Final report on ETSAP WS series: Approaches to include energy trade in TIMES energy system modelling – practices, recommendations and further research needs.

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Foreword

This report summarizes the outcome of three workshops about modelling of energy trade in TIMES energy system models. The workshop series has provided an overview of the approaches that are used in the ETSAP community, identified knowledge needs and gaps, facilitated discussions and suggestions for best practices of modelling. The workshop series is partly financed by ETSAP, however the work is primarily financed from ETSAP partners through ongoing research projects.

The workshop series is relevant to the ETSAP Annex XV “Energy Systems and Sustainable Development Goals” since it relates directly to the objective “Research and Development” by contributing to “pathways to the net zero GHG emissions systems” and “improved modelling of variable renewables and short-term system operational issues in long-term energy systems modelling”, where energy trade plays an important role. The knowledge exchange perspective also contributes to the objective “Tools Maintenance, Improving and Capacity Building” by increasing the transparency, openness, and affordability of the TIMES model generator, associated software and data sets.

In general, it has been a great interest among the ETSAP partners to meet and discuss this topic that is of common interests among energy system modellers. This is confirmed by a high participation rate, both in person and online. However, we experienced some challenges with aligning discussion with members that attend in person and members that attend online in the hybrid meetings. A learning from this experience is that it can be a better solution to have pure digital and pure physical meetings. Nevertheless, this WS series has contributed to increase the knowledge among, enhance collaboration between and motivate researchers in the ETSAP community. The input from, and discussions with, all participants has been highly valuable and the outcome of the WS series is a result of the preparation to, and the common effort in all the three WSs.

Background

National energy systems are in a state transition. This transition to shift towards low-carbon, renewable-based energy mix is often driven by the growing environmental concerns associated with climate change. However, incorporating a larger share of renewables into the electricity generation mix poses technical and market related challenges. These are inherent with variable renewable resources (e.g., wind power, solar power) whose output is non-dispatchable and can experience significant spatial and temporal variations. This can add more variability and unpredictability to energy system operation, thus increasing the system's balancing needs. Furthermore, variable renewable energy is often characterized with very low variable costs, which may contribute to a decline in whole-sale electricity prices. As the share of renewable energy increases, the long-term merit order effect may therefore adversely impact the balancing supply. In light of this, cross-border electricity trade can become an important source to provide efficient balancing supply for many countries. Therefore, it is utmost important to accurately model cross-border electricity trade by considering the availability and the impact of power flow on the price of electricity, especially in national models. Additionally, there are high expectations for the role of "green hydrogen" in industries, transport, and other sectors where direct electrification cannot be easily implemented. Increased use of sustainable biofuels is also expected, which would require cross-border trade in many countries. Nevertheless, estimating the potential for international trade volumes of biomass for energy purposes proves to be challenging.

Despite the importance of cross-border energy commodity trade in the low-carbon transition of energy systems, incorporating the dynamics of different energy markets into regional and national TIMES models is not straightforward. Often, these markets are outside the spatial scope of the models, making it difficult to evaluate the impact of long-term energy system development. For instance, how can price elasticities to traded volumes be accurately modelled? How does the development of national models influence the electricity price in neighbouring countries? Furthermore, the design of the TIMES models related to spatial resolution, temporal resolution, and the representation of short-term uncertainty in supply and demand can influence the model results on trade.

Various approaches exist to integrate cross-border trade in TIMES models. This project aims to provide an overview of the approaches that is used in the ETSAP community, identify knowledge needs and gaps, and facilitate discussions and idea exchange regarding best practices for modelling cross-border energy trade in national TIMES models. In addition to electricity trade, this project will also address trade of fuels that are a part of an international market, such as biofuels and hydrogen, that face the same modelling challenges as electricity trade.

Workshop series overview

The Workshop series was split in three Workshops over one day that was held in different locations with the following focus:

WS1: Current modelling practices

16th of September 2022

Organised by Institute for Technology (IFE), Kjeller, Norway

WS Responsible: Institute for Technology (IFE), Kjeller, Norway

Participants: 15 digital and 10 in person

WS2: Main challenges

30th of November 2023

Organised by Centre of Global Energy Policy (CGEP), New York, United States

WS Responsible: Luleå Technical University (LTU), Sweden

Participants: 14 digital and 20 in person

WS3: Best modelling practices

22nd of March 2023

Organised by Luleå Technical University (LTU), Sweden

WS Responsible: University College London (UCL), United Kingdom

Participants: 13 digital and 8 in person

The main findings of the WS are presented at the ETSAP summer WS in Colorado, United States, the 15th of June 2023. In the following, a summary of each of the three WSs are summarised in separate sections.

Main findings:

This section is dedicated to give a short overview of the main fundings of the three WSs.

A first conclusion is that energy trade plays a crucial part in the energy system transition, however it is challenging to incorporate in energy system models due to e.g., spatial, and temporal limitations, uncertain market structures and geopolitical considerations and impact of climate change. The modelling approach of energy trade varies across TIMES modelers, in which the workshops have provided valuable knowledge sharing on common practices and challenges.

