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RECEIVED
28 April 2023

REVISED
30 August 2023

ACCEPTED FOR PUBLICATION
4 September 2023

PUBLISHED
19 September 2023

LETTER

Low-carbon electrification as a multi-system transition: a socio-technical analysis of Norwegian maritime transport, construction, and chemical sectors

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Keywords: electrification, multi-level perspective, multi-system interaction, transition pathways, electricity system

Abstract

Electrification of end-use sectors is widely seen as a central decarbonisation strategy. However, the process of electrification is rarely discussed beyond electric end-use technologies such as electric vehicles or heat pumps. While electrification of end-use sectors is about new types of consumption, it also requires new technological interfaces with the electricity system. The paper provides a first conceptualisation of electrification as a multi-system interaction process, involving changes in both end-use sectors and in the electricity system. Electrification is thought to involve two core processes: (1) transitions in systems where electric niches challenge fossil energy regimes, and (2) reconfiguring patterns of multi-system interactions across production, distribution, and use of electricity. Through a case study design, we compare three sectoral cases that differ substantially in degrees and speed of electrification: ferries, construction sites and ammonia production. We explain these differences by analysing how the actors, technologies and institutions in each system shaped both the diffusion of electric end-use technologies and the interactions with the electricity distribution system. We find that the speed and ease of electrification depend on varying mixes of technological, actor, and institutional change processes. The severity and pervasiveness of grid connection challenges are arguably the most important finding. Grid connection challenges were significant in all three cases and continue to hamper electrification in two cases. Based on those findings, we conclude that grid capacity is increasingly problematic. Electricity system actors are overwhelmed with new demand, resulting in long lead times. And, they are further constrained by institutions that were designed to optimise for the efficient operation of existing assets rather than to innovate and transform electricity grids.

1. Introduction

Electrification of end-use sectors is a key strategy in most net-zero transition scenarios (IEA 2021, Luderer *et al* 2022). Many of these scenarios include techno-economic analyses of end-use technologies such as electric vehicles and heat pumps as well as massive deployment of renewables (Edelenbosch *et al* 2018, Knobloch *et al* 2020, 2021, Milovanoff *et al* 2020). Moving beyond these analyses, we aim to make two contributions to electrification debates.

First, while comprehensive in scope, techno-economic analyses say little about the role of actors and institutions in realizing scenarios. We draw on sustainability transition studies to conceptualize electrification as a multi-system transition process involving coupled changes in production and distribution systems as well as end-use sectors (McMeekin *et al* 2019). While electrification of end-use sectors is about new types of consumption, it also requires new interfaces with the electricity distribution system, at the same time as the production system expands and decarbonizes in parallel. Few studies have analysed the process of electrification as interaction between these systems and sectors[4].

Second, we contribute empirically by analysing electrification processes in three end-use sectors that have received little scholarly attention: maritime transport, construction and chemical sectors looking at electrification of ferries, construction machines, and ammonia production. We analyse electrification of these sectors in Norway, which is a global frontrunner in low-carbon electrification. Electricity, generated almost entirely from renewable sources (especially hydropower), is the primary energy carrier in Norwegian households for space and water heating, while 78% of new cars were electric in 2022. Other countries may thus learn from Norway's electrification processes. Other countries may thus learn from Norway's electrification processes.

Our analysis is guided by an extended version of the multi-level perspective (MLP), which conceptualises socio-technical systems as consisting of technologies, actors, and institutions (Geels 2004, Geels and Turnheim 2022). Focusing on these three dimensions, we analyse the diffusion and implementation of electric technologies as well as interactions with the electricity distribution system.

2. Conceptual framework

The MLP suggests that transitions involve multi-dimensional interactions between radical niche-innovations and existing regimes in the context of broader 'landscape' developments (Geels and Turnheim 2022). Since most MLP studies focus on single systems, we draw on recent multi-system interaction research within the transitions literature (McMeekin *et al* 2019, Rosenbloom 2020, Andersen and Geels 2023) to broaden the analytical scope. Figure 1 schematically illustrates how electrification involves two core processes: (1) transitions in systems, which involve niche-innovations struggling against existing regimes, e.g. battery-electric ferries against the diesel-power ferry regime; electrolysis against the natural gas refraction regime in ammonia production; and electric machinery versus diesel machines in construction; (2) creating new and reconfiguring existing patterns of multi-system interactions across production, distribution, and use of electricity. We expect that both processes are challenging and contested because there are likely to be structural differences and tensions between actors, institutions, and technologies in different systems (Rosenbloom 2019). Low-carbon electrification thus happens through innovation in, parallel expansion of, and new connections across production, distribution, and consumption domains in what inherently is a multi-system transition.

The speed of electrification processes in end-use sectors is likely to vary, depending on the momentum of niche-innovations and the degree of tensions in connecting to the electricity distribution system. To empirically analyse both processes, we lean on literature about technology, actors, and institutions.

Technological diffusion literature (Rogers 2003, Geels and Johnson 2018) suggests technological complexity, cost, turnover rates, and competence requirements influence adoption speeds in end-user sectors. Large-scale, expensive technologies with high asset longevity tend to diffuse slowly, while modular technologies that preserve existing capabilities and infrastructure or have high turnover rates may diffuse faster. Technologies requiring major investments in complementary technologies also tend to diffuse more slowly (Grubler 2012). For example, extending electricity grids can be costly and challenging, especially if it involves not just building a new cable but also deeper grid reconfigurations to increase capacity (Andersen 2014, Tenggren *et al* 2016). Challenges may also involve the creation of new interface technologies such as batteries or charging stations.

Since the primary actors in our sectors are firms and policymakers, we mobilise insights from strategic choice theory (Child 1997, Wüstenhagen and Menichetti 2012) to explain 'why' firms adopt low-carbon innovations and the resource-based view of the firm (Barney 1991, Oliver 1997) to explain 'how' they adapt. For companies, we distinguish two main strategic motivations: regulatory compliance and the perception of economic opportunities based on considering costs and direct or long-term benefits of adopting low-carbon innovations. Considerations that shape 'how' and 'how fast' firms adopt include financial resources (in relation to adoption costs) and technical capabilities (especially if they need to acquire new ones). Strategic motivations for policymakers are climate mitigation and a desire to support sectors (especially if these face international competition).

