A ROADMAP TOWARDS SMART GRID ENABLED HARBOUR TERMINALS

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ABSTRACT

This paper attempts to apply modern smart grid energy management techniques to a generic harbour terminal setting, so as to explore future potentials of technical, economic, and emission performance improvements. After analysis of major harbour load types, renewable energy sources (RES) and electric storage integration are proposed as the main transition measures to adopt, as they could already generate a sound level of energy and capacity credits under the concurrent electricity tariff system. A scenario-based energy balance analysis is executed to evaluate the effectiveness of proposed configuration under different component dimensions. Cost- and price-sensitivity is also reflected in the study, which is revealed to shed major impact over optimal selection of RES and storage units.

INTRODUCTION

Currently, a number of major European harbours have received EU incentives [1] [7] to introduce novel energy management measures to reduce their carbon footprint of operation. As the majority of harbours around the world are currently relying on a mixture of electricity and diesel fuel [2] to power major machineries onsite, a quite conspicuous solution for drastically reducing a harbour's carbon emission is to supply diesel-powered devices (mainly vehicles and cranes) directly from the power grid [5] [6]—actually, this shift of energy source is already under way in quite a number of harbours.

This increasing trend of total electrification in harbour terminals has of course posed higher requirements on local utility's hosting capability. The variety and unique operational features of terminal loads have both further complicated this task [4], eventually to the point of calling for novel smart grid type of energy management solutions to mitigate technical problems as well as to reduce carbon footprints even further.

To this end, a combination of smart grid technology options such as onsite renewable energy sources (RES), electric storage devices, load shedding / demand response programs, as well as advanced metering and dispatch system has shown inspiring potentials of not only technically achieving such energy management targets, but also economically commercializing relevant business cases.

This paper will be thus focused on the introduction of smart grid technologies to harbour terminals using the following four-step analysis approach: (1) terminal load analysis, (2) smart grid scenario construction, (3) energy balance study, and (4) benefit identification. Following sections will be organized exactly in this order.

TERMINAL LOAD ANALYSIS

According to article [3], two biggest contributors to harbour energy consumption are cranes and reefers. The cranes can be roughly categorized into two major types: ship-to-shore (STS) quay cranes [5] and stacking yard cranes such as rubber tyred gantry (RTG) cranes [6]. In addition, report [1] has also identified office buildings and outdoor lighting as important energy consumers.

In order to facilitate case study, an exemplary medium-size harbour is modelled in this paper with these five load types dimensioned according to Table 1. The total capacity need of 11 MW can be met via a MV grid.

Installed Capacity					
	STS	RTG	Reefer	Office	Lighting
Size	650 kW	220 kW	10 kW	300 kW	200 kW
Number	9	16	100	1	1
Total	5850 kW	3520 kW	1000 kW	300 kW	200 kW
Habor	10870 kW				

Table 1: Installed Capacities of Main Harbour Loads

With the availability of measurement data (same source as report [1] [2]), the 15-min peak demand of the harbour is found to be much smaller than its capacity rating, as can be seen from Table 2. This is mainly caused by short peaks of crane operation (Figure 1 & 2).

Measured Capacity -- 15 min Value					
	STS	RTG	Reefer	Office	Lighting
Peak	509.1 kW	533 kW	376.2 kW	218.1 kW	154.3 kW
Habor	1791 kW				