Suggestions for further collaboration on energy trade that was discussed by TIMES modelers include:

- Further knowledge sharing on practical experience with already available TIMES features through ETSAP webinar series, e.g., capacity investment function, electricity price curves, electricity grid modelling, multi-objective function etc. TIMES modellers are encouraged to contact the ETSAP management group to plan for date and topic of webinar. It is further proposed to have webinars twice per year where TIMES extensions/updates to the code will be presented.
- Creating common approaches on energy trade modelling, e.g., electricity price-quantity curves and hydrogen modelling
- Collaborate with other institutes/organizations to build on existing models and data availability related to energy trade, e.g., the hydrogen model of IEA.
- Initiate ETSAP project proposals related to topics addressed in the workshops. Technology briefs on topics such as hydrogen trade and tracking of critical mineral use was discussed in the workshops.

Workshop 1: Current modelling practices

The primary objective of the first workshop was to identify the current modelling practices and further research needs when modelling energy trade in TIMES energy system models. Prior to the workshop, all participants were asked to fill out a survey and to prepare a short presentation on the current modelling practices used in their respective TIMES model(s). The workshop discussions were centred around these presentations.

Table 1: List of participants Workshop 1. Presenters are marked with a star.

Institute/ University	**Country**	**Name**	Digital	Physical
Luleå University of Technology (LTU)	Sweden	Anna Krook Riekkola*		x
Luleå University of Technology (LTU)	Sweden	Parvathy Sobha		x
University College Cork (UCC)	Ireland	Olexandr Balyk	x	
University College Cork (UCC)	Ireland	Ankita Gaur*		x
University College Cork (UCC)	Ireland	Connor McGookin	x	
University College Cork (UCC)	Ireland	Andrew Smith	x	
University College London (UCL)	UK	Rachel Freeman	x	
University College London (UCL)	UK	Mark Barratt*	x	
VTT Technical Research Centre	Finland	Tiina Koljonen	x	
VTT Technical Research Centre	Finland	Antti Lehtila*	x	
Centre of Global Energy Policy (CGEP)	US	James Glynn*	x	
Centre of Global Energy Policy (CGEP)	US	Taiba Jafari	x	
VITO-EnergyVille	Belgium	Pieter Valkering		x
VITO-EnergyVille	Belgium	Andrea Moglianesi*		x
VITO-EnergyVille	Belgium	Marco Ortiz Sanchez	x	
VITO-EnergyVille	Belgium	Negar Namazifard	x	
Chalmers University of Technology	Sweden	Kushagra Gupta	x	
Research on Energy System (RSE)	Italy	Maria Gaeta	x	
Research on Energy System (RSE)	Italy	Fabio Lanati*	x	
Paul Scherrer Institute (PSI)	Switzerland	Lidia Stermieri	x	
Institute for Energy Technology (IFE)	Norway	Pernille Seljom		x
Institute for Energy Technology (IFE)	Norway	Kristina Haaskjold*		x
Institute for Energy Technology (IFE)	Norway	Eva Rosenberg		x
Institute for Energy Technology (IFE)	Norway	Stine Fleicher Myhre		x
Institute for Energy Technology (IFE)	Norway	Miguel Chang		x
Total			**15**	**10**

Definition of energy trade

Energy trade is the process of purchasing and selling various energy commodities across regions to take advantage of the fluctuations in the energy market and to increase security of supply.

Energy trade in TIMES energy system models

Prior to the WS, all participants provided a short-written reply to the following questions/survey. The participants were also asked to address these in the presentation of the workshop.

How does your TIMES model(s) and analysis consider energy trade of e.g., electricity, hydrogen and biofuels.

- What is the spatial resolution of your model (number of regions, countries)?
- What commodities are traded between internal and external regions?
- How do you model energy trade of these commodities? Including capacity expansion and what constraints are included, e.g., availability factors, trading volume, bi/unidirectional trade etc.
- How do you adjust energy trade parameters, e.g., prices in external regions (impexp), with the focus of various analysis?

Energy trade can occur between municipalities, counties, states/regions, countries, and continents depending on the spatial resolution of the energy system model. In addition, different energy commodities can be traded, ranging from electricity, fossil fuels, biofuels, hydrogen, synthetic fuels and even CO2 allowances. In many cases, institutes work with multiple energy system models with different spatial resolution to enable analyses on both regional, national, and international level. These models can also be linked to improve exogenous input parameters, reducing the limitations of the models and enabling better decision-making. In Table 5, an overview of the different models used by ETSAP members is presented, along with the traded commodities for each of the respective models. Two of the models, JRC EU TIMES and ETSAP-TIAM are models that are used and adapted by many of the ETSAP members. Here we present characteristics of the official model versions.

Table 5: Traded commodities of different energy system models for each ETSAP member.

		Fossil fuels								
Member/ Commodity	**Electricity**	**Coal**	**Natural gas**	**Crude oil/oil**	**LNG**	**Bio-fuels**	**Hydrogen**	**Synthetic fuels**	**Nuclear fuels**	**CO2**
Global models										
VTT	X, Y	Y	Y	Y	Y	Y		Y	Y	Y
ETSAP-TIAM	Y	Y	Y	Y	Y		Y	Y	Y	Y
European models										
VTT	X, Y	Y	Y	Y	Y	Y		Y	Y	Y
JRC EU TIMES	Y	(Y)	Y	Y	Y	Y	Y		Y	Y
TIMES PanEU	X, Y	Y	Y	Y	Y	X, Y	X, Y	Y	Y	Y
IFE	Y	(Y)	(Y)	(Y)		(Y)				
National models										
UCC	X, Y	X, (Y)	X, (Y)	X, (Y)	X, (Y)	X, (Y)	X, (Y)			
PSI	X, Y	Y	Y	Y		Y	Y	Y	(Y)	Y
VTT	X	X	X	X	X	X	X	X	X	X
LTU	X, Y					X, Y				
VITO	Y	(Y)	(Y)	(Y)		(Y)	(Y)	(Y)	(Y)	(Y)
RSE	X, Y	Y	Y	Y	(Y)	Y	(Y)	Y	(Y)	
IER	X, Y	Y	X, Y	Y	Y	Y	X, Y	X, Y	Y	Y
UCL	Y	Y	Y	Y	(Y)	Y	(Y)		(Y)	
IFE	X, Y	(Y)	(Y)	(Y)		(Y)	X			
Regional/City Models										
Chalmers	X		X		X	X				

