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Capacity with a pOsitive enviRonmEntal and societAL footprInt: portS in the future era

COREALIS
THE PORT OF THE FUTURE

D.4.2: Port Energy Assessment Framework and Green Cookbook

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Table of Contents

List of Figures

List of Acronyms

Abbreviation / acronym	**Description**
AGV	Automatic Guided Vehicles
BOS	Balance Of System
CAPEX	Capital Expenditure
CO2	Carbon Dioxide
DC	Direct Current
DoD	Depth of Discharge
DSM	Demand Side Management
EEA	European Emission Allowances
EMS	Energy Management System
ERTG	Electric Rubber Tired Gantry
EV	Electric Vehicle
HFO	Heavy-Fuel Oil
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
MDO	Marine Diesel Oil
MPP	Maximum Power Point
MV	Medium Voltage
Nox	Nitrogen Oxides
OPS	Onshore Power Supplies
PCT	Piraeus Container Terminal
PM	Particulate Matter
PV	Photo Voltaic
QC	Quay Crane

Abbreviation / acronym	Description
RCD	Residual Current Device
RES	Renewable Energy Source
RMG	Rail Mounted Gantry
ROI	Return on Investment
SoC	State of Charge
Sox	Sulphur Oxides
TEU	Twenty-Foot Equivalent Unit
TSO	Transmission System Operator
ULCV	Ultra Large Container Vessel
VOC	Volatile Organic Compound

Executive Summary

Lowering the port's environmental footprint is one of the core high-level objectives of COREALIS. Funded under the European Union's Horizon2020 Framework Programme, the goal of COREALIS is to develop a strategic, innovative framework, supported by disruptive technologies, including Internet of Things (IoT), data analytics, next generation traffic management and emerging 5G networks, for cargo ports to handle upcoming and future capacity, traffic, efficiency and environmental challenges. Within this framework, the proposed beyond state-of-the-art innovations, target an increased efficiency and optimized land use, while being financially viable, respecting circular economy principles and being of service to the urban environment.

The current report provides a description of the energy assessment framework through the analysis and modeling of the energy consumption in the port environment. This analysis (cost benefit analysis/ feasibility study) is used to investigate the port's potential of becoming an energy prosumer through a micro-grid implementation. The document is connected to Task 4.2: COREALIS Energy Assessment Framework and Green Cookbook.

1. Introduction

This document aims to provide an energy assessment framework for the Piraeus Container Terminal (PCT). The scope of this document is to investigate cost-effective solutions for the integration of renewable energy sources with energy storage, the reduction of the carbon-footprint of the port in particular and the improvement of the air-quality of the port-environment in general. To achieve this goal, a purpose-built simulation environment is created which analyses and models the energy consumption of the port, the integration of renewable energy sources, the flexibility offered by battery storage and the interaction with the grid. The simulation environment takes several constraints into account, such as the power of the grid connection and the energy content of the battery and allows us to draw conclusions regarding the self-sufficiency of the port, the cost of the different solutions and the achievable CO_2-reduction.

In its current configuration, the medium voltage grid of the port is a load-only environment which supplies different loads ranging from impressive quay cranes, yard cranes and reefer yards to mundane office buildings, warehouses and lighting. No energy storage or generation sources are present. The different loads are presented, including their grid connection and consumption.

Next, two candidate renewable energy sources for the medium voltage grid are introduced, limited to the most mature large-scale solutions, i.e. PV-generation and wind turbines. Hydro-power and geothermal generation are not suited for the PCT environment and insufficient relevant data (both technical and economical) is available on emerging technologies such as tidal and wave power to be included in this simulation. Battery storage is also introduced as this is required to match the intermittent production of the renewable energy sources with the load demand and allows to connect higher power levels of renewable generation without reinforcing the grid connection.

The electrical grid of the PCT port is described as this is the backbone which supplies the existing loads and which will connect the renewable generation and battery storage in the future.

In a first step towards battery integration, a basic scenario is developed which determines the required battery content in function of the available grid connection when no RES-power is available. This sets a minimum requirement to the combination of grid-connection and battery storage/power when load shedding needs to be avoided.

In a second step, the simulation environment is explained which allows to analyse and model the power-flows between the renewable generation, the battery storage, load and grid connection. This simulation takes different objectives into account such as peak shaving of the renewable generation and load demand, maximization of the self-consumption of the renewable energy, maximization of the self-sufficiency of the load demand by the local generation and storage and the determination of the RES-curtailment and load-shedding. The output generated by the simulation gives these different objectives in function of the grid connection power and energy content of the battery.

The simulation is further extended to allow the determination of the cost in function of the same grid connection power and energy content of the battery. This calculation takes the aging of the battery, the degradation of the PV-modules, separate prices for the battery inverter and PV-inverters and the cost of the wind turbines into account to achieve an accurate estimation of the total cost and cost per kWh of renewable energy. The cost includes both the RES-generation as well as the storage which is required to increase the self-consumption and self-sufficiency.

The CO_2-impact of the renewable generation and battery storage is determined, both in absolute value as in CO_2 per kWh of generated electricity. This shows a considerable potential for CO_2-reduction which is calculated both in absolute value as in cost per tonne CO_2.

In the final chapter different scenarios are presented in which the simulation environment is used to find the optimal combination of PV, Wind Turbines and storage for:

The case when only the current PCT load is present

The previous case, but additionally the diesel yard-vehicles are entirely replaced with electric drive vehicles.

The previous case, but additionally the container ships are shore-powered to allow the shut-down of onboard diesel-generators.

In these cases, a solution is presented in which the highest amount of renewable energy is used to supply the port without excessive cost.

2. Loads in Piraeus Container Terminal

The electrical grid in the Piraeus Container Terminal provides electricity to a wide range of loads. This ranges from buildings such as offices and maintenance buildings, lighting and very specific loads related to the port-activities;

The most notable structures are the gigantic Quay Cranes (QC, Figure 1) which hoist the containers of the ship and put them on a flatbed truck on the landside. This can be manned Terminal Tractors, but also unmanned trucks, Automatic Guided Vehicles (AGV's) are possible. The Quay Cranes in PCT cover both older and newer generations of QCs. The older QCs are fed by a 6,6 kV or 20 kV reel and are equipped with a 1200 – 1600 kVA transformer to connect the drives to the medium-voltage grid. These older QC represent one third of the total QC installation. 19 QCs of the latest generation represent the main part of the QC installation. These are capable of unloading the largest container ships in the world, which are capable of transporting 21.000 TEU containers. These towering giants are equipped with an 1800 kVA transformer and a 20 kV reel to achieve the medium voltage grid connection. Although they are few in number, at a total of 31 cranes, they represent 40 % of the total load of the port.

Figure 1: Quay Crane unloads Container Ship in PCT

Two types of Yard Cranes are used in PCT; Rail Mounted Gantry cranes (RMG, Figure 2) and Electric Rubber Tired Gantry cranes (ERTG). Yard Cranes are used to unload the container from the Terminal Tractor or AGV and store the container in a free location in the stack. Both Yard Cranes require significantly less power than the Quay Cranes due to the limited height and width of the stack compared to a container ship. The RMG requires a 510 kVA grid connection and is fed by a 20 kV reel. The ERTG generally requires a 400 kVA grid connection and is connected to the medium voltage grid by a 1 kV reel. There are currently some 45 ERTGs operational in PCT, connected to 11 2500 kVA transformers. Hence every transformer feed multiple ERTGs. This is not the case for the 22 RMGs which are equipped with a dedicated transformer. Over 60 Yard Cranes are present in PCT, yet they consume approximately half of the QCs at around 20 % of total consumption.

Figure 2: New RMGs installed at PCT

Another typical load for ports is the Reefer Containers which are used to store and transport cooled goods. PCT offers 5 reefer stacks (Figure 3) for a total of 1300 reefers. The reefer locations are mostly fed by 3 2500 kVA transformers which are connected to the 20 kV medium voltage grid. The transformers provide three-phase 400 V_{ac} to the reefers. The power rating of the 3 transformers is significantly higher than the reefer consumption, but most likely the transformers are used in a 2+1 configuration where 2 transformers supply the reefer load while the third is kept in reserve to replace a failed transformer if required. From the point of view of connected power, the reefers are a medium load in the port, but due to the constant power required to keep the reefers cool they represent some 25-30% of the total load of the port and are only second to the huge Quay cranes.

Figure 3: Reefer stack

As this cookbook wants to provide insight in the port of the future and its future infrastructure, additional loads are added in the simulations.

A first such load is the electric vehicle. Currently PCT uses some 130 Terminal Tractors which are diesel powered to transport the containers inside the port facility. Electrification of these vehicles offers a huge cost and fuel savings potential and is economically viable even when the higher capital cost of the electric Tractor is taken into account. Few other vehicles are present at the yard, a few reach stackers and straddle carriers are present for emergency situations and exceptional loads, but these represent a negligible part of the fuel consumption in the terminal.

A second interesting electric load is the provision of shore power to the moored ships. This allows to shut down the onboard diesel-generators of the container ships and offers the potential of significant better air quality in the port environment as the combustion of Heavy-Fuel Oil (HFO) or Marine Diesel Oil (MDO) is replaced by clean electricity. This requires high-power grid connections to the medium voltage grid as these container ships consume several MW to power their internal loads.

3. Renewable Energy Sources and Battery Storage

Renewable Energy Sources (RES) produce electrical power with a much lower carbon footprint and fewer harmful emissions than fossil-fuel based electricity generation. In the case of PCT two RES are considered, photo-voltaic generation and wind-turbines.

Photo-voltaic (PV) generation is based on PV modules which convert solar radiation to electricity. A typical module consists of 60 cells in series, but 72-cell and 90-cell versions are also available. A typical 60-cell module has a Maximum Power Point of approximately 36 V and some 7 to 9 A. These modules are connected in series to attain higher voltage strings. Some PV modules stick to the older 1 kV standard, but in industrial installations newer PV modules are combined into 1,5 kV strings. These strings are either individually connected to a dedicated MPP-tracker input of the PV-inverter or connected in parallel to a single MPP-tracker with a higher current capability. Industrial PV-inverters are equipped with several MPP-trackers with a combined output of tens of kW up to the MW range. The largest single roof PV installations have already exceeded the 10 MW mark (Figure 4).

Figure 4: Large-scale rooftop-PV installation

Several opportunities are present in PCT to install PV; PCT has a 7500 m^2 warehouse to store dry cargo and chilled/frozen goods, which would be very suited. The roof of this warehouse is ideally suited to install PV-generation and could accommodate a 1 MW PV power plant. Other suited buildings are the administration building, the repair shop for the terminal trucks and future newly build warehouses.

The second type of renewable generation is wind energy. Urban wind generation is not considered here as most of these small wind turbines are only intended for recreational purposes, resulting in excessive maintenance costs and high downtime when used for industrial purposes. Only MW-wind turbines are considered as they are intended to operate at high uptime and produce electricity at a competitive cost per kWh. Compared to PV-generation, wind turbines have less fluctuations in the energy production through the seasons and through day-night cycles. Unfortunately, they are more difficult to install in a port environment, although e.g. the port of Antwerp has successfully integrated 55 turbines, mostly 3 MW turbines, with an annual yield of 385 GWh.

Both renewable energy sources have the drawback of being intermittent power sources, with strongly fluctuating power outputs due to the availability of solar radiation and wind. The output can fluctuate strongly in a matter of seconds, with large intra-day differences. Moreover, the output of these intermittent sources does not match the power demand of the load. This results in poor self-consumption of the locally generated renewable energy, while the production peaks can cause grid stability issues. To tackle these and other problems the grid infrastructure is extended with battery storage. The battery storage can provide several grid services:

a. Peak shaving of load peaks: When the load demand increases to temporary high values, the battery can cover the load peak while the grid delivers the base load. This results in a more stable power delivery of the grid to the load and allows temporary load peaks above the power rating of the grid connection.

b. Peak shaving of RES peaks allows to install RES with a higher power rating than the grid connection. Excessive RES power is stored in the battery.

c. The excessive RES power is now available in the battery and will be primarily used to supply power to the load at a later instant. This significantly improves the (local) self-consumption of the RES production as less RES-energy is diverted towards the grid.

d. The combination of renewable energy directly delivered to the load and load covered by the battery strongly increases the self-sufficiency of the local load demand. The contribution of grid power to the total load demand decreases, resulting in less dependency of the local load on externally generated electricity.

e. The battery can also be used to increase the (short-term) grid stability by counteracting the rapid fluctuations of the RES production. However, this out of scope of the current work as this requires short-term power simulations with a temporal resolution in the ms-s range. This work focuses on long-term energy simulations, taking into account an entire year of load and production data, with a temporal resolution of a quarter-hour.

The model in this project is not biased towards any specific battery technology, as long as the technology is able to store the required amount of energy and charge-discharge at acceptable power levels. However, at a certain point an estimation of the storage cost is required to translate the theoretical model into a feasible potential solution. At this point the preferred implementation of the battery storage is Li-ion high energy-batteries (Figure 5). These batteries are suited for hour-range storage;

a. Li-ion is highly efficient, with 95 % percent charge-discharge cycle efficiency.

b. The self-discharge is low, a few percent per month.

c. The battery can last several thousand charge-discharge cycles and has a life-time expectancy of 10 to 20 years.

d. The life-cycle cost is reasonably low compared to other battery technologies.

e. The power rating of the battery is sufficiently high compared to the energy-content, resulting in usable power levels for this type of simulation.

Figure 5: Containerized Li-ion storage with power conversion stage and auxiliaries

4. Piraeus Container Terminal Electrical Grid

The Piraeus Container Terminal is equipped with an extensive medium voltage grid which feeds the previously mentioned loads. The primary substation is substation 0 which is on the one hand connected to the 150 kV high voltage grid and on the other hand supplies the entire medium voltage grid of the port with electricity. Here, the 150 kV high voltage is transformed to a medium voltage of 20 kV. The grid consists of 2 main rings. A first medium voltage ring supplies substation 1, 2 and 3. The second main ring supplies substation 4, 6 and 7. As these substations are connected in an open ring configuration, the grid has N+1 redundancy. This means that the failure of a single cable can be diverted by rerouting the power through the other cables. This is not valid for substation 5 which is connected to substation 2 through a single cable. The same is valid for the power supply of the main building which has a separate cable and transformer towards substation 0. This brings the total number of substations to 8. In its current configuration only, loads are connected to the grid;

1. The 31 Quay Cranes represent 40% of the load. They are connected to substation 2, 4 and 6. Each quay crane has a dedicated 20 kV/400 V transformer for the main drive power. The newest generation of QCs is also equipped with a separate 250 kVA transformer for the auxiliary loads. Together they consume some 17 GWh per year.

2. In the yards the containers are being handled by 22 RMGs and 45 ERTGs. The RMGs each have a separate 20 kV/400 V transformer with a 510 kVA capacity. This is not the case for the ERTGs, as the 45 ERTGs are connected to a total of 4 transformer stations. In these transformer stations the voltage is reduced from 20 kV to 1 kV. The stations are equipped with 3 2500 kVA transformers in an N+1 configuration. This ensures that the connected ERTGs (on average 11 per station) can remain fully operational if one transformer fails. Individual cables connect the ERTGs to the transformer stations. The benefit of this solution is that the power distribution between transformer station and ERTG occurs at a low voltage, hence less expensive power equipment can be used. Inside the ERTG the voltage is further reduced to 400 V. The Yard Cranes consume at around 8 GWh yearly.

3. The reefer containers have a power supply similar to the ERTGs. Several transformer stations are located across the port, with 3 2500 kVA transformers in an N+1 configuration to increase the redundancy. Contrary to the ERTG-stations, the secondary voltage is 400 V, such that the power can be used directly by the reefers without further conversion. The reefers consume some 11 GWh yearly.

4. Together the Quay Cranes, Yard Cranes and Reefers represent 90% of the electric load in the PCT port. The remaining 10 % is divided between the lighting and the buildings. The lighting is located on Pier 2 and 3, consumes 2,7 GWh and represents 6% of the load. 4 buildings are located on the premises of the port,

being the administration, operation and workshop buildings and the warehouse. These 4 buildings consume 1,7 GWh and represent 4 % of the load.

In total the electrical grid transports over 40 GWh of electricity to the different loads. The PCT load behaviour is relatively stable, as the port handles ships on a 24h base and 364 days per year. The average load is 4,6 MW, with a base load of 2 MW and recurring peak loads above 6 MW.

5. Base Case – Batteries used for load shaving

As discussed in the previous chapter, the medium voltage grid of PCT is subjected to moderate power fluctuations; The base load is quite high at 2 MW due to the continuous character of port operations, but still peaks above 6 MW occur, especially when several of the powerful Quay Cranes are in operation simultaneously to unload a one or two large container ships. In this chapter we try to asses which requirements are imposed on the battery storage if it is added to deliver load peaks. By delivering load peaks, the grid connection itself can be smaller (or avoid costly grid reinforcements) and the power drawn from the grid is more stable.

Before we start with complicated calculations to find the optimum battery which is able to both store as much RES-production as possible to increase the PV-self-consumption and self-sufficiency as well as provide peak power for the load, we look at the most basic requirements of the battery. The most basic conditions of the grid occur when no RES-power is available, hence the load can only be covered by the grid and the energy stored in the battery. As no RES is available to charge the battery, the recharging of the battery is entirely covered by the grid. This means that sufficient grid power needs be available to both cover the load and recharge the battery. Hence, the basic requirement of the grid-battery combination is that the grid connection needs to be sufficiently powerful to allow recharging of the battery, while the battery needs to have sufficient energy content to cover the load as long as it exceeds the grid connection with sufficient power to cover the load peaks.

A first example is the required battery to cover the normal load of the container terminal. The container terminal has a high base load of 2 MW and short peaks above 6 MW. The grid connection needs to be at least the average load power to allow sufficient recharging of the battery. With a high base load, this average is fairly high. The required battery content is shown in Figure 6. Below 5,3 MW, the required battery content increases rapidly due to the high average vs peak load. We will later calculate the optimum grid connection at 5,1 MW. At this grid power, the required battery content to cover the load in absence of RES is 2,2 MWh. We will later see that the optimal battery in this scenario (PCT-load only) has an energy content of 25 MWh, hence the minimal battery content can be easily attained.

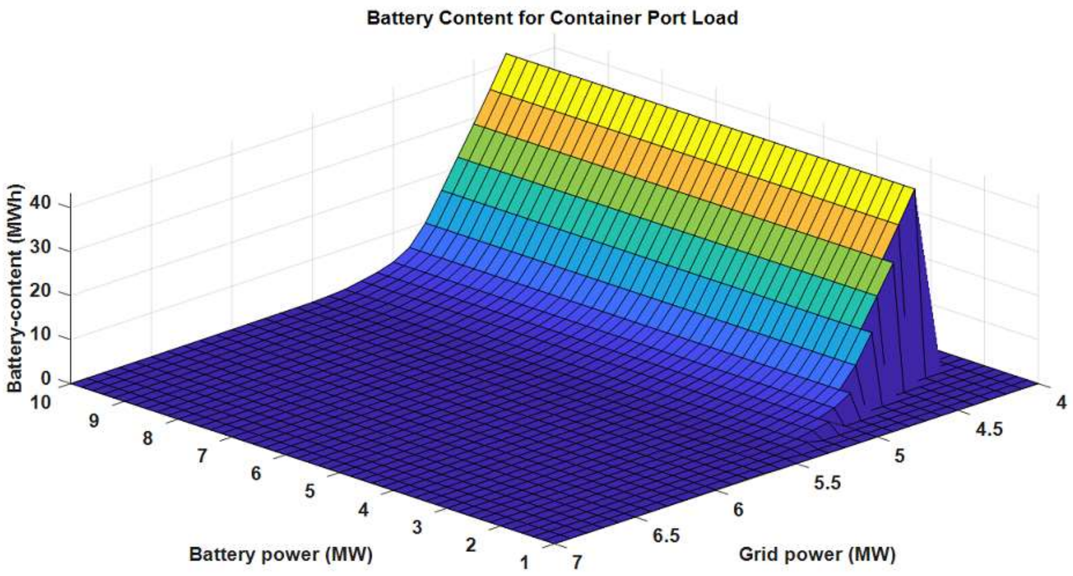

Figure 6: Required battery content and power to cover the warehouse load.

