Long-term Influence of the Gradual Naval Fleets Decarbonization on the Flexibility of an Integrated Energy System

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ABSTRACT

To achieve the transition towards net-zero carbon economy and transport, reducing the emissions of greenhouse gases and improving the quality of life in the coastal areas, decarbonization of various naval fleets will be essential. In this research, gradual decarbonization, using different hybrid, electric and hydrogen technologies for decarbonization of fleets engaged in activities such as fishery, passenger transport and transport of goods near the coast is investigated and modelled in connection to the power systems' configuration. The energy system analysis and simulations are carried out in H2RES, a linear energy systems' configuration optimization software. It considers capacity expansion, decommission and unit commitment in the sectors of power generation, heating, industry, and transport. In this particular case, transport sector module is expanded to provide realistic modelling of different naval fleets' energy consumption, on the example of fishery fleet. This is performed through the inclusion of learning curves of different technologies that are expected in the naval transport, to replace the old internal combustion engine power drives and the demand curves that characterize the fishery fleet. Results include the changes in the variable renewable energy integration in the sectors of energy demand, general and bottom-up assessments of economic benefits and emissions reduction. Results demonstrate that the presented approach can offer better insights into the changes that are needed in an energy system based on renewable energy sources, in case of detailed modelling of the energy needs emphasized by a fishery fleet and different dynamics of its decarbonization. Through internalization of all costs, the resulting system also achieves better economic results as a whole and from the bottom-up perspective.

Keywords: Naval transport decarbonization; Long-term energy planning; H2RES; Detailed decarbonization pathways; Variable renewable energy integration.

1. INTRODUCTION

Decarbonization of different sectors of energy demand is a process necessary to achieve an integrated, smart energy system with zero greenhouse gas emissions. This process includes electrification in sectors such as passenger and freight transport on land and sea. Literature is currently rich with research on the topic of road transport electrification and the interaction between this sector of demand and the power system. For example, in [1], the interconnection of 100% renewable energy and transport systems is emphasized. For the increase of variable renewable energy sources (VRES) integration, such a synergy is very influential and allows for faster VRES build-up and increased economically feasible uptake in shorter time period, as discussed in [2] for the vehicle-to-grid concept (V2G). In the insular and coastal context, local energy planning can rely heavily on electrified road transport, which is shown in [3] and [4], respectively for the interconnected archipelago. Also, V2G has been recognized in numerous studies as a promising flexibility option. Utilizing responsive loads, effective thermal unit ramp management, and optimizing the discharge of plug-in electric vehicles (PEVs) contribute to the swift restoration of the power grid. The resolution of the integrated power and reserve scheduling challenge has been addressed through the application of mixed-integer linear programming (MILP) methodology in [5]. This flexibility option is also a feat in the industrial zone operations [6]. Even the possibilities to handle planned outages on the day-ahead level for plug-in EV's parking lots are being developed [7]. A large body of research concerns V2G operation of road vehicles in microgrids [8].

For maritime transport, the research focus has been on the fuel switch that would enable emissions reduction in naval transport. In [9], Ridjan et al. discuss the use of synthetic fuels in the transport sector, including naval transport. Also, expanding on the smart island concept, [10] proposes a method of using locally produced renewable energy for fuelling the ferry lines between the islands. A more detailed review of the alternative fuels for large vessels in naval transport was performed both in [11] (focusing on the terminology and cost competitiveness) and in [12], which focused on the techno-economic analysis of different alternative propulsion systems for larger ships.

Efforts are underway globally to electrify fishing fleets, aiming to achieve significant emission reductions by shifting from traditional fossil fuel to hybrid and electric propulsion systems. Yet, the widespread electrification of these vessels necessitates a transformative and sustainable shift, entailing the establishment of secure and dependable battery-charging infrastructure along coastlines [13].

A significant review of 100% renewable energy scenarios on islands didn't mention the electrification of the fishing fleet as an option [14], neither was this the case in [15]. Also, the V2G operation of the electrified naval fleet was not mentioned in the recent report on the fishing fleet electrification [16].

To model such systems, very often the EnergyPLAN simulation model [17] was used on a national level [18], [19]. Very interesting research featuring this energy planning tool based on the simulation approach in recent years used the case of Aaland Island, where V2G was assumed to include the fishing fleet and other waterborne vessels [20]. This was also the case with [21], which targeted isolated island systems. However, to prove the relevance of specific vehicle fleets, an approach with unit commitment would be more appropriate, while including the whole spread of technologies on the national system level. Such an approach is offered through using Dispa-SET, for example in the case of Western Balkans [22]. But also, to follow the long-term development of the system's configuration through the years of changes in the number of electrified vessels, H2RES model is ultimately chosen, as being able to follow both issues, unit dispatch [23] and long-term investments [24].

In the seafood product value chain, fishing vessels use the most energy and generate the highest levels of hazardous gases, and the fossil fuel usage of 40 billion litres resulted in 179 million tons of CO_2-eq emissions [25]. The Paris Agreement [26], in effect since November 2016, sets policies to limit global warming to 1.5°C or below 2°C from pre-industrial levels. The Glasgow Climate Pact [27], adopted in 2021, builds on this, enhancing mitigation, increasing climate finance, recognizing climate impacts and other climate acts by 2030. A key focus is on phasing out coal and fossil fuel subsidies, demonstrating a collective effort to accelerate the transition to a more sustainable and climate-resilient future. Relating this to fisheries, sustainable practices align with the broader goals of these agreements [28]. Although fishing vessels are significantly smaller compared to the cargo and passenger fleet, the predominant use of fossil fuels has a significant impact on emissions of harmful gases [29]. The International Maritime Organization (IMO) has taken significant steps to reduce the environmental impact of maritime operations and accidents, however, these measures are currently mostly intended for ships of 400 GT or above, which excludes fishing vessels [30]. The fishing sector is better regulated due to the Common Fisheries Policy and the European Maritime, Fisheries and Aquaculture Fund (EMFAF). The Common Fisheries Policy (CFP) [31] provides regulations for the fisheries industry, but the measures are more focused on the restoration of fish stocks, landing requirements, enhancing economic performance, etc. Hayton conducted a case study for an inland waterway tugboat and showed a 62% reduction in fuel consumption by implementing electric propulsion [32]. However, electrification in the fishing sector, as described in [33], showed a 40.2% reduction in carbon footprint with extremely high costs, making it unfavourable for implementation. The duration of fishing trips that can last over 10 hours and thus require batteries of large capacity, and the price of electricity influenced by the electricity mix consisting of low shares of RES affects the overall system costs and makes this type of investments unviable. For this reason, the present research aims to model the influence of electrification of fishing fleets in the context of the energy system in the transition towards systems based 100% on VRES, using the long-term energy planning approach, that includes unit dispatch on the hourly level (studying the influence on the VRES integration) and dynamics of the fleet electrification in the overall optimization target towards zero-emissions system.