Table 2: Actual Measurement of 15-min Peak Demands

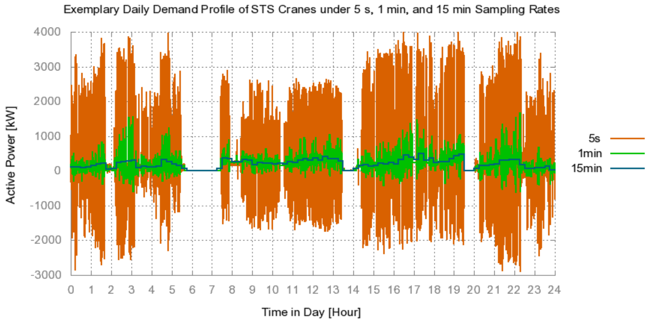

Figure 1: STS Crane Power Demand in a Typical Day

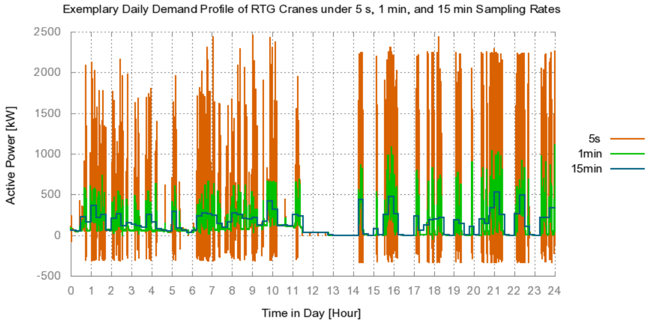

Figure 2: RTG Crane Power Demand in a Typical Day

The frequent positive-negative load spikes in Figure 1 & 2 correspond to crane operation cycles of hoisting up a container (motoring), horizontal travel, and lowering down the container (generating) [3] [1]. Such a cycle normally takes only half a minute to two minutes, thus most utility electricity meters are not able to trace such second-scale peaks with their 15-min average readings.

Reefer load profile in a day is comparatively much more stable, as can be seen from Figure 3. The large quantity of reefer units in a harbour also helps to offset starting power peaks (> 200% of stable working point) of individual reefer units [7].

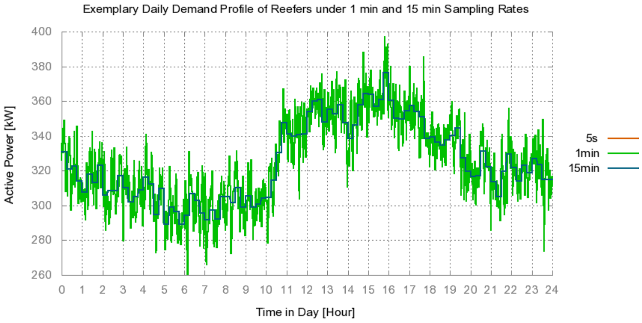

Figure 3: Reefer Power Demand in a Typical Day

Similar to reefer profile, office load profile also follows salient day-night cycles (Figure 4)—according to article [1], office loads in harbour mainly consist of air conditioners, fridges, and UPS units.

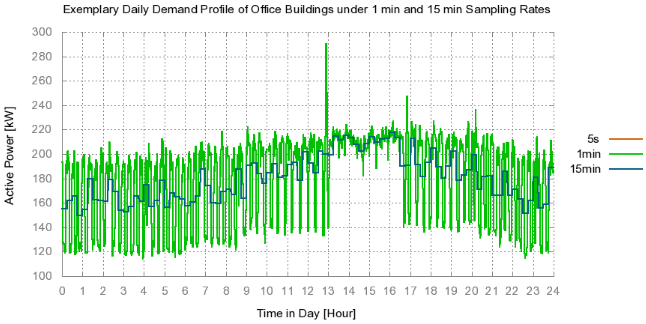

Figure 4: Office Power Demand in a Typical Day

Finally, outdoor lighting load profile is shown in Figure 5—a daily operation cycle between 8pm and 8 am can be easily identified.

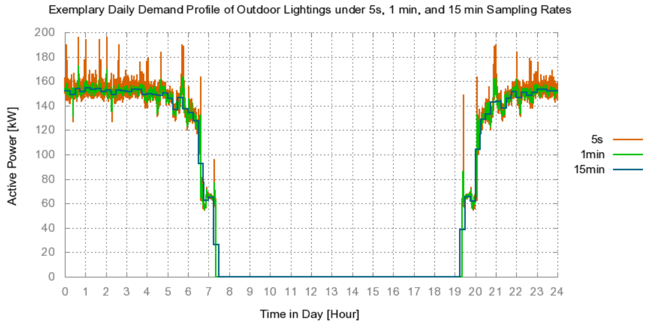

Figure 5: Lighting Power Demand in a Typical Day

Note that these presented daily profiles have been factor adjusted, such that their daily average power demand equals annual average values. In this way, these typical profiles can be used to estimate annual energy demand of the harbour, as shown by Table 3. It can be seen that reefers and cranes respectively consume 34% and 38% of total demand in this case study—of course, in some harbours reefer power consumption can reach up to 60% of total [1] when most cranes are powered by diesel.

