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Ports as zero-emission hubs

A quantitative case study

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SINTEF Industry

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Introduction and background

Ports take centre stage to reduce environmental impacts and to strengthen shipping's competitiveness. The Green shift means that they need to adapt to new demand, requirements and expectations from users, owners and other actors. As service providers, authority and business actor, ports will be important to facilitate this transition. Hence, it is paramount to explore how ports can develop towards zero-emission energy hubs and take an active role contributing to emission reductions in the transport and business chains they are part of. The European Sea Ports Organization (2016) points out that ports are central with respect to import, export, storage and distribution as well as production of energy. Many ports work actively to facilitate for energy transition – some of these activities are explored in international research but there is little to be found concerning the role of ports in particular (Bjerkan and Seter, 2019).

Both Grønt Kystfartsprogram's "Sea map" (DNV GL, 2016) and the National Transport Plan (Samferdselsdepartementet, 2017) see the future role of ports as zero-emission "energy hubs", with charging opportunities, onshore power supply (OPS) and infrastructure for alternative fuels for both land and maritime transport. Internationally, often also transhipment, storage and refinement of fossil fuels are an important part of port operations. Transition to more sustainable forms of energy requires also to discuss how to maintain and develop such ports.

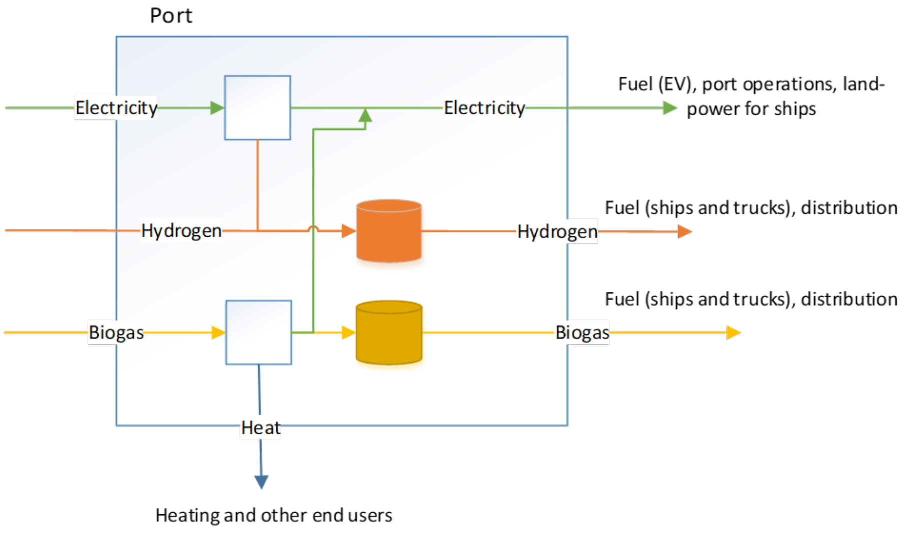

FIGURE 1. EXAMPLE OF A PORT AS AN ENERGY HUB, MODELLED AS A NETWORK OF COMPONENTS WITH ENERGY FLOWS. NOTE THAT ENERGY CAN ALSO BE MOVED IN TIME THROUGH STORAGE IN BATTERIES OR AS HYDROGEN

There exist various interpretations of ports as energy hubs. Often, they refer to the potential for providing low- and zero-carbon energy to different end users at the port and beyond. Energy hubs are seen as both central points in a region and central nodes in a network where multiple energy distribution systems intercept and energy flows can be converted, see Figure 1. They allow refuelling of energy carriers, conversion, and production or generation of energy (e.g., photovoltaics (PV), wind turbines, hydrogen). Integrating different energy carriers allows for system performance improvements such as peak shaving. Energy hubs represent an interface between energy infrastructures and connect not only flows but also actors such as users, operators, and providers of energy or technologies. Hence, studies of this concept should take a systems perspective.