Previous models that addressed the electrification of the fishing fleet [21] and its possible use in the V2G concept [20] used the one-point, simulation approach based on an hourly analysis of one year of the system operation. The novel approach presented in this research brings important steps forward, as it represents a long-term energy system’s configuration optimization model:

- Modelling of the fishery fleet is done in a more detailed way as compared to the previously published works;
- Unit dispatch of the energy system is analyzed, especially for flexibility options.
- Dynamics of electrification of the fishery fleet with additions of the new units as well as the corresponding shares of different types of units in the demand are analyzed.
- Dynamics of charging, discharging and state of charge of the batteries of the fishery fleet through the designated time framework is analyzed.

It is hypothesized that certain nautical fleets, such as fishing fleets, are not performing their primary function in the wintertime, which enables them to stay connected to the grid (in the port or dock) and provide auxiliary services or balancing services to the power grid. Further on, the presented method represents a step further compared to the simulation approaches that include only one year in the consideration, since in the presented way, it is possible to follow the increase in the size of electrified fishery fleet together with the developments of other flexibility options in the national energy system and ensure that such electrification is performed using the energy from VRES.

2. METHODS

To model a national energy system and in particular the effect of the electrification of the sectors of demand, H2RES model is used. The H2RES model considers the planning of an energy system in short-to-long horizons, with capacity additions optimized for each of the technologies, including variable renewable and Power-to-X technologies. Additionally, the model considers hourly scale resolutions for energy dispatch (unlike models that use simpler time slices within a time period) [24].

The model considers the sectors of power generation, heating both in district heating and in individual systems, industry, transport, and transformations, expanded with naval fleet capable of providing flexibility services. A flexibility option for the energy system, relevant for this research in H2RES, is provided by electric storage, either through electric vehicles (EVs) or stationary storage. For the case of EVs, H2RES considers that EVs can act as variable storage (depending on driving profiles given to H2RES) and provide vehicle-to-grid (V2G) services. In the case, that the charging requirements for the fleet are implemented as an exogenous demand, the model will have to adapt to that case which may be challenging due to the variability of the generation. In the opposite case, with flexibility in mind, the model is presented with the demand for travel of the fishing fleet and the availability for charging. In this case, the model itself determines when and at which power level to charge the batteries. Therefore, this technology is then able to provide balancing services to the energy system itself. The modelling of the technical characteristics that determine the available battery capacity and charging or discharging power is similar to the approach in the EnergyPLAN model [34] and Internal Combustion Engine (ICE) vehicles. Also, the H2RES model was recently verified by comparison with the renowned commercial tool PLEXOS [23], and tested in demand response and reserve modelling for small island communities [35].

H2RES has an installed “legacy” number of different types of vehicles that are eventually decommissioned. Furthermore, as decommission happens, along with RES and CO_2 level constraints, H2RES optimizes the investment of EV and FCEV (number of vehicles needed) in order to satisfy a predefined transport demand. The investments into EV and FCEV are constrained by the limitations on the sale of new vehicles, their investment price, and restrictions on emissions. The same logic is applied to the naval fleets, taking into account electrical vessels. To include the naval fleet, the specific behaviour and periods of performing the primary role are taken into account. This behaviour needs to be modelled according to each fleet that is added to the model and can be specific. Critical information include:

- Availability of the vessels in connection to the power system and specific installed power of electrical chargers;
- Vessels own consumption of energy;
- Size of batteries on the typical vessel;
- Number of vessels and dynamics of the electrification of the considered fleet.

Depending on the type of fleet the operative characteristics differ significantly (Supplementary Material 1). This can best be seen from the route itself, from container vessels that have specific long-distance routes to passenger vessels and inland waterway vessels where these routes are also determined, but significantly shorter. This has a direct impact on fuel consumption, but differences can also be seen in technical features (design, construction, capacity,...). Fishing vessels, although they are more similar in size to the passenger fleet than to the container, usually have much longer routes than the passenger fleet. However, in calculations, the length of the route is not a problem, but its variability, both in terms of location and duration, brings difficulties in assessments. Precisely, because of these differences, the naval fleet cannot be viewed in a generalized way and mathematical models must be adapted to their specific characteristics. The data above is used to model the fleet in H2RES and subsequently, the results of the optimization are compared to the model without the inclusion of such fleet. The version of the H2RES model used for this research has among other demands, defined the demand in the sector of short-distance maritime transport. This demand is presented to the model in the hourly useful energy demand terms. Therefore, the demand is the same for internal combustion, electric or hydrogen fuel cell electric propulsion technologies. The only difference is in efficiency level which dictates the primary energy demand. The model used the multiplication factors of 1,1 for electric propulsion, 2,3 for internal combustion and 1,5 for hydrogen fuel cells. These numbers are presented as the ratio of energy per travelled distance. Therefore, its units are kWh/km. The numbers for the efficiency of internal combustion engine-powered vessels were generated based on the data obtained on the travelled distance of the short distance maritime transport obtained through the Croatian Bureau of Statistics [38] and the energy demand obtained through the statistical report Energy in Croatia [39].

Another determining factor is the definition of time when the vessels are at sea or are docked in the harbours. When docked in harbours, it is estimated that the vessels have the possibility to connect to the ground power network and therefore charge its batteries or send the electricity back to the grid if V2G is used.