Annual Energy Demand					
	STS	RTG	Reefer	Office	Lighting
Demand	1.8 GWh	1.3 GWh	2.8 GWh	1.6 GWh	0.6 GWh
Habor	8.2 GWh				

Table 3: Annual Energy Demands of Harbour Loads

By aggregating all five types of loads together, the total demand profile of the examined harbour can be obtained as Figure 6. The stable 'base load' part of reefer, office, and lighting contrasts sharply with stochastic load peaks from STS and RTG cranes. Figure 6 also reveals that the modelled harbour operates on a 24 h basis with no obvious recession of container traffic during night time.

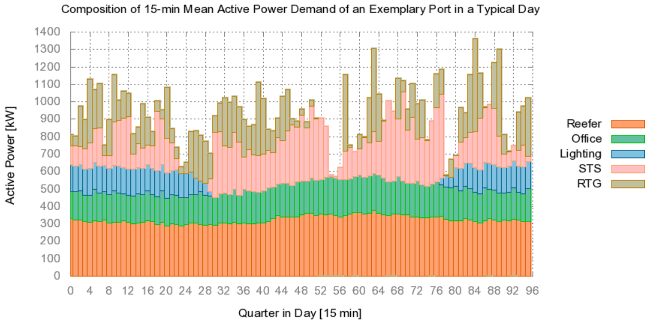

Figure 6: Composition of a Harbour's Load Demand

It should be noted that demand response potentials on 15 min scale are rather limited in this case, as most load peaks are caused by STS and RTG cranes, which can be hardly interrupted by load shedding or load dispatch schemes due to real-time nature of container handling task. Although reefers, air conditioners, and fridges are good candidates for minute-scale peak shaving actions [7], they are too slow for following crane operation peaks, and their contributable capacity pales before the power draw of cranes. Thus peak shaving is considered as a task of electric storage unit only in this paper.

SCENARIO AND METHOD DEFINITION

In scope of this paper, the main objectives of smart grid implementation for a harbour can be described as a two-fold problem: energy consumption reduction and peak power demand reduction. The energy part of target can be reached via installation of onsite RES units, which also helps harbours to reduce carbon footprint; whereas the (peak) power part of goal needs to be met by means of electric storage units.

With consideration of harbour terminal load demand level and physical site limitations (space, natural resource, etc.), two onsite RES options are suggested here as photovoltaic (PV) and wind turbine (WT) generator units, whereas applicable storage technologies are primarily Li-on and flow batteries.

In scope of this paper, a cascaded series of smart grid scenarios (see Figure 7) are proposed based on variations of the following four sensitivity factors:

(1) RES generation configuration

(2) Storage energy & power dimensions

(3) Daily RES output level

(4) Tariff and cost level

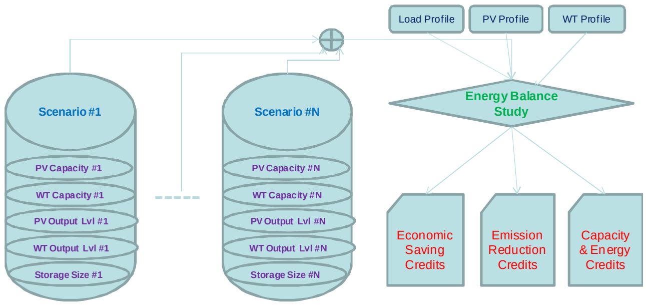

Figure 7: Scenario-Based Simulation Approach

The fourth factor will be introduced later in economic evaluation section as it has no direct interactions with the other three. To start off, scenario definitions for the first two factors are provided here in Table 4.

Gen-Scn	PV-kW	WT-kW	Sto-Scn	kW	kWh
Gen1	0	0	Sto1	0	0
Gen2	0	1000	Sto2	400	400
Gen3	1500	0	Sto3	800	1200
Gen4	1500	1000	Sto4	1600	3200

Table 4: Scenario Definition for RES and Storage Sizes

It can be seen that the RES generation scenarios simply enumerate all viable combinations of PV and WT while trying to maximize the dimensions of both. The storage scenarios, on the other hand, adopt a stepwise approach for increasing both power and energy ratings of the unit. Due to the limited availability of data, energy balance study of the harbour has to be performed on a daily basis—this is exactly why the third sensitivity factor is needed: this factor introduces three levels (High, Mid, and Low) of RES output to account for the stochastic nature of PV and WT generation. Figure 8 shows the impact of this factor on daily PV and WT profiles.

