2025 ANNUAL REPORT

Swedish
Electricity Storage
and Balancing Centre

Swedish Electricity Storage and Balancing Centre

Established 2022

Annual report 2025

Swedish Electricity Storage and Balancing Centre (March 2026)

https://www.sesbc.se

Cover page: Summer school for PhD students and industry, image Marcus Folino

Illustration: p. 14 Astrid Hedenström, pp. 8–9 Shutterstock/VikiVector

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STEADY PROGRESS

2025 was the fourth year of SESBC, and we are making steady progress. Martin Lundberg from Lund University became our first graduated PhD, and many other students are progressing in their studies. I want to take the opportunity to offer my warmest thanks to all of you for the great work.

It was fantastic to meet everyone in Uppsala at the centre conference, and I am glad to see that the number of participants increases year by year. These days give me a lot of energy, and I really enjoyed all the presentations and the poster exhibition. I believe it is truly important to meet in person at least once a year. A special thanks goes to our international guests Julia Matevosyan and Göran Andersson for the great engagement and contribution to the event.

We have a fantastic PhD network, and the summer school was such a great event, with a large number of attendees both from academia and industry. Thank you to all teachers and organizers that have made these three days a success.

During 2025, we began preparing for the application for the continuation of our centre for five more years. The application was submitted in January 2026, and new partners will join us in the next period to further strengthen the consortium, complement value chains, and contribute with the needed knowledge and competence. As part of the strategy to enhance the collaboration between academic and non-academic partners, we have also organized a series of workshops aiming at identifying synergies and opportunities for new high-impact projects. We look forward to continuing in this direction while building a strong, internationally competitive team. The current geopolitical situation is putting an unprecedent awareness on the need for a robust and secure electric power system, and our activities and results are an important contribution in this direction.

Thank you all for your hard work and dedication throughout 2025!

Massimo Bongiorno, Director

A hub for competence development in system flexibility

Swedish Electricity Storage and Balancing Centre (SESBC) is a key enabler for reaching the 100% renewable system through the establishment of a cross-disciplinary and internationally competitive Swedish hub for excellence in research and industrial collaboration, as well as providing recommendations, results, and guidance for policy makers.

The mission

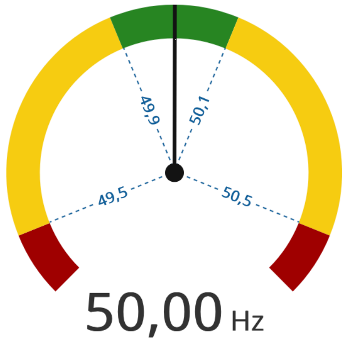
To provide society with ground-breaking knowledge, innovative technical solutions and highly qualified researchers and engineers within the field of balancing the electric power systems. This is achieved by creating a platform for research and development, which will help to accelerate the transition to the future electric power system, enabling the achievement of the national energy policy targets and the Swedish industry to increase its competitiveness.

Main overarching aims

- To connect a wide range of expertise and facilitate strong collaborations among stakeholders.
- To build competence and to drive cutting-edge research on efficient integration of renewables.
- To investigate and develop solutions on energy storage and flexibility for continuous balancing of the future power systems.
- To transfer knowledge and results to society.

BALANCING THE POWER SYSTEM

A large electric power system converts and transmit huge amounts of energy, with practically no buffer and very small margins. Balancing such a system to ensure system stability and robustness for all operational conditions, at all times, and for practically all kinds of disturbances and variations in load and generation, is a tremendous assignment, fulfilled by transmission system operators (TSOs) and suppliers of stabilizing means.



There are basically two different kinds of balances that have to be fulfilled in an AC-system; the obvious active power balance and the more abstract reactive power balance. The active power balance is a systemwide issue and compensation and control can be made anywhere in the system, as long as the transmission capacity is sufficient, while the reactive power balance must be achieved locally.

ACTIVE POWER

Balancing functions and reserves have to take care of:

1. The prognoses errors in both generation (especially wind and sun) and in the load
2. Natural variations in generation and load within the bidding period (e.g. 1 hour or 15 minutes)
3. Sudden events that unexpectedly change the generation or infeed to the system or the load or output from the system

Control means typically used in modern power systems (like the Nordic one):

1. Inertia in the rotating machines, that reduces the magnitude of the rate-of-change-of-frequency (RoCoF), to allow time for hydro units to react on a frequency excursion
2. Fast Frequency Response (FFR); acts within a second, at frequencies around 49.6 Hz, aimed as a support to the synchronous machines in low inertia situations, and realized as a step change in active power
3. Frequency Containment Reserve for Normal operation (FCR-N); a continuous control function, with a droop, to keep the frequency within 49.9 – 50.1 Hz; mainly provided by the hydro power units
4. Frequency Containment Reserve for Disturbances (FCR-D); a continuous control function for fast frequency restoration measures in case of disturbances, active in the ranges 49.9-49.5 Hz (up), and 50.1-50.5 Hz (down), mainly provided by hydro power units
5. aFRR – automatic frequency restoration reserve
6. mFRR – manual frequency restoration reserve

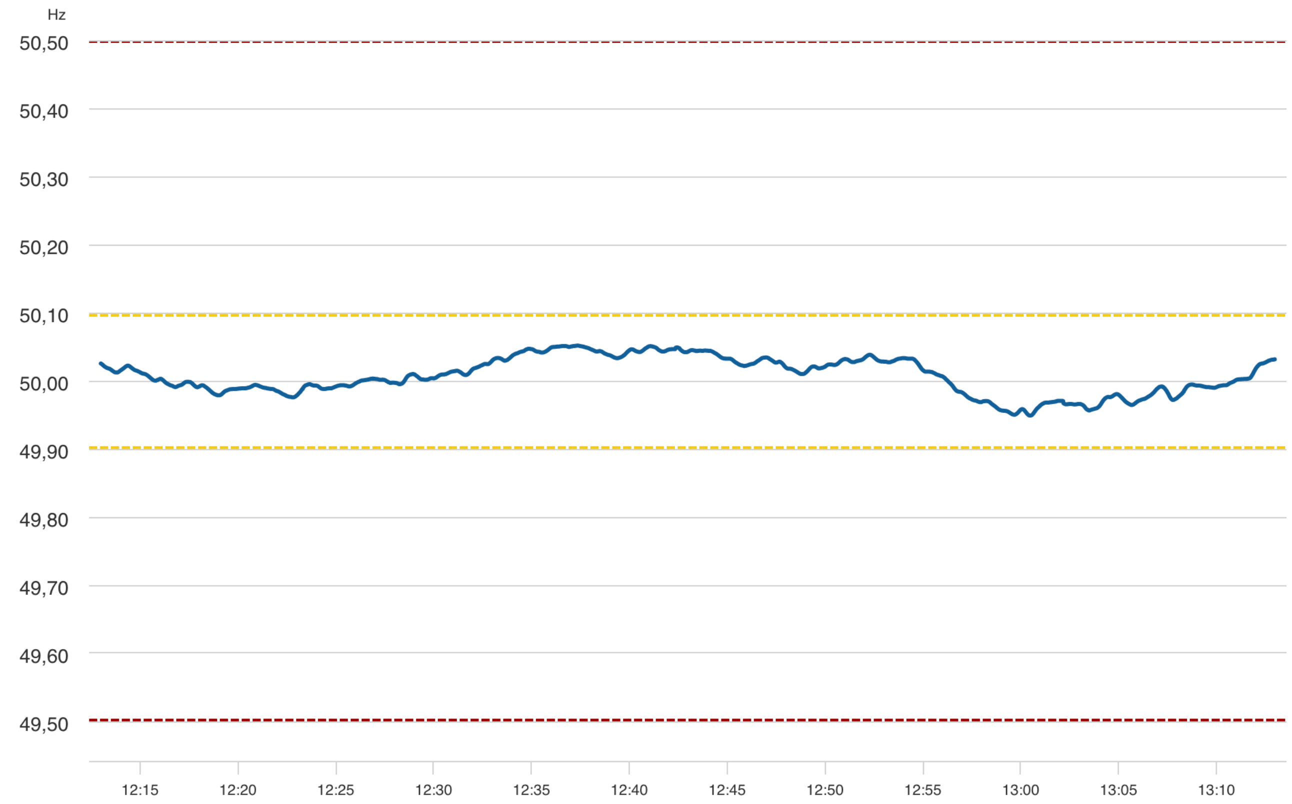
REACTIVE POWER

Balancing functions and reserves are related to the voltage control, and have to take care of:

1. The voltage variations due to prognoses errors in active power flow
2. The voltage variations due to natural variations in active power load and generation
3. The voltage variations due to sudden events, such as trip of transmission capacity, load, or generation

Control means typically used in modern power systems (like the Nordic one):

1. Voltage control by synchronous machines and converters feeding in active power to the grid
2. Shunt devices, like Static Var Compensators (SVCs), reactors (with or without tap-changers), capacitors
3. Series devices, like series capacitors, controllable or non-controllable
4. Synchronous condensers and Flexible AC Transmission Systems (FACTS) devices, like Static Synchronous Compensator (STATCOMs)



The power system is constantly balanced to the frequency 50 Hz, within a tolerance of 0,1. If the frequency rises above 50,5 Hz or drops below 49,50 Hz, other countermeasures are to be taken as the system runs out of FCR-D, such as support from neighboring synchronous areas via High-Voltage Direct Current (HVDC) links.
The image above is from Svenska kraftnät's website:
https://www.svk.se/om-kraftsystemet/kontrollrummet/

System inertia and margins
All control actions in feed-back controlled systems take time, therefore, there must be system inherent inertia and margins to ensure that critical system state variable not go beyond critical limits. In many systems there is a sequence of control measures, from fast acting short term actions to slower but more resilient actions.

Besides the balancing, there is a number of power quality issues to ensure in a modern power system, as summarized by ENTSO-E (Grid-Forming Capabilities: Towards System Level Integration):

1. Creating (forming) system voltage
2. Contributing to fault level (short circuit power)
3. Contributing to total system inertia (limited by e.nergy storage capacity and the available power rating of the PPM or HVDC converter station)
4. Supporting system survival to enable the effective operation of low frequency demand disconnection for rare system splits
5. Acting as a sink to counter harmonics and inter-harmonics in system voltage
6. Acting as a sink to counter any unbalance in system voltage
7. Preventing adverse control system interactions

REFLECTIONS BY THE CHAIR – NIKLAS THULIN

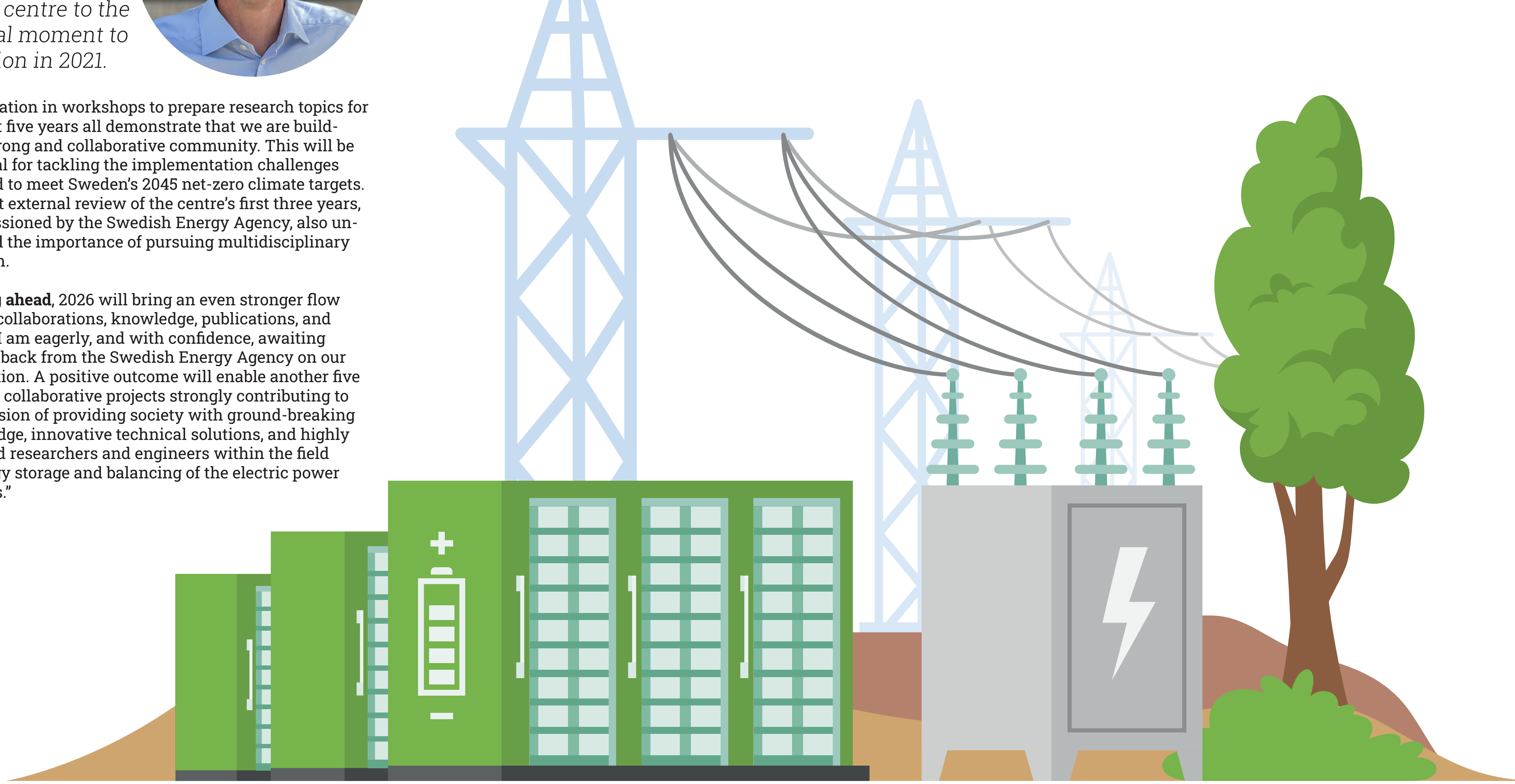
"As I write this it's been a few weeks since we submitted the application for another five years of activities in the centre to the Swedish Energy Agency. This also feels like a natural moment to reflect on what has passed since the initial application in 2021.

Over this period, geopolitical tensions have increased significantly, bringing renewed attention to resiliency, local supply chains, distributed energy systems, and the dependency and origin of fossil fuel supply. Electricity supply and the power grid are now more frequently discussed in everyday media. Major events such as the Iberian Peninsula blackout in April 2025 have highlighted the need for robust solutions for stability and balancing as the share of electricity from solar and wind continues to grow. Day-ahead spot prices, demand charges ("effekttariffer"), and zonal prices have all become common topics of dinner-table conversations.

One clear success story is the rapid development of Li-ion-based battery energy storage systems (BESS). These exceeded all expectations set five years ago. In 2025 alone, global deployments of more than 100 GW were reported, up from around 10 GW in 2021. According to Bloomberg New Energy Finance's "Energy Storage Systems Cost Survey 2025", the global average BESS system price for utility scale projects was around 100 EUR/kWh in the end of 2025, down from about 400 EUR/kWh in 2021. Combined with increasing lifetimes, BESS has now become a cost-effective solution for grid balancing and for firming supply from intermittent renewables.

As the SESBC research projects advance, 2025 has brought several milestones. We have celebrated our first PhD and Licentiate thesis defences and seen a growing number of scientific publications. Record attendance at the annual conference in Uppsala, stronger engagement from the International Advisory Board in events such as the summer school and the conference, active knowledge exchange in the industry forum, rising interest from new companies in joining the centre, and broad participation in workshops to prepare research topics for the next five years all demonstrate that we are building a strong and collaborative community. This will be essential for tackling the implementation challenges required to meet Sweden's 2045 net-zero climate targets. A recent external review of the centre's first three years, commissioned by the Swedish Energy Agency, also underlined the importance of pursuing multidisciplinary research.

Looking ahead, 2026 will bring an even stronger flow of new collaborations, knowledge, publications, and theses. I am eagerly, and with confidence, awaiting the feedback from the Swedish Energy Agency on our application. A positive outcome will enable another five years of collaborative projects strongly contributing to our mission of providing society with ground-breaking knowledge, innovative technical solutions, and highly qualified researchers and engineers within the field of energy storage and balancing of the electric power systems."



FIRST GRADUATED PHD

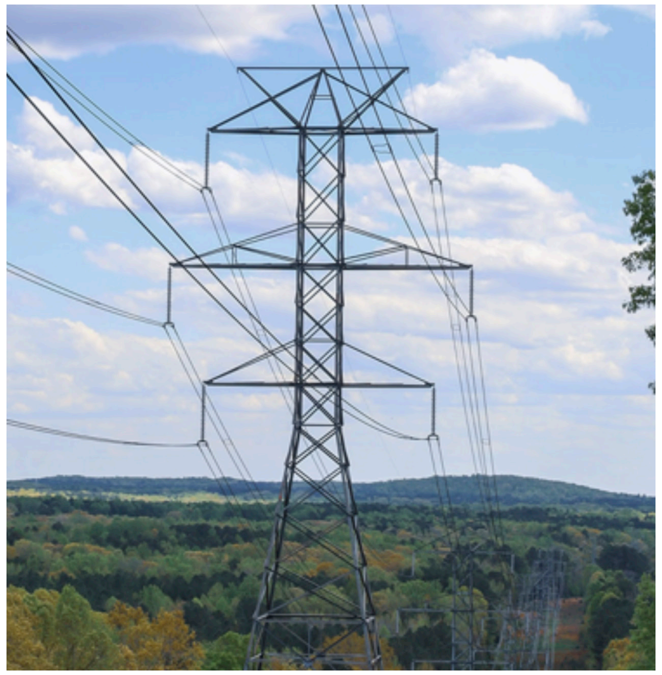
Martin Lundberg from Lund University successfully defended his PhD thesis on 3 October, 2025 becoming the first PhD graduate at SESBC. His research has been part of the Research & Innovation layer, Systems, in the project "Managing Grid Capacity with Storage".

The thesis deals with alternative "non-wire" solutions to grid reinforcement, which allow the expansion rate of renewable energy sources to be increased with minimal need for infrastructure upgrades. To achieve this, control features already built into the power electronic converters that connect wind and solar power plants to the grid are utilised. Through control algorithms developed within the research project, the flexibility of these grid resources can be utilised to adapt production to respect the grid's current (or power) and voltage limits. If other flexible grid resources, such as energy storage systems, are available, they can also be used to optimise the grid capacity usage. By controlling the charging and discharging of energy storage systems in different parts of the grid, virtual power lines can be created, and the total grid capacity can be increased without the need for new lines.

The thesis is available at Lund University's research portal: https://portal.research.lu.se/en/publications/grid-capacity-challenges-and-opportunities

INCREASED GRID CAPAPCITY WITH "VIRTUAL POWER-LINES" - INTERVIEW WITH MARTIN LUNDBERG

There is a need to increase grid capacity, but it can take many years before new power lines are in place. "Virtual power lines" is a concept where batteries are used to control the electricity flows, enabling a higher utilization of the existing grid. Martin Lundberg, PhD student at Lund University, has in his research shown that it is technically possible and safe to use batteries, and other resources, to increase the grid capacity without exceeding its physical limitations.



What is your background, Martin?
"I started my studies at Uppsala University and then continued as a PhD student in Lund with Professor Olof Samuelsson as my supervisor. For my first two and half years, I was in a European project working on accelerating the integration of renewable energy in distribution networks. Then SESBC started, and I continued in the project Managing grid capacity with storage.."

What is this project about?
"The goal is to find ways to use energy storage solutions to quickly and safely increase the capacity of the power grid. There are physical limitations in the power grid for how much electricity can be transferred, and more capacity is needed to handle the large expansion of renewable energy production. Wind turbines and solar panels can be constructed relatively quickly, but adding more power lines to increase the capacity can take many years. What I have done is to analyse how batteries and other resources can be controlled to make sure the full capacity of the grid is used but not exceeded. I have also investigated what can be described as virtual power lines. These virtual power lines, that consist of batteries, can increase the capacity of the existing grid without the need of building new lines. The idea is that these types of solutions can be implemented much faster than new power lines so that it will be possible to connect more renewables to the grid faster."

What do you mean by virtual power lines?
"The concept of a virtual power line is when you are using batteries to store surplus energy and transfer it later when there is grid capacity. For example, take a power line connected to a large wind farm has a 100 MW limitation, but you have a temporary high production, and for, say, an hour, you want to continuously transfer 200 MW. With a virtual power line, you would transfer 100 MW through the power line and charge the remaining 100 MW into a battery at the beginning of the line. At the same time, 100 MW is discharged from another battery at the end of the line. The result is that 200 MW is transferred, with 100 MW through the actual power line, and 100 MW is transferred 'virtually' by the batteries. During periods of low production, the stored excess energy in one battery is used to recharge the depleted battery on he other side, which 'resets' the virtual power line."

What about safety?
"In the grid, there are capacity margins for handling component failures. For example, if one power line fails, it is compensated for by transferring more power through the remaining lines. To do that, lines normally have to be operated well below their maximum capacity. I have done calculations that show that the concept of virtual power lines can replace some of the safety margins within the system. If the batteries handle component failures, then it's possible to use a larger share of the power lines' maximum capacity."

Can you describe your research making this possible?
"To keep it short I have developed control algorithms for batteries and other grid resources to handle grid capacity. I have used analytical methods and simulations to test that it's technically possible, and of course that it doesn't create negative impacts on the rest of the grid. If anyone wants to dig deeper, I recommend reading more about virtual power lines here and the coming thesis summarising the research. You are also most welcome to contact me."

What happens next?
"My work indicates that it's possible to use batteries to increase the grid capacity. The next natural step would be to test these findings with actual batteries in experiments. There is an upcoming post-doc project in the centre addressing this."

GOALS

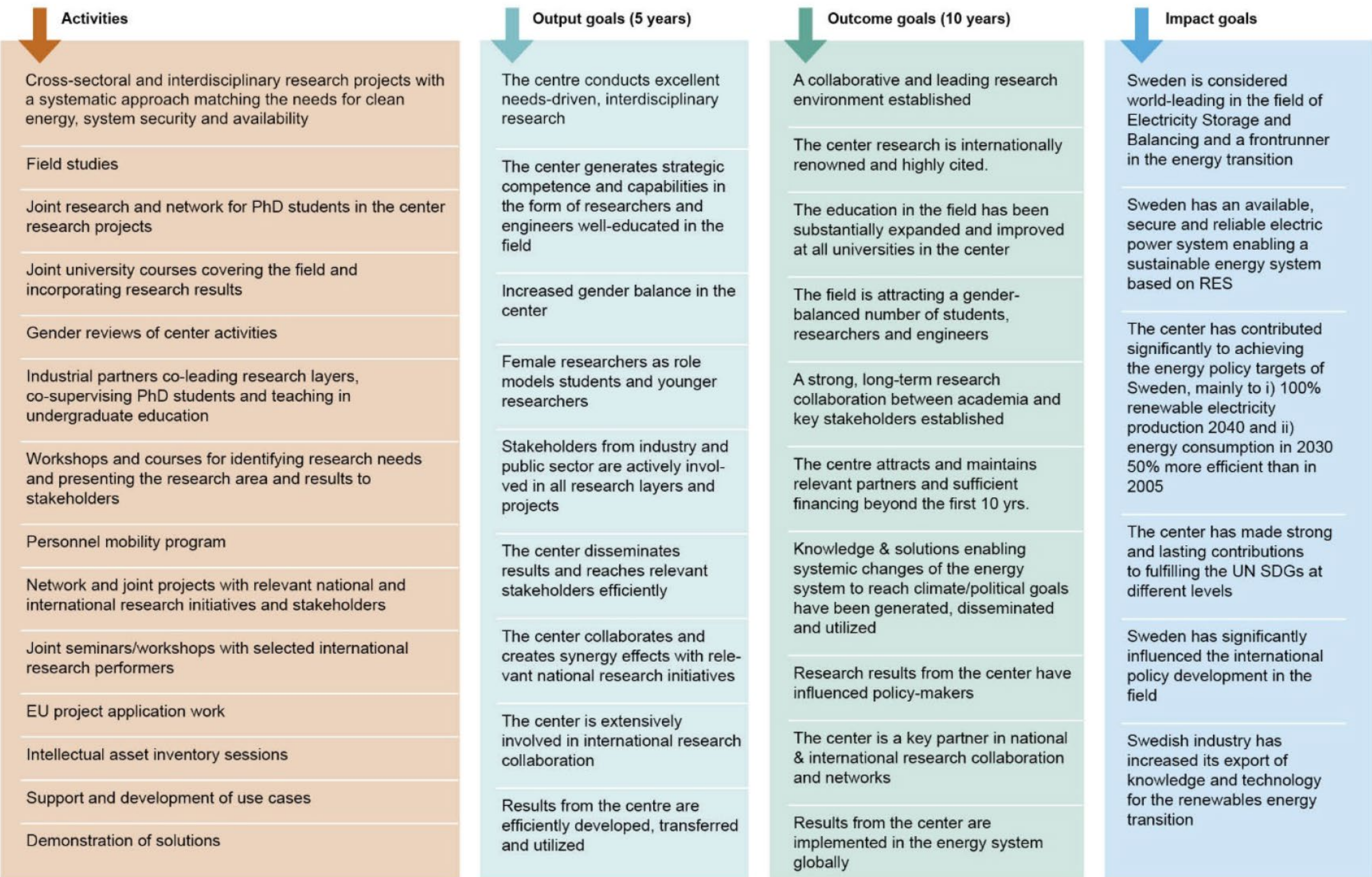
SESBC is in its fourth year and the work continues to further enhance the centre as a competent, collaborating and inspirational research community.

Activities
The centre's activities focus on strengthening research, collaboration and competence development. Research projects form the core of the work, supported by reference group meetings that reinforce a cross-sectoral research environment. The Industry Forum serves as a platform for engagement with non-academic partners and broadens participation across the centre's activities.

PhD activities expanded through the PhD student network, the yearly summer school and networking workshops with active industry involvement. SESBC also organised workshops and courses to identify emerging research needs and share results with stakeholders. In parallel, the centre continues its work to foster a safe, inclusive and inspiring research environment, and a reviews on diversity and inclusivity has been conducted. Together, these activities strengthen collaboration between academia and industry and support the translation of research into societal impact.

Output goals 5 years
To reach the five-year output goals the centre has so far conducted a range of activities. The centre strives to develop strategic competencies and capabilities by educating highly skilled researchers and engineers in the field. This is conducted in an environment where everyone feels safe and inspired. Since the field has a skewed gender balance, the centre is finding ways to promote female role models that can inspire students and early-career researchers. The participation of stakeholders from industry and the public sector is of utmost importance for the centre. Here, the Industry Forum plays an important part in activating participation in all research layers, research projects and centre's activities at large.

Outcome and impact goals
In the long-term we are setting up the foundation to become an international collaborative and leading research environment. Ultimately it is about creating a strong link between academia and industry where research results are implemented in society.



KEY PERFORMANCE INDICATORS

In 2025, more projects have been granted funding, and the centre has largely passed the target of at least 20 PhD students and PostDocs. In addition, the first PhD dissertation took place during last year. As expected, the number of publications has drastically increased as compared with the previous years; many publications are co-authored with industrial partners, and the corresponding target has been reached under 2025. The centre has continued to host several workshops, seminars and courses, including the yearly summer school; all activities have been largely appreciated by the centre's partners. Furthermore, during the year, more affiliated activities have been initiated. Utilization activities have continued during 2025.

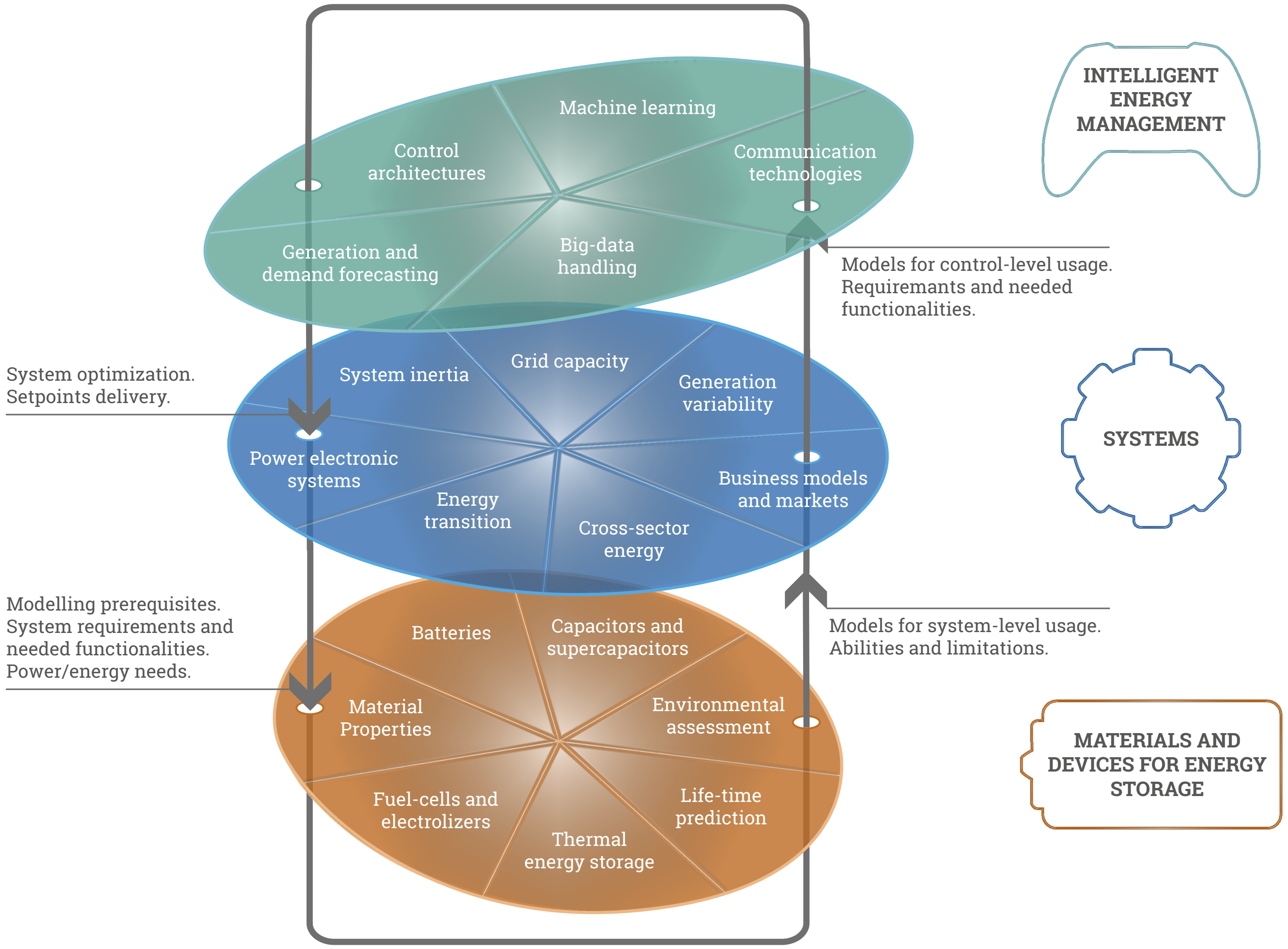
A special mention is to be dedicated to the KPI related to gender balance in the centre. During 2025, the centre management, in cooperation with the Chairman of the Program Council, has discussed this KPI and the way how it was formulated in the original application. It has been concluded that its formulation was too general and open for interpretations. For this reason, it has been decided to expand the KPI and divide it into categories, in order to provide a better overview of the gender balance in the centre. Four main categories have been defined, with the aim to reach a minimum of 40/60 gender balance ratio in each of them: centre management, PhD students and postdocs, senior researchers, and industry representatives active in the centre. As it can be seen from the analysis of the new KPIs in Table 1, the gender balance in the centre management, and among the PhD students and postdocs is good and above the target. At the same time, the gender balance for senior researchers and especially for the industry representatives needs effort and to be improved. It is of importance to consider that the centre has little influence on these two categories, particularly when it comes to the persons appointed from the industry partners. A diversity mapping in the centre has also been done during the year, to get an overview of the different disciplines engaged in the centre, the age distribution as well as nationalities.

