
2024
ANNUAL
REPORT
CATELLA
Swedish
Electricity Storage
and Balancing Centre

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and Balancing Centre

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Annual report 2024

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https://www.sesbc.se

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CONTENTS

SESBC IS GROWING

2024 has been an intense year for SESBC, with a number of exciting activities and the addition of E.ON as a new partner. We have been visible, both at national and international level, and received several requests for new collaborations.

I am very glad to see how all partners are continuously strengthening the centre. Some have even decided to increase their financial support; this shows that we are on the right path and is a validation of the importance of our research areas.

A highlight for me during the year has been seeing so many people at our centre conference in Lund, and the fantastic poster session, with a room full of students happy to show their results. There has been a stark contrast from our first conference, where we had a rather small room looking a bit empty. Overall, there are now many ongoing activities, and I feel that there is a lot of positive energy and engagement in the team. Everyone is eager to discuss and learn from each other. It is of outmost importance to keep stimulating the dialogue between industry and academia. There are a lot of good examples in this direction, like the establishment of the Industry Forum, but we can do even more in the future.

We are a very ambitious centre taking a holistic approach to very important and challenging questions, and that takes some time to build up. I feel that we are on a good trajectory, but we need to stay focused and not forget to analyse what we can do better in preparation for a second stage.

Thank you all for your hard work during 2024!

Massimo Bongiorno
Director

A hub for competence development in system flexibility

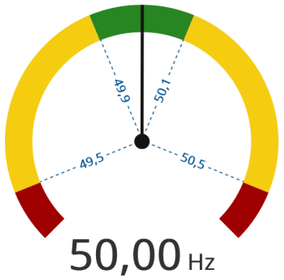
Swedish Electricity Storage and Balancing Centre (SESBC) is a key enabler for reaching the 100% renewable system through the establishment of a cross-disciplinary and internationally competitive Swedish hub for excellence in research and industrial collaboration, as well as providing recommendations, 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 over-arching 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. 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. 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. 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 function.
6. mFRR – manual frequency restoration function.

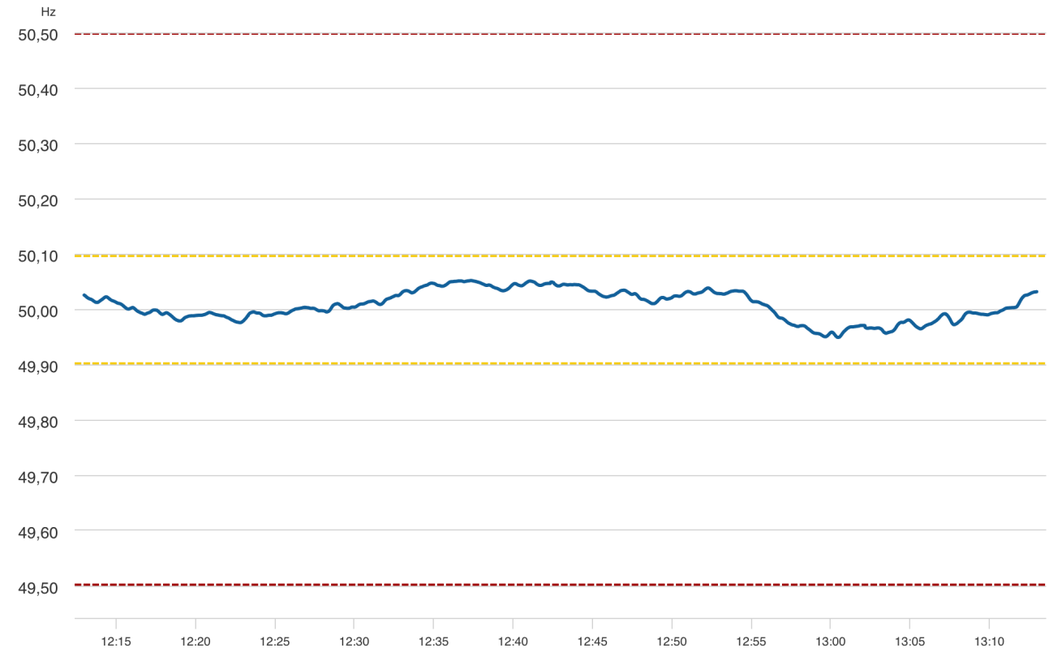
REACTIVE POWER

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 SVCs, reactors (with or without tap-changers), capacitors.
3. Series devices, like series capacitors, controllable or non-controllable.
4. Synchronous condensers and FACTS devices, like 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 HVDC links. The image above is taken 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.

VIEWS FROM THE CHAIR

We got the opportunity to ask SESBC's program council chair Niklas Thulin a few questions about himself, and his views on the centre.

Niklas, what is your background?

"I was born and raised in Småland and moved to Gothenburg to study mechanical engineering at Chalmers University, where I also earned a licentiate degree in chemistry with a focus on composite materials. After completing my licentiate, I was a consultant in the automotive industry until I joined Volvo Powertrain in 2004. Rather quickly I was lured into the field of electrification and alternative drivetrains. The electrification community was rather small back in the day, and it felt like I knew almost all the PhD students and researchers in Sweden active in this area. After a few years at Volvo Penta, which included our first steps in battery energy storage solutions and 2nd life, I moved to Volvo Energy in 2022, where I now work alongside over 120 colleagues. As Head of Battery Energy Storage System product offer my main responsibilities are to plan, define and initiate future products, services and business models."

What is your involvement in SESBC?

"I have been involved already from the beginning, both as project representative and as Volvo's program council member. Since this summer I was also appointed chair of the program council. I try to engage as much as possible operationally in the research projects we are supporting from Volvo. These interactions are usually both energizing and educational."

Can you describe Volvo Energy's Interest in SESBC?

"Volvo Energy has the purpose to accelerate electrification and drive circularity. We have several responsibilities in the Volvo Group including securing infrastructure required for zero-emission vehicles (charging and hydrogen), battery circularity (refurbishing, repurposing and recycling) and battery energy storage systems (BESS).

As the vehicle industry transitions, the dependency on the grid and the power system increases significantly. Charging is mostly seen as problem for the grid, but I am confident that chargers and vehicles also can play an important role in providing storage, balancing and flexibility.

We're eager to contribute our perspective to SESBC and support building knowledge, while learning from other actors in the ecosystem. Enabling the energy infrastructure for electric trucks and machines is not something we can do alone. This collaboration helps us expand our network, gives us visibility while also identifying future potential employees and specialists."

What opportunities and challenges do you see for SESBC?

"The major strength of SESBC is bringing together grid ecosystem organizations of different size, maturity, knowledge and roles. However, managing this diversity of perspectives and interests can be difficult and it is important to also ensure necessary competition and business confidentiality. Expectations on time frames can also be a challenge. Industry typically seeks answers here and now while academia usually has the luxury of longer time horizons."

What expectations do you and Volvo have from the SESBC collaboration?

"Bringing a behind-the-meter perspective I am personally eager to learn more about the larger grid functionality and its dependencies. I'm also curious about storage solutions beyond lithium-ion and how distributed resources in society can be better utilized.

From Volvo we expect to gain practical outcomes from the projects, like battery lifetime modelling, that can be integrated into our projects and business. We also anticipate seeing commercial partnerships emerge through collaborations within the centre and hope to bring PhD students into our organization.

For SESBC, I hope the centre will establish itself as a key platform in the ecosystem, fostering new collaborations also with international centres and actors. For example, in the US a new national R&D centre dedicated to grid energy storage was recently launched."

If you look into the future - what would be the optimal outcome?

"Ultimately the portfolio of projects in the centre will contribute to incorporating more affordable renewable energy in the Swedish grid. I also hope to see that research and collaboration in SESBC have created new business opportunities and supported scaling of some of the smaller companies involved in the centre. Having established more international knowledge sharing and relationships would in my book also be a successful outcome."

Niklas Thulin Head of Battery Energy Storage System at Volvo Energy, and Chair of SESBC program council.

