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KPN CleanExport – Results report

Selected key findings from CleanExport

- The main focus within the field of energy system optimization models resulted in the development of the EnergyModelsX (EMX) as a modular, multi-energy, modelling framework, as well as major advancements of the existing power system model EMPIRE to include multiple energy carriers.
- A key result is that Norway can remain and further develop its role as an energy export nation in a decarbonized European energy system.
- Investments in renewable electricity generation is paramount for future clean energy export, independent of the form (hydrogen, ammonia, electricity) in which the clean energy is exported.
- The outlook for future Norwegian hydrogen exports indicates hydrogen production from natural gas reforming with CCS in the initial phase with a latter potential of hydrogen from electrolysis. This initial natural gas dominance is due to the lack of available electricity in the coming years.

Description of the project's objectives and background

CleanExport was developed in the wake of the Paris agreement and the need for decarbonisation of the European energy system. Given the reliance of the Norwegian economy on fossil fuel extraction and export, CleanExport investigated how Norwegian clean energy exports will develop subject to a (potentially) reduced demand for fossil fuels in European countries. During the course of the CleanExport project, there were two black-swan events; the Covid-19 pandemic and the Russian invasion of Ukraine. Both events significantly altered the European energy system and resulted in large variations in both energy demand, supply, and consequently price. In addition, major legislation was enacted in the European Union through the revision of the Renewable Energy Directive, the European Green Deal, and REPowerEU.

In this changing energy and geopolitical landscape, the main objective of CleanExport proposal, to "**provide strategic guidance and investment support for exploiting Norway's potential for future clean energy export to Europe",** became even more important. The main objective was accompanied by several sub-objectives:

1. Integration and harmonization of energy system expansion planning tools to allow techno-economic quantitative analysis of the complete energy system.
2. Study of the complementarity and synergies between renewable sources, natural gas, hydrogen, ammonia, and CCS within an energy system context.
3. Establish high-quality input data and define the most relevant case studies.
4. Investigate how large-scale Norwegian hydrogen production for energy export can trigger a domestic hydrogen market.
5. Education of one PhD student and one postdoc on topics related to mathematical optimization models for integrated natural gas and power markets and operation flexibility for low-carbon energy systems.

Results achieved under the project explained in the context of the project objectives

CleanExport has developed extensive results supporting both the main objective and the sub-objectives. Key results focusing on energy export analyses were achieved with a total of 8 case studies, 4 with a pan-European scope and 4 focusing on the North Sea region or a single Norwegian region specifically. The individual case studies investigated the export of clean energy from Norway under a set of differing assumptions which simultaneously allowed understanding the impacts of said assumptions.

Specifically, the results indicate that a significant increase in renewable electricity generation is required within Norway, independent of the future clean energy export. A second important take-away message from the results is that Norway can deliver large amounts of clean hydrogen (both from natural gas reforming with CCS and electrolysis) to Europe. In addition, Norwegian natural gas will most likely play an important role in the European energy transition as it can be seen as secure supply, especially considering the change in natural gas supply of Europe given the Russian invasion of Ukraine. Natural gas is in these future scenarios partly decarbonized in Norway through hydrogen production in natural gas reforming with CCS and partly in Europe through the application of CCS outside Norway. The results furthermore show that Norway plays an important role for storing captured CO_2 from Europe. These analyses are answering the main objective as they allow for an improved understanding of how external decisions may impact the cost optimal development of the Norwegian clean energy export infrastructure. In addition, the analyses increased the understanding of the synergies between renewable electricity generation, natural hydrogen, ammonia, and CCS, and hence, answering sub-objective 2.

The case studies in *CleanExport* utilized two individual energy system model, the established European power system model EMPIRE and a novel developed multi carrier model named EnergyModelsX (EMX) for in-depth analyses of individual regions. The development of EMX focused on incorporating knowledge from different internal and external models to create a holistic model for unbiased analyses of the integrated energy systems to achieve sub-objective 1. Within the project, collaborations were established to incorporate the wider energy system in EMPIRE and provide input data to EMX from EMPIRE results. Routines for linking both models for more reliable results were investigated and applied for reliable boundary conditions used in the EMX models.

CleanExport focused on utilizing reliable input data in the energy system analyses as aimed for in sub-objective 3. These input data were either directly obtained from internal first-principle models or thoroughly reviewed when obtained from external sources. The collected input data forms the basis for subsequent applications of the individual model instances for further analyses with modified research questions. As outlined above, major external and internal events affected the energy landscape in the European Union. These changes were utilized to define the most relevant case studies for future Norwegian energy export with a focus on CCS, hydrogen, and natural gas.

Subobjective 4 was limited addressed during the course of the project due to the results from case studies highlighting the preferred production of hydrogen form natural gas reforming with CCS. In that respect, hydrogen production was limited to current natural gas processing facilities on the coastline, reducing the impact on inland Norwegian hydrogen demand. Close collaborations of key researchers in *CleanExport* and the project *Hydrogen Pathways 2050* allowed transferring knowledge obtained in *CleanExport* to Hydrogen Pathways 2050 which focuses on the transformation of the Norwegian energy system and the role of hydrogen.

Regarding sub-objective 5, *CleanExport* educated one Ph.D. student with a planned defence in summer 2024 on large scale energy system optimization models. In addition, one postdoc deepened his understanding regarding the flexible control of power plants. Furthermore, 2 master students were directly linked to *CleanExport* and several additional master students worked on extensions of the developed energy system models. In total 4 summer researchers were educated at SINTEF Energi within the field of energy system analyses and mathematical optimization.