Results (Output goals)	Metrics (Key performance indicator)	5-yr target	2022-2025
World-leading knowledge and competence			
Excellent needs-driven, interdisciplinary research	# peer-reviewed publications in high-impact journals	60	25
	# conference presentations	60	37
	# conference keynote presentations	10	7
	# PhD theses	10	1
	Share of projects with interdisciplinary approach	50%	67%
Strategic competence and capabilities in the form of researchers and engineers	# PhDs graduated	10	1
	# PhDs and post-docs in centre research projects	20	27
	# graduate & undergraduate courses by the centre # students participating in the courses	8 10	4 168
Increased gender balance in centre*	Gender balance ratio in centre projects & management	+20%	
Gender balance ratio in centre management		40/60%	49/51%
Gender balance ratio PhDs and postdocs		40/60%	42/58%
Gender balance ratio senior researchers		40/60%	31/69%
Gender balance ratio industry representatives		40/60%	23/77%
Strong national and international collaboration			
Stakeholders are actively involved in all centre activities	# industry partners per centre project	5	4.1
	# new academic-public-private collaborations	18	14
	# peer-reviewed co-publications between partners	10	13
Results reach stakeholders efficiently	# persons in centre program for personnel mobility	20	3
	# workshops with relevant national stakeholders	24	11
	# follow-on projects (triggered by centre results) that were initiated by non-academic stakeholders	10	2
	# courses & seminars for staff from industry # attendees at the courses & the seminars	8 200	23 928
Collaboration with relevant national research initiatives	# joint activities/projects with relevant national research initiatives	4	4
	# centre projects granted funding from other sources	12	4
Extensive international collaboration	# workshops/seminars with international partners # international attendees at the workshops/seminars	16 300	9 53
	# international partners in centre projects	10	4
	# projects with international partners	10	4
Increased utilization of research results and competence			
Results are efficiently developed, transferred and utilized	# intellectual asset inventory sessions	9	0
	# intellectual assets created	18	8
	# workshops for use case development	9	2
	# demonstration projects performed	9	0

Table 1, summary of SESBC KPIs

RESEARCH & INNOVATION LAYERS

Cutting-edge research is conducted with focus on three research and innovation layers:



Intelligent Energy Management

This layer explores how to effectively gather, process and distribute the available data using innovative connectivity solutions, and how to design novel machine-learning and control methods to achieve the goal. With the combination of distributed measurements, communication and control for energy management it will be possible to build an energy network that will provide the desired robustness and resilience and at the same time optimally take advantage of the flexibility offered by generation, end-use and storage units. The research in this layer is based on models, constraints, network configurations and requirements developed in the Systems layer.

Projects

- Optimal usage and properties of battery storage units using 2nd life batteries
- Intelligent energy data management and online decision-making
- Storage and flexibility for enhancement of grid capacity
- Synchronized grid-forming systems
- Modelling platform for Building-to-Building-to-Grid services (B2B2G)

Systems

The main scope of this layer is to define and develop models, methods and technical solutions for the future renewables-based electric power system, which makes the best use of flexibility sources considering grid capacity and business aspects in different time scales. The Systems layer covers the entire system, once the appropriate boundaries are decided, at the cost of details. The different solutions for energy storage and system control are mapped, evaluated and ranked, providing requirements and needed functionalities as an input for the other R&I layers.

Projects

- Three aspects of balancing – production, energy storage and new consumption
- Business models for energy storage
- Modeling the regional energy transition
- Managing Grid Capacity with Storage
- Power-electronic solutions for resiliency and capacity enhancement in MV grids
- High voltage AC-transmission systems for grid-connection of offshore wind farms
- Global value chains for local energy systems
- Role of flexibility measures in distribution grids

Material and Energy Devices

Energy devices serve several purposes: functionality control of the driven object (such as grid, drive, electrolyzing), energy conversion and energy storage. We focus the discussion on energy devices that do not release CO2 emission in operation; hence, heat engines using biofuels are left out of the scope of the centre. The prospective energy storages are mapped based on their power and energy capabilities. Regarding the power capability, the duration of various power levels as a function of time are established, so that these can be mapped towards the needs from the Systems layer. To combine these storages to accomplish 'hybrid units' that better match the performance requirements from the Systems layer is a great possibility that is also in focus.

Projects

- High-power vanadium redox flow batteries
- Hydrophobic cationic sieve enabling rechargeable aluminium-lignin batteries
- Novel Dielectric Diagnostics Method for Materials for New Generation of High-Performance Capacitors
- High temperature battery technology
- Towards a more efficient use of PEM fuel cells and electrolysers
- New Catalysts for Electrolysis/Fuel Cell Purposes
- Performance evaluation of battery-based energy storages for various duties, in terms of power, energy and environmental impact
- AI methods for development and condition monitoring of energy storage devices

INTELLIGENT ENERGY MANAGEMENT

OPTIMAL USAGE AND PROPERTIES OF 2ND LIFE BATTERIES FOR ENERGY STORAGE

Second life batteries are batteries that have ended usage in their first application but are in good enough condition to allow a second application. With the expected electrification of the transport sector, there will be very large quantities of such 2nd life batteries of highly different degree of ageing, properties and expected remaining lifetime. The abundance, their short response-time, and low energy and power density requirements, make grid applications of battery energy storage systems (BESS) with 2nd life batteries highly interesting. Examples of potential applications are frequency control, energy balancing to compensate for variations in renewable energy sources, and power peak shaving.

Research questions

To promote employment of 2nd life BESS we need to operate them in the best possible way. However, optimal operation of BESS in the grid is a truly challenging control problem as it has to take into account:

- bidding for multiple services to the grid (frequency control) with uncertain remunerations and different timeframes
- uncertain forecasts, i.e. weather conditions and consumer loads, that will affect future prices over a given time-horizon
- energy arbitrage, i.e. charging/buying at low prices and discharging/selling at high prices
- operating costs, including installation and replacement of battery packs.

This is yet an unsolved problem, for which this project aims to find a solution.
One economically particularly important element that has either not been included, or has been oversimplified in previous work, is the cost of battery ageing and how this ageing is affected by the usage. In the optimisation mentioned above, a prediction of the cost will depend on the predicted ageing of the batteries. No two battery packs are identical, and for second life batteries any initial differences will be amplified and depend on previous usage in their first life, for which there is very limited information. Consequently, we need to develop self-adapting ageing models that for each individual battery adapt to the observed decrease in energy and power capabilities. This is the second focus area of this project.

In addition, the project also aims to:

- show how, for given available battery packs of different properties and conditions, the packs should be configured. For example, how should packs be sorted, and should they be connected in parallel on the DC or AC side of the converter(s)?
- identify key parameters that determine the success of a BESS installation.

Involved in the project

Torsten Wik, Benedick Lees

Partners

Chalmers, Volvo Energy, Repono, Swedish Energy Agency

PROJECT RESULTS 2025

In order to avoid excess waste generation and provide much needed energy storage capacity, lithium-ion (Li-ion) batteries, when retired from their 1st-life, can be repurposed or given a 2nd-life in lower-stress storage roles.

To do so, and to determine for what purpose, accurately predicting the degradation rate of 2nd-life Li-ion batteries' state of health is highly important, yet difficult, owing to the lack of available data from cells of sufficient aging variety. Additionally, as there are no formal standards on what information may come with potential 2nd-life batteries, it is hard to predict their subsequent behaviour. While certain models do exist for predicting degradation of certain cell types/chemistries, such models typically rely on extensive data from the battery's 1st-life and do not generalize well over different types of cell.

We have established a novel entropy-based theoretical approach, and a novel entropy-based algorithm, for predicting 2nd-life batteries' behaviour. The proposed model hybridizes simple machine learning methods with a lightweight model based on physics, centred around approximating the amounts of generated irreversible thermodynamic entropy and Shannon entropy (information entropy).

Tests of this model on three different Li-ion battery types (LFP, LCO, NMC) show that the model is able to make accurate predictions on 2nd-life battery lifetime while only requiring data from one single cycle. Subsequent sampling is shown to further improve model accuracy, placing this novel algorithm on par with state-of-the-art ML-estimates, but without the need for extensive training or reliance on extensive data from 1st-life.

During this last year, the project has seen the development of a predictive algorithm and evaluation method for battery degradation. Specifically, an algorithm that utilises a combination of thermodynamic and information entropy through a hybrid model to accurately predict battery SOH, across several types of battery cell and chemistry, using only a single discharge cycle from a given cell to draw predictions from, has been developed.

Currently this method is further improved by also considering control entropy and validated on data that have been made publicly available, where cells have first been aged in realistic drive cycles and then used in a second application in cycles typical of different kinds of peak shaving. After extensive cleaning and preprocessing of this huge dataset preliminary results of SOH prediction are very promising.

Another result of testing the method is that we can now discover a capacity knee around 40 cycles before it happens from a hockey stick behaviour of the entropy. We are now writing an article on this jointly with Xiaolei Bian.

Using also control entropy gives us higher sensitivity making the method potentially useful for online entropy. This will be tested on fast charging data with reference electrode to see if degradation can be assessed in the fast time scale, potentially be used as a tool for optimized fast charging, something that can have a significant impact as the electricity prices are now given every 15 minutes, thus corresponding to 4C charge or discharge.

Publications 2025

Journal papers
B. Strugnell-Lees, E. Evdokimova and T. Wik. (2025). An entropy-based, self-adaptive predictive algorithm for battery degradation. Journal of Power Sources, Vol 656: 237920. Doi 10.1016/j.jpowsour.2025.237920

Affiliated journal paper
Zhang, H., Liu, X., Altaf, F. and Wik, T.A transferable physics-informed framework for battery degradation diagnosis, knee-onset detection and knee prediction (2025). Journal of Power Sources, Vol 657, 238028. Doi: 10.1016/j.jpowsour.2025.238028

TANDEM: INTELLIGENT ENERGY DATA MANAGEMENT AND ONLINE DECISION MAKING

The electrification of transportation and industry challenges utilities and grid owners as energy demand rises faster than grid capacity can expand. To address this, TANDEM focuses on enhancing flexibility in energy distribution through efficient big data handling and processing.

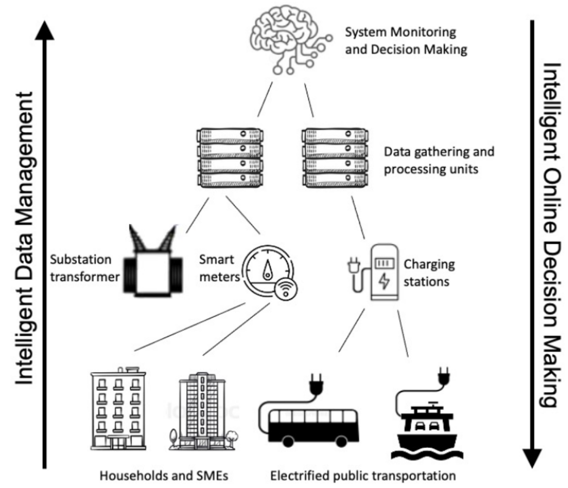
This includes online monitoring to identify bottlenecks, improved forecasting methods for flexibility needs, and economic control applications to optimize flexibility orders. Supported by over a decade of collaboration among academic and industrial experts, TANDEM aims to facilitate informed decision-making in Smart Grids and Advanced Metering Infrastructures.

Intelligent Energy Management: effective energy management is crucial for ensuring a sustainable and reliable power supply. In this context, "intelligence" is built on two fundamental pillars: (1) sensing and sharing of data, and (2) processing of that data to extract valuable insights.

Illustration online decision making

The interconnected nature of data sharing and processing: sensing and sharing of data involves collecting real-time information from various sources, such as smart meters, sensors, and other devices within the energy grid. This data can reveal important patterns and trends in energy consumption, generation, and distribution. Once sensed, such data must be shared and communicated effectively among different stakeholders, e.g., households, small and medium-sized enterprises (SMEs), and charging stations for electrified transportation and analyzed to generate actionable insights. This analysis can help identify inefficiencies, predict demand, and optimize energy usage.

TANDEM's vision: In this context, TANDEM aims to boost data processing in both existing and future AMIs and Smart Grids. The project's primary focus is on energy balancing and storage within multi-actor systems that involve a variety of participants, including households, SMEs, and public transportation charging stations.



TANDEM seeks to advance state-of-the-art in several key areas:

1) Smart Stream Data Preparation, to automate the selection of crucial data for further analysis, enabling scalable data validation and monitoring, filtering out unnecessary information and focusing on the most relevant data points.

2) Models for Electrification and Renewable Energy: to create models to promote the electrification of various sectors and enhance the integration of renewable energy sources. This includes developing tariffs designed to lower peak loads, encouraging consumers to shift their energy use to off-peak hours, thereby balancing the load on the grid and reducing the need for additional generation capacity.

3) Improved Prognosis Techniques: to establish techniques for better forecasting at multiple levels within the system hierarchy. This encompasses everything from smart meters to electric vehicles and third-party applications. By enhancing prediction capabilities, TANDEM will help energy providers make informed decisions about supply and demand, ultimately leading to a more resilient energy system.

Involved in the project

Vincenzo Gulisano, Romaric Duvignau, Marina Papatriantafilou, Wania Khan, Joris van Rooij, Mariliis Lehtveer

Partners

Chalmers, Göteborg Energi, Swedish Energy Agency

PROJECT RESULTS 2025

INTELLIGENT ENERGY MANAGEMENT

Several Master theses were conducted in collaboration with Göteborg Energi, reinforcing the practical dimension of the work and generating insights that will both inspire future theses and contribute to the planned SESBC project extension. Detailed results include:

Results and publications (4 journal, 5 conference) contributing to the TANDEM project goals, regarding: efficient algorithms and systems for managing data and information to facilitate decisions in cyber physical systems in general and in energy systems in particular, supporting needs of grid utilities, such as that operated by Göteborg Energi, in taking advantage of their sensed data for better efficiency and flexibility.

Examples are:

- Continuous monitoring for data exploration, continuous data summarization; parallel and stream processing methods for generation of data-frequency statistics out of data streams (journal article, open-source software https://doi.org/10.5281/zenodo.15593109)
- Clustering-based analysis to enable to identify meaningful consumption profiles, detect anomalies, and interactively explore complex temporal consumer patterns (Master thesis, workshop publication, open-source software: https://github.com/rasmusthorsson/CLUE
- Data-driven resource management, matching and optimization of distributed energy resources for energy-sharing communities, 2 journal articles, with software library for energy for peer energy sharing optimization https://github.com/dcs-chalmers/pypesol published at the ACM SIGENERGY site https://energy.acm.org/resources/. The PyPESOL library provides a modular and extensible framework for modeling and solving optimization problems related to energy consumption, storage, and sharing.
- Implementation of data validation pipelines using both stream processing and Complex Event Processing as underlying paradigms, tested with real data and within the real data validation ecosystem existing at Göteborg Energi.

Publications 2025

Journal papers

R. Duvignau, V. Gulisano, M. Papatriantafilou and R. Klasing, Geographical Peer Matching for P2P Energy Sharing. IEEE Access, vol. 13, pp. 9718-9738, 2025

R. Duvignau, N. Gillet, R. Klasing, "Greediness is not always a vice: Efficient discovery algorithms for assignment problems. Discrete Applied Mathematics, Volume 378, 2026, Pages 65-86, ISSN 0166-218X

V. Jarlow, C. Stylianopoulos, M. Papatriantafilou, QPOPSS: Query and Parallelism Optimized Space-Saving for finding frequent stream elements. Journal of Parallel and Distributed Computing, Volume 204, 2025

V. Q. Ngo, M. Papatriantafilou (2025). CHK and the balancing act of maintaining heavy-hitters in stream processing. PVLDB Endowment, Vol 18 (9), 2025.

Conference papers

R. Duvignau, V. Gulisano, M. Papatriantafilou. "PyPESOL: The Python P2P Energy Sharing Optimization Library". Proceedings of the 16th ACM International Conference on Future and Sustainable Energy Systems (E-Energy '25). ACM 2025. Netherlands

L. Magnusson, R. Thorsson, V. Quang Ngo, M. Papatriantafilou, J. van Rooij, M. Chigrichenko. CLUE – Cluster-based Load Understanding and Exploration: Summarizing High-Dimensional Electricity Grid Data for Scenario Analysis. Proceedings of the Workshop on Relaxed Semantics in Data Analytics Pipelines -Co-located with ACM International conference on Distributed Event-Based Systems (DEBS) 2025. Sweden.

G. Appetito, V. Gulisano, E. Medvet. Automated Discovery of CEP Applications with Evolutionary Computing. ACM International conference on Distributed Event-Based Systems (DEBS) 2025. Sweden

J. Liu, V. Gulisano. On-demand Memory Compression of Stream Aggregates through Reinforcement Learning. ACM International Conference on Performance Engineering (ICPE) 2025. Canada.

M. Hilgendorf, M. Papatriantafilou. "LMQ-Sketch: Lagom Multi-Query Sketch for High-Rate Online Analytics." 39th International Symp. on Distributed Computing (EATCS DISC 2025), Germany, 2025

Reports

Our code library PyPESOL The Python P2P Energy Sharing Optimization Library (https://github.com/dcs-chalmers/pypesol) has been published on the ACM SIGENERGY portal: https://energy.acm.org/resources/

Data analysis open-source software CLUE : https://github.com/rasmusthorsson/CLUE "CLUE -- Clustering-Based Load Understanding and Exploration", to enable to identify meaningful consumption profiles, detect anomalies, and interactive exploration of complex temporal consumer patterns

Data analysis open-source software for parallel and streaming data summarization of outliers/most frequent data-element instances in high-rate/high-volume data: CHK and the balancing act of maintaining heavy hitters in stream processing https://zenodo.org/records/15593109

Bachelor & Master theses

L. Magnusson and R. Thorsson. CLUE – Cluster-based Load Understanding and Exploration: Summarizing High-Dimensional Electricity Grid Data for Scenario Analysis. Master thesis. Göteborg University, Sweden. https://gupea.ub.gu.se/handle/2077/89783 (Co-supervisors: V. Quang Ngo, M. Papatriantafilou from Chalmers University of Technology, J. van Rooij, M. Chigrichenko from Göteborg Energy)

Vaibhav Talari, Nadia Papa. Event Detection in Smart Meter Data with Complex Event Processing. Master thesis in collaboration with Göteborg Energi (https://odr.chalmers.se/items/0330d18d-1815-4be7-987c-8a7518100b42, Vincenzo Gulisano)

Finding Needles in the Haystack. A CEP Approach to Detect Recurring Grid Issues. Erik Larsson, Josef Ngo. Master thesis in collaboration with Göteborg Energi (https://odr.chalmers.se/items/cbba431d-7e07-4c36-abac-78c73bd77582, Vincenzo Gulisano)

INTELLIGENT ENERGY MANAGEMENT

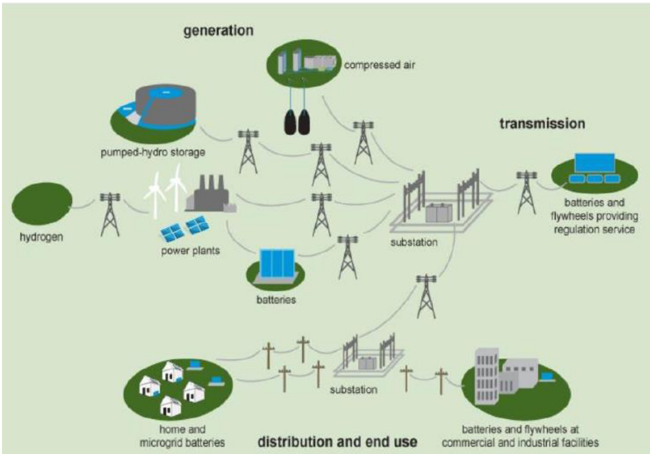
STORAGE AND FLEXIBILITY FOR ENHANCEMENT OF GRID CAPACITY

The reduction of CO2 emissions motivates the use of renewable energy sources like wind and solar power, which are dependent on weather conditions and thus variable in time. Electricity energy production must always equal consumption at every instant. This project aims to technologies to mitigate energy imbalances due to renewable energy sources.

A decrease in CO2 emissions is necessary to reduce the global warming. One component in this reduction is to reduce the use of fossil-based fuels in electricity generation and shift production towards renewable energy sources such as wind-power and solar-power. The shift to such sources comes with additional challenges for the electricity system. One important issue is the inherent variability of such energy sources as the level of possible production changes with meteorological factors beyond our control. A fundamental property for an electrical power system in stationary operation is that the produced electric power must equal the electric power consumed in the loads. Uncontrollable variations in either load or production must hence be balanced by changes in other parts of the system. This project aims to study how this balancing can be accomplished from two perspectives. In the first perspective we study how energy storage systems can be placed and dimensioned to optimally absorb the variability. In the second perspective we study how the energy markets can be designed to promote loads to participate in balancing the variability of the renewable sources by aligning the load level with the production levels and thus reduce the need for energy storage.

Electrical storage

The first perspective is devoted to development of analysis and design methodology to optimally deploy electricity storage systems to an existing grid with the purpose of providing balancing services to the grid to mitigate the adverse effects of the variability of renewable energy sources. This ultimately entails to determine the best geographical locations to use and decide on power rating and energy storage capacity by means of mathematical models and optimization.



Power markets

The second perspective considers how energy market models and the regulatory framework can be evolved into a real-time market model which seamlessly incorporate demand response participation at a large scale. We will develop a simulation methodology which can be used to assess the performance of a specific market model implementation applied to a given network topology and characterize the properties of investigated market models with respect to variations, stability, and efficiency.

Involved in the project

Masoume Shabani, Thomas Rylander, Tomas McKelvey, Giuseppe Durisi, Jan R Svensson, Massimo Bongiorno

Partners

Chalmers, Lund University, Hitachi Energy, Svenska kraftnät, Texel , Vattenfall Eldistribution, Soltech Energy Solutions, Swedish Energy Agency

PROJECT RESULTS 2025

We are developing fundamental statistical models for variability in production and consumption that can be used to determine the energy storage capacity needed to provide an overall power balance.

In 2025, the project advanced the development of a simple, transparent, and robust methodology for energy storage sizing:

In the work the wind power generation and demand in the Swedish SE3 region has been used as a case study and been evaluated regarding both the technical performance and economic feasibility of energy storage deployment to overcome the generation-demand imbalance.

Implementation of a data-driven storage-sizing method
A systematic approach was developed to estimate the minimum energy storage capacity required to fully balance generation–demand mismatches for a full calendar year. The minimum required storage capacity is shown to be directly related to the difference between the maximum and minimum valus of the integral of the power mismatch over a full year. The resulting analysis provided the minimum required capacity, which served as the reference upper bound for the next stage of the study.

Evaluation of hybrid supply performance
The analysis was extended to hybrid configurations that combine a reduced battery size with an external energy source (i.e. import of energy). Simulations were conducted for a range of battery capacities to determine how external support can reduce overall system cost and storage requirements while maintaining uninterrupted operation.

Economic assessment and sensitivity analysis
Using base-case assumptions of a battery cost and an external energy cost, total annual system costs were calculated for multiple scenarios. Sensitivity studies explored the impact of the energy storage cost-to-electricity price ratio (σ) on total system cost and the economically optimal energy storage size.

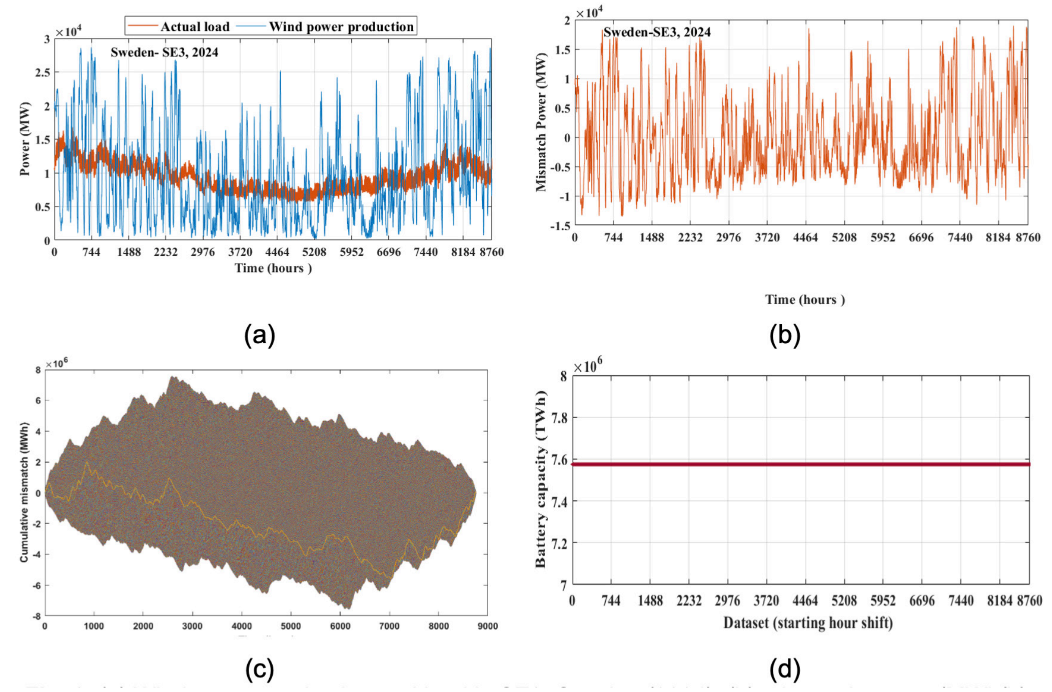


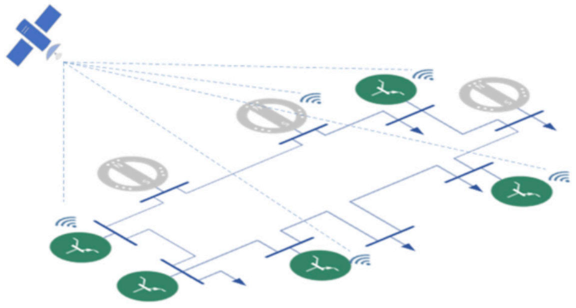
Figure. (a) Wind power production and load in SE3, Sweden (2024); (b) mismatch power (MWh/h); (c) cumulative mismatch curves across different starting points; (d) required battery capacity across different starting points

Publications 2025

No publications during 2025

SYNCHRONIZED GRID-FORMING SYSTEMS

The aim of this project is to propose and investigate control solutions for grid-connected converters to favor large integration of renewables in the power systems. In particular, the focus is on the development of control strategies that allow enhancement of system's stability and flexibility in power-electronic dominated grid, by controlling the instantaneous energy flow between selected generating units through bi-directional communication links.



The European Union has the ambitious target of at least 27% of energy to come from renewable energy sources (RES) by 2030, with an associated CO_2 emissions reduction target of at least 40% (relative to 1990) and at least a 27% saving in energy usage by the same date. Some future European energy scenarios even foresee a very high-RES penetration, and Sweden aims for a 100% renewables generation capacity by year 2040. To address the challenges associated with high penetration and integration of RES in the European system, innovation and development in several research areas, such as system integration, interoperable services, novel controllable devices and coordination schemes are needed in order to guarantee the availability and reliability of the power systems.

The electric power grid is a complex system that continuously requires balance between energy production and consumption, due to its inability to store energy. Furthermore, the system must be available, stable and able to cope with large events, such as short-circuit faults. A high penetration of RES, connected to the grid through power-electronic converters, might negatively impact these critical properties.

It has already been reported in the literature that a large amount of power-electronically interfaced RES might lead to several challenges for the power system such as reduced physical inertia and reduced synchronizing capability following disturbances. Conventional synchronous generators tend to automatically provide inertial and dynamic reactive power support due to the inherent nature of the machines. This is not the case for power-electronic based generation units and can lead to stability issues when the majority of the produced electrical power comes from RES.

Several converter-control solutions to overcome the aforementioned problems have been proposed in the literature, to provide the grid with vital functionalities, such as inertia and frequency support, and black start capability. Converters provide these ancillary services only at the connection point based on local measurements and local control action. Depending on the entity of the event as well as on the characteristics of the system, both in terms of number of synchronous machines available and geographical location of the generating units, this might result in large investments both in terms of need for energy storage and converter requirements.

As intelligence and measurements availability will be spread all-over the system, it is reasonable to consider that in the future converters will communicate and cooperate through bi-directional communication links, aiming at taking full advantage of the flexibility, controllability and speed of response that characterize modern power-electronic converters to increase the robustness and resiliency of the future RES-dominated grid.

Involved in the project

Kavian Kamalinejad, Massimo Bongiorno, Mebtu Beza, Anant Narula, Jan R. Svensson, Robert Eriksson, Daniel Karlsson, Lisa Göransson, Olof Samuelsson

Partners

Chalmers, Hitachi Energy, Svenska kraftnät, DNV, Soltech Energy Solutions, Vattenfall Eldistribution, Lund University, Swedish Energy Agency

PROJECT RESULTS 2025

During 2025, the project developed and applied a structured workflow to analyze angular stability in converter-dominated power systems, progressing from control-parameter-level analysis to system-level assessment under realistic operating conditions.