How would you like the Industry Forum to function?

"I believe the forum has an important role in highlighting and framing current challenges and gaps seen by the industry partners. Pollinating these with academic interests will support the collaboration in the centre and stimulate innovation. I also hope that the forum members will act as SESBC ambassadors within their own networks, attracting new partners to the centre."

Finally, can you share any none-work related triva about yourself?

"Outside of work, I have a house and garden from the seventies and two teenagers at home, which currently leaves little time for hobbies. I do enjoy photography a lot and have even had some exhibitions. A fun fact is that one of my electron microscopy images from my research was featured on the cover of the Journal of Materials and Science. It was a great feeling holding that in my hands, when papers were still on paper."

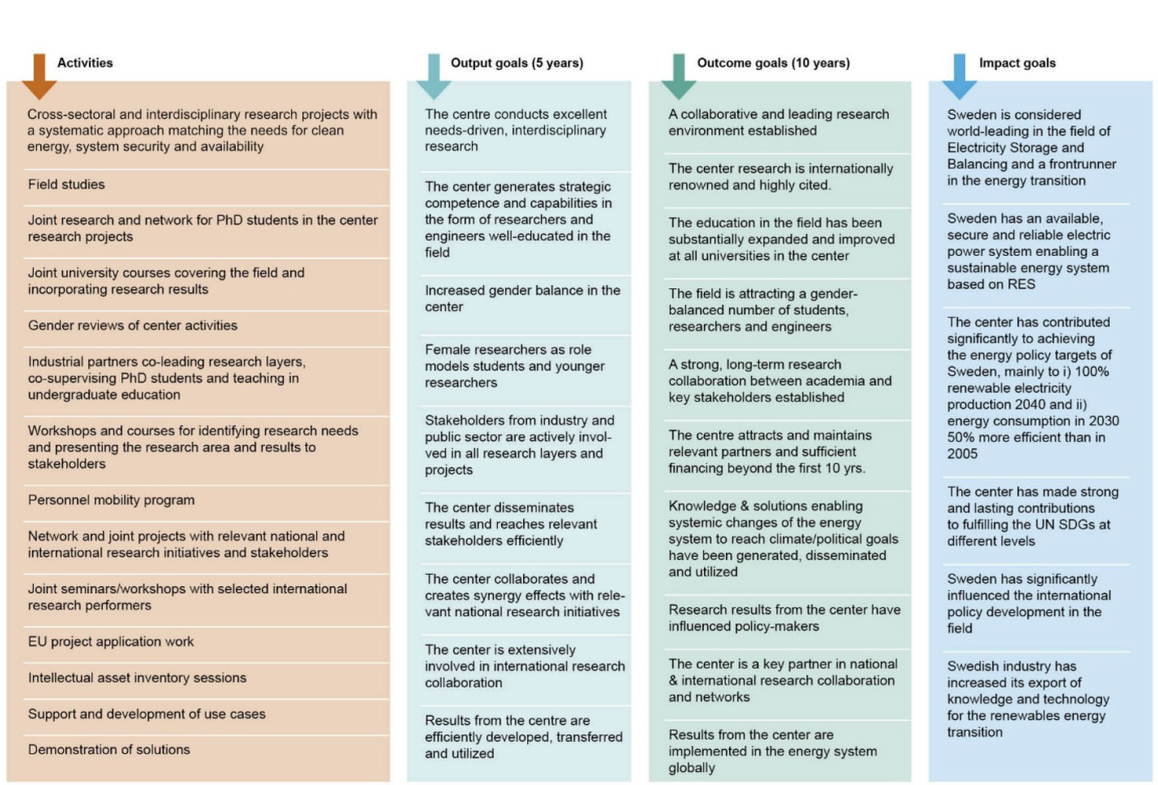
GOALS

SESBC is in its third year and we continue the work to further enhance the centre as a competent, collaborating and inspirational research community. Here, the many successful activities during 2024 and the previous years play an important part.

Activities
The foundation of the centre lies in the development and conduction of research projects, where there have been many activities during the last year. Several reference group meetings have taken place, playing an important part in creating a cross-sectoral research environment. The Industry Forum initiative has been launched during the year as a meeting place for non-academic partners. The PhD students network has taken off with the first summer school and network workshop, and the industry has been actively involved in the PhD students' progression. Additionally, SESBC has organized workshops and courses to identify research needs and presented findings to stakeholders. During the year, SESBC has also initiated a review to evaluate diversity and inclusivity within the centre.

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 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

SESBC continuously monitors all key performance indicators (KPIs). Since the centre started in 2022, many targets, such as number of PhD theses and publications, are expected to be fulfilled in the later years of the first stage of the centre.

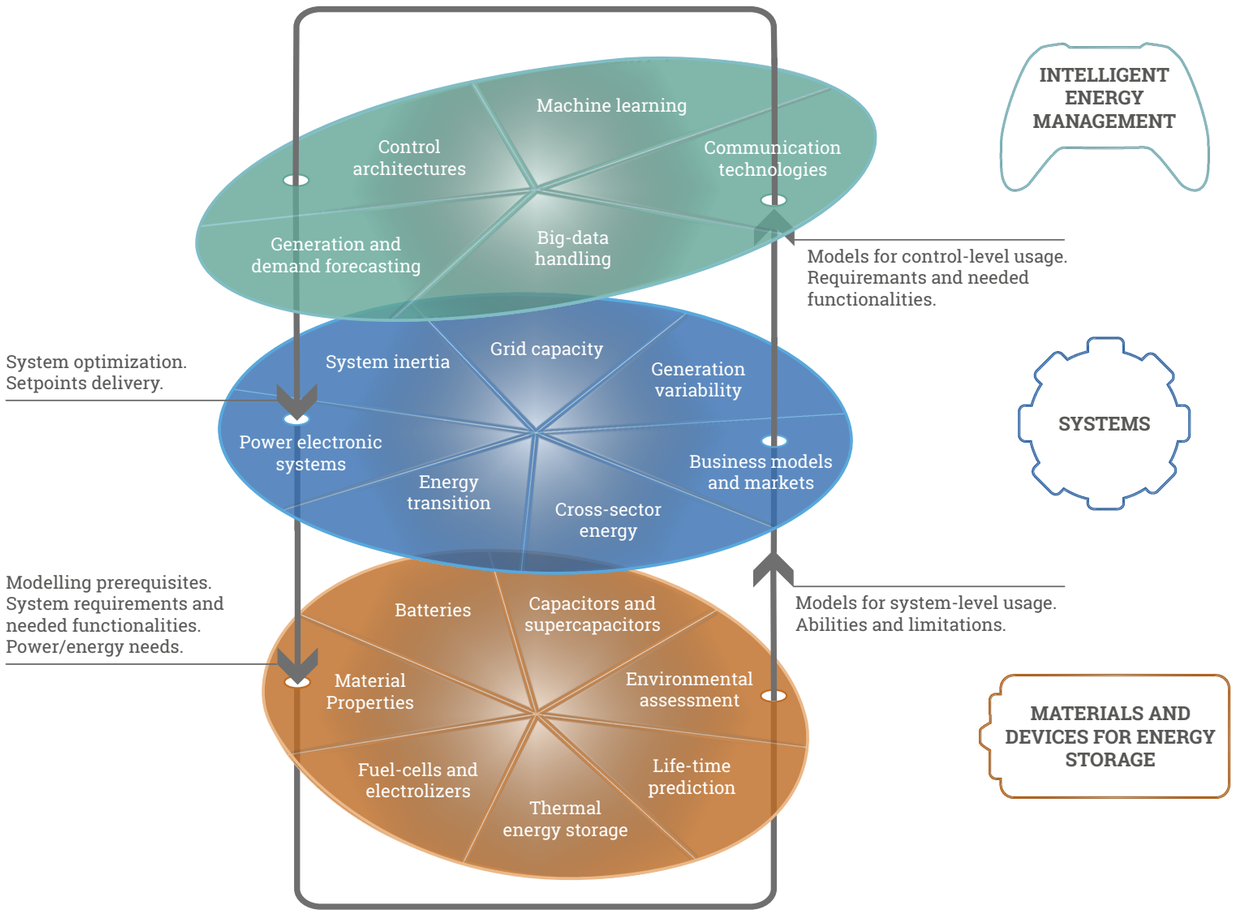
In 2024, the centre could see most of the granted project up and running, and publishing results in highly-ranked international conferences and journals.. The centre has hosted several workshops, seminars and courses, which means that some KPIs have already been fulfilled. The goal for gender balance is unfortunately moving in the wrong direction. The numbers shown in the table below, is related to the gender balance ratio for the overall centre. When it comes to the Centre Management, there is a 57/43% division between the women and men. For the Programme Council the same division is 47/53%. This indicates that a good gender balance in the leading roles for the centre has been achieved. On the other hand, only 27% of the active researchers are women and for the industry representatives, only 22% are women. For the KPIs in the section Increased utilization of research results and competence, the centre is planning activities for later since more results will need to come from the projects before they can be started.

