.3 Perspectives

This report is only an example of the opportunities and benefits of energy storage systems. The advantages showed in this work are not exclusive to the Port of Gävle, or ports in general. ESSs are already being applied in various sectors, successfully making processes more efficient and profitable. Research is advancing fast, which offers ESSs a promising future.

Apart from having economic benefits, employing ESSs limits energy consumption, making it more responsible. A generalised use of energy storage systems in sectors like energy, transport or industry could play a key role in their sustainable development, which is crucial in a time when energy demand is incessantly growing, with its subsequent environmental consequences. More specifically and looking at the Sustainable Development Goals set by the United Nations, storing and reusing energy can contribute to goals 7 (*affordable and clean energy*), 9 (*industry, innovation and infrastructure*), 12 (*responsible consumption and production*) and 13 (*climate action*); and indirectly to goal 3 (*good health and well-bei*ng) by reducing local pollution emissions.

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Appendix A

Theoretical background

With the aim of calculating the minimum power and energy requirements to hoist containers, energy and movement expressions from classical mechanics have been used. These are shown in this annex.

Linear uniformly accelerated motion

As the hoisting and trolley velocities are known, as well as the initial and ending accelerations, the equations for a linear uniformly accelerated motion will be used to calculate the hoisting and trolley time:

$$x = x_0 + v_0 t + \frac{1}{2} a t^2 \tag{1}$$

$$v = v_0 + at \tag{2}$$

Where,

- x is the ending position.
- x_0 is the initial position.
- v is the ending velocity.
- v_0 is the initial velocity.
- a is the acceleration.
- t is time.

When velocity is constant, one can use the same equations making $a = 0$.

Potential energy and associated power

The variation of gravitational potential energy, for a height difference in which the variation of the gravity acceleration is considered negligible, is written as:

$$\Delta E_p = m\ g\ \Delta h \tag{3}$$

Where,

- m is the mass of the object of which potential energy is being calculated.
- g is the gravity constant. The local gravity in Sweden will be used in this report, $g \approx 9.82\ \text{m/s}^2$.
- Δh is the height variation of the object.

This variation of potential energy will be the maximum recoverable energy when hoisting down a container.

Dividing expression (3) by a time variation – time deriving, if the variation is infinitesimal –, one gets:

$$\frac{\Delta E_p}{\Delta t} = m\,g\,\frac{\Delta h}{\Delta t} \tag{4}$$

And having into account that the time derivative of energy is power, and the derivative of a displacement is velocity:

$$P_p = mgv \tag{5}$$

Where,

- P_p is the power associated to potential energy.
- v is the velocity of the object.

Equation (5) will be used to calculate the minimum power needed to lift a container, having into account that the hoisting velocity is known.

Kinetic energy and associated power

During the phases of acceleration and deceleration, the velocity of a container changes. Therefore, there is a change in kinetic energy, which demands a certain amount of power.

Kinetic energy is defined as:

$$E_k = \frac{1}{2}mv^2 \tag{6}$$

Where,

- m is the mass of the object of which the kinetic energy is being calculated.
- v is the velocity of the said object.

The power given to increase kinetic energy is obtained by deriving (6).

$$P_k = \frac{dE_k}{dt} = \frac{d\left(\frac{1}{2}mv^2\right)}{dt} = mv \cdot \frac{dv}{dt}$$

$$P_k = mva = Fa \tag{7}$$

Where:

- a is the acceleration of the object.
- F is the force applied on the object.