In the first stage, the focus was on understanding how control parameters influence the angular stability of grid forming converters under dynamic grid conditions. A control-aware analytical framework was established by modeling the interaction between a grid forming converter and the grid using an analogy with a torsional spring-mass-damper system. This representation provides clear physical insight into how angle disturbances propagate through the system. As illustrated in Figure 1(a), the converter-grid interaction can be interpreted in terms of inertia, stiffness, and damping effects. Frequency-domain analysis was then employed to characterize the system response, revealing frequency ranges in which angle deviations between the converter and the grid are either attenuated or amplified, as shown in the Bode plots in Figure 1(b) and the corresponding inter-mass angle gain in Figure 1(c).

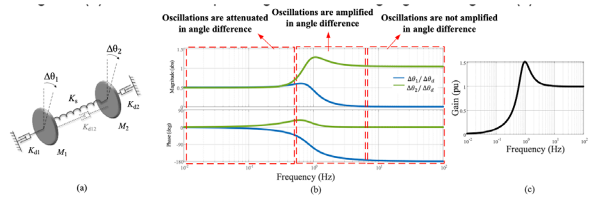


Fig. 1: (a) Torsional spring–mass–damper system. (b) Bode plots of the transfer function from angle disturbance to the angle of each mass. (c) Gain of the inter-mass angle difference with respect to the angle disturbance.

The results demonstrated that key control parameters, such as active-power controller bandwidth, AC voltage controller bandwidth, active damping, and virtual impedance, have a pronounced impact on the amplification of angle differences. In particular, faster control action improves convergence speed but may significantly increase overshoot and mid frequency amplification, thereby elevating the risk of angular instability. These effects are systematically illustrated in Figure 2, which highlights the influence of active-power controller bandwidth, virtual inductance, and virtual resistance on angle deviation amplification. Time domain simulations with phase jump disturbances were used to validate the analytical findings and to further illustrate the practical implications of controller tuning.

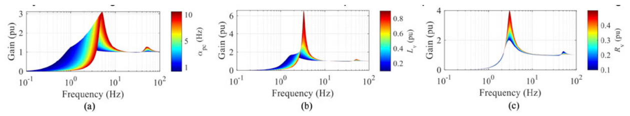


Fig. 2: Impact of controller tuning on the angle deviation amplification, illustrating the effects of (a) active-power controller bandwidth, (b) virtual inductance, and (c) virtual resistance.

Building on these insights, the second stage extended the analysis to the multi-converter level, where multiple converters interact through a realistic network. A quas-static modeling framework was developed to assess transient stability while retaining the essential dynamics of converter controls. This approach enables efficient computation of dynamic power-angle trajectories without relying on computationally intensive electromagnetic transient simulations. The method was applied to a representative offshore wind power plant connected to an onshore grid and supported by a grid forming STATCOM.

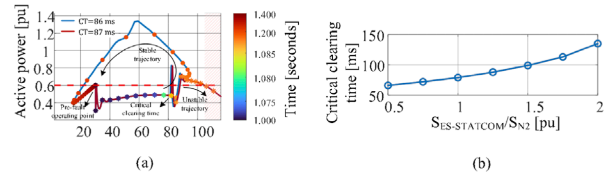


Fig. 3: (a) Dynamic P–δ trajectories of an equivalent wind-farm converter, comparing stable and unstable operating conditions as a function of fault-clearing time. (b) Effect of a supplementary converter in the system (STATCOM) and its capacity on the transient stability of the wind farm.

The resulting dynamic P-δ trajectories, shown in Figure 3(a), illustrate stable and unstable operating conditions as a function of fault clearing time. The analysis further demonstrates the influence of an additional system converter on overall stability. In particular, Figure 3(b) highlights how the presence and capacity of a grid forming STATCOM affect the transient stability margin of the wind farm. Moreover, The results confirm that grid forming operation improves stability margins, especially under weak grid conditions, while also revealing a strong sensitivity to virtual admittance selection and controller tuning.

Publications 2025

Conference papers

K. Kamalinejad, A. Narula, M. Bongiorno, M. Beza and J. R. Svensson, "Impact of Control Parameters on Angular Stability of Grid-Forming Converters Using Virtual-Admittance Based Control," 2025 Energy Conversion Congress & Expo Europe (ECCE Europe), Birmingham, United Kingdom, 2025, pp. 1-6, doi: 10.1109/ECCE-Europe62795.2025.11238912.

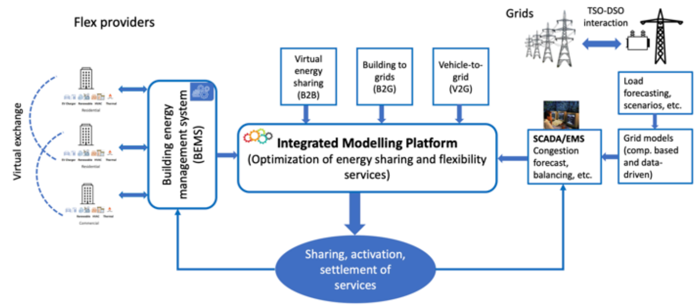
K. Kamalinejad, S. Mohtat and A. R. Zamani, "Comprehensive Derivation of Small-Signal Model for Virtual-Admittance Based Grid-Forming Modular Multilevel Converters," 2025 Energy Conversion Congress & Expo Europe (ECCE Europe), Birmingham, United Kingdom, 2025, pp. 1-6, doi: 10.1109/ECCE-Europe62795.2025.11238501.

Publications under review

K. Kamalinejad, A. Narula, M. Beza, M. Bongiorno, Lazar Stojanovic, and J. R. Svensson "Impact of Control and System Parameters on Transient Stability in Multi-Converter Systems: Insights from Quasi-Static Modeling" PSCC 2026 - Electric Power Systems Research.

K. Kamalinejad, A. Narula, M. Bongiorno, M. Beza and J. R. Svensson, "A Frequency-Domain Study of Damping and Synchronizing Characteristics of Virtual Admittance-Based Grid-Forming Converters", International Journal of Electrical Power and Energy Systems.

MODELLING PLATFORM FOR BUILDING-TO-BUILDING-TO-GRID SERVICES (B2B2G)



With on-going energy transition, power systems are facing challenges from renewable based generation, increased electricity demand and uncertainty due to electrification of transport and industries. Main challenges are related to the demand-supply balance and grid capacity constraints. Flexibility from end-users (e.g., buildings) could contribute to addressing these challenges.

Buildings are becoming increasingly active with massive integration of solar photovoltaic (PV) panels, electric vehicle (EV) chargers, battery energy storage, heat-pumps, etc., and could potentially contribute to addressing the challenges. This project will enable buildings to share energy between buildings within a community and to provide flexibility to support the grids.

Aims
The project will develop simulation tools and solutions to i) enable virtual energy sharing in between buildings, i.e., building-to-building (B2B) service within a community as well as between the community and other stakeholders in cases of excess or deficits of energy produced (e.g., other communities, grids, etc.); ii) enable buildings and electric vehicles to provide flexibility to support grids' operation through building-to-grid (B2G) and vehicle-to-grid (V2G) services. The aim is also to make buildings active and controllable resources to support more secure and renewable-rich networks.

Research approach
The overall methodology of B2B2G is as based on an iterative approach which will support "fast and incremental" development of work and results. It is composed of four modules, including: (i) "Needs and challenges" representing the foresight of the project; (ii) "Innovative services" representing novel developments; iii) "Integrated modelling platform" representing the core structure on which the novel developments are based; (iv) "Assessment and Deployment" representing the results assessments and potential for deployment. These modules are interconnected to receive inputs and deliver outputs from/to the other modules within the projects. The proposed methodology is iterative which implies that the inputs and outputs are continuously updated according to the obtained results, knowledge and experiences generated in the previous iterations. Using iterative, incremental development and short assessment cycles, it is flexible to inform involved partners with feedback, enabling a regular update of the progress and an easy-to-use process of managing changes to the plans during the project lifetime.

Expected results
The main expected results of the project will include the following:

- Specifications of virtual energy sharing framework and functionalities and specifications of B2G's and V2G's functionalities.
- An integrated modelling platform, as a decision support tool, for e.g., analysis of impacts and interactions with the grids (TSOs, DSOs) by different future scenarios, market mechanisms, business cases, etc., of innovative services offered by buildings, such as virtual energy sharing, building-to-grid services, vehicle-to-grid services.
- Assessment of cost-effectiveness and business models of the services through case studies and demonstrations. The evaluation will consider i) Benefits to the grids, e.g., how grid operation can be improved and ii) Benefits to the buildings, e.g., how much building cost can be saved? How much profits from providing flexibility services and from sharing of energy.
- Guidelines and specifications for potential piloting and deployment of solutions in real buildings by stakeholders, business cases for energy sharing, B2G, V2G services as well as suggested policy changes.

Involved in the project
Tuan Lee, David Steen, Chalmers; Elis Nycander, Ali Fotouhi, Claes Sommansson, Daniel Chima

Partners
Chalmers, Svenska kraftnät, E.ON Energidistribution, Volvo Cars, Chalmers Industriteknik

PROJECT RESULTS 2025

Within this reporting period, we have developed a self-consumption (SC) and Local Energy Community (LEC) based energy trading/sharing mechanisms (see figure 1) for comparative studies from a DSO's perspective. These comparative studies aim to identify the pros and cons of energy-sharing mechanisms.

Preliminary results have been achieved during this period as summarized below. An IEEE CIGRE LV network rated at 20/0.4 kV was used in case studies to represent a distribution system with 6 prosumers. The Feeder is categorized based on load type into three categories, Commercial, Residential and Industrial. The load profiles used to construct the non-prosumer demand and the candidate location of Renewable Energy assets.

The case study results have showed that prosumers in LEC framework utilize their resources more leading to increased max line loading and decreased bus voltages.

Consumption cost of prosumers in LEC is observed to be lesser than SC case, as LECs enable more local consumption.

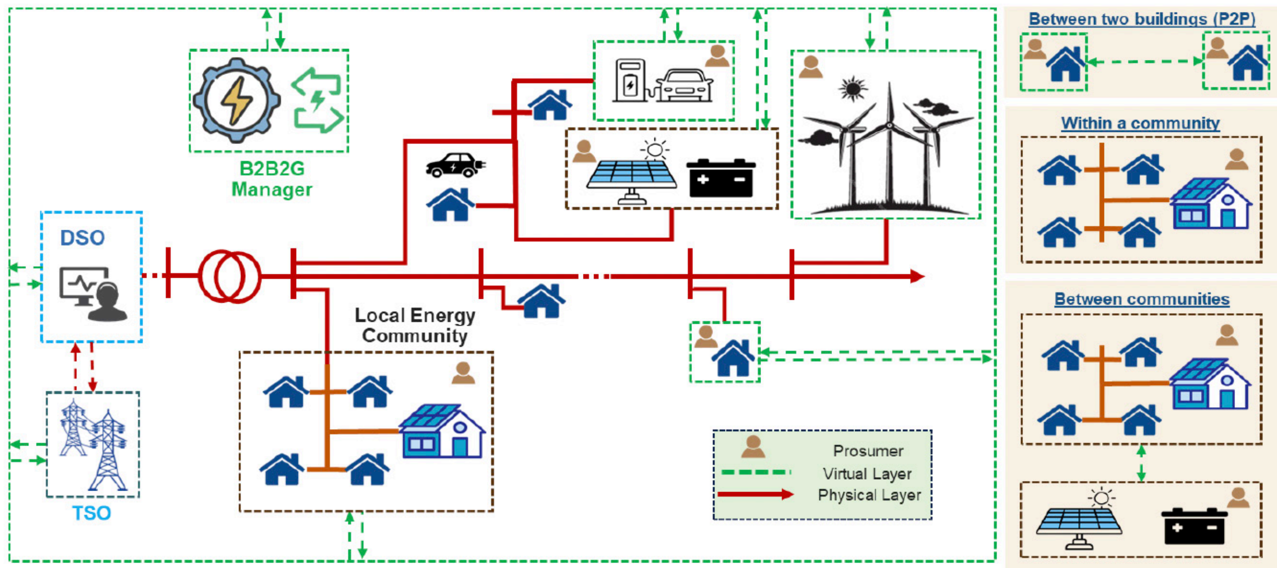


Figure 1: Alternative energy sharing mechanisms within LECs in distribution systems

Publications 2025
No publications during 2025

MODELING THE REGIONAL ENERGY TRANSITION

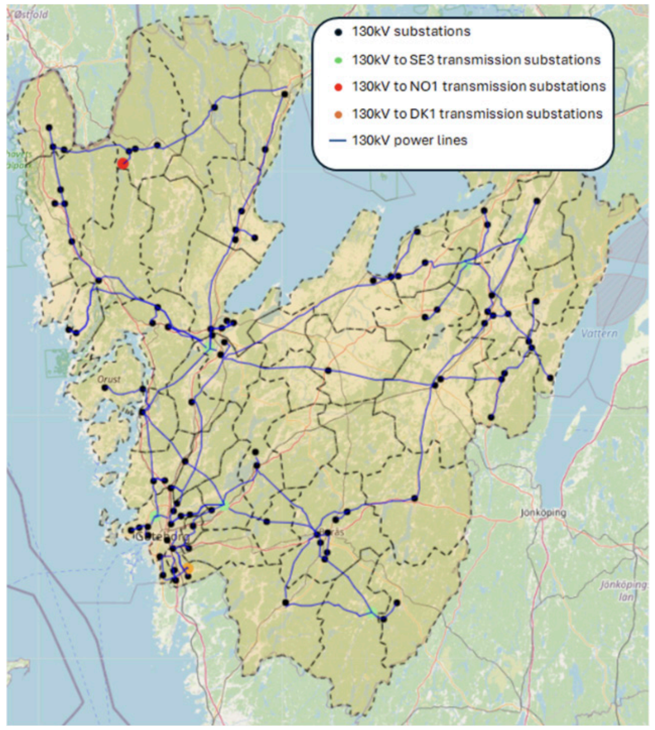
Investigating the interaction between electricity, heat and hydrogen to facilitate the energy transition in a congested region.

The regional level of the energy transition is gaining importance, both because of existing and expected limitations in the transmission grid but also because it is easier to create mutual understanding and collaboration on the regional level.

The aim of the proposed project is to design a modeling tool for integrated energy systems which can support the identification of cost-efficient investments in generation and flexibility on local level considering electricity, heat and hydrogen as energy carriers. The model builds on three ongoing PhD projects at the division of Energy Technology; one with focus on the 130kV power grid, one with focus on hydrogen infrastructure and one with focus on district heating. Within the proposed project, the methods developed in these 3 PhD projects would be combined to a coherent tool to investigate cost-efficient regional transition pathways representing the infrastructure of electricity, hydrogen and heat.

Care is taken to give a physical representation of electricity, hydrogen and heat infrastructure which is appropriate for the regional scope. An extensive set of technologies will be included as investment options, with a particular focus on representing technologies coupling the three energy carriers (such as combined heat and power plants, heat pumps, electric boilers and electrolysers) and flexibility options (including batteries, hydrogen tank storage, hydrogen LRC storage, hydrogen pipline storage, heat tank storage, heat storage in buildings, strategic charging of electric vehicles).

The tool is intended for decision support for regional actors, such as regions, länsstyrelser and regional grid owners. Within the project the tool will be tested on the Västra Götaland region.



Involved in the project
Niclas Mattsson, Lisa Göransson, Viktor Walter, Magnus Danielsson

Partners
Chalmers, Västra Götalandsregionen, Svenska kraftnät

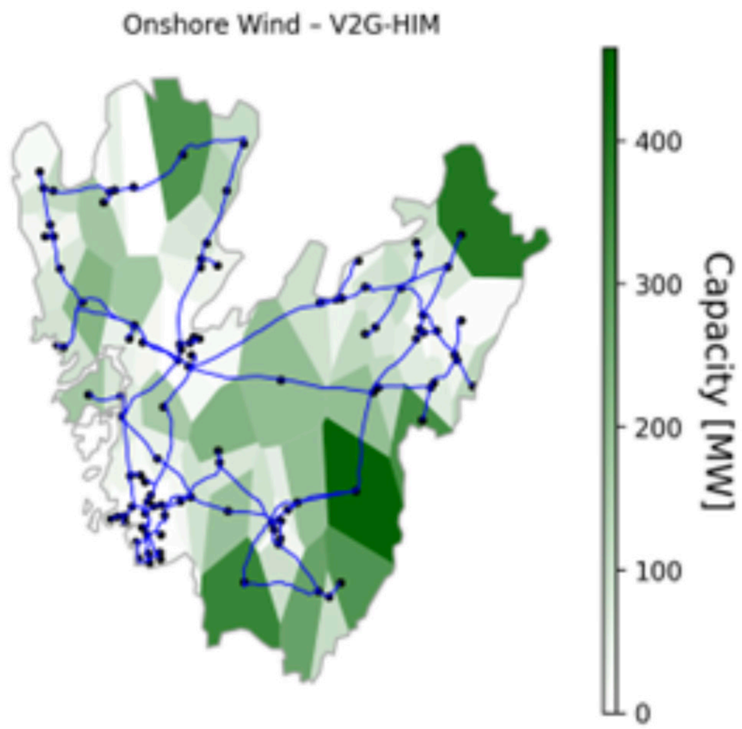
SYSTEMS

PROJECT RESULTS 2025

This year the project has supported the development of a model of a regional energy system model with power flow limitations on the 130 kV network at its core.

Within the project, this model has been adapted for co-development and sharing with other researchers. Example output of the model is given in the figure below, which illustrates cost-efficient onshore wind power deployment across the region given an electrification of industry and transport.

The project has also supported the comparison between different methods to implement hydrogen infrastructure in energy system models and a method has been selected for the implementation in the regional energy system model. The integration is starting during fall 2025.



Cost-efficient onshore wind power deployment across the Västra Götaland region given an electrification of industry and transport

Publications 2025
No publications during 2025

THREE ASPECTS OF BALANCING – PRODUCTION, ENERGY STORAGE AND NEW CONSUMPTION

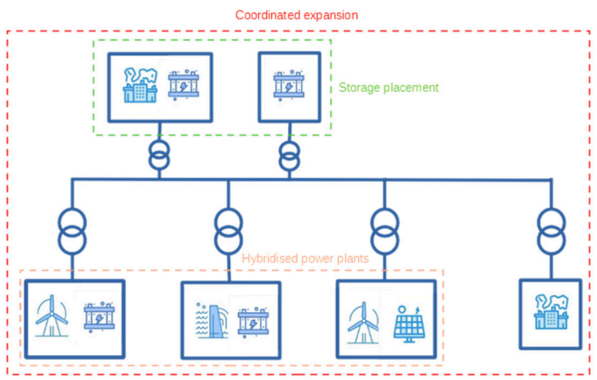
Sweden aims for an electric power system with net zero-carbon emissions. Common for such electricity systems is that they will consist of high shares of renewable energy sources, up to 100% of the total power production. The variation in renewable generation creates a substantial need for balancing and for optimal use of the existing assets.

The key to manage the power balance is flexibility, both from generation and demand side. In this respect, energy storage can provide flexibility on both sides and is often considered as a third source of flexibility. This project will target all types of flexibility, in terms of: Coordination and more effective use of different technologies for power generating plants, Optimal storage location for local- and peak-power provision, system capacity enhancement and ancillary services provision Feasible development trajectories of V-RES, batteries, grid and electrolysis using a whole-system approach.

This project targets all three sources of flexibility – consumption, generation, and storage – to support the development towards electricity supply from 100 % renewables generation. In response to these challenges, a joint project proposal between Uppsala University, Chalmers University and Lund University has been developed, aiming at investigating, and identifying solutions under three different aspects of balancing: generation, storage, and new consumption.

Uppsala University will focus on demonstrating how combining power plants of different types with each other and with storage is beneficial for contributing with ancillary services, balancing, and also possibility for island operation. Hybridisation and Virtualisation of remote storage combined with coordinated operation can benefit the grid. The outcome will be optimisation methods for combining resources. Simulation models for different types of storage and power plants will be studied in a common platform for interchangeability.

Chalmers University will focus on optimal location of energy storage for system capacity enhancement and ancillary services provision, both in transmission and in distribution grids. The project aims at demonstrating

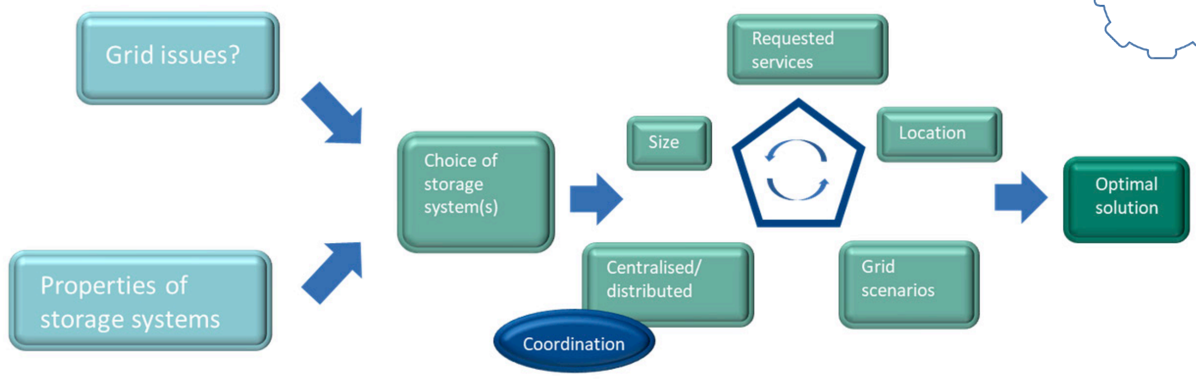


how the location of electricity storage affects the value of the installation, with respect to various grid scenarios and system services, in addition to the pure energy storage capability. Storage systems under investigation include, but are not limited to: batteries, hydro dams and power-to-hydro-gen-to-power (for example, H2-driven steam turbines). Local power and peak-power provision, as well as frequency control and others are services to be considered.

Lund University will focus on how the capacity developments of V-RES, new consumption (mainly electrolysis), electricity storage (mainly batteries) and grid affect each other. Optimization will be used to find feasible combinations, but in contrast to presenting scenarios for certain years like 2035 and 2045, the aim is here to present trajectories with yearly resolution showing how the four parts could develop. Similar emphasis is on how changes in each part affect the others. Probabilistic methods are attractive, and the aim is to use these also with the time-dependencies introduced by storage. The evaluation of each year is based on hourly resolution, and faster variations are disregarded and left to the other two subprojects. A whole-system approach is used considering generation, transmission and distribution networks, and consumption and the aim is to involve representatives from all these in the project.

Involved in the project
Olof Samuelsson, Urban Lundin, Torbjörn Thiringer, Sara Fogelström, Massimo Bongiorno, Peiyuan Chen

Partners
Uppsala University, Lund University, Chalmers, Akademiska hus, DNV, Göteborg Energi, Herrljunga El, Hitachi Energy, Liquid Wind, Mölndal Energi, Nilson Energy, Port of Göteborg, Repono, Soltech Energy Solutions, Svenska kraftnät, Texel, Vattenfall Eldistribution, Volvo Energy, Volvo Cars, Swedish Energy Agency



Idea for the project:

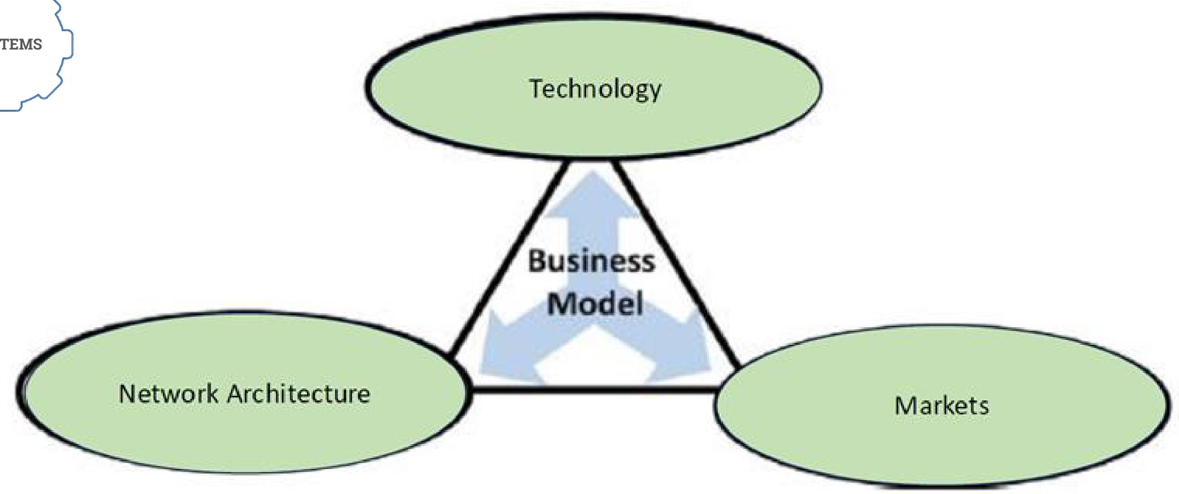
PROJECT RESULTS 2025

The project's doctoral research activities progressed steadily during 2025, with parallel modelling efforts carried out at Chalmers University of Technology and Uppsala University. The work focused on developing and adapting simulation models to support analysis of future electricity grids and energy storage solutions under Swedish conditions.

The PhD student in Chalmers' part of the project is working 50% on the project. During 2025, the PhD student has continued to develop the model of the medium voltage grid in PowerFactory, based on the well-known Cigré benchmark model for medium-voltage grids. The PhD student has added solar panel to all busbars in the model as well as prepared it for an increase in consumption of electricity. Together with another PhD student in the Centre had a series of meetings with Vattenfall Eldistribution in order to better understand the main characteristics of a Swedish distribution grid, together with the main differences compared with the implemented Cigré model (based on a German distribution grid). From this, the medium voltage model has been adapted to Swedish conditions. There will also be two models, instead of one, one representing a Swedish urban area and one representing a rural grid in Sweden. In addition to developing the model in PowerFactory, two script in Python has been developed, on how to control and change the parameters in PowerFactory as well as run quasi-dynamic simulations in PowerFactory. The other Python script loads the results from the simulations in PowerFactory and searchers for anomalies in the data, for example when voltage levels at busbars exceeds a certain level. Annual report 2 (2) Project no: SYS2023-23

The Uppsala PhD student started in May 2025 has initiated modelling a pumped storage plant. He is studying how to use variable speed technology to provide ancillary services in pump-mode. The modelling takes into account the motor/generator, control and dynamics of the turbine and waterways in the simulation tool Matlab/Simulink. Initial results have been obtained. The electrical machine is a Doubly Fed Induction machine that has potential to change speed about +/- 7% which results in a power flexibility of about +/- 30%. The work continues with modelling the water ways which puts boundary conditions on the speed of control and also pose potential dangers inside the power plant.

Publications 2025
No publications during 2025



BUSINESS MODELS FOR ENERGY STORAGE

In this project, we investigate business models for energy storage based on a case study approach. The ambition is to provide a comprehensive overview of current and potential business models for energy storage in the Swedish context. The collaborative project is run by Chalmers together with CIT Renergy, Volvo Energy, Svenska Kraftnät and Södra.

The project started with an initial mapping of energy storage technologies and application areas. Now, the search for cases that can display a variety of business models applied or contemplated by different actors and at different levels in the grid is on-going. The business model cases will focus on the services and values generated by energy storage solutions based on how these are combined with other resources by different actors and their business partners. Based on these studies, we aim to provide a comprehensive view of the current and emerging business models for energy storage.

Business models and business networks

We rely on the Industrial Network Approach to business markets. It means that we consider companies as inter-connected by business relationships in network-like, inter-organizational, structures; No business is an island.

So, to be able to capture the business logic, the business models need to be understood and conceptualized as integrated parts of their business network contexts.

Case studies

The project takes a qualitative method approach and will carry out a range of case studies to provide an understanding of the business actors' concerns when considering; investments in and operation of various energy storage solutions, the selling and buying of physical resources and services related to energy storages, and the real or perceived values that can be captured by energy storages in combination with other resources. Also, the interaction with other actors and the nature of their relationships and/or market transactions are to be described and analyzed. Among the case studies we will focus on second-life batteries and their uses in different applications e.g., in combination with other resources in wind and solar parks, mobile and stationary support to increase grid capacity, while other cases will focus on industrial applications and flexibility in operations. Other areas of interest include energy storage as a key component in energy communities.

Involved in the project
Colin Kimbrell, Anna Dubois, Frida Lind

Partners
Chalmers, Volvo Energy, Södra, Svenska kraftnät, CIT Renergy, Västra Götalandsregionen, Swedish Energy Agency

PROJECT RESULTS 2025

The results from this year from our project are mainly connected to continued data collection (in terms of conducted interviews and other secondary sources) and parallel data analysis. During this year, we have presented our work at different conferences and received valuable feedback.

One paper is also under review, so we have been working with revising this paper. Other conference papers are being developed for journal submission. In parallel, we are working on a general report to summarize findings relevant to work packages 1-3 for a wider audience, including the SESBC members.

In summary, work has been done in the following areas
Analyzed how business actors perceive possible business models for the electrification of transport and in this analysis, vehicle batteries are considered as the focal resource. Three battery related network settings have been identified, which typically are addressed separately: transport, energy and circularity. In this analysis, we identified three types of business models (to be) adopted by BEV OEMs.

I. Integrated battery as a component,
II. Integrated battery as a service
III. Swappable battery as a service.

These three identified business models differ and contain their own value creation logics.

The above has also provided data and insights into two of our continued overarching research questions: 1) How are energy storage and balancing solutions as resources integrated in the electricity system and how are they embedded in emerging business networks? How are values created through the interaction of ES&BS resources and how can these values be conceptualized in terms of how they are distributed across actors whose resources are combined? Particularly as regards battery energy storage systems (BESS).

Begun investigating the phenomenon of community energy, i.e. the aggregation of especially modular energy technologies such as solar panels and battery storage in behind-the-meter applications, and how this relates to broader grid developments. So far we have seen that many business actors are getting involved in this space, applying a wide range of business models. Our investigation is particularly interested in how these niche actors engage with 1) the communities in which they operate to achieve not only business results but also socio-economic benefits to the respective communities and 2) incumbent actors in the energy and electricity systems, such as large energy companies and distribution system operators, and how these emerging business activities impact on those entities and the continued stability and reliability of the grid. Examples of current and future SESBC partners relevant to this research: E.ON, Göteborg Energi, and Varberg Energi.

