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Designing the hydrogen supply chain for maritime transportation in Norway ⋆

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Abstract. We study the problem of locating hydrogen facilities for the maritime transportation sector in Norway. We present a multi-period model with capacity expansion to obtain optimal investment and expansion decisions and to choose optimal production quantities and distribution solutions. The objective is to minimize the sum of investment, expansion, production, and distribution costs while satisfying the demand in each period. Hydrogen production costs are subject to economies of scale which causes non-linearity in the objective function. We model long-term investment and expansion costs separately from short-term production costs. The short-term production costs depend on the installed capacity and production quantities. We analyze two models that differ in investment decision flexibility and two demand scenarios: demand only from the maritime sector and demand from the whole transportation sector in Norway. The results show that the scenario with higher demand does not lead to a higher number of built facilities due to the economies of scale. The model with higher flexibility leads to higher capacity utilization in the first periods and thus significantly lower production costs. The results further indicate that the initial demand is too low to build a steam methane reforming facility, instead only electrolysis facilities are built in both scenarios and both models.

Keywords: Facility location · Capacity expansion · Hydrogen supply chain

1 Introduction

Emission reduction in the transportation sector is a crucial step in order to meet the emission targets set in the Paris agreement on climate change. In 2015, the Norwegian parliament decided that CO_2 emissions must be decreased by at least 40% (compared to 1990) towards 2030 in an attempt to reach the targets of the

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Paris agreement. As a consequence of this ambitious decision, fossil fuels have to be replaced by alternative zero-emission fuels. The use of hydrogen fuel cells is considered as one way to decarbonize the transport sector and to decrease the emission of greenhouse gases (GHG) [12].

In 2017, the transport sector in Norway was responsible for emitting 15.8 mill. tons CO_2, accounting for 23% of all CO_2 emissions [1]. CO_2 emissions from domestic inland water and coastal transport in Norway accounted for 8.7% of emissions from the transport sector in 2018. Introducing zero-emission fuels such as hydrogen in maritime transportation can therefore considerably reduce emissions of CO_2. However, limited experience with hydrogen as fuel and uncertainty about hydrogen availability may affect the smoothness of the transition to hydrogen fuels [22]. One way to create an initial demand for hydrogen is to require that high-speed passenger ferries and car ferries have to use hydrogen as fuel when public transport contracts are renewed. In general, demand for hydrogen is expected to increase in the years to come and the production infrastructure has to adjust to this growth [11]. As such, the infrastructure needed to cover demand from the maritime sector can help ensuring a stable hydrogen supply also for other transportation sectors in Norway [12].

The two most relevant hydrogen production technologies for Norway are electrolysis (EL) and steam methane reforming with carbon capture (SMR+) [14]. While electrolysis is a more profitable technology in small-scale production (50–5,000Nm^3/h), SMR+ is more favourable when producing large quantities of hydrogen (50,000–100,000Nm^3/h). Scaling up the production results in lower average costs, leading to economies of scale. This property is significant for SMR+, but it also applies to electrolysis [20]. Figure 1.1 shows the economies of scale in the long-term hydrogen cost function. Note that the cost-axis uses a logarithmic scale.