3. CASE STUDY

The H2RES model is applied to the Croatian energy system (described in detail in [24]) to comprehend the role of flexibility options in the decarbonization of the power, industry, heat and transport sectors. This time, particular attention is given to the naval sector, and concretely the fishery fleet. The Croatian fishing fleet consists of 7,808 vessels, with a share of 20% inactive vessels, and it is responsible for 5,74% of the total catch in the Mediterranean area [40]. Purse seiners make up about 5% of the total fishing fleet but present the backbone of Croatian fisheries with over 90% of landing weight and almost 55% of landing value [41].

Fishing operation primarily refers to the process of catching fish and includes production elements such as fishing vessels, fishing equipment, fishers, and consumables. Therefore, the vessels are classified by the fishing operation as purse seiners, trawlers, gillnetters, longliners etc. Depending on the fishing method employed, vessel design considerations vary, balancing factors such as engine power, manoeuvrability, and endurance [42]. The fishing process is carried out using all those inputs, and the outputs are landed catch and profit [40]. Depending on the targeted species, habitat, and knowledge of the fishers, several types of fishing gear and vessels may be employed during the catching process. All of the mentioned inputs have a significant impact on the overall energy system of a vessel. For instance, fuel expenditures for a trawler account for 40–50% of overall annual costs, whereas for tuna purse seiners, this percentage rises to 70%. The same differences are found in fuel consumption – purse seining tuna consumes 1500 l per tonne of land fish, while trawling cod consumes approximately 530 l per tonne of land fish [41]. Purse seiners are typically utilized for capturing schooling fish such as tuna, mackerel, and herring. In contrast, trawlers have the flexibility to operate in both shallow and deep waters, enabling them to catch a diverse range of fish depending on the location and season. It's worth noting that the catch from trawlers has a greater market value compared to small pelagic species caught by purse seiners [43]. Taking into account that there are significant differences between the types of fishing vessels, which affect the operational regimes, in this paper only one type of fishing vessel is chosen as a representative model.

The fishery fleets' behaviour while performing the primary role of fishing is considered in order to model its demand and availability. The general presentation of an operational regime of a purse seiner is represented in Figure 1. The operational regime is additionally supported by data obtained by direct monitoring of fuel consumption on a purse seiner. The data is displayed in the "MAPON" software, which provides information about routes, fuel consumption, speed, etc. and a representation of the workgraph is given in Supplementary Material 5.

Further on, to define the availability of the fishing fleet, the periods in a year when the trips can be performed are defined as follows:

- Fishing forbidden – from 1.1.2023. till 28.2.2023.
- Spring – 1.3.2023. till 30.4.2023.
- Summer – 1.6.2023. till 31.8.2023.
- Autumn – 1.9.2023. till 31.10.2023.
- Winter – 1.11.2023. till 25.12.2023.

Having in mind the legally mandated fishing ban and co-financed suspension of fishing activities to facilitate the restoration of fish stocks (maximum of 20 days per month of activity) [21], the schedule for the shipping activity is determined. This in turn dictates when the fleets are inactive as well. When they are inactive, they are considered to be available for the charging/discharging of the batteries. The distribution of availability of the fishing fleets is represented in Figure 2a. The availability takes into account several issues, such as refurbishment of the fleet during the period when fishing is forbidden, different availability throughout the week due to fishing trips, and the fact that not all of the ships are on the trip at the same time [45].

The remaining data for the fleet is provided in the Table 1.

Table 1 Specific data for the fleet

Specific data for the fleet and trips		
Summer trip el. consumption (specific)	23,509	kWh
Winter trip el. consumption (specific)	23,013	kWh
Number of vessels:	4096	
Average yearly rate of replacement:	3,33%	yearly
Average battery capacity estimate:	40	kWh
Charger capacity:	7	kW

Using the data for a purse seiner in the five previous years (2015-2019), the average electricity consumption of a ship per year was calculated to be 3892,47 kWh for 70 fishing trips. With the yearly replacement rate (replacing diesel ships with electrical ones), the calculation of the influence of this particular fleet on the national energy system is calculated until the year 2050. Average vessel lifetime of 30 years is assumed, meaning that the entire fleet will be replaced by 2050.

From the data on availability and cumulative demand, the distribution of energy demand was calculated. The distribution is the negative of the availability dataset. Its values match the demand for energy in useful energy terms at corresponding hours. The distribution is displayed in Figure 2b.