In subsequent chapters the load profile for the electric vehicles is determined. The electric vehicle charging is dominated by long periods of steady power consumption, e.g. 660 kW for 9 hours and 800 kW for 12 hours, and experiences no peaks at all. Above 800 kW, the required battery content is zero, but below 800 kW the required battery content increases very steeply to above 4 MWh at a 500 kW grid connection. This is illustrated in Figure 7.

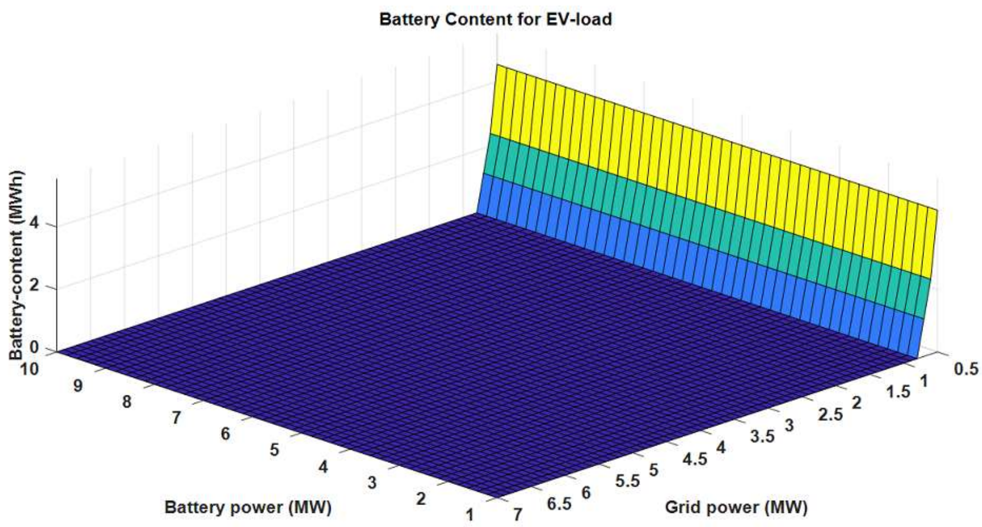

Figure 7: Required battery content and power to cover Electric Vehicle charging.

Both previous loads are combined in the last example, see Figure 8. As the PCT-load is combined with the EV-load, the base load increases to 2,4 MW. The average load increases to 5 MW, hence the previously determined grid connection of 5,1 MW is now too close to the average power. In a subsequent chapter we will prove that the optimal grid connection for the combination of PCT-load with Electric Vehicles increases to 5,7 MW while the optimal battery has a 27 MWh net energy content. For the 5,7 MW grid connection, the required battery to prevent load shedding is only 1,8 MWh, hence the actual 27 MWh battery will have no problem to avoid the load shedding. If the grid connection would have remained the same, the required battery to prevent load shedding would increase to 15,6 MWh. This would have put a lot of constraints on the battery utilisation by the Energy Management System, hence the 5,7 MW grid connection is the right choice.

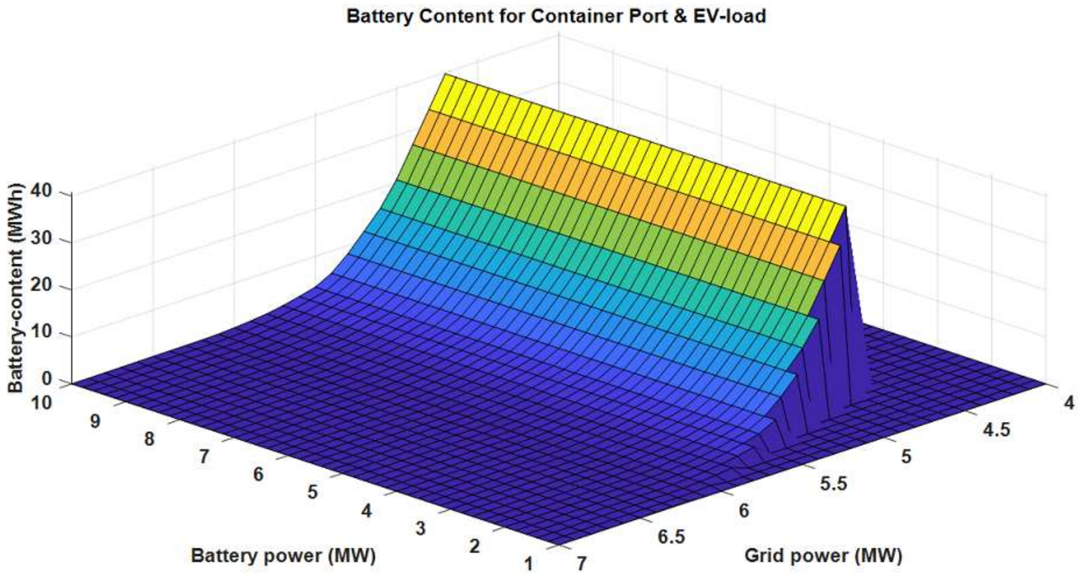

Figure 8: Battery requirements for Warehouse load and Electric Vehicle charging.

The most important lesson drawn from these examples is that we can determine a minimum battery content to avoid load shedding for a given grid connection. This can be used in more complicated use cases of the battery as the minimum state-of-charge to prevent load shedding and as a lower limit of the allowable energy content of the battery.

6. Multi-objective Energy Management System

When the battery is used for a single purpose, the state-of-charge (SoC) management of the battery is fairly simple. For instance, referring to the previous chapter, when the battery is used in a grid with only loads, the single purpose of the battery is to avoid load shedding by providing peak power when the load exceeds the grid connection power. The energy management system tries to keep the SoC of the battery as high as possible. The battery is recharged whenever the load power is below the grid connection power, and stops when the battery is fully charged.

A complementary example is the use of batteries to store excess PV-generation. When the grid connection power is lower than the peak power of the PV-generation, a battery can be added to store the excess PV energy and discharge the battery when the PV power drops below the grid connection power. The energy management needs to keep the SoC of the battery as low as possible. This is again a fairly simple Energy Management System (EMS). This is also beneficial for the grid stability as the peaks above the grid connection power are absorbed by the battery. The grid connection power remains at its maximum during PV fluctuations as the battery is discharged with the power disparity between PV generation and grid connection power.

However, the task of the EMS becomes far more difficult when different purposes need to be met in the algorithm of the EMS. This is the case in our algorithm where, for example, loads are combined with PV-generation. On the one hand the battery needs to have a high SoC to cover the load when required, while on the other hand the SoC needs to be low to accept excess PV generation. The different requirements imposed on the EMS are discussed in the following paragraph.

6.1 Objectives of the Energy Management System

The power-flow simulation determines to which degree a certain combination of battery storage and grid connection is able to deliver multiple objectives simultaneously. For this purpose, a simulation is run which controls the power-flows between the RES generation, load, battery storage and grid connection. The simulation can both be used for simulations at node level (e.g. single grid connection which feeds a warehouse) or at port-level (taking into account all port loads and port-wide RES generation). The different objectives are:

1. RES-peak shaving: The simulation allows to install RES-generation with a higher power rating than the grid connection. This is necessary to increase the self-sufficiency of the port. RES generation has an intermittent production and the equivalent full-load hours is fairly low, e.g. at around 1000 hours for PV, while the load is present all year long. When the RES-prediction forecasts peak RES-production exceeding the grid connection power, the EMS aims at discharging the battery to a SoC-level that allows to store the excess RES-production.

2. Load-peak shaving: The simulation also allows to connect more load power than the grid connection. This allows to add more load at a certain grid node without any grid-reinforcements. When the predictor forecasts excess load above the grid connection, the EMS aims at charging the battery to a sufficiently high SoC-level that avoids load shedding. The lessons learned from the previous chapter can be put into practice here.

3. Grid constraints: Both previous cases allow to put restrictions on the grid connection, as both the load and RES supply to the grid are limited. This limit can be set at the nominal power of e.g. the transformer, but can also be below the physical grid restrictions. This can be useful when the power drawn from the medium voltage grid needs to restricted, e.g. to allow additional loads on the MV-grid or to lower peak consumption fees.

4. Maximize RES self-consumption: In order to increase self-consumption of the RES-production, any excess RES-generation which is not needed to cover the load is stored in the battery on the condition that the battery is not fully charged. When the load exceeds the RES-production at a later stage, the battery can be discharged to increase the self-consumption and free up the battery for the next RES-peak. The RES-generation is only diverted to the grid when the load is low and the battery is full. These measures allow to maximize the RES-self-consumption.

5. Maximize Autarky (Self-sufficiency of the grid): A forth objective is to maximize the autarky or the ability of the local RES-generation to cover the load demand. The measures taken for the maximisation of the self-consumption already increase the autarky. An additional measure is that the battery will supply the load entirely, which allows to reduce the grid power to zero in some cases. This can be very useful when excess RES-generation is predicted and allows to quickly discharge the battery such that it is prepared to store excess RES power at a later instance.

6. RES-curtailment: Curtailment is an action performed by RES-generation to lower the output below the maximum available production. PV-inverters can achieve this by lowering the actual string-voltage below the maximum-power point voltage, while wind-turbines can achieve this by adjusting the pitch control of the blades. Although the EMS tries to avoid curtailment as much as

possible, sometimes it is necessary to avoid overload on the grid. This can occur when the RES-production exceeds the combined load and grid connection power while the battery is fully charged. The EMS tries to avoid curtailment by postponing the charging of the battery in some cases such that the RES power can be fed to the grid while the battery is reserved for excess generation later on. This action does not alter the RES-self-consumption or autarky as the battery is fully charged sooner or later. However, in some cases these measures are still inadequate to avoid RES-curtailment; The battery is fully charged and the maximum amount of RES-power is fed back to the grid.

7. Load-shedding: Load shedding is an action where the power supplied to the load is restricted or entirely cut-off. This can happen when the grid connection power is below the load demand and both the battery and available RES are unable to supply sufficient additional power. In some cases, load shedding is not allowed, e.g. for the Quay and Yard Cranes as this interferes with the proper operation of the port. However, in some cases load shedding could be acceptable for limited amounts of time, e.g. for reefers as they have limited thermal inertia and can maintain temperature in the absence of the power supply. Even better would be to combine or extend the Energy Management System with Demand Side Management (DSM) so that the load demand can be shifted in time to avoid load shedding. This is not considered in this simulation as the port environment is less suited for DSM and would make the simulation overly complicated.

6.2 Power-flow Calculations

In order to deal with these multiple, sometimes contradictory, objectives, the Energy Management System of the simulation uses a total of 23 distinct states, depending on the current load and RES-generation, the expected load and RES-generation and the state of charge of the battery. The simulation also takes the grid power restrictions and battery power into account.

The input to the simulation is the load profile and RES profile over the span of an entire year with a quarter hour resolution. This ensures that the simulation covers all possible situations from low and high demand to varying RES production between day and night and across all 4 seasons. The simulation calculates the power-flows in between the RES-production, load, battery and grid as well as the RES-curtailment and load shedding by allowing the Energy Management System to control the charging and discharging of the battery, the division of the RES-production between load, battery and/or grid and the division of grid power between the load and battery. The different power-flows are illustrated in Figure 9.

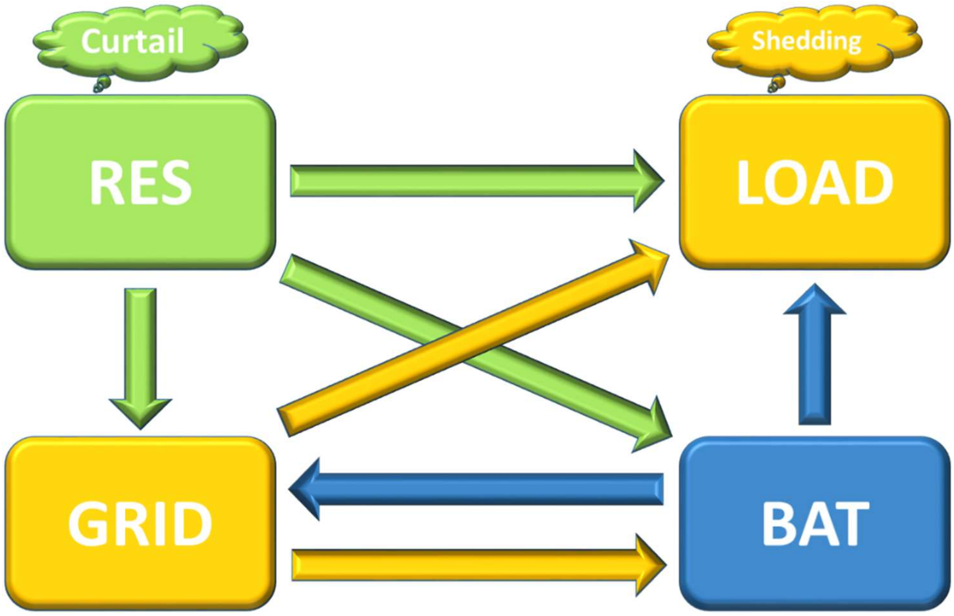

Figure 9: Power-flows between different actors of the simulation.

The different power-flows are calculated for the entire one-year span of the simulation and used to determine several objective-related outputs. These outputs are determined for an entire range of both the grid connection power and battery energy content. This can be used in further processing steps to dimension the grid connection and energy-content of the battery, and to determine derivative data such as the cost of the installation, the electricity price, the CO_2-reduction, the CO_2-impact per kWh of electricity and the cost per ton CO_2-reduction. The outputs of the simulation are:

1. The self-consumption of the RES-generation by comparing the RES-production used by the load to the total RES-production. The RES-production used by the load is either directly used by the load or stored in the battery and later used to feed the load. The RES-production stored in the battery which is later redirected to the grid or the grid power used to charge the battery is not taken into account in these calculations.

2. The autarky is determined by comparing the same RES-production used by the load to the total load demand. The battery improves the autarky by allowing more locally generated power to be consumed by the load.

3. The power and energy exchanged with the grid is determined. The EMS threats the grid limits as hard constraints which are never too be exceeded, hence these boundaries are always respected. The energy exchanged with the grid provides useful information which is used to check the validity of the self-consumption and autarky calculations.

4. Several data concerning the battery are also calculated. The energy throughput over an entire year of the battery is calculated, referring to the accumulated energy stored in the battery. This is compared to the energy content of the

battery to determine the equivalent full-load cycles of the battery. Furthermore, it is checked

a. Which part of the available energy content is effectively used by the Energy Management System, to ensure the proper operation of the EMS and to avoid over-dimensioning of the battery (see Figure 10).

b. Which charge and discharge power are effectively requested from the battery. This will never exceed the nominal power of the battery as this is treated as a hard constraint by the EMS. However, the requested power can be lower than the nominal power and allows to reduce the battery-inverter power.

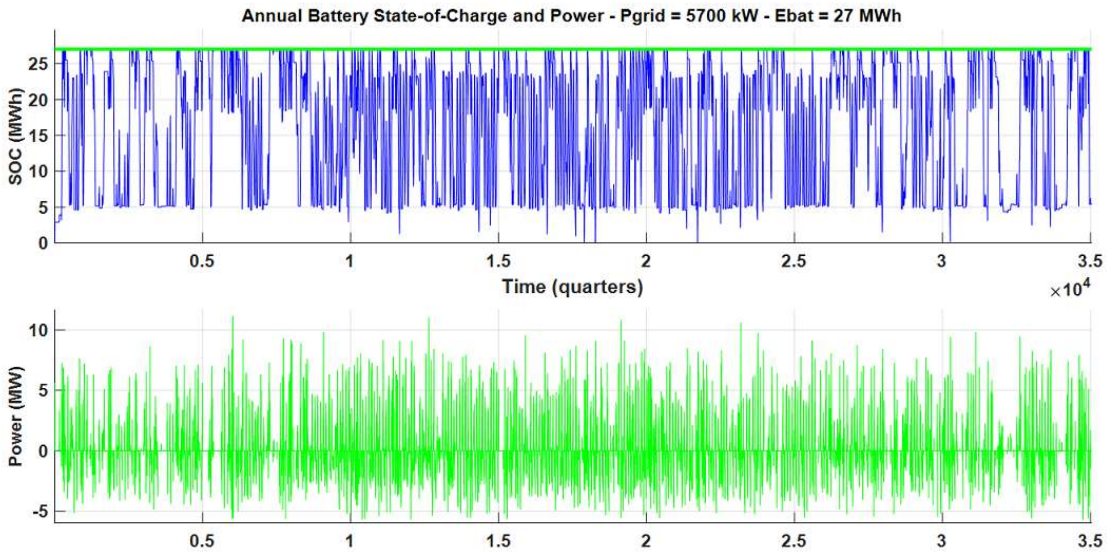

Figure 10: Battery SoC and (dis)charge power over entire year (PCT+EV load case).

5. The effective RES-generation is determined by taking the available and curtailed RES-power into account.

6. The load shedding, if any, is determined. This is avoided in most cases, but can occur when a small battery is combined with a small grid connection.

6.3 Outputs of the power-flow simulation with EMS

To illustrate the functioning of the simulation and EMS, we demonstrate the results of the power flow when the port is equipped with 10 MW of PV and 21 MW of Wind Turbines to cover the load. The load comprises both the normal Container Terminal loads as well as the electric vehicle load of 140 terminal tractors, reach stackers and straddle carriers. Both loads together consume some 43 GWh annually and draw a peak load of 7,2 MW.

The PV-inverters are optimised to obtain the lowest cost per kWh produced. The PV-inverters are rated at 7,4 MW, which not only optimizes the cost of the PV-system, but also reduces the peak load towards the grid. The PV-installation produces some 15 GWh annually. Additionally, 7 wind turbines with a power rating of 3 MW are added, these have a peak power output of 21 MW and produce 44 GWh annually. This gives a combined maximum yield of 59 GWh for the Renewable Energy Sources in the absence of curtailment.

The different outputs of the simulation for this particular example are discussed in the next figures. The grid power ranges from 4 to 7 MW as 7 MW is the current power rating of PCTs grid connection and we have proven in the previous section that grid connections below 4 MW will result in unacceptable levels of load shedding. The useful energy content of the battery ranges from 5 MWh to 50 MWh.

Figure 11 shows the annual production of the PV and wind turbines, i.e. the effective yield after the curtail losses have been subtracted, in function of the grid power and battery content. The effective production strongly depends on the available grid power and increases with some 5 GWh between the lowest grid connection of 4 MW and the highest grid connection of 7 MW. The impact of the battery size is smaller: The effective production increases 1,5 GWh between the 5 and 50 MWh battery for the 4 MW grid connection and varies 0,8 GWh for the 7 MW grid connection. In total the impact between the lowest grid connection and smallest battery on the one hand and the highest grid connection and largest battery on the other hand is 6 GWh or some 10% of the available production.

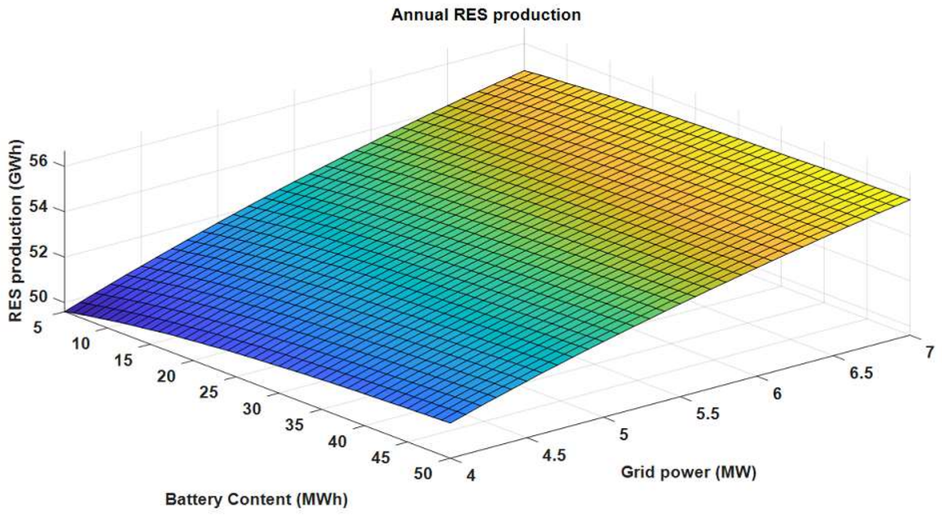

Figure 11: Annual RES-production

The impact of these results is clearly visible in Figure 12. The RES-curtailment drops from some 8 GWh at the lowest grid connection of 4 MW to 3,4 GWh at the highest grid connection of 7 MW. Hence the grid connection power causes a 4,4 GWh difference in RES-curtailment, while the battery has little impact on the RES curtailment.