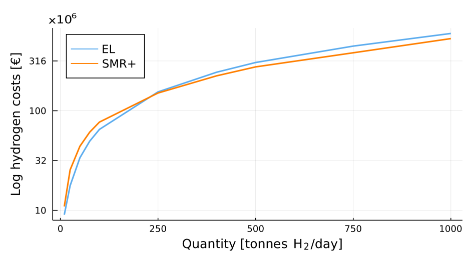


Fig. 1.1: Long-term hydrogen costs

In this paper, we study the problem of how to design the hydrogen supply chain for maritime transportation in Norway. The problem consists of investment and expansion decisions, production quantities, and distribution solutions. It belongs to the category of facility location problems with capacity expansion. An early review of pioneering papers dealing with capacity expansion can be found in [21]. Shulman [31] and Dias et al. [10] study a multi-period plant location problem with discrete expansion where a plant is modelled as a set of facilities in the same location. Capacity expansion is achieved by building an additional facility and the facility size must be chosen from a finite set of capacities. The production costs are defined for each facility and depend only on facility type and quantity produced in the facility. Behmardi and Lee [5] study a multi-period multi-commodity capacitated facility location problem with capacity expansion and relocation. The modelling approach differs from previous papers as Behmardi and Lee [5] work with dummy locations to relocate capacity. The dummy locations are used for modelling purposes to shift the capacity. Customers can only be served from real facilities. Torres et al. [32] present a comparison of multi-period facility location problems with growing demand where opening and closing decisions are allowed at any time during the planning horizon. Jena et al. [17] introduce a multi-period facility location model with a capacity expansion, reduction, and the option to temporarily close the facility. In their work, capacity expansion is modelled by the modification of existing facilities. Jena et al. [18] present a facility location problem with modular capacities where capacity expansion, as well as partial closing and reopening, are allowed. An extension of their model is published in [19] where also facility relocation is allowed. Castro et al. [6] present a large-scale capacitated multi-period facility location model where a set of capacitated facilities is progressively built during the planning horizon and simultaneously a maximum amount of operating facilities in each period is specified.

Facility location and supply chain design problems with a focus on hydrogen infrastructure are discussed in [3], [24] and [13]. In the work by Almansoori and Shah [3], a multi-period hydrogen supply chain for Great Britain is studied. However, in their work, expansion is not allowed. Myklebust et al. [24] present a case study from Germany and study the impact of demand and input costs on the optimal technology choice. Han et al. [13] present a different approach where an optimization model for the hydrogen supply chain with given production capacities is considered.

Economies of scale cause non-linear production costs. Several approaches for how to incorporate non-linear production costs in facility location problems have been published in the literature. Holmberg [15] introduces a piecewise linear staircase cost function that enables to model different production costs at different capacity levels. Correia and Captivo [7] present the modular capacitated facility location model and emphasize the advantage of the modular formulation as it enables to take economies of scale into consideration. They separate investment and operational costs and provide different unit operational costs for each facility size. Van den Broek et al. [34] study facility location problem with non-linear, non-convex, and non-concave objective function. They follow the idea of non-linear costs depending on installed capacity as presented in [7] however, they introduce a linear staircase cost approximation. The approach presented in [34] can capture economies as well as diseconomies of scale.

For more examples of facility location and supply chain design see the excellent reviews by Melo et al. [23], and Arabani et al. [4]. Review on multi-period facility location problems can be found in [26].

In this paper, we investigate the impact of demand and decision flexibility on the optimal design of the hydrogen infrastructure for maritime transportation in Norway. In particular, we study where to locate hydrogen production facilities, which capacity and production technology to install, and which period to choose for investment and expansion.

We distinguish between long-term costs and short-term costs. Long-term costs consist of investment and expansion costs, while the short-term costs are given as production costs, representing capital expenses (CAPEX) and operational expenses (OPEX) respectively.

The investment and expansion represent the long-term decision because a built facility cannot be closed down during the planning horizon. The short-term production costs depend on installed capacity and its utilization. We allow the production rate to deviate from the installed capacity, allowing for a more flexible production schedule. However, deviating from the installed capacity leads to increasing unit costs [29]. We carry out our analysis using two models and two demand scenarios. In the first model, opening new facilities is allowed during the whole planning horizon, while in the second model, opening facilities is restricted to the first period. In the first demand scenario, we assume demand only from the maritime sector, while in the second scenario, demand from the whole transportation sector in Norway is considered.

The remainder of this paper is organized as follows: in Section 2, we provide a mathematical formulation of the dynamic facility location problem with capacity expansion. Case description and computational results are discussed in Sections 3 and 4, respectively. Conclusion is presented in Section 5.