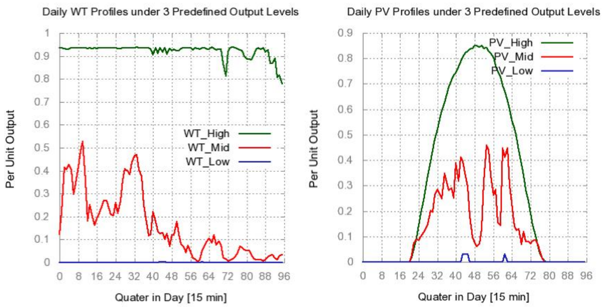

Figure 8: Daily WT and PV Profiles for 3 Output Levels

Now with the availability of input data (load and RES profiles) and scenario definition, energy balance simulations can be performed to examine potential impacts of adopted smart grid technologies on harbour's energy consumption patterns.

Since the only controllable source of active power in this smart grid configuration is the storage unit, an LP-QP based energy balancing algorithm proposed by article [8] will be adopted here to explore full potentials of peak load shaving under a harbour context. Note that the algorithm assumes perfect load forecast is available beforehand; therefore the peak shaving credits obtained in this fashion should be viewed as best-case results.

ENERGY BALANCING RESULTS

In this section, the effects of RES adoption and storage dispatch on the 15 min consumption profile of examined harbour will be graphically illustrated for selected scenarios.

Firstly, the adjusted harbour demand profiles with no RES installation (Gen1) are shown in Figure 9 for different storage sizes. Obviously, the smallest storage size proposal (400 kW / 400 kWh) could already achieve about 293 kW of peak reduction credit. Further increase of storage size to 800 kW / 1200 kWh could extend this credit to about 393 kW, although arguably this improvement is too small for the extra investments.

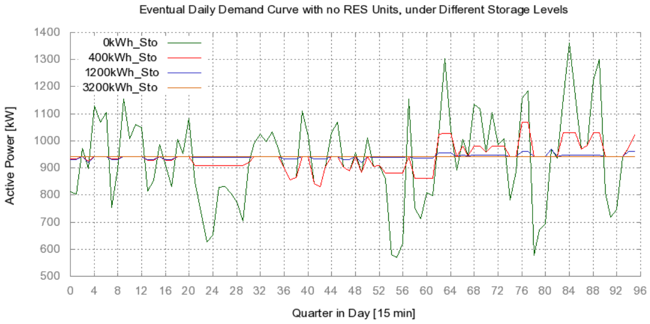

Figure 9: Adjusted Harbour Load Demand with no RES

In Figure 10, the adjusted harbour demand profiles with 1 MW WT installation (Gen2) is shown for Mid-Output case under different storage sizes. Now the 400 kW / 400 kWh storage size brings about approximately 229 kW of peak reduction credit; while further improvement of this index to 345 kW calls for ultimate storage size of 1600 kW / 3200 kWh.

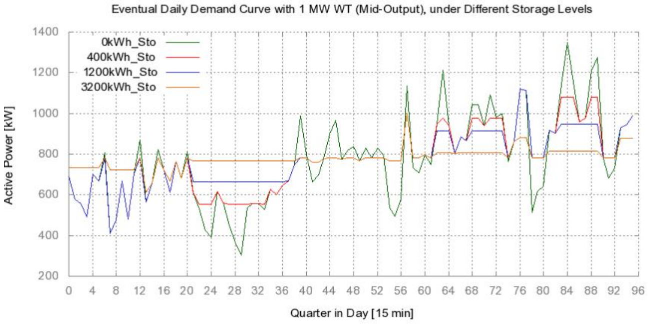

Figure 10: Adjusted Harbour Load Demand with WT

Similarly, Figure 11 shows the adjusted harbour demand profiles with 1.5 MW PV units (Gen3) for Mid-Output case under different storage sizes. Peak reduction credit under 400 kW / 400 kWh stays close to WT case at around 233 kW; whereas maximum storage capacity of 1600 kW / 3200 kWh now leads to 552 kW of peak reduction, a clear sign of performance improvement.

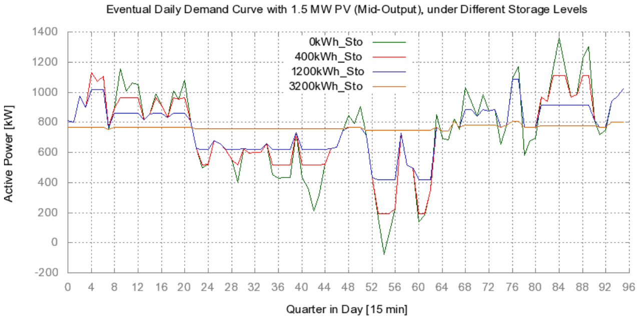

Figure 11: Adjusted Harbour Load Demand with PV

Finally, the peak shaving performance of storage unit under PV-WT hybrid condition (Gen4) for Mid-Output case is close to that of PV only scenario—400 kW / 400 kWh and 1600 kW / 3200 kWh capacities now respectively lead to 240 kW and 529 kW credits, as shown by Figure 12.