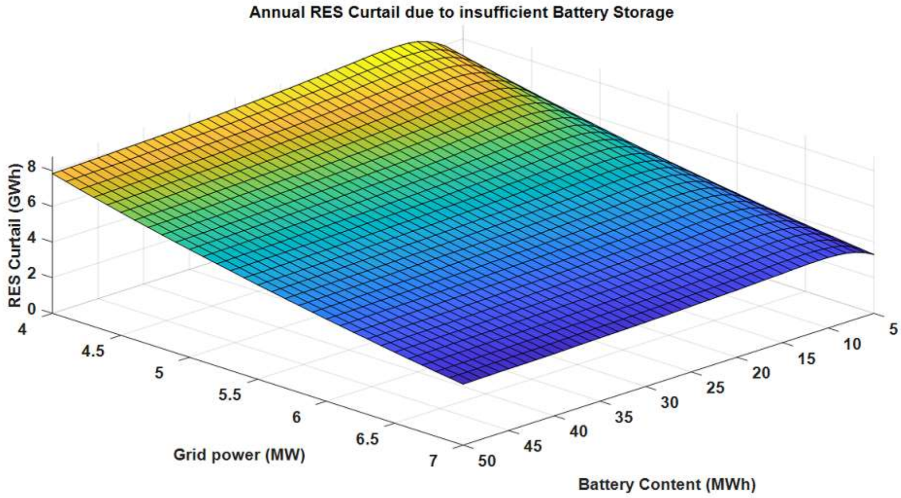

Figure 12: Annual RES curtailment

Figure 13 shows the load shed in function of the grid power and battery content. With a grid connection of 5 MW and 5 MWh battery, the annual load shedding is a mere 10 MWh (0,25 ‰ of the consumption), even though the peak load is 7,2 MW in this scenario (PCT-load with added EVs). If the battery increases to 20 MWh, the load shedding is entirely avoided. Hence, this relatively compact 20 MWh battery allows to reduce the grid connection 2 MW below the 7 MW load peak (if the only concern is the load shedding).

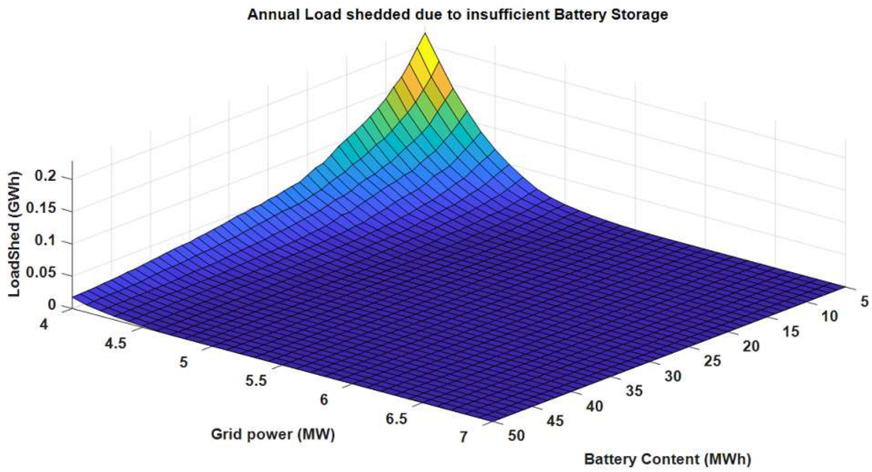

Figure 13: Annual load-shedding

Figure 14 shows the self-consumption of the RES-generation by the local load. The grid power has little influence on this outcome, the main contribution in the rise of the self-consumption is due to the increase in the battery content. Without the battery the self-consumption is an already impressive 59 % as the combination of PV and wind turbines offers excellent (in terms of renewable energy) coverage of the load demand. However, the battery is able to increase the self-consumption even more, e.g. the self-consumption increases to 65 % with a 28 MWh battery. A further increase in the energy content of the battery has little effect: A 50 MWh battery will only increase the self-consumption to below 67 %. Hence, the first 28 MWh causes a 6 % increase in self-consumption, while the last 22 MWh results in a less than 2 % increase of self-consumption.

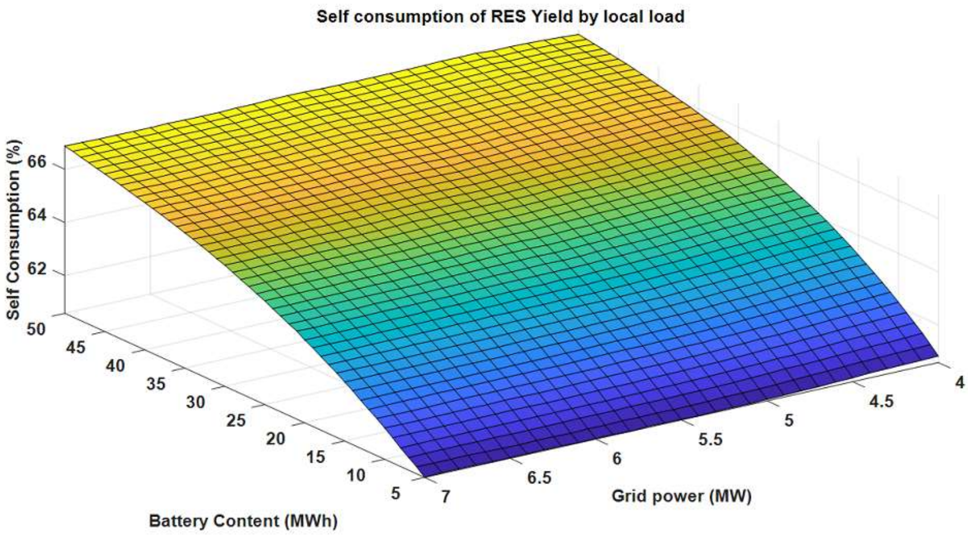

Figure 14: Self-consumption of the PV-production

Figure 15 shows the self-sufficiency of the local load by the RES production. As the RES-production at 59 GWh is much larger than the 44 GWh load demand, the autarky/self-sufficiency is much higher than the self-consumption. In the absence of batteries, the autarky already reaches an impressive 79 %. Using the same 28 MWh battery as in the previous example, the autarky increases with 8 % to above 87 %. This is quite an impressive achievement and exceeds the initial expectations of the alpha-version of the cookbook where the autarky was limited to an already decent 60 %. Adding more batteries has limited effect on the autarky, a 50 MWh battery only results in a small increase of the autarky to 90 %. Similar to the self-consumption, we can conclude that the grid connection has no noticeable impact on the autarky. This confirms the importance of the battery-storage to increase the self-consumption and self-sufficiency of the grid.

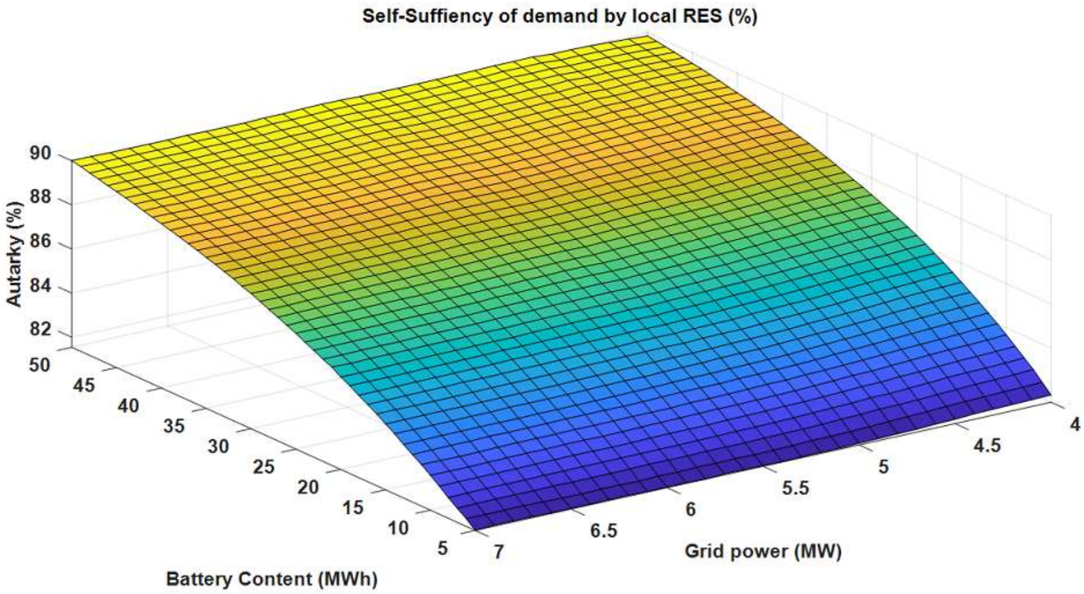

Figure 15: Self-sufficiency of local load coverage by RES and battery

In the last figure of this chapter, we illustrate the importance of the battery storage by showing the Annual Energy Throughput of the battery (Figure 16). The battery is able to store several GWh of renewable energy, which significantly reduces the curtailment of the renewable energy sources, and thus explains the improvements in self-consumption and self-sufficiency. Even a small 5 MWh battery can store below 2 GWh of RES-energy, while the largest 50 MWh battery can store 6 GWh of RES-energy, which is 10 % of the total RES-production!

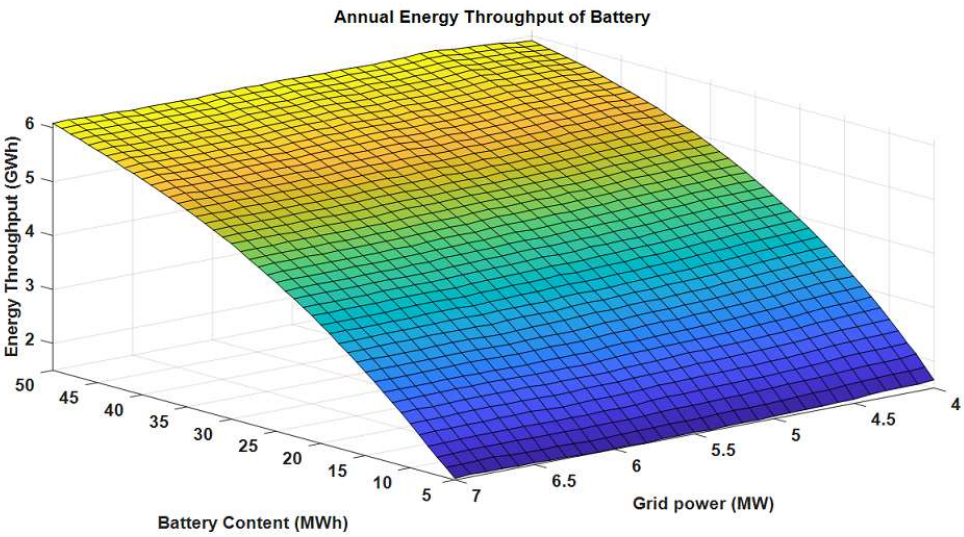

Figure 16: Annual Energy Throughput of the Battery Storage

7. Cost calculations

The previous chapters have proven that the Renewable Generation can cover significant parts of the load in the port. This is further increased by the addition of batteries which can increase the RES-self consumption and self-sufficiency of the port from below 60 and 80 % respectively to some 65 % to 90 % respectively. Hence, the installation of these assets significantly reduces the electricity purchase cost of the port. On the other hand, the purchase and installation of the Renewable Production and Battery Storage does represent a considerable (capital cost) investment. In this chapter the cost of the locally produced electricity will be determined, as well as the purchase cost of the remaining electricity for the load demand and the profit which can be obtained by selling excess RES-electricity to the grid. Taking all of these factors into account, the cost per kWh for the renewable energy is determined. In subsequent chapters this information will be used to compare the avoided cost of the purchased electricity with the cost of the RES-generated electricity to find the optimal RES and battery installation.

First, we determine the amount of battery capacity that is actually required to accommodate the net battery content which is taken into account in the simulations. We call this actual battery capacity the gross battery capacity, this corresponds with the physical battery capacity.

First, we must take the limited Depth of Discharge (DoD) of the battery into account; The battery should neither be charged to 100 % of its capacity nor be discharged to 0 % of its capacity to prolong the cycle life of the battery. A typical value is 80 % DoD, this means that only 80 % of the battery content is available for cycling.

Next, we must take the ageing of the battery into account. As the number of cycles increases, the battery will deteriorate and less energy content is available. This deterioration has to be taken into account while dimensioning the battery. For high quality batteries, the number of cycles can amount to very high value of 8000 cycles, but this will result in 40 % deterioration. Therefore, the simulation takes the number of cycles of the battery during the entire exploitation period into account. The higher the number of cycles during this exploitation period, the higher the gross capacity of the battery needs to be to ensure that the required capacity is available at the end of the exploitation period. The deterioration is defined for a certain DoD, but both have to be combined to calculate the gross energy content. This is shown in Figure 17. E.g. for a 20 MWh battery, the gross battery content is some 29 MWh, of which 5 MWh is required to limit the DoD and 4 MWh is provided to cover the ageing of the battery during the entire exploitation period.

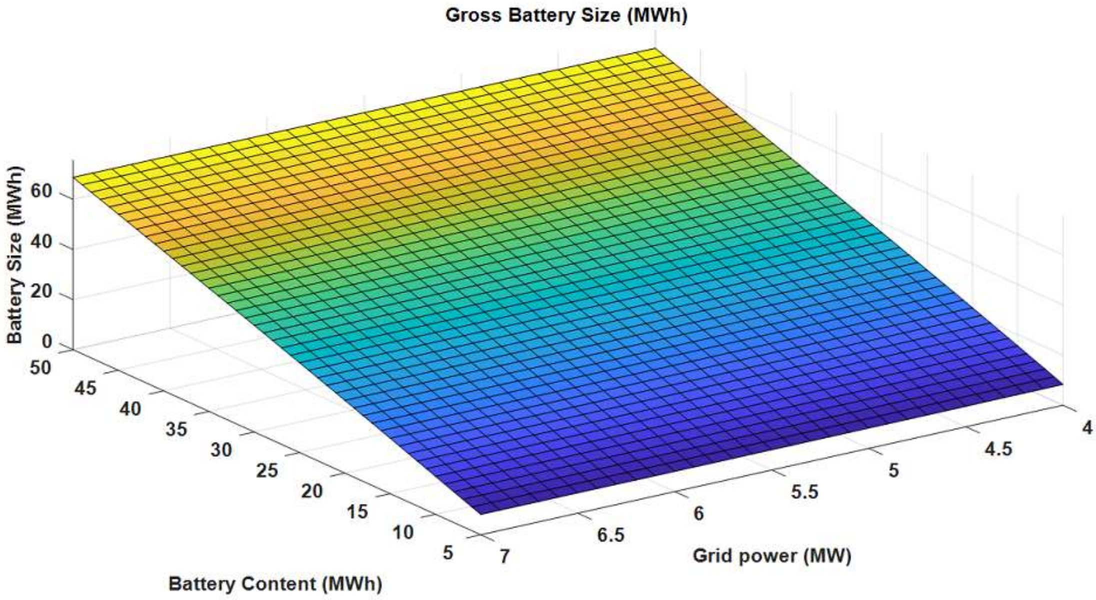

Figure 17: Gross battery size determination

Next to the calculation of the gross energy content of the battery, the size of the battery-inverter is determined. The (dis)charge power is limited to 1C, meaning that the (dis)charge power in kW is limited to the value of the energy content in kWh. E.g. a 1 MWh battery has a maximum charge and discharge power of 1 MW. Furthermore, the actual maximal charge and discharge power of the battery in the simulation is taken into account. When this actual power is lower than the 1C limit, this means that the battery does not need to use its full potential and hence the inverter power rating can be limited to the actual power used in the simulations. This reduces the battery-inverter cost. In subsequent chapters we will show that this is a safe assumption and that the (dis)charge power of the battery stays well below 1 C.

For the PV-installation, the optimal PV-inverter power rating is calculated. In a following chapter we will show that there is room for 10 MW of PV-modules in the port vicinity. The optimal rating of the PV-inverters is determined at 7,4 MW to achieve the lowest cost per kWh. The cost of the PV-inverter is estimated near 120 €/kW, the cost of the PV-modules ranges between 300 and 350 € per kW-peak, while the Balance-of-System Cost is estimated near 600 €/kW.

The wind turbines are already equipped with an optimal inverter, so no optimization is required here. The wind turbine-cost is estimated at 1650 €/kW, this includes the foundation, tower, wind-turbine and Balance-of-System Cost.

In order to calculate the total cost of the renewable generation with battery storage, the cost of the PV-modules and PV-inverters are calculated separately, the wind turbine cost is taken into account and the cost of the battery modules and battery inverters is added as well. In this cost calculation the different life-expectancies of the devices is taken into account, e.g. the wind turbines are expected to last 25 years, while the battery inverters need to be replaced every 10 years.

Figure 18 shows the total cost of the entire installation over the exploitation period. In this example we use an installation with 10 MW of PV and 21 MW of wind turbines as this combination of RES is optimal to supply renewable power to the port, both with and without electrification of the in-port vehicle fleet. In the absence of battery storage, the total cost of the renewable generation stays below 30 M€. When more and more battery storage is added, the total cost of the installation can double to 60 M€ for a very large 50 MWh battery. Obviously, the battery content has a significant impact on the total cost of the installation and needs to be chosen very carefully to keep the electricity price at or below the current cost.

In this cost-calculation the cost is determined over the entire exploitation period of the installation of 15 years. The cost of the components is rescaled from the life-expectancy of the particular component to the exploitation period. The 15 years period is chosen as it is a realistic lifetime for some crucial components. A well-maintained battery operating within its specified range, can last 15 years. The same is true for the terminal tractors, which can be operated for 15 years, certainly when electric traction is used. The PV-modules and wind turbines will operate far longer and are expected to last for 25-30 years. This total cost gives an idea of the required capital investment, but more importantly it is used to determine the cost per kWh of electricity produced.

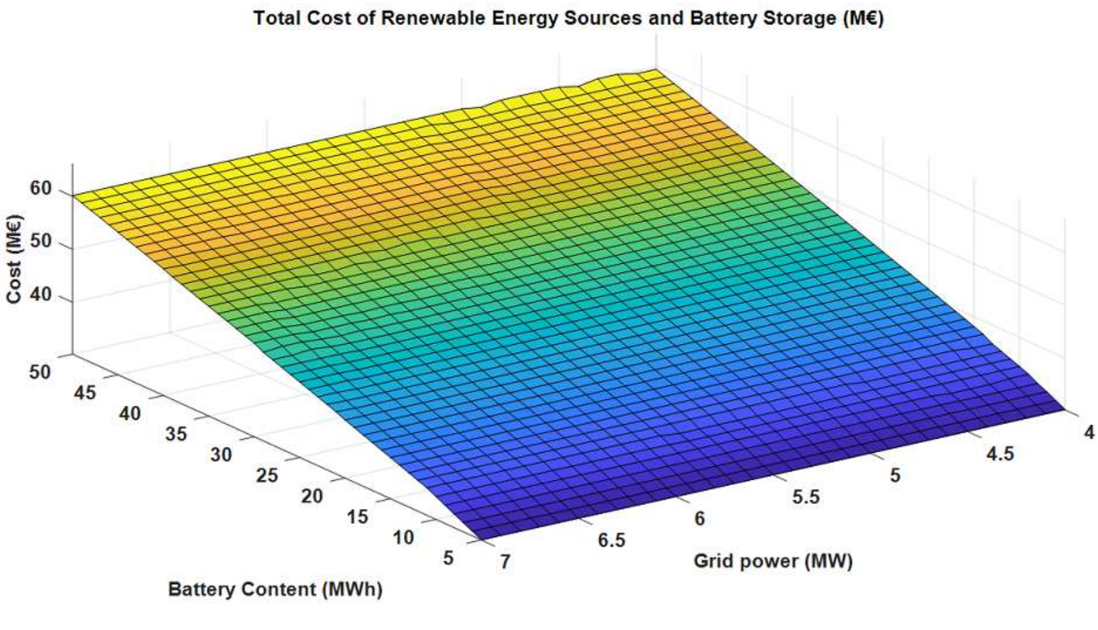

Figure 18: Total cost of renewable generation and storage over 15-year exploitation.