2 The mathematical programming model

We formulate our problem as a multi-period facility location problem with capacity expansion. The goal is to determine the optimal strategy for opening and expanding hydrogen production facilities such that demand is satisfied. Closing facilities is not allowed. The objective is to minimize the discounted sum of investment and expansion costs, production costs, and distribution costs.

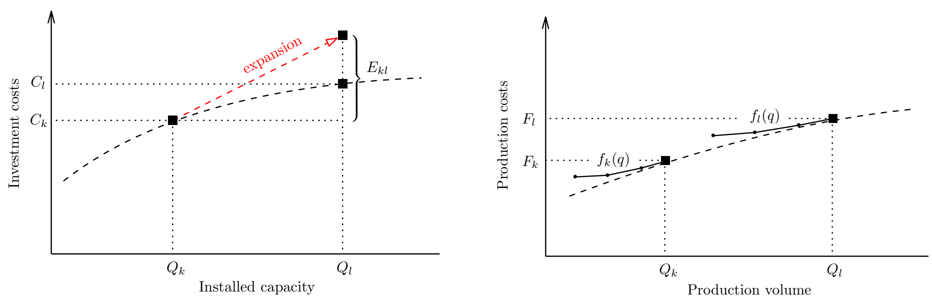
We provide two models for our multi-period facility location problem with non-linear objective function and capacity expansion. In the first model, investing in a new facility is allowed in each period, while in the second model, the initial investment can only be made in the first period. In both models, capacity expansion is allowed for each facility once during the planning horizon, and technology change is not permitted. We assume that the cost functions are independent of selected locations and investment time. Each technology is characterized by its own cost function. However, the general properties described in Subsection 2.1 apply to both considered technologies. The mathematical formulation is then presented in Subsection 2.2.

2.1 Modelling approach

We model investment decisions as a choice from a discrete set of available capacities similar to [7]. Capacity expansion here means modifying an existing facility and is modelled as a discrete jump between available capacities. This approach is also used in [18].

To model the cost of investing, expanding, and operating facilities, we separate the long-term investment and expansion costs from the short-term production costs. Each installed capacity has its own short-term production cost function. We model the short-term production costs as a piecewise linear, convex function. This is similar to the approach presented in [30]. From the point of view of short-term production costs, higher utilization of smaller capacity is always more favourable than smaller utilization of higher installed capacity.

Expanding capacity implies an additional investment as well as switching over to a new short-term production cost function. Figure 2.1a illustrates our approach for modelling the expansion of facilities. Let Q_k be the initially installed capacity and C_k the corresponding investment costs. The expansion costs of expanding from capacity Q_k to capacity Q_l are denoted as E_{kl}. As $C_k + E_{kl} > C_l$. Investing in a smaller facility and expanding to a larger capacity is more expensive than opening the bigger facility right away.



(a) Investment and expansion costs (b) Production costs

Fig. 2.1: Short-term and long-term costs

Due to separating the long-term investment and expansion costs from the short-term production costs, expansion implies moving from one short-term production cost function to another. An example of this can be seen in Figure 2.1b. Before expanding the facility from capacity Q_k to capacity Q_l, the production cost function $f_k(q)$ applies, whereas function $f_l(q)$ is valid after the expansion has taken place.

2.2 Mathematical formulation

Let us first introduce the following notation:

Sets

- $\mathcal{B}$ Set of breakpoints of the short-term cost function
- $\mathcal{I}$ Set of possible facility locations
- $\mathcal{J}$ Set of customer ports
- $\mathcal{K}$ Set of available discrete capacities
- $\mathcal{P}$ Set of periods
- $\mathcal{T}$ Set of available production technologies

Parameters and coefficients

- C_{ikt} investment costs in location i, for point k of capacity function, and technology t;
- D_{jp} demand in port j in period p;
- E_{klt} costs of expansion from capacity in point k to capacity in point l for technology t;
- F_{bkt} costs at breakpoint b of the short-term cost function given for capacity k and for technology t;
- L_{ijp} 1 if demand at location j can be served from facility i in period p, 0 otherwise;
- Q_{bkt} production volume at breakpoint b of the short-term cost function, for capacity point k and technology t;
- T_{ijp} transportation costs from facility i to customer j in period p;
- y_{iklt0} initial facility variable;
- δ_p discount factor in period p;
- τ_p length of time period p in years;

Decision variables

- x_{ijp} amount of customer demand at location j satisfied from facility i in period p;
- y_{ikltp} 1 if facility is opened in location i in period p, with originally installed capacity k, operated capacity l, and technology t, 0 otherwise;
- μ_{biltp} weight of breakpoint b at location i for capacity point k and technology t in period p.