X: domestic trade, Y: International trade, (Y): Uni-directional international trade

As national models are often multiregional, both domestic trade and international trade is allowed. However, in some models, fossil fuels and biofuels are only available for import, in which the commodities are purchased at an annual price that is period specific. For European and global models, the spatial resolution is lower, and hence only international trade occur between countries.

Methods for incorporating energy trade in TIMES models

Many different methodologies are used to incorporate electricity trade in TIMES models, while trading of other energy commodities are often dealt with in a more homogeneous manner. In this section, we focus mainly on the modelling of electricity trade, in which four approaches have been identified:

- Exogenous electricity price input
- Levelized cost of electricity (LCOE)
- Price-quantity curves
- Exogenous trade volumes

Exogenous electricity price input

The most common approach to model import and export of electricity is by using exogenous price input for regions that are outside the spatial scope of the model. This methodology is used among others by UCC, VTT, PSI, RSE, LTU, IER and IFE. Prices are often provided by other European or Global energy/power system models. The price set usually varies both on time-slice level and between periods. As the future price development is highly uncertain, it is common to use different price projections depending on scenario analyses.

Existing cross-border interconnection capacities are usually defined according to statistics (e.g., ENTSO-E for Europe). Some models further allow for new investments in capacity expansion, while other models only include existing and potentially planned interconnectors. For new investments, input parameters on cost estimates and upper capacity potentials are added. Transmission losses are often included as a fixed percentage of the flow, usually in the range of 5-10%.

Moreover, availability factors are commonly used to compensate for the coarse representation of power flows. They are given as a percentage of the capacity, with the intention of limiting the total flow on the interconnectors, as these are rarely used at full capacity. To be consistent with the electricity price profiles, these values are often provided by the same external model. Another known method is to use historical values based on previous flows on the respective interconnectors.

Despite being the most common approach to model electricity trade, it involves several limitations. As the price profiles are exogenous input, it is not possible to capture the price elasticity of different import/export volumes. Correspondingly, the price development in external regions is not dynamically changing with the amount of electricity it sells or purchases. Another limitation of using exogenous price inputs from other models is that assumptions and production profiles are not always aligned, meaning that e.g., the profiles for wind power production can be based on different weather years.

Levelized cost of electricity (LCOE)

Another methodology to determine import/export prices of electricity is through the levelized cost of electricity of different technologies. For each time-slice and year, the marginal technology is identified qualitatively. Based on the same techno-economic parameters used in the model, e.g., fuel prices, taxes etc., the LCOE is calculated for each of the marginal technologies and allocated to the respective time-slice. In comparison to using price input from other models, this approach allow for consistency in data in which trading is not incentivized by favourable/unfavourable assumptions. The method has been used by LTU to analyse different climate mitigation pathways, in which scenario analysis was performed with e.g., different EU-ETS price levels. One of the limitations of the method is that it requires continuous updating, both in terms of which is the marginal technology in each time-slice and to the LCOE calculation. This is especially important for emerging technologies, such as solar PV and offshore wind, in which technology development is moving fast.

Price-quantity curves

A more complex methodology used to model import/export price curves has been adopted by VITO, PSI and IER. The benefit of this approach is that it captures better the elasticity between price and demand.

VITO uses a European-level dispatch model to generate electricity import and export price-quantity curves for each time-slice. The method can be either price-specific or quantity-specific:

- Price-specific: Several import processes, each representing a power production technology in a neighbouring country, is defined with a fixed price in each period and a variable intra-year availability.
- Quantity-specific: Several import processes, each representing the import power quantity unit. The price changes in each time-slice, rather than in each period as with price-specific. This method does not allow to track emissions as the import technology is not defined.

Similarly, PSI use price curves for imports and exports of fuels and energy carriers. The curves are either obtained by European and Global modelling results or based on external studies on the potential of producing the different energy carriers at different locations, e.g., for synthetic fuels and biofuels. The IER uses price potential curves for hydrogen and synthetic fuels. These curves are previously calculated based on global renewable energy potentials with high resolution GIS models. Based on a continuous supply curve for the mentioned energy carriers, discrete steps for price and potential are calculated and implemented in TIAM.

It is possible to include price elasticity of traded energy prices by adapting the TIMES Damage cost option. This implies that the price of import or export can depend on the quantity that is traded. This feature is however currently only supporting annual price curves specified for energy trade, with the price coefficients optionally shaped by timeslice-specific base prices, but not independent timeslice-specific price curves. It is however possible to further develop the TIMES code to enable modelling of elastic trade related to timeslice-specific energy price curves, such as electricity prices.