Summary of SESBC key-performance indicators

Results (Output goals)	Metrics (Key performance indicator)	5-yr target	2022-2024
World-leading knowledge and competence			
Excellent needs-driven, interdisciplinary research	# peer-reviewed publications in high-impact journals	60	10
	# conference presentations	60	12
	# conference keynote presentations	10	
	# 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	19
	# graduate & undergraduate courses by the centre	8	0
	# students participating in the courses	10	0
Increased gender balance in centre	Gender balance ratio in centre projects & management	+20%	-13%
Strong national and international collaboration			
Stakeholders are actively involved in all centre activities	# industry partners per centre project	5	4,6
	# new academic-public-private collaborations	18	14
	# peer-reviewed co-publications between partners	10	0
Results reach stakeholders efficiently	# persons in centre program for personnel mobility	20	0
	# workshops with relevant national stakeholders	24	2
	# follow-on projects (triggered by centre results) that were initiated by non-academic stakeholders	10	0
	# courses & seminars for staff from industry	8	20
	# attendees at the courses & the seminars	200	540
Collaboration with relevant national research initiatives	# joint activities/projects with relevant national research initiatives	4	0
	# centre projects granted funding from other sources	12	0
Extensive international collaboration	# workshops/seminars with international partners	16	5
	# international attendees at the workshops/seminars	300	50
	# international partners in centre projects	10	0
	# projects with international partners	10	0
Increased utilization of research results and competence			
Results are efficiently developed, transferred and utilized	# intellectual asset inventory sessions	9	0
	# intellectual assets created	18	0
	# workshops for use case development	9	0
	# demonstration projects performed	9	1

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

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
- Design of the next generation of slurry flow cells for electrical energy storage
- New bio-gel electrolytes for Zn-lignin batteries
- 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

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 battery energy storage systems (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.

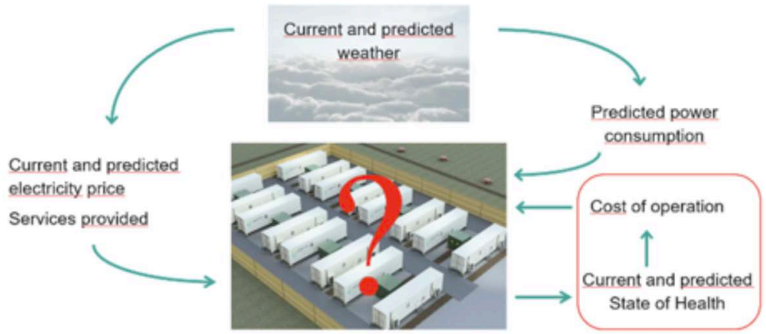
Involved in the project

Torsten Wik, Benedick Lees

Partners

Chalmers, Volvo Energy, Repono, Swedish Energy Agency

INTELLIGENT ENERGY MANAGEMENT



PROJECT RESULTS 2024

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.

This algorithm has been tested over three different battery cell types with three different battery chemistries, and different cycling parameters, and has yielded highly accurate results with all datasets. Moreover, this model has the capacity to generate additional, more educated, guesses after additional cycles in a given batteries life, enabling it to run in real-time alongside the battery during operation. Moreover, based on the current research, it is highly likely that this algorithm will be able to generalize well over (in theory) any type of battery energy system, making it highly adaptable and very useful for any institution or facility that may not have exact information on the performance data of received second-hand batteries. Currently, a version of this algorithm is being implemented in a larger series of datasets, which will facilitate additional functionality and offer additional insights.

Perhaps more importantly than the algorithm itself though, is the developed methodology from this research: the findings from this research would indicate that it is possible to use entropic features to a predictive metric for physical system degradation. Assuming this to be true (pending additional research) it may be possible to characterize the degradation of not only battery systems, but also other energy storage systems such as capacitors, using entropic characteristics and system data.

At present, this algorithm is being modified and applied to more extensive datasets, not previously available, with the aim of developing more accurate predictions, developing a more advanced understanding of the best predictive characteristics to use for evaluation of energy storage systems, and developing a more sufficient ability to self-adapt over time. From this, it should be possible to determine the optimal usage parameters, and real-time lifespan, for various second-life batteries and potentially additionally energy storage systems.

Publications 2024

No publications during 2024

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.

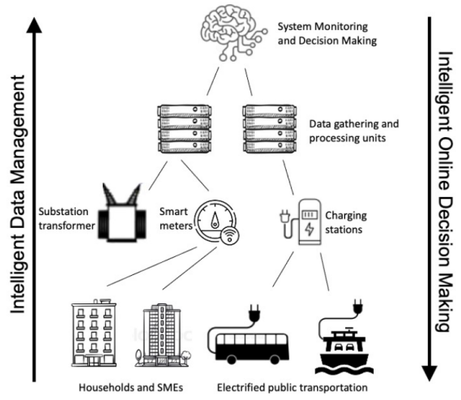
This includes online monitoring to identify bottlenecks, improved forecasting methods for flexibility needs, and economic control applications to optimize flexibility orders. Supported by over a decade of collaboration among academic and industrial experts, TANDEM aims to facilitate informed decision-making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

INTELLIGENT ENERGY MANAGEMENT

PROJECT RESULTS 2024

This year, research within the project focused on areas closely aligned with its objectives. One key area of investigation was online decision-making processes aimed at efficiently utilizing renewable resources and managing energy data.

In particular, the concept of Optimization as a Service is being explored, to address the design and implementation challenges of creating a scalable framework that can handle increasing volumes of optimization problems effectively.

Another area of focus was Geographical Peer Matching for Peer-to-Peer (P2P) Energy Sharing. The research examined challenges such as matching geographically distributed peers and the computational effort required to determine efficient local matches. A variety of approaches were proposed and analyzed, both theoretically and empirically, to achieve cost-effective and computationally efficient peer matching. These efforts represent important progress in the project's goals and contribute to ongoing advancements in energy optimization and resource management.