Acciaro et al. (2014) define energy hubs as "geographical concentration of high-energy demand and supply activities, where energy-intense industries, power generation, distribution and related activities and projects are located." Energy-related port activities happen, hence, in two areas: generation (supply) and consumption (demand). Geidl et al. (2007) see hubs as units converting, conditioning and storing multiple energy carriers and, thus, as interface between energy infrastructures and/or loads. This allows for optimization of energy flows with respect to, e.g., costs, emissions, and availability. Demands can be met by utilizing flexibility and storage possibilities, which increases system performance and efficiency and, thus, reliability.

Damman et al. (2019b) discuss the scope for ports to accelerate sustainable energy transition as actors in a wider transport and energy regime. Ports are seen as taking an active role and the question is how they can manage and utilize that role in the best possible manner with two (institutional) understandings competing: as public authorities and as actors in industrial value chains.

User perspectives are an important element in the "energy hub" concept. On one hand, ports can affect user behaviour by, e.g., setting OPS standards and incentives to change arrival times and thus level out demand profiles. On the other hand, port users generate much of the energy demand. They may ask for implementation or use of new technologies. Also, users typically access many ports – which raises issues of coordination, timing, standardization etc. The question of where to draw system boundaries emerges. How much can ports affect other operators, e.g., would enforcing emission limits on visiting vessels simply relocate the pollution problem?

In this respect, ports take on roles as energy provider/producer (with energy an excess product or produced solely for that purpose), "broker", facilitator, but also institution encouraging the use of zero-emission energy technologies. Planning for efficient energy management requires interaction of not only operators and users but also grid managers and local community managers (Acciaro et al., 2014). The authors mention Port Energy Management as important concept, centred on equipment, operations and transportation management, terminal design and operation, energy supply and delivery, land use planning.

There is a close relation between sustainability transition and physical infrastructure, e.g., related to vessel lifespan or availability of space. This yields both lock-ins/path dependencies and windows of opportunity. Established technologies are often tightly integrated in existing systems and practices, allowing only incremental changes, while sustainability challenges typically require development and implementation of more radical innovation and introduction of entirely novel solutions. To avoid suboptimal investments and lock-in to certain solutions, optimal interaction between various energy sources, technologies and users in and around the port should be achieved. New solutions to provide flexibility, storage and conversion of energy can yield more stable supply and better economic viability. Increased flexibility helps to reduce demand spikes and, thus, the need for infrastructure investments. Hence, focus is increasingly on how to develop ports as integrated energy systems in a green transition.

Ports can impact energy transition both in the port itself, for sea transport and for hinterland transport (Bjerkan et al., 2021). They connect maritime and land-based systems, albeit with varying degree of influence. Regulatory frameworks may function differently in different regional and local contexts (e.g., technological and industry specialisation, regional development goals) – affecting the scope for ports to accelerate sustainable energy transition. The development of ports as energy hubs requires new knowledge, for example on technical solutions, tools for techno-economic analyses composing solutions adapted to a specific port, and organization of interactions between various actors. The energy-hub concept has tightly interwoven technical, market, policy and social aspects and a holistic systems perspective is beneficial when analysing its application to different ports (Damman et al., 2019a).

Optimization-based economic analyses facilitate decision processes to ensure rational and robust solutions with respect to business models, technology choices and dimensioning etc. They suggest ways to satisfy economic or environmental goals or to secure profitability as good as possible, taking into account assumptions and constraints such as area availability/restrictions, monetary aspects, technical issues but also security-of-supply or regulatory requirements. For example, security concerns may demand production and storage of certain energy carriers to be distanced from areas with public access while logistics would prefer the opposite to ease refuelling or sales of said energy carriers with growing popularity/demand. Another example is discussions about business models for provision of onshore power supply – should this be part of port services or organized as a separate company, how should relations to local energy providers be formed, how to design and address tariffs etc. Optimization helps facing challenges and uncertainty regarding, e.g., electrification of port operations, technical maturity, prices, demands for new energy carriers. The approach facilitates finding suggestions for innovative new configurations, avoiding lock-ins. It can also suggest ways to get out of lock-ins or to best accommodate new solutions easing the transition to more sustainable operations. Typically, optimization models can be adapted easily to changed assumptions and, hence, find suggestions for solutions that are robust and flexible under various conditions.