Exogenous trade volumes

In addition to using exogenous electricity price input, RSE has also incorporated a methodology where import/export volumes on interconnectors are determined based on output from a European electricity market model. The resulting trade volumes are imposed as an input to TIMES for each time-slice level, and can either be constrained as a fixed level (FX) or as a range (LO,UP) to give more flexibility. RSE use this approach usually with lower time-slice resolution (12 timesteps).

Methods for other energy trade

For trade of other non-electricity commodities, such as fossil fuels, biofuels and hydrogen, the modelling approach is more homogenous across TIMES communities. Commonly, prices for these commodities are defined on an annual level and based on projections from e.g., IEA or output from other models. Moreover, additional limits on trade volumes are often defined to represent low availability or high demand of biomass. As with electricity trade, constraints and input parameters are scenario specific and can for example relate to a country’s energy dependence or national production policies.

Workshop 2: Identifying the challenges

The primary objective of the second workshop was to identify the main challenges of modelling energy trade in TIMES energy system models. The workshop was structured in three parts, focusing on trade of different commodities: 1) Electricity, 2) Material and critical minerals, and 3) gas and liquids. A keynote speaker started each part by presenting a provocative talk on the topic, followed by discussion around the physical and virtual table.

Table 2: List of participants Workshop 2.

Institute/ University	**Country**	**Name**	Digital	Physical
Luleå University of Technology (LTU)	Sweden	Anna Krook Riekkola		x
Luleå University of Technology (LTU)	Sweden	Parvathy Sobha		x
University College Cork (UCC)	Ireland	Olexandr Balyk		x
University College Cork (UCC)	Ireland	Hannah Daly		x
University College Cork (UCC)	Ireland	Ankita Gaur	x	
University College Cork (UCC)	Ireland	Andrew Smith	x	
University College London (UCL)	UK	Rachel Freeman	x	
University College London (UCL)	UK	Paul Dodds	x	
University College London (UCL)	UK	Mark Barrett	x	
VTT Technical Research Centre	Finland	Tiina Koljonen	x	
VTT Technical Research Centre	Finland	Antti Lehtila	x	
Centre of Global Energy Policy (CGEP)	US	James Glynn		x
Center on Global Energy Policy (CGEP)	US	Bryn Stecher		x
Centre of Global Energy Policy (CGEP)	US	Kathryn Longobardi		x
Centre of Global Energy Policy (CGEP)	US	Lewis Wu		x
Centre of Global Energy Policy (CGEP)	US	Zhiyuan Fan		x
Centre of Global Energy Policy (CGEP)	US	Anne-Sophie Corbeau	x	
Centre of Global Energy Policy (CGEP)	US	Taiba Jafari	x	
Centre of Global Energy Policy (CGEP)	US	Caitlin A. Norfleet	x	
VITO-EnergyVille	Belgium	Andrea Moglianesi	x	
VITO-EnergyVille	Belgium	Juan Correa Laguna	x	
Chalmers University of Technology	Sweden	Kushagra Gupta	x	
University of Stuttgart (IER)	Germany	Markus Blesl		x
University of Stuttgart (IER)	Germany	Drin Marmullaku		x
University of Stuttgart (IER)	Germany	Felix Lippkau		x
Danish Energy Agency (DEA)	Denmark	Simon Andersen		x
University of Geneva (UNIGE)	Switzerland	Roman Kanala	x	
Esmia Consultants	Canada	Kathleen Vaillancourt		x
Esmia Consultants	Canada	Mathilde Bourque		x
Institute for Energy Technology (IFE)	Norway	Pernille Seljom		x
Institute for Energy Technology (IFE)	Norway	Kristina Haaskjold		x
Institute for Energy Technology (IFE)	Norway	Eva Rosenberg		x
Institute for Energy Technology (IFE)	Norway	Mari Lyseid Authen		x
Institute for Energy Technology (IFE)	Norway	Kari Espegren		x
Total			**14**	**20**

Electricity trade

One of the main challenges identified for modelling electricity trade in long-term models is to capture the **hour-to-hour variability and balancing needs**. However, most energy system models for long-term analysis use a coarser time resolution in which hourly variations in production and prices are not properly captured. The need for flexibility solutions, such as energy storage, will therefore be underestimated. Moreover, the energy system needs to be designed to also cope with extreme events. A challenge for energy system modelers is to include the **peak capacity** needed for these few hours of the year to ensure security of supply. These challenges will be even more significant as we move from around 22% of renewable energy coverage in consumption [1] to perhaps 80-90% coverage in 2050 [2]. We also need to consider that peak segments will be changing as we move towards more renewable based systems. One of the knowledge gaps in the modelling community is to understand the "error" we are making by using aggregated models. More research is needed to understand with parts of the system are impacted the most and to which extent we are over/underestimating capacity and balancing needs.

Another element adding complexity to the peak challenge is the impact of **climate change**. It is not only the share of renewables that will increase, but also the weather is expected to change in the future. It is already challenging to choose representative weather years and many modelling communities use stochastic programming to evaluate how sensitive the system is to different weather years. Results show that investment decisions in renewable capacity, storage and grid infrastructure is impacted. To capture the climatic changes towards 2030 and 2050 is therefore important. Moreover, climate change is not expected to happen equally across regions, making the challenge even greater.