We present a multi-period model where investment and expansion decisions are allowed during the whole planning horizon. The changes in formulation needed for the first-period model are presented at the end of this section. The problem is given as:

$$\begin{aligned}\min \sum_{i\in\mathcal{I}}\sum_{k\in\mathcal{K}}\sum_{l\in\{l\geq k:l\in\mathcal{K}\}}\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\delta_p C_{ikt}\left(y_{ikltp}-y_{iklt(p-1)}\right)+\\ \sum_{i\in\mathcal{I}}\sum_{k\in\mathcal{K}}\sum_{l\in\{l>k:l\in\mathcal{K}\}}\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\delta_p E_{klt}(y_{ikltp}-y_{iklt(p-1)})+\\ \sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}}\sum_{p\in\mathcal{P}}\delta_p\tau_p T_{ijp}x_{ijp}+\\ \sum_{b\in\mathcal{B}}\sum_{i\in\mathcal{I}}\sum_{l\in\mathcal{K}}\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\delta_p\tau_p F_{blt}\mu_{biltp},\end{aligned} \tag{1}$$

subject to:

$$\sum_{k\in\mathcal{K}}\sum_{l\in\{l\geq k:l\in\mathcal{K}\}}\sum_{t\in\mathcal{T}}y_{ikltp}\leq 1, \qquad p\in\mathcal{P}, \tag{2}$$

$$\sum_{l\in\{l\geq k:l\in\mathcal{K}\}}y_{ikltp}\geq\sum_{l\in\{l\geq k:l\in\mathcal{K}\}}y_{iklt(p-1)}, \qquad i\in\mathcal{I},k\in\mathcal{K},t\in\mathcal{T},p\in\mathcal{P}, \tag{3}$$

$$y_{ikltp}-y_{iklt(p-1)}\geq 0, \qquad i\in\mathcal{I},k\in\mathcal{K},l\in\{l>k:l\in\mathcal{K}\},t\in\mathcal{T},p\in\mathcal{P}, \tag{4}$$

$$\sum_{b\in\mathcal{B}}\mu_{biltp}=\sum_{k\in\mathcal{K}}y_{ikltp}, \qquad i\in\mathcal{I},l\in\mathcal{K},t\in\mathcal{T},p\in\mathcal{P}, \tag{5}$$

$$\sum_{j\in\mathcal{J}}x_{ijp}=\sum_{b\in\mathcal{B}}\sum_{l\in\mathcal{K}}\sum_{t\in\mathcal{T}}Q_{blt}\mu_{biltp}, \qquad i\in\mathcal{I},p\in\mathcal{P}, \tag{6}$$

$$\sum_{i\in\mathcal{I}}x_{ijp}=D_{jp}, \qquad j\in\mathcal{J},p\in\mathcal{P}, \tag{7}$$

$$x_{ijp}\leq L_{ijp}D_{ip}, \qquad i\in\mathcal{I},j\in\mathcal{J},p\in\mathcal{P}, \tag{8}$$

$$y_{ikltp}\in\{0,1\}, \qquad i\in\mathcal{I},k\in\mathcal{K},l\in\{l\geq k:l\in\mathcal{K}\}t\in\mathcal{T},p\in\mathcal{K}, \tag{9}$$

$$x_{ijp}\geq 0, \qquad i\in\mathcal{I},j\in\mathcal{J},p\in\mathcal{P}, \tag{10}$$

$$\mu_{biltp}\geq 0, \qquad b\in\mathcal{B},i\in\mathcal{I},k\in\mathcal{K},t\in\mathcal{T},p\in\mathcal{P}. \tag{11}$$