The cost per kWh of electricity produced is shown in Figure 19. For a rather small 5 MWh battery, the cost is below 4 c€/kWh, but the cost increases to above 7 c€/kWh for a 50 MWh battery. This means that there is clear economic incentive to keep the battery size below a certain limit, as the electricity cost with renewables and battery should not exceed the current electricity cost of PCT. The actual electricity cost depends on the power drawn, the season, week vs weekend and the hour of consumption. All of this is used to calculate the electricity cost in the scenario without any RES and battery storage, such that we can make the comparison between the business-as-usual scenario and the RES & storage scenario. Once this comparison is made, the maximum battery size can be determined and conclusions can be drawn regarding the attainable levels of self-consumption and self-sufficiency.

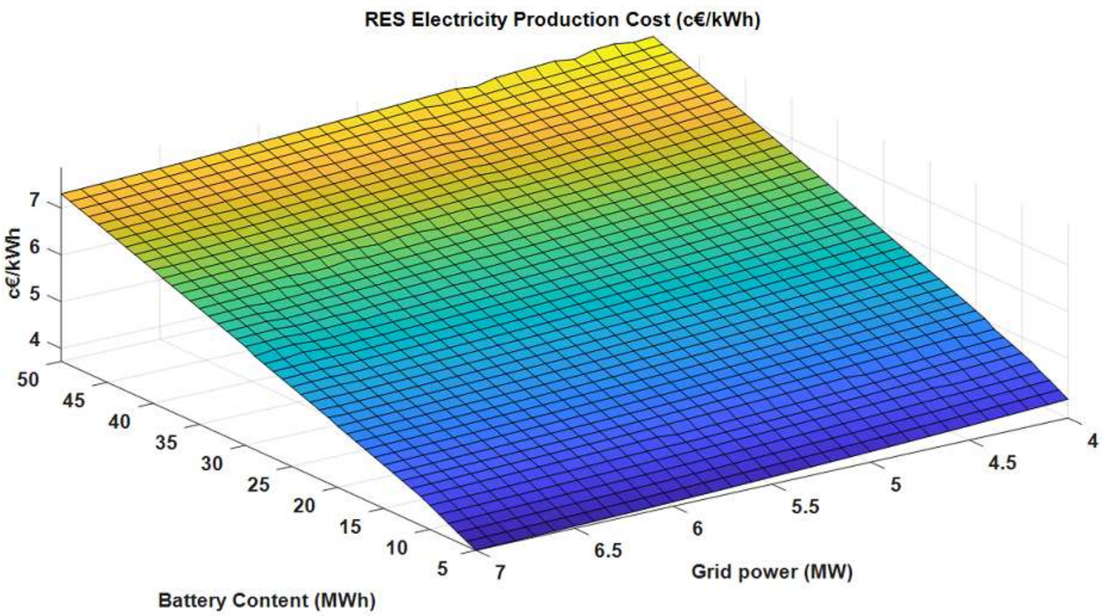

Figure 19: Cost per kWh electricity over 15-year exploitation period

However, in order to make the comparison complete, we have to take into account the part of the load demand which is still covered by the grid connection. Even in the RES & storage scenario, autarky never reaches 100 %, so part of the consumption is covered by the grid. The residual annual purchase cost is shown in Figure 20. Whereas the annual electricity cost is some 2,5 M€ in the business-as-usual scenario, this is far lower when renewable energy and storage is available due to the high self-sufficiency provided by the RES-generation. Even with a small 5 MWh battery, the cost is near 400 k€, which drops even further to 250 k€ at the highest battery ratings.

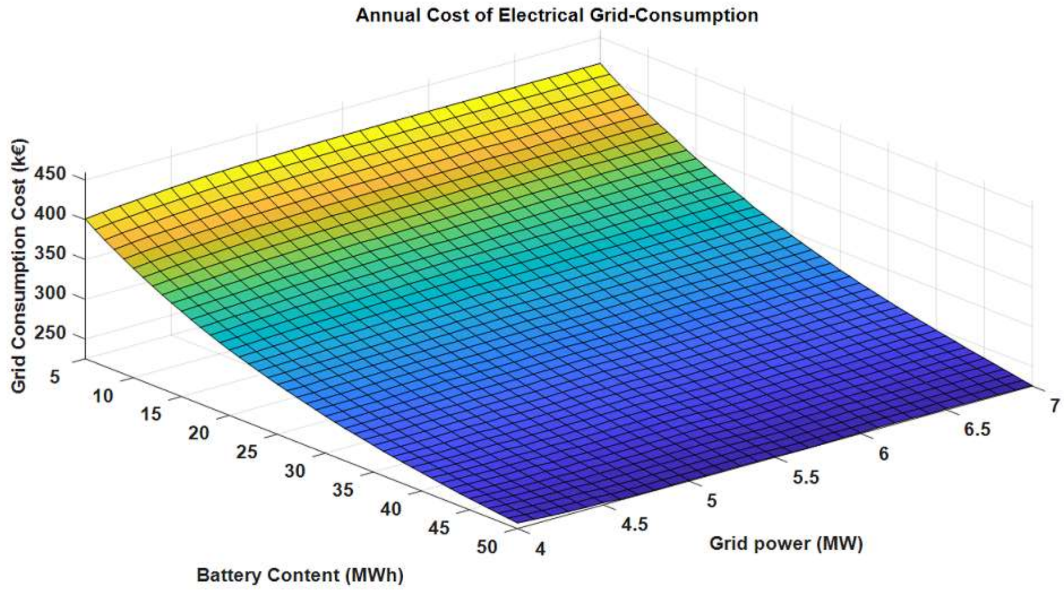

Figure 20: Annual cost of Grid-consumption

Next to the residual annual purchase cost, we also have to take the profit into account. This profit is generated by selling the excess RES-generation to the grid. In Greece, the current incentive scheme values RES-generation at around 69 €/MWh, both for PV and Wind. For each grid power/battery size case, the excess RES-production is calculated and the profit gained by selling this excess electricity is determined as shown in Figure 21.

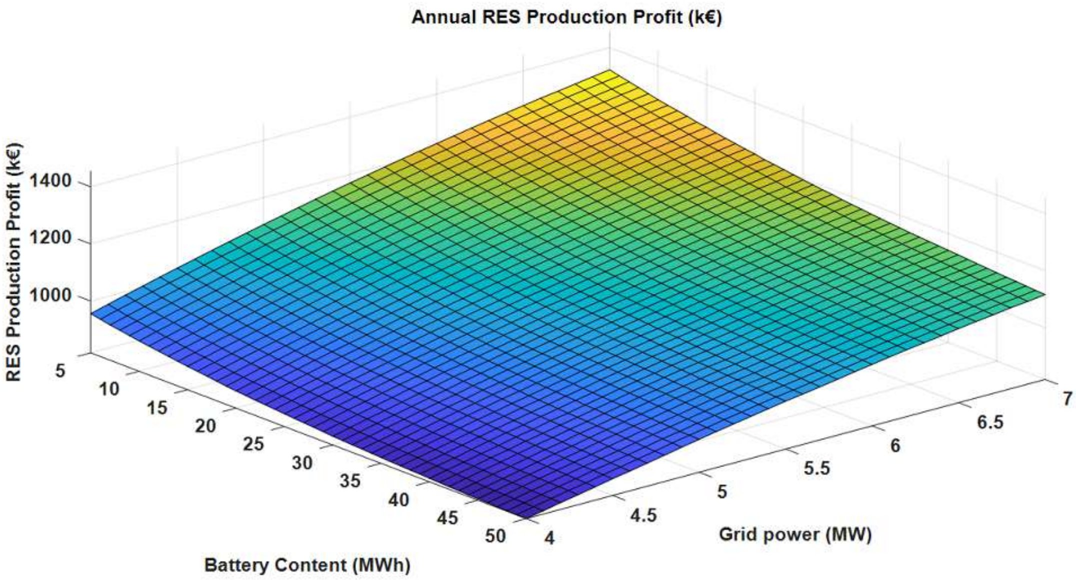

Figure 21: Annual profit by selling excess RES-energy

The cost of the renewable energy is combined with the residual annual purchase cost and the annual excess RES profit and subsequently compared to the business-as-usual scenario without RES to find the equilibrium between both cases. This is used to determine the optimal battery size, which is used in the following chapters.

Furthermore, it has to be stressed that even when the electricity cost of RES & storage is break-even with the current electricity cost, the installation of the renewable energy and battery has additional advantages;

- The addition of the battery avoids costly grid-reinforcements. These reinforcements would otherwise be necessary to cope with the peaks originating from the RES-installation, which has a higher peak power than the load.

- Also, the peaks originating from the load can be covered. This allows us to investigate the OPS-scenario in which the 9,5 MW load peak exceeds the current grid connection capacity of 7 MW by far. The battery allows the addition of the OPS-load, while avoiding costly grid-reinforcements.

- The load behind the grid-connection has attained some degree of autonomy due to the presence of the battery. Short interruptions of the power supply, generally defined as interruptions below 1 or 3 minutes, can be prevented as the battery and RES can supply the load briefly. The power quality of the grid thus improves due to the addition of the RES and battery.

- During favourable conditions, the RES-generation and battery storage can cover the load demand during long-term interruptions lasting for several hours. However, the Energy Management System does not actively control the RES and storage to ensure this, as this would increase the battery size and costs, so this advantage cannot be guaranteed.

- The grid stability of the transmission network (high voltage grid), which feeds the medium-voltage grid of the port, can be improved by the battery as the load and RES-production peaks disappear and the power remains at a stable level for longer periods of time. With the introduction of more renewables in the grid, the TSO (Transmission System Operator) finds it harder to maintain grid stability. Hence, some compensation from the TSO can be expected (now or in the future) if the port actively supports the grid stability.

An important disclaimer is that the additional grid costs for peak power and CO_2-tax have been omitted. Although this would make the business-as-usual scenario more expensive and consequently easier for the RES & storage to compete, it would make the proposed solution more expensive. While still competitive for the Greek situation, the solution would be unattractive for some other European countries. For instance, while a 40 GWh consumer pays at around 75 €/MWh in Greece, this is only 60 €/MWh in the Netherlands. Therefore, we willfully keep the price of the renewable solution below 60 €/MWh in order to keep it representative for other countries.

8. CO_2-impact

In this chapter the CO_2-impact of the renewable energy sources and battery is calculated. First the total CO_2-impact of the installation itself is calculated. This is compared to the effective yield of renewable electricity to determine the CO_2-impact per kWh of electricity. Hence, if we manage to limit the curtailment of the RES-generation, this will have a positive impact as more renewable energy is generated by the same installation. As the CO_2 per kWh is much lower for the renewable energy sources compared to the current fossil fuel-based electricity production in Greece, the CO_2-reduction can also be determined. In a last step the cost of the renewable sources and battery installation is compared to the CO_2-reduction to determine the cost per tonne CO_2-reduction.

First the total CO_2-impact of the installation is calculated. For this purpose, the CO_2-footprint of the PV-modules, PV-inverters, Wind turbines, battery-modules and battery-inverters is taken into account. The inverters have a CO_2-footprint of 124 kg CO_2/kW (nominal power), the batteries have a CO_2-footprint of 123 kg CO_2/kWh (kWh gross energy content as this represents the physical size), the PV-modules have a CO_2-footprint of 824 kg CO_2/kW (module peak power) and the wind turbines have a CO_2-footprint of 526 kg CO_2/kW. As the ratings of the different components are determined in the simulation, the total CO_2-impact can be easily determined.

This is shown in Figure 22, which gives the impact in (metric) tonnes. It is clear that the RES-installation has a large impact as the CO_2-impact is already 14 ktonnes for a 5 MWh battery. When a larger battery is required, the CO_2-impact will increase in excess of 22 ktonnes when the battery reaches 50 MWh.

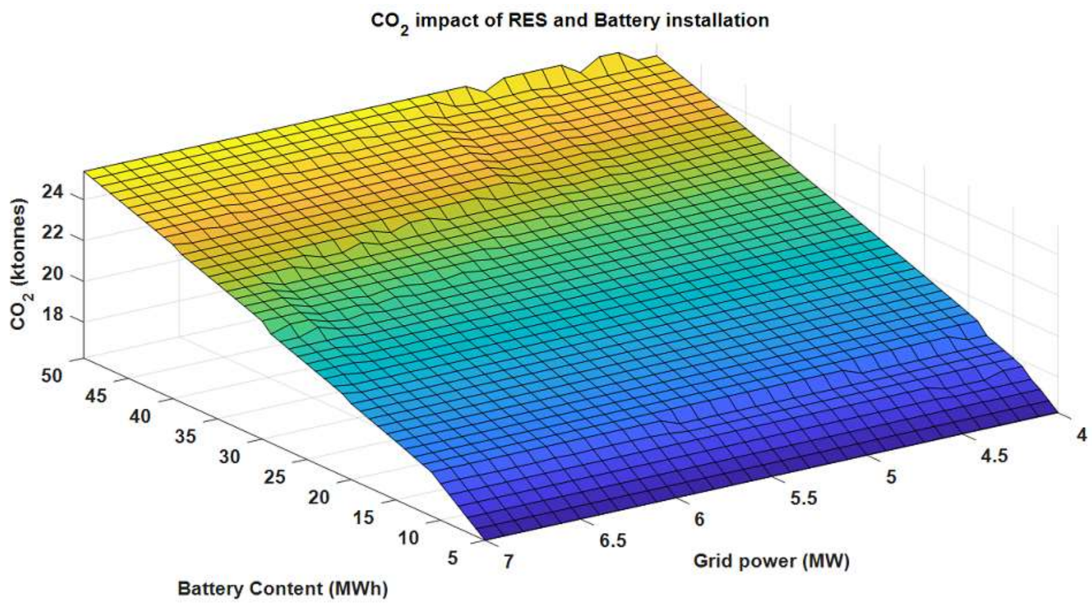

Figure 22: Total CO_2-impact of the Renewable Energy Sources and battery installation.

The total CO_2-impact is divided by the electricity generation to determine the CO_2 per kWh of produced electricity. The electricity generation takes the losses due to the curtailment into account, such that only the effective yield is used in the calculations, as well as the degradation of the PV-modules. Once again, the total exploitation period is set at 15 years, such that a realistic figure for the electricity production is obtained. The results are shown in Figure 23. When using a relatively small battery, the CO_2 per kWh is below 20 g CO_2/kWh and increases to some 30 g CO_2/kWh for a large 50 MWh battery. The grid connection power has a negligible impact on the g CO_2/kWh, the main impact is due to the increase in battery size.

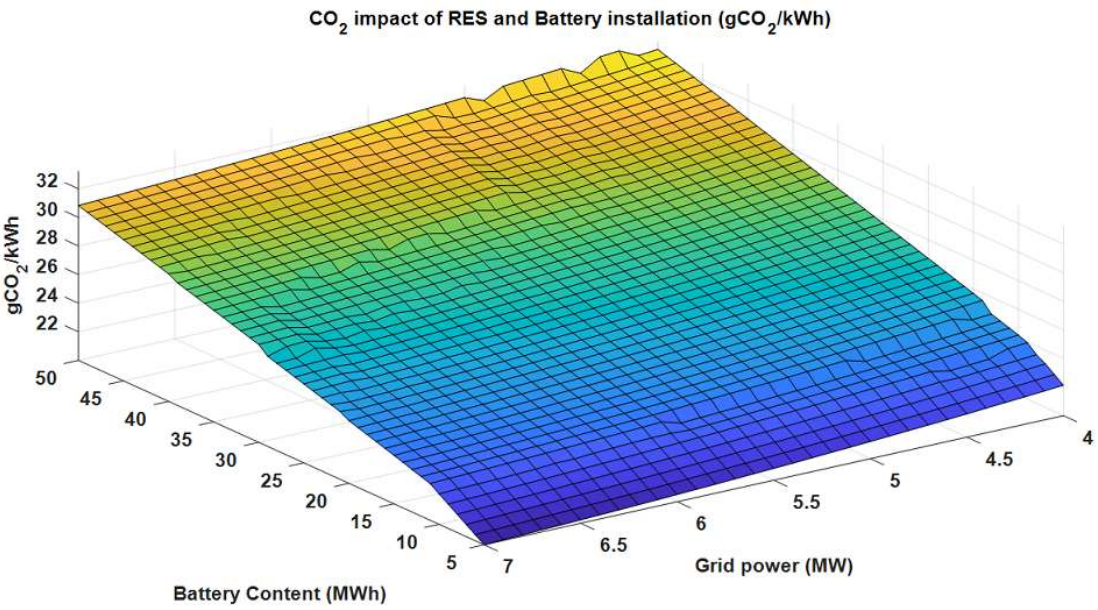

Figure 23: CO_2/kWh with renewable generation and battery

Although the CO_2 per kWh increases with the energy content of the battery, the absolute value is very low compared to the Greek energy mix. The current electricity mix in Greece produces electricity at 1167 g CO_2/kWh, mainly because 70% of the electricity production in Greece originates from conventional thermal generation. Hence, the renewable production can achieve significant CO_2-reductions. The CO_2-reduction is determined over the entire exploitation period of 15 years, taking into account the purchased electricity over this period and the renewable energy production over this period. The degradation of the PV-modules is taken into account as these will produce slightly less energy over the years. The results are shown in Figure 24. At low grid connection power levels, the reduction is less due to the RES-curtailment, so less renewable energy is produced to replace the fossil-based purchased electricity. At increasing levels of grid connection power, less curtailment is necessary, which results in higher amounts of CO_2-reduction. The size of the battery also has a small impact on the CO_2-reduction. Contrary to what the previous figure would suggest, the CO_2-reduction increases (!) with larger battery sizes, despite the fact that the g CO_2/kWh increases with the battery. Although the battery itself causes more CO_2-emissions, it also allows to recover more of the curtailed RES-energy. As the impact of less curtailment is much higher than the impact of the CO_2-emissions of the battery itself, the CO_2-reduction improves (!) by using a larger battery.

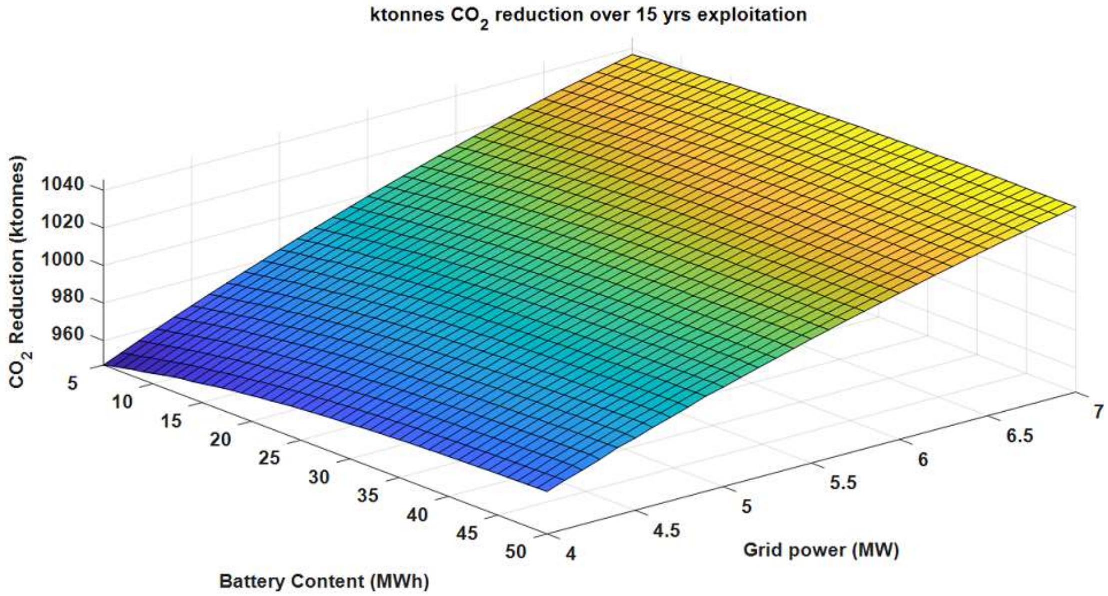

Figure 24: CO_2-reduction with RES over 15-year exploitation period.