Lastly, peak segments are also driven by **demand side flexibility**. One option is to include demand side response as endogenous technologies in the model. This could include e.g., flexible EV charging, smart hot water tanks and battery storage in buildings. Another option is to link energy system models to dispatch models.

Another issue is to capture the true conditions of **interconnectors.** Most TIMES models assume linearized power flows, in which direction of flows, bottlenecks and losses are not adequately represented. As higher shares of renewables increase the frequency of transmission bottlenecks, more detailed grid modelling, beyond import and export capacities, is needed to account for physical conditions such as flows, transmission losses, and curtailment due to overloaded cables. Today, modelling communities deal with this in a simplified manner, using availability factors to limit the use of the full capacity. These factors are defined on an annual basis, meaning that the same share of capacity is available for all hours. The reality of which cables are often overloaded during peak hours is therefore not accounted for.

Challenges:

- Understanding the "error" originating from the limited temporal resolution models on electricity trade capacity and balancing needs.
- How to capture the need for peak capacity for the few hours of the year where extreme events occur? How will peak segments change as we move towards more renewable based systems?
- How to capture the impact of climate change on the need for electricity trade, in view of the spatial variations of weather-related renewable electricity production and electricity demand?

- How to analyze domestic and cross-border demand side flexibility and its impact on peak capacity needs?
- How to capture in our models the physical conditions of transmission lines (losses, overloading etc.) and the consequence for cost-optimal energy system planning?

Proposal for solutions to discuss at WS3:

- Ancillary market modelling: Sketch for BS markets
- Price-elasticity curves: Elastic-Supply-Curves.pdf
- High resolution runs: Capacity investments as input to high resolution runs
- Monte Carlo analysis: Addressing Uncertainty in TIMES Using Monte Carlo Analysis
- Electricity grid modelling: TIMES-Grid-Features
- Timeslice tool to optimize representative days: Time-slice tool

Trade of materials and critical minerals

Another challenge related to energy trade, that is often not considered (or simplified) in energy system models, is the trade of critical minerals and materials. In the latest net zero report by IEA [3], they emphasize that the energy transition is set to drive considerable growth in **critical mineral demand**, up to six times by 2040 compared to today. In particular, mineral demand for use in EVs and battery storage is a major force, growing at least thirty times to 2040. Lithium, followed by graphite, cobalt and nickel sees the fastest growth. Moreover, expansion of electricity networks will lead to large increase in copper demand for power lines. The production of these minerals is also largely concentrated to some few nations, where China is largely dominating the processing operations of most critical mineral segments.

Concerning the large challenges related to scarcity of lithium, cobalt, and nickel, it will be important to include alternative solutions to lithium-rich battery **energy storage** in the models. One solution is lithium-free batteries, however these chemistries are still at a very early stage and both cost and performance is uncertain. Other storage options include district heating storage and hydrogen storage as alternative to electricity.

With a larger focus on circular economy, it is also becoming increasingly relevant to consider **recycling and reuse** of materials and products. For example, recycling requirements are becoming stricter for batteries to deal with scarcity of supply. The expected rise in demand for batteries is also driving interest in reuse of EV batteries in 2nd life applications. The topic of recycling and reuse has been addressed for some materials by some modelling communities. For example, VITO has developed a scrap model for steel products in which recycling possibilities are enabled. The ETSAP proposal on modelling of the industry sector and material efficiency will be relevant to explore how the demand for materials will evolve in the future. The main focus should be on the most important materials for the energy transition, in particularly those having high energy intensity, but also on materials that are in competition.

Another topic to address is the **change in products** being traded in the future. In relation to the recent Russian invasion, we might see a shift in supply of products across Europe. Some products might be produced to a larger extent in-house, while others will be outsourced and imported. The prices of critical minerals are also largely impacted by geopolitical factors and the world economy, in which we have seen a huge increase following the invasion of Ukraine and the COVID pandemic. How these prices will evolve in the future is however largely uncertain. A knowledge gap is how to model the **flow of materials and minerals** in energy system models. A first step can be to track the flows and perform analysis using other tools such as LCA. In longer term, a global energy system model would be needed to capture the flow between all countries and regions. The global TIMES model, TIAM, is proposed as one option. Some work is already in process to track demand for different segments. … is looking at the building construction, estimating the demand for materials in buildings. LTU is planning to perform similar studies on the transport sectors.

Challenges:

- How to consider scarcity of specific minerals in the models, e.g., impact limited resources of lithium, cobalt and nickel on battery energy storage?
- How to model the cross-border flows of materials and minerals in energy system models, including the effect of recycling and reuse of materials and products?
- How to consider changes in global industrial production patterns, for example in response to renewable energy availability and geopolitics?

Gas and liquids trade

The Russian invasion has led to an immediate need for more **gas and LNG supply** in Europe. In the period August-November 2022, the EU gas consumption dropped by more than 20% compared to same period from 2017-2021 due to significant decrease in Russian gas imports [4]. From supplying more than 50% of EU's gas consumption in 2021, Russia's share decreased to about 12% In the end of 2022 [5]. The reduced gas imports have mainly been compensated by a sharp increase in imports of liquified natural gas (LNG). To ensure sufficient supply of LNG, many projects are now being revised and new plans for LNG production are being presented. One of the issues is that new LNG projects will likely not start before 2025, while supply is needed now. In the long term, it is also uncertain what the need for LNG (and LNG infrastructure) will be. Going towards 2030/2040, Europe should be less dependent on gas driven technologies and to a greater extent be electrified. It will therefore be important to build infrastructure that is compatible for other energy transition technologies, e.g., hydrogen.