This working paper is an outcome of the project "Transition towards zero-emission ports" (TRAZEPO), a competence-building project financed by the Research Council of Norway in the EnergiX programme (2018 – 2021, project number 281002). SINTEF collaborated with Kystverket, Norske Havner and the ports of Kristiansand, Narvik and Oslo to build knowledge about ports' contribution to reducing emissions and to sustainable energy transition in a Norwegian context. The project studied a) opportunities and barriers ports face with respect to sustainable transition, b) strategies, solutions and instruments that would be most relevant for given geographic, marked and socio-cultural differences, and c) how ports' contributions to energy transition can be developed and strengthened in a systems perspective. This was approached primarily from a socio-technical perspective on sustainable transition, also called "sustainable transition studies", complemented by quantitative approaches like mathematical modelling and optimization. The paper summarizes work done in task T2.3 Quantitative modelling, helping to find out which effects in terms of emission reductions and cost savings could be realized by developing ports as zero-emission energy hubs and which particular steps should be taken.

The next section highlights features of the optimization approach. Then, the considered case study, the port of Kristiansand as a zero-emission energy hub, is described and selected results are presented. The final section summarizes and concludes.

A quantitative approach to develop energy hubs

Optimization-based economic analyses

Ports as energy hubs can be modelled as networks of various components where energy can be produced, stored or used with possibilities for energy flow between the components, see Figures 1 and 3. This facilitates developing quantitative models based on mathematical descriptions of the problem. Such models can be solved by means of specialised software that finds optimal solutions under given assumptions on, e.g., costs and future demand for various products and technical solutions.

The model captures both the interplay between the various technologies and underlying dynamics. In particular, utilization of charging capacity will vary considerably over a day with effect peaks and according costs and requirements for infrastructure. Stationary batteries may be used to reduce effect peaks by charging the batteries in periods with low load. Also interaction with local hydrogen production is conceivable, using an electrolyser in such periods. Quantitative economic models can be run over several time periods to study profitability of investment decisions on technology choice and component sizing. Such an analysis would be adapted to each single port and takes into account existing infrastructure, options/barriers to put new technology into use and local variations in future demand for OPS, charging and alternative fuels. It is also possible to add requirements on emission reductions to investigate how to reduce, e.g., CO_2 emissions in a best possible way.

Model description

All elements in the modelled system are represented as *nodes* with specified properties. Between each pair of nodes, *products* can flow such as hydrogen (compressed or liquid), oxygen, electricity, water, natural gas.

The main goal of the model is to suggest which nodes should be installed, at which time and with which capacity and how to operate the system under dynamic conditions to achieve the best possible net present value over the planning horizon. Note that node capacity can be modelled in power (flow), typically for production nodes, or in energy (volume) for storage nodes.

The time horizon of the model is divided into *strategic periods* (T^{SP}), typically one year or longer. All infrastructure investments happen at the start of these periods. Each strategic period includes a sequence of *operational periods* (T^{OP}), for which infrastructure usage is analysed. The total length of the operational periods might be shorter than the strategic period they correspond to. In such a case, the operational results are scaled up accordingly.

In the following, main elements of the optimization model are explained. Kaut et al. (2019) provides a full model description.

Decisions suggested by the model belong to two categories. The first one concerns investment and capacity decisions on a strategic level while the second category deals with operational decisions. The table below gives an overview of these decision variables.

Name	**Description**
$\boldsymbol{cap_{n,sp}}$	Capacity of node n in period $sp \in T^{SP}$
$\boldsymbol{add_{n,sp}}$	Additional capacity added at period start
$\boldsymbol{inv_{n,sp}}$	Whether new capacity is added in a period or not
$\boldsymbol{flow_{n,m,p,t}}$	Flow of product p between nodes n and m at time $t \in T^{OP}$
$\boldsymbol{flow}_{n,p,t}^{\boldsymbol{in}}$	Combined inflow of product to the node
$\boldsymbol{flow}_{n,p,t}^{\boldsymbol{out}}$	Combined outflow of product from the node
$\boldsymbol{use}_{n,t}$	Capacity usage for the node
$\boldsymbol{use}_{n,sp}^{\boldsymbol{max}}$	Maximum capacity usage for the node
$\boldsymbol{s_{n,t}}$	Inventory at the end of each operational period

Similarly, *constraints* are divided into those handling capacity investments and constraints ensuring that the operational flow is correct.