The objective function (1) is the discounted sum of investment costs, expansion costs, distribution costs, and production costs. Restrictions (2) guarantee that only one facility can be opened at the given location. Constraints (3) ensure that a facility can expand but cannot be closed. Capacity expansion is allowed only once during the planning horizon. The variable y_{ikltp} contains information about the initially installed capacity k as well as the capacity l at which it is currently operated. After expansion, the operated capacity l is higher than the installed capacity k. Inequalities (4) ensure that capacity index l can change only once. Equations (5) ensure that production is allocated only to opened facilities and that the short-term production cost function depends on operated capacity. Equations (6) express the requirement that the whole production has to be distributed to customers. Equations (7) ensure demand satisfaction, while constraints (8) specify if customer j can be served from facility i. Restrictions (9) - (11) are the binary and non-negativity requirements.

In our second model, a facility can only be opened in the first period. Expansion is still allowed in later periods. In this model, constraint (12) replaces constraint (3):

$$\sum_{l \in \{l \geq k : l \in \mathscr{K}\}} y_{ikltp} = y_{ikkt1}, \qquad i \in \mathscr{I}, k \in \mathscr{K}, t \in \mathscr{T}, p \in \mathscr{P}. \quad (12)$$

The rest of the model is identical to the first model.

3 Case study

In this section, we present the input data for the problem of designing the Norwegian hydrogen supply chain for maritime transportation. We include 17 candidate locations for hydrogen facilities on the Norwegian west coast. The candidate locations for hydrogen production are obtained from the interactive map set up by Ocean Hyway Cluster [28].

We consider two hydrogen production technologies: EL and SMR+. We approximate the facility capacity by 8 discrete points for EL and 7 points for SMR+. The discrete points are given in Table 3.1. We use the same discretization of capacity for both technologies, but we do not consider SMR+ for the smallest capacity. In Table 3.1, we provide facility investment costs and production costs per kilogram at the discrete capacity points. Note that with decreasing utilization, the production costs per unit increase. [33]

Discrete capacity	1	2	3	4	5	6	7	8
Capacity [tonnes/day]	0.6	3.1	6.2	12.2	30.3	61.0	151.5	304.9
Investment EL [mill. €]	1.4	6.0	11.2	20.5	46.5	87.2	197.7	371.5
Investment SMR+ [mill. €]	-	23.9	39.9	65.2	127.7	204.3	402.1	709.2
Production EL [€/kg]	1.95	1.61	1.53	1.45	1.43	1.42	1.40	1.38
Production SMR+ [€/kg]	-	1.91	1.61	1.42	1.28	1.18	1.04	1.00

Table 3.1: Investment and production costs for EL and SMR+ at discrete capacity points

The production rate for an EL facility can vary between $20-100\%$ of the installed capacity [25]. We define a piecewise linear, convex short-term production costs for each discrete capacity. We approximate the short-term production costs by a piecewise linear function with breakpoints at $20\%, 50\%, 80\%$ and 100% of installed production quantity. For simplification, we use the same production rates for SMR+. We use the model by Jakobsen and Åtland [16] for calculating investment and short-term production costs for electrolysis and SMR+.

We calculate the expansion costs as the difference between the investment costs of opening two facilities with different capacities plus an additional mark-up. We assume the mark-up for expansion to be 10% of the difference in investment costs.

We derive the costs of distributing one kilogram of hydrogen for one kilometer for distances up to 800 km from [9]. To obtain the costs for distributing up to 1000 km, we extrapolate the distribution cost function. The distribution costs per kilometer and kilogram hydrogen are then valid for the appropriate interval as shown in Table 3.2. If a customer is located in the same municipality as a facility, we assume zero distribution costs. We set the distance limit between production facility and customer to 1000 km. Hydrogen distribution over 1000 km is suitable for pipelines. However, pipelines are not considered relevant for Norway [8].