Considering the challenges with gas supply in Europe and the need to decarbonize heavy (non-el) transport and industry sectors, several modelling communities are studying the role of **hydrogen** in future national and European energy systems. The trade of hydrogen is however complex, as it can be transported in numerous forms (e.g., compressed, liquified, ammonia, synthetic, blended with gas) and through different transport options (e.g., pipelines, trucks, ships). Moreover, hydrogen is still an early-stage technology, and it is therefore uncertain which countries will be suppliers and where demand will occur. As a first step, modelers can use existing studies, such as IEA [6] and IRENA [7], that gives an indication of future supply countries depending on LCOH, hydrogen strategies and plans for RES expansion, existing infrastructure, etc.

Several modelling communities have also performed own studies on **hydrogen trade modelling** in the European energy system. For example, IER uses trading distance matrices to evaluate both national and European trade of hydrogen. One study considers seaborne transport of liquified hydrogen, in which shipping routes were collected for all potential connection. Another study evaluates the trade of compressed hydrogen through pipelines in Europe, using distance matrices to create costs of pipeline connections. The main challenges of these methodologies is the time consuming process of

creating such distance matrices and to collect consistent data on costs and performance of trade options.
Another discussion point for hydrogen value chains is the competitiveness and complementarity of **green and blue hydrogen**. As the "greenness" of hydrogen depend on the energy mix of where it is produced, it is not necessarily the case that hydrogen produced from electrolysis is emission free. This is particular the case in the current European energy system, however the carbon intensity of generation in Europe will largely change going towards 2030 and 2050. It is therefore important to capture embodied emissions of both blue and green hydrogen in the models to create a fair comparison of the two. A challenge is to capture the entire value chain in energy system models. Moreover, hydrogen produced from renewable energy is also influenced by its intermittency. Large-scale green hydrogen production is therefore likely to be dependent on storage solutions, adding on an additional cost that is not often captured in energy system models.

Challenges:

- How to cover the compatibility of new infrastructure for gas and LNG in response to the gas crisis with alternative future carriers like hydrogen?
- How to model hydrogen trade given its numerous possible forms (e.g., compressed, liquified, ammonia, blended with gas) and transport options (e.g., pipelines, trucks, ships) and associated cost uncertainty?
- How to capture embedded emissions of green hydrogen production and import in the models to create a fair comparison with blue hydrogen?
- How to capture temporal variability of green hydrogen production and trade and its consequence for (additional) energy storage need?
- How to deal with spatial variability of hydrogen production and consumption, the uncertainty in future demand and supply locations, and its consequence for hydrogen distribution?

The **trading and storage of CO2** is also an important aspect of energy system scenarios for the future. For some countries, it can be an option to pay other countries to store their CO2 in order to reduce emissions. This is the case in e.g., Sweden, where CO2 is planned to be exported to Norway to be stored on the continental shelf. Also, Denmark is having ongoing projects for storing CO2 both onshore and offshore. As this challenge is not possible to address as an isolated European country, collaboration projects are proposed to find solutions for modelling the trade of CO2.

Challenge:

- How to address cross-border transport and storage of CO2, e.g., to Norway, and the competition for the limited CO2 storage resources?

Workshop 3: Improving methodology

The primary objective of the third workshop was to identify common solutions to address the main challenges identified at the second workshop on modelling energy trade in TIMES energy system models. The structure of the workshop was based on the results of a survey distributed to the ETSAP members prior to the workshop, where the aim was to identify which of the identified challenges within the three trade focus areas: 1) Electricity, 2) Material and critical minerals, and 3) gas and liquids, was most important to address. Three breakout rooms were created, in which each group discussed potential solutions to the challenges, rotating on each of the focus areas. A Miro board was used as a tool to collect outputs from the discussion.

Table 3: List of participants Workshop 3.

Institute/ University	**Country**	**Name**	Digital	Physical
Luleå University of Technology (LTU)	Sweden	Anna Krook Riekkola		x
Luleå University of Technology (LTU)	Sweden	Parvathy Sobha		x
Luleå University of Technology (LTU)	Sweden	Jonas Forsberg		x
University College London (UCL)	UK	Rachel Freeman		x
University College London (UCL)	UK	Edison Zhou	x	
University College London (UCL)	UK	Jana Fakhreddine	x	
University College London (UCL)	UK	Dan Zhang	x	
University College London (UCL)	UK	Paul Dodds	x	
University College London (UCL)	UK	Meixi Zhang	x	
VTT Technical Research Centre	Finland	Tiina Koljonen	x	
VTT Technical Research Centre	Finland	Antti Lehtila		
Chalmers University of Technology	Sweden	Kushagra Gupta	x	
University of Geneva (UNIGE)	Switzerland	Roman Kanala	x	
Centre of Global Energy Policy (CGEP)	US	James Glynn		x
Paul Scherrer Institut (PSI)	Switzerland	Panos Evangelos	x	
Paul Scherrer Institut (PSI)	Switzerland	Meixi Zhang	x	
Royal Institute of Technology (KTH)	Sweden	Shravan Kumar Pinayur Kannan	x	
VITO-EnergyVille	Belgium	Pieter Valkering		x
VITO-EnergyVille	Belgium	Juan Correa Laguna	x	
VITO-EnergyVille	Belgium	Andrea Moglianesi	x	
Institute for Energy Technology (IFE)	Norway	Pernille Seljom		x
Institute for Energy Technology (IFE)	Norway	Kristina Haaskjold		x
Institute for Energy Technology (IFE)	Norway	Eva Rosenberg	x	
Total			**13**	**8**