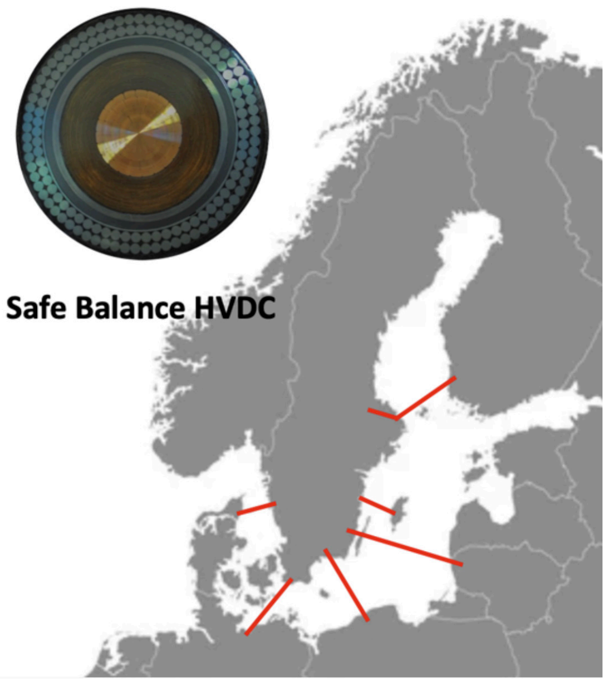
Publications 2025

Conference papers
C. Kimbrell. (2025) Who delivers on the promise of community energy? Evaluating niche–regime interactions in Swedish energy communities, ECPR General Conference, Thessaloniki, 26-29 August.
C. Kimbrell, A. Dubois, F. Lind, L. & Huang. "Understanding a key resource in a complex emerging network setting: The case of energy storage and balancing solutions", presented at the 41st annual IMP Conference, 20-22 August, Gothenburg, Sweden, 2025.
L. Govik, C. Kimbrell, and F. Lind. "Sharing resources across boundaries: Cases of batteries and charging applications of a Vehicle OEM", presented at the 41st annual IMP Conference, 20-22 August, Gothenburg, Sweden, 2025.
L. Govik, C. Kimbrell, and F. Lind. "Batteries and sustainable business models – Collaboration in internal and external networks", Nofoma Conference, 37th annual NOFOMA conference, Copenhagen, Denmark, 10-12 June, 2025.

Reports
V. Stenberg, F. Lind, C. Kimbrell, and A. Dubois. Business models for electricity storage and balancing solutions: Draft report, 2025

SAFE BALANCE HVDC: ENSURING INSULATION INTEGRITY AND OPERATIONAL SAFETY IN ENERGY BALANCING

The Safe Balance HVDC project aims to enhance the reliability of Sweden's HVDC transmission system in response to new European regulations that demand quicker energy balancing.



These regulations significantly increase the frequency of voltage polarity reversals, placing additional stress on Mass-Impregnated (MI) cables. By optimizing voltage reversal intervals and benchmarking Partial Discharge (PD) detection systems, the project seeks to maintain insulation integrity and operational safety, ensuring the long-term resilience of Sweden's electricity infrastructure.

The European Commission's Regulation (EU) 2017/2195 mandates a reduction in energy balancing intervals from 60 to 15 minutes, a change that places increased operational demands on HVDC systems. This regulation affects Sweden's HVDC network, which relies heavily on Mass-Impregnated (MI) cables for cross-border power transmission. These cables are critical for Sweden's energy safety, facilitating over 70% of its electricity import and export capacity. However, frequent voltage polarity reversals due to faster energy balancing intervals accelerate the aging of these cables, increasing the risk of failure.

Objectives and Approach

The Safe Balance HVDC project addresses the challenges associated with increased polarity reversals in MI cables. It focuses on three primary goals:

Optimize Voltage Reversal Strategies: The project aims to develop operational strategies that minimize the adverse effects of rapid polarity reversals on MI cable insulation. By studying voltage profiles and simulating cable response under various conditions, the project seeks to identify optimal voltage reversal profile that minimizes insulation stress.

Evaluate Insulation Aging: Through controlled laboratory experiments, the project will assess the dielectric properties and aging behavior of MI cable insulation under different stress conditions. Key techniques include DC conductivity measurements and dielectric frequency response analysis, which provide insights into the cable's lifespan and failure thresholds under high-frequency polarity reversals.

Benchmark Partial Discharge Detection Systems: To ensure reliable PD detection during rapid voltage reversals, the project will compare commercial PD systems against advanced in-house systems developed at Chalmers. This benchmarking process will assess each system's effectiveness in detecting insulation degradation, contributing to safer HVDC operations.

Involved in the project

Yuriy Serdyuk, Thomas Hammarström, Xiangdong Xu, Björn Sonerud

Partners

Svenska kraftnät, with additional collaboration from Fingrid and Energinet, Chalmers University of Technology, Swedish Energy Agency

PROJECT RESULTS 2025

According to EU Regulation 2017/2195, the time intervals for power balancing are to be reduced from 4 hrs to 15 min that leads to increasing frequency of DC polarity reversals in LCC-HVDC, which enhance the stress on insulation of high voltage cables. This year, we explore the effect of the shortened balancing intervals on mass-impregnated (MI) pressboards by analyzing their DC conductivity and loss tangent.

The dielectric response measurements were performed using test voltages containing a small AC signal, defined by the ~1% field ripple, superimposed on a DC bias (~1 kV/mm). The results show that at 15 min interval, a high post-reversal conductivity peak appeared followed by a monotonic decay. At 4 hrs interval, the measured conductivity dropped abruptly and a secondary rise was seen, which is likely due to the space-charge release/ re-injection and slow polarization recovery. For the loss tangent measurements under AC+DC voltage, after reversal, an increase in loss tangent was observed, followed by decaying quasi-periodic fluctuations around a value that stabilizes after about 150 s. When employing the shorter interval, the fluctuations of the magnitudes of the loss factor increased, however, without influencing the stabilization time notably. Applying a higher DC voltage magnitude increased the amplitude of fluctuations, yet resulting in a reduced steady-state loss tangent. It was further observed that the direction of the reversal had negligible effect on the steady-state value. The presented results provide information to evaluate the effect of shortened balancing intervals on HVDC massimpregnated cables and will be the basis for the next step of the project.

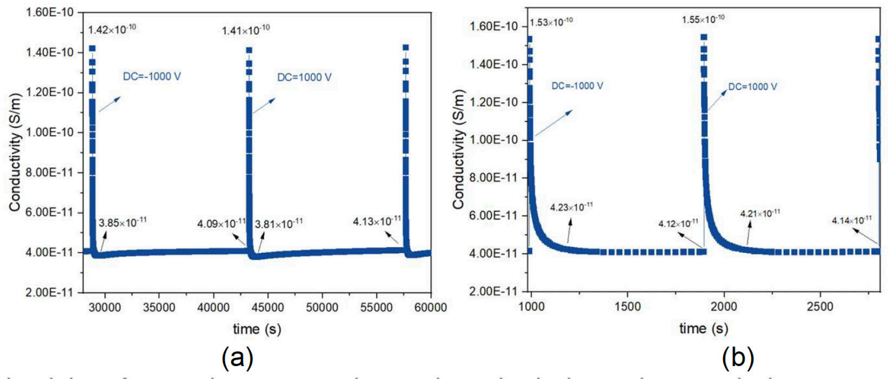


Fig.1 DC conductivity of mass-impregnated pressboards during voltage polarity reversal at a DC bias of ±1 kV: (a) reversal interval 4 hrs; (b) reversal interval 15 min.

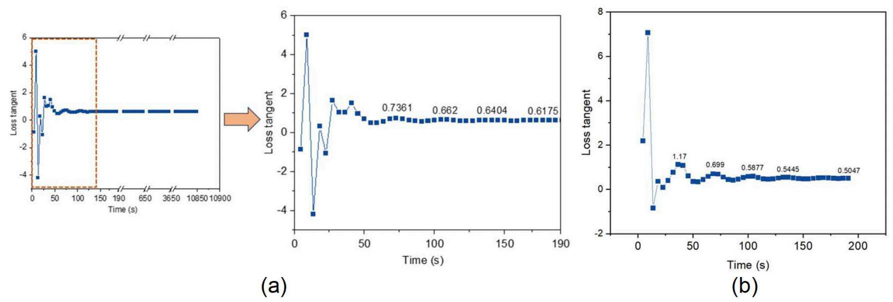


Fig.2 Loss tangent of mass-impregnated pressboard during DC voltage reversal (−1 kV → +1 kV): (a) Δt = 3 h; (b) Δt = 3 min.

Publications 2025

Conference papers

J. Hao, X. Xu, T. Hammarström, Y. Serdyuk, B. Sonerud, "Impact of shortened balancing intervals on HVDC mass-impregnated cables", published in Jicable HVDC'25 - Turin 20/22 October 2025

H. Novljanin; C.-A. Ryeskog; Y. V. Serdyuk, "Predicting Water Tree Growth in Polyethylene Insulation Using FE Model Based on State Variable M. M. Bordeori"; IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Manchester, United Kingdom, 14-17 September 2025

Y. V. Serdyuk; T. Hammarström , Water Tree Growth in XLPE Polymeric Insulation Induced by Various Types of Defects M. M. Bordeori; Y; IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Manchester, United Kingdom, 14-17 September 2025

SYSTEMS

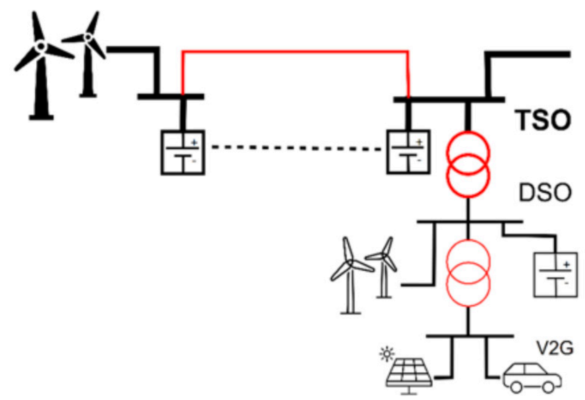
MANAGING GRID CAPACITY WITH STORAGE GRID SCHEME

This project aims to assess methods to increase the capacity of the Swedish power system using energy storage as well as enhanced control of generation and consumption. These Non-Wire Alternatives provide a potentially faster and more flexible approach than conventional network upgrades, which take 3-15 years to complete.

Electrification of the Swedish industry and transportation sectors leads to significant increase in electric power consumption over the next 20-30 years. The number of V-RES (variable renewable energy resources) in the system is expected to increase further to meet the demand. The developments in generation and consumption lead to insufficient capacity in power lines and transformers (shown red in the illustration). More grid capacity for power transfer is thus needed, but construction of new lines to reinforce the grid is not keeping up with the need. Distribution line projects typically take 3-5 years to complete, and transmission line projects have lead times of 10-15 years. Alternative methods for network capacity enhancement are needed to maintain the pace of the energy transition.

To capture the future Swedish power system, the project develops system models with associated V-RES scenarios. It then proposes methods to manage the capacity challenges: On one hand coordinated battery energy storages at transmission level are controlled to act as Virtual Power Lines. On the other hand, V-RES and consumption at transmission and distribution levels are controlled in a coordinated manner.

Grid capacity needs of the future Swedish power system
Aiming at studies relevant for 2045 and 2050, a simulation model of the Swedish power system with explicit representation of the transmission network is developed. The model is combined with scenarios for V-RES in 2045-2050 to quantify the needs for grid capacity. Each scenario is one year with hourly resolution and the scenarios represent different weather years such as dry, wet, windy or calm.



Virtual transmission lines
In operation, a power line is characterized by a certain power entering one end of the line and the same power (less losses) simultaneously leaving the other end. If battery energy storages are installed at each end of the line (see illustration), they can act as a Virtual Power Line: When power enters one end of the line, additional power can enter that battery storage. Simultaneously, the same power is drawn from the other battery storage. Controlled in this way, the two battery storages increase the transfer capacity between the two ends of the line. The project develops real-time control strategies for the battery storages forming the virtual power line.

Coordinated capacity management in transmission and distribution networks
Both TSOs (Transmission System Operators) and DSOs (Distribution System Operators) need to manage the capacity of their grids to permit electrification and expansion of V-RES. TSOs and DSOs are separate organizations, but their electricity networks are closely coupled, and it is important the capacity management of one network is not detrimental to the other. The project develops methods for coordinated capacity management of TSO and DSO networks.

Involved in the project
Martin Lundberg, Olof Samuelsson, Emil Hillberg

Partners
Lund University, Chalmers, DNV, Göteborg Energi, Hitachi Energy, Svenska kraftnät, Vattenfall Eldistribution, Volvo Energy, Swedish Energy Agency

PROJECT RESULTS 2025

SYSTEMS

The focus during 2025 has been on Martin Lundberg's PhD thesis, which concludes the project. Titled "Grid capacity – challenges and opportunities" it is about managing grid capacity with flexibility.

This project has focused modelling and control of Virtual Power Lines (VPLs), which means co-ordinated control of battery storages in the transmission network. This is his third case of controlling flexibility resources to permit grid-connection of more Variable Renewable Electricity Sources (V-RES). The two previous cases were targeted in the earlier ANM4L project, where Martin contributed with control of flexible resources to manage voltage and congestion in the distribution network. The three cases have used the same control strategy based on a PI-controller that activates flexibility (typically curtailing V-RES or charging/discharging batteries) first when voltage or current has reached its maximum (or minimum) value. The evolution is clearly visible when comparing the control schemes for voltage management and congestion management at the distribution level (see Figure 1) with congestion management at the transmission level, see Figure 2.

The work shows that a Virtual Power Line has the potential to alleviate grid capacity bottlenecks, and its main advantage is that it is installed at two discrete locations in contrast to a physical transmission line affects numerous landowners along its path. This results in significantly shorter lead time for a VPL.

During 2025, two project partners have taken the opportunity to investigate related issues in MSc degree projects:

- Is a Virtual Power Line an alternative to physical reinforcement at distribution level? Göteborg Energi extended one of their grid development projects by letting the student investigate the use of one, two or three battery storages. Simulations were carried out in PowerFactory using actual grid data.
- Large frequency deviations are usually brief and of limited amplitude. How much grid capacity in MW need to be allocated to a x MW battery storage providing the frequency control service Fast Frequency Response? Svenska Kraftnät engaged a student to investigate this using a combination of historical frequency data and network data.

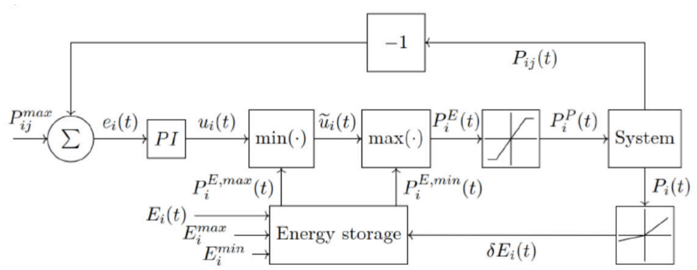


Figure 2. The control scheme based on PI-control for congestion management at transmission level, using the Virtual Power Line concept.

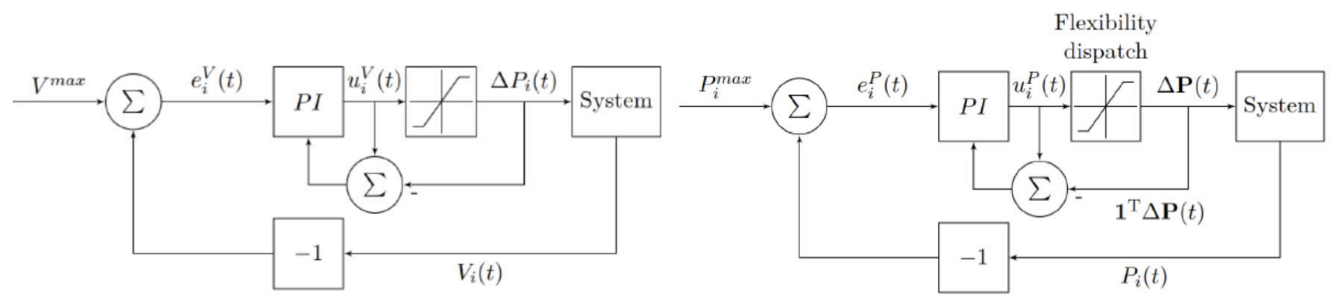


Figure 1. The control schemes based on PI-control for voltage management (left) and congestion management (right) at distribution level.

Publications 2025

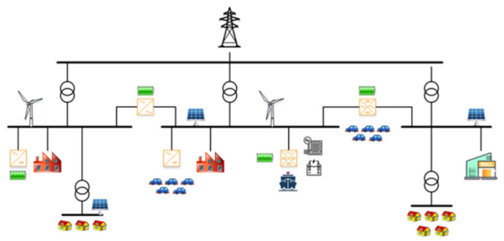
Doctoral theses
M. Lundberg, "Grid Capacity – Challenges and Opportunities", 2025, Lund University, ISBN 978-91-985110-6-2.

Bachelor and Master theses
S. Lian, "Kapacitetsallokering för batterilager som levererar snabba reserver", 2025. MSc degree project supervised by O. Samuelsson, Lund University and K. Linnanheimo, Svenska Kraftnät.
D. van Calck, "Exploring the Use of Batteries to Permit Connection of New DSO Customers", MSc degree project supervised by O. Samuelsson, Lund University and E. Blomgren, Göteborg Energi.

POWER-ELECTRONIC SOLUTIONS FOR RESILIENCY AND CAPACITY ENHANCEMENT IN MV GRIDS

The aim of this project is to propose, develop and evaluate power-electronic based solutions for enhancement of the resiliency and capacity of the future distribution grids in the voltage range between 10 kV and 33 kV.

In particular, the focus will be on the development of converter topologies and configurations that will facilitate integration of energy storage and hydrogen production, and services for the grid, such as power re-routing, voltage control, power quality improvement, system strengthening, phase balancing and losses minimization/optimization, thus allowing grid expansion and large integration of renewables.



Today's distribution grids are going through a major evolution, driven primarily by the electrification of industrial processes and the integration of new types of loads. Furthermore, the connection of distributed energy resources at the medium voltage level is continuously growing, mainly due to the increase in renewable generation and energy storage systems.

The distribution grid is evolving from a passive network characterised by unidirectional power flow, predictable loads, and passive elements toward a distribution grid that is part of an integrated energy system that combines several energy sectors (for example, electricity, heat, gas, and transportation), with unpredictable loads, local generation, and storage. In this context, system flexibility is essential to cope with some of the challenges of future power systems. Solutions that provide advances in flexibility are of utmost importance for the future power system, making this an increasingly important topic to consider for operation and planning and for policy makers. The evolution of the distribution grid requires new flexibility mechanisms to integrate the different resources safely and efficiently, together with effective use of existing infrastructures and better levels of quality and supply security. This calls for a holistic approach for optimal coordination and control of the generation, storage, and end units connected to electric power systems. Power electronics will be one of the key flexibility enablers, which acts as an interface between generation, storage, and loads and will allow to effectively cope with energy balancing. As a difference compared to the transmission grid, the distribution grid is relatively uncontrolled. Power-electronic based devices are typically installed for power quality enhancement and for grid code compliance of large loads.

With the growing integration of distributed generation and variable loads, a major challenge is the need to expand and strengthen the existing distribution network. Although this could be solved by building new lines, in practice, this can be difficult and economically inconvenient. This raises another important challenge: the need to maximise and effectively use the hosting capacity of existing grids. In practice, it is common for some feeders to be partially loaded, while others tend to be more saturated. Power electronics can be used to allow power/energy rerouting and to take advantage of all existing assets to allow for an increasing level of generation and loading without the need to build new lines. These energy hubs can be seen as an integrated solution to efficiently accommodate power flow control, virtual meshing, and integration of generation and consumption of different types and nature, such as renewables, fuel cells, batteries, thermal storage, or electrolyzers.

Involved in the project
Massimo Bongiorno, Lluc Figureras Llerins, Mebtu Beza

Partners
Chalmers, Hitachi Energy, Vattenfall, Göteborg Energi, Mölndal Energy, Herrljunga El, Port of Göteborg, Västra Götalandsregionen, Akademiska Hus, Soltech Energy Solution, Swedish Energy Agency

PROJECT RESULTS 2025

SYSTEMS

This project develops and evaluates power-electronic (PE) solutions for increasing distribution grid hosting capacity. Solutions such as back-to-back converter links enable controllable power-flow exchange between feeders.

This functionality can relieve grid constraints and improve the utilization of existing grid infrastructure, thereby increasing the grid's usable capacity. This capacity enhancement has been assessed using the Feasible Operation Region (FOR), which consists of all feasible operating points in a distribution grid or feeder (for example, in the TSO/DSO interface). The collection of feasible operating points defines the FOR, which provides a system-level view of the grid's ability to accommodate generation and demand.

To determine where PE devices should be deployed and how they should be rated, an analytical optimization model based on the LinDistFlow formulation, including PE devices (e.g., back-to-back converters and STATCOMs), has been developed to identify suitable locations and ratings. The resulting locations and ratings have then been used to evaluate the impact of the PE solutions on the grid FOR and usable capacity.

The method has been tested on a modified version of the well-known CIGRE MV Network Benchmark model using yearly time-series load and generation data. A case study with significant load growth and integration of wind generation has been analysed. The obtained results show that the proposed framework effectively quantifies the capacity enhancement provided by the PE solutions and could serve as a valuable tool for estimating the grid's ability to supply load. Figure 1 illustrates the obtained results for one of the investigated case studies: interconnecting grid feeders through a back-to-back converter link doubles the FOR and increases grid hosting capacity by 60%.

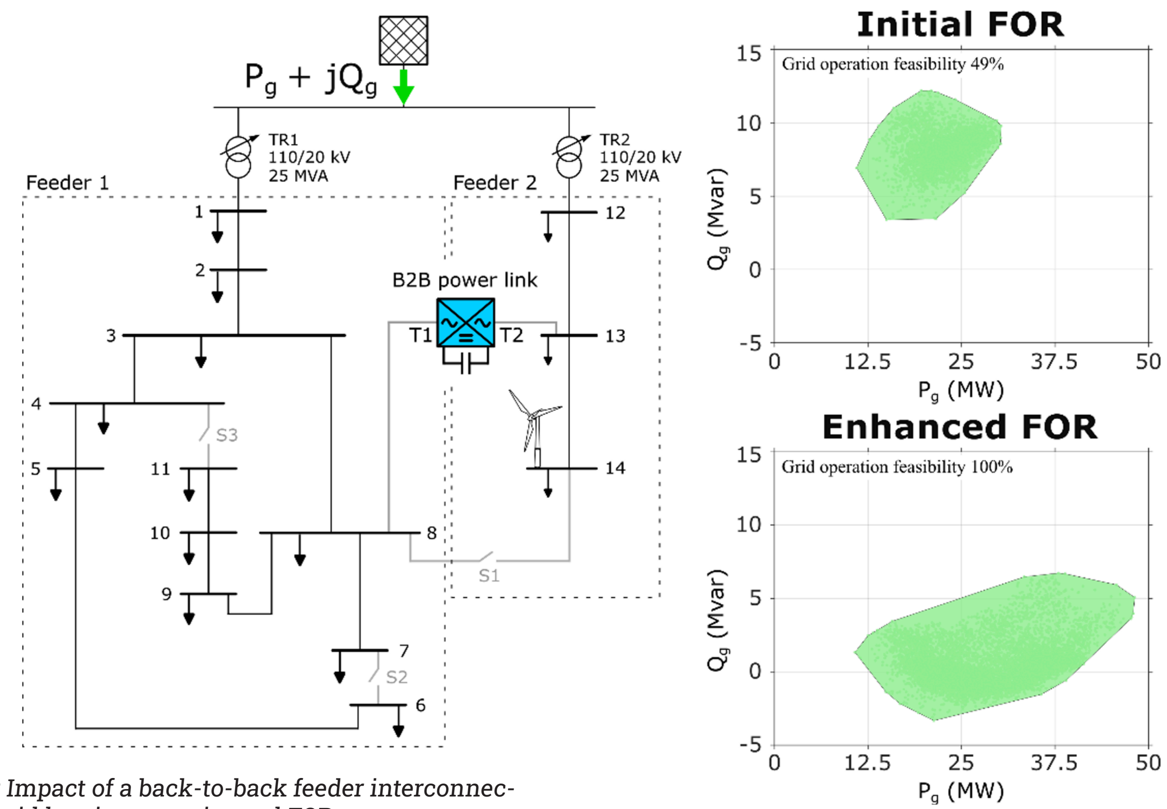


Figure 1: Impact of a back-to-back feeder interconnection on grid hosting capacity and FOR.

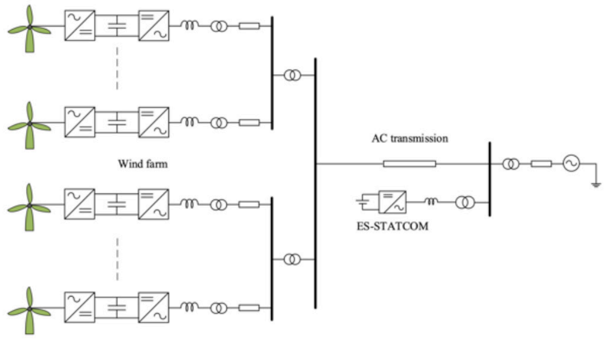
Publications 2025
No publications during 2025

Publications under review 2025
L. Figueras Llerins, M. Bongiorno, P. Chen, J. R. Svensson, "Computation of Feasible Operation Region of Distribution Grids with Power-Electronic Devices", Power Systems Computation Conference, Cyprus, 2026.

SYSTEMS

HIGH VOLTAGE AC-TRANSMISSION SYSTEMS FOR GRID-CONNECTION OF OFFSHORE WIND FARMS

This project aims to explore and compare two key technologies used to transmit electricity from offshore wind farms to the shore: HVAC (High Voltage Alternating Current) and HVDC (High Voltage Direct Current). The goal is to understand the practical limitations of HVAC, particularly over long distances, and identify how it compares to HVDC. Offshore wind farms are far from the coast, and transmitting the electricity they generate poses technical challenges that need careful analysis to ensure the system remains stable and reliable.



General Problem and Approach

Offshore wind power plants (OWPPs) generate electricity from wind turbines located far away from the shore, and this electricity needs to be transported over long distances to the onshore grid. HVAC is commonly used for shorter distances, but it may become less efficient or unstable over long distances, especially when compared to HVDC, which is better suited for long transmission distances. However, HVDC systems are more expensive and complex to implement. The project seeks to determine where HVAC reaches its limits and when it makes sense to switch to HVDC.

To investigate this, the project focuses on developing analytical methods to evaluate the stability of HVAC-connected offshore wind farms. The analysis covers different scenarios and operating conditions, including normal system operations and fault conditions. A key part of the study is to understand the root causes of harmonic instability. In simple terms, harmonic instability refers to unwanted fluctuations in the electrical system that can lead to power quality issues and even failures. By identifying the factors causing these instabilities, the project aims to improve the reliability of HVAC systems for offshore wind farms.

Ancillary Services and Energy Storage

Offshore wind farms are not only required to generate power but also provide ancillary services to the grid, such as voltage control or energy balancing. These services help keep the grid stable, especially when the wind farm is connected to a weaker grid or when other wind farms are nearby. The project will evaluate how much energy storage is required to provide these ancillary services effectively. This is critical because energy storage systems can help smooth out fluctuations in power generation, particularly in renewable energy systems like wind farms, where the output can vary depending on wind conditions.

Expected Outcomes

The project's primary outcome will be a comprehensive guideline on the use of HVAC systems for offshore wind farms. It will outline the necessary hardware, control strategies, and stability requirements to extend the use of HVAC in these applications. Additionally, the project will compare HVAC solutions with HVDC to determine the technical break-even point between the two technologies. This comparison will help decision-makers understand when it is better to switch from HVAC to HVDC for long-distance power transmission.

In summary, the project will provide valuable insights into optimizing the transmission of electricity from offshore wind farms, ensuring that future renewable energy systems are both stable and efficient. By identifying key system parameters and control strategies, the project aims to enhance the reliability of offshore wind power plants, making them more viable for widespread use in energy grids.

Involved in the project

Anant Narula, Massimo Bongiorno, Mebtu Beza, Jan R. Svensson, Daniel Karlsson

Partners

Chalmers, Hitachi Energy, Svenska kraftnät, DNV, Vattenfall Eldistribution, Swedish Energy Agency

PROJECT RESULTS 2025

Focussed on developing analytical models for small-signal analysis of an HVAC offshore wind power plant (WPP), see fig 1.

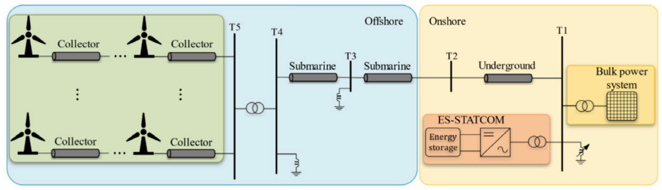


Figure 1: Single-line diagram of the considered offshore wind power plant

Compared two small-signal modeling approaches for converter systems using different dq reference frames: one defined by the system's rated angular frequency ωN and the other by its fundamental angular frequency ωg. Both methods were shown to be analytically equivalent, while the dq frame based on grid frequency (dqωg) provides clearer insight into system behavior during grid disturbances and enables direct evaluation of frequency-droop and inertial responses—key metrics for assessing frequency stability and grid-forming performance.

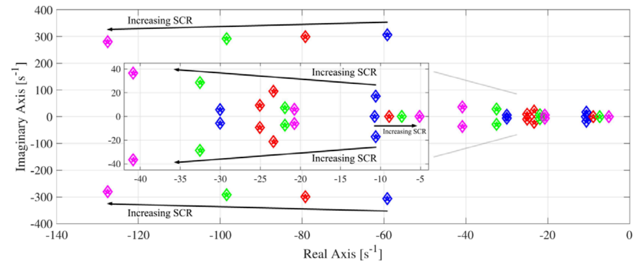


Figure 2: Comparison of poles of closed-loop transfer matrices in dqωN frame (depicted with star markers) and dqωg frame (depicted with diamond markers) for four different values of SCR at PCC: 1.5 (blue), 3 (red), 5 (green), 10 (magenta).

Proposed Power Response Matrix (PRM)–based small-signal modeling approach was evaluated against conventional dq-impedance methods for system-level analysis of converter-dominated systems. While both approaches produce equivalent results, the PRM method simplifies practical implementation by enabling direct aggregation without requiring reference-frame alignment.

The PRM-based modelling approach was utilized to study impact of converter control strategies and transmission distances on dominant oscillation modes, harmonic interactions, and energy storage requirements in the considered HVAC-offshore wind power plant.