Although institutional theory distinguishes formal and informal institutions (North 1991), we

[4] Socio-technical systems cover the elements in production, distribution, and consumption domains or sub-systems that together fulfil societal functions. In the context of electrification, however, the consumption domain is comprised of multiple sub-systems ranging from housing and industrial production to transport where each sub-system has idiosyncratic configurations of actors, institutions, and technologies. Sectors are narrower than sociotechnical systems and delineated according to a specific set of products (e.g. chemicals, cars, steel, or electronics) or services (e.g. electricity distribution or finance) (Malerba 2002). We use the notion of a sector to describe and distinguish various consumption sub-systems. Multi-system interactions in this paper are thus concerned with interactions between electricity production and distribution sub-systems (henceforth merely systems), on the one hand, and end-use sectors (sub-systems), on the other. We prefer sector over sub-system because it is closer to standard jargon in the energy and climate change domains. Note that operation of each sub-system/sector is organized around one or several sociotechnical configurations of varying degrees of structuration (regimes and niches).

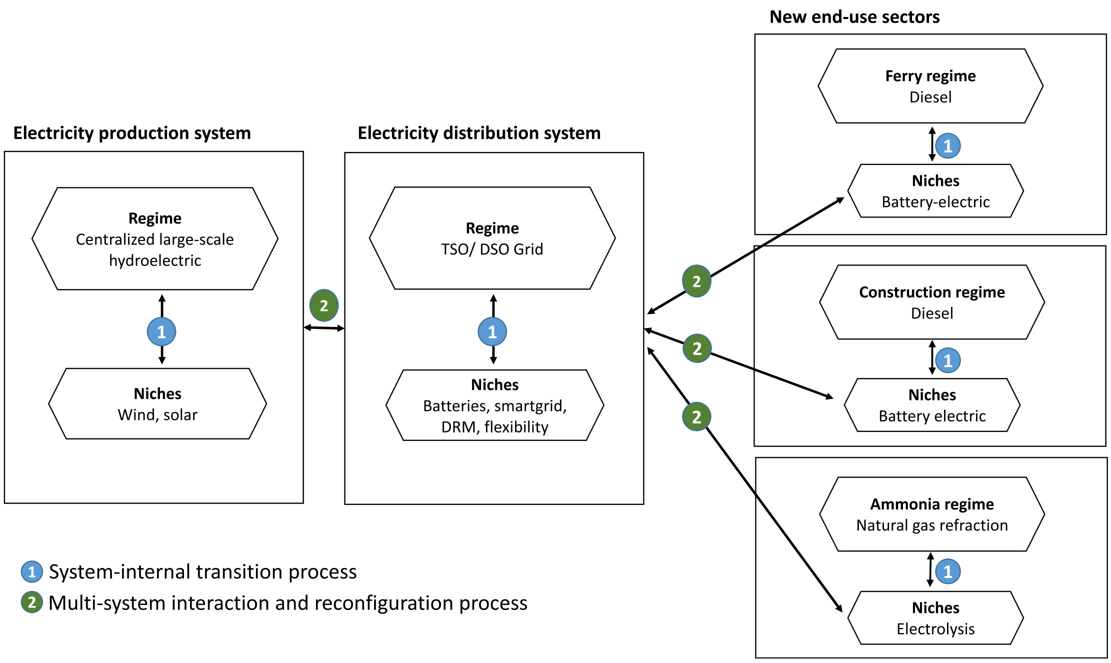

Figure 1. Analytical framework for electrification as multi-system interaction process.

focus on formal ones, including policy goals, regulations, subsidy schemes and other incentives.

3. Research design

We use a comparative case study design, which aims to analyse and explain the varying speed and ease of electrification in three end-use sectors. Speed and ease of electrification were highest for ferries, medium for construction, and low for ammonia production. Our analysis aims to explain these differences in terms of varying technological, actor-related and institutional drivers of technology adoption and the degree of challenges in connecting with the electricity distribution system.

Focusing on the 2015–2022 period, our analysis draws on primary data from 38 interviews with policymakers, companies, and other organizations (appendix A). We also analyse documents including media archives, government white papers, commissioned industry reports, and company annual reports (appendix B, tables B1–B4).

The next section presents our analyses of the three cases, which first address the technological, actor-related and institutional dimensions that shaped new technology adoption in each sector and then the interactions with the electricity distribution sub-system, which also has technical, actor-related and institutional dimensions. The text references respondents using R-numbers and documents using D-numbers.

4. Analysis

4.1. Electrification of ferries in the maritime transport sector

Ferries that transfer vehicles and people along the coast are a vital part of public transport in Norway. There are about 130 car passenger ferry routes, operated by around 200 vessels. Routes are owned either by the state or by municipalities. Route owners contract private ferry operators to provide transport services. There are about 10 large companies that operate multiple ferry routes. Before new contract periods start, operators contact shipyards to build or retrofit ferries to comply with contract specifications.

Over the last decade, a policy-led transition to zero-emission ferries has started to unfold, driven by the diffusion of electric ferries (figure 2). As of 2022, about 33% of car-passenger ferries have been fully electrified. Adopted policies to only procure zero-emission taking effect from 2023, is set to drive further electrification (D20/D21/D22).