The last step is to calculate the cost per tonne CO_2-reduction. The CO_2-reduction is now divided by the total cost of the renewable energy and battery installation. The results are calculated on a 15-year exploitation period of the installation. The results are shown in Figure 25. The main influence on the results comes from the battery size. For relatively small batteries, the cost varies between 10 and 17 €/tonne, with the highest cost at the lowest grid connection power due to the increase in RES-curtailment. Using the largest battery size, the cost increases to between 42 and 48 €/tonne. Hence, the prices vary around the current price of 25 €/tonne CO_2 in the European Emission Allowances (EEA). The battery size will determine whether or not the installation is cost effective to participate. However, the main goal and income revenue of the installation is the production of electricity at or below the current level. The CO_2-compensation should never be considered as the main parameter of the business model of the installation, but only as a possible additional revenue for the installation. For this reason, we will not take the cost per tonne CO_2 into consideration to determine the optimal battery size.

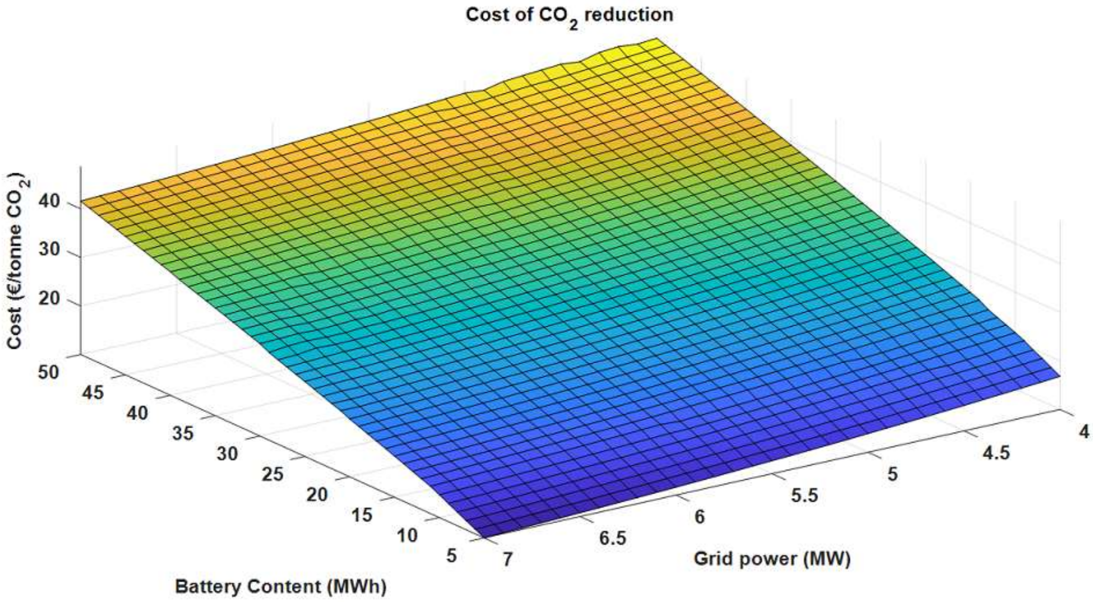

Figure 25: Cost per (metric) tonne CO_2-reduction

9. RES-plants allocation and dimensioning

9.1 Photo-Voltaic Generation

The first renewable energy source which can be used in the Port of Piraeus is PV. At first, we accommodate as much PV as possible on the rooftops of the buildings. Unfortunately, this gives only a rather small 2,5 MW PV-plant as the rooftop area is limited. Therefore, PV is also installed on nearby fields to increase the output to some 10 MW. This number remains fixed for all simulations as we want to provide sufficient PV-generation compared to the Wind generation. Moreover, PV has its peak production in summer, while the wind turbines peak in the winter. Hence, it's beneficial to have both as this lessens the seasonal variation of the renewable generation and thus increases the self-sufficiency of the port. 10 MW of PV generation is realistic, the port of Rotterdam has investigated its PV potential and has estimated 50 to 100 MW of PV generation is attainable.

9.2 Rooftop PV on buildings:

Firstly, we take 3 of the existing buildings into account and one planned second warehouse with the same surface as the existing warehouse. The total surface of the combined roofs is approximately 17550 m^2, of which the largest part is provided by the 2 warehouses (Figure 26), which have a rooftop area of 7500 m^2 each. The remaining rooftop area is provided by the office buildings and workshop, with respectively 1800 m^2 and 750 m^2. Using high performance PV modules producing 330 W per module and taking into account a usable/total roof area of 70 %, this roof area can accommodate 2,5 MW of PV-modules.

Figure 26: PCT Warehouse

9.3 West-side PV fields

North-west of the container terminal several hills are available to build PV-fields. 4 fields are selected, the location and dimensions are shown in Figure 27. In total these 4 fields have a surface area of 5,1 hectares. The land use efficiency of PV-installations (for these kinds of hills) is approximately 600 kW of PV modules per hectares, which roughly equates to 3000 m^2 of PV modules per 10.000 m^2 of land. The DC-power (combined power of the modules) of these PV installations is 3072 kW. These fields are located at 700 m from the main substation, so the distance is very short for a medium voltage connection.

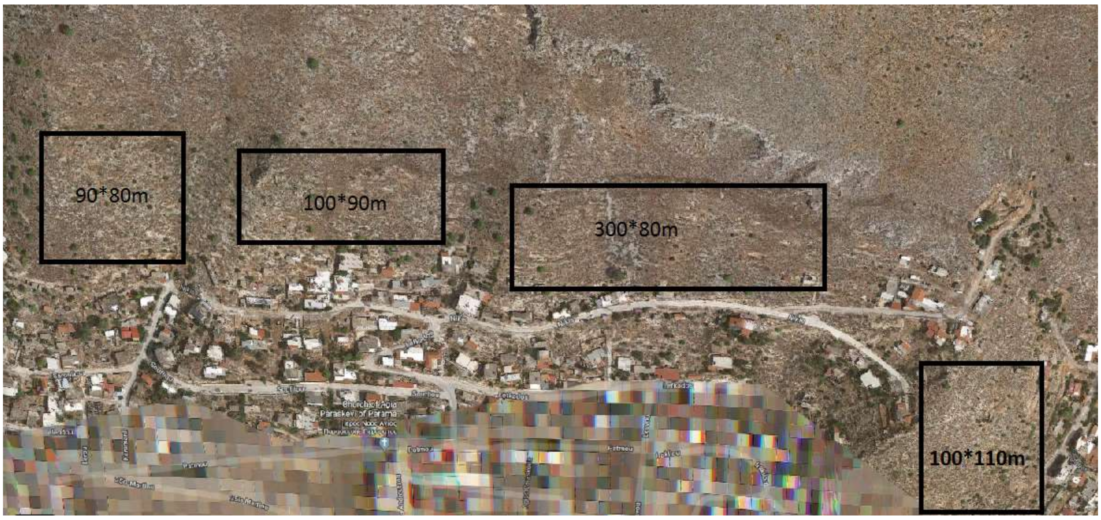

Figure 27: PV-fields north-west of the terminal

9.4 East-side PV fields

North-east of the container terminal, a single PV field is selected, which measures 180 by 400 m (Figure 28). The surface covers some 7,2 hectares, which translates to 4,3 MW of PV modules at 600 kW/hectare.

Figure 28: Large PV-field north-east of the terminal

9.5 Wind Turbine Generation

The second renewable energy source which can be used in the Port of Piraeus are Wind Turbines. During the simulation we will vary the number of wind turbines, depending on the load scenario. We use a generic 3 MW wind-turbine with actual power production measurements for land-based wind-turbines, so the production in the simulations is probably an underestimation as near-shore turbines produces more energy than their inland counterparts. In order to keep the simulations realistic, the number of wind turbines needs to be a discrete number. This avoids unrealistic scenarios where the optimal RES-generation for a particular load scenario is met by e.g. 2,73 wind turbines.

The choice of the wind-turbine is based on the Port-of-Antwerp which houses more than 15 (!) wind turbines with a power rating of 3 MW (Figure 29). These turbines have a hub height of 115 m, the diameter covered by the blades is 113 m! Other wind turbines are also present, resulting in 55 operational turbines in the PoA.

Figure 29: Wind turbines in the Port of Antwerp.

10. Scenario Development and Determination of Optimal RES-power plant and battery storage

The previous chapters provided the necessary context to understand the circumstances and functioning of the electric grid in the Piraeus Port. Subsequent chapters introduced the power flow simulation, which determines the energy flows between the renewable generation, different loads, battery storage and grid connection for a range of battery sizes and grid connections. The obtained results provide insight in the influence of the grid connection power and battery size on objectives such as self-consumption of the renewable energy, self-sufficiency of the port, achievable effective RES-production and RES-curtailment, electricity cost (in total and per kWh), CO_2-impact of the installation and obtainable CO_2-reduction. In this chapter we aim to determine the optimal size of the renewable power plant (PV and wind turbines), grid connection and battery energy content for a given scenario, i.e. from the wide range of possibilities in the previous chapters, we narrow down to a single choice and draw conclusions on the attained self-consumption, self-sufficiency, effective RES-production, cost and CO_2-impact.

Different scenarios are investigated;

- In the first scenario the focus is on the existing electrical infrastructure of the port, with electrical quay cranes, yard cranes and reefer yards. The optimal PV, wind turbines and battery size are determined for the current PCT load.
- In the second scenario the PCT load is expanded by replacing all present fossil-fueled yard vehicles, mostly terminal tractors, by electric drive vehicles. The scenario elaborates on the financial rationale of the electric drive, as well as the required charging infrastructure. The impact on the renewable generation, battery storage and grid connection is investigated and discussed.
- In the third scenario the second scenario is expanded by the provision of shore power to the moored ships. This allows to shut down the onboard diesel-generators of the container ships. The impact on the renewable generation, battery storage and grid connection is investigated and discussed.

10.1 Scenario 1 – Current PCT Load

10.1.1 RES-generation matches load demand

In this first case the only load present is the current PCT load, being the different Quay and Yard Cranes, the Reefer Containers and the lightning/buildings. At first it might seem obvious to match the generation of the Renewable Energy Sources (RES: PV and

Wind) with the load demand. This is illustrated in the two figures below. In this example the RES consists of some 10 MW of PV-generation and 12 MW of Wind-turbines (Figure 30). The combined annual production of both sources is 40 GWh and matches the load demand of the port. The grid-connection is optimized at 5.4 MW and the optimal battery has a net energy-content of 22 MWh.

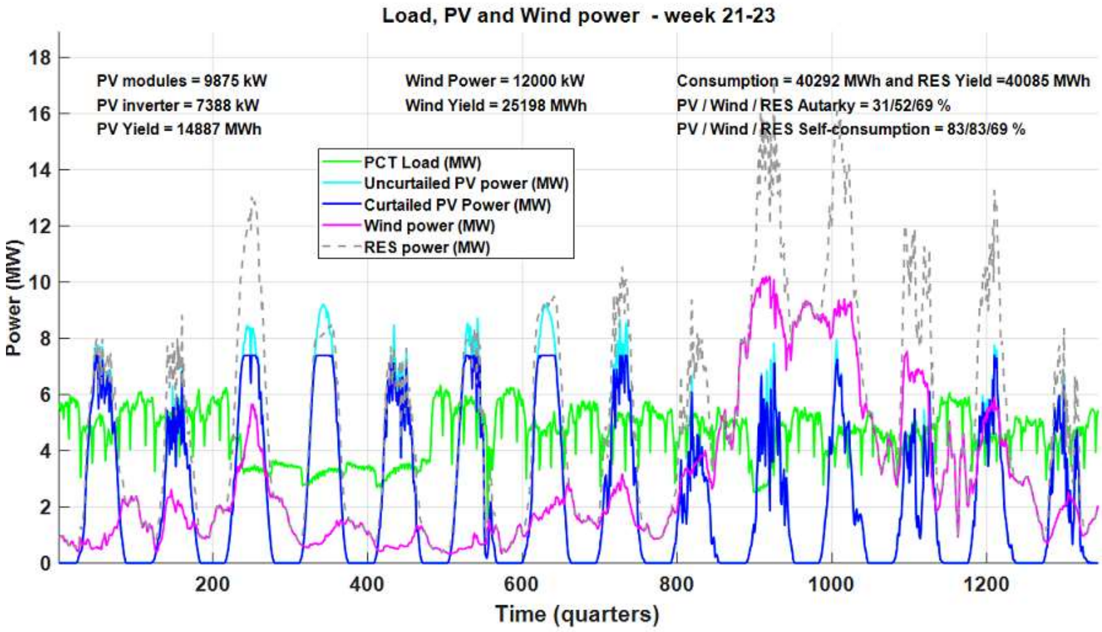

Figure 30: PCT load only, 10 MW PV, 12 MW WT, RES input

With this combination of PV, wind turbines and batteries the self-sufficiency of the port is 78 %, while 78 % of the RES-production is consumed within the port (Figure 31). The electricity cost of the renewable energy is 57,4 €/MWh and is on par with the cost of the purchased electricity. As the self-sufficiency is quite high, the port only needs to import 9 GWh of electricity to cover the 40 GWh load demand. Some 8 GWh of electricity is exported to the grid. At 69.2 €/MWh for RES-production in Greece, this returns a profit of 546 k€.

This combination allows to produce electricity without economic consequences for the port, but the environmental benefits are huge; The port is able to produce almost 80% of its own electricity at 25 g CO2-eq/kWh, which is extremely low compared to the current 1167 g CO2-eq/kWh for electricity in Greece. This results in a CO_2-reduction of 662 ktonnes over 15 years. A total of 765 MWh of RES-production is curtailed.

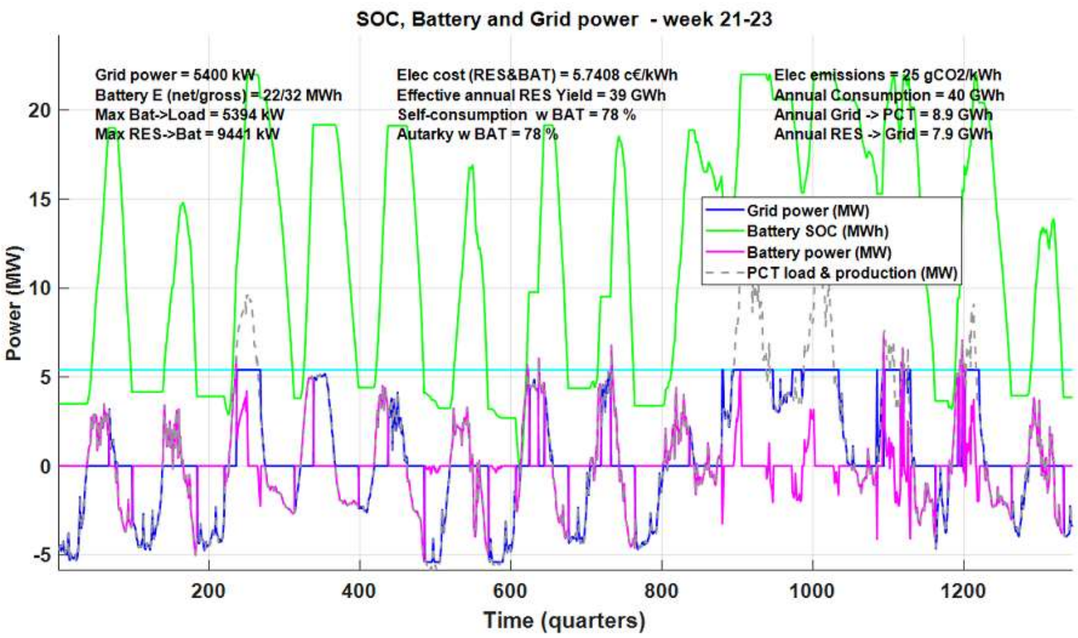

Figure 31: PCT load only, 10 MW PV, 12 MW WT, Output

10.1.2 Optimized surplus RES-generation

Although these results are already very promising, further optimization of the renewable generation and battery-storage can be achieved. Better results are obtained by increasing the wind-turbine production, see Figure 32. The optimum is found at a combination of 10 MW PV and 21 MW of Wind Turbines. The RES-production is combined with battery-storage with a net energy-content of 25 MWh. A total of 31 MW of renewable production might seem excessive compared to a load with an average demand of 4 MW, but the numbers are convincing: The autarky increases from 78 % in the previous case to 89 % in this case. This means that only 11% of the energy needs to be imported, hence the port only needs to import 4,4 GWh of electricity over the entire year. The Renewable Sources produce 59 GWh annually, of which 61 % or 35,9 GWh is consumed in the port, while 16,1 GWh is delivered to the grid. This turns the port into a net-exporter of renewable energy!

The remaining 7 GWh of RES-production is curtailed as this can neither be delivered to the load, nor stored in the battery, nor delivered to the grid. This is a very acceptable curtailment-portion (12% of the RES production) and is necessary to boost the self-sufficiency of the port without increasing the grid connection or spending an uneconomic amount of money on battery-storage. This allows us to keep the cost of the renewable generation, including RES and batteries, at 57,7 €/MWh. Hence, no cost increase occurred compared to the previous situation.

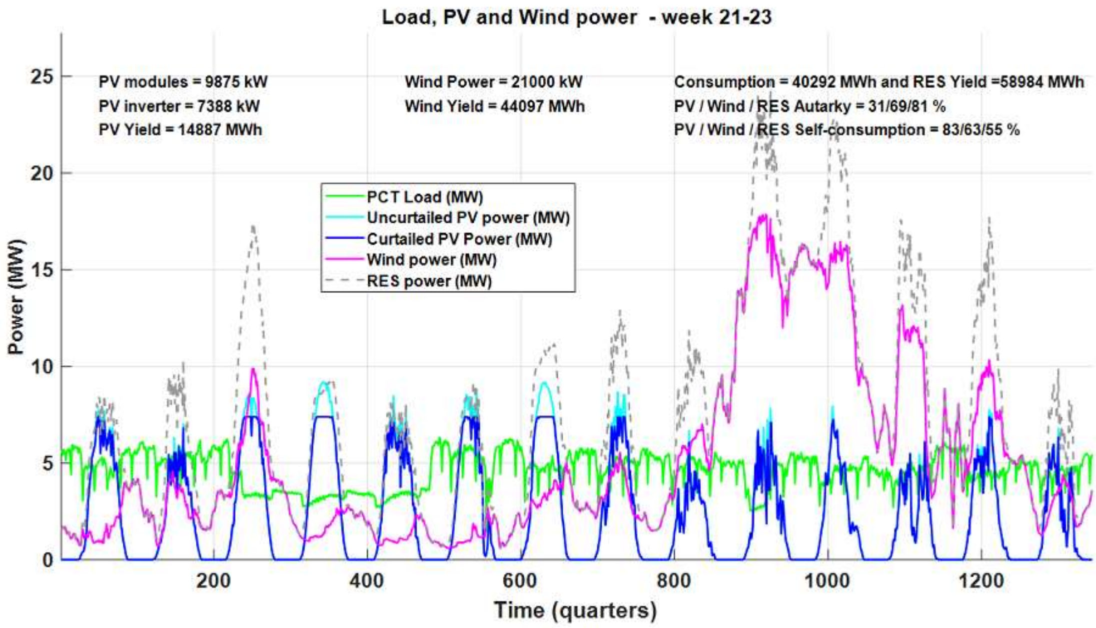

Figure 32: PCT load only, 10 MW PV, 21 MW WT, RES input

Another benefit compared to the previous situation is that the grid-connection is now at its lowest point and can be reduced to 5,1 MW, see Figure 33. As we are to add some significant load in the following cases, this is a prime objective to take into account. If we add any more RES and want to achieve economical equilibrium, the grid-connection needs to be increased as more renewable energy needs to be exported to the grid to turn in some profit. Hence, the current solution is the optimum solution to increase the self-sufficiency of the port without increasing the grid connection.