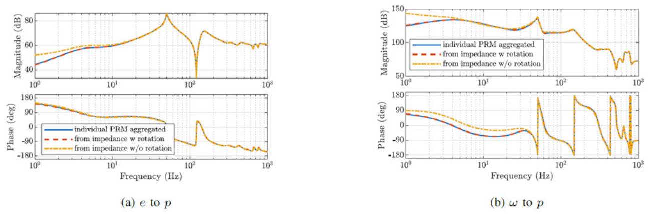


Figure 3: Top row transfer functions of the resulting PRM of the considered offshore wind power plant.

Publications 2025

Journal papers

A. Narula, M. Bongiorno, P. Mattavelli, M. Beza, J. R. Svensson and W. Liu, "Evaluation and Comparison of Small-Signal Characteristics of Grid-Forming Converter Systems in Two Different Reference Frames," in IEEE Open Journal of Industry Applications, vol. 6, pp. 206-220, 2025, doi: 10.1109/OJIA.2025.3564501.

W. Liu, M. Bongiorno, A. Narula, and J. R. Svensson, "Grid impedance estimation during large SCR drop events with grid-forming converters," IEEE Transactions on Industrial Electronics.

Conference papers

W. Liu, A. Narula, M. Bongiorno, and J. R. Svensson, "Grid impedance estimation with large SCR disturbances based on grid-forming converter," Proc. 26th European Conf. on Power Electronics and Applications (EPE'25), France, Mar. 2025.

K. Kamalinejad, A. Narula, M. Bongiorno, M. Beza, and J. R. Svensson, "Impact of control parameters on angular stability of grid-forming converters using virtual-admittance-based control," Proc. IEEE Energy Conversion Congress and Exposition (ECCE) Europe, UK, 2025.

A. R. Z. Babgohari, J. Wang, M. Beza, M. Bongiorno, A. Narula, and J. R. Svensson, "Understanding converter interactions using active and reactive characteristics: A comparison between grid-following and grid-forming control," Proc. IEEE Energy Conversion Congress and Exposition (ECCE) Europe, UK, 2025.

J. Wang, A. R. Z. Babgohari, M. Beza, M. Bongiorno, A. Narula, and J. R. Svensson, "A frequency-domain stability margin indicator for grid-connected converter systems," Proc. IEEE Energy Conversion Congress and Exposition (ECCE), USA, 2025.

Publications under review 2025

Journal papers

P. Imgart, A. Narula, M. Bongiorno, M. Beza, J. R. Svensson, J. P. H. Hasler, and P. Mattavelli, "Decoupled PQ grid-forming control with tunable converter frequency behaviour," IEEE Open Journal of Industry Applications.

K. Kamalinejad, A. Narula, M. Bongiorno, M. Beza, and J. R. Svensson, "A frequency-domain study of damping and synchronizing characteristics of virtual admittance-based grid-forming converters," International Journal of Electrical Power and Energy Systems.

L. Stojanovic, A. R. Zamani, A. Narula, P. Mattavelli, M. Bongiorno, M. Beza, and J. R. Svensson, "Aggregation of power response matrices for system-level analysis in converter dominated power systems," Electric Power Systems Research.

K. Kamalinejad, A. Narula, L. Stojanovic, M. Beza, M. Bongiorno, and J. R. Svensson, "Impact of control and system parameters on transient stability in multi-converter systems: Insights from quasi-static modeling," Electric Power Systems Research.

L. Stojanovic, A. Narula, P. Mattavelli, M. Bongiorno, and J. R. Svensson, "Power-response matrix framework: Intuitive frequency-domain analysis of offshore wind farm," Proc. IPEC 2026, Japan.

J. Wang, M. Beza, M. Bongiorno, A. Narula, and J. R. Svensson, "Revisiting GFM and GFL converter stability: A subsystem interaction perspective," Proc. IPEC 2026, Japan.

GLOBAL VALUE CHAINS FOR LOCAL ENERGY SYSTEMS

A transition to an electricity system based on solar and wind power and a range of new energy conversion and storage technologies will shift the geopolitical and environmental concerns from fuel supply and combustion to the entire value chain of energy devices. The aim of this project is to monitor and analyze the temporal evolution and spatial distribution of these value chains by compiling datasets of global product flows. This is done to inform technology developers and policymakers about supply risks, environmental impacts, and potential geopolitical concerns.

The goal is to understand the practical limitations of HVAC, particularly over long distances, and identify how it compares to HVDC. Offshore wind farms are far from the coast, and transmitting the electricity they generate poses technical challenges that need careful analysis to ensure the system remains stable and reliable.

General Problem and Approach

Offshore wind power plants (OWPPs) generate electricity from wind turbines located far away from the shore, and this electricity needs to be transported over long distances to the onshore grid. HVAC is commonly used for shorter distances, but it may become less efficient or unstable over long distances, especially when compared to HVDC, which is better suited for long transmission distances. However, HVDC systems are more expensive and complex to implement. The project seeks to determine where HVAC reaches its limits and when it makes sense to switch to HVDC.

To investigate this, the project focuses on developing analytical methods to evaluate the stability of HVAC-connected offshore wind farms. The analysis covers different scenarios and operating conditions, including normal system operations and fault conditions. A key part of the study is to understand the root causes of harmonic instability. In simple terms, harmonic instability refers to unwanted fluctuations in the electrical system that can lead to power quality issues and even failures. By identifying the factors causing these instabilities, the project aims to improve the reliability of HVAC systems for offshore wind farms.

Ancillary Services and Energy Storage

Offshore wind farms are not only required to generate power but also provide ancillary services to the grid, such as voltage control or energy balancing. These services help keep the grid stable, especially when the wind farm is connected to a weaker grid or when other wind farms are nearby. The project will evaluate how much energy storage is required to provide these ancillary services effectively. This is critical because energy storage systems can help smooth out fluctuations in power generation, particularly in renewable energy systems like wind farms, where the output can vary depending on wind conditions.

Expected Outcomes

The project's primary outcome will be a comprehensive guideline on the use of HVAC systems for offshore wind farms. It will outline the necessary hardware, control strategies, and stability requirements to extend the use of HVAC in these applications. Additionally, the project will compare HVAC solutions with HVDC to determine the technical break-even point between the two technologies. This comparison will help decision-makers understand when it is better to switch from HVAC to HVDC for long-distance power transmission.

In summary, the project will provide valuable insights into optimizing the transmission of electricity from offshore wind farms, ensuring that future renewable energy systems are both stable and efficient. By identifying key system parameters and control strategies, the project aims to enhance the reliability of offshore wind power plants, making them more viable for widespread use in energy grids.

Involved in the project

Björn Sandén, Chunshuo Ge, Anders Nordelöf, Rickard Arvidsson

Partners

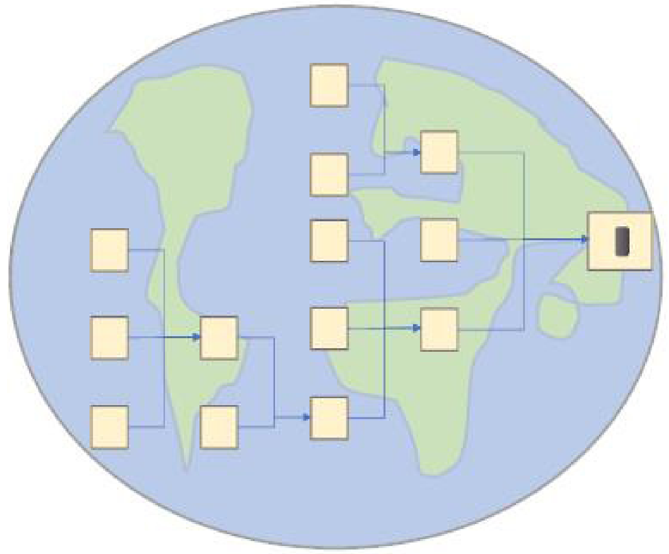
Chalmers, Västra Götalandsregionen, Volvo Energy, Hymeth, Soltech Energy Solution, Hydri Solutions, SAFT, Swedish Energy Agency

PROJECT RESULTS 2025

Indicators of temporal and spatial flexibility was developed, empirically tested and described in paper I, currently under a second review. To capture broad trends in flexibility strategies in different regions of the world this study develops two indicators: a gross spatial flexibility indicator (GSF) and a gross temporal flexibility indicator (GTF).

The indicators are tested on a sample of countries. At present, publicly available data is not sufficient to support easy indicator construction. The German MaStR platform is an exception and could serve as inspiration to database construction in other countries.

In paper II customs data were explored to test if it could fill in the data gaps discovered in paper I. The test was successful, and paper II provides results in the form of BESS deployment over 200 countries and 12 years (GTF indicator data for all countries in the world), as well as data on countries of origin. This paper was presented at a conference and invited to be further developed for a special issue. The method based on customs data is now being further developed in paper III with the aim of informing life cycle assessment data bases on so called "marked processes" to better represent the spatial distribution of value chains and the origin of critical metals and raw materials in general. A licentiate thesis presentation is planned for January 2026.



Mapping global value chains

Publications 2025

Conference contribution (oral presentation)

C. Ge, R. Arvidsson, and B. Sandén (2025), "Tracing global value chain transformation using customs data – a case study on lithium-ion battery-based energy storage systems". 16th International Sustainability Transitions (IST) Conference in Lisbon, Portugal, June 24-26

Publications under review 2025

Journal paper

C. Ge, R. Arvidsson, and B. Sandén (2025), Monitoring long-term trends of spatial and temporal flexibility in electricity systems, under review in Energy conversion and management: X.

C. Ge, R. Arvidsson, and B. Sandén (2026), Tracing global value chain transformation using customs data with a case study on lithium-ion battery energy storage systems, under review in Environmental Innovation ánd Societal Transitions

SYSTEMS

ROLE OF FLEXIBILITY MEASURES IN DISTRIBUTION GRIDS

In the transition to climate neutral energy systems, electrification of the industry and transport sectors enabled by electricity from wind and solar power play a central role. Finding means to balance a varying electricity supply from solar power and wind power with electricity demand on distribution grid level can facilitate the energy transition on this level. Thus, the aim of the proposed project is to assess the role of flexibility measures to balance supply and demand in distribution grids.

This project investigates the role of flexibility measures in distribution grids, considering best available technologies as well as feasible and likely development of flexibility measures in terms of technology and cost. The possibility to manage variations on distribution grid level relying only on flexibility measures with relatively robust supply chains will also be investigated.

The project takes departure in the fact that if variations in wind and solar power are managed on distribution grid level using flexibility measures available locally, the variability to be managed, as well as the access to flexibility measures, on higher voltage levels is reduced. Within the project we investigate how flexibility measures on distribution grid level impact the interaction between the distribution grids and its surrounding.

The overall aim of the project is to determine future roles of flexibility measures in distribution grids based on estimates of feasible and likely technical development and cost reductions of flexibility measures. Specifically, the aims are to:

- Identify the role of flexibility measures in future electricity system
- Provide new knowledge for understanding the needs for flexibility in distribution grids.
- Assess how the development of flexibility measures impact their relevance and role in future distribution grids

The project has developed a model to assess flexibility in distribution using Västra Götalandsregionen (the West Sweden Region) as an example. This region is of particular interest since it has a strong electricity import dependency and there is a gap between the electricity needed for the electrification of industry and the amount of grid capacity that can be expanded by the Swedish TSO (Svenska kraftnät). Thus, it should be of great value to understand to what extent can flexibility measures ease the pressure on the future import capacity as well as on the distribution grid.

Mapping of the electricity infrastructure of Västra Götalandsregionen

A mapping of Västra Götalandsregionen (VGR) grid is used as study the role of flexibility measures, while also depicting the sub-transmission electricity system to identify bottlenecks in the grid and how flexibility measures could help alleviate the bottleneck issues. The current model utilizes data from open-source database such as OpenStreetMap to model the distribution/sub-transmission electricity system (i.e. power lines, substations, and power plants).

The model being developed
A cost-minimising bottom-up energy systems model has been developed. The model has the following overall characteristics:

- Greenfield study (future net-zero system)
- Implements electricity, heating, and gas (H2) sector
- Emphasis on electricity system
- Flexibility measures include:
- Energy storages
- Demand side management
- Others

First results from the model have been obtained, showing the electricity generation dispatch and storage charge/discharge variations in the modelled region.

We expect the following results from the project:
- Investments of generation and storage technologies
- Generation dispatch and storage charge/discharge
- Implementation costs of certain technologies
- Utilize these to identify role

Involved in the project
Pandu Prianto, Filip Johnson, Lisa Göransson

Partners
Chalmers, Västra Götalandsregionen, Göteborg Energi, Vattenfall eldistribution, Svenska kraftnät, Soltech Energy Solution, Repono, Swedish Energy Agency

PROJECT RESULTS 2025

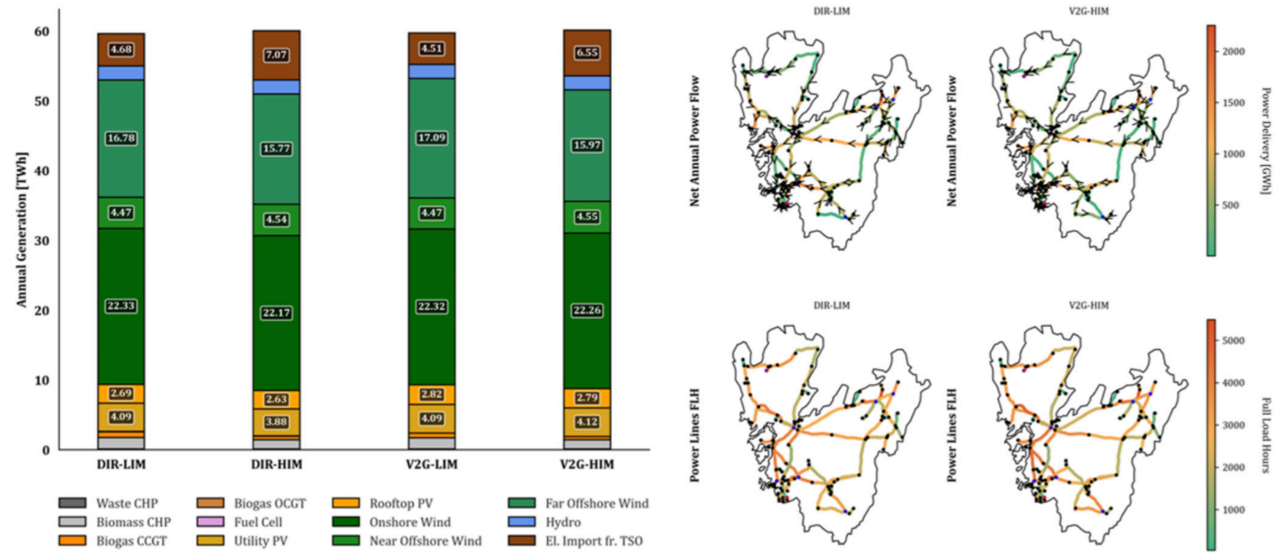
SYSTEMS

This year a model of a regional energy system model has been finalized and tested, using Västra Götalandsregionen as a case study. The model accounts for power flow limitations on the 130 kV network at its core with an infrastructure based on data available on open source database (OpenStreetMap).

The modelling currently depicts future electricity systems of Västra Götaland in Year 2050, studied under four different case studies to represent the increased import limits from national grid and vehicle-to-grid (V2G) availability.

The project produces a model that can be used as a tool to provide an insight into regional energy systems development under different case studies. The following can be concluded from the modelling that has been used in the project:

- It is cost-efficient to meet the demand by local generation
- Batteries investment are motivated by the abundance of local generation and the possibility to alleviate congestion nearby generation and demand centres
- Batteries play the role to alleviate congestion and managing local variations



The figure illustrates the annual generation of different technologies and the annual power lines utilization from the model results. The results found that the vast majority (80-85%) of the annual electricity demand can be met cost-efficiently by local electricity generation, mainly in the form of wind and solar power.

Publications 2025

A. Toktarova, L. Göransson, F. Johnsson (2025). Electrification of the energy-intensive basic materials industry – Implications for the European electricity system. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2024.08.016

J. Ullmark, L. Göransson, F. Johnsson (2025). Representing net load variability in electricity system capacity expansion models accounting for challenging weather-years. Energy. https://doi.org/10.1016/j.energy.2024.134346

N. Phan, H. Hellsmark, L. Göransson, F. Johnsson (2025). Electrifying tensions: Stakeholder narratives to electrification of industry and transport in Sweden. Energy Research and Social Science. https://doi.org/10.1016/j.erss.2025.104142

PILOTING DYNAMIC FAST FREQUENCY RESERVE (FFR) FROM ENERGY STORAGE SYSTEMS

As the energy grid evolves to include more renewable sources like wind and solar, maintaining stability becomes increasingly challenging. This project explores a new approach called dynamic Fast Frequency Reserve (FFR), using advanced energy storage systems to quickly respond to changes in grid frequency. By testing this technology in both lab and real-world settings, researchers aim to improve grid reliability and help shape future energy solutions that are cleaner, smarter, and more resilient.

As the world transitions to cleaner energy sources like wind and solar, maintaining the stability of the electricity grid becomes more complex. Traditional power plants, which use large spinning turbines, naturally help stabilize the grid by resisting sudden changes in frequency. However, renewable sources don't provide this stabilizing effect, making the grid more vulnerable to disturbances. To address this, grid operators are exploring new ways to quickly respond to frequency changes and keep the system balanced.

One promising solution is Fast Frequency Reserve (FFR)—a service that rapidly injects or absorbs power to stabilize the grid when frequency drops or rises unexpectedly. While FFR already exists in a basic form, it is currently "static," meaning it reacts once and then stops, without adjusting to ongoing changes. This project aims to pilot a more advanced version: dynamic FFR, which continuously adjusts its output in real time based on the grid's needs.

The focus of this pilot is on using energy storage systems, such as batteries, to deliver dynamic FFR. These systems can respond within milliseconds, making them ideal for this kind of service. The project builds on earlier lab-scale experiments using supercapacitors and converters, and now seeks to test the concept on a larger scale using commercial battery installations.

General Approach
The project will begin with controlled lab tests at lab-environment first in Uppsala, where researchers will simulate grid conditions and evaluate how well the energy storage system can deliver dynamic FFR. Key performance factors include response time, stability, and accuracy of the power output. If the lab tests are successful, the team will move on to real-world trials using larger systems, such as Vattenfall's battery installation in Uppsala.

The project also includes a detailed analysis of technical limitations, such as delays in control signals and the impact of frequent small adjustments on battery lifespan. These insights will help manufacturers fine-tune their systems and ensure they meet future grid requirements.

Control Implementation: The project will adapt a previously tested dynamic FFR control model for use in larger battery systems. This includes tuning the controller to minimize time delays and ensure closed-loop stability.

Power Oscillation Damping (POD-P)
A secondary goal is to test whether the same battery system can also help dampen power oscillations, a different but related grid stability service.

Comparative Testing
Although not part of the SESBC-funded work, parallel research will compare dynamic FFR with other control strategies like synthetic inertia and virtual synchronous generators.
Battery Aging Models: The team will use existing models to estimate how dynamic FFR affects battery health over time, helping to balance performance with longevity.

Broader Impact
This project is part of the Swedish Energy Storage and Balancing Centre (SESBC) and contributes directly to its system-level goals. It supports the development of new grid services that are essential as more renewable energy is integrated. The results will be valuable not only for transmission system operators like Svenska kraftnät, but also for battery manufacturers, energy companies, and policymakers.
By demonstrating how dynamic FFR can be implemented using commercially available technology, this project aims to pave the way for a more resilient and flexible power grid—one that can keep pace with the rapid changes in how we produce and consume electricity.

Involved in the project
Urban Lundin, Danilo Laban, Vinicius Albuquerque, Robert Eriksson

Partners
Uppsala University, Vattenfall R&D AB, Svenska kraftnät, SVC (Swedish center for Sustainable Hydropower)

PROJECT RESULTS 2025

The Fast Frequency Reserve (FFR) was introduced as a fast-acting grid reserve to handle increased frequency fluctuations due to decreased system inertia. Is it activated as a step increase in power when system frequency drops, the fastest activation time is 0.7 seconds at 49.5 Hz. To further develop FFR would be to make it dynamic with a proportional part, but still reduce gain at high frequencies to be stable.

It is important to see if this theoretical performance can be met with a real world-system. Using an existing Super Capacitor and inverter we set out to implement the band-pass control in real hardware (NI-Labview).The system was initially tested for synthetic inertia and has a response time of < 10 ms. Typical Battery systems are limited by BMS systems to around 100 ms.

The results shows that the system well reproduce the desired response from the super-capacitor. At higher frequencies (sine-in sine-out tests) the performance (in amplitude) drops slightly. The next step is to use fitted transfer function and make system simulations. We have also investigated other frequency stabilizing measures and will compare with D-FFR.

In summary, D-FFR seems to provide a positive contribution to frequency control. Hardware can provide the desired response and qualification tests can be defined.

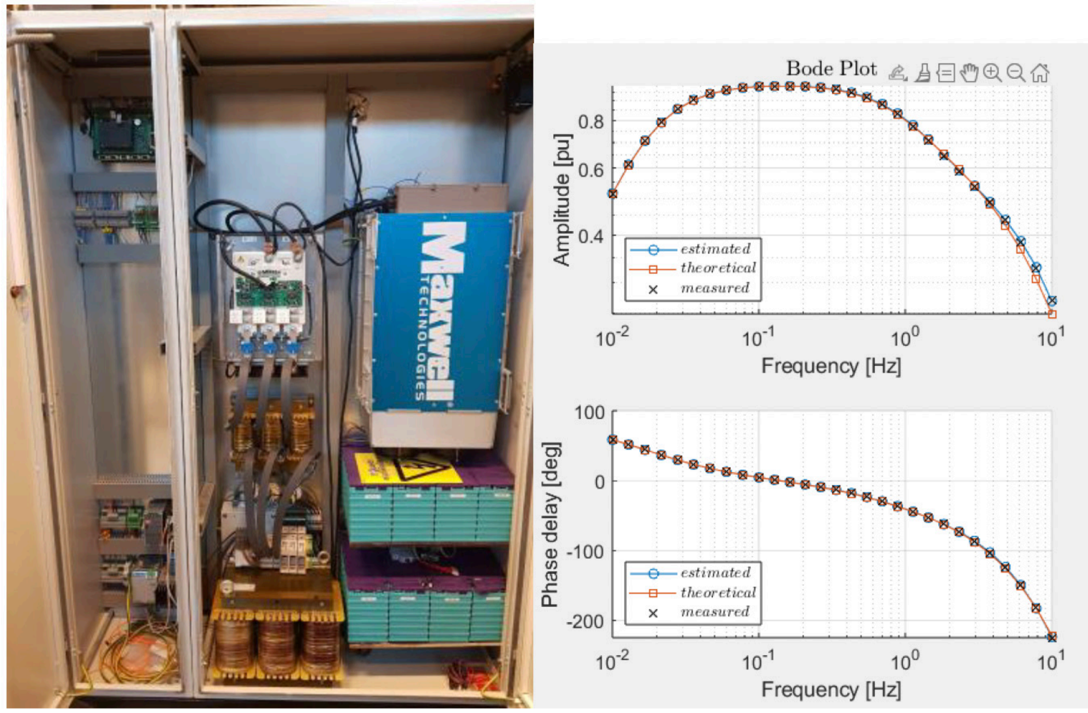


Figure (left) Hardware used for the real life-tests of the suggested implementation of D-FFR. (right) The desired and measured response. It can be seen that the desired response is met by the hardware with a small deviation at higher frequencies.

Publications 2025
No publications during 2025

HIGH-POWER VANADIUM REDOX FLOW BATTERIES

To overcome the challenges of direct usage of renewable electricity in power grids, the distributed electricity production requires the similarly distributed electricity storage system.

Here, large-scale battery energy storage systems (BESS) can be used for buffering loads at strategic network nodes to alleviate congestion in storage-as-transmission. With a plethora of available BESS technologies, vanadium redox flow batteries (VRFB) are a promising energy storage candidate. However, the main drawback for VRFB is the low power per area of the cell. In this project we will address the mechanism of VRFB operation at both molecular and device levels. We intend to explore the catalysis of the reactions happening on positive and negative electrodes of VRFB to boost the current output of VRFB.

Challenges of renewable electricity

The low cost of renewables have catalyzed a mass-scale adoption of renewable energy sources that will further gain momentum in coming years. This shift towards intermittent sources, however, poses unprecedented challenges for power grids due to mismatches between supply and demand both in time and, crucially, location. For instance, solar power generation drops off in the evening sunset just before peak demand, creating the difference between energy demand and the amount of available solar energy throughout the day. Moreover, transmission limitations result in variations of real-time electricity prices of hundreds of dollars per MWh between locations that are separated by only a few kilometres. The extreme variability of congestion costs indicates that with more distributed energy production, a similarly scaled distributed energy storage system is needed to mitigate the expansion of transmission and distrbution infrastructure.

Battery energy storage systems

Here, large-scale BESS can be attractive by buffering loads at strategic network nodes to alleviate congestion in what has been called storage-as-transmission, or "Grid Booster'. To achieve deep decarbonization of the power grid and to relieve congestion without large-scale construction of expensive power lines, considerable energy storage will be necessary in densely populated areas as well. This makes safety and footprint of BESS installation an important part of the design. With a plethora of available BESS technologies, VRFBs are widely considered a promising energy storage candidate. The uniqueness of VRFB is the possibility to set independently the power of the battery by the size of the device and the energy for the battery by the size of the tank for liquid reagents. However, the main drawback of VRFB is the low power per area of the electrode/cell, which implies that the cell must be large to produce a certain amount of power and/or that multiple cells must be assembled in parallel to increase the power, which increases the costs. On another side, VRFB is aqueous, which implies lower costs on thermal management in comparison with other BESS. In parallel, vanadium electrolyte can be 100% recycled.

Challenges of VRFB addressed by our project

Existing VRFB still have a low energy density. Our collaborative project is focused on this problem. The rate capabilities of VRFB are limited by the slow kinetics of posolyte reaction because of its complex mechanism. The detailed mechanism of posolyte reactions of VRFB is not resolved yet as well as the individual and combined roles of electrolyte, membrane and electrodes. We are using physicochemical techniques positive electrode process on. Then, we will utilize this knowledge at the higher level of the device operation: the combination of electrode, electrolyte and the membrane. The cross-contamination of active components of positive and negative electrodes, the main reason of VRFB failure, will be also investigated on the device level. Finally, we intend to create the comprehensive model of the device to help the design of the high-power VRFB.

Involved in the project

Mikhail Vagin, Pawel Wojcik, Miguel Villicana Aguilera, Penghui Ding, Reverant Crispin, Viktor Gueskine

Partners

Linköping University, RedoxMe, Swedish Energy Agency

PROJECT RESULTS 2025

During 2025 we have continued to develop our new electrolyte concepts for stable high-temperature (80 °C) lithium-metal battery operation, suitable for demanding environments such as converter halls.

The project has initiated a new approach by introducing an ionic liquid (IL) additive into a benchmark carbonate electrolyte (commercial name LP30), enhancing thermal and electrochemical stability and enabling dendrite-free Li deposition. The IL's bulky cations and charge delocalized anions lead to a reorganization of the Li^+ solvation structure, strengthening the Li^+ – anion coordination, and reduce solvent participation in the solvation of Li^+. This leads to a delay of Li^+ depletion at the anode surface during charge, lowering surface charge density and suppressing field amplification at protrusions, thereby promoting uniform, compact Li growth.

Electrochemical tests in symmetric and full Li//LTO cells demonstrated significantly improved cycling stability with the IL-modified electrolyte. Complementary analyses, including Raman spectroscopy, broadband dielectric spectroscopy (BDS), and X-ray photoelectron spectroscopy (XPS), revealed the formation of a stable, predominantly inorganic, solid electrolyte interphase (SEI) with high ionic conductivity. Scanning electron microscopy confirmed a uniform Li morphology, without dendritic features, after charging, correlating interfacial reconstruction with enhanced electrochemical performance and long-term cycling stability. Figure 1 shows data from extended cycling with a Li-foil of limited thickness, compatible with practical applications, where the optimized electrolyte (Pyr14FSI-LP30) shows very stable cycling compared to the base line organic electrolyte LP30.

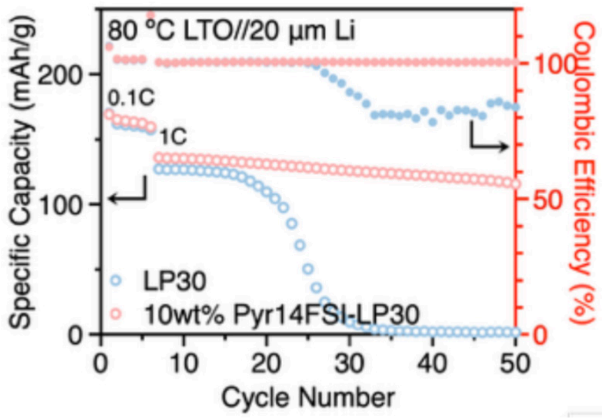


Figure 1. Cycling data of a LTO-cell with the optimized electrolyte (Pyr14FSI-LP30) and a more conventional carbonate-based electrolyte (LP30).

Publications 2025

Licentiate theses

Q. Wu, "Ionic liquid-based electrolyte for high-temperature lithium-metal batteries", planned for december 2025, Chalmers University of Technology.

HYDROPHOBIC CATIONIC SIEVE ENABLING RECHARGEABLE ALUMINIUM-LIGNIN BATTERIES

In the quest for cleaner and sustainable energy, aluminium metal batteries are emerging as a promising alternative to the widely used lithium-ion batteries. Aluminium is abundant, affordable, and has the potential to store large amounts of energy. However, developing efficient aluminium batteries comes with challenges, such as instability when exposed to water-based solutions.

By exploring innovative approaches, including advanced electrolytes such as water-in-salt electrolyte and sustainable materials such as lignin, this project aims to create a new generation of rechargeable batteries that are not only powerful and safe but also environmentally friendly.

In our pursuit of sustainable energy solutions, aluminium metal batteries are emerging as a strong contender, offering a potential leap beyond the limitations of conventional lithium-ion batteries. Lithium-ion technology, while revolutionary, faces challenges such as the limited availability of lithium, high costs, safety and significant environmental impacts from mining. Aluminium, however, presents an exciting alternative with its abundance, cost-effectiveness, safe and favorable electrochemical properties.

Why Aluminium?