Distance [km]	1-50	51-100	101-200	201-400	401-800	801-1000
Costs	0.00498	0.00426	0.00390	0.00372	0.00363	0.00360

Table 3.2: Hydrogen distribution costs in [€/km/kg H_2]

We use two demand scenarios where hydrogen demand is increasing during the planning horizon (see Figure 3.1). In the maritime sector, demand moderately increases until period 11. In period 11, the coastal route Bergen-Kirkenes starts to operate on hydrogen fuels which causes a significant increase in demand. Until period 3, there is no difference between the two demand scenarios. In the whole transportation sector, the main demand growth is in periods 4 and 9 which corresponds to years 2025 and 2030. These dates represent two strategic phases for hydrogen transition in heavy transport and long-distance bus transport [11].

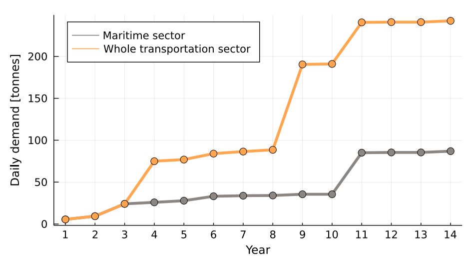


Fig. 3.1: Development of hydrogen demand during the planning horizon

- Maritime: high-speed passenger ferries, car ferries, and coastal route Bergen-Kirkenes, [2] and [27]
- All transportation: maritime sector plus road traffic and railway sector, [11]

Aarskog and Danebergs [2] and Ocean Hyway Cluster [27] present high-speed passenger ferry and car ferry routes that are relevant for hydrogen fuel as well as their bunkering locations. They list 51 relevant customer locations for the maritime sector and assume that new contracts for public transportation services will require a zero-emission solution and that hydrogen will be selected as fuel. For the whole transportation sector, the list of customers is extended to 70 locations and consists of bunkering ports and several inland locations relevant for hydrogen consumption in road traffic and the railway sector.

In our case, we assume the discounting interest rate to be zero. Thus, the discount factor δ_p is equal to one in each period.

4 Computational results

The model is implemented in Mosel and solved with Xpress Optmizer Version 36.01.10. All calculations were run on a laptop with a Intel(R) Core(TM) i7-10510U CPU @ 1.80GHz processor and 16GB RAM.

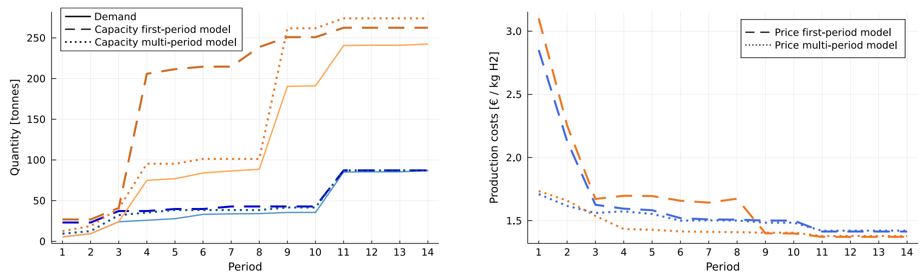
A summary of the main results of both demand scenarios and both models can be found in Table 4.1. We provide the main characteristics of the built infrastructure as the number of built facilities and the number of expansions. Total capacity and average size refer to the installed capacity and average facility size in the last period. The total costs represent the sum of investment, expansion, production, and distribution costs. The average hydrogen costs are calculated over the entire planning horizon average. Note that the chosen technology is electrolysis in all cases.

Demand scenario	maritime		all transportation	
Investment decision	first-period	multi-period	first-period	multi-period
Built facilities #	12	13	13	13
Expansion #	9	2	10	4
Total capacity [tonnes/day]	87.2	87.2	262.5	274.0
Average size [tonnes/day]	7.2	6.7	20.2	21.1
Total cost [mill. €]	606.0	578.0	1658.7	1594.1
Average hydrogen costs [€/kg]	2.73	2.61	2.53	2.43

Table 4.1: Hydrogen infrastructure characteristics.