4. RESULTS

Results of the implementation of the new technologies in the short-distance shipping (fishing) sector are presented in Figure 3a. Precisely, the figure shows the shares of each type of fleet in the final demand which is the travelled distance. As can be observed, the model starts in 2025 by slowly increasing the share of battery electric vessels. The increase is the highest between 2025 and 2030. It results in more than 60 % of the trips being carried over by the battery electric vessels in 2030. After 2030, the shift starts to slow down as the model is balancing out between the necessity to satisfy the emissions constraints and wants to reduce the total investment cost by waiting for the price to drop as well as to make use of the entire lifespan of the portion of existing units. Nevertheless, battery electric vessels take over all of the demand by 2045. The results on the investments show that the model invested only in electric vessels. The total investments are displayed in Figure 3b (unit equals one vessel). When compared with the plot for travelled distance, it is important to observe that the investment in 2030 is smaller than the one in 2035, but it had a much greater impact on the share of technology option. This is because, in the model, it is allowed to increase the size of the fleet by up to 50 % while maintaining the same energy demands. This allowed the model to more efficiently utilize the vessels that were acquired in 2030 since they had a bigger replacement potential for ICE vessels than the ones in 2035. Therefore, it chose to use only parts of the fleet to accomplish the tasks. Charging of the vessels is performed in accordance with the exogenously defined demand cycles. For example, when the demand is low as in periods from 0 to 1300, the charging periods are infrequent, but they significantly increase in frequency during high-demand periods. The total charging power reaches a maximum of 25 MW and therefore does not significantly affect the national energy system but has the potential to affect local parts of the system in the coastal areas, especially if the distribution lines are of insufficient capacity. Charging distributions for the 2025, 2035 and 2050 are displayed in the Figures 4 and 5. Supplementary Material’s figures 2-4 display the results for year 2030, 2040 and 2045. The data is divided into 4 segments that correspond to the year quarters. Therefore, to Q1 corresponds January, February, and March. To Q2, April, May, and June. To Q3 July August and September. Q4 consists of October, November, and December. The figure also displays the share of renewable electricity in power generation at the time of vehicle charging for the hours in each month. As can be observed, in the majority of cases, the electricity that is used for charging the vessels’ batteries is close to 100% renewable or with a high share of renewable energy. The months included in Quarter 1 are characterised by a lack of sunlight. In this period, wind generation prevails, sometimes even generating overproduction, and at these hours, the system prefers charging in order to utilize the available energy. Due to the seasonality of the fishing, in this period, there is no big energy demand for the vessels itself. Most of the charging in this period is performed as a grid balancing service instead. In Q2, there is a mix of active periods when the energy is required and the periods when the fleets are inactive. When the fleets are inactive, the model uses their batteries very frequently as a flexibility source in the system, but it uses only a small portion of the batteries. In the periods when the fleets are active and therefore at the reduced availability for charging, the charging is performed at much higher power levels in order to utilize the available time for charging. In all cases, the charging is performed mostly by locally generated renewable electricity in the national energy system as in this case Croatian energy system. The portion that is not considered renewable, in this case, corresponds to the imports of electricity, released from the storage as for example, stationary storage and fossil fuel-sourced electricity. Although the availability of energy generation is lower in winter months, at the same time due to the low demand in the maritime sector, the dispatch of the charging is scheduled to make use of the available renewable electricity. This results in a higher share of renewable electricity used in winter months than in summer months, when the general availability of renewable electricity generation is higher. Therefore, in the summer months presented by Q2 and Q3, charging is often performed with electricity that is less than 80% renewable. The results for 2020 are not displayed here since they display only the empty charts. This is the result of the impossibility of adding new capacities and new technologies in 2020. This was a historical year in the model with fixed capacities. Therefore, in that year, no changes to the system were made. The changes that are the result of the optimization are therefore visible for the results for 2025 and after. In 2025, displayed in Figure 4a, the share of RES that was used for charging did in most cases not pass 90% due to still insufficient generation capacities of VRES. The exception is a couple of instances in the fourth quarter when the generation from VRES is high. At this stage, the model did not yet implement a big quantity of power to X options that will be able to utilize available energy while also not having a big capacity of VRES. In other instances, the values were as low as 34%, while in one instance even reached 0% when the import of electricity was required. In this case, the charging was performed a very small capacities mostly not surpassing the 1 MW. Exceptions are the peaks of up to 5 MW. In the cases when very low input power is used, only the battery losses are covered due to self-discharge. In 2035, as displayed in Figure 4b, the charging capacities are much higher since the fleet size in this case is bigger as well. Charging goes up to 20 MW. Also, the RES share of the electricity used for charging is mostly 100 % as the system underwent the power generation transformation as well. In 2050, the increase in both power and share of RES is more evident. In this case, also, the lower availability of the fleets for charging in Q1 and Q2 is visible. In this case, the variations in RES share also exist, but they are lower as compared to the previous years. With further system development, partially with the expansion of the battery-powered maritime fleet, the unutilized power generation is reduced. The higher utilization of charging can be observed by comparing the values of input electricity flows, which are significantly higher in the case of 2050, mostly above 90 % of RES. Also, in some instances, charging is required in times of insufficient renewable generation, thus resulting in the share of RES in the electricity supply of 60% or less. It should be noted that the share of RES at 60 % concerns only the domestic RES generation. Therefore, the electricity is not necessarily fossil-sourced in the cases where the RES is less than 100 %. In that case, it can be generated by non-RES power plants in Croatia or imported whereas the imported electricity is also likely to increase in RES share by 2050 as other countries undergo the transition as well. The results for 2050 are displayed in Figure 5. As observed in the plots of the charging distributions, renewable electricity presents the bulk of the electricity used for charging. The results for charging duration curves are displayed in Figure 6. By observing the data, it can be concluded that the share of RES electricity varies throughout the years. Also, besides the maximum RES share, the duration at which it remains consistent varies. Therefore, in 2025, 100 % RES is reached only for a very limited number of hours. The duration of the high-RES share increases each year. It can also be observed that 2035 is the outlined and the system does not have the highest share of RES in charging in 2050. This can be explained by the higher electricity demands for charging at the same time and therefore the model is less able to choose only to charge with 100 % RES electricity. The state of charge (SOC) of vehicles correlates with the use cycles, as displayed on the Figure 7. The state of charge of the battery changes in response to the energy demand levels as well as to the availability of charging, as indicated in Figure 2.

5. DISCUSSION

It is possible to argue that previous approaches ([20], [21]) also demonstrate the hourly operation of the fishery fleet in the V2G mode, but it is done on the isolated cases of island energy systems, in a simulation approach, for a chosen energy system configuration. In previously published articles, which dealt with the electrification of the passenger fleet ([33], [37]), the advantages of electrification were shown. In addition to them, fishing boats are gradually introduced, which work in parallel with the passenger fleet and with electrified road vehicles in H2RES. The biggest problem is in the summer period, due to the high demand for energy from the tourism sector (passenger fleet) and at the same time fishing boats. However, the potential of renewable energy (especially solar) is great in this period, for the observed case study. This model takes into account the specific working regime of purse seiners and exploits it to provide flexibility to the electrical energy network.

Also, the model brings forward endogenized dynamics of energy transition (Figures 3 and 7) and can follow the optimal pathway towards the goals that are set before the energy system, ensuring that the fleet's decarbonization is put in the context of time and development of the energy system as a whole, which is visible through the results in Figures 4-6, and also, for the participation in the balancing of the system as a whole, in Supplementary Material 2-4. The contribution of the naval fleet electrification to the balancing of the entire power system is small for the selected case study, but without its presence, other technologies would have to fill the role. The fact that the fleet charging was performed during peak generation times proves that this is the optimal approach.