Aluminium (Al) is the third most abundant element on Earth, constituting about 8.21% of the Earth's crust, far surpassing the mere 0.0065% that lithium occupies. This abundance makes aluminium not only cheaper (22 SEK per kilogram) but also more sustainable, with a significantly lower environmental footprint in terms of extraction and processing. Beyond its abundance, aluminium possesses a high redox potential (-1.66 V vs SHE), meaning it has the capacity to store and release large amounts of energy: an essential feature for high-performance batteries.

However, the path towards development of practical aluminium batteries is not without its challenges. The primary challenge is the instability of aluminium when exposed to aqueous (water-based) electrolytes, which are crucial for safe and efficient battery operation. When aluminium comes into contact with water, it triggers the hydrogen evolution reaction (HER), a side reaction that degrades the battery over time. Furthermore, aluminium tends to form a passive oxide layer on its surface, which impedes its electrochemical performance. Another significant issue is dendritic growth, where needle-like structures form on the aluminium surface during subsequent charging/discharging. These dendrites can penetrate through separator and cause short circuits, posing serious safety risks.

The Solution: Water-in-Salt Electrolytes

To overcome these challenges, the project aims to adopt an innovative solution which is the use of "water-in-salt electrolytes" (WiSE). In a typical battery, the electrolyte—a solution that conducts ions between the battery's electrodes—is made up of water and dissolved salts. However, in a WiSE, the concentration of salt is so high that it greatly reduces the amount of free water molecules available for water electrolysis. This highly concentrated environment stabilizes the aluminium by minimizing the side reactions with water, which in turn suppresses the unwanted hydrogen evolution reaction and reduces the risk of dendrite formation.

A Glimpse into the Future: Aluminium-Lignin Batteries

The ultimate objective of the project is not only to prove the viability of aluminium batteries but to also demonstrate their application in a sustainable manner. Here, another fascinating development comes into play: the combination of aluminium with lignin. Lignin is a natural biopolymer found in plants, particularly in wood, and is very inexpensive (1-4 SEK per kilogram). It has electrochemical activity, meaning it can participate in storing and releasing energy. However, lignin is naturally an electrical insulator, which makes it challenging to use directly in a battery. To overcome this, lignin can be combined with materials that conduct electricity, such as carbon. In fact, our team and Ligna Energy, have already demonstrated that lignin-carbon composites can work as cathode materials in batteries. By pairing lignin with aluminium, we aim to develop a cost-effective, safe, and sustainable battery system suitable for large-scale energy storage.

A rechargeable aluminium-lignin battery could revolutionize energy storage by offering a green alternative to current technologies. Imagine a world where your smartphone, electric vehicle, or even the power grid is powered by batteries made from common, abundant materials like aluminium and lignin, rather than rare and environmentally taxing metals like lithium and cobalt. This technology holds the promise of reducing the ecological footprint of energy storage, making it a key component in the global shift towards renewable energy.

Involved in the project

Ziyauddin Khan, Reverant Crispin, C. Moyses Araujo, Anna Martinelli, Nicole Abdou, Leandro Franco, Anders Hägerström

Partners

Linköping University, Ligna Energy, Swedish Energy Agency

PROJECT RESULTS 2025

MATERIALS AND DEVICES FOR ENERGY STORAGE

In 2025, the project has investigated the plating/stripping behavior of aluminum in a 4 m Al(OTf)3 water-in-salt electrolyte (WiSE).

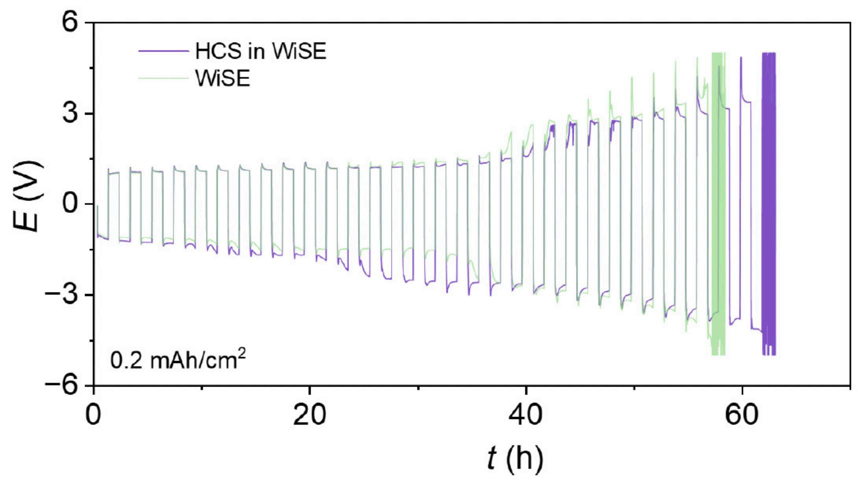
WiSE systems are known to suppress parasitic water redox reactions due to their high salt concentration and the limited availability of free water molecules. Since commercial aluminum foil is naturally covered with a passivating aluminum oxide layer that is ionically insulating, direct aluminum deposition is typically hindered.

To overcome this limitation, the aluminum foil was pretreated in an EMIMCl:AlCl3 ionic liquid solution inside a glove box. This treatment facilitated the dissolution of the native oxide layer and the formation of a thin inorganic interphase, which is reported in the literature as a stable and oxidation-resistant layer. The treated foil was then used to perform galvanostatic plating/stripping experiments in symmetric coin cells assembled with WiSE and WiSE containing a hydrophobic cationic sieve (HCS) additive. The tests were conducted at a current density of 5 µA cm-2. The results demonstrated a notable enhancement in the cyclic stability of aluminum plating/stripping in the presence of HCS.

While the symmetric cell with pure WiSE operated stably for approximately 100 hours, the HCS-containing cell exhibited extended cycling stability up to 400 hours, along with reduced overpotentials compared to the WiSE-only system.

In the previous experiments, the applied current density was relatively low, which directly limited the utilization efficiency of aluminum and, consequently, the overall device performance. To further evaluate electrochemical behavior under more practical operating conditions, we increased the current density to 0.2 mA cm-2 and examined the plating/stripping characteristics of aluminum in both WiSE and HCS-modified WiSE electrolytes (see figure).

As expected, an increase in current density led to higher overpotentials; however, the rise was significantly larger than anticipated. This behavior can be attributed to the sluggish kinetics of Al3+ ion transport in the electrolyte and the possible reformation of a passivating oxide layer on the aluminum surface during cycling. Notably, the cell containing the HCS additive exhibited slightly improved cyclic stability compared to the pure WiSE system, suggesting that the proposed interfacial engineering concept is effective. Nevertheless, further optimization of key parameters, such as electrolyte composition, additive concentration, and interphase stability, is essential to achieve lower overpotentials and enhanced long-term cycling performance.



Galvanostatic plating/stripping of Al in WiSE and WiSE with HCS at high areal capacity (0.2 mAh/cm2) equivalent to 0.2 mA/cm2 capacity.

Publications 2025

V. Joseph, N. Kim, S. Y. Lee, R. Crispin, T. H. Park, and Z. Khan, "Water-in-salt hydrogel electrolyte for dendrite-free Zn deposition," Energy Advances, vol. 4, pp. 1167–1178, 2025.

V. Joseph, R. Crispin, and Z. Khan, "Hard carbon from wood and its constituents: Toward sustainable sodium- and potassium-ion battery anodes," Renewable and Sustainable Energy Reviews, vol. 223, p. 116060, 2025.

D. Kumar, K. Brijesh, K. Bindu, B. Ramzan, S. Kumar, and Z. Khan, "$K–O_2$ batteries: Overcoming challenges and unlocking potential," EES Batteries, vol. 1, pp. 1083–1101, 2025.

M. Tariq, K. Ahmed, Z. Khan, and Md. Sk. Palashudin, "Biomass-derived carbon dots: Sustainable solutions for advanced energy storage applications," Chemistry – An Asian Journal, vol. 20, e202500094, 2025.

NOVEL DIELECTRIC DIAGNOSTICS METHOD FOR MATERIALS FOR NEW GENERATION OF HIGH-PERFORMANCE CAPACITORS

High-voltage capacitors play a critical role in ensuring stability and efficiency within modern electrical power systems. However, the materials used in these capacitors often encounter significant challenges under extreme conditions, including high electric fields and temperature fluctuations. This project seeks to develop an innovative diagnostic method to effectively characterize these materials under such harsh conditions, ultimately leading to the enhancement of material performance and the creation of the next generation of high-performance capacitors.

Project Overview

High-voltage capacitors are crucial for maintaining stability and efficiency in modern power systems. They filter high-frequency content from power electronics, improve power quality, reduce harmonic distortion, and contribute to power factor correction and energy storage. However, the dielectric materials in these capacitors, typically polymer-based films, face significant challenges under extreme conditions, such as high electric fields and temperature fluctuations, which can impact their performance and reliability. By considering environments with high electric fields and temperature variations, the project focuses on improving the reliability and efficiency of high-voltage capacitors and facilitating the development of the next generation of high-performance capacitors to meet the demanding requirements of the modern power system.

The Problem

Current diagnostic methods, such as dielectric frequency response (DFR), are inadequate because they don't replicate the extreme conditions dielectric materials face in operation. Traditional tests use electric fields much lower than those in real-world applications, which can exceed several hundred kV/mm. Moreover, these methods often fail to simulate the broad temperature ranges these materials endure, resulting in an incomplete understanding of their performance. This gap increases the risk of capacitor failure, potentially compromising the reliability of power grids.

Project Goal

This project aims to develop an advanced diagnostic method and test facilities to accurately assess dielectric materials under conditions that closely replicate real-world environments. By measuring the dielectric response across a wide range of electric fields and temperatures, this approach will offer deeper insights into material behavior under combined electrical and thermal stresses. The objective is to create a high-voltage, high-temperature DFR measurement technique suitable for both laboratory research and industrial applications. This characterization development will support the next generation of high-performance capacitors with improved energy density and reliability.

Conclusion

This project will enhance the reliability and performance of high-voltage capacitors by developing advanced diagnostic methods. These improvements will drive the innovation of next-generation capacitors, contributing to more stable and efficient power grids that can meet the growing demands of modern energy systems.

Involved in the project

Daniel Svensson, Thomas Hammarström, Xiangdong Xu, Yuriy Serdyuk, Stanislaw Gubanski, Olof Hjortstam, Sari Laihonen, Riddhi Ghosh

Partners

Chalmers, Hitachi Energy, Swedish Energy Agency

MATERIALS AND DEVICES FOR ENERGY STORAGE

PROJECT RESULTS 2025

In 2025, the project focused on improving the usability and functionality of the high-voltage dielectric frequency response (HV-DFR) measurement system, moving from a purely research prototype toward a practical measurement tool.

A major outcome was the development of a dedicated graphical user interface (GUI) that integrates all control, measurement, and data-handling tasks previously performed through command-line scripts. The GUI provides an intuitive, window-based environment where the user can configure instrument settings, define measurement parameters, and monitor system status in real time. It communicates with all components of the setup—including the signal generator, high-voltage amplifier, data acquisition card, and Arduino-controlled relay switching unit—allowing fully automated measurement sequences.

Within a single interface, the operator can select between frequency sweep, DC-bias test, and singleshot modes, specify voltage levels, frequency ranges, and offsets, and then initiate a complete calibrated measurement cycle. The program automatically manages relay switching between the test object, the vacuum reference capacitor, and the discharge state; synchronizes data acquisition; and saves all data in a structured directory format organized by date, time, and measurement type.

This eliminates manual steps, reduces user error, and ensures consistent file organization for later data analysis and comparison. Additionally, GUI includes real-time visualization of the acquired signals, improving transparency and user feedback during long measurement runs. Together, these developments have made the HV-DFR system significantly more efficient, user-friendly, and accessible for others, paving the way for broader adoption of the method.

Additionally, the influence of electrode fabrication technique on dielectric loss measurements in polymer films was systematically quantified. In this study, polymer films were prepared with two common electrode types: gold-deposited electrodes (physical vapor deposition in a clean environment) and airbrushed silver paint. It was shown that silver paint can introduce additional losses that are not from the bulk material, particularly in very low-loss materials such as capacitor-grade polypropylene. In contrast, for materials with intrinsically higher losses, such as polyethylene terephthalate, the added loss from the silver paint is much less significant. These results define when inexpensive painted contacts are acceptable and when they are not. The findings were published and presented at IEEE CEIDP 2025 conference.

Finally, the high-voltage DFR system itself was demonstrated and documented at a mature level. The setup was shown to resolve loss factors down to the 10^{-5} range and to capture field-dependent dielectric behavior up to approximately 36 kV/mm, and this work was published in IEEE Transactions on Dielectrics and Electrical Insulation. In parallel, a technical review of metallized film capacitor technology was written. That review covers modern capacitor film design (segmentation, heavy-edge design, selfhealing behavior, internal series structures, etc.) and connects those design features to lifetime, voltage capability and failure behavior in real applications.

This provides context for why high-field, low-loss dielectric characterization is relevant for SESBC's industrial partners and how the measurement method developed in this project can be used to support capacitor development.

Publications 2025

Conference papers

D. Svensson, T. Hammarström, X. Xu, O. Hjortstam, Y. V. Serdyuk, "Comparison of Various Types of Electrodes for Dielectric Frequency Response Measurements on Thin Films," IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP 2025), Manchester, UK, 2025.

Reports

D. Svensson, "State of the Art of Metallized Film Capacitors for High-Voltage Applications," PhD midterm seminar, Chalmers University of Technology, May 2025.

Publications under review 2025

Conference papers

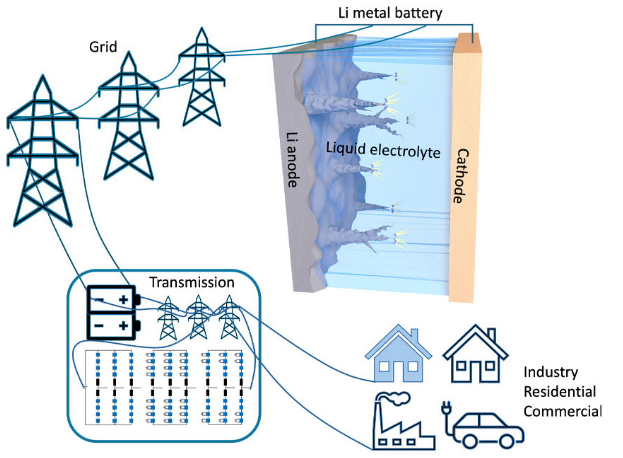
D. Svensson, T. Hammarström, X. Xu, Y. V. Serdyuk, O. Hjortstam, "Development of a Setup for High-Field Dielectric Frequency Response Characterization," IEEE Transactions on Dielectrics and Electrical Insulation, 2025.

HIGH TEMPERATURE BATTERY TECHNOLOGY

Energy storage in the grid is crucial to its stability and efficiency since it is the key to suppress the sharp fluctuations and to avoid interruption of continuous power supply. Li-ion batteries are currently the dominant energy storage technology from portable electronics to large-scale grid energy storage. However, the utilization of LIBs within grid units working at high temperature is hindered by the rapid decay of their electrochemical performance. New battery technology allowing working temperatures at 50-80°C has potential for significant impact on design of energy storage systems for grid applications.

The aim of the project is to enable the integration of batteries as energy storage in high temperature environments in grid applications. The overall goal is to develop cell concepts with long cycle life, high power and energy density at 50-80°C combined with sustainability from materials point of view. The temperature range is compatible with the environment of power-electronic convertors in grid applications and the aim is also to evaluate the concepts with respect to typical cycling patterns in these systems. The aim is to uncover the aging mechanism at high temperature and to design advanced electrolytes to allow working temperatures at 50-80°C compatible with long cycle life, high safety, and good energy/power performance.

Currently, market of grid scale energy storage (GSES) application is still dominated the LIBs, but they are insufficient to meet all needs of energy storage in an effective way. For instance, LIBs as energy storage solution for the convertor unit of the grid needs to be placed outside the converter hall, which is usually working at high temperature (50°C-80°C), decreasing the possibility for distributed systems and new architecture of the storage system. The road block is that the performance of current LIBs will decay significantly, shortening the lifespan of energy storage system. In addition, operating LIBs at this temperature would pose considerable safety concerns.



Electrolytes as the key for high temperature stability

The reasons for performance decay of LIBs at high temperature is mainly related to the electrolyte. High temperature induces enhanced decomposition of the electrolyte components, organic solvents and Li-salt, resulting in development of resistive interphases that rapidly reduces the performance but can also result in gas evolution with potential catastrophic failure. Thus, the development of advanced electrolytes is considered as the main direction for high-temperature batteries. Two main avenues can be explored with either modifying the liquid electrolyte formulation by changing the solvent and/or solvent/salt ratio or moving to solid electrolytes, which are generally more stable and less flammable.

In the project we start from a bottom-up approach by looking at solvents and salts with high temperature stability and considering an electrochemistry-based model for aging behaviour at high temperature by quantitative evaluation of capacity loss, decomposition of electrolyte and cell impedance. The projects build upon a collaboration between Chalmers University of Technology and Karlstad University to benefit from both experimental and modelling approaches, paired with input from industry on the needs from an application point of view.

Involved in the project

Quan Wu, Aleksandar Matic, Moyses Arauyo

Partners

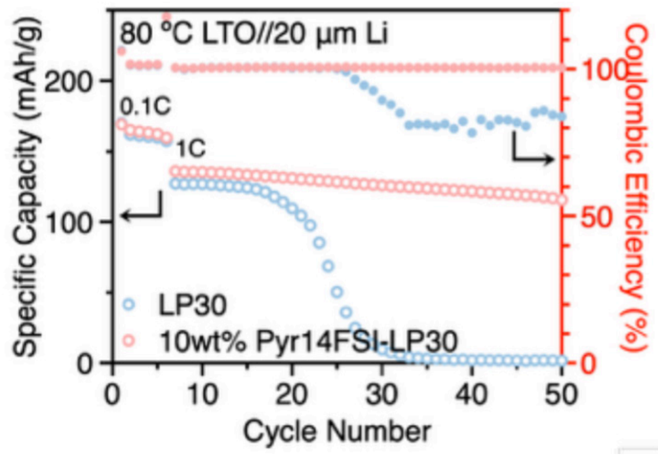
Chalmers, Hitachi Energy, Västra Götalandsregionen, Volvo Energy, Swedish Energy Agency

PROJECT RESULTS 2025

During 2025 the project has continued to develop our new electrolyte concepts for stable high-temperature (80 °C) lithium-metal battery operation, suitable for demanding environments such as converter halls.

We have initiated a new approach by introducing an ionic liquid (IL) additive into a benchmark carbonate electrolyte (commercial name LP30), enhancing thermal and electrochemical stability and enabling dendrite-free Li deposition. The IL's bulky cations and charge delocalized anions lead to a reorganization of the Li^+ solvation structure, strengthening the Li^{+-} anion coordination, and reduce solvent participation in the solvation of Li^+. This leads to a delay of Li^+ depletion at the anode surface during charge, lowering surface charge density and suppressing field amplification at protrusions, thereby promoting uniform, compact Li growth.

Electrochemical tests in symmetric and full Li//LTO cells demonstrated significantly improved cycling stability with the IL-modified electrolyte. Complementary analyses, including Raman spectroscopy, broadband dielectric spectroscopy (BDS), and X-ray photoelectron spectroscopy (XPS), revealed the formation of a stable, predominantly inorganic, solid electrolyte interphase (SEI) with high ionic conductivity. Scanning electron microscopy confirmed a uniform Li morphology, without dendritic features, after charging, correlating interfacial reconstruction with enhanced electrochemical performance and long-term cycling stability. Figure 1 shows data from extended cycling with a Li-foil of limited thickness, compatible with practical applications, where the optimized electrolyte (Pyr14FSI-LP30) shows very stable cycling compared to the base line organic electrolyte LP30.

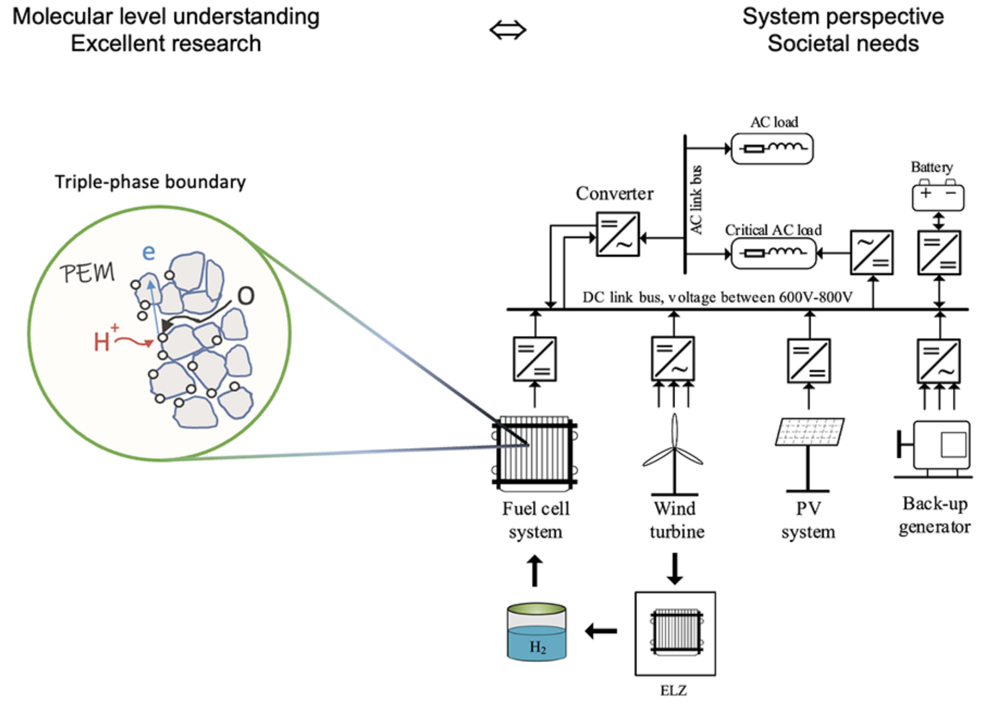


Cycling data of a LTO-cell with the optimized electrolyte (Pyr14FSI-LP30) and a more conventional carbonate-based electrolyte (LP30).

Publications 2025

Licentiate theses

Q. Wu, "Ionic liquid-based electrolyte for high-temperature lithium-metal batteries", December 2025, Chalmers University of Technology.



TOWARDS A MORE EFFICIENT USE OF PEM FUEL CELLS AND ELECTROLYSERS

PEM is the abbreviation for proton exchange membrane, a crucial component at the heart of PEM fuel cells and PEM electrolysers. This type of devices convert chemical energy in electricity (fuel cells) and vice versa (electrolysers), using hydrogen as an energy vector. PEM devices are currently extremely relevant for the transition into a sustainable energy system with decarbonization as a central aim.

PEM fuel cells and PEM electrolysers are at focus in this project for being mature technologies ready for a larger scale implementation. These PEM devices are based on similar components, making results and breakthroughs of this project of mutual interest and of double value. The aim is to develop advanced experimental methods that can support us in understanding performance at the molecular level as well as degradation mechanisms. The results will guide the design of materials and components, with focus on the triple phase boundary, to enable highest efficiency and durability. The triple phase boundary consists in the contact point of the gas phase (hydrogen or oxygen gas, i.e. the reactants), the solid phase (the catalyst, on which the electrochemical reaction takes place) and the liquid phase (the electrolyte, responsible for the transport of protons), which must all cooperate for an efficient operation of the device. Accessing these sites is an extremely challenging task, which require innovative thinking as well as breaking down the bigger problem into smaller sub-projects. Electron microscopy (primarily SEM), vibrational spectroscopy (Raman spectroscopy) and electrochemistry are currently at focus, while fuel cell tests have just started to be performed thanks to the involvement of a new postdoc. The project has the potential to contribute to the System layer, by providing relevant data for the design of a suitable grid / PEM device interface, with particular focus on operational conditions. Also, the needed interface between PEM devices and other energy storage devices like batteries and supercapacitors, makes obvious connections within the layer Materials and Devices for Energy Storage.

Involved in the project

Dylan Schulz, Anna Martinelli, Anders Palmqvist

Partners

Chalmers, Västra Götalandsregionen, Smoltek, Celcibus, Hymeth, Ionautics, Hydri Solutions, Hitachi Energy, Svenska kraftnät, NanoScientifica, Swedish Energy Agency

PROJECT RESULTS 2025

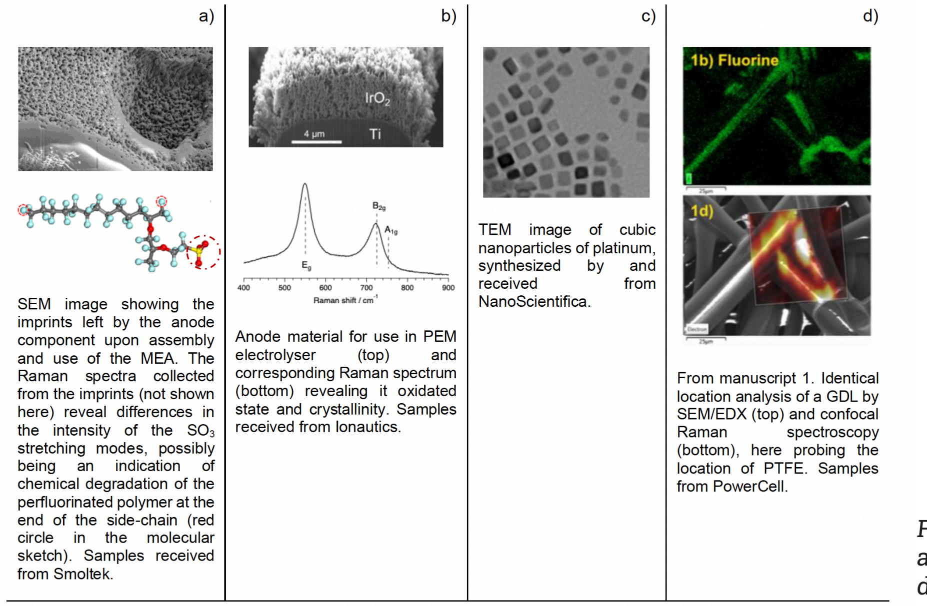
The industrial partners in the project that have the possibility to share samples are de facto Smoltek, Ionautics and NanoScientifica. We have made progress with all of them in different ways, as explained below.

Smoltek develops large area, carbon fiber-based anode materials loaded with extremely low amounts of the catalyst iridium oxide, for use in PEM electrolysers. Here, we have made progress in understanding how to use SEM and EDX to probe the spatial location of the ionomer, with particular attention to whether this method can or cannot help in understanding possible degradation mechanisms during cell operation. To this end, we also make extensive use of confocal Raman spectroscopy, the two techniques now converging in telling that during use, the solid anode support made of titanium grains leaves imprints into the membrane surface, these being areas where spectroscopic signatures indicate a chemical degradation (Figure 1a). We are now cross-checking these results to ensure conclusions from identical locations; ideally, we will be able to correlate mechanical and chemical degradation to performance changes in the cell.

Ionautics also develops anode materials for use in PEM electrolysis, based on a patented deposition method that results in more or less dense films of iridium / iridium oxide. Through our collaboration, and in particular by the use of Raman spectroscopy, we could help in understanding the chemical state of iridium, in terms of crystallinity and oxidation (Figure 1b).

NanoScientifica has a niched competence in the synthesis of metal nanoparticles and has delivered custom made cubic particles of platinum. We have characterized them by simple TEM imaging by now (Figure 1c), while electrochemical characterization is also ongoing in collaboration with the group of Mathilde Luneau. The goal here is to use these nanoparticles in an operating PEM fuel cell and follow possible morphological changes due to use, by identical location TEM imaging.

Finally, through a master thesis project in collaboration with PowerCell, we are finalizing an original scientific article about the spatial distribution of PTFE across different types of GDLs and its impact on fuel cell operation at dry oxygen conditions. The preparation and characterization of the GDL substrates was performed in our labs (Figure 1d) while the fuel cell tests were done at the facilities of PowerCell.



a) SEM image showing the imprints left by the anode component upon assembly and use of the MEA. The Raman spectra collected from the imprints (not shown here) reveal differences in the intensity of the SO_3 stretching modes, possibly being an indication of chemical degradation of the perfluorinated polymer at the end of the side-chain (red circle in the molecular sketch). Samples received from Smoltek.

b) Anode material for use in PEM electrolyser (top) and corresponding Raman spectrum (bottom) revealing it oxidated state and crystallinity. Samples received from Ionautics.

c) TEM image of cubic nanoparticles of platinum, synthesized by and received from NanoScientifica.

d) From manuscript 1. Identical location analysis of a GDL by SEM/EDX (top) and confocal Raman spectroscopy (bottom), here probing the location of PTFE. Samples from PowerCell.

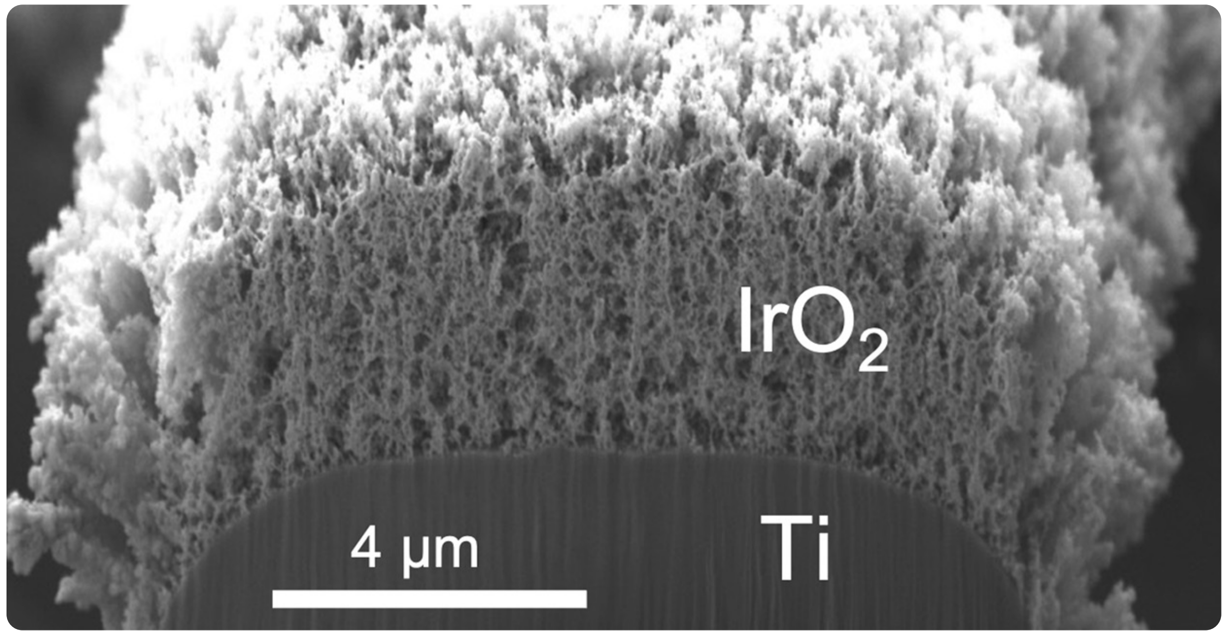
Figure 1. Examples of results achieved within the project during the year 2025.