Further topics of investigation in the streamline, focus on data summarization as a means of “distilled” information. This can be extracted through monitoring in varying time-space granularity; the outcomes are expected to facilitate further analysis and investigation, associated with lowering peaks, dynamic tariffs, adaptive charging schedules, and flexible contracts. This activity is in synergies with the VR project EPITOME and the MSCA EU action RELAX-DN

Publications 2024

Journal papers

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V. Gulisano, A. Margara, “Aggregates are all you need (to bridge stream processing and Complex Event Recognition),” The 18th ACM International Conference on Distributed Event-Based Systems (DEBS 2024). https://doi.org/10.1145/3629104.3666032

Vincenzo Gulisano, Alessandro Margara, Marina Papatriantafilou. “On the Semantic Overlap of Operators in Stream Processing Engines,” ACM/IFIP International Middleware Conference. 2024. https://doi.org/10.1145/3652892.3654790

B. Havers, M. Papatriantafilou and V. Gulisano. “Research Summary: Enhancing Localization, Selection, and Processing of Data in Vehicular Cyber-Physical Systems. Advanced tools, programming languages, and PLatforms for Implementing and Evaluating algorithms for Distributed systems, (ApPLIED), in conjunction with PODC,” 2024, https://doi.org/10.1145/3663338.3663680

B. Havers, M. Papatriantafilou, V. Gulisano, “Nona: A Framework for Elastic Stream Processing,” 44th IEEE International Conference on Distributed Computing Systems (ICDCS), 2024, https://doi.org/10.1109/ICDCS60910.2024.00071

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V. Q. Ngo, M. Papatriantafilou, “Cuckoo Heavy Keeper and the balancing act of maintaining heavy-hitters in stream processing,” CoRR abs/2412.12873, 2024, https://doi.org/10.48550/arXiv.2412.12873

V. Jarlow, C. Stylianopoulos, M. Papatriantafilou, “QPOPSS: Query and Parallelism Optimized Space-Saving for Finding Frequent Stream Elements”, 2024, doi: arXiv preprint arXiv:2409.01749, https://doi.org/10.48550/arXiv.2409.01749

Bachelor & Master theses

M. Scaccabarozzi [in collaboration with Göteborg Energi] “Empirical Assessment of Energy Consumption Forecast Techniques for Monitoring Systems,” 2024.

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J. Liu, V. Gulisano, “On-demand Memory Compression of Stream Aggregates through Reinforcement Learning,” ACM/SPEC ICPE 2025.

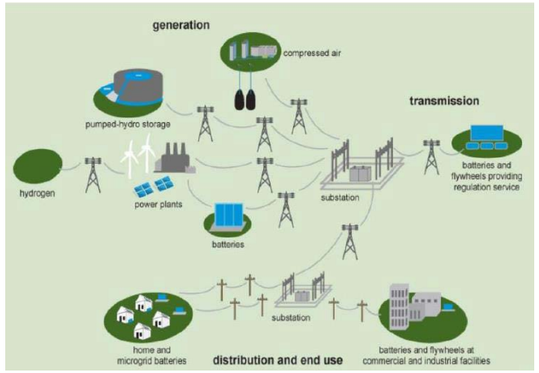
STORAGE AND FLEXIBILITY FOR ENHANCEMENT OF GRID CAPACITY

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

INTELLIGENT ENERGY MANAGEMENT

PROJECT RESULTS 2024

We are developing advanced statistical models for optimal sizing of energy storage systems to balance power mismatches effectively.

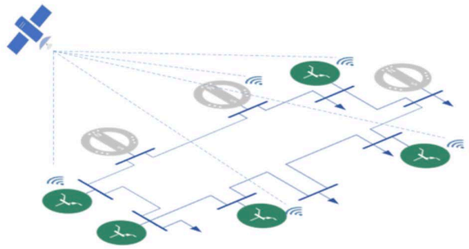
To ensure real-world applicability, we analyze and validate our approach using historical data from actual case studies, specifically targeting variability in renewable energy production (particularly wind and solar power) and electricity consumption patterns within Swedish bidding zones (SE1, SE2, SE3, SE4), while also exploring various future scenarios. Utilizing simulation-based analyses and cumulative mismatch curve approaches, our research will provide robust tools for optimizing the sizing of energy storage solutions essential for grid balancing.

Publications 2024

No publications during 2024

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 CO2 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

INTELLIGENT ENERGY MANAGEMENT

PROJECT RESULTS 2024

The project's focus in this stage has been on both the damping and synchronizing properties of a grid-forming converter connected to an AC grid.

For this, a simple grid as the one illustrated in Fig. 1 has been considered. Particularly, studies have been conducted aiming at identifying how different parameters in a grid-forming control structure impact the damping power at different frequency regions.
As an example, the following figure presents the impact of virtual inductance and resistance, key components of the virtual-admittance based grid-forming strategy, on the damping properties of the studied system.

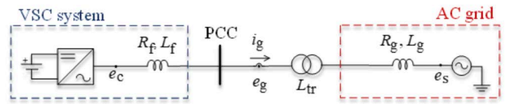


Fig. 1: A grid-forming converter connected to the AC grid.

Moreover, the impact of control parameters and the dynamics of the grid-forming converter on synchronizing properties has been investigated. To achieve this, a torsional spring-mass-damper model has been developed as an analogy to the electrical system. Then, the linearized model of the electrical system has been derived for the analysis, as shown in Fig. 3. Finally, the project has analyzed synchronizing stability under angular disturbances, such as a phase jump in the AC grid, to evaluate the system's response and stability characteristics.

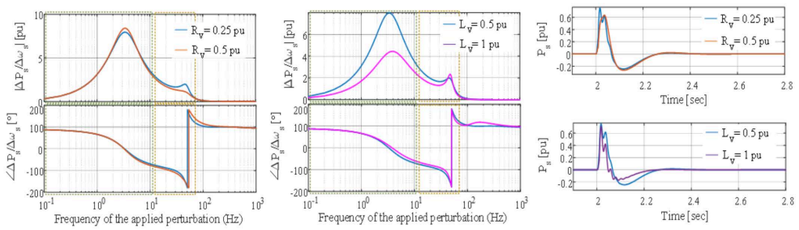


Fig. 2: Impact on virtual impedance on damping properties of the studied system from frequency and time-domain results

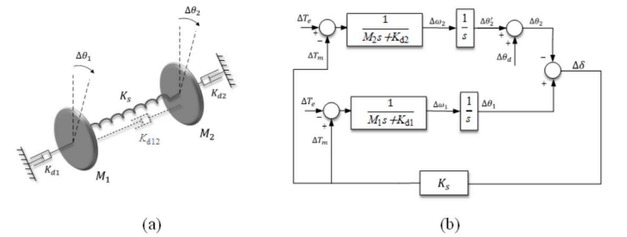


Fig. 3: (a) Torsional spring-mass-damper system. (b) Linearized block diagram of system.

Publications 2024

Conference papers

K. Kamalinejad, A. Narula, M. Bongiorno, M. Beza and J. R. Svensson, "Investigation of Control Parameters' Impact on Damping Property of Grid-Forming Converters," 2024 IEEE Energy Conversion Congress and Exposition (ECCE)

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

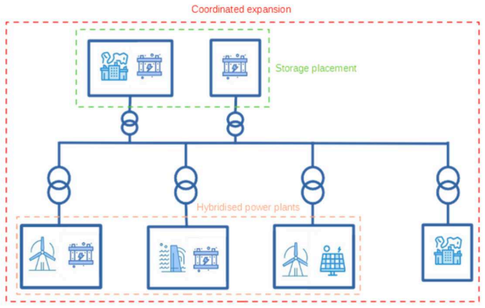
Sweden aims for an electric power system with net zero-carbon emissions. Common for such electricity systems is that they will consist of high shares of renewable energy sources, up to 100% of the total power production. The variation in renewable generation creates a substantial need for balancing and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



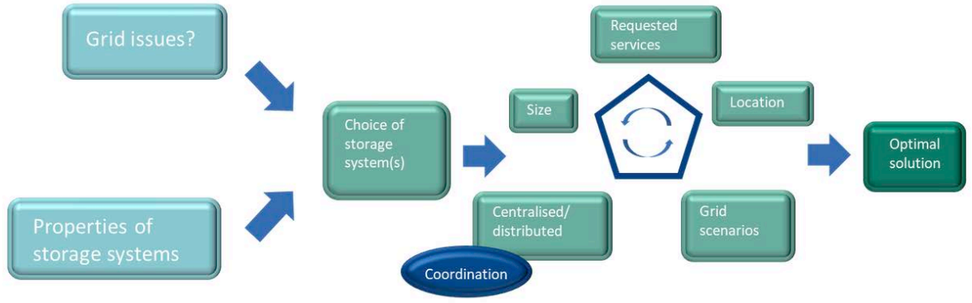
Lund University will focus on how the capacity developments of V-RES, new consumption (mainly electrolysis), electricity storage (mainly batteries) and grid affect each other. Optimization will be used to find feasible combinations, but in contrast to presenting scenarios for certain years like 2035 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:

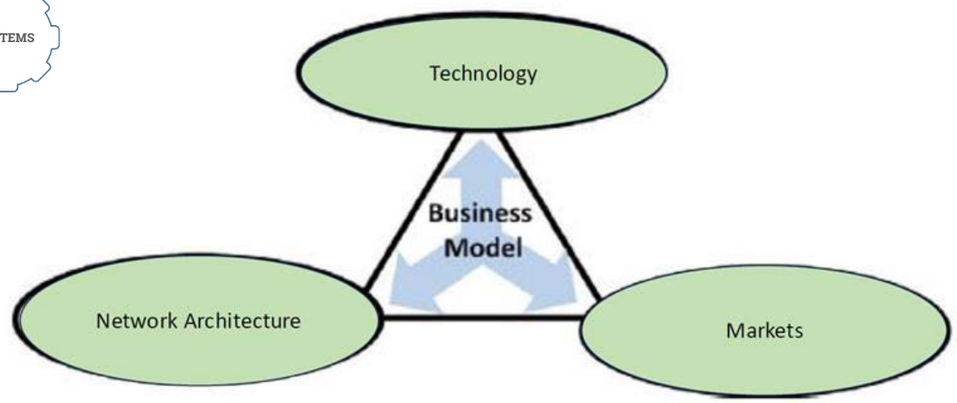
PROJECT RESULTS 2024

The PhD student in Chalmers' part of the project is working 50% of her time on the project. During 2024, a literature review has been done.

The review looked at different types of storage systems and their properties as well as challenges for the distribution grid with more distributed power generation. The most important properties of storage systems were power, energy, lifetime, activation time, number of cycles and efficiency, and the study therefore focussed on this. For the challenges for the distribution network, the following were highlighted: generation-load balancing, bottlenecks in transmission, hosting capacity, voltage variations, other power quality issue and protection issues. In addition to the literature review, a model of the medium voltage grid in the Cigre benchmark model has been setup in the software Power Factory. The model has been adapted with one part for residential and commercial and another part for industrial, instead of one part for rural area.

Publications 2024

No publications during 2024



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 2024

The results from this year from our project are mainly connected to data collection gaining an understanding of energy storage, involved actors, technologies and starting to sketch opportunities for business models. In greater detail, we are working with the following 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? To answer this question, we analyse current and emerging business models around the respective Energy Storage and Balancing Solutions (ES&BS) technologies in the Swedish electricity system. Tackling the issues involved in ES&BS not only requires a focus on technological solutions but also concerns how various actors develop their businesses through new and existing business relationships and how those organizations collaborate to support technological development and implementation.

2) How are values created through the interaction of ES&BS resources and how can these values be conceptualised in terms of how they are distributed across actors whose resources are combined? As mentioned above, a variety of both public and private actors, from producers and consumers to system and market operators, are involved in the electricity system. Thus, the relationships of interest involve business-to-business, business-to-consumer as well as public–private interactions mediated through their respective resources. The values captured through these interactions will vary depending on the actors involved, the technology interface in question, and the position in the grid.

Publications 2024

Conference papers

C. Kimbrell, F. Lind & A. Dubois, "At the transport and energy interface. Swedish transportation research conference (STRC)," Chalmers, 16-17 October, 2024

Publications under review 2024

Conference papers

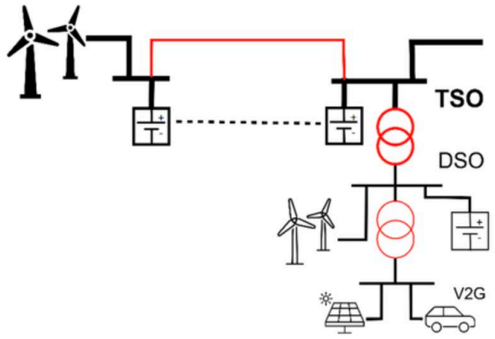
C. Kimbrell, "Who delivers on the promise of community energy? Evaluating niche–regime interactions in Swedish energy communities," submitted to ECPR General Conference, 26-29 August, 2025

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," submitted to the IMP Conference, 20-22 August, 2025

L. Govik, C. Kimbrell, & F. Lind, "Sharing resources across boundaries: Cases of batteries and charging applications of a Vehicle OEM," submitted to the IMP Conference, 20-22 August, 2025

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.



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

Martin Lundberg, Olof Samuelsson, Emil Hillberg

Partners

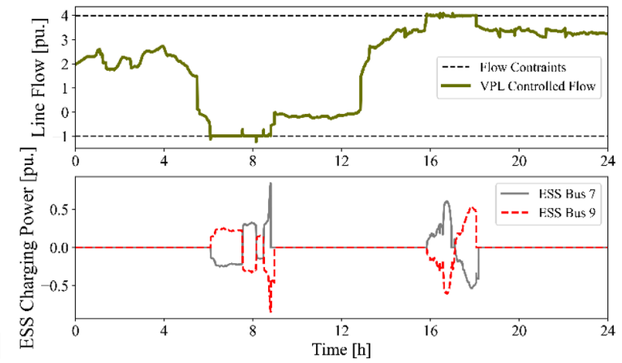
Lund University, Chalmers, DNV, Göteborg Energi, Hitachi Energy, Svenska kraftnät, Vattenfall Eldistribution, Volvo Energy, Swedish Energy Agency

SYSTEMS

PROJECT RESULTS 2024

During 2024, the project has focused on research on Virtual Power Lines (VPLs). Based on the initial simulations in an SESBC MSc degree project, PhD student Martin Lundberg has worked on modelling and simulation of one and two VPL.

The developed analytical dynamic VPL model is applicable to any type of energy storage and includes all relevant parameters such as losses during charging and discharging but also idling losses. The methodology is based on power flow calculations and uses sensitivities such as Power Transfer Distribution Factors that are central to the ENTSO-E Flow-Based Capacity Allocation methodology. Results have been obtained for several use cases:



- Excessive flows through a single transmission line. This is illustrated in the figure, where the flow is controlled to respect the flow constraints, that here are different in the two directions, see upper graph. The lower graph shows the charging and discharging of the energy storages at the two ends of the line.
- Control of total flow in a transmission corridor with multiple transmission lines.
- Keeping line flows within temporary limits during N-1 events.

Two important observations are:

- When the VPL is sized and controlled to avoid overloading one line in a power transfer corridor, the other lines can take on more load. The increase in transfer capacity through the corridor is then several times greater than the increase in the controlled line.
- The N-1 state is particularly interesting as the VPL needs to be sized only for the N-1 situation, which has a time limit of 15 minutes, while it provides increased transfer capacity in the normal state.

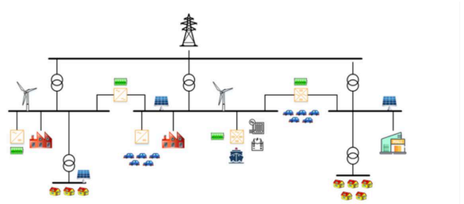
Publications 2024

No publications during 2024

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 2024

The three main areas of work that the project has focused on during 2024 are:

An extensive literature research on power system resiliency, capacity, reliability, security and stability, configuration and operation of medium voltage distribution networks, hosting capacity quantification methods, and distribution-level power-electronics.

Developed a set of fully functioning simulation tools and models. These tools and models serve as the basis for carrying out the different capacity assessment studies.

Distribution grids with different characteristics and needs have been considered.

Developed a time series-based method for hosting capacity quantification of distribution grids. Different grid scenarios with various levels of consumption, penetration of distributed energy resources, and loads with different characteristics have been considered. This method is used to identify the network operation limits and determine the appropriate location and ancillary services to be provided by the power-electronic solutions for capacity enhancement.