Technology: One reason that electrification was relatively rapid is that fitting batteries and electric motors in a ship hull is a matter of component substitution rather than radical design changes (Bugge *et al* 2022). Due to safety regulations, e-vessels need a backup propulsion system, which means electric ferries also have backup combustion engines. This somewhat increased cost and complexity but also implied that operators could start with new ferry services

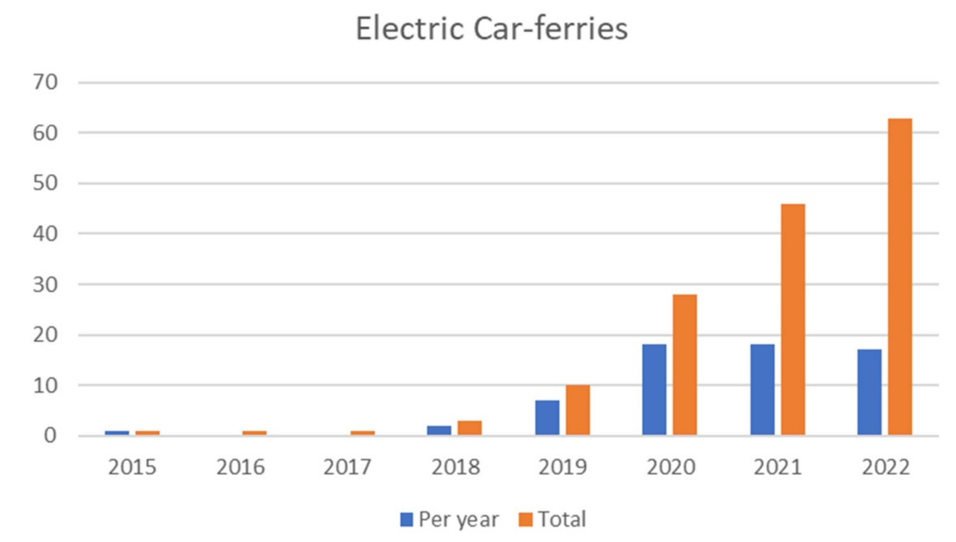

Figure 2. Number of electric car ferries in Norway, 2013–2025 (Norsk klimastiftelse 2022).

(often using biofuel) even if electric grid connections and charging technologies were lagging (R7/R10). Capital expenditures for electric ferries are higher but operational costs (on energy and maintenance) lower than traditional ferries (R10/R11). The somewhat higher cost did not hamper adoption, because of policy instruments such as investment support and R&D grants (Steen *et al* 2019, Sæther and Moe 2021).

Actors: In the context of public and political debates about emission reductions from maritime transport, policymakers launched a development contract in 2010 for a pilot project with an electric ferry, Ampere, which became operational in 2015. The project's success paved the way for a parliamentary decision in 2015 to require that all ferries would be zero-emission where possible (Sjøtun 2019). Although the shift to electric ferries required learning and new competence building, ferry operators did not actively resist these plans and policies because the shift was not seen as overly complicated and because higher costs were compensated (R7/R9/R13). Ferry electrification was also enabled by presence of local ship manufacturing firms with the technical capabilities to retrofit or rebuild vessels and by entry of local electric engineering firms (as local ABB and Siemens subsidiaries) providing needed electronics capabilities (Bugge *et al* 2022). The absence of losers and opposition, and the presence of capable manufacturers and operators help explain the relatively high speed of ferry electrification.

Institutions: National policymakers introduced subsidies and investment support for early movers, while route owners introduced new public procurement contracts that paid more for electric ferries. The comprehensive policy strategy thus set targets and helped firms reorient through subsidies and public procurement contracts.

Interaction with electricity distribution sub-system: Electric ferries required both new ***technological*** connections to the electricity distribution system and new technologies to charge batteries when ferries are docked. The problem was that many ferry quays are in peripheral areas with weak grids that struggled to provide sufficiently large amounts of power during short charging periods. Grid connection therefore frequently required not just new cables, but also deeper reconfiguration of local grids, which is expensive and can take years (R8/R9/R17). To avoid long waits, some ferry operators therefore started to explore and implement alternative interface technologies such as onshore battery banks and battery swapping solutions, which added costs and required new competencies but accelerated the process (R7/R11/R14). Local grid variability, technological immaturity of charging solutions, and lack of standardized solutions were challenges that hampered grid connection (R7/R11). Ferry-grid connections were also hampered by ***regulatory institutions***. The revenue model for Distribution System Operators (DSOs), which pays these companies for the number of customers (sales points) served and for the minimization of capital cost, disincentivised DSOs to engage with ferry electrification because they would only gain one new customer and may have to spend a lot of money on local grid reconfiguration (R8/R9). In terms of ***actors***, the demand for grid connection and charging technology came from ferry operators, who initially underestimated the technical and institutional challenges, which frequently led them to contact DSOs only *after* they had won an electrified ferry route contract (R14). Although DSOs are legally obliged to grant requested grid connections, they engaged relatively reluctantly (because of their revenue model and because ferry operators were not a priority) (R7/R10/R13/R16). DSOs consequently often let ferry operators wait or advise alternative solutions like onshore battery banks. Interactions between ferry operators and multiple DSOs mostly happened on a project-by-project basis, which created uncertainties and meant that ferry operators with multiple routes could only limitedly standardise solutions. There were few efforts to share experiences between projects or stimulate discussions between wider actor communities to standardize and aggregate lessons about new charging technologies (R14). Adjustments with regard to charging and grids were mostly made by maritime actors and new interface actors that intermediated between DSOs and ferry operators. Ferry operators, for instance, explored and implemented alternative charging solutions, while the route owners adapted procurement procedures as well as planning and travel timetables to better fit the grid system.

In sum, while electric ferry adoption progressed relatively rapidly, grid-connection was more problematic, slowing down the process and leading to suboptimal configurations.

4.2. Electrification of machinery in the construction sector

Around 60% of construction projects are publicly procured by state and municipal entities through competitive tendering. Most construction industry firms are small or medium-sized enterprises that serve as subcontractors to larger contractors. Machinery is usually provided to projects by machine contractors and/or equipment rental firms.

Spearheaded by the city of Oslo and closely followed by all larger cities and surrounding municipalities, a transition to zero-emission construction processes has emerged in the past 5 years (R21/R22/R23). Lacking a mature electric machine sector, local actors imported standard diesel machines from international suppliers and repurposed them with electric motors. They first repurposed electric excavators in 2018, followed by electric wheel loaders, dumper trucks, and belted diggers up to 32 tons (R18). By 2022, around 180 electric machines were in use, and 5% of new machine sales were electric (D47), see figure 3. While this market penetration is medium-fast, electric machines represent a smaller fraction of the machine park due to replacement lag effects.