Publications under review 2025

Journal papers

D. Schulz, M. Ringström, S. R. Sankar, and A. Martinelli "Role of native binder in controlling the PTFE distribution in gas diffusion layers for PEM fuel cells", International Journal of Hydrogen Energy (submitted October 2025)

D. Schulz, X. Wen, B. Pennincks, S. Sasidharan, L. Strandberg, F. Wenger and A. Martinelli "Large area PEM electrolyzer anodes with low iridium loading on carbon nanofibers with stable structures during assembly/disassembly and operation", (in manuscript)



NEW CATALYSTS FOR ELECTROLYSIS/FUEL CELL PURPOSES

Hydrogen is considered a key enabling technology for the decarbonization of electricity supply and grid balancing. However, proton exchange membrane water electrolysis (PEMWE), the only CO2 free hydrogen production source that is adapted to renewable energy sources, is dependent on the rare noble metals Ir and Pt. In fact, only 8 tons of Ir is extracted yearly and to reach the global goals for hydrogen installations 10-50 times more Ir needs to be extracted every year.

In this project, we aim to develop porous catalyst layers to decrease the noble metal content to below 1/10 of what is used today whilst maintain or increasing critical performance parameters such as efficiency and lifetime.

Industry demand for efficient low loading IrO2 catalyst

There is today a very strong interest from industry to develop nanostructured IrO2 catalyst with high performance even when the amount (loading) of the catalyst layer is drastically reduced to minimize the need for Ir in their next generation of electrolyzer systems. The technology we have developed is suitable for a long range of materials and nanostructures but with the tremendous industry demand for more efficient IrO2 catalyst, we are focusing this project to help industry to find a solution suitable for their next generation electrolyzer that will enable large scale utilization of green electricity for hydrogen production.

Scaling of synthesis method to industrial size with high productivity

The experimental set-up is today suitable for production of test samples up to an active area of 150 cm2. In production samples are in the range of 3,000-10,000 cm2. Two approaches for scaling are now under development.

Involved in the project

Ulf Helmersson, Sebastian Ekeroth, Rommel Viloan, Johan Ahlström, Joakim Ekspong

Partners

Linköping University, Ionautics, Smoltek, Volvo Energy, Chalmers, Swedish Energy Agency

MATERIALS AND DEVICES FOR ENERGY STORAGE

PROJECT RESULTS 2025

The shift from hollow cathode to magnetron sputtering sources has been highly successful. Over the past year, our efforts were focused on developing IrOx coatings with controlled porosity. As shown in Figure 1, two types of coatings deposited using magnetron sputtering exhibit different structure, density and porosity. Notably, the performance that we derive from the denser catalyst layers deposited using magnetron sputtering have outperformed those that we have initially synthesized using hollow cathode sputtering. The use of denser coatings significantly improved the adhesion, resulting in easier handling and better durability during PEM testing.

We have continued the upscaling efforts by increasing the power density in the sputtering process from approximately 2 to 8 W/cm2. The increase in power density resulted to higher deposition rates, which are now comparable to those typically required for industrial-scale processes. Further optimization of the process at higher power densities are on-going to maintain the crystallinity, structure and performance during PEM testing.

On the actual PEM testing, the focus centred on long term stability of the produced catalyst layers. This entailed PEM testing for >1000 hrs under realistic PEM conditions (see Figure 4), followed by post-mortem analysis to evaluate the crystallinity and structural integrity of the catalyst layer. These investigations provide insights into the degradation mechanisms and durability, which will guide catalyst layer design and process parameters to meet stringent requirements in industrial applications.

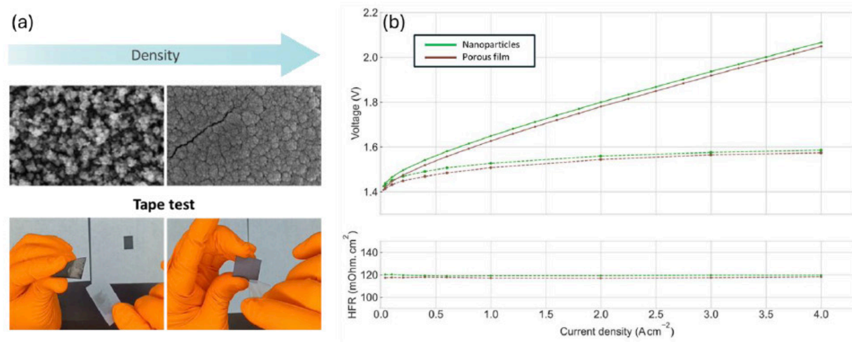


Figure 1. (a) IrOx coatings with different density and porosity produced using magnetron sputtering. The SEM image at the upper left is composed of distinct nanoparticles while the other SEM image is from a porous film. Tape tests on these two distinct structures indicate better adhesion on the PTL with the denser coating. (b) Polarization curves from testing of nanoparticle and porous thin film with 0.3 mgIr/cm2 loading with 5 cm2 active cell area. The temperature was maintained at 80°C at atmospheric pressure. Dashed lines indicate the HFR-corrected data. All MEAs used commercially available coated cathodes with 0.3 mgPt/cm2 and Nafion 115 membrane.

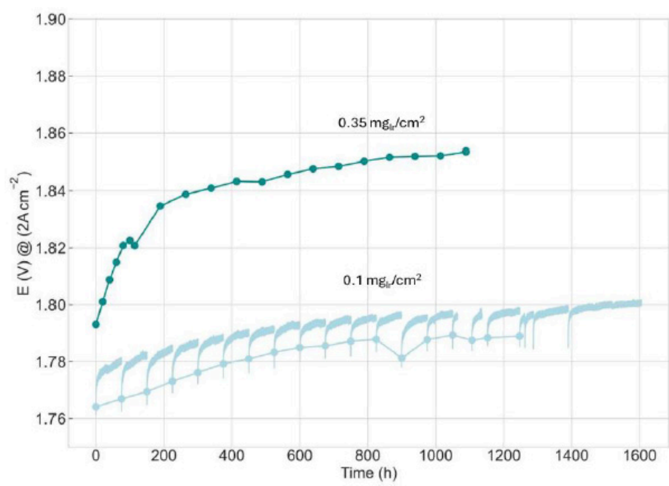
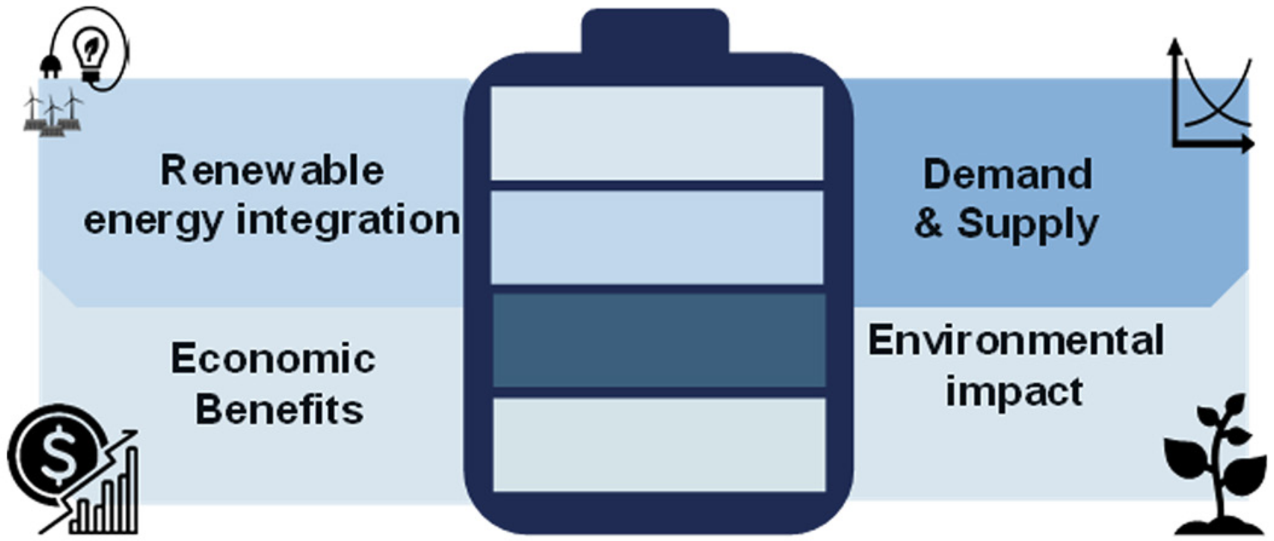


Figure 2. Long term stability at 2A/cm2 of porous films with loadings of 0.1 and 0.35 mgIr/cm2. The upper curve was tested with a 1.45 – 2 V cycling (1 cycle/min) while the lower curve had a 2 A/cm2 hold. Circular markers are data from polarization curves.

Publications 2025

No publications during 2025



PERFORMANCE EVALUATION OF BATTERY-BASED ENERGY STORAGES FOR VARIOUS DUTIES, IN TERMS OF POWER, ENERGY AND ENVIRONMENTAL IMPACT

In this project various storages, with a basis in Li-ion technologies are investigated in terms of their power and energy ability, linked to their environmental impact. The environmental impact is both determined during the user phase as well as during the extraction phase.

In the centre of the storage investigation are the Li-ion battery technologies, with various cathode materials containing both Cobalt and Nickel as well as LFP which is a technology without these heavy rare-earth metals. The power and energy capacity varies with these cathode materials, and by changing the anode material to Lithium titanate oxide a very high power-ability can be obtained.

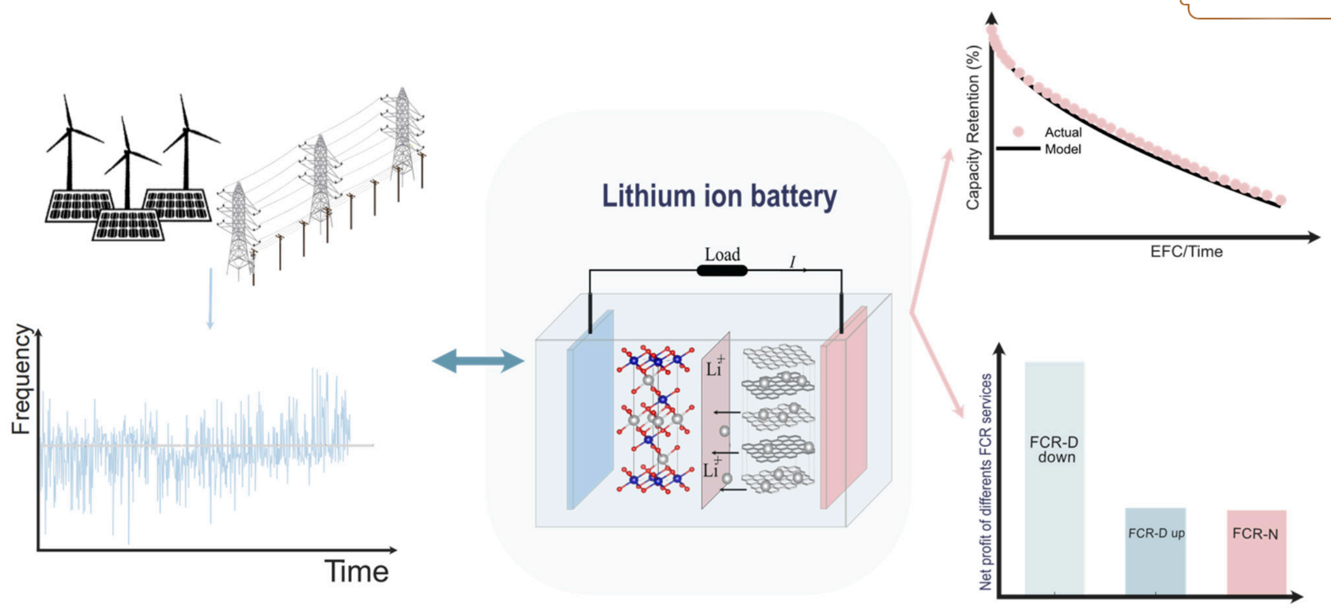
Furthermore, by designing electrodes with different thicknesses the power versus energy capacity can be altered. Additional storage elements such as supercapacitors and fuel cells, and to a small extent Hydro power are lightly covered in order to bring a completeness around the storage. The requirements on the storage systems are also established. Here, other activities within the centre as well as already ongoing activities at the division of Electric Power Engineering will be utilized the overall aim of this project is to find suitable battery-based storages for various duties in a 100 % fully renewable electric energy system.

Involved in the project

Meryem Ahouad, Torbjörn Thiringer, Evelina Wikner, Anders Nordelöf, Tatiana Andrade

Partners

Chalmers, Soltech Energy Solutions, RedoxMe, Volvo Energy, Volvo Cars, Västra Götalandsregionen, Swedish Energy Agency,



Schematic of a lithium-ion battery providing frequency containment reserve (FCR), illustrating the relationship between operational use, calendar and cycling ageing, and the associated economic value.

PROJECT RESULTS DURING 2025

During this year, an ageing model for lithium iron phosphate (LFP) cells was developed to evaluate the economic potential of battery systems participating in frequency ancillary service markets.

The model accounts for both calendar and cycle ageing mechanisms, enabling reliable predictions of capacity fade under various operational scenarios. Model parameters were calibrated and validated using laboratory data obtained from LFP cells exposed to representative frequency regulation duty cycles. The comparison between modelled and measured results demonstrated strong consistency. To translate these findings into practical insights, the ageing model was integrated into a techno-economic framework. This integration allowed quantification of the degradation costs associated with different levels of service participation, facilitating an in-depth assessment of the trade-off between ancillary service revenues and the costs of battery wear. The analysis revealed that participation in frequency regulation services can be economically advantageous.

Publications 2025

Conference papers

M. Ahouad, A. Sunjaq, E. Wikner and T. Thiringer, "Economic Assessment of Battery Energy Storage for Frequency Regulation in the Nordic Power Systems," 2024 20th International Conference on the European Energy Market (EEM), Istanbul, Turkiye, 2024, pp. 1-5, doi: 10.1109/EEM60825.2024.10608974

T. S. Andrade, T. Thiringer and M. Ahouad, "Plug-in fuel cell electric vehicles: Are they more cost-efficient than battery electric vehicles?," 2023 IEEE PES 15th Asia-Pacific Power and Energy Engineering Conference (APPEEC), Chiang Mai, Thailand, 2023, pp. 1-6, doi: 10.1109/APPEEC57400.2023.10561968

Bachelor theses

H. Ekeroth, H. Karlsson, J. Lindberg, N. Lindow, K. Mahmutovic, E. Sander, "Dimensionering av laddningsdepå for tunga elektrifierade fordon", 2025, Supervisors, M. Ahouad, T. Thiringer

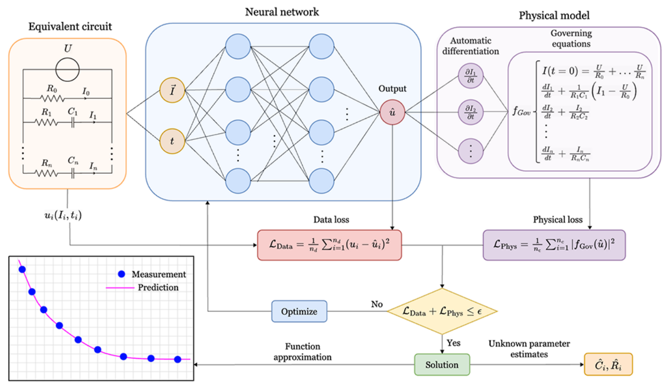
AI METHODS FOR DEVELOPMENT AND CONDITION MONITORING OF ENERGY STORAGE DEVICES

This project aims to develop a physics-based AI framework for the characterization, performance evaluation, and lifetime prediction of energy storage devices, including high-voltage power capacitors, batteries, and supercapacitors. By utilizing AI techniques such as Physics-Informed Neural Networks (PINNs), the project will enhance material selection and condition monitoring, ensuring reliable operation under various stress conditions.

The outcome will contribute to the development of a new generation of energy storage devices that can meet the growing demands of modern power systems, particularly with the integration of renewable energy sources and HVDC technology.

This research project focuses on developing a physics-based AI framework to improve the performance and lifespan of energy storage devices like high-voltage power capacitors, batteries, and supercapacitors. These devices are vital in modern power systems for short- and mid-term energy storage, enabling stable grid operation and power quality control. However, during operation, they are often subjected to overstresses, which reduce their lifespan. We aim to address these challenges by using AI-driven methods for material characterization, performance evaluation, and lifetime prediction. Energy storage devices play different roles in power systems depending on their properties. Batteries, for instance, are efficient in applications that require high energy density but suffer from slow response times and relatively low power density, making them unsuitable for transient high-power demands such as those posed by renewable energy sources. On the other hand, supercapacitors offer a much faster response and higher power density, making them more suitable for applications like grid stabilization, where high amounts of energy need to be released quickly. Meanwhile, metalized film capacitors provide the highest power density and are crucial for high-voltage power grid applications due to their efficiency and reliability.

To address current shortcomings in the design and performance of these devices, the project proposes using a physics-based AI method, specifically Physics-Informed Neural Networks (PINNs). These AI models incorporate



the fundamental physics governing the devices, described by partial differential equations (PDEs), into the machine learning framework. The models are expected to improve upon traditional methods, such as finite element modeling (FEM), which struggle with numerical problems in highly nonlinear conditions or when dealing with steep gradients in charge density distribution.

The project will explore the use of PINNs and other AI techniques to simulate the transport of electrical charges, dielectric polarization, and aging mechanisms in energy storage materials. The goal is to develop models that can predict the performance and aging of materials based on their responses to electric field stress and temperature variations. These models will ensure that energy storage devices can operate reliably within specified ranges of electric field strength and temperature, while also predicting their lifetime. The project will benefit from data provided by industrial partners and ongoing research, and its applicability will be tested across various energy storage technologies, including batteries and supercapacitors.

This research is highly relevant to the evolving energy landscape, where the integration of renewable energy sources and the use of High Voltage Direct Current (HVDC) technology demands more reliable, efficient, and durable energy storage devices. By developing AI-based tools for material characterization and condition monitoring, the project will contribute to a more sustainable and resilient energy system.

Involved in the project

Emir Esenov, Yuriy Serdyuk, Thomas Hammarström, Christian Häger, Olof Hjortstam, Jorge Solis, Reverant Crispin

Partners

Chalmers, Karlstad University, Linköping University, Hitachi Energy, RedoxMe, Ligna Energy, Swedish Energy Agency

PROJECT RESULTS 2025

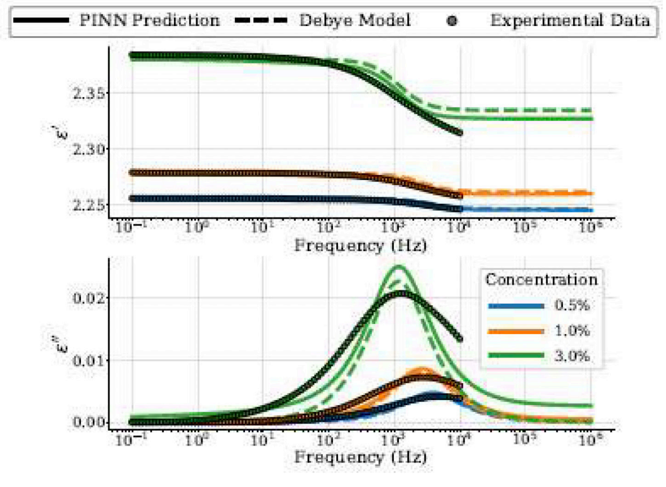
In 2025, the activities withing the project mainly focused on implementation of physics-informed neural networks for inverse equivalent circuit modelling of dielectric response data in frequency domain. This task was successfully accomplished, and the results of the work were summarized in a paper presented on IEEE CEIDP2025 conference. A journal paper has been written and is to be submitted in the fall 2025.

The conducted work resulted in a PINN framework for modeling dielectric response of materials. Its efficacy for parameter extraction in frequency-domain DR analysis has been examined. Through systematic evaluation of synthetic data with up to three Debye processes and DC conductivity, it was demonstrated that PINNs accurately recover all model parameters even under significant Gaussian noise levels. The embedded physics acts as a natural regularizer, preventing overfitting without requiring additional regularization techniques, while maintaining computational efficiency with small network architectures and minimal hyperparameter tuning. The introduction of dedicated parameter subnetworks extends the framework's capability to model functional dependencies on external variables, as demonstrated through the analysis of polypropylene–meso-erythritol experimental data.

PINN successfully learned smooth, physically consistent concentration trends for all Debye parameters, validating the applicability of the approach to real-world materials characterization (see figure below). The monotonic increase of all parameters with additive concentration aligns with physical expectations and demonstrates the model's ability to capture meaningful material relationships.

The results of the study also highlighted some limitations. The sensitivity of relaxation time parameters to noise, attributed to their involvement in higher-order terms and multi-order magnitude spans, suggests that informed initialization is necessary for these parameters. Moreover, the systematic deviations observed at higher additive concentrations, particularly the overly sharp loss peaks in energy dissipation, underscore fundamental limitations in the flexibility of the Debye model. These findings point toward the need for more complex dielectric relaxation models such as Cole–Cole or Havriliak–Negami formulations to achieve improved fidelity with real-word materials.

Future work will focus on extending the framework to incorporate more flexible relaxation models and validating the approach across a broader range of dielectric materials and operating conditions. The demonstrated success in recovering both individual parameters and their functional dependencies provides a foundation for physics-informed characterization methodologies that can adapt to the increasing complexity and diversity of modern dielectric materials.



PINN Predictions of dielectric response for polypropylene films across additive meso-erythritol concentrations, along with extracted experimental data and calculated Debye solution with the PINNs learned DR parameters.

Publications 2025

Conference papers

E. Esenov, O. Hjortstam, Y. Serdyuk, T. Hammarström, C. Häger, F. Pousaneh, Inverse modeling of dielectric response in time domain using physics-informed neural networks, 2025 Annual Report. of IEEE Conference on Electrical Insulation and Dielectric Phenomena CEIDP2025, Manchester, UK, September 2025.

Publications under review 2025

Journal papers

E. Esenov, O. Hjortstam, Y. V. Serdyuk, C. Häger, T. Hammarström, A Physics-Informed Neural Network Approach to Debye Modeling of Dielectric Response Data, IEEE Trans. Diel. Elec. Insul. 2025, to be submitted.

ACTIVITIES 2025

SESBC CONFERENCE

The third annual SESBC conference took place in Uppsala at Botaniska hotellet, 15–16 October. The event was well attended with an increased number of participants since previous conferences. The conference also included network activities, a poster session, and a study visit at Ångström Advanced Battery Centre, Uppsala University.

SEMINARS & WORKSHOPS

Online seminars
There have been two SESBC arranged online seminars.

Road maps workshops
SESBC arranged two roadmap workshops to jointly define new projects for the continuation of the centre.

mFRR EAM: the new way of balancing the Nordic Power System, 11 November
Online seminar from SESBC's Systems layer. Invited speaker Ellika Wik, Power System Specialist from Svenska kraftnät.

Material layer lunch to lunch workshop and study visit in Karlstad, 16–17 June
Presentation of ongoing research activities, ideas exchanges across projects, and discussions on future directions. Following the workshop there was also a study visit to Glava Energy Center.

PHD NETWORK

The second SESBC Summer School, was held at Chalmers University of Technology on 19-21 August 2026. The theme this time was on long-term energy storage with focus on PEM fuel cells and electrolysers. During this school, we had the opportunity to learn from Björn Aronsson at Vätgas Sverige as well as we got a lecture by Professor Christina Rooth from Bayreuth University, Germany.

Apart from the Summer School that is the main gathering activity for the PhD Network, SESBC provides all PhD students and Postdocs the opportunity to speed date with representatives of our non-academic partners. This is typically organized in smaller groups with a rotating scheme. In addition, a series of online DUO Seminars, for the PhD Network only, has been planned, which will start in early 2026.

INDUSTRY FORUM

22 September – a meeting was held with participants from SESBC's Industry Forum at E.ON's facilities in Malmö. At the meeting, E.ON presented its ongoing development work in electricity storage and balancing, including advanced local flexibility trading, new contract types for flexibility, and solutions combining batteries with district heating and cooling. In the workshop part of the meeting, the possibilities for running pilot and demonstration projects in affiliation with SESBC were discussed, and an inventory of potential demo sites and projects was made. The forum also held a meeting during the SESBC conference.

Established in 2024, the centre's Industry Forum is a meeting place for non-academic partners to voice their interests on equal terms, regardless of financial contribution. It is an open platform for discussion on various perspectives of the centre activities, to create focus groups to explore topics of shared interest and to influence the centre's strategy and research directions.

SESBC presence at international conferences

- ECPR General Conference
- 16th ACM International Conference on Future and Sustainable Energy Systems (E-Energy '25). ACM 2025
- Workshop on Relaxed Semantics in Data Analytics Pipelines co-located with ACM International conference on Distributed Event-Based Systems (DEBS) 2025
- ACM International conference on Distributed Event-Based Systems (DEBS) 2025
- 39th International Symp. on Distributed Computing (EATCS DISC 2025)
- 2025 IEEE Energy Conversion Conference Congress and Exposition (ECCE)
- The 26th European Conference on Power Electronics and Applications
- 41st annual IMP Conference
- 37th annual NOFOMA conference
- Jicable HVDC'25
- 16th International Sustainability Transitions (IST) Conference
- IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP 2025)
- International Conference on the European Energy Market, EEM
- Asia-Pacific Power and Energy Engineering Conference, APPEEC
- Industrial Marketing & Purchasing Conference 2025
- Energy politics, policy and governance at the ECPR General Conference
- The 8th International Symposium on Energy Materials Chemistry

SESBC workshop in Gothenburg 8 May.

COLLABORATION

Presenting ideas, research activities and industry needs combined with study visits and workshops are important tasks to understand how the centre can work together. There have been several activities and collaborations both between SESBC partners and other actors. The collaborations involve industry partners, international academic institutions, researchers, and associated projects.

Several initiatives with various activities such as interviews, reference groups, meetings and workshops have taken place during the year.

Industrial collaboration

As in the spirit of SESBC, throughout 2025 there has been a continuous and direct involvement of industrial partners in research projects to: better define targets, increase understanding of technologies in the specific application, and communicate results. Here follows some highlights.

A joint effort from Vattenfall Eldistribution, Herrljunga EL and Göteborg Energi has been made for the definition of models and scenarios for medium-voltage grids with high penetration of power electronics and energy storage, including provision of realistic load profiles based on actual measurements. Hitachi Energy has actively contributed on the definition and selection of different power-electronic solutions for medium-voltage grids, as well as on activities within the concept of grid-forming control. In particular, the latter has resulted in the submission of 4 first filings for patent applications. Volvo AB has provided data from their 2nd life BESS installations. The potential of a patent is being evaluated together with Ionautics. Mölndal Energi, Göteborg Energi and Akademiska Hus have contributed to model information and data of various kind. CheckWatt and Vattenfall regarding energy storages and data exchange. Discussions have also taken place with Revus, who has offered to support in the development of a flow battery. A technical site visit to Nexans AS in Norway has been conducted. Continuous collaboration with CIT Renergy on joint activities. Collaboration with Ionautics on confocal Raman spectroscopy, which has become a crucial tool to understand the physical state of catalytic particles in advanced anode materials for electrolysis applications. Collaboration with Powercell on spatially mapping the distribution of PTFE in GDL substrates for fuel cell applications. Continuous work is being done with the investigation of carbon-fiber based anode materials developed by Smoltek. Furthermore, there has been a collaboration with the European Battery Hub at the European Synchrotron Radiation Facility on the characterization of interfaces and with the department of Chemistry at Chalmers and the Swedish NMR-center on ion transport in the new electrolyte formulations.

Academic & International collaboration

The already existing collaboration with the University of Padova has been further strengthened under 2025, resulting in a new affiliated research project granted under the CETPartnership initiative, 1 journal publication, several journal publications that are currently under review, and several publications accepted for international conferences that will take place in 2026. There is an ongoing collaboration with Tampere University for gold-deposited polymer samples, and another with Göteborg Energi on the City Energy Transition. Stockholm School of Economics and Chalmers' Department of Technology Management and Economics have co-written an article (currently under review) and a conference paper. There have been co-organized conference sections on energy politics, policy and governance at the ECPR General. Spectroscopic techniques have come to a use in in many projects run within the centre but led by other research leaders, for instance those coordinated by Linköping University and Chalmers. A group of PhD students and Postdoctoral researchers from different disciplines and all active in the centre has been initiated during 2025. Collaboration with NREL with proposals have been exchanged as to how to move forward in terms of working together to accelerate PEM testing and development of catalyst layer. There are ongoing interactions with University of Massachusetts Amherst and with the University of Bordeaux (LaBRI, France); the latter has led to results documented in research articles published in international peer-reviewed venues, while there is an extended ongoing activity involving joint-supervision of a PhD project with prospect of a double degree (University of Bordeaux and Chalmers). There is a potential for future collaborations within the CETPartnership project application on the interaction between distribution and transmission grids. Participation in a study of a proposed capacitive expansion model together with representatives from Quantified Carbon Ltd., and researchers from KTH and NTNU. There are maintained and active international ties with Fingrid (Finland) and Nexans (Norway). The published Jicable 2025 paper further strengthens international visibility and data sharing with global utilities and manufacturers. Supervision of master's students in collaboration with CleanWatts (Portugal) as part of course group project. Representatives from the department of chemistry at Chalmers have been invited to give invited talks the University in Beyreuth in a first step towards possible future collaborations and exchange programs.

Associated projects

- "Nätresiliens – Bostäders Möjligheter att Bidra till ett Mer Resilient Elnät"
- "Hydrogen for Propulsion of Electrified Vehicles – System Aspects on On-Board Versus Off-Board Hydrogen-to-Electricity/Thermal Energy Conversion", are associated projects collaborating with the SESBC initiative to address grid impact needs and advancements in fuel cell technology
- FFI-project on a related theme where Volvo is the industry partner – "New conditions for optimized freight transport solutions"
- The Swedish Energy Agency's project "Aging-Aware Techno-Economic Decision Making for Optimal Usage of EV Batteries over Full Lifecycle". This project is also with Volvo. An FFI-application has been filed for a continuation of this project
- The Swedish Energy Agency's project "Analysis of the conditions for embedding the battery swapping model in the Swedish context"

David Steen and Massimo Bongiorno participated in the panel of Chalmers Area of Advance Energy's seminar on costs of stabilizing the electricity grid.