6. CONCLUSIONS

The research has demonstrated the potential for electrification of coastal fishing fleets and the use of such technologies for the integration of sectors of energy consumption in transport and the power sector. Even though the distribution curves and demand profiles of this sector are highly irregular and of a seasonal nature, the H2RES model was shown as an appropriate end-effective model for taking this additional load into the system. The main reason for simplicity in implementation is a relatively small scale of the demand consisting of 6,6 GWh with peak loads of 24 MW. Also, the H2RES model is of perfect foresight variety meaning that it can account for the changes in the availability of charging or the demand distribution. Results show that charging of fishery fleets is performed in times of abundance of energy generated from VRES. Also, although the availability of renewable energy generation is lower in the winter months, the charging managed to be performed using mostly locally generated renewable energy partly due to the specific load distribution which places the majority of the charging demand during the summer when the renewable energy generation is more abundant as well.

Further research will analyse the interactions with power systems and the effect on the investments into demand response and power to X technologies, aiming to more precisely determine the contribution of electrified fishery fleets in balancing the power grid. Also, available power levels, especially potential bottlenecks at the ports will be analysed.

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8. LITERATURE

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Figure 1. Route characteristics of a container vessel [36], a dredger [37] and a fishing vessel

Figure 2 a) Estimated availability of the fleet, b) Demand load of the fishing fleet – useful energy units

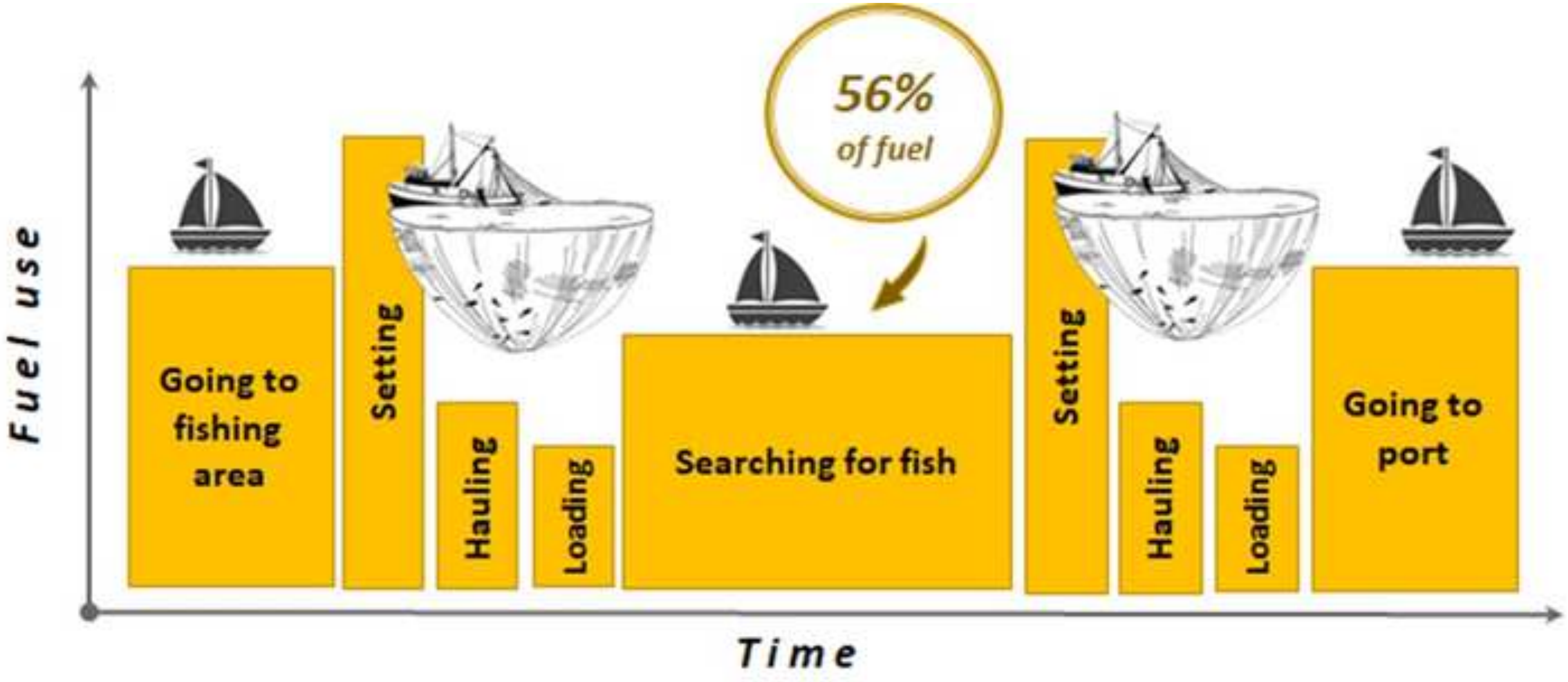
Figure 3 a). Share of technology in terms of the travelled distance by the vessel type [pkm], b) Investments into new units

Figure 4 a) Ship charging and RES share distribution in the year 2025, b) Ship charging and RES share distribution in the year 2035