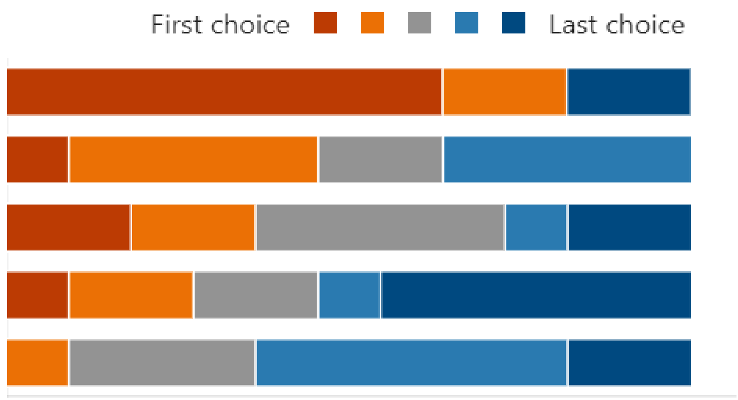
Survey on main challenges

Prior to the WS, all participants received a survey where they were asked to prioritate the challenges based on what they considered to be the most important challenges to cover during the third workshop. The challenges along with the resulting prioritization is presented below, for each of the tree trade categories.

Electricity trade

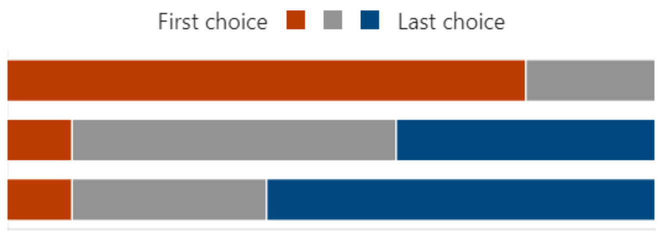
Challenges:

- Accurately representing electricity trade capacity and balancing needs given models' limited **temporal resolution**
- Representing electricity trade peak capacity needs for certain hours with **extreme events**
- Capturing the impact of **climate change** on the spatial variation of electricity production and demand
- Analysing (cross-border) **demand side flexibility** and its impact on peak capacity needs
- Representing the physical conditions of **transmission lines** (losses, overloading, etc.)



1. Temporal resolution
2. Demand side flexibility
3. Extreme events
4. Transmission lines
5. Climate change

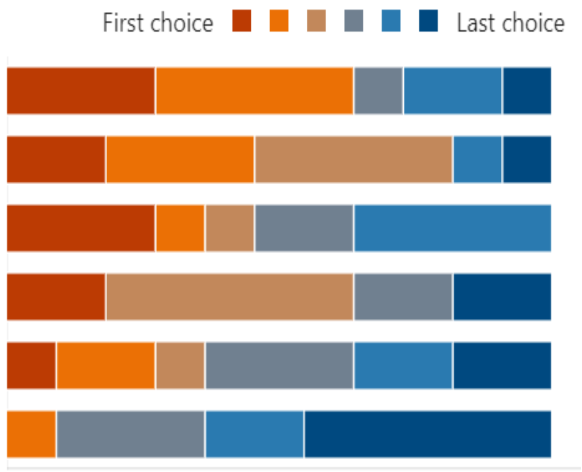
<u>Materials and critical minerals</u>
Challenges:
- Considering **scarcity of specific minerals** in the models (e.g., lithium, cobalt, nickel for battery energy storage)
- Modelling the energy system effects of **recycling and reuse** of materials and products
- Covering **changing global industrial production patterns**, for example in response to renewable energy availability and geopolitics



1. Recycling and reuse
2. Changing global industrial production patterns
3. Scarcity of specific minerals

<u>Gas and liquids</u>
Challenges:
- Modelling the compatibility of new **infrastructure for gas and LNG** with alternative carriers as hydrogen
- How to model **hydrogen trade** given its numerous possible chemical/physical **forms and transport options** and associated cost uncertainty?
- Capturing the **embeddded emissions of green hydrogen** production and import in the models
- Capturing the **temporal variability of green hydrogen** production and consumption and its consequences for hydrogen distribution
- Addressing cross-border **transport and storage of CO2** and the competition for the limited CO2 storage resources

1. Hydrogen trade, forms and options
2. Temporal variability green H_2
3. Compatibility new gas infra
4. CO_2 transport
5. Spatial variability H_2 supply & demand
6. Embedded emissions of green H_2



From the discussion on the survey results of gas and liquids, it was also identified a need to consider hydrogen trade in close connection to need for electricity grid expansion. It was also discussed the need to include trading of district heat, however currently the district heat is mostly on a local level. Morover, it is believed that the same methodology used for modelling trade of gas and liquids can likely be incorporated to district heat if found neseccary to model.

Biomass: There will be a separate workshop on the bio in collaboration with the IEA TCP on biomass. The workshop will be held together with the ESTAP WS in Italy this autumn.