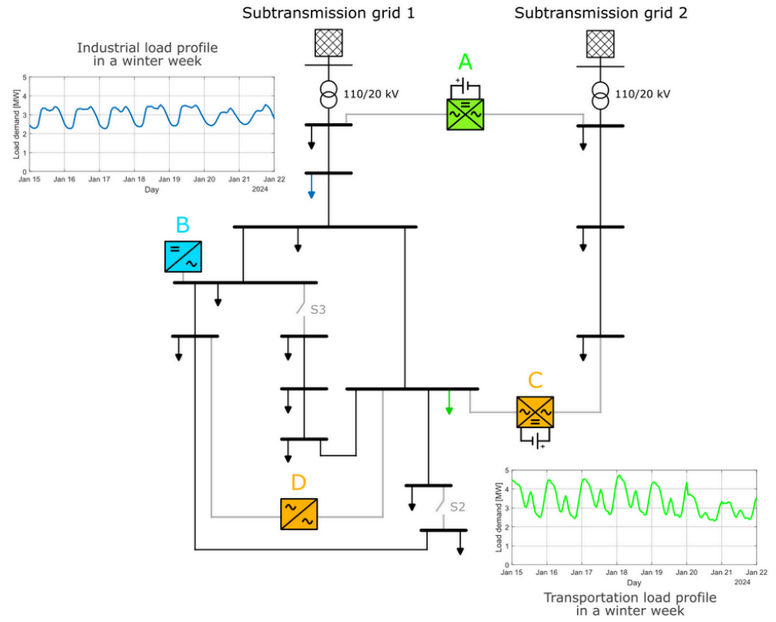


Figure. CIGRE MV Network Benchmark used for capacity assessment studies.

Publications 2024

No publications during 2024

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.

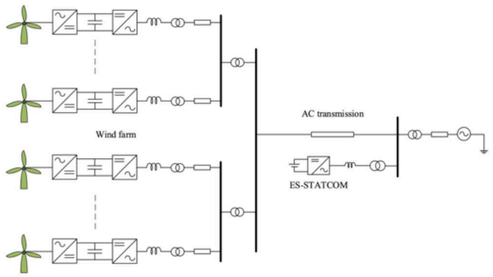
General Problem and Approach

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 2024

Developed an analytical model to assess the small-signal stability of an HVAC offshore wind power plant (WPP), as illustrated in Figure 1.

Using this analytical model, recommendations are provided for selecting the most appropriate control structure for a Static Synchronous Compensator (STATCOM) located at the onshore grid-connection point of the WPP.

Proposed a novel small-signal modeling approach based on the Power Response Matrix (PRM), as illustrated in Figure 2, to analyze the risk of control interactions, identify dominant oscillation modes, and assess the contribution of subsystems to the overall stability of modern power systems. Unlike the conventional impedance-based modeling approach, the PRM-based approach enables the validation of grid services offered by converter systems and simplifies the aggregation of subsystems for small-signal analysis in large, interconnected power systems.

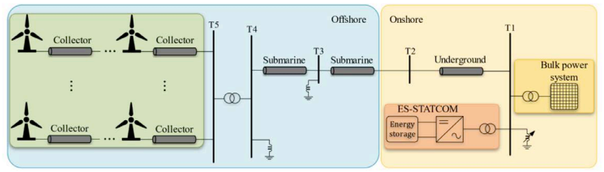


Figure 1: Single-line diagram of the considered offshore wind power plant

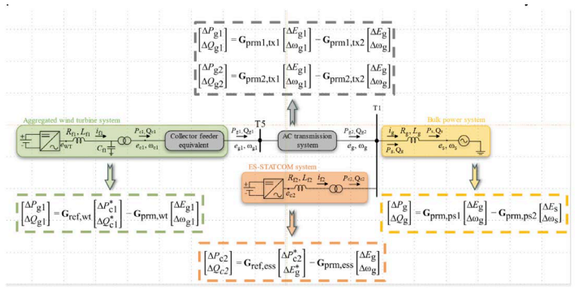


Figure 2: Proposed modeling approach for small-signal analysis of large interconnected systems

Publications 2024

Journal papers

A. Narula, P. Imgart, M. Bongiorno, M. Beza, "Empowering offshore wind with ES-STATCOM for stability margin improvement and provision of grid-forming capabilities," Electric Power Systems Research, Vol. 234, 2024, 110801, ISSN 0378-7796, https://doi.org/10.1016/j.epsr.2024.110801.

P. Imgart, A. Narula, M. Bongiorno, M. Beza and J. R. Svensson, "External Inertia Emulation to Facilitate Active-Power Limitation in Grid-Forming Converters," in IEEE Transactions on Industry Applications, vol. 60, no. 6, pp. 9145-9156, Nov.-Dec. 2024, doi: 10.1109/TIA.2024.3443792.

Conference papers

A. Narula, P. Imgart, M. Bongiorno, P. Mattavelli, M. Beza and J. R. Svensson, "Power-Response Matrix-Based Modeling of Converter Systems for Small-Signal Analysis," 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 4724-4731, doi: 10.1109/ECCE55643.2024.10860906.

A. R. Zamani, M. Beza, M. Bongiorno, A. Narula and J. R. Svensson, "Impact of the Reactive Behavior of Grid-Connected Converters on Resonance Stability," 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 4781-4787, doi: 10.1109/ECCE55643.2024.10861535.

Publications under review 2024

Journal papers

A. Narula, M. Bongiorno, P. Mattavelli, M. Beza, J. R. Svensson, 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.

Conference papers

W. Liu, A. Narula, M. Bongiorno, J.R. Svensson, "Grid Impedance Estimation with Large SCR Disturbances based on Grid-Forming Converter", 26th European Conference on Power Electronics and Applications, 2025.

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

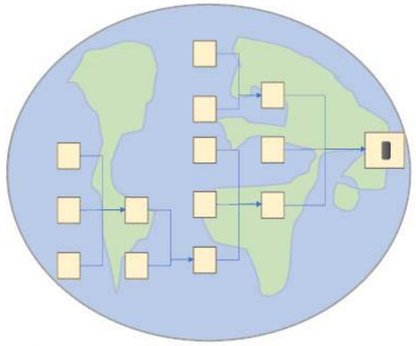
Björn Sandén, Chunshuo Ge, Anders Nordelöf, Rickard Arvidsson

Partners

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

PROJECT RESULTS 2024

Indicators of temporal and spatial flexibility was developed, empirically tested and described in paper currently under review. With increasing shares of solar and wind energy in current electricity systems, the type and scale of flexibility required from electricity systems is changing.



Mapping global value chains

Both temporal and spatial flexibility, and combinations of the two, may help balancing electricity supply and demand. To capture broad trends in flexibility strategies in different regions of the world this study develops two indicators: a spatial flexibility indicator (SFI) and a temporal flexibility indicator (TFI). The indicators are tested on a sample of countries including Australia, Germany-Luxembourg-Austria (GLA region), Sweden and the USA. By normalising storage and transmission capacity to average power demand these indicators are shown to enable comparisons across time and across regions and countries of different size. 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 the next part of the project different customs data bases were explored and tested in terms of their strengths and weaknesses in providing the data required for the project. A pilot study was conducted and presented at a conference. This work is now deepened with the aim of producing two papers and a licentiate thesis in 2025. The first of these two papers builds on paper one and will explore the possibility to monitor temporal flexibility development (installed battery capacity) in more than 150 countries over time. The second will use simar data sets to inform life cycle assessments (environmental assessments of technologies) by adding geographical nuance to representations of supply chains.