Central R&D tasks and key roles in the project implementation

CleanExport was structured in four individual work packages focusing on individual aspects when analysing the decarbonization of Norwegian energy exports. *WP1 – Scenarios for clean energy export*, led by Miguel Muñoz Ortiz (SINTEF Industri, SI), provided the foundation for the subsequent analyses by investigating the changing energy landscape in Europe with annual updates of the scenarios. Especially changing legislation through the revision of the renewable energy directive was a focus. It furthermore provided an overview of the individual interdependencies between the different energy carriers that were utilized for defining the boundary conditions (and be aware of potential implications of omitting other technologies) in the case studies.

WP2 – Energy system tools analysis and adaptation, led initially by Dr. Julian Straus and later by Dr. Espen Flo Bødal (both SINTEF Energi, SE), analysed multiple existing energy system models to identify strengths and weaknesses of each. In this respect, WP2 allowed for the subsequent model development within WP3. Individual concepts from these models were subsequently implemented in EMX. A second important task in WP2 was related to developing multi-scale models of individual process components by Dr. Gaurav Mirlekar under supervision of Prof. Lars Nord (both NTNU). It was initially planned to use these multi-scale models directly in the energy system optimization models through surrogate models, but it was soon realized that the increase in computational complexity did not warrant their direct application. Instead, the developed models improved the understanding of flexibility of different technologies.

WP3 – Holistic energy system tool development, led initially by Dr. Brage Rugstad Knudsen and later by Dr. Julian Straus (both SE), was one of the main work packages within *CleanExport*. Based on the initial analyses conducted in WP2, this work package resulted in the development of the EMX energy system optimization framework. EMX was designed as a flexible framework that can be easily adjusted by the user for specific case studies. This potential was shown by multiple summer researchers in SINTEF which contributed either directly to the development of EMX or worked with the application in a multitude of different analyses within *CleanExport* and in other projects. The development of EMX was coordinated by Dr. Lars Hellemo (SI) and Dr. Julian Straus (SE) with significant work conducted by Dr. Espen Flo Bødal, Sigmund Eggen Holm, and Dr. Dimitri Pinel (all three SE).

The Ph.D. student Goran Durakovic also conducted work within WP3 under supervision of Prof. Pedro Crespo del Granado and Prof. Asgeir Tomasgard (all NTNU). The work focused on the incorporation of first hydrogen and subsequently natural gas coupled with industrial energy demand within the well-established EMPIRE power system model. The modified EMPIRE model was applied for several case studies in WP4 with a focus on the transition of the complete European energy system.

WP4– Investment decisions for future energy exports, led by Dr. Rahul Anantharaman (SE), conducted all case studies within *CleanExport* based on the developed EMX framework and the new versions of the EMPIRE model. The case studies using EMX focused on individual aspects of future clean energy export from Norway while the EMPIRE model was developed sequentially with more and more available technologies to analyse the impacts of modelling choices as well.

International collaborations

The Ph.D. student of *CleanExport* spent several months at MIT in the group of Prof. Paul Barton financed by the Fulbright scholarship program. The fruitful collaboration on optimization large scale non-convex problems resulted in one journal draft paper which is currently in the revision process.

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Significance/benefits of the results

The focus on energy system optimization models in WP2 and WP3 provides both the industrial and research partners with a) an overview of existing models and their benefits, b) a new version of a sector-coupled European electricity model, and c) a novel flexible energy system modelling framework (EnergyModelsX, EMX) that can be tailored to the specific needs in individual analyses. EMX is available on GitHub[1] under a permissive open-source license allowing the exploitation of the framework by any interested party. The key benefit of EMX is related to providing a user with a very large degree of flexibility regarding the design of a specific model instance, that is, *e.g.*, which cost description is used for a technology in each region, how efficiencies are modelled, or which technologies are available in the individual regions. EMX is already applied in 10-15 projects financed by the EU, the Norwegian Research Council, or directly by industry highlighting its merits compared to competing models.

The results investigating future potential of Norwegian clean energy exports developed in WP4 provide both industrial partners and policy makers information regarding under which assumptions Norway may remain an energy export nation. This is especially important for understanding how a Norwegian energy export infrastructure is impacted by external circumstances. Hence, they provide improved knowledge regarding the individual energy export options.

A further important result from the project is the analyses of the impact of modelling details on results. The analyses show the importance of assumptions regarding how technologies are modelled and provide potential solutions for maintaining a computationally tractable optimization problem and simultaneously acknowledging the non-linearity of the world.

Dissemination and utilisation of the results

The results created in *CleanExport* have culminated in several published journal papers, and draft papers which will be submitted to peer-reviewed journals in 2024. During the project period, results from the project have been discussed and presented to the industry partners in biannual technical seminars, as well as webinars. In addition, *CleanExport* results were presented at several conferences and used as background for the writing of op-eds. A key legacy of *CleanExport* is related to the EMX modelling framework and the modifications to the EMPIRE model. EMX was presented through JuliaCon 2023 and two open webinars that are available on YouTube. It is applied in multiple subsequent projects, including EU projects, NFR projects, and the newly granted FME *InterPlay*. SINTEF is furthermore in contact with several industrial partners to facilitate the incorporation of EMX within their organizations. As a final event, *CleanExport* arranged an open/by invitation final seminar with the title "Clean Energy Export from Norway" in Oslo, with about 35 attendees from research, industry, and NGOs. This seminar proved to be an important and high-impact event that spread our best knowledge and results far beyond the project group and participating partners. Furthermore, results from *CleanExport* are combined with the results from several different FME projects lead by SINTEF and NTNU to form the background material for a podium discussion at Arendalsuka 2024.

[1] https://github.com/EnergyModelsX