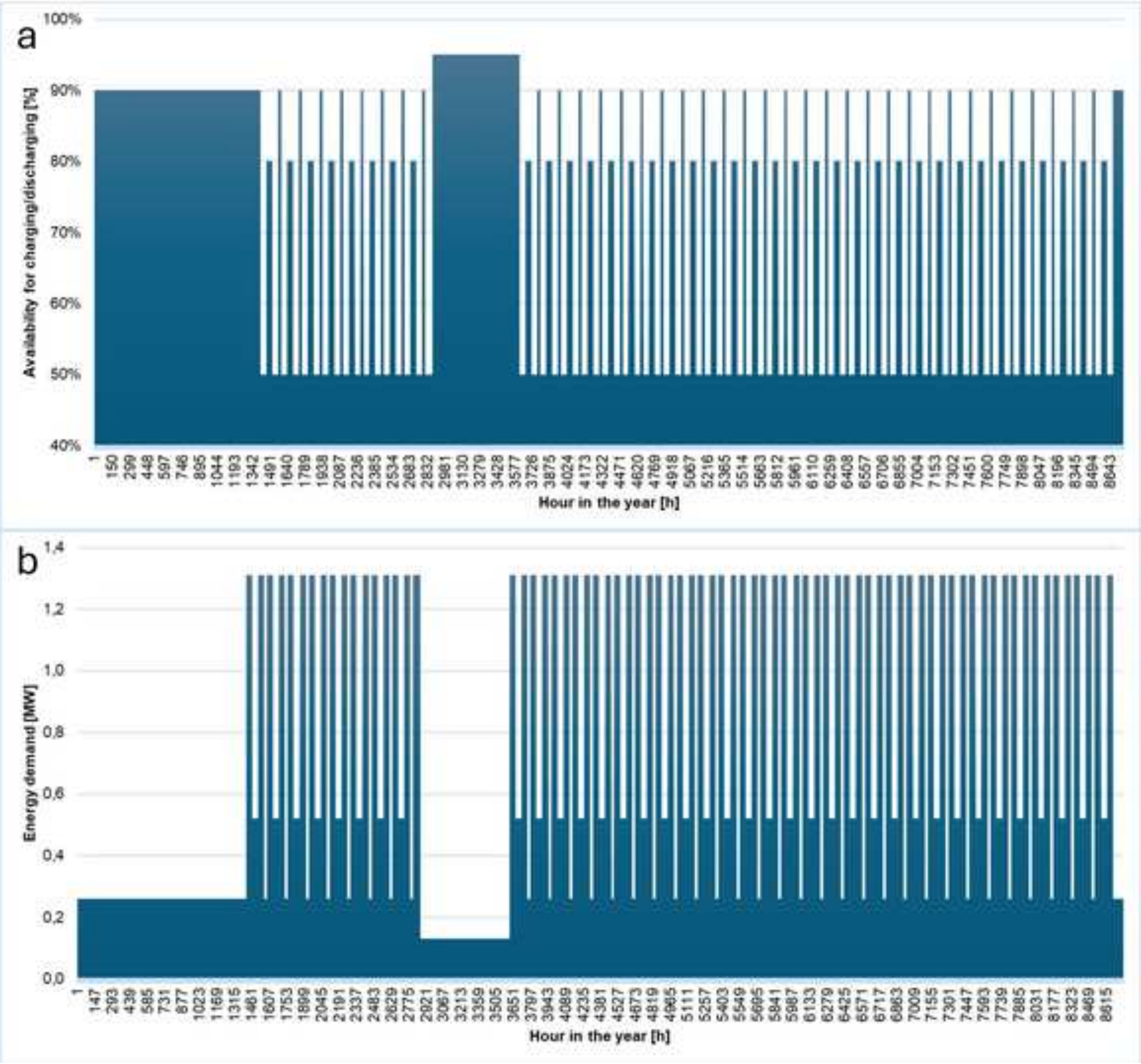
Figure 5. Ship charging and RES share distribution in the 2050

Figure 6. Ship charging duration curve

Figure 7. Ships' batteries SOC



56%
of fuel
Fuel use
Going to fishing area
Setting
Hauling
Loading
Searching for fish
Setting
Hauling
Loading
Going to port
Time


a
100%
90%
80%
70%
60%
50%
40%
Availability for charging/discharging [%]
1
150
299
448
597
746
895
1044
1193
1342
1491
1640
1789
1938
2087
2236
2385
2534
2683
2832
2981
3130
3279
3428
3577
3726
3875
4024
4173
4322
4471
4620
4769
4918
5067
5216
5365
5514
5663
5812
5961
6110
6259
6408
6557
6706
6855
7004
7153
7302
7451
7600
7749
7898
8047
8196
8345
8494
8643
Hour in the year [h]
b
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
Energy demand [MW]
1
147
293
439
585
731
877
1023
1169
1315
1461
1607
1753
1899
2045
2191
2337
2483
2629
2775
2921
3067
3213
3359
3505
3651
3797
3943
4089
4235
4381
4527
4673
4819
4965
5111
5257
5403
5549
5695
5841
5987
6133
6279
6425
6571
6717
6863
7009
7155
7301
7447
7593
7739
7885
8031
8177
8323
8469
8615
Hour in the year [h]