Total capacity available at the start of each strategic period is tracked for all nodes (N)

$$\boldsymbol{cap}_{n,sp} = \boldsymbol{cap}_{n-1,sp} + \boldsymbol{add}_{n,sp}, \qquad n \in N, sp \in T^{SP}$$

where newly added capacity cannot exceed an upper limit

$$\boldsymbol{add}_{n,sp} \leq Add_n^{max} \boldsymbol{inv}_{n,sp} \qquad n \in N, sp \in T^{SP}$$

The following operational constraints apply to all nodes. Capacity used in an operational period cannot exceed the capacity available in the respective strategic period ($SP(t)$)

$$\boldsymbol{use}_{n,t} \leq \boldsymbol{cap}_{n,SP(t)} \qquad n \in N, t \in T^{OP}$$

Total inflow and outflow of each product are tracked by summing over all incoming and outgoing flows, respectively

$$\boldsymbol{flow}_{n,p,t}^{\boldsymbol{in}} = \sum_{\boldsymbol{m \in N}} \boldsymbol{flow}_{m,n,p,t} \qquad n \in N, p \in I, t \in T^{OP}$$

$$\boldsymbol{flow}_{n,p,t}^{\boldsymbol{out}} = \sum_{\boldsymbol{m \in N}} \boldsymbol{flow}_{n,m,p,t} \qquad n \in N, p \in I, t \in T^{OP}$$

Production nodes are nodes that convert input products into output products based on a (linear or piecewise linear) production function. Their capacity is defined in terms of the inflow or outflow of a specific product. The table below provides an overview of the types of production nodes used in the model.

Node	**Input**	**Output**	**Capacity**
Fuel cell	Hydrogen	Power	$\boldsymbol{flow}_{n,Power,t}^{\boldsymbol{out}}$
Electrolyser	Power	Hydrogen	$\boldsymbol{flow}_{n,Power,t}^{\boldsymbol{in}}$
Compressor	Hydrogen, Power	Hydrogen	$\boldsymbol{flow}_{n,p,t}^{\boldsymbol{out}}$

A *market* can sell or purchase a product within lower and upper limits.

$$S_n^{min} \leq \boldsymbol{flow}_{n,p,t}^{\boldsymbol{out}} \leq S_n^{max} \qquad n \in M, t \in T^{OP}$$

$$P_n^{min} \leq \boldsymbol{flow}_{n,p,t}^{\boldsymbol{in}} \leq P_n^{max} \qquad n \in M, t \in T^{OP}$$

Storage levels cannot exceed invested capacity in the operational periods

$$\boldsymbol{s}_{n,t} \leq \boldsymbol{use}_{n,t} \qquad n \in S, t \in T^{OP}$$

Each storage node can store only one product, p, with mass balance to be satisfied when adding and removing products

$$\boldsymbol{s}_{n,t} = \boldsymbol{s}_{n,t-1} + \boldsymbol{flow}_{n,p,t}^{\boldsymbol{in}} - \boldsymbol{flow}_{n,p,t}^{\boldsymbol{out}} \qquad n \in S, t \in T^{OP}$$

Filling and emptying speeds may be constrained by upper limits

$$\boldsymbol{flow}_{n,p,t}^{\boldsymbol{in}} \leq R_n^{in} \qquad n \in S, t \in T^{OP}$$

$$\boldsymbol{flow}_{n,p,t}^{\boldsymbol{out}} \leq R_n^{out} \qquad n \in S, t \in T^{OP}$$

The *objective function* to be maximized represents the net present value of investments and operations over the planning horizon

$$\eta = \sum_{t \in T^{OP}} \rho_t \boldsymbol{ncf}_{\boldsymbol{n,t}} + \sum_{sp \in T^{SP}} \sigma_{sp} \left(\boldsymbol{capex}_{\boldsymbol{n,sp}} + \boldsymbol{opex}_{\boldsymbol{n,sp}} + \boldsymbol{maint}_{\boldsymbol{n,sp}} \right)$$

Here, $\boldsymbol{ncf}_{\boldsymbol{n,t}}$ is the net cash flow associated with operations in period t. These are mainly related to markets where products are purchased or sold with prices varying over time. $\boldsymbol{capex}_{\boldsymbol{n,sp}}$ and $\boldsymbol{opex}_{\boldsymbol{n,sp}}$ are capital and operational costs, respectively, associated with investments. Finally, $\boldsymbol{maint}_{\boldsymbol{n,sp}}$ are maintenance costs for replacing components in a node as they reach the end of their lifetime.