Technology: The adoption of electric machines is relatively easy because they require few new skills to operate. They offer less noise and vibration, but electric cables can get in the way and limit reach, while batteries limit operating time. Current battery-electric machines can operate for 3–5 h before they need (fast) charging (R18/R19/R20/D31/D34). Electric machines are about three times more expensive to buy, but they last longer and cost less to operate (R18)[5]. Price reductions are likely, but require a larger market so that international suppliers will start producing factory-built electric machines combined with lower battery prices and improved performance. International suppliers watch the Norwegian niche closely but need a bigger market to justify new factory models. Technically, the Norwegian machine park could be electric within 7 years, which is the lifespan of diesel-powered construction machinery (R18). Many firms prefer to postpone investment until there are cheaper factory-built machines with longer operating times or changeable batteries (R23). This is likely to slow diffusion in the coming years.

Actors: Municipal policy actors initiated the transition because they felt mandated by voters to be more ambitious about climate mitigation. In 2016, the city of Oslo committed to 95% emissions reduction by 2030, which led it to require all public construction to be zero-emission by 2025 (R25). Similar goals were subsequently adopted by other urban municipalities (D39-D44).

Electric machinery has so far mainly been purchased by a few large machine contractors and large rental operations with sizeable machine parks, whose customer base include public actors. In 2022, they represented about 3% of all machine contractors, which is a group of firms that mostly consists of small businesses or one-man operations for whom the adoption of electric machines is too expensive. Net-zero construction tenders stimulate construction firms to hire electric machines from rental operations or machine contractors. The additional costs of electrification are borne by public construction clients because firms factor it into tenders.

Institutions: To drive the transition, local policymakers set demanding goals and wrote contract tenders that paid more for zero-emission construction projects, while also weighting environmental performance equal to price (environment 30%, price 30%, quality 40%) in tenders. The absence of similarly demanding goals and support policies on the national level is slowing the transition (R25). In 2020, national policymakers set a target for 70% electrification of construction by 2030, which lags many local goals. And while the national government supports adoption of electric machinery and charging infrastructure, they also subsidise diesel for construction machines. The lack of cohesive policies is causing uncertainties and waiting games that slow electrification. Contractors say they will invest in

[5] Diesel machines usually operate for 7–12 000 h, whereas electric machines can operate for up to 50 000 h.

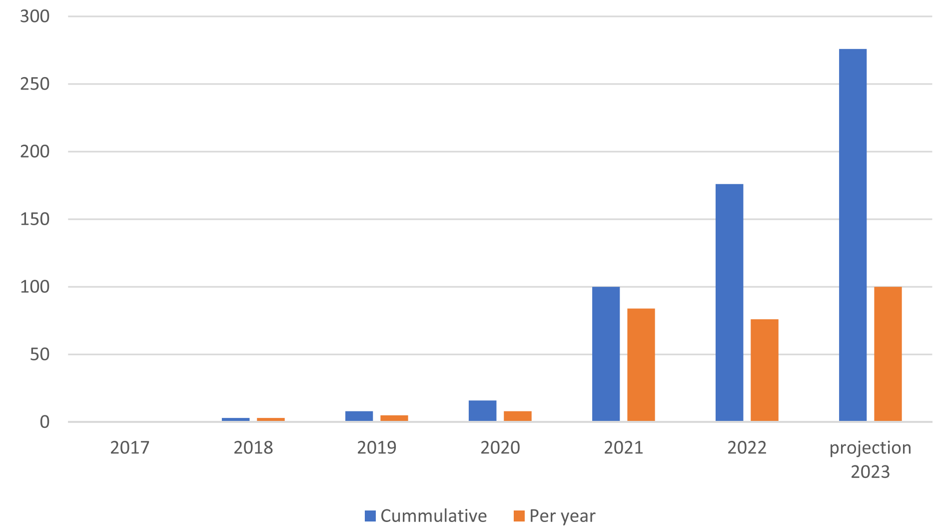

Figure 3. Total number of electric machines in Norwegian construction (based on data from suppliers and industry association).

electric machinery when developers demand zero-emission sites; private construction clients hesitate to demand zero emission construction unless it is mandated by government; and city administrations struggle to legally impose demands on private firms while the national government hesitates to impose such demands (R18/R23).

Interaction with the electricity distribution subsystem: Construction sites are temporary and move around, which makes permanent ***technological*** grid connections infeasible. Fossil-based construction sites are usually temporarily connected to the grid with cables above ground and a panel in a steel cabinet. This solution does not provide enough power to charge electric machines. When the finished building represents a permanent electricity need, DSOs can make early grid upgrades so that the building project can tap into it to power construction machines, this however requires involving DSO in early project-planning phases (R21R22/R25). Another solution are new interface technologies such as container-sized batteries, which since 2021 are sometimes offered as part of an electric machinery package. The battery-containers charge from the grid overnight and provide extra wattage for fast charging during the day (R27). While technical solutions exist, machine electrification is often hampered by ***institutions***. Contractors complain about the mindset and operating practices of DSOs which they see as not service-minded and unresponsive to their needs (R23). Which relates to *regulatory institutions* such as the DSO revenue model and mandate, discussed above. Because of these problems, new ***actors*** (consultants and specialized firms) have appeared to handle grid interactions (R27/R26). Site managers have also started to develop new competencies such as better planning charging needs and load balancing (R23). Oslo's Climate Agency also looked into the grid connection issue and found that future power needs for electrification of construction sites exceeded the planned capacity by 70% (D35/D36). This, in turn, led to the creation of a standing working group with the DSO to coordinate and plan future grid use (R25).

In sum, while electric machinery adoption is slowly progressing (although somewhat hampered by policy misalignments), challenges in distribution grid connection are being circumvented with new interface technologies and services provided by new actors.