Publications 2024

Conference paper

C. Ge, B. Sandén, "Mapping the global distribution of supply chains using customs data," SETAC Europe 26th LCA Symposium, Göteborg, October 2024

Master theses

H. Bolinder, E. Fredriksson, "Livscykelanalys av storskaligt laddsystem (AC) för elektriska fordon: En vagga-till-grind analys med avseende på dess påverkan på global uppvärmning," Examensarbete inom högskoleingenjörsprogrammet Ekonomi och Produktionsteknik, (2024)

Publications under review 2024

Journal paper

C. Ge, A. Nordelöf, and B.A. Sandén, "Monitoring spatial and temporal flexibility in electricity systems," submitted for publication in Energy conversion and management: X, (2024)

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 the West Sweden Region ("VG regionen") 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 the VG region

A mapping of the Västra Götaland (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 Johnnson, Lisa Göransson

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

SYSTEMS

PROJECT RESULTS 2024

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.

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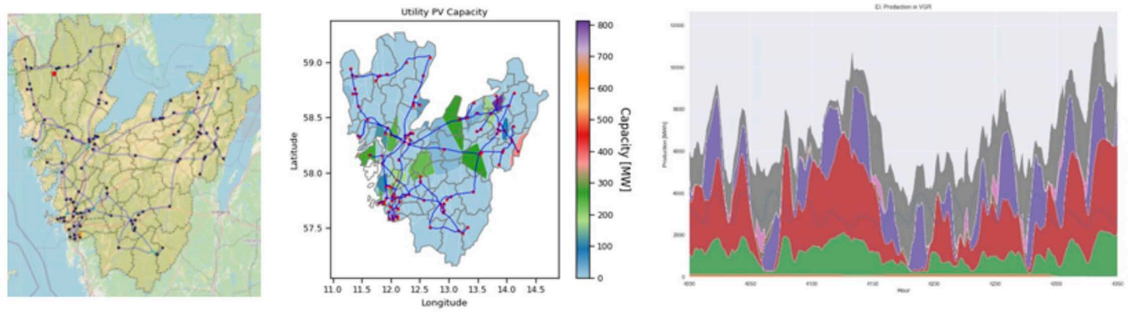
The project has developed a model and methodology for answering selected research questions, which then it is decided that the current model utilise open-source database to depict the distribution/sub-transmission electricity system. First results from the model have been obtained, showing the electricity generation dispatch and storage charge/discharge variations in the modelled region. The modelled and preliminary results from the model is presented below

The model is discussed with relevant stakeholders and interested parties to seek for feedback and improvement. Initial scenarios and study cases have also been developed to answer the relevant research questions. The following results are expected from the project: (1) Investments of generation and storage technologies, (2) generation dispatch and storage charge/discharge, (3) implementation costs of certain technologies. Based on results (1) – (3), the role of flexibility measures in future system can be identified.



The modelled region (left), distribution of investment (middle), dispatch of electricity generation and storage in selected period (right)

Publications 2024
No publications during 2024

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

MATERIALS AND DEVICES FOR ENERGY STORAGE

PROJECT RESULTS 2024

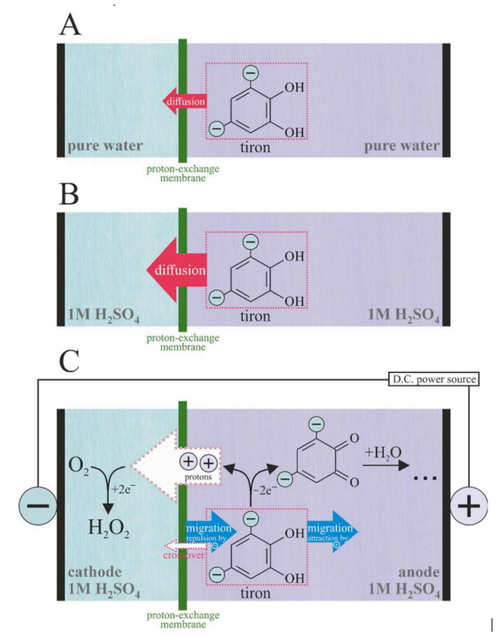
To analyse the processes occurring during redox flow battery (RFB) charging we designed a flow electrolyser with a PEM positioned between two electrodes. The applied compression between the electrodes minimizes ohmic losses during electrolysis.

To evaluate the contributions of different ionic transport mechanisms across the PEM, including diffusion and migration, we examined the time-dependent concentration of cross-transported redox probe under both zero-current (no electrolysis) and non-zero-current (electrolysis active) conditions.

Both the positive and negative electrode compartments of the electrolyser were supplied with the same solvent, either deionized water (Fig. 1A) or 1 M H2SO4 (Fig. 1B). To establish a concentration gradient across the PEM as a driving force for diffusion, the positive electrode compartment contained 0.05 M of a redox probe. The crossover of the redox probe into the negative electrode compartment was quantified using UV-vis spectrophotometry. The permeability of the PEM to the redox probe was determined from the time-dependent concentration increase in the negative electrode compartment. The quantification of redox probe transport across the PEM during charging (Fig. 1C) was only feasible in the presence of 1 M H2SO4.

To investigate electrolysis-induced transport phenomena within the bulk of the PEM, we conducted in-situ ATR-FTIR measurements on a PEM-based cell. Electrolysis initiation resulted in an increased presence of unbound water within the membrane, altering the polymer chain environment. Principal Component Analysis (PCA) of ATR-FTIR spectra revealed that water molecules begin migrating into the membrane immediately upon current application, continuing in a linear fashion throughout the measurement period. In contrast, the rate of water-proton interactions exhibited a nonlinear increase, eventually reaching saturation. The emergence and growth of redox probe-related peaks upon electrolysis onset confirmed the transport, highlighting its crossover through the PEM.

We also conducted a computational study of the redox probe concentrations in a 1D electrolyzer model under both zero and non-zero current conditions, using experimental values for the diffusion coefficient of the redox probe and initial concentrations.



Publications 2024

Journal papers

P. Ding, M. Vagin, M.J Jafari, A.Y. Mehandzhiyski, V. Gueskine, T. Abrahamsson, I. Zozoulenko, T. Ederth, R. Crispin, "Migration-mitigated crossover of organic redox anion across proton-exchange membrane," Sustainable Energy & Fuels, 2024, 8, 4882-4892

Doctoral theses

P. Ding, "Organic Materials-based Electrochemical Flow Cells for Energy Applications", 1st March 2024, Linköping University

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

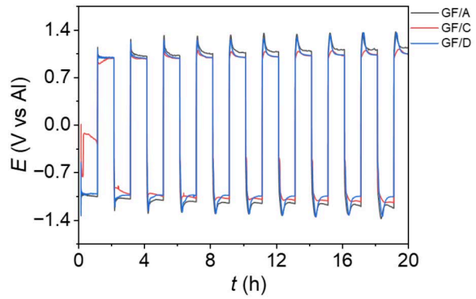
Partners

Linköping University, Ligna Energy, Swedish Energy Agency

PROJECT RESULTS 2024

In 2024, experiments were conducted to optimize the utilization of separators, which play a key role in aluminum metal batteries.

Summary: The proper selection of a separator can suppress dendrite formation, provide better thermal stability, and enhance electrochemical performance. Typically, glass fiber separators have been predominantly used with conventional electrolyte systems, specifically the 1-ethyl-3-methylimidazolium chloride:aluminum trichloride (EMIMCl:$AlCl_3$) electrolyte. However, literature suggests that this electrolyte is highly corrosive, even affecting stainless steel and titanium. Therefore, we evaluated various separators, including different types of glass fiber (A, B, C, and D), highly crosslinked cellulose membranes, and water-in-salt electrolyte-based hydrogels (WISH), to assess their suitability for aqueous aluminum metal batteries. We conducted electrodeposition tests of aluminum at a fixed current rate in a water-in-salt electrolyte with a concentration of 4M Al(OTF)3. The obtained results are summarized in the table 1.