Case study – battery and hydrogen storage

Kristiansand port

We demonstrate some aspects of this optimization model on a case inspired by the port of Kristiansand. This port is located in the south of Norway and, due to its short distance to mainland Europe, a leading Norwegian roro/ferry port. Passenger ferries depart daily to Denmark, with about 1.2 million passengers per year, while goods transport has connections to Germany, Belgium, the Netherlands and Great Britain. In 2020, the port had over 1500 vessel arrivals, of which 50 % passenger ships and 33 % mixed cargo ships, but also tankers, bulk ships and offshore vessels called (Statistics Norway, 2021). The port aims at becoming an environmentally-friendly traffic hub with considerable growth towards 2025 within, for example, offshore and cargo segments. This includes offering onshore power supply, LNG and hydrogen; also autonomous landing and navigation systems are being prepared (NorConsult, 2018).

FIGURE 2. PORT OF KRISTIANSAND (SOURCE: KRISTIANSAND HAVN)

The port has been described as highly motivated to explore and implement new technologies, seeing opportunities for sustainability transition and how to facilitate it. They aim to be lean and flexible and have a high willingness to risk and test new solutions (Damman et al., 2019b). Among other measures, mobile OPS units have been acquired and an OPS solution dedicated to offshore supply vessels is provided. There are electrical cranes and a substantial PV roof installation, producing about 85.000 kWh/year. For the future, Kristiansand's general port strategy (Kristiansand Havn, 2016) envisages a solution with full electrification at the core, combined with alternative fuels and hybrid solutions for vessels. The strategy describes local, regional and national framework and directives for OPS. It outlines a plan to roll out OPS, with prioritization according to "impact per money", giving first priority to large vessels and regular traffic. This plan is to be realized in several phases, from mobile facilities via measures to expand capacity in various areas to full electrification. The port also accommodates the development of new vessel technologies such as hybrid, fully electrified, combinations with LNG.

Case description and results

The case study explores how a specific technology may interact with existing infrastructure and energy usage. For this purpose, the impact of utilizing a stationary battery on the total cost of electricity is investigated for different battery capacities. Primarily, the impact will happen through reducing effect peaks due to demand for charging current varying throughout the day. Battery prices are steadily decreasing and battery usage to handle load variations becomes more profitable. However, investments must be seen in interaction with other infrastructure and energy usage and production. In addition to the battery, the technologies in the considered system comprise PV, electrolyser, fuel cell, and hydrogen storage, see Figure 3. Electricity can be purchased from the grid (outside the system) but also produced by PV while hydrogen can be purchased from outside. Outputs from the system are a) electricity, to be used as fuel for electrical vehicles, for port operations and for OPS and b) hydrogen, to be used as fuel for trucks and ships and for further distribution. In the system, hydrogen may help to level out long-term fluctuations in supply and demand while energy storage in a battery is used in the shorter term.