4.3. Electrification of ammonia production in the chemical sector

Fertilizer company Yara operates the only ammonia facility in Norway. The production uses natural gas and is a significant source of emissions. Plans for electrification emerged around 2016/2017, after a technical evaluation found that the plant was less suited for carbon capture and storage (CCS). Currently 1% of its hydrogen is produced with electrolysers, which means that electrification is so far slower than in the other two cases.

Technology: Ammonia production involves two processes, hydrogen production and conversion to ammonia. Electrification in this case means substituting hydrogen made from natural gas with hydrogen produced by electrolysing water. Yara's green hydrogen is produced as a result of a pilot project, a 5 MW electrolyser which opened in 2022. A larger 24 MW electrolyser is under construction, which will increase the share of green hydrogen to 5%. Because hydrogen is a feedstock, electrolyser technology can be introduced as a front-end add-on to ammonia production, which enables a stepwise substitution. Up to 10% of green hydrogen can be blended in without requiring further changes in the overall ammonia production process. Shifting fully to green hydrogen would thus increase technical complexity and cost (R28). Although electrolysers are considered relatively mature, they are expensive, and experience with large-scale applications is still limited (R28/R29). This suggests that full electrification will be a slow process.

Actors: Because policymakers only limitedly drive industrial decarbonisation, the electrification of ammonia production is primarily driven by strategic motivations (R28/R29). The decision to electrify, despite the technological uncertainty and high price of electrolysers, was made believing electrolyser prices would come down (R28), and in the context of global expectations of green hydrogen's role in decarbonisation scenarios (IEA 2019). In 2016, Yara created an internal working group to explore technological options to decarbonize production and identify business opportunities for green ammonia. They initiated strategic interactions with food system actors (about crops using zero-emission fertilizers) and shipping industry actors (about ammonia as future shipping fuel). In 2018/19, Yara and electrolyser company NEL received a government grant and entered a partnership that resulted in the first pilot. Yara's strategic motivations increased in 2019, when the International Maritime Organization pointed to ammonia as a future shipping fuel (R28). This potential growth market, the availability of inexpensive green electricity, coupled with policy signals about the strategic importance of hydrogen for Norway (D51-53), led to a surge of research collaborations and feasibility studies for electric ammonia production in Norway. In 2021, three industrial heavyweights (Yara, Statkraft, Aker Hozions) joined forces in a venture called HEGRA, which aimed to develop a value chain for green hydrogen and green ammonia in Norway—starting with the electrification of Yara's ammonia plant. Although the project was granted 25 million EUR for a pilot plant, the partnership was dissolved in 2022 because of 'strategic differences'. Yara nevertheless continued and established Yara Clean Ammonia as an independent company.

Institutions: The Norwegian governance style towards large internationally-oriented firms tends to be 'arm's length' and accommodating rather than interventionist. Climate policy and industrial policy are consequently closely integrated. Although policymakers have not articulated specific goals, green industry policy strategies over the last decade have cultivated a vision of electrification-led green industry growth, using Norway's access to hydroelectricity and existing competencies with hydrogen, shipping, and the power sector (D5/D12D50/D51). To materialise this vision, policymakers have offered support for R&D and pilot projects. Industry actors, however, are calling for instruments to facilitate upscaling such as contracts for difference, which have been discussed but not yet introduced.

Interaction with the grid: Because green hydrogen production requires large electricity volumes, Yara has applied to the transmission system operator (TSO) to ***technologically*** connect their plant to the transmission grid. Legally, the TSO cannot refuse requests to connect to the grid, but the electricity volumes required cannot be accommodated without deep redesign of the transmission grid in the area as well as the construction of new transmission lines. This would implicate lengthy licensing, public consultations and other ***institutional processes*** because redesigning the transmission grid intersects with political decisions about offshore wind licences and transmission line locations. The TSO is poorly equipped to deal with the institutional processes for this kind of large-scale electrification, which cause delays (R30/R38). The main ***actor***, Yara, is pursuing four courses of action. First, it directly interacts with the TSO. But their application to connect from 2021 is still formally unanswered because of the institutional challenges discussed above. Second, they interact with policymakers in three different ministries to align and advance decisions about grid redesign with political decisions about onshore and offshore wind licencing and future transmission grid lines. Third, they cooperate with other actors in the area to construct their own connection to the transmission grid as a public-private partnership, which is costly and risky but would likely speed up the grid connection process. Fourth, Yara is exploring the option of onsite (or nearby) renewable energy production, which would diminish the grid connection needs.

In sum, although electrification of ammonia production is progressing, the speed is so far relatively slow because of the high cost, technical complexity of plant conversion, and because of grid connection problems.

5. Conclusions

The three cases demonstrate that electrification is indeed a multi-system phenomenon, which involves transitions in end-use sectors (driven by diffusing niche-innovations) as well as new connections to the electricity distribution system. With regard to the former, the three cases show that the speed and ease of transitions in end-use sectors depend on varying mixes of technological, actor-related, and institutional processes. With regard to the distribution system, we find that grid connections were key bottlenecks in all three cases that continue to hamper electrification in two cases.

More specifically, the three cases varied in speed and challenges due to sector-specific transitions and grid connection. In ferry electrification, which is the fastest case, sector-internal adoption was relatively

Table 1. Case comparison.