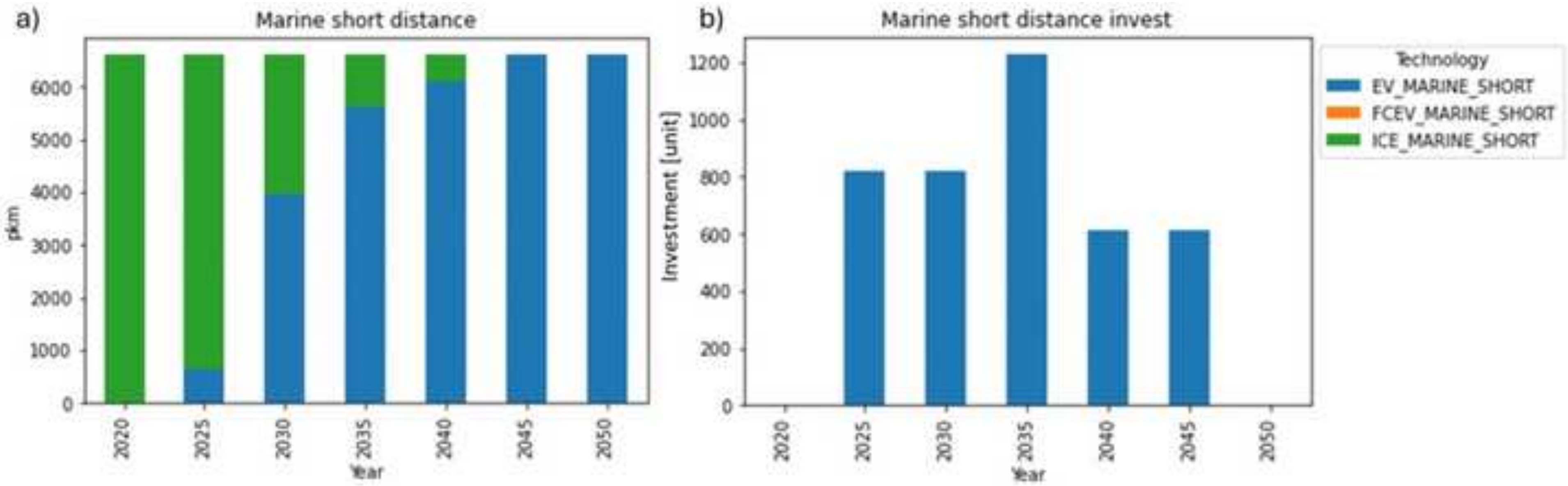
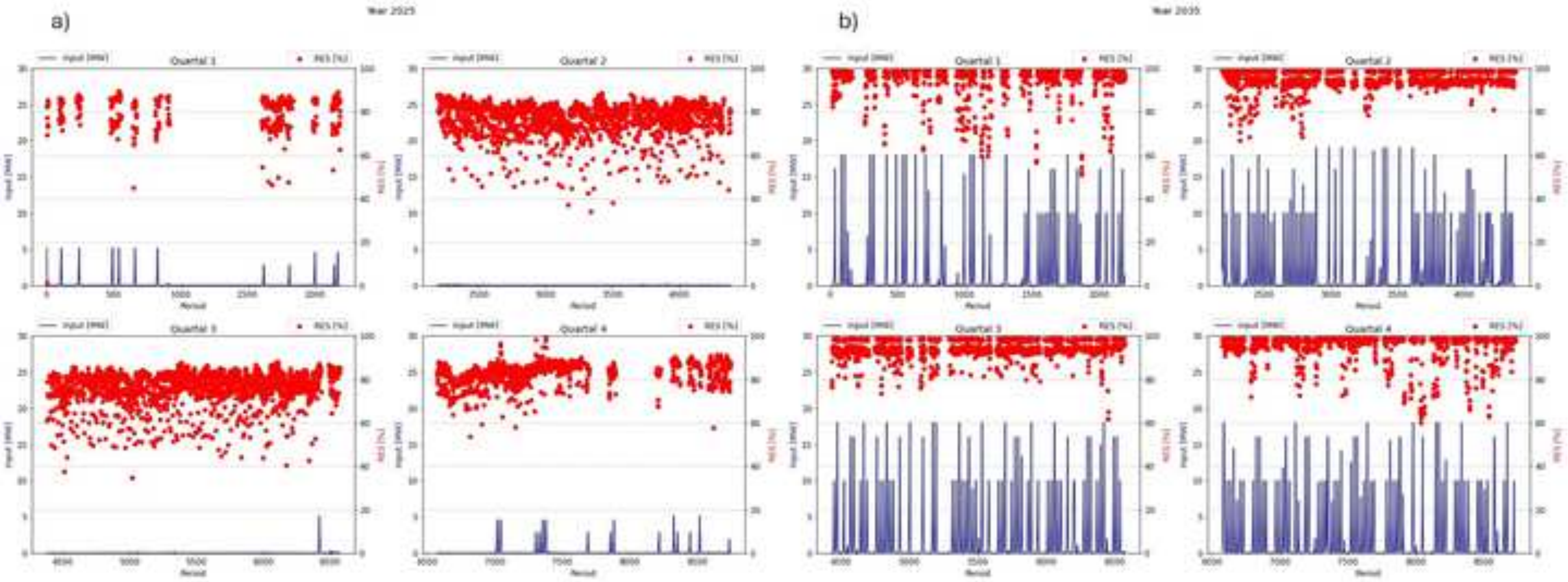
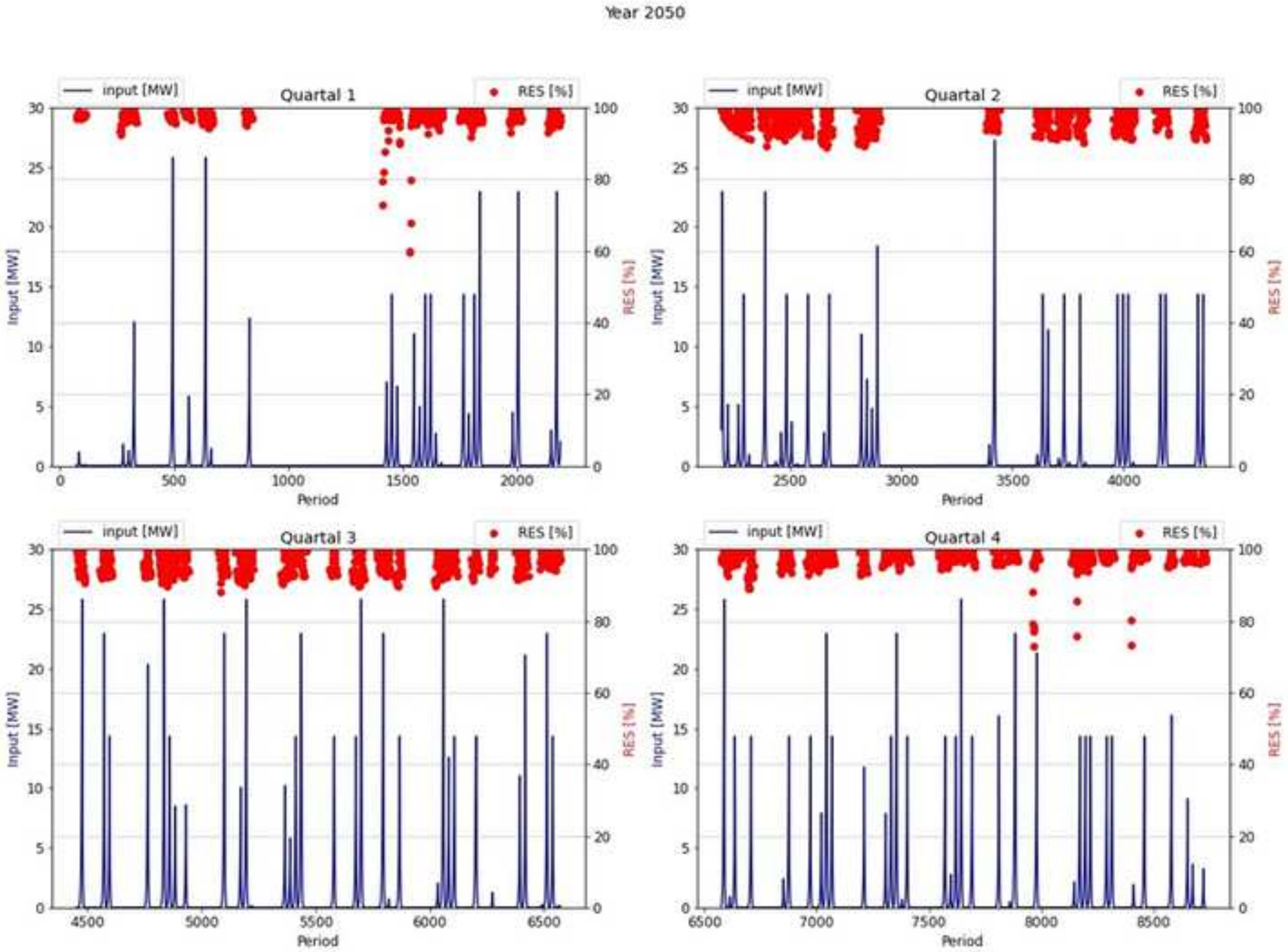