Comparing the maritime sector and the whole transportation sector (all transportation), the installed capacity significantly increases in the scenario with higher demand, but not the number of built facilities. In the maritime sector, using the first-period model, the number of built facilities is 12. In all other cases, the number of built facilities is 13. As a result, the average facility size in the last period is almost three times higher in the scenario for the whole transportation sector comparing to the scenario for the maritime sector. The results further show that the expansion option is more often used in the first-period model as the number of expansion is 9 and 10 for the maritime and the whole transportation demand scenario, respectively. For the first-period model, expansion is the only way how increase capacity and so it leads to a higher number of expansions compared to the multi-period model which enables to build facilities later during the planning horizon.

Table 4.1 further indicates that the capacity utilization is better in the scenario for the maritime sector where the installed capacity is only slightly higher than demand in the last period. The installed capacity is 87.2 tonnes per day for both models and demanded hydrogen amount is 86.9 tonnes per day. In the whole transportation sector scenario, the infrastructure can daily provide 20 or 37 tonnes of hydrogen more than is the demanded amount for the first-period and the multi-period model, respectively.



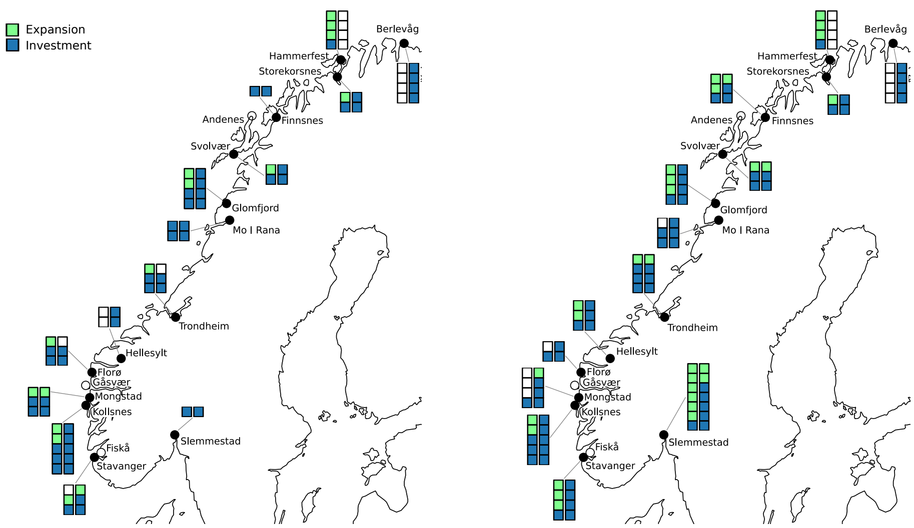
(a) Daily demand and installed capacity (b) Average production costs

Fig. 4.1: Illustration of installed capacity and average production costs in each period for both demand scenarios and both models. Blue lines refer to the maritime scenario and orange lines to the whole transportation sector.

Figure 4.1a provides an overview of installed capacity during the planning horizon. The capacity difference between installed capacity and demand is generally low in the maritime scenario independently of the used model. In the whole transportation sector scenario, the first-period model expands in the period 4 and then the installed capacity is 2.7 times higher than the demand. In the multi-period model, the significant increase in capacity comes in period 9 where three of the four expansion in this scenario are performed and then the increase in capacity is significantly higher than the increase in demand. However, the difference is much lower than in the first-period model and the low capacity utilization affects only periods 9 and 10. The reason is that expansion is allowed only once so the expansion is performed directly to the target size. Figure 4.1a also shows that from period 11 onwards, demand remains constant and the installed capacity is just slightly higher than demand because the investment and expansion decision aimed to satisfy this target value of demand. In addition, the choice of capacities is limited by the discrete available capacities. With our choice of discrete capacities, the lower demand in the maritime scenario can be satisfied with low excess capacity. When larger capacities are needed, it becomes more difficult to successively build the capacity in line with growing demand because differences between adjacent capacities are increasing.