Electrification process	Socio-technical dimension	Ferry electrification	Electrification of construction	Electrification of ammonia production
Sector-internal adoption	*Technology*	Relatively easy component substitution; moderately expensive;	Electric machinery technically immature and relatively expensive compared to diesel versions.	Very capital-intensive and technologically complex; modular scale-up possible, but requires plant retrofit beyond 10%.
	Actors	Ferry operators comply with policy goals; their switch to electric ferries is relatively uncomplicated; additional costs compensated by new ferry contracts.	In response to net-zero contract tenders, companies purchase or hire electric machinery from a few large rental or machine operators; many actors wait for more developed cheaper versions; adoption may remain challenges for the many SMEs in this fragmented industry.	Yara engages for strategic reasons; capital costs are main concern.
	Institutions	Policy goals and various instruments (including public procurement via new ferry contracts) drive transition.	Municipal goals and instruments (including contract tenders) drive transition; misalignment with national policy creates problems.	Policymakers offer some support for R&D and pilots, but not yet for upscaling
Electricity system interaction	*Power needs*	Substantial, requiring grid adjustments.	Limited and temporary	Gigantic, requiring transmission grid redesign
	Institutions	Institutions disincentivise DSOs to engage with ferry electrification, causing long lead times for grid upgrades that slow down electrification.	Institutional problems with DSOs circumvented with alternative solution	Institutional and political problems hamper electrification, causing uncertainties and long lead times (10–12 years).
	Technological interaction	Slow creation of connections; charging infrastructure immature; new interface technology (stationary battery systems)	New interface technology (battery-containers) solve technical grid connection issues.	Want to speed up by building connector cable privately. Complex because of scale.
	Actor interaction	Ferry companies pursue connections, but DSOs respond slowly; ferry companies pursue alternative options supported by new interface actors	Grid connection problems provide opportunities for new interface actors.	TSO unresponsive. Yara pursues multiple alternative options

quick and smooth, while grid connection challenges hampered the process, leading to ad-hoc suboptimal solutions. In construction electrification, which is our medium-speed case, grid connection challenges are being overcome with new interface technologies (mobile battery containers). Sector-internal adoption has been advanced by a few large actors but was hampered by policy misalignments. In ammonia electrification, which is our slowest case, sector-internal adoption is progressing smoothly but slowly (because of high cost and technical complexity), while major grid connection challenges threaten to hold electrification back. Table 1 provides a more differentiated explanation of the relative speed and ease of sector-internal and grid connection processes, using the factors discussed for technology, actors, and institutions in section 2.

Our analysis makes several contributions to analyses of low-carbon electrification (IEA 2021, Luderer *et al* 2022). *First*, electrification should be seen as a sociotechnical process that is inherently sector-specific in terms of the configurations of actors, institutions, and technologies needed to electrify. *Second*, it reveals the challenges related to actors, institutions, and technologies for ensuring timely and adequate grid connections. Indeed, The Norwegian frontrunner case shows that grid capacity is increasingly a key bottleneck. Grid actors are overwhelmed with applications, resulting in long lead times, because they are constrained by institutions that were designed to optimise efficient operation of existing assets, not to extend and transform electricity grids. Interestingly, we observe that in the interface between distribution system and end-use sectors, the former hardly changes but instead imposes its regulations and logic onto the latter, indicating unequal power relationships between systems. One reason is that end-use sectors are under pressure to decarbonize and therefore partly destabilized while the distribution system so far is not. This suggests that a transition in the distribution system may be needed to ensure rapid electrification. *Third*, our analysis showed that in the face of grid bottlenecks, new interface actors and interface technologies emerged to mitigate problems via cross-system intermediation and business models. This suggest that interface innovation and experimentation can mitigate tensions in electrification created by rigid distribution system regime, e.g. by use of novel flexibility technologies as batteries, demand-response, and ICTs (Andersen *et al* 2023). This is a new phenomenon in low-carbon electrification which merits more attention.

These insights have broader relevance because low-carbon electrification is a central strategy for most countries in reaching net-zero emission goals including major expansion of electricity supply and grids (IEA 2021). Our findings are relevant for policymakers because inter-sectoral bottlenecks are already delaying low-carbon electrification, e.g. there are long queues in connecting to the grid for both new production and consumption in the US and the UK (Mooney 2023), missing cross-sector connections slow down production and utilization of green hydrogen (Mäkitie *et al* 2022), and cross-sectoral tensions inhibit timely provision of transition minerals (Gong and Andersen 2023). To mitigate the risks of delays in electrification, we suggest that policymakers pay more attention to sector specificities (e.g. particular configurations of actors, institution, and technologies) and multi-system interaction processes (e.g. how new interfaces are created and power relations).

Overall, we suggest that connections to grid infrastructures (and possible grid adjustments) deserve more academic and policy attention because associated challenges will likely become more pervasive and visible in the coming years as electrification processes unfold in more sectors and countries.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Appendix A. List of interviews

R-number	Informant	Sub-case
1	Energi Norge 1 Industry association	Scoping
2	Energi Norge 2 Industry association	Scoping
3	Energi Norge 3 Industry association	Scoping
4	Norsk Industri 1Industry association (not transcribed—notes)	Scoping
5	Norsk Industri 2 Industry association (not transcribed—notes)	Scoping
6	Skyss Regional procurer of ferry services	Maritime
7	NPRA (National Public Road Administration)	Maritime
8	MøreNett 1 DSO (engineer)	Maritime
9	Mørenett 2 DSO (Board member)	Maritime
10	Fjord1 Ferry operator	Maritime
11	Norled Ferry operator	Maritime
12	Torghatten Ferry operator	Maritime
13	Trønder energinett DSO	Maritime
14	ZERO Environmental NGO	Maritime
15	Trondheim Havn Harbour company	Maritime
16	REN Business association for DSOs	Maritime
17	NVE Norges vassdrags- og energidirektorat	Maritime
18	NASTA Machine supplier	Construction
19	Backe General contractor (project manager)	Construction
20	Backe General contractor (site manager)	Construction
21	Bymiljøetaten Oslo—Public procurer of construction	Construction
22	Bergen municipality—Public procurer of construction	Construction
23	Skanska General contractor (procurement)	Construction
24	CRAMO Machine contractor/machine rentals	Construction
25	Klimaetaten Oslo Municipality—Policy actor	Construction
26	BKK electrification—consultancy	Construction
27	Aneo Build Power sector/batteries	Construction
28	Industry actor	Industry
29	Industry actor	Industry
30	Lede nett—DSO	Industry
31	Enova 1—public support schemes	Industry
32	Enova 2—public support schemes	Industry
33	NVE Norges vassdrags- og energidirektorat	Industry
34	Industry actor	Industry
35	Industry actor	Industry
36	Industry actor	Industry
37	Energy company	Industry
38	Statnett—TSO	Industry

Appendix B. List of documents

Table B1. Electrification strategy and electricity system.