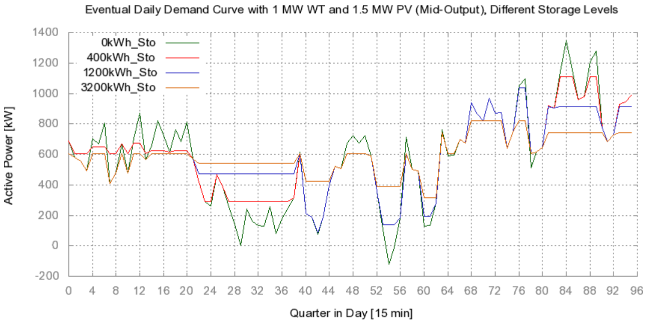

Figure 12: Adjusted Harbour Load with WT & PV (1)

Attention should also be paid to the High-Output situations, where maximum demand is normally not an issue anymore, but minimum demand (export to grid) can become too large to handle, as illustrated by Figure 13 (Gen4 scenario). Here the energy balancing algorithm also deploys storage to offset export peaks.

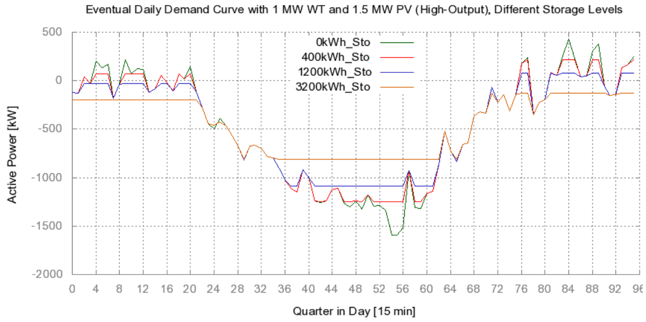

Figure 13: Adjusted Harbour Load with WT & PV (2)

As a summary, the installation of RES units in general reduces the potential peak shaving credits of smaller storage units; but larger storage units might benefit from PV presence instead.

Finally, Figure 14 gives an exemplary breakdown view of energy supply under Gen4 (PV plus WT) and Sto 2 (400 kW / 400 kWh) situation.

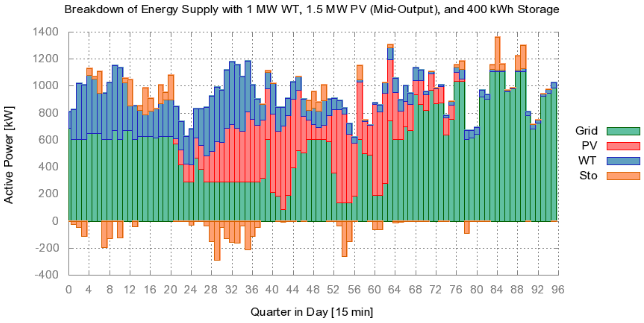

Figure 14: Energy Supply Breakdown with WT & PV

ECONOMICS AND EMISSION ANALYSIS

This section aims to explore the economic effectiveness and emission reduction credits of proposed smart grid technologies. For this purpose, a proper benchmarking framework needs to be established in the first place—namely, a pessimistic, a medium, and an optimistic tariff and cost scenario are modelled here as the fourth sensitivity factor, which is illustrated by Table 5.

Price-S	Grid	Grid	Storage	PV	WT
	€/kW*a	€/kWh	€/kWh	€/kW	€/kW
Pessimistic	70	0.07	900	4000	2500
Medium	90	0.1	600	3200	1800
Optimistic	110	0.13	400	2500	1200

Table 5: Scenario Definition for Tariffs and Costs

In this study, network tariff consists of a demand charge (€/kW*a) part and an energy charge (€/kWh) part; while RES and storage costs are respectively simplified into per-kW and per-kWh indices. The application of these three economic scenarios to proposed RES and storage configurations leads to results shown by Table 6.