Figure 4.1b shows the average hydrogen production costs. In the first three periods, the multi-period model performs significantly better because it allows to build only a few facilities with high utilization in the first periods and to build more later when demand increases. This advantage of the multi-period model also leads to lower total costs and about 5% lower average hydrogen costs than the first-period model.

Figure 4.1 as a whole further illustrates the economies of scale, as increasing demand leads to lower unit production costs. We can see an exception in the first-period model in the scenario for the whole transportation sector. The average production costs in period 4 and 5 are higher than the costs in period 3 and then again the costs increases in period 8. Due to the capacity expansion in period 4 and 8 (see Figure 4.1a), the increase in capacity is significantly higher than the demand growth. The capacity utilization is low, and the unit production costs increase.



(a) Maritime transportation (b) Whole transportation sector

Fig. 4.2: Investment and expansion structure of opened hydrogen facilities. The column height corresponds to the installed discrete capacity. Left columns represent the first-period model and right column represent the multi-period model.

The optimal investments in opening and expanding facilities for both models and both demand scenarios are illustrated in Figure 4.2. Figure 4.2a shows the hydrogen production infrastructure for maritime transportation and Figure 4.2b shows the infrastructure when the whole transportation sector is considered. The blue boxes denote the discrete capacity that was originally invested in, and the green boxes represent the additional discrete expansion capacity. Comparing the Figures 4.2a and 4.2b, there is no big difference in the infrastructure design in the northern part of Norway because most of the demand in that region comes from the maritime sector. The main difference and also the highest density of opened facilities is in the southern part of Norway. In the maritime scenario in the first-period model (left column), the facilities in Mongstad and Florø are larger than in the whole transportation sector scenario even if the demand in the whole transportation sector is higher and the basic demand from the maritime sector is the same. In the whole transportation scenario, the facility in Slemmestad expands already in period 4 to the target size (see Figure 4.1) and helps to satisfy the demand on the west coast.

The demand in the first periods is very low. Because of that, the infrastructure has to be successively built to satisfy demand from the first period. Later, when demand increases, there are already several smaller facilities that still have to be used and satisfy a part of this demand. The remaining requested hydrogen amount is not large enough to build a new SMR+ facility. An SMR+ facility is favourable for quantities higher than 210 tonnes hydrogen daily which is just slightly lower than hydrogen demand in the last period. As a result, due to the low initial demand level, there are built smaller EL facilities in all tested cases.

5 Conclusion

We study the optimal hydrogen infrastructure for maritime transportation in Norway. We use two multi-period models and analyze two demand scenarios. We consider capacitated modular facility location problem with economies of scale and two possible production technologies. We allow the production rate to differ from the installed capacity for both technologies.

Scenario with higher demand does not lead to a higher number of built facilities suggesting that the maritime sector can help to create a hydrogen infrastructure that can be used for the whole transportation sector later. Due to economies of scale, increasing demand with a stable number of facilities leads to lower production costs. This further indicates that higher initial demand could help to achieve higher competitiveness of hydrogen.

The impact of hydrogen demand generated by the road traffic sector on the size of the Slemmestad facility reflects that it would be worth considering candidate facility locations in the inland southern part of Norway.

As the investment decision flexibility has a significant impact on the designed infrastructure, a natural extension of this work is to allow facility closing and technology change during the planning horizon.

The infrastructure design and overall costs highly depend on the demand scenario. An extension of this work is to introduce uncertain demand and thus several demand scenarios and construct a stochastic optimization model. It will be also interesting to analyze the technology choice and the cost structure if we consider uncertainty in costs.

Considering international maritime transportation, ships may purchase fuel in foreign countries. It may increase the uncertainty in demand and lead to pressure on the hydrogen price in Norway. A complex model where the impact of international hydrogen purchasing on national hydrogen demand and hydrogen price is studied is subject to future work.

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