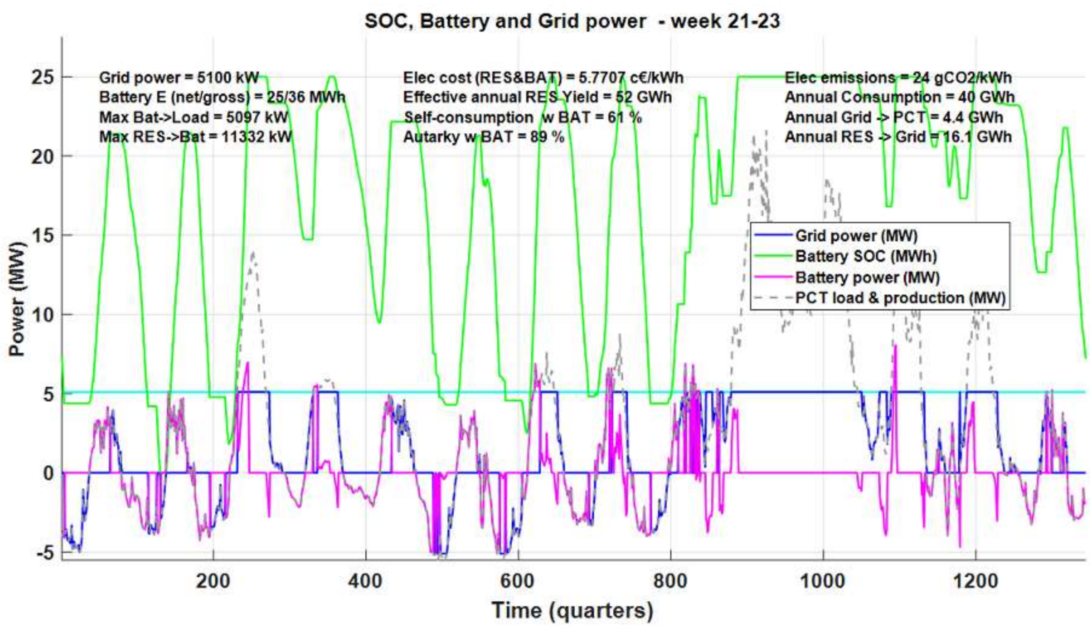

Figure 33: PCT load only, 10 MW PV, 21 MW WT, Output

Compared to the previous solution more wind-turbines are required and the net-storage increases with 3 MWh, but this solution also allows to increase the CO_2-reduction from

662 ktonnes in the previous case to 880 ktonnes over the 15 years exploitation period as both the self-sufficiency of the port and the export of renewable energy increases.

This proves that significant parts of the electricity consumption of the port can be generated with renewable electricity at a competitive price. The battery plays a key role in this achievement. In total it stores 4,3 GWh of renewable energy, of which 3,4 GWh is used to cover the load demand of the port and 0,9 GWh is exported to the grid. The first part allows to boost the autarky of the grid from 81 to 89 %, while the self-consumption increases from 55 to 61 %. The second part boosts the exported amount of renewable energy, as this energy would otherwise be curtailed and lost. In order to achieve this, the battery is discharged at peaks up to 5 MW and charged with renewable energy with peaks up to 11,3 MW (!). All of this is achieved with a 25/36 MWh battery (net/gross energy-content). The most recent 40-foot containers from Kokam can store up to 5,3 MWh per container, so 7 containers would be sufficient to reach this gross content. The maximum charge and discharge power of these 7 containers is 70 MW (!). In our application, we stay well below these power ratings. In order to connect these battery containers to the grid, 2 containers with 6 MW power supplies are sufficient, bringing the total amount of containers to 9 to achieve this level of storage and power.

10.2 Scenario 2 – PCT Load expanded with Electric Yard Vehicles

10.2.1 Motivation of Yard Vehicle Electrification

In this first part we compare diesel driven yard vehicles to their electrical counterparts, mainly terminal tractors, but also reach stackers and straddle carriers. As these vehicles are spending a lot of time idling while waiting to receive or deliver a container and are subjected to a lot of stop-and-go traffic, the diesel vehicles achieve poor efficiency and consume some 9,1 l/h on average. This results in an annual fuel consumption of some 27.000 litres, but this can go up to 38.000 l annually per vehicle! Even though these vehicles are allowed to use the much cheaper commercial diesel fuel, the fuel cost is still very high at 30 k€ annually per vehicle. On the contrary, electrical vehicles are able to achieve 5 to 7 times the efficiency of the conventional fossil fueled vehicles. The electric drive vehicles (Figure 34) consume some 75-100 kWh daily, resulting in a fuel cost of less than 3 k€ annually. Moreover, the electric drive requires less maintenance compared to the diesel drive: The benefit per vehicle is estimated at 4500 € per year. This sums up to an annual saving of more than 30 k€ for the electric vehicle.

Figure 34: Electric Terminal Tractor

On the other hand, the electric driven terminal tractor has an initial cost of 210 k€, while the diesel driven counterpart costs 110 k€, so we need to compensate for a 100 k€ additional cost. In this additional cost we have included a small on-board ac-charger of 11 kW, which is commonly found in electric vehicles. This on-board charger has the benefit that the impact on the grid capacity is limited, even if tens of vehicles are charging simultaneously (see next chapter). The limited charging capacity is also beneficial for the aging of the battery and the efficiency of the charging process, which easily exceeds 95% at these power levels.

Figure 35: 11 kW wall-box (slow charging)

The grid-infrastructure for these slow chargers is estimated at 1 k€ per vehicle, as the charger is part of the vehicle itself and the grid infrastructure is limited. In this particular case we provide 2 330 kW power supplies which each consist of a 400 kVA medium to low-voltage transformer, a low-voltage busbar and 3 feeders with 160 A protection and 10 wall-boxes per feeder. As we take 140 vehicles and 60 slow charging points into account, this can be provided at around 140 k€ or 1 k€ per vehicle. On top of this a mode 3 wall-box (Figure 35) is required which provides the communication with the on-board charger (control pilot) and a circuit breaker with integrated RCD. In large numbers, these 16 A three-phase wall-boxes cost some 500 € per vehicle, bringing the total slow charging cost to 1,5 k€ per vehicle.

Figure 36: 600 kW fast charger with local battery storage [Courtesy of Kalmar].

Fast charging of these vehicles is provided by 8 fast chargers. Each fast charger is able to provide fast charging for up to 10 vehicles during a 12 h shift. The fast charger has a 100-kW ac-grid connection, a 100-kWh battery for peak shaving and a 600-kW dc-dc converter to charge the battery of the electric vehicle. The cost of this charger, including installation and grid connection cost is estimated at 210 k€ (50 k€ battery, 60 k€ BOS-cost and 100 k€ for the 100-kW ac-converter and 600 kW dc-dc converter). As 8 chargers are required for 140 vehicles (see next chapter), the cost per vehicle is 12 k€.

Both electric and diesel driven yard vehicles have a similar lifespan of approximately 15 years. The electric vehicle has an additional cost of 100 k€ for the vehicle, and 1,5 k€ and 12 k€ respectively for the slow and fast charging infrastructure. As mentioned earlier, the annual saving of the electric vehicle on fuel cost and maintenance is more than 30 k€, hence the Return on Investment (ROI) is less than 4 years for a vehicle with a lifespan of some 15 years.

In this work we do not focus on the replacement planning of the existing diesel vehicles with electric vehicles, but rather we aim to provide the context and data that prove that the purchase of new electric vehicles is a sound economic decision when the container terminal needs to acquire new vehicles to replace old diesel vehicles. With the same focus in mind, the next chapter aims to prove that the charging of these vehicles can be incorporated in the renewable grid infrastructure we have proposed previously. We will examine the impact of the vehicle charging on the load demand, required amount of renewable generation, battery storage and grid connection.

10.2.2 RES-generation and battery dimensions for scenario 2

The Piraeus Container Terminal has already achieved important steps in the electrification of the port as the Quay and Yard cranes are fully electrified. The next step in the electrification of the port is to replace the current fleet of fossil fueled terminal tractors, reach stackers and straddle carriers with electric driven vehicles. As explained in the previous section, the electric driven counterparts require a higher capital investment, but due to the much lower fuel cost, the return on investment is only 4 years, including the charging infrastructure.

In order to model the charge behaviour of the electric vehicles, some assumptions are taking into account. PCT receives some 4 to 8 ships per day to load and unload. During the normal days with 4 ships being handled in an entire day, we assume 60 vehicles, or half of the vehicle-fleet, are required to handle the containers. As sufficient vehicles are available, slow charging of the batteries is allowed. As discussed, the slow charging is performed with 3-phase mode 3 chargers (on board ac-chargers) at a current of 16 A, which is the lowest nominal rate for mode 3 chargers. This result is a charge power of 11 kW, which is beneficial for both the grid and the battery. As the batteries are being charged at 0.1 C (assuming 100 kWh batteries), this prolongs the battery life. The vehicles are recharged in 9h charging sessions, resulting in total charge of 99 kWh. At a charging efficiency over 95 % during slow charging, some 95 kWh is available for the vehicle which is well above the average consumption of 75-100 kWh per day. The charging of the fleet is performed in 2 sessions with 30 vehicles per session. Both sessions require 330 kW of charging power (30 vehicles at 11 kW) and last 9 h. Hence, the charging of the vehicles requires some 6 MWh per day in this scenario. The slow charging scenario occurs 4 days a week.

During the busy days, the 140 electric vehicles are required to handle the containers. 60 vehicles are still allowed to slowly charge, but in this case all 60 are charging at the same time. This produces a 660 kW load (60 * 11 kW) which lasts for 9h. The remaining 80 vehicles are charged with fast chargers [1]. These fast chargers can recharge the battery of the vehicle with a flash-charge of 600 kW during 3 minutes (see Figure 36). Due to the high losses generated during this charging event, we take 15 % losses into account in the charger and battery, so some 25 kWh is actually stored in the vehicle. This requires some 4 charging sessions per vehicle during the 12 hour shift. A single fast charger is able to accommodate the charging of up to 10 vehicles, as the charging time per vehicle is only 3 minutes. Hence, 8 fast chargers are required to accommodate the 80 vehicles. Without local battery storage these fast chargers would result in a peak load of several MW on the PCT grid, theoretically doubling the required grid capacity as 8 synchronized chargers would produce a load peak of 4,8 MW. As the energy per charge event is rather low, this is the perfect situation to introduce local storage in the charger. When the fast charger is equipped with a 100 kW grid connection and 100 kWh local storage (see earlier), it can accommodate 8 fast charging sessions in 1,5 hours, while on average only 3-4 charging sessions are required per hour per charger for 10 vehicles. This reduces the peak load for 8 fast chargers from 4,8 MW to 800 kW. This 800 kW load is present during 12 hours and incorporates the 15 % of losses occurring in the fast chargers. On average these 80 vehicles still receive 100 kWh of actual storage in the vehicles. In this scenario we assume that the slow charging of the

60 vehicles is done before the 8 fast chargers start drawing 800 kW for 12 hours. In practice, the electricity supplier imposes a capacity tariff on the port, so there is a strong incentive for PCT to spread the charging of the vehicles over time. In total the slow charging of 60 vehicles combined with the fast charging of 80 vehicles consumes 15,5 MWh in a single day. This fast charging scenario occurs 3 days a week. On a yearly basis, the consumption of the electric vehicles amounts to 3,5 GWh, including the losses during charging, which is less than 10 % increase of the PCT load demand. The load profile of the electric vehicle charging is shown in Figure 37.

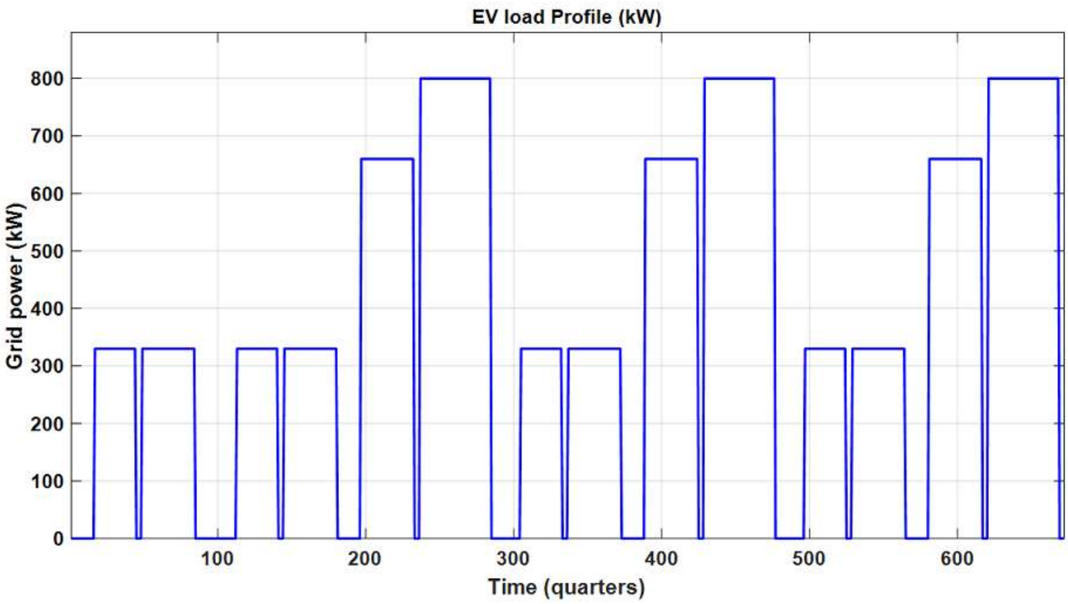

Figure 37: EV load profile (1 week)

As mentioned, the electric vehicles represent a 3,5 GWh increase in load demand from 40,3 GWh to 43,8 GWh. The optimum solution to cover this load demand is to use the same Renewable Generation Sources, i.e. 10 MW PV and 21 MW wind turbines, while the energy storage is increased from the previous 25 MWh to 27 MWh of net energy content (Figure 38). As the load power increases substantially, most notably by the 800 kW drawn for 12h by the fast chargers, the grid connection also increases from 5,1 MW to 5,7 MW. Hence, the EV-load has a clear but limited impact on the electricity infrastructure. The self-sufficiency of the port slightly decreases, from 89 % to 87 %, but the self-consumption improves substantially from 61 % to 65 %.

The 3,5 GWh EV-load is covered by a combination of the following power flows;

- The curtailment of the RES decreases with 1753 MWh (!) and the direct export to the grid also decreases to allow more renewable energy to flow to the load, in total the direct delivery of RES power to the load thus increases with 2150 MWh.
- Some 200 MWh of the previously grid-exported energy is now delivered to the battery, while the export from the battery to the grid decreases. This allows the

battery to provide 233 MWh of stored RES-energy to the EV-load. This means that 68% of the additional EV-load is covered due to the better utilisation of the RES-energy! This explains why the self-consumption increases by 4 %.

- The remaining 32 % of the EV-load is covered by increasing the grid consumption from the previous 4,4 GWh to 5,6 GWh.

This also implies that the curtailment portion of the RES-yield has been significantly reduced, from 12 % with only the PCT load to 9 % when the EV-load is added.

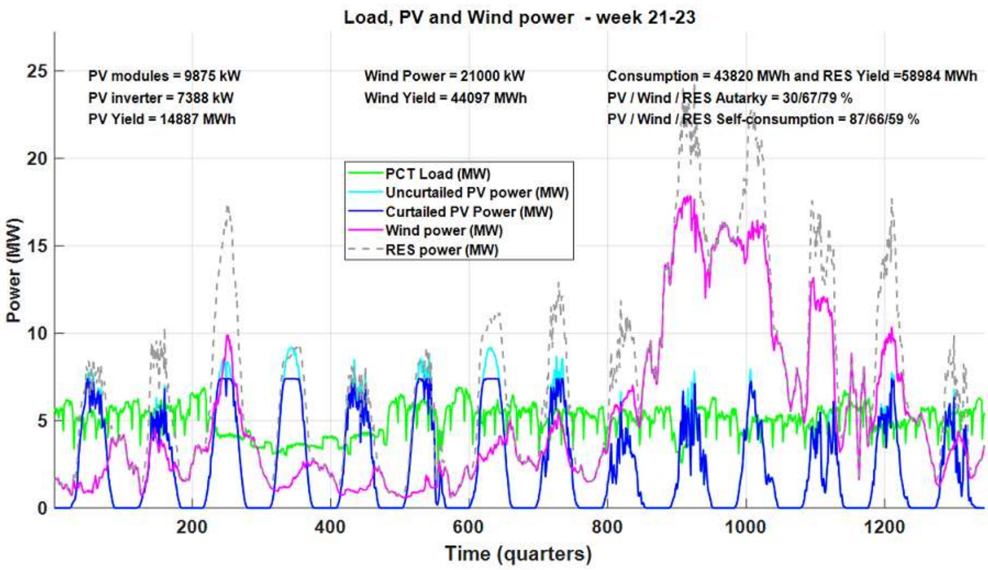

Figure 38: PCT & EV load, 10 MW PV, 21 MW WT, RES input

The cost of the renewable generation, including RES and batteries, remains stable at 57,3 €/MWh (Figure 39). Hence, no cost increase occurred compared to the previous situation. The battery increases slightly with 3 MWh gross energy content, but the load demand increases 9 % while the renewable generation remains unaltered, thus allowing to keep the electricity price stable. The grid connection has increased with 600 kW to 5,7 MW. This is only possible because the battery and the Energy Management have the priority to avoid load shedding. Even though the load peak is 7,2 MW, the grid connection can be reduced to 5,7 MW. As an extra safety precaution, this load peak can be coped with using a 5 MWh battery, such that even the loss of 80 % of the battery storage does not result in any load shedding.

As less RES-energy is curtailed while the RES-generation remains the same and the battery hardly increases, the equivalent CO_2-emissions slightly increase to 27 g CO_2-eq/kWh as it includes not only the renewable generation, but also the CO_2-impact of the EV-battery, the fast and slow chargers and the battery in the fast charger.

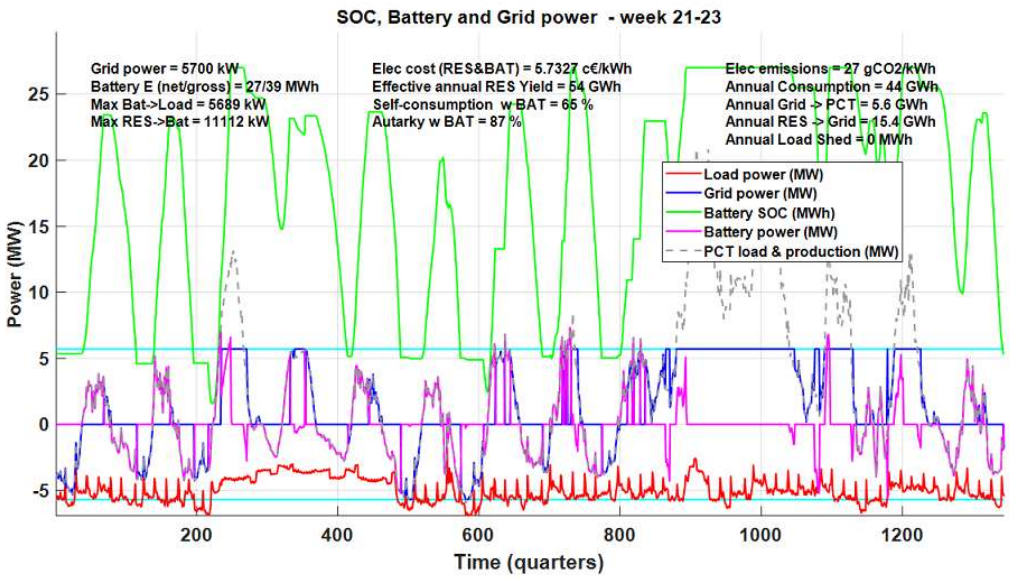

Figure 39: PCT & EV load, 10 MW PV, 21 MW WT, Output

Even more impressive is the gain in CO_2-reduction we managed to achieve by replacing the diesel drivetrains with electric ones. Previously we achieved an 880 ktonnes reduction over 15 years, but by replacing the diesel vehicles, an extra 105 ktonnes can be saved over 15 years. Moreover, the battery stores more RES-energy and more RES-energy is delivered to the load, resulting in a total additional CO_2-reduction of 135 ktonnes and a total CO_2-reduction of 1015 ktonnes for the entire port over 15 years.

10.3 Scenario 3 – PCT Load expanded with Electric Yard Vehicles and Onshore Power Supply

10.3.1 Motivation of Onshore Power Supply

In this third scenario we expand the electrical load in the port by providing onshore power supply to the ships. This allows the ships to shut down their auxiliary engines while they are at berth. An estimated reduction of 70% NOx and VOC emission, about 60% PM and SOx emission, and about 50% CO emissions can be obtained by the use of shore-based electricity supply. This is also illustrated in Figure 40. From this figure it is clear that the main concern is the reduction of NO_x, SO_x and PM emissions which have a devastating effect on the local air quality. This effect gains importance, when we take into account that many large ports are very near major cities, e.g. Rotterdam and Piraeus/Athens, so the number of people affected by the local air quality is very high. Irrespective whether the shore power is produced by coal generation or renewables, the NO_x, SO_x and PM emissions will vastly improve by adapting onshore power supplies for the ships in the port. However, when we are able to generate the shore power with renewable energy sources, the NO_x, SO_x and PM emissions will practically disappear, while the CO_2-emissions will reduce from some 1000 g CO_2-eq/kWh to a mere 25 g CO_2/kWh. Hence the combination of renewable production and onshore power supply is a clear winner for vast improvements in local air quality and overall CO_2-emissions.