a)
Marine short distance
pkm
0
1000
2000
3000
4000
5000
6000
2020
2025
2030
2035
2040
2045
2050
Year
b)
Marine short distance invest
Investment [unit]
0
200
400
600
800
1000
1200
2020
2025
2030
2035
2040
2045
2050
Year
Technology
EV_MARINE_SHORT
FCEV_MARINE_SHORT
ICE_MARINE_SHORT

Figure 4


a)
Year 2025
b)
Year 2035
Quartal 1
Quartal 2
Quartal 3
Quartal 4
Input [MW]
RES [%]
Period


Year 2050
Quartal 1
Quartal 2
Quartal 3
Quartal 4
input [MW]
RES [%]
Input [MW]
RES [%]
Period
0
5
10
15
20
25
30
0
20
40
60
80
100
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500

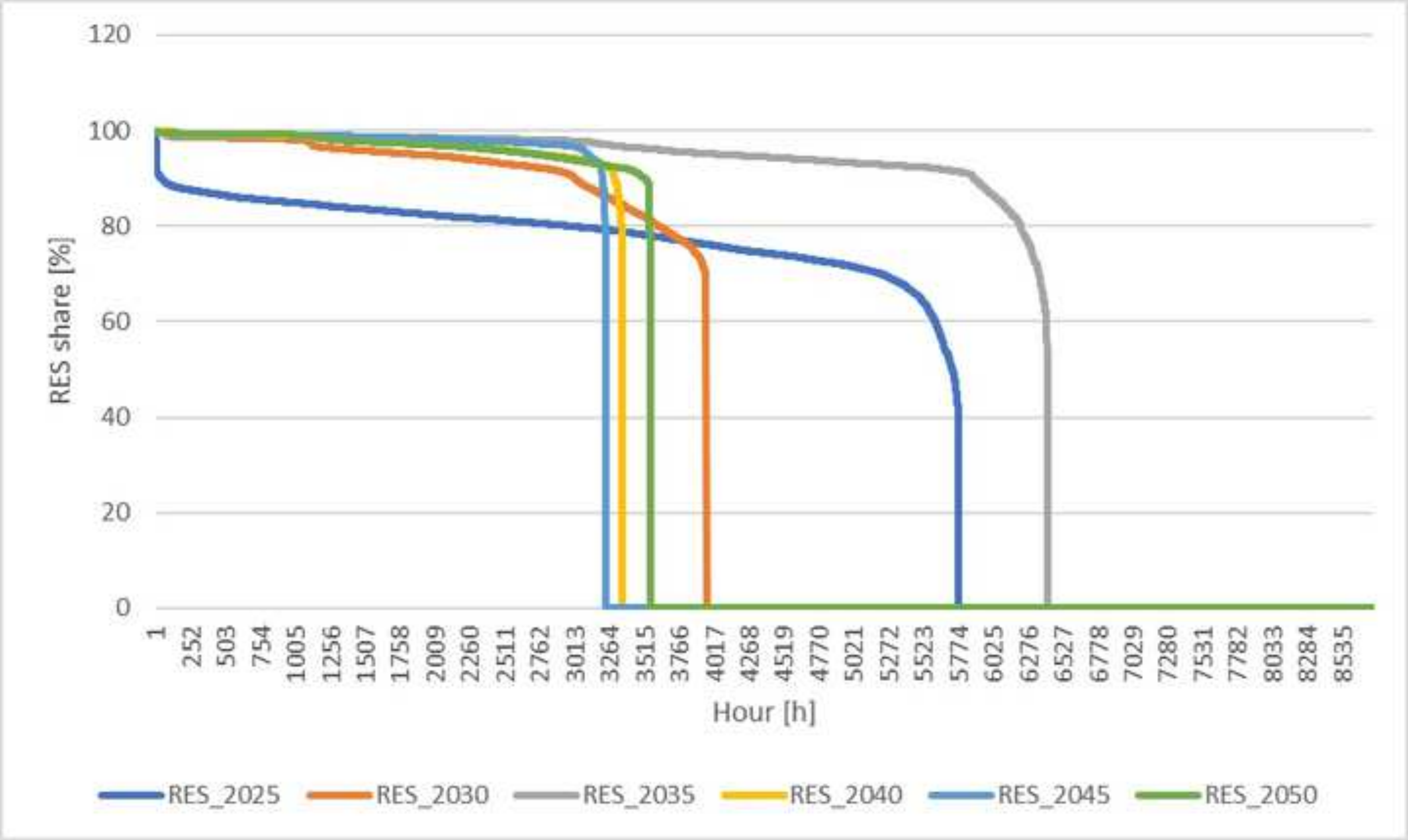

120
100
80
60
40
20
0
RES share [%]
1
252
503
754
1005
1256
1507
1758
2009
2260
2511
2762
3013
3264
3515
3766
4017
4268
4519
4770
5021
5272
5523
5774
6025
6276
6527
6778
7029
7280
7531
7782
8033
8284
8535
Hour [h]
RES_2025
RES_2030
RES_2035
RES_2040
RES_2045
RES_2050

Figure 7

Click here to access/download;Figure;Figure_7.jpg