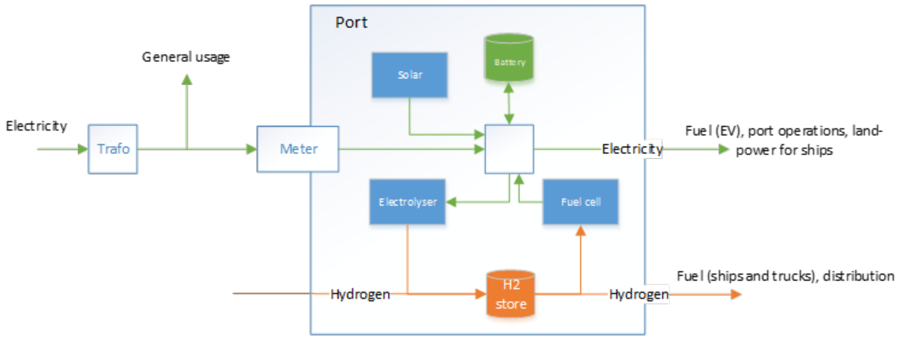

FIGURE 3. SYSTEM OF TECHNOLOGIES AND ENERGY CARRIERS CONSIDERED IN THE CASE STUDY

The port of Kristiansand has, in collaboration with Agder Energi, the municipality of Kristiansand and Agder county authority, mapped effect and energy usage related to the port area at Vestre Kvadraturen. The case study combined these usage profiles with information on hourly electricity prices, monthly variation of grid prices and hourly variation of PV production. All these parameters were derived from statistics for the year 2019.

The aim of the optimization model is to suggest cost-optimal investments and operation of the system over a 20-year horizon such that demand can be satisfied. Figure 4Figure 5 give examples for results of this type of economic analyses. Figure 4 shows the peak-smoothing effect of various battery sizes and the resulting impact on the total electricity costs. Figure 5 visualizes outcomes of a sensitivity analysis that shows best possible battery size for different battery prices. With lower prices, it becomes more beneficial to invest in considerably larger batteries, in particular to handle load variations over short periods of time.

This study evaluated the effect of battery prices under given (historical) energy price and demand profiles. Further analyses may be concerned with, for example, investigating scenarios with increased demand for electricity or hydrogen, the value of load flexibility, variations in demand and local production of hydrogen, changes in future electricity prices.

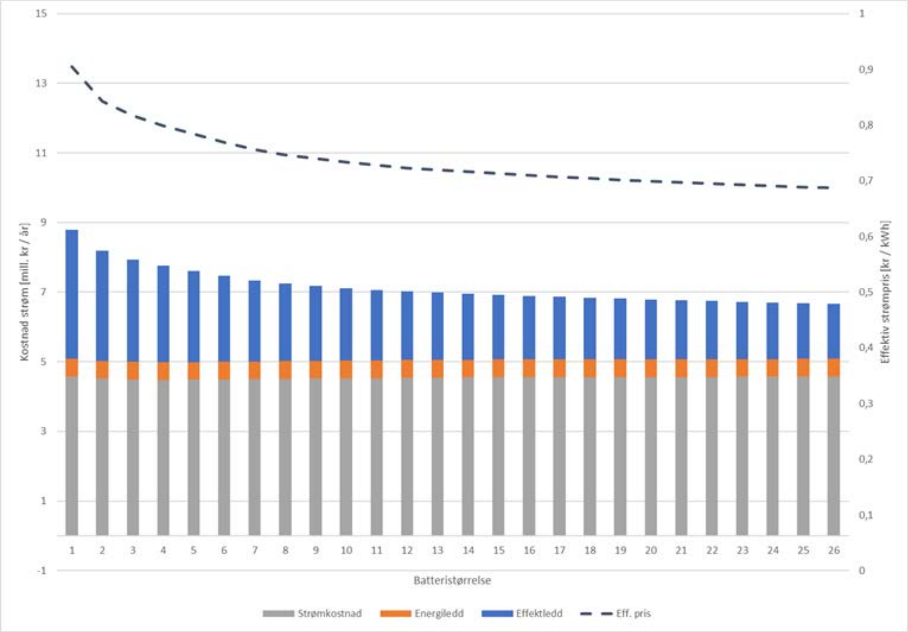

Figure 4. Impact of battery sizes (MWh) on electricity costs through smoothing effect peaks. The dashed line shows the resulting total electricity costs (mill. kr/year) while the bars show the composition of the price for energy bought from the grid (kr/kWh): grey – electricity purchase price, orange – energy term, blue – effect term