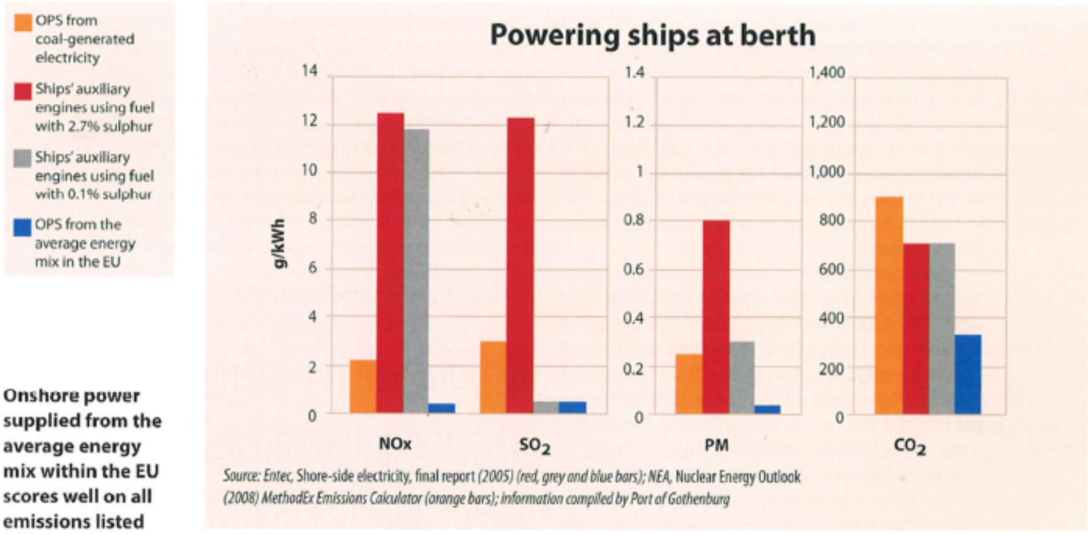

Figure 40: Impact of replacing on-board power generation with onshore power.

If all the seagoing and inland ships in Europe used an onshore power supply, this would amount to 3500 GWh of annual consumption or 0,1 % of the consumption in Europe. While this represents a small change in the electricity production, it represents a significant investment in the onshore power supplies themselves. The ship-side OPS retrofit capital cost can range from $400,000 to $2 million per ship due to the wide variety of ship designs [6]. These costs have been coming down as more retrofits have led to more streamlined and standardized designs. Nevertheless, the investment per port is significant. A schematic overview of an onshore power supply from the grid to the ship is given in Figure 41.

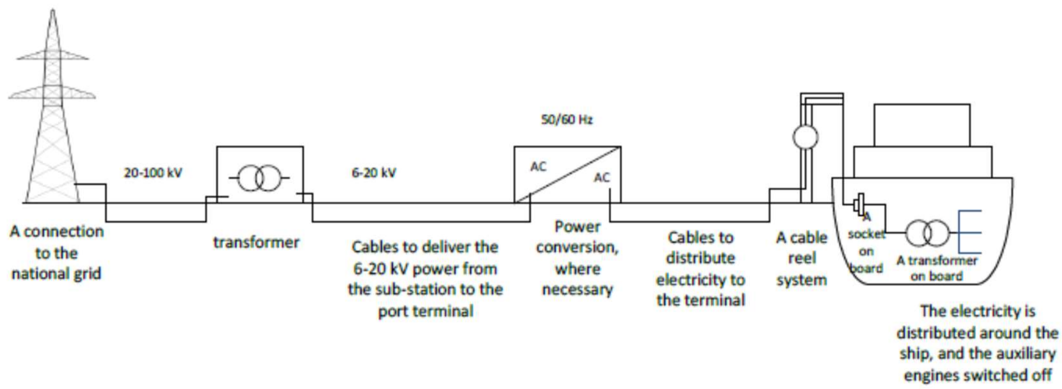

Figure 41: Scheme of power supply from grid to ship [Courtesy of D. Tarnapowicz]

In order to decrease the cost of the onshore power supply, relevant standards have been introduced. This allows uniform voltages, connectors and cable handling equipment among the different ports and allows suppliers (such as e.g. ABB and Siemens) to offer solutions with a certain degree of standardisation. For larger vessels the relevant standard is the *IEC/ISO/IEEE 80005-1, High Voltage Shore Side Electricity* standard, which is relevant for power supplies from 1 up to 20 MVA per vessel. These connections are mostly realised at 6,6 and 11 kV. The higher voltage reduces the required current rating of the cable and allows to supply the power with 1 or 2 cables. Previous low voltage systems required several heavy low voltage cables in parallel, consequently the shore connection could take up to 2 hours to complete. As a lot of ships are usually moored for a few hours before continuing their trip, this would take 4 hours out of the berthing time, which is far too long. Currently, a further automatization of the connection process is required, as this takes less time, is safer for the operators of the heavy cables and makes the synchronisation between ship and shore less error prone, see Figure 42.

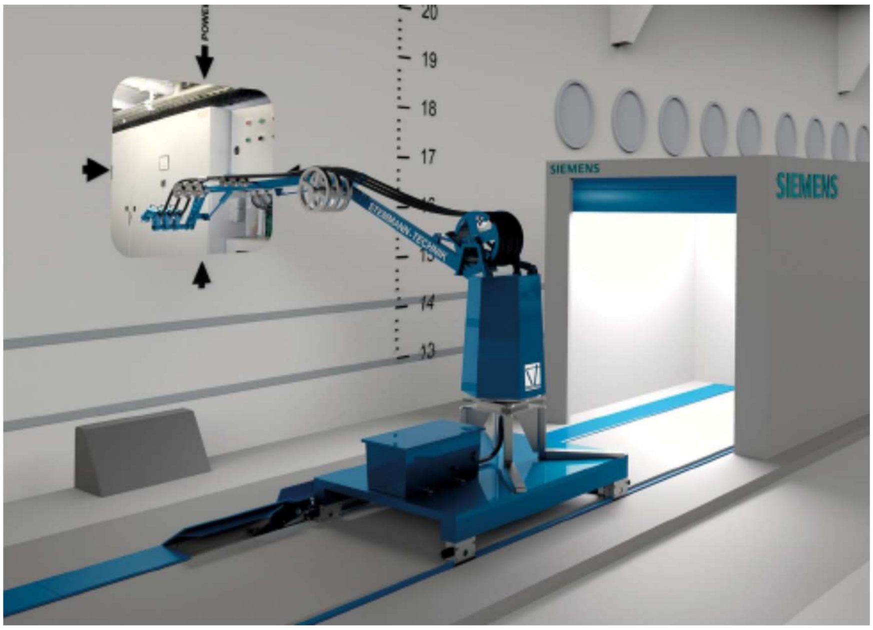

Figure 42: High voltage onshore power connection [Courtesy of Siemens]

A major problem for the use of onshore power supplies in European ports is that most ships operate at frequency of 60 Hz, while the frequency of the European grid is 50 Hz. Passive components such as transformers can't change the frequency, so converters are required. As such frequency converters have become common products for most equipment manufacturers, the challenge lies in the fact that (large) ships require medium-voltage converters with a power rating of several (tens of) MWs, which is far less common than Low-voltage converters. Nevertheless, these converters are already on the market. Commonly a frequency converter station requires a first set of converters to convert the 50 Hz grid power to DC power. Next a second set of converters is connected back-to-back to the first set, and converts the DC power to a 60 Hz power supply for the ships.

The power conversion station can either be set up in a decentralized way, where each ship has a dedicated converter station to supply the ship or in a centralized way where a single station supplies multiple vessels. This lowers the CAPEX as the same equipment can be shared over multiple vessels. Moreover, as the peak consumption of the different vessels is not simultaneously, the total power can be below the sum of the individual ship connections. However, the implementation of the centralized solution (see Figure 43) is more challenging, as the converter station supplies the same phase of the voltage to all connected ships, so the ships voltage (frequency, amplitude and phase) needs to synchronize with the voltage supplied by the converter station.

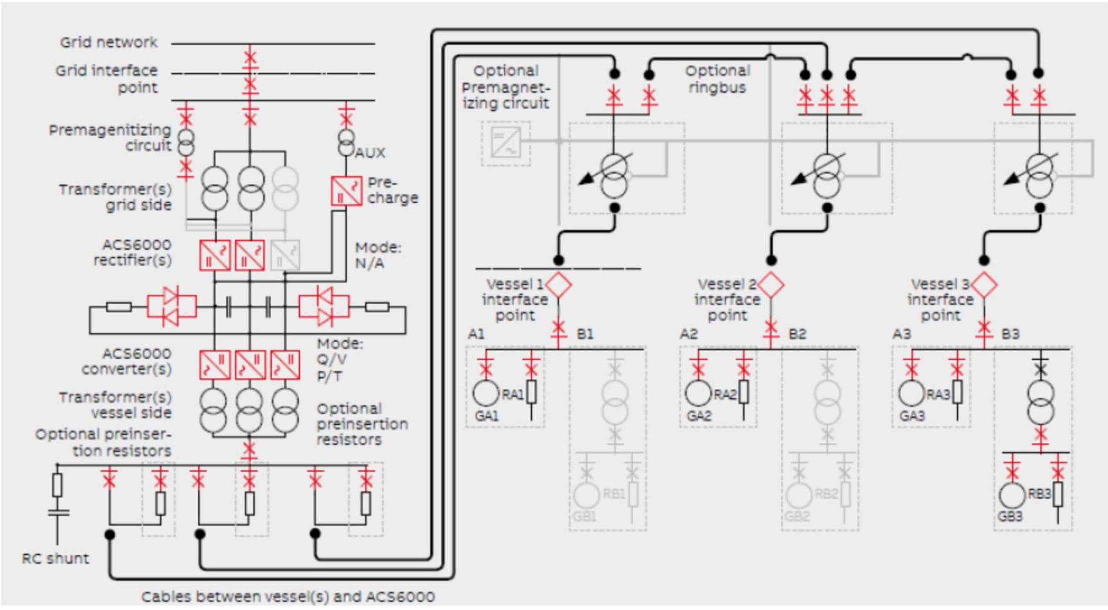

Figure 43: Centralized Converter Station supplies multiple vessels [Courtesy of ABB]

Although the Piraeus Container Terminal receives most of its containers from gigantic ocean-going container ships which carry as much as 20.000 TEU simultaneously, the containers still need distribution to the rest of Europe. A large part of these containers is transported by rail and trucks, but part of the containers is transferred to smaller feeder vessels which have a much smaller capacity, mostly at around 1000 TEU, but up to 3000 TEU. These vessels are much smaller, which enables them to visit smaller ports with less draft. These smaller ports lack the huge quay cranes to unload the 20.000 TEU giants, but are able to unload the smaller ships. These feeder vessels transport reefer containers and thus require electrical power to supply the reefers. However, their total electricity demand is much lower. A typical example is the Astrosprinter feeder, an 800 TEU vessel equipped with 150 reefer slots. The ship is equipped with two (redundant) 760 kVA diesel-generators to supply the reefers in port. In order to provide these feeders with an onshore power supply we estimate that a 500 kW/625 kVA shore power connection is sufficient to provide power to the reefers. These power levels do not require a high-voltage connection, hence the onshore power supply standard was expanded with the *IEC/ISO/IEEE 80005-3, Low Voltage Shore Connection* standard for low voltage connections up to 250 A at various low voltage levels from 400 to 690 V.

In order to model the load demand imposed by the onshore power supplies (OPS) of the ships, we assume that 3 different kinds of loads can be expected;

- Feeder vessels with a gross tonnage at around 10.000 tonnes and 1000 TEU capacity require a 500 kW OPS. The port can accommodate up to 3 vessels simultaneously using low voltage connections.

- NeoPanamax container ships with a gross tonnage at around 140.000 tonnes and 13.000 TEU capacity require a 1500 kW OPS.

- Ultra Large Container Vessel (ULCV) with a gross tonnage at around 200.000 tonnes and 20.000 TEU capacity require a 2300 kW OPS. The port can accommodate 1 NeoPanamax and ULCV simultaneously using a single centralized converter station with 2 high-voltage connections.

These numbers are confirmed in Figure 44.

	Average power output (kW) for different ship types and size (GT) while at berth						
Ship type	< 999	1000-4999	5000-9999	10000-24999	25000-49999	50000-99999	>100000
Oil Tanker	37	161	352	476	646	834	1 032
Chemical Tanker	106	289	531	723	864	1 434	1 536
Gass Tanker	111	254	667	836	1 078	2 816	3 556
Bulk	26	80	132	197	261	350	438
General cargo	12	66	149	259	416	579	704
Container	31	121	332	473	864	1 535	2 295
RORO Cargo	28	94	213	415	529	668	735
Reefer	44	153	319	542	672	800	960
Passenger	20	119	272	570	1 194	2 100	2 912
Offshore Supply	45	144	345	553	912	1 144	1 248
Other offshore	42	149	251	417	575	643	685
Other activity	28	173	344	569	988	1 282	1 600
Fishing	43	149	284	454	454	454	454

Figure 44: Average power per ship [Courtesy: Islands formandskabsprogram 2014]

10.3.2 Load profile of the onshore power supply

First the load profile of the OPS is discussed. In line with the load profile of the electric vehicles, a load profile is constructed where the port is both subjected to normal days with 4 ships being handled and busy days where 8 ships are handled in a single day.

During the normal days 1 NeoPanamax container ship is supplied in the first half of the day while drawing a constant power of 1500 kW. During the second half of the day a single feeder draws 500 kW through its low voltage grid connection. The other two ships are not equipped with OPS. This profile is visible in the first part of Figure 45 and is repeated 4 days per week.

During busy days 2 feeders draw 1000 kW, 500 kW each, through their low voltage grid connection in the first half of the day. In the second half of the day a single ULCV is berthed and draws 2300 kW. This profile is repeated 3 days per week. The entire profile is shown in Figure 45.

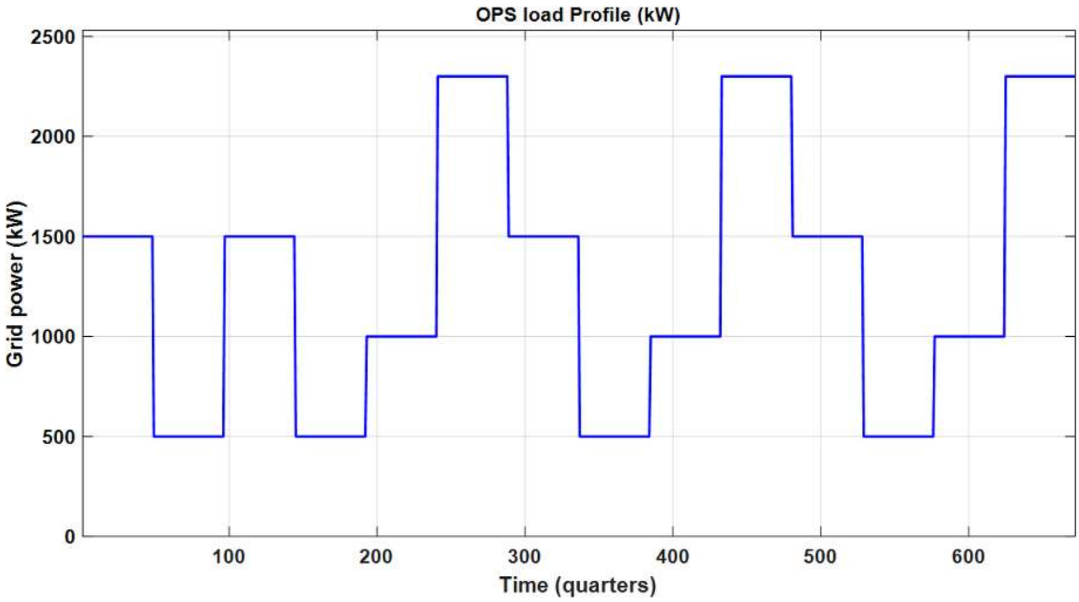

Figure 45: Load profile of Onshore Power Supply.

This load profile poses quite a challenge for the existing infrastructure. The base load increases with 700 kW from 2,4 MW in scenario 2 (PCT with EV) to 3,1 MW in this scenario as the OPS load never drops below 500 kW over an entire year. The OPS also introduces an additional peak load of 2300 kW. In scenario 2 the peak load is 7,2 MW, which is very near the maximum grid power of 7 MW. However, in this scenario the peak load increases to a massive 9,5 MW. As the maximum grid power is limited at 7 MW for PCT, this poses a heavy burden on the battery and its energy management system as the battery needs to maintain sufficient charge to ensure that all excess power above 7 MW can be delivered. It's also clear that the battery is a must-have asset in this scenario as the RES-generation is intermittent and a combination of grid and battery power is required to prevent load shedding.

We have shown in the previous scenario's that a grid connection of 5,7 MW was optimal for scenario 2. The OPS load has an average power of 1,3 MW, hence we can already see that the optimal grid connection power in this scenario will be very near the maximum grid connection power of 7 MW. On average the load demand of scenario 2 was 5 MW, increasing to 6,3 MW in this scenario, so this is the absolute minimum the grid connection power can attain. In practice it becomes increasingly difficult to prevent load shedding when the optimized grid connection approaches the average load demand. This is confirmed by the simulations in which the optimal grid power will always be near the 7 MW maximum, irrespective of the amount of intermittent renewable generation. Keeping this information in mind, it is decided to restrict the OPS load profile to this particular load profile. Adding more shore power can only be met by increasing the grid connection power and would require alterations to the high-voltage grid near the port and a complete overhaul of the substation which connects PCT to the high-voltage grid. This is beyond the scope of the Green Cookbook. Hence, this chapter should be considered as a guideline for the maximum amount of OPS-load which can be provided with the existing grid connection infrastructure.

A last remark concerns the simultaneity between the Electric Vehicle load and the OPS-load. Obviously, the number of vehicles required in the yard depends on the number of containers which are being loaded/unloaded on the ships. Hence the normal and busy days for the EVs and OPS concur. This is also visible in the combined load profile shown in Figure 46. The 800 kW peak load of the fast chargers concurs with the 2300 kW peak load of the ULCV, creating a large 3100 kW peak load that lasts for several hours. This simultaneity puts extra stress on the energy management system and on the ability of the battery storage to provide the peak demand.

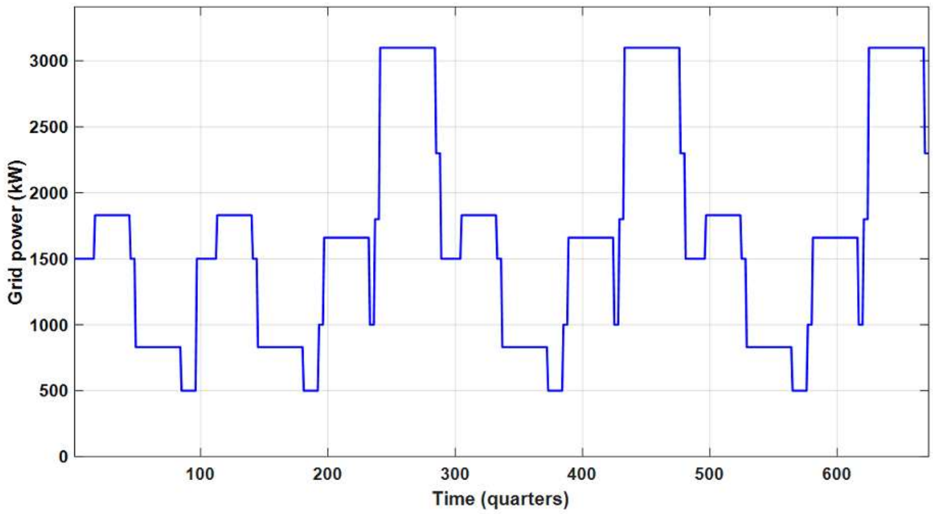

Figure 46: Combined load profile of Electric Vehicles and Onshore Power Supply.