Proposed solutions

<u>Electricity trade</u>

Solution	Challenge	Method	Project opportunities
Common approach on electricity import/export price-quantity curves	1	1. Apply open-source dispatch models (VITO approach) 2. Electricity price curve functionality (Damage cost function)	- Harmonized modelling approach in several national TIMES models - Potential ETSAP project
Shared European dispatch model	1, 3	Create a European dispatch model, using results from national TIMES models. - Build a database with contribution of each ETSAP member - Harmonize scenario assumptions	- Part of project on import/export price-quantity curves - Model can be either TIMES or developed based on other existing dispatch models within ETSAP - Translating national scenarios to European level
Capacity investment function to assess impact of hourly temporal resolution	1	Using the capacity investment functionality to lock invested capacity and run hourly operation.	- Functionality needs to be tested and potentially improved - Potential ETSAP project
Climate change impact on renewable production and trade	5	Using the capacity investment functionality, running hourly operation with better representation of renewable production. - Can use climate scenario dependent availability factors and capacity factors per technology type. - Need to also include extreme temperature impacts on transmission efficiency and losses.	- Functionality needs to be tested and potentially improved - Climate future data is available from the ISIMIP project (wind, temperature, precipitation, humidity etc.) [ISIMIP Repository - Search]
Assess impact of extreme events on capacity investments	3	Using the capacity investment functionality to lock invested capacity and run hourly operation. Include more extreme weather conditions, e.g., very dry years combined with low wind and solar resources.	- Functionality needs to be tested and potentially improved
Webinars on demand side flexibility	2	Presentations related to industrial flexibility, V1G/V2G, heating flexibility, flexible EV charging etc.	Webinar Series

		- Assess how demand-side flexibility competes with electricity trade	

Materials and critical minerals

Solution	Challenge	Method	Project opportunities
Defining which materials are "critical", both now and in the future	3	- Different dimensions to measure: Supply risk, economics importance, geopolitical risks and environment effect. Different indicators can be used to discuss these dimensions. TIMES functionalities: - Geopolitical trade restrictions representing supply risk for regional level - Supply chains for mining/extraction of metals and minerals - Cost curve for 10 most critical minerals - Multi-objective functionality to minimize use of minerals	- Using IEA critical minerals report and the European Critical Raw Materials Act to define which minerals are to be assessed in the models - Potential topic of PhD Dongping Zhou at UCL - Potential technology brief on critical minerals
Assess synergies between ports for shipping materials and ports for hydrogen	3	Common methodology on how to include ports in models at different scale (local, national, regional, global)	Knowledge sharing through e.g., webinar series
Webinars on soft linking to LCA models	1, 3	Sharing experience on how TIMES models can be linked to LCA models to better capture restrictions and emissions related to critical minerals. - How to avoid double counting when using LCA data (especially for energy use and CO_2 emissions)	Webinar series

Gas and liquids

Solution	Challenge	Method	Project opportunities
Collaboration with IEA	1, 2, 3	Using high temporal resolution data from the IEA's hydrogen production model as input to TIMES models.	ETSAP project proposal, in collaboration with IEA Technology brief on hydrogen trade
Establish a common methodology to model hydrogen trade		Topics to be addressed: - Monthly duration storage - Shorter duration trade - Hourly dependent production - Seasonal dependent demand - Different hydrogen delivery infrastructure (ships, pipes, road tankers, tube trailers) - Transport of hydrogen using other molecules (ammonia, LOHC etc.)	Adopt methodology from ETSAP members, e.g., trade distance matrices (IER). Build on ETSAP hydrogen modelling project

The current modelling practices, addressed challenges, and proposed solutions were presented to the ETSAP members at the Summer ETSAP workshop the 15th of June 2023. In general, the workshop series on energy trade identified a need for knowledge sharing related to the TIMES features that are available at the ETSAP webpage. In many cases, functionalities that could help address challenges related to energy trade are already available, but the extent of usage is limited. Sharing practical experiences on the utilization of different functionalities in TIMES models can lead to enhanced efficiency and problem-solving capabilities among ETSAP members. Additionally, the collaborative approach makes it easier to identify areas where functionalities can be improved to meet specific needs. The ETSAP Webinar Series act as a good platform for such knowledge sharing. Some of the features proposed at the workshop include (but not limited to):

- Electricity price curves (Damage cost function)
- Ancillary market modelling
- Capacity investment function
- Electricity grid modelling
- Multi-objective function

Other topics relevant for the ETSAP Webinar Series has also been identified:

- Demand side flexibility
- Linkage with LCA models

TIMES modellers are encouraged to contact the ETSAP management group to propose dates and topics for presentations in the ETSAP webinar series, and they will further take care of the administrative preparations.

References

1. European Environment Agency, *Share of energy consumption from renewable sources in Europe.* 2022.
2. International Energy Agency (IEA), *Net Zero by 2050.* 2021.
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4. Eurostat, *EU gas consumption down by 20.1%*. 2022.
5. European Council, *Infographic - Where does the EU's gas come from?* 2023.
6. International Energy Agency (IEA), *Global Hydrogen Review 2021.* 2021: p. 126.
7. International Renewable Energy Agency (IRENA), *Geopolitics of the Energy Transformation: The Hydrogen Factor.* 2022.

Pictures from meetings and social events