References	Document title & description (year)	Source
D1	Report: Long-term market analysis Nordics and Europe 2020–2050 (2021) *(Langsiktig markedsanalyseNorden og Europa 2020–2050)*	Statnett (TSO)
D2	Report: Electrification measures in Norway: Consequences for the power system (2020) *(Elektrifiseringstiltak i Norge—Hva er konsekvensene for kraftsystemet)*	The Norwegian Water Resources and Energy Directorate (NVE)
D3	Report: Long term power market analysis 2020–2040 (2021) *(Langsiktig kraftmarkedsanalyse 2020–2040)*	The Norwegian Water Resources and Energy Directorate (NVE)
D4	Policy report: 'Climate-cure': National plan for emissions abatement (2020) *(Klimakur 2030)*	Norwegian Environment Agency (and multiple agencies)
D5	White paper: Power to change—energy policy towards 2030 (2015–2016) *(Meld. St. 25 (2015–2016) Kraft til endring—Energipolitikken mot 2030)*	Ministry of Petroleum and Energy
D6	Report: The power grid in a fully electric Norway (2019) *(Strømnettet i et fullelektrisk Norge)*	DNV-GL for Energi Norge
D7	Report: Faster energy transition: 1, 5 °C—How can Norway contribute? (2019) *(Raskere energiomstilling: 1, 5 °C—Hvordan Norge kan gjøre sin del av jobben)*	DNV- GL for Energi Norge
D8	Report: An electric Norway—from fossil to electricity (2019) *(Et elektrisk Norge–fra fossilt til strøm)*	Statnett report
D9	Report: Norwegian and Nordic effect balance towards 2030 (2022) *(Norsk og nordisk effektbalanse fram mot 2030)*	The Norwegian Water Resources and Energy Directorate (NVE)
D10	Report: Analysis and forecast of Nordic power production towards 2040 (2019) *(Analyse og framskrivning av kraftproduksjon i norden til 2040)*	The Norwegian Water Resources and Energy Directorate (NVE)
D11	Report: Statkraft's Low-emission scenario 2022 (2022) *(Statkrafts Lavutslipps-scenario 2022)*	Statkraft report
D12	White paper: Putting energy to work—long term value creation from Norwegian energy resources (2021) *(Meld. St. 36 (2020–2021) Energi til arbeid—langsiktig verdiskaping fra norske energiressurser)*	Ministry of Petroleum and Energy
D13	Report: Grid on time—developing the electricity grid «Official Norwegian Reports 2022:6» *(NOU 2022: 6 Nett i tide—om utvikling av strømnettet)*	Ministry of Petroleum and Energy
D14	Report: More of everything—faster «Official Norwegian Reports 2023:3» *(NOU 2023:3 Mer av alt—raskere: Energikommisjonens rapport)*	Ministry of Petroleum and Energy
D15	Report: Long-term market analysis Norway, Nordics and Europe 2022–2050 (2023) *(Langsiktig markedsanalyse Norge, Norden og Europa 2022–2050)*	Statnett report
D16	Action plan to increase the proportion of green public procurements and green innovation (2022) *(Handlingsplan for økt andel klima- og miljøvennlige offentlige anskaffelser og grønn innovasjon)*	Agency for Public and Financial Management (DFØ)

Table B2. Electrification of ferries.

References	Document title & description	Source
D17	Best practice connecting buses, ferries and speed boats to the electricity grid (2020) *(Beste praksis for tilknytning av busser, ferger og hurtigbåter)*	Energi Norge
D18	Report: Is there capacity in the grid for electric cars, buses and ferries? (2017) *(NVE rapport: Har strømnettet kapasitet til elektriske biler, busser og ferger?)*	The Norwegian Water Resources and Energy Directorate (NVE)
D19	Report: Cost of zero- and low-carbon solutions in municipal ferry routes (2020) *(Merkostnader som følge av lav- og nullutslippsløsninger i fylkeskommunale ferjesamband)*	DNV/Ministry of Transport
D20	Report: Low- and zero- emission criteria in public procurement of ferry and speed boat services? (2022) *(Lav—og nullutslippskrav ved anskaffelse av ferger og hurtigbåter)*	Agency for Public and Financial Management (DFØ)
D21	White paper: Climate plan 2021–2021 *Meld. St. 13 Klimaplan for 2021–2030*	Ministry of Climate and Environment/Ministry of Petroleum and Energy
D22	White paper: Greener and smarter—the maritime industry for tomorrow (2020) *Meld. St. 10 (2020–2021) Grønnere og smartere—morgendagens maritime næring.*	Norwegian Ministry of Trade, Industry and Fisheries
D23	The Government's action plan for green shipping (2019) *Regjeringens handlingsplan for grønn skipsfart*	Government/Multiple ministries
D24	Electrification of shipping: Status for shore power in gateway ports (2020) *Elektrifisering av skipsfarten Status for landstrøm i stamnetthavnene*	ZERO/grønt skipsfartsprogram
D25	Mapping the potential for battery-electric ferries in Norway (2024) *Kartlegging av potensialet for batteridrift på ferger i Norge*	ZERO
D26	Report: Maritime opportunities—blue growth for a green future: The government maritime strategy (2015) *Maritime muligheter—blå vekst for grønn fremtid Regjeringens maritime strategi*	Norwegian Ministry of Trade, Industry and Fisheries
D27	Maritim 21—strategy for research, development and innovation in the maritime sector (2022)	Norwegian Ministry of Trade, Industry and Fisheries/Norwegian research council
D28	Maritim 21 (2016) An integrated maritime strategy for research, development and innovation *(Maritim 21: En helhetlig maritim strategi for forskning, utvikling og innovasjon)*	Norwegian Ministry of Trade, Industry and Fisheries/Norwegian research council
D29	Maritim 21: An integrated maritime research and innovation strategy (2010) *(Maritim 21: En Helhetlig Maritim Forsknings- og Innovasjonssatsing)*	Norwegian Ministry of Trade, Industry and Fisheries/Norwegian research council

Table B3. Electrification of construction sites.