10.3.3 Scenario 3 results with existing RES-generation and battery dimensions

In this first approach for scenario 3 we use the same RES-generation plant as in scenario 2. This allows us to evaluate the impact of the additional load demand on the different results such as self-sufficiency, cost and CO_2-impact if the OPS-service is provided to the ships without alteration of the RES-generation. The RES generation thus remains unaltered at 10 MW PV and 21 MW of wind turbines. The maximum RES-production is 59 GWh (see Figure 47). The load has increased from 44 GWh in scenario 2 to 55 GWh in this scenario as the OPS load is 11,2 GWh. Compared to the previous scenario the battery is slightly increased from a 27 MWh to a 31 MWh net content, bringing the gross content to 43 MWh. The battery is subjected to a maximum discharge power of 7 MW and a maximum charge power of 11 MW, which is a very modest 0,25 C effort for such a large battery. As discussed in the previous section, the grid power increases to 7 MW as the OPS load increases the average power with 1,3 MW.

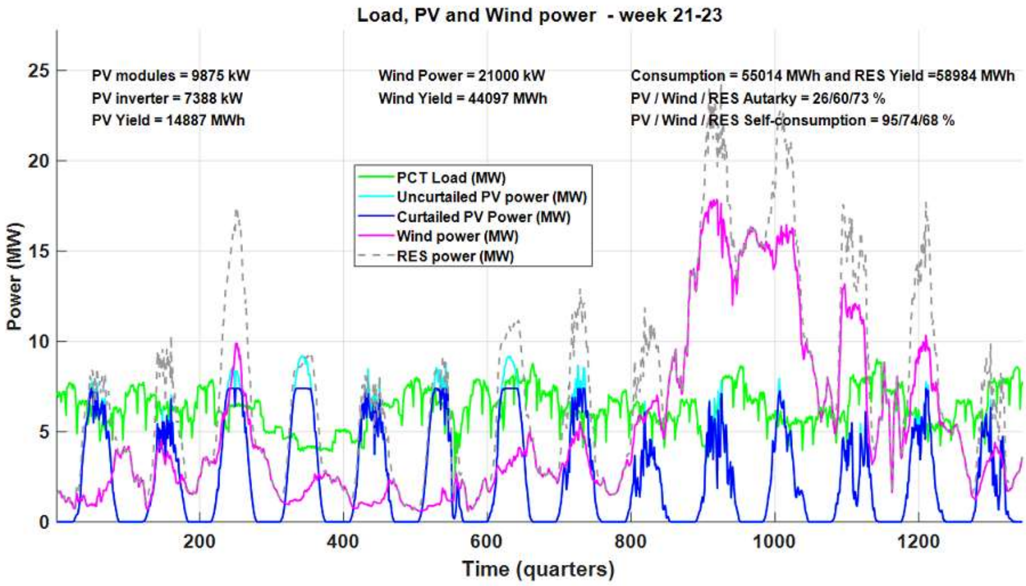

Figure 47: PCT, EV & OPS load, 10 MW PV, 21 MW WT, RES input

As the RES-generation remains the same, the battery only slightly increases and the load demand increases, the electricity cost can be maintained near 57 €/MWh including the renewable generation and batteries. This does not include the cost of the Electric Vehicles and OPS equipment as we are only interested in the electricity production and storage here. With the 31 MWh battery, the self-sufficiency can reach 80%, while 74% of the 59 GWh of generation is consumed within the port. The RES curtailment drops to a very low 2,4 GWh as the effective yield is 56,5 GWh. The electricity import and export of the port are almost at the same level, with an import of 11,1 GWh and 12,6 GWh export (Figure 48). Due to the increase of the load, the electricity import has almost doubled.

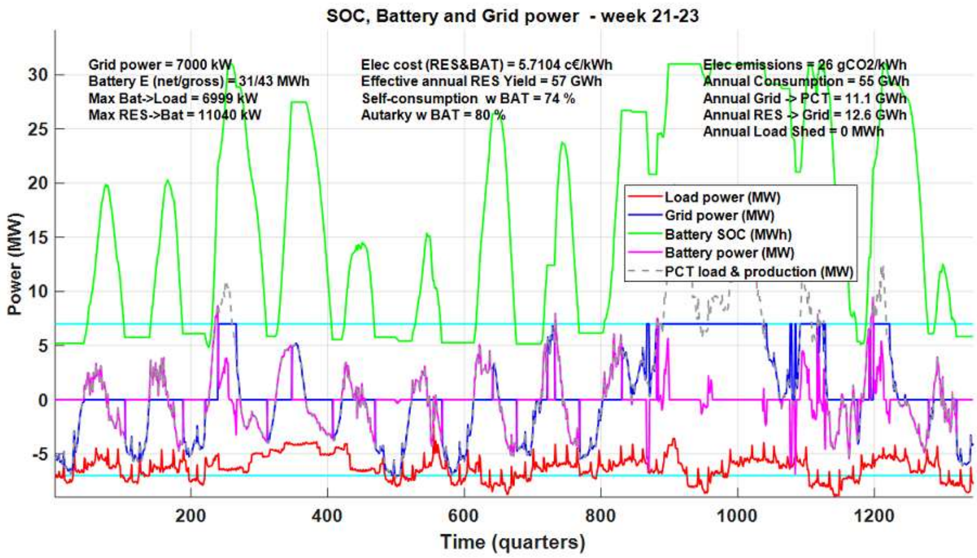

Figure 48: PCT, EV & OPS load, 10 MW PV, 21 MW WT, output

The CO_2-impact of the RES generation, inverters and storage, including the equipment in the vehicles, chargers and OPS inverters, is 26 g CO_2-eq/kWh. This is at the same level as the previous scenario. Although the CO_2-impact of the OPS-converters is substantial at 2,3 MW and although the import of conventional electricity has increased, this had been offset by the lower RES-curtailment. Looking at the total CO2-reduction achieved in this scenario during the 15 year exploitation period, a significant improvement is achieved; While the previous scenario achieves 1015 ktonnes, this scenario allows to increase the reduction with an additional 173 ktonnes to 1188 ktonnes.

10.3.4 Scenario 3 with maximum RES-generation

Although the results of the previous iteration of scenario 3 are very promising, we are unable to achieve the same high-levels of self-sufficiency as scenario 1 and 2 where almost 90% of the load is covered by the renewable generation. A lower self-sufficiency means that more "dirty" electricity needs to be imported from the grid, which limits the achievable CO_2-reduction by replacing diesel fuel in the yard vehicles and power supply of the ships. To this end, the RES-production is gradually increased and evaluated. The results of this evaluation is that the self-sufficiency can be restored to 90% by increasing the number of wind turbines with 5 additional turbines to a total of 12 3 MW turbines (Figure 49). The RES-production thus includes 10 MW of PV and 36 MW of wind turbines, giving a total RES-production of 90,5 GWh. Increasing the RES-production any further is rather futile as the grid-connection power is limited and an increasingly larger portion of renewable production needs to be curtailed. In the configuration with 12 wind turbines, the RES-curtailment is an acceptable 18% of the total RES-production.

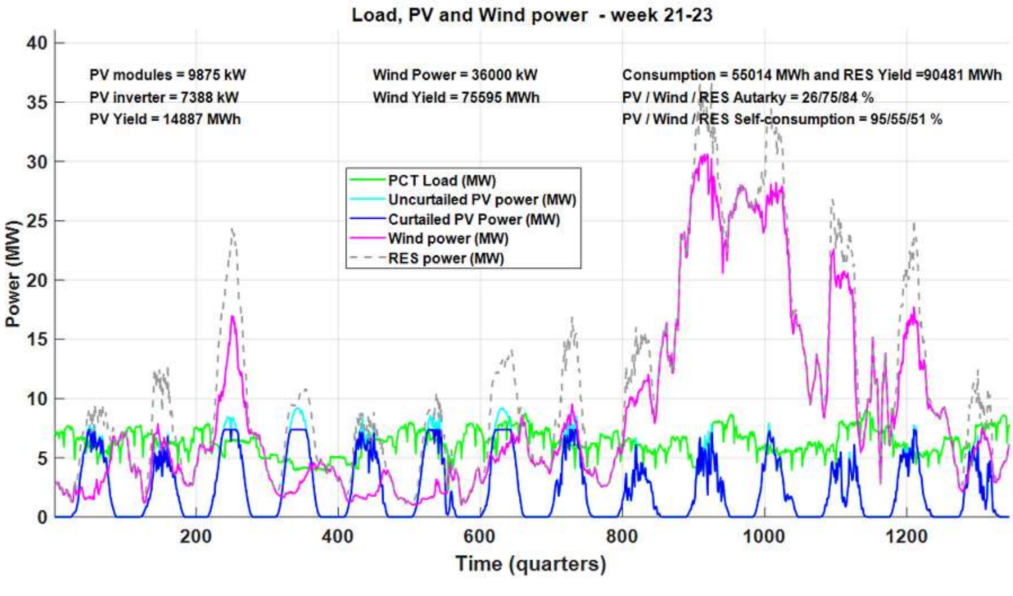

Figure 49: PCT, EV & OPS load, 10 MW PV, 36 MW WT, RES input

The battery decreases 1 MWh both in net and gross energy content compared to the first iteration with 7 wind turbines, so the difference is negligible. The maximum discharge power of the battery remains unaltered at 7 MW, but the charge power increases from 11 to 15 MW. Still, this is mere 0,35 C, so the battery can easily cope with this amount of charge power. The grid power remains at 7MW, but the import has been drastically reduced from 11 GWh to less than half at 5,3 GWh. On the other hand, a lot of excess renewable energy is available as the RES produces 90 GWh, while the load is 55 GWh. This results in the export of almost 25 GWh of renewable electricity to the grid. While the autarky has increased to an impressive 90%, the self-consumption has been drastically reduced. While the self-consumption reached 74 % in the previous iteration, this is now reduced to 55 % as a large part of the renewable electricity is either exported to the grid or curtailed.

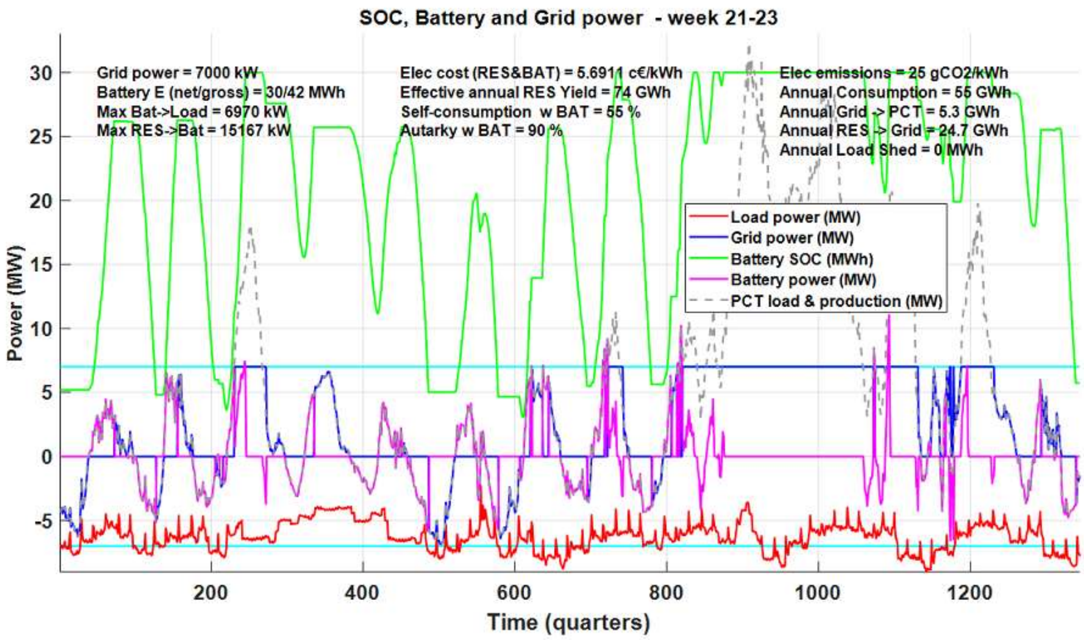

Figure 50: PCT, EV & OPS load, 10 MW PV, 36 MW WT, output

The cost remains near 57 €/MWh including the renewable generation and batteries (Figure 50). The CO_2-impact of the RES generation, inverters and storage, including the equipment in the vehicles, chargers and OPS inverters, has slightly decreased from 26,3 to 24,7 g CO_2-eq/kWh. Looking at the total CO_2-reduction achieved in this final iteration of the third scenario, another significant improvement has been achieved; While the previous iteration achieved a total reduction of 1188 ktonnes, this has been increased to 1524 ktonnes. This is caused by the larger part of the renewable electricity in the electricity consumption, but also in the replacement of diesel fuel for the electric vehicles and onshore power supply.

The conclusion of the third scenario is that both iterations with respectively 7 and 12 wind turbines and a fixed PV-installation of 10 MW are valid solutions for the RES provision. The first solution has the benefit that this amount of RES is valid in all 3 scenarios, ranging from providing renewable energy to the current PCT load, going to the addition of electric yard vehicles and finally to the addition of onshore power supply to the moored ships. Which each additional step the self-sufficiency of the port deteriorates, but even in the final load scenario 80% of the load is covered by the renewable energy. The second solution allows to increase the self-sufficiency of the port and the achieved CO_2-reduction, but obviously requires a higher capital investment as 5 additional wind turbines of 3 MW need to be provided. Hence, both solutions are valid and the choice for each one depends on the priorities of the port.

11. Conclusions

The Green Cookbook creates an energy assessment framework for ports in general and the Piraeus Container Terminal (PCT) in particular. A model has been created which allows to investigate and analyse the impact of renewable energy sources and battery storage on the transition from fossil-fuelled to a more sustainable and local electricity generation. The models aims to maximize the self-consumption of the renewable generation by the local load and maximizes the ability of the local generation to cover the load demand. Simultaneously the model takes the constraints of the grid connection into account, aims to divert the peaks in the RES-generation towards the battery, while the load peaks are covered by discharging the battery. If this not attainable, the RES-production can be curtailed. The model is also able to shed the load if this is required to operate the grid within its limitations. However, this functionality is not used in any of the presented solutions. All of these different objectives can be determined in function of the energy content of the battery and power of the grid connection.

The simulation also determines the cost of the installation comprising the renewable generation, its inverters, the battery and the battery inverters. This allows to calculate the price per kWh of renewable energy (including storage). The results presented in the different scenarios always make sure that the total electricity cost of the renewable solution is on par with the electricity cost in the situation when only grid-power is purchased. To this end the electricity cost of the renewable solution is calculated, including storage, and the purchase cost of the remaining grid power together with the profit made by exporting part of the renewable energy. All of this is compared with the grid-power-only solution to determine the break-even points for the electricity cost in function of the grid power and battery storage.

This allows us to determine the optimal grid power in the first step towards an optimal solution. The optimal grid power is chosen such that load shedding is prevented when a minimal amount of battery storage is available. A minimum amount of storage is always required as the load would otherwise draw more peak power than the grid connection allows. Once the grid power has been determined, the optimal amount of battery storage can be determined. The battery storage is chosen such that the aforementioned break-even in the electricity cost is achieved. Once these factors are known, we can easily determine the attainable levels of self-consumption and self-sufficiency with the chosen battery, as well as RES-curtailment, total cost of the installation and CO_2-reduction potential.

In a first scenario the optimal solution for the current PCT load including the quay and yard cranes, reefer yards and buildings is investigated. The main conclusion that can be drawn from this first scenario is that excess renewable generation offers a lot of benefits without financial penalty. Comparing RES-generation that equals the load demand with RES-generation with 50 % excess generation shows that

- The self-sufficiency of the port can be substantially increased from below 80 to 90 % without increasing the electricity cost

- Excess generation allows the port to become a net-exporter of renewable electricity and as such allows the port to contribute to the national green energy targets instead of being considered as a main contributor to the pollution.

- The peak power drawn by the grid connection can be drastically decreased, e.g. in the example of PCT the peak power is reduced from 6,7 to 5,1 MW. This allows tens of thousands of euros cost savings annually. Much more important is that it allows to increase the load demand in the port without an entire new grid connection for the port.

In the second scenario the entire fleet of diesel fueled yard vehicles, consisting mainly of terminal tractors, but also straddle carriers, reach stackers and other mobile equipment, is replaced with electric driven vehicles. The economic feasibility of the electric drive is discussed, but the required charging infrastructure, its impact on the grid and CO_2-contribution is also taken into account. Several conclusions can be drawn from this scenario;

- The impact of the electric yard vehicles on the power consumption of the port, even when the entire fleet is replaced, is rather limited. This is due to the high efficiency and low consumption of the electric vehicles as they are ideally suited for the stop-and-go and low-speed traffic which can be typically found in ports. The power consumption is only 3,5 GWh, which is only 10% of the PCT consumption. For comparison: The 31 Quay cranes consume 17 GWh or 5 times as much as the 140 yard vehicles.

- As the increase in load demand is limited, the renewable generation can remain the same, hence no extra PV or wind turbines are required. The battery requires a less-than-10% increase in energy content while the power rating of the battery converters remains the same. Surprisingly, two thirds of the required energy for the vehicle charging stems from a better utilisation of the existing generation, with 50 % of the energy coming from previously curtailed energy and 25 % from a better match between load and production. The remaining 25% is covered by importing more energy.

- The grid connection needs to increase from 5,1 to 5,7 MW, but remains well below the maximum power connection of 7 MW. The port remains a 10 GWh net exporter of renewable energy, which is some 17 % of the renewable production.

- This scenario also proves that the per-vehicle-cost of the charging infrastructure is easily overestimated. Although the cost of a single 600 kW fast charger is high, one must take into account that the entire fleet of 140 vehicles only requires some 10 of these chargers in addition of some 60 slow chargers.

Crucially important in this charger configuration is to understand that the vehicles only require some 75-100 kWh per 12h shift and that the addition of a small 100 kWh battery to the fast charger allows it to provide power to several vehicles while limiting the grid connection to some 100 kW.

In the third scenario the impact of Onshore Power Supply is investigated. The economic feasibility of the OPS is omitted as this would require an elaborate study which goes beyond the scope of this work. The technical feasibility is thoroughly explained and makes the distinction between the capital intensive medium voltage multi-megawatt connection for the large container ships and the cheaper low voltage hundreds-of-kW connection for the smaller feeder vessels. It is crucially important to understand that this work has opted to search for the limits of OPS within the existing infrastructure, i.e. the additional load of the OPS needs to be supplied within the existing 7 MW grid connection of the port. OPS as such is already struggling to prove its economic feasibility, an additional investment in the grid connection infrastructure would only add insult to injury. For this purpose, the OPS infrastructure is limited to either a large or ultra large container ship which respectively draws 1,5 or 2,3 MW. Both ships cannot be supplied simultaneously. In between the slots occupied by the large ships 1 to 3 feeders can be supplied at 500 kW. This results in an additional average load of 1,3 MW and is the maximum the port can sustain without grid reinforcements. This is sufficient to supply approximately half of the vessels that visit the port.

Nevertheless, at 11,3 GWh the OPS is a huge load which is only second to the Quay cranes and on par with the reefers in the yard. The grid power inevitably increases to its maximum power near 7 MW. Surprisingly the previously calculated renewable generation of 10 MW PV and 21 MW wind turbines can still provide decent numbers at 80 % self-sufficiency and an additional CO_2-reduction of 20% while the battery requires a 10% increase in gross content compared to the previous case to some 42-43 MWh. The self-consumption increases to an unrivalled 74 %, but the port ceases to be a net exporter of renewable energy.

Adding more renewable energy (from 7 to 12 3 MW wind turbines) can restore the port to 90 % self-sufficiency and a severe net-exporter of green energy to 20 GWh annually. Moreover, this increases the CO_2-reduction compared to the previous case to 50% as the renewable electricity covers more EV and OPS load and offsets large amounts of conventionally generated electricity.

The overall conclusion of this Green Cookbook is that the combination of PV, wind turbines and storage can provide renewable energy to both the existing infrastructure of the port as well as electric yard vehicles and onshore power supply to the ships. A constant in all the investigated scenarios is that self-sufficiency of the port cannot exceed 90% as this would require an excessive amount of battery storage. Clearly, total self-sufficiency of the port can only be attained by the addition of long-term storage in green hydrogen or derivative products such as green ammonia or methanol. Hence, the grid connection remains a vital part of the port infrastructure. Equally important is that this grid connection allows the port to become a net exporter of renewable energy. This can allow a significant change in the social appraisal of the port from a “dirty” industry associated with harmful NOx, SOx and other emissions to an important contributor to sustainable port operations and port environment.