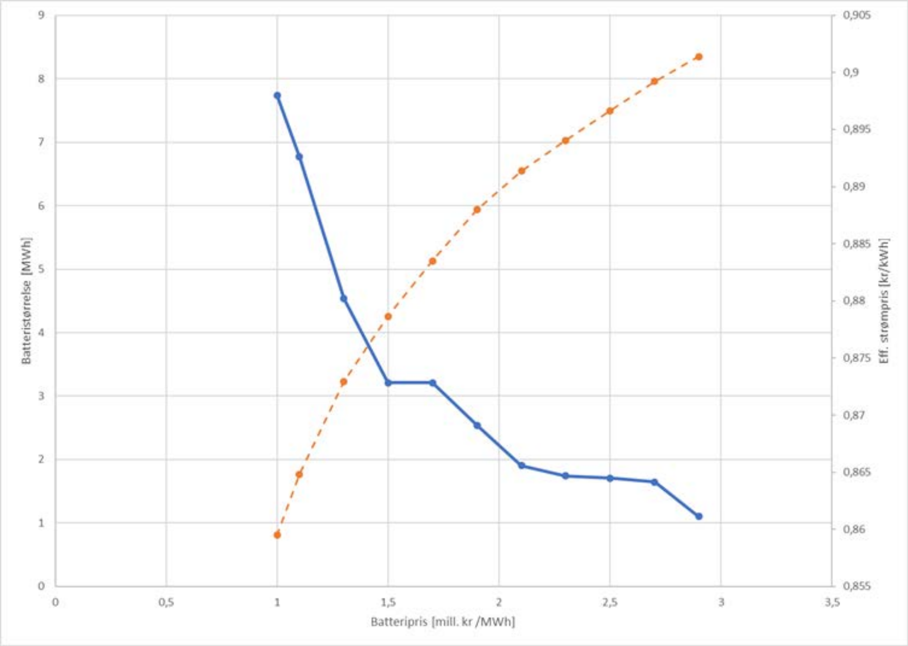

Figure 5. Dependency of optimal battery size on price (mill. kr/MWh), blue line, and resulting electricity costs (kr/kWh) incl. electricity price and network charges, orange line

Given that ports are expected to provide various fuels and energy carriers in the future, such analyses will be valuable in both early evaluation phases and for potential subsequent investments. They can provide answers about which technologies to consider for investment, at which time investments should be done and which dimensions to choose. The analyses will also provide insight into interactions between existing and new infrastructure and technologies and may point out ways to evade lock-in situations.

Summary

Being an intersection between land- and sea-based activities, ports have a central role in the transition to zero-emission transport. Under the concept of energy hubs, they provide zero-and low-emission energy for port operations and users. Ports may take a multitude of roles in this, e.g., energy and service provider, operator, business actor, facilitator, authority. Developing ports as energy hubs requires the consideration of a variety of tightly interwoven aspects, necessitating a systems perspective that involves both qualitative and quantitative research.

This working paper outlined how quantitative approaches such as optimization-based economic analyses can contribute to this work. The underlying model considers energy hubs as systems of various interacting technologies and energy carriers and investigates how to design and use the system (cost-)efficiently to match fluctuating production, demands, sales etc. The approach was demonstrated on a case inspired by the port of Kristiansand, studying a system based on electricity and hydrogen technologies. It shows the impact on total electricity costs of using a stationary battery to smooth load peaks.

Optimization-based analyses are rather easily adaptable to changed assumptions about parameters such as costs or demands. The models allow to study interactions in more complex systems rather than investigating single technologies separately. Hence, they can be beneficial for decision support to provide specific suggestions and for what-if analyses to explore system designs and behaviour under different situations. Comparative analyses help also to ascertain conditions for achieving goals or reaching tipping points (e.g., "When is own energy production sustainable?"). In contrast, qualitative methods help to develop broad scenarios for transition and innovation and, hence, development of energy hubs at larger scale. This, in turn, can point out measures and goals to accelerate the transition processes. Qualitative research may discuss policies, innovation, transition processes, i.e., external conditions and premises. Such methods may identify interesting directions where quantitative methods may fill in needed information, e.g., increasing need for flexibility, moving from a transport system view to a broader energy system view. They help also to expand the focus from local solutions to larger systems and to look at longer value chains. This explores new roles and business models for ports and, e.g., promising collaboration models with energy companies and users.

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We study the role of the energy system in the transition to the zero-emission society.