COMMUNICATION & OUTREACH

Balancing the electricity grid and renewable energy sources have a large impact and are publicly debated topics. So, it's important that policy-makers, and the society at large, are aware of advancements in the field. SESBC has worked actively with three owned channels, and participated in various media outlets and other communication activities.

Newsletter
SESBC has published a monthly newsletters with research news and informing about events and activities within the centre.

Website
SESBC's website is the information hub where all the projects have been published together with several relevant news articles and events.

LinkedIn
SESBC's LinkedIn account now has 1,500 followers and had many viral posts during 2025. The most viewed was from the Summer School event which had over 10,000 views (right).

Podcast
Anna Svensson from Hitachi Energy and Massimo Bongiorno participated in the podcast "Verapodden" to get more people interested in the electricity grid (25 June). https://verapodden.podbean.com/e/kraftelektronik-%e2%80%93-en-revolution-i-elnatet/

MEDIA COVERAGE


DEBATT
Dagens industri
Avbrutna energiförhandlingar öppnar möjligheter

Opiniated article by Filip Johnsson and Lisa Göransson published in Dagens industri.

Below are examples of media coverage on program related topics.

- Experterna om kärnkraften – tidsplanen ifrågasätts, Expressen 21 Aug https://www.expressen.se/nyheter/sverige/experterna-om-karnkraften-tidsplanen-ifragasatts/
- Expert om svenska kraftnätet: Systemet är robust, GP, 28 April https://www.gp.se/nyheter/sverige/expert-om-svenska-kraftnatet-systemet-ar-robust.15b176a1-5a39-427d-9df2-cf9ac8933bda
- Rapport: Vind och sol fixar klimatomställningen om marknaden får styra, Sveriges Radio, 31 Jan https://www.sverigesradio.se/artikel/rapport-vind-och-sol-fixar-klimatomstallningen-om-marknaden-far-styra
- In Zweden stimuleert een brede consensus over klimaatactie een energietransitie in de productie, Soestnu 8 Jan https://www.soestnu.nl/in-zweden-stimuleert-een-brede-consensus-over-klimaatactie-een-energietransitie-in-de-productie/
- Förnybar energi växer snabbast - går om fossilt kol i elproduktion, Sveriges Radio, 19 Dec https://www.sverigesradio.se/artikel/fornybar-energi-utsedd-till-arets-genombrott-av-science
- Avbrutna energiförhandlingar öppnar möjligheter, Dagens industri, 19 Sep https://www.di.se/debatt/avbrutna-energiforhandlingar-oppnar-mojligheter/
- Chalmersforskaren: Northvolt-satsningen var inte förgäves. Sveriges Radio, 15 March https://www.sverigesradio.se/artikel/chalmersforskaren-northvolt-satsningen-var-inte-forgaves

TALKS AND PRESENTATIONS

Results applying modelling methodology developed has been presented to the industry council of west Sweden, led by the governor, and regular meetings with Länsstyrelsen Västra Götaland, and the Västra Götalandsregionen.

As part of the SmallTalks [about Nanoscience] initiative at Chalmers, a popular science presentation was given about the research in the project "Towards a more efficient use of PEM fuel cells and electrolysers" and how fuel cells work.

Participation in Open Energy Modelling Workshop at KTH (March)

Lees, B. & Wik, T. Poster presentation at Reglermöte in Lund (June 11-13)

M. Vagin, "An Introduction to Electrocatalysis on Functional Polymers", Public Trial Lecture for the Associate Professor, Linköping (2 May)

Matic A., Batterier — Från atom till cell, Vetenskapsfestivalen, Göteborg (April)

David Steen and Niklas Thulin, speakers at EVS38 (May)

David Steen and Massimo Bongiorno were in the panel on Chalmers Area of Advance Energy's initiative seminar discussing the costs of balancing the electricity grid (Feb)

FINANCIAL REPORT

Total costs up until the year 2025 have been 108.7MSEK. Of these, 46.3MSEK are cash costs covered by the Energy Agency and the industry partners, while 62.4MSEK are in-kind costs by industry and academia.

The initial budget for the centre is 162.7 MSEK and has today increased to 165.4MSEK. More details on the centre's budget and its division into categories can be found in Table 1.

Figure 1 displays how much of the budget for the different categories has been used, while Figure 2 shows the total budget allocation. All numbers are in comparison to the 2022 budget.

After the fourth call for projects, most of the cash from the Swedish Energy Agency and the industry partners has been allocated. The difference between budget and actual costs in Figure 1 (in terms of academia and, especially, industry in-kind) is due to the delay in the start of the projects during the start phase of the center. Furthermore, some of the total in-kind contribution from industrial partners in the original budget has been converted into cash contribution. The remaining budget will be utilized for activities during 2026

Table 1. Total centre budget

	Budget (kSEK)				Actual costs up until 2025 (kSEK)				Balance to be utilized in stage one (kSEK)			
	Cash (EM+Industry)	In-kind academia	In-kind industry	Sum	Cash (EM+Industry)	In-kind academia	In-kind industry	Sum	Cash (EM+Industry)	In-kind academia	In-kind industry	Sum
Centre management	7,946	0	0	7,946	6,950	1,868	1,450	10,268	996	-1,868	-1,450	-2,322
Projects	66,394	54,231	36,811	157,435	39,354	40,092	19,031	98,478	27,039	14,139	17,780	58,958
Sum	**74,340**	**54,231**	**36,811**	**165,381**	**46,304**	**41,960**	**20,482**	**108,745**	**28,035**	**12,271**	**16,330**	**56,636**
Initial budget in 2022				**162,692**				**108,745**				**53,946**

Figure 1. Budget & Actual costs

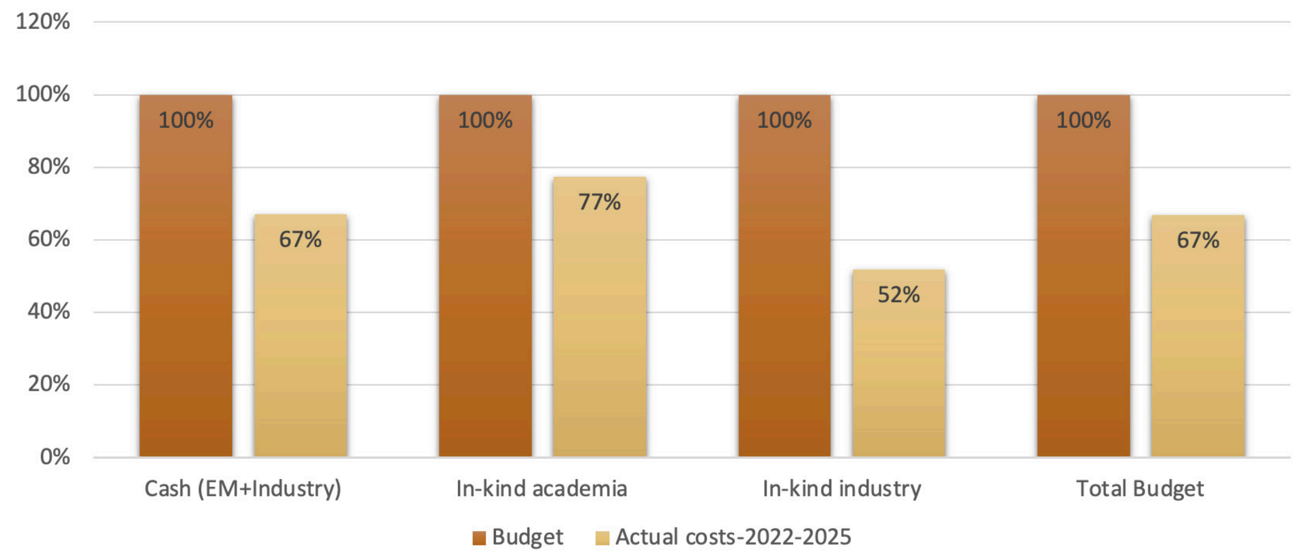
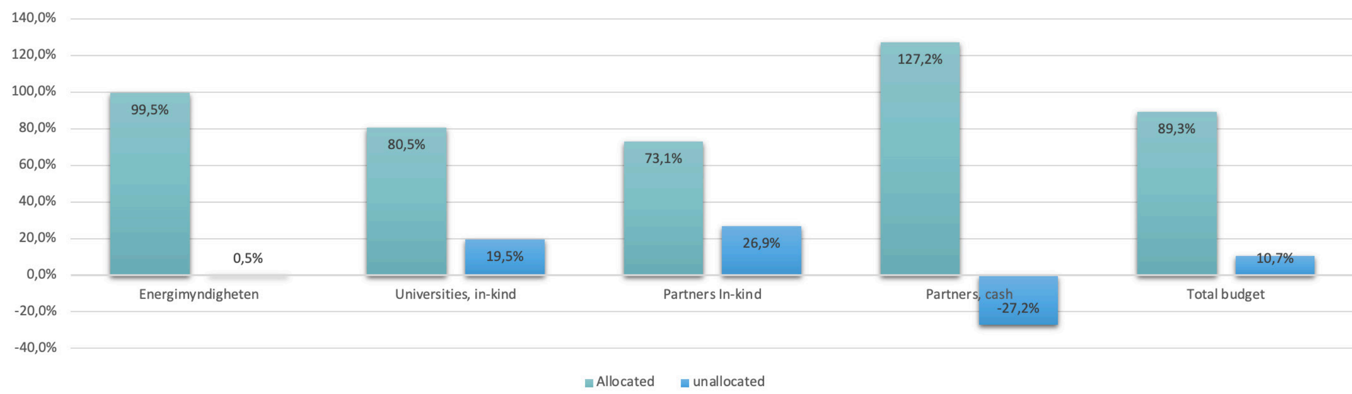


Figure 2. Total centre budget allocation



ORGANISATION

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Centre Management

Operational board
Director and
R&I layer leaders

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Anna Abelius
Coordinator Events


Shruthi Murigayya Hiremath
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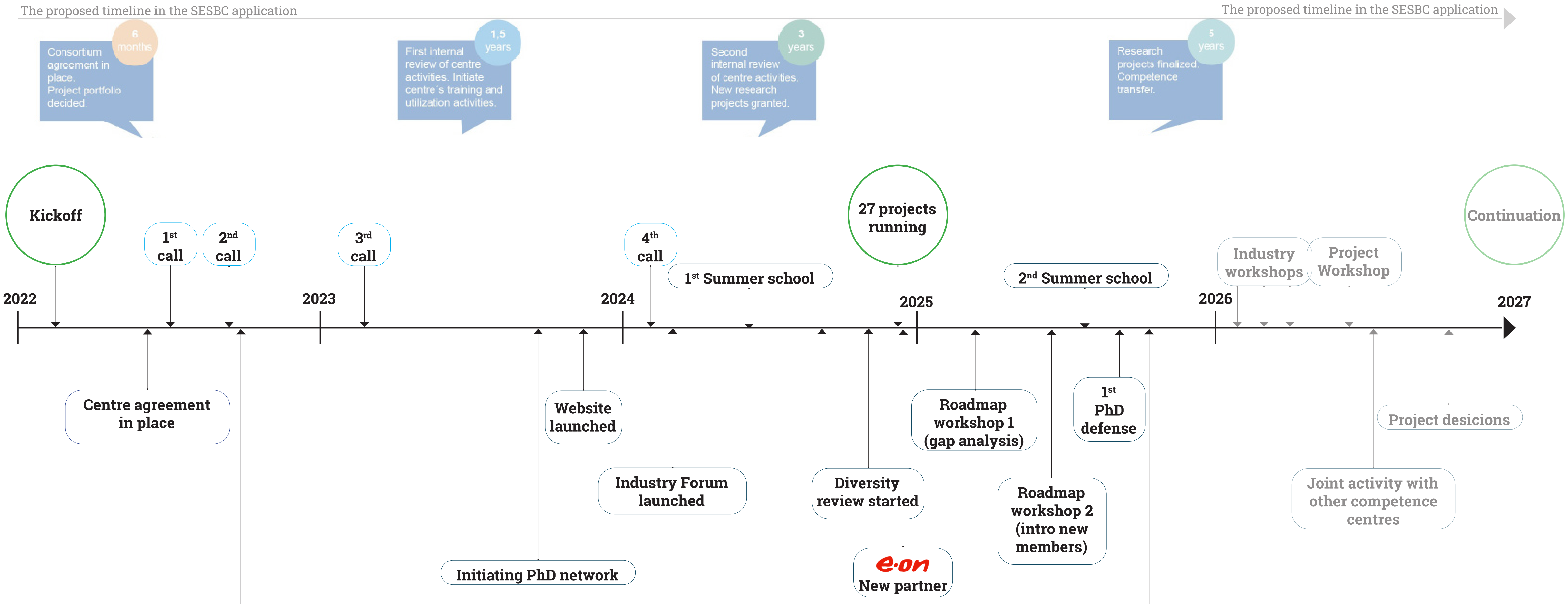
TIMELINE



First SESBC conference
Norrköping

Second SESBC conference
Lund

Third SESBC conference
Uppsala

PUBLICATIONS 2025

Licentiate & Doctoral theses

M. Lundberg, "Grid Capacity – Challenges and Opportunities", 2025, Lund University, ISBN 978-91-985110-6-2.

Q. Wu, "Ionic liquid-based electrolyte for high-temperature lithium-metal batteries", December 2025, Chalmers University of Technology.

Journal papers

A. Narula, M. Bongiorno, P. Mattavelli, M. Beza, J. R. Svensson, and W. Liu, "Evaluation and comparison of small-signal characteristics of grid-forming converter systems in two different reference frames," IEEE Open Journal of Industry Applications, vol. 6, pp. 206–220, 2025, doi: 10.1109/OJIA.2025.3564501.

A. Toktarova, L. Göransson, and F. Johnsson, "Electrification of the energy-intensive basic materials industry – Implications for the European electricity system," International Journal of Hydrogen Energy, 2025, doi: 10.1016/j.ijhydene.2024.08.016.

B. Strugnell-Lees, E. Evdokimova, and T. Wik, "An entropy-based, self-adaptive predictive algorithm for battery degradation," Journal of Power Sources, vol. 656, p. 237920, 2025, doi: 10.1016/j.jpowsour.2025.237920.

C. Kimbrell, "Who delivers on the promise of community energy? Evaluating niche–regime interactions in Swedish energy communities," in Proc. ECPR General Conf., Thessaloniki, Greece, Aug. 26–29, 2025.

D. Kumar, K. Brijesh, K. Bindu, B. Ramzan, S. Kumar, and Z. Khan, "K–O batteries: Overcoming challenges and unlocking potential," EES Batteries, vol. 1, pp. 1083–1101, 2025.

J. Ullmark, L. Göransson, and F. Johnsson, "Representing net load variability in electricity system capacity expansion models accounting for challenging weather years," Energy, 2025, doi: 10.1016/j.energy.2024.134346.

M. Tariq, K. Ahmed, Z. Khan, and M. P. Sk, "Biomass-derived carbon dots: Sustainable solutions for advanced energy storage applications," Chemistry – An Asian Journal, vol. 20, p. e202500094, 2025.

N. Phan, H. Hellsmark, L. Göransson, and F. Johnsson, "Electrifying tensions: Stakeholder narratives to electrification of industry and transport in Sweden," Energy Research & Social Science, 2025, doi: 10.1016/j.erss.2025.104142.

R. Duvignau, V. Gulisano, M. Papatriantafilou, and R. Klasing, "Geographical peer matching for P2P energy sharing," IEEE Access, vol. 13, pp. 9718–9738, 2025.

R. Duvignau, N. Gillet, and R. Klasing, "Greediness is not always a vice: Efficient discovery algorithms for assignment problems," Discrete Applied Mathematics, vol. 378, pp. 65–86, 2026.

V. Jarlow, C. Stylianopoulos, and M. Papatriantafilou, "QPOPSS: Query and parallelism optimized space-saving for finding frequent stream elements," Journal of Parallel and Distributed Computing, vol. 204, 2025.

V. Joseph, R. Crispin, and Z. Khan, "Hard carbon from wood and its constituents: Toward sustainable sodium- and potassium-ion battery anodes," Renewable and Sustainable Energy Reviews, vol. 223, p. 116060, 2025.

V. Joseph, N. Kim, S. Y. Lee, R. Crispin, T. H. Park, and Z. Khan, "Water-in-salt hydrogel electrolyte for dendrite-free Zn deposition," Energy Advances, vol. 4, pp. 1167–1178, 2025.

V. Q. Ngo and M. Papatriantafilou, "CHK and the balancing act of maintaining heavy-hitters in stream processing," Proc. VLDB Endow., vol. 18, no. 9, 2025.

W. Liu, M. Bongiorno, A. Narula, and J. R. Svensson, "Grid impedance estimation during large SCR drop events with grid-forming converters," IEEE Transactions on Industrial Electronics, to be published.

Conference papers

A. R. Z. Babgohari, J. Wang, M. Beza, M. Bongiorno, A. Narula, and J. R. Svensson, "Understanding converter interactions using active and reactive characteristics: A comparison between grid-following and grid-forming control," in Proc. IEEE Energy Conversion Congress and Exposition (ECCE) Europe, UK, 2025.

C. Ge, R. Arvidsson, and B. Sandén, "Tracing global value chain transformation using customs data – A case study on lithium-ion battery-based energy storage systems," in Proc. 16th Int. Sustainability Transitions (IST) Conf., Lisbon, Portugal, Jun. 24–26, 2025.

D. Svensson, T. Hammarström, X. Xu, O. Hjortstam, and Y. V. Serdyuk, "Comparison of various types of electrodes for dielectric frequency response measurements on thin films," in Proc. IEEE Conf. on Electrical Insulation and Dielectric Phenomena (CEIDP), Manchester, UK, 2025.

E. Esenov, O. Hjortstam, Y. V. Serdyuk, T. Hammarström, C. Häger, and F. Pousaneh, "Inverse modeling of dielectric response in the time domain using physics-informed neural networks," in Proc. IEEE Conf. on Electrical Insulation and Dielectric Phenomena (CEIDP), Manchester, UK, Sep. 2025.

G. Appetito, V. Gulisano, and E. Medvet, "Automated discovery of CEP applications with evolutionary computing," in Proc. ACM Int. Conf. on Distributed Event-Based Systems (DEBS), Sweden, 2025.

H. Novljanin, C.-A. Ryeskog, and Y. V. Serdyuk, "Predicting water tree growth in polyethylene insulation using an FE model based on state variables," in Proc. IEEE Conf. on Electrical Insulation and Dielectric Phenomena (CEIDP), Manchester, UK, Sep. 2025.

J. Hao, X. Xu, T. Hammarström, Y. V. Serdyuk, and B. Sonerud, "Impact of shortened balancing intervals on HVDC mass-impregnated cables," in Proc. Jicable HVDC '25, Turin, Italy, Oct. 20–22, 2025.

J. Liu and V. Gulisano, "On-demand memory compression of stream aggregates through reinforcement learning," in Proc. ACM Int. Conf. on Performance Engineering (ICPE), Canada, 2025.

J. Wang, A.R.Z. Babgohari, M. Beza, M. Bongiorno, A. Narula, and J. R. Svensson, "A frequency-domain stability margin indicator for grid-connected converter systems," in Proc. IEEE Energy Conversion Congress and Exposition (ECCE), USA, 2025.

K. Kamalinejad, A. Narula, M. Bongiorno, M. Beza, and J. R. Svensson, "Impact of control parameters on angular stability of grid-forming converters using virtual-admittance-based control," in Proc. IEEE Energy Conversion Congress and Exposition (ECCE) Europe, Birmingham, United Kingdom, 2025, pp. 1–6, doi: 10.1109/ECCE-Europe62795.2025.11238912.

K. Kamalinejad, A. Narula, M. Bongiorno, M. Beza, and J. R. Svensson, "Impact of control parameters on angular stability of grid-forming converters using virtual-admittance-based control," in Proc. IEEE Energy Conversion Congress and Exposition (ECCE) Europe, UK, 2025.

K. Kamalinejad, S. Mohtat, and A. R. Zamani, "Comprehensive derivation of small-signal model for virtual-admittance-based grid-forming modular multilevel converters," in Proc. IEEE Energy Conversion Congress and Exposition (ECCE) Europe, Birmingham, United Kingdom, 2025, pp. 1–6, doi: 10.1109/ECCE-Europe62795.2025.11238501.

Kimbrell, C., Dubois, A., Lind, F., and Huang, L., "Understanding a key resource in a complex emerging network setting: The case of energy storage and balancing solutions," presented at the 41st Annual IMP Conf., Gothenburg, Sweden, Aug. 20–22, 2025.

L. Govik, C. Kimbrell, and F. Lind, "Batteries and sustainable business models – Collaboration in internal and external networks," in Proc. 37th Annual NOFOMA Conf., Copenhagen, Denmark, Jun. 10–12, 2025.

L. Govik, C. Kimbrell, and F. Lind,, "Sharing resources across boundaries: Cases of batteries and charging applications of a vehicle OEM," presented at the 41st Annual IMP Conf., Gothenburg, Sweden, Aug. 20–22, 2025.

L. Magnusson, R. Thorsson, V. Q. Ngo, M. Papatriantafilou, J. van Rooij, and M. Chigrichenko, "CLUE – Cluster-based load understanding and exploration: Summarizing high-dimensional electricity grid data for scenario analysis," in Proc. Workshop on Relaxed Semantics in Data Analytics Pipelines, co-located with the ACM Int. Conf. on Distributed Event-Based Systems (DEBS), Sweden, 2025.

M. Hilgendorf and M. Papatriantafilou, "LMQ-Sketch: Lagom multi-query sketch for high-rate online analytics," in Proc. 39th Int. Symp. on Distributed Computing (EATCS DISC), Germany, 2025.

M. Ahouad, A. Sunjaq, E. Wikner and T. Thiringer, "Economic Assessment of Battery Energy Storage for Frequency Regulation in the Nordic Power Systems," 2024 20th International Conference on the European Energy Market (EEM), Istanbul, Turkiye, 2024, pp. 1-5, doi: 10.1109/EEM60825.2024.10608974

R. Duvignau, V. Gulisano, and M. Papatriantafilou, "PyPESOL: The Python P2P energy sharing optimization library," in Proc. 16th ACM Int. Conf. on Future and Sustainable Energy Systems (e-Energy '25), ACM, Netherlands, 2025.

T. S. Andrade, T. Thiringer and M. Ahouad, "Plug-in fuel cell electric vehicles: Are they more cost-efficient than battery electric vehicles?," 2023 IEEE PES 15th Asia-Pacific Power and Energy Engineering Conference (APPEEC), Chiang Mai, Thailand, 2023, pp. 1-6, doi: 10.1109/APPEEC57400.2023.10561968

W. Liu, A. Narula, M. Bongiorno, and J.R. Svensson, "Grid impedance estimation with large SCR disturbances based on grid-forming converters," in Proc. 26th European Conf. on Power Electronics and Applications, France, Mar. 2025.

Y. V. Serdyuk and T. Hammarström, "Water tree growth in XLPE polymeric insulation induced by various types of defects," in Proc. IEEE Conf. on Electrical Insulation and Dielectric Phenomena (CEIDP), Manchester, UK, Sep. 2025..

Reports

Our code library PyPESOL The Python P2P Energy Sharing Optimization Library (https://github.com/dcs-chalmers/pypesol) has been published on the ACM SIGENERGY portal: https://energy.acm.org/resources/

Data analysis open-source software CLUE : https://github.com/rasmusthorsson/CLUE "CLUE -- Clustering-Based Load Understanding and Exploration", to enable to identify meaningful consumption profiles, detect anomalies, and interactive exploration of complex temporal consumer patterns

Data analysis open-source software for parallel and streaming data summarization of outliers/most frequent data-element instances in high-rate/high-volume data: CHK and the balancing act of maintaining heavy hitters in stream processing https://zenodo.org/records/15593109

Stenberg, V., Lind, F. Kimbrell, C. & Dubois, A. Business models for electricity storage and balancing solutions: Draft report, 2025

D. Svensson, "State of the Art of Metallized Film Capacitors for High-Voltage Applications," PhD midterm seminar, Chalmers University of Technology, May 2025.

Bachelor & Master theses

D. van Calck, "Exploring the Use of Batteries to Permit Connection of New DSO Customers", MSc degree project supervised by O. Samuelsson, Lund University and E. Blomgren, Göteborg Energi.

E. Larsson, J. Ngo, Finding Needles in the Haystack. A CEP Approach to Detect Recurring Grid Issues. Master thesis in collaboration with Göteborg Energi (https://odr.chalmers.se/items/cbba431d-7e07-4c36-abac-78c73bd77582, Vincenzo Gulisano)

H. Ekeroth, H. Karlsson, Jakob Lindberg, Noah Lindow, Kerim Mahmutovic, Ella Sander, "Dimensionering av laddningsdepå för tunga elektrifierade fordon", 2025, Supervisors, Meryem Ahouad, Torbjörn Thiringer

L. Magnusson and R. Thorsson. CLUE – Cluster-based Load Understanding and Exploration: Summarizing High-Dimensional Electricity Grid Data for Scenario Analysis. Master thesis. Göteborg University, Sweden. https://gupea.ub.gu.se/handle/2077/89783 (Co-supervisors: V. Quang Ngo, M. Papatriantafilou from Chalmers University of Technology, J. van Rooij, M. Chigrichenko from Göteborg Energy)

T. Vaibhav, P. Nadia. Event Detection in Smart Meter Data with Complex Event Processing. Master thesis in collaboration with Göteborg Energi (https://odr.chalmers.se/items/0330d18d-1815-4be7-987c-8a7518100b42, Vincenzo Gulisano)

S. Lian, "Kapacitetsallokering för batterilager som levererar snabba reserver", 2025. MSc degree project supervised by O. Samuelsson, Lund University and K. Linnanheimo, Svenska Kraftnät.

Publications from affiliated projects

W. Liu, M. Bongiorno, A. Narula, J. R. Svensson, Grid Impedance Estimation during Large SCR Drop Events with Grid-Forming Converters, 2025-12-16, IEEE Transactions on Industrial Electronics, 10.1109/TIE.2026.3661054

Patents and first filings from affiliated activities

W. Liu, M. Bongiorno, J. R. Svensson, and J.-P. Hasler, "Method and control device for impedance estimation of an electrical power network," first filing, P240362EP01, 2025

W. Liu, M. Bongiorno, J. R. Svensson, and J.-P. Hasler, "Control device and method for active power control in grid-forming converter," first filing, P240268EP01, 2025

M. Bongiorno, J. R. Svensson, and J.-P. Hasler, "Control device for grid-forming control, power supporting system, and method," first filing, P240133EP01, 2025.

Y. Khayat, R. Heydari, J.-P. Hasler, and M. Bongiorno, "Method implemented in a grid forming control system, a grid forming control system and electrical power network system," first filing, P240186EP01, 2025.

Publications under review 2025

Journal papers

C. Ge, A. Nordelöf, and B. Sandén, "Monitoring long-term trends of spatial and temporal flexibility in electricity systems," Energy Conversion and Management: X, under review, 2025.

C. Ge, R. Arvidsson, and B. Sandén, "Tracing global value chain transformation using customs data with a case study on lithium-ion battery energy storage systems," Environmental Innovation and Societal Transitions, under review, 2026.

D. Schulz, M. Ringström, S. R. Sankar, and A. Martinelli, "Role of native binder in controlling the PTFE distribution in gas diffusion layers for PEM fuel cells," International Journal of Hydrogen Energy, submitted Oct. 2025.

D. Schulz, X. Wen, B. Pennincks, S. Sasidharan, L. Strandberg, F. Wenger, and A. Martinelli, "Large area PEM electrolyzer anodes with low iridium loading on carbon nanofibers with stable structures during assembly/disassembly and operation," manuscript in preparation.

E. Esenov, O. Hjortstam, Y. V. Serdyuk, C. Häger, and T. Hammarström, "A physics-informed neural network approach to Debye modeling of dielectric response data," IEEE Transactions on Dielectrics and Electrical Insulation, to be submitted, 2025.

J. Wang, M. Beza, M. Bongiorno, A. Narula, and J. R. Svensson, "Revisiting grid-forming and grid-following converter stability: A subsystem interaction perspective," in Proc. Int. Power Electronics Conf. (IPEC), Japan, 2026.

K. Kamalinejad, A. Narula, M. Beza, M. Bongiorno, L. Stojanovic, and J. R. Svensson, "Impact of control and system parameters on transient stability in multi-converter systems: Insights from quasi-static modeling," in Proc. Power Systems Computation Conf. (PSCC), 2026; extended version submitted to Electric Power Systems Research.

K. Kamalinejad, A. Narula, M. Bongiorno, M. Beza, and J. R. Svensson, "A frequency-domain study of damping and synchronizing characteristics of virtual admittance-based grid-forming converters," International Journal of Electrical Power and Energy Systems, submitted.

K. Kamalinejad, A. Narula, L. Stojanovic, M. Beza, M. Bongiorno, and J. R. Svensson, "Impact of control and system parameters on transient stability in multi-converter systems: Insights from quasi-static modeling," Electric Power Systems Research, submitted.

L. Figueras Llerins, M. Bongiorno, P. Chen, and J. R. Svensson, "Computation of feasible operation region of distribution grids with power-electronic devices," in Proc. Power Systems Computation Conf., Cyprus, 2026.

L. Stojanovic, A. R. Zamani, A. Narula, P. Mattavelli, M. Bongiorno, M. Beza, and J. R. Svensson, "Aggregation of power response matrices for system-level analysis in converter-dominated power systems," Electric Power Systems Research, submitted.

L. Stojanovic, A. Narula, P. Mattavelli, M. Bongiorno, and J. R. Svensson, "Power-response matrix framework: Intuitive frequency-domain analysis of offshore wind farms," in Proc. Int. Power Electronics Conf. (IPEC), Japan, 2026.

P. Imgart, A. Narula, M. Bongiorno, M. Beza, J. R. Svensson, J.-P. H. Hasler, and P. Mattavelli, "Decoupled PQ grid-forming control with tunable converter frequency behaviour," IEEE Open Journal of Industry Applications, submitted.

Conference papers

D. Svensson, T. Hammarström, X. Xu, Y. V. Serdyuk, O. Hjortstam, "Development of a Setup for High-Field Dielectric Frequency Response Characterization," IEEE Transactions on Dielectrics and Electrical Insulation, 2025.

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