D30	Report: The potential for emission reductions of fossil free and emission free construction sites (2018) (*Potensialet for utslippsreduksjon ved fossil- og utslippsfrie bygge- og anleggsplasser*)	DNV for Oslo Municipality/Climate agency
D31	Report: Mapping experiences with fossil free construction sites (2018) (Erfaringskartlegging av krav til fossilfrie byggeplasser)	Multiconsult for Oslo Municipality//Climate agency
D32	Report: Consequences of zero emission construction sites (2022) (*Utslippsfri byggeprosess i Oslo: konsekvensutredning*)	SINTEF for Oslo Municipality//Climate agency
D33	Policy/city council decision: Standard climate and environmental demands for municipal construction sites (2019) (*Standard klima- og miljøkrav til oslo kommunes bygge- og anleggsplasser*)	Byrådssak 1091/19
D34	Report: Zero emission digger: Learning from electrification of construction machinery (2020) (*Nullutslippsgravemaskin. Læringsutbytte fra elektrifisering av anleggsmaskiner*)	SINTEF
D35	Report: Forced electrification of heavy transport and construction in Oslo towards 2030 (2022) (*Forsert elektrifisering av tungtransport og bygg- og anleggsektoren i Oslo mot 2030*)	Hafslund rådgivning for Oslo Municipality//Climate agency
D36	Report: Infrastructure for electric transport: What are DSO's role and responsibilities? (2021) (*Infrastruktur for elektrisk transport: Hvilket ansvar skal nettselskapene ha?*)	AFRY Management Consulting for Nelfo, EFO og Bellona
D37	Government action plan for fossil free construction sites in transport (2021) (*Handlingsplan for fossilfrie anleggsplasser innen transportsektoren*)	Ministry of Transport
D38	Policy strategy: Climate strategy for Oslo towards 2030 (*Klimastrategi for Oslo mot 2030*)	Oslo Municipality
D39	Policy strategy: Green strategy for Bergen (2022–2030) (*Grønn strategi: Klimastrategi for Bergen*)	Bergen Municipality
D40	Policy strategy: Climate- and environmental strategy 2018–2030 and action plan 2022–2026 (*Klima- og miljøplan 2018–2030 Handlingsplan 2022–2026*)	Stavanger Municipality
D41	Policy strategy: Environmental strategy for construction 2023–2026 (*Miljøstrategi for bygg og anlegg 2023–2026*)	Trondheim Municipality
D42	Policy strategy: Climate- and environmental strategy for construction (2021) (*Klima- og miljøstrategi Bygg og anlegg*)	Kristiansand Municipality
D43	Policy strategy: Municipal plan for climate and energy 2021–2030 (Kommunedelplan klima og energi)	Fredrikstad/Sarpsborg
D44	Action- and economic plan 2022–2025 (*Handlings- og økonomiplan*)	Drammen municipality
D45	Newspaper op.ed: Large municipalities' as construction clients want climate-friendly solutions (*Storkommunene som byggherrer vil ha mer klimavennlige løsninger*)	Signed by seven mayors in National newspaper Aftenposten
D46	Public statement: Cities can contribute to a change of pace in climate policy, if the government is willing! (*Storbyene kan bidra til et taktskifte i klimapolitikken, hvis regjeringen vil!*)	Norwegian Association of Local and Regional Authorities (KS) city network
D47	MGF press release Q4 statistics (2022) Q1 and Q2 statistics (2023)	Maskingrossistenes Forening (MGF)

Table B4. Electrification of ammonia.

References	Document title & description	Source
D48	Report: Electrification of land-based industry in Norway: A mapping of technical potential and consequences for the electricity grid (2020) *(Elektrifisering av landbaserte industrianlegg i norge En kartlegging av teknisk potensial og konsekvensene for kraftnettet)*	The Norwegian Water Resources and Energy Directorate (NVE)
D49	Report: Common energy- and industry policy platform *(Felles energiog industripolitisk plattform)*	LO & NHO + others
D50	Report: Process 21 Synthesis report Norwegian process industries' roadmap combining growth and zero emissions by 2050 (2021) *(Prosess 21: Hovedrapport)*	Ministry of Trade, Industry and Fisheries/Norwegian Industry
D51	Report: Green electric value chains (2020) *(Grønne elektriske verdikjeder)*	Confederation of Norwegian Enterprise (NHO)
D52	Report: Synthesis report about production and use of hydrogen in Norway (2019) *(Synteserapport om produksjon og bruk av hydrogen i Norge)*	DNV for Ministry of Climate and Environment/Ministry of Petroleum and Energy
D53	Policy strategy: Goverment Hydrogen strategy (2020) *(Regjeringens hydrogenstrategi)*	Ministry of Climate and Environment/Ministry of Petroleum and Energy
D54	Reservation of grid capacity (2023) *(Reservasjon av nettkapasitet)*	Letter from Statnett to Yara
D55	Consultation response to government white paper: Putting energy to work—long term value creation from Norwegian energy resources (2020) *(Innspill til Stortingsmelding om langsiktig verdiskaping fra norske energiressurser)*	YARA public consultation response
D56	Report: Area plan for Telemark og Vestfold (2022)	Statnett report
D57	Report: Consumption, off-shore wind and grid in south east Norway (2022) *(Forbruk, havvind og nett på Sør og Østlande)*	Statnett report
D58	Corporate report: Growing a climate positive food future (2020)	Yara integrated report
D59	Corporate report: On course to a nature-positive food future (2022)	Yara sustainability report
D60	Consultation response from Porsgrunn municipality to: Grid on time—developing the electricity grid «Official Norwegian Reports 2022:6» *(Høringssvar fra Porsgrunn kommune til «Nett i tide—om utvikling av strømnettet»)*	Porsgrunn municipality public consultation response
D61	Public consultation note: Changes in regulation of grid and energy markets (2020) *(Notat: Endringer i forskrift om nettregulering og energimarkedet (tilknytning av uttak med vilkår om utkobling eller redusert strømforsyning)*	Ministry of Petroleum and Energy

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