Scenario	Pessimistic Costs		Medium Costs		Optimistic Costs	
	Gain/Loss	Mio €	Gain/Loss	Mio €	Gain/Loss	Mio €
	Power	Energy	Power	Energy	Power	Energy
Gen1Sto1	0	0	0	0	0	0
Gen1Sto2	-0.100	0	0.095	0	0.249	0
Gen1Sto3	-0.714	0	-0.250	0	0.095	0
Gen1Sto4	-2.514	0	-1.450	0	-0.705	0
Gen2Sto1	0	-2.644	0	0.337	0	0.518
Gen2Sto2	-0.149	-2.644	0.031	0.337	0.171	0.518
Gen2Sto3	-0.869	-2.644	-0.449	0.337	-0.149	0.518
Gen2Sto4	-2.568	-2.644	-1.519	0.337	-0.790	0.518
Gen3Sto1	0	0.082	0	1.146	0	2.060
Gen3Sto2	-0.159	0.082	0.019	1.146	0.157	2.060
Gen3Sto3	-0.840	0.082	-0.412	1.146	-0.103	2.060
Gen3Sto4	-2.513	0.082	-1.448	1.146	-0.703	2.060
Gen4Sto1	0	-2.562	0	1.483	0	2.577
Gen4Sto2	-0.139	-2.562	0.044	1.483	0.187	2.577
Gen4Sto3	-0.796	-2.562	-0.355	1.483	-0.034	2.577
Gen4Sto4	-2.513	-2.562	-1.448	1.483	-0.703	2.577

Table 6: Results of Economics Evaluation

In Table 6, power part of cost and revenue respectively correspond to storage integration and saved demand charges; and energy part of cost and revenue are in turn caused by RES installation and saved energy charges. And an NPV factor of 12.5 is taken for 20 years' period. Study results indicate that WT is economically efficient under all three cost levels; PV and storage becomes viable under medium & optimistic scenarios. Since medium scenario is closest to reality, the configuration of Gen4 (1.5 MW PV and 1 MW WT) and Sto2 (400 kW / 400 kWh) is proposed as final solution, for which a cost/revenue breakdown is shown by Figure 15.

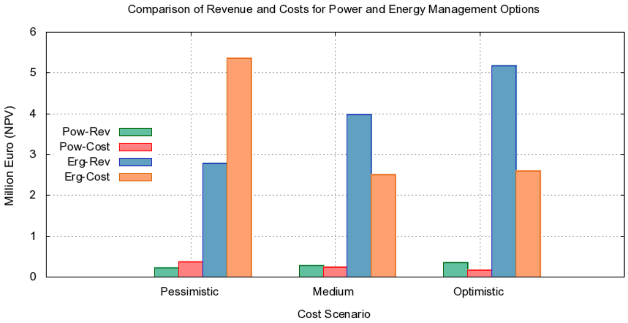

Figure 15: Revenues and Costs Comparison

Emission saving in this study is primarily associated with RES contribution, as can be seen from Figure 16. Obviously, the proposed Gen4 configuration could potentially reduce carbon footprint of a fully electrified harbour by almost 40% (counting also exported energy).

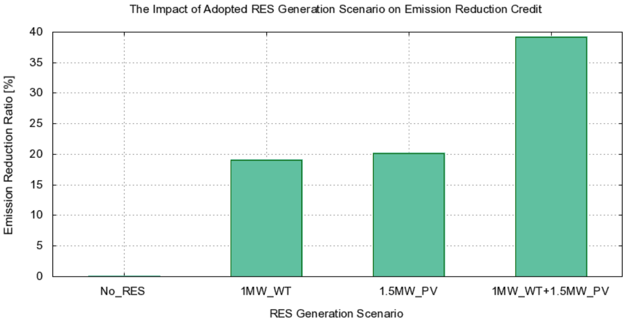

Figure 16: Emission Reduction Credits Comparison

CONCLUSIONS

This paper has showcased the potentials of smart grid technology introduction to a fully electrified harbour. Positive business cases are obtained for a hybrid WT-PV-storage installation, which simultaneously helps the harbour owner reduce his demand and energy charges on top of reduced carbon emission level.

The future opportunities of smart grid implementation in harbour, however, are not limited to RES and storage integration case presented in this paper. As more ships are given the possibility of being electrified from the shore while berthed, and more transportation vehicles in harbour are driven by electricity, more demand response and active control options will be available as well.

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