Separator	Current mA/cm2	Stable ycling (time in h)	Remarks if any
GF/A	0.05	30	Moderate
GF/B	0.05	20	Bad
GF/C	0.05	72	Good
GF/D	0.05	70	Good
WISH	0.05	10	Bad
Cellulose membrane	0.05	0.08	Worst

Table 1: *Key performance indicators for different separators tested for Al battery in WISE (4m $Al(OTf)_3$)*

Publications 2024

No publications 2024

Publications under review 2024

Journal papers

V. Joseph, R. Crispin, Z. Khan, "Wood-Derived Hard Carbon in Sodium and Potassium Ion Batteries: Mechanisms, Challenges, and Future Directions"

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 2024

This year, substantial progress was made in advancing the high-voltage dielectric frequency response setup. The setup consists of a signal generator, DAQ card, high-voltage amplifier, and a custom-designed electrode system optimized for thin metallized polymeric films.

A variable vacuum capacitor was integrated to enable lossless reference measurements, ensuring high measurement accuracy. Current sensing is achieved using an RC-shunt, while a high-voltage switch allows seamless transitions between the vacuum capacitor and the test object. To improve measurement precision, buffer circuitry was implemented to minimize stray capacitance differences between switch positions.

The existing Python script for the dielectric frequency response technique was further updated to improve automation and data processing capabilities. Additionally, specialized samples were received from Tampere University, Finland. These samples were gold-evaporated using physical vapor deposition (PVD), providing excellent electrical contact between the sample surface and the electrode system, which is critical for accurate dielectric measurements.

Results from the evaluation of various data acquisition (DAQ) systems for this setup were presented in the paper "Evaluation of Data Acquisition Systems for Dielectric Frequency Response Measurements" at the IEEE ICD 2024 International Conference on Dielectrics in Toulouse, France. This study assessed multiple DAQ systems to identify the most suitable option for high-precision dielectric measurements.

Publications 2024

Conference papers

D. Svensson, T. Hammarström, X, Xu, O. Hjortstam, Y. Serdyuk, "Evaluation of Data AcquisitionSystems for Dielectric Frequency Response Measurements," Proc. 5th IEEE International Conferenceon on Dielectrics, ICD 2024, Toulouse, France, June 30 – July 4, 2024, doi: 10.1109/ICD59037.2024.10613244.

Publications under review 2024

Conference papers

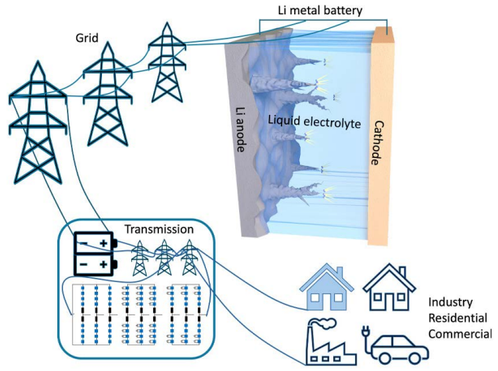
D. Svensson, T. Hammarström, X, Xu, O. Hjortstam, Y. Serdyuk, "Comparison of Various Types of Electrodes for Dielectric Frequency Response Measurements on Thin Films," submitted to IEEE Conference on Electrical Insulation and Dielectric Phenomena CEIDP2025, Manchester, UK, September 2025.

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

MATERIALS AND DEVICES FOR ENERGY STORAGE

PROJECT RESULTS 2024

During 2024 a new concept has been proposed for an electrolyte that can enable stable operation at high temperature (target temperature 80°C), compatible with e.g. the environment in a convertor hall. The concept is based on the use of ionic liquid with an inherent thermal and chemical stability.

To overcome the strong interactions normally limiting the applicability of such systems a formulation based on two different anions and with additives was developed to optimise the local environment around Li-ion transport as well as interface stability. The concept was tested both in symmetric cells and in a full Li-metal cell with a lithium iron phosphate cathode (LFP) and the results clearly show an increased cycling performance with the new electrolyte concept. In particular, the importance of additives for the cycling stability was clear from these experiments.

To further understand the origin behind the improved cycling stability and the role of additives a detailed investigation was performed with respect to the local ion coordination in the electrolyte (Raman spectroscopy), ion mobility (NMR diffusometry) and surface layer formation (X-ray photoelectron spectroscopy, XPS). The results from these experiments show that the additives play a key role in altering the coordination structure of the Li-ions which in turn can be connected to nature of the surface layer formed on the anode during cycling. A stable and highly ion conductive layer is key to long cycle life and stable deposition and with the new electrolyte formulation we found that a predominately inorganic surface layer was formed. The morphology of the Li-electrode after cycling in the new electrolyte was also investigated by cryo electron microscopy and one can clearly see that with the optimised electrolyte a much more dese structure was formed after prolonged cycling which is necessary to ensure a long cycle life. Figure 1 shows data from extended cycling with a Li-foil of limited thickness, where the optimised electrolyte (NS-DAIL) shows very stable cycling.

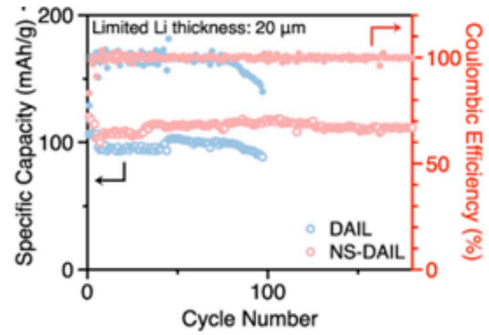
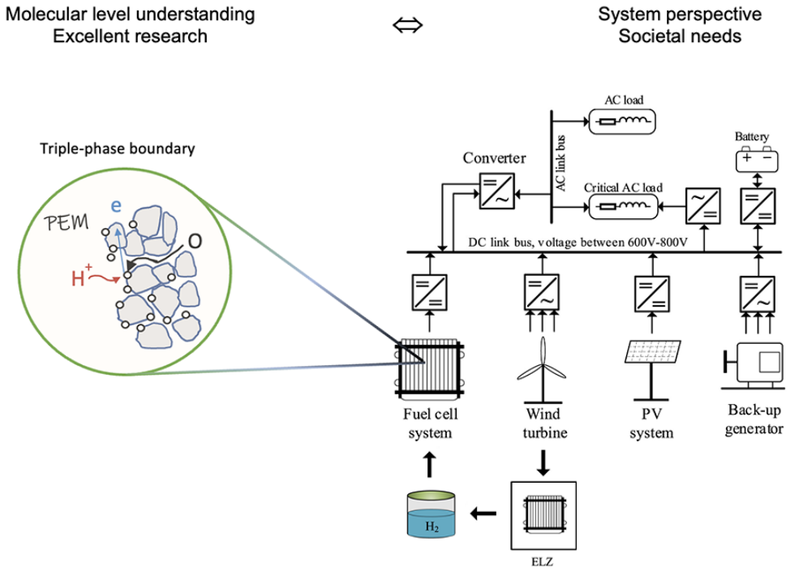


Figure 1 Cycling data of a LFP-cell with the optimised electrolyte (NS-DAIL) and a more conventional dual anion ionic liquid electrolyte.

Publications 2024

No publications during 2024



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 in-situ fuel cell tests will also be performed at a later stage of the project. 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

MATERIALS AND DEVICES FOR ENERGY STORAGE

PROJECT RESULTS 2024

During this year, one main focus of the project has been the characterization of the advanced anode materials developed by Smoltek. Here, we have developed spectroscopic and optical methods to verify the chemical identity of the carbon nanofibers, their efficient coverage by platinum and the presence of iridium catalyst.

Detailed properties of the carbonaceous parts could be studied by conventional Raman spectroscopy, while to penetrate in depth the porous structure a combined FIB-SEM and micro-Raman spectroscopy had to be employed. This method has relevance for any porous, micro-structured materials whose in-depth properties are difficult to access. One particular aspect investigated has been the role of the ionomer added to the carbon-based nanorods, which by SEM-EDX has been chemically identified and spatially mapped. This, and ongoing electrochemical tests, are being correlated to the performance curve of a PEM electrolyser tested over the exceptional period of 1000 hours. Current hypotheses that we discuss for the lost performance, reflected by an increased overpotential, are the morphology change of the ionomer through the nanorods at the catalyst side and/or the partial chemical degradation of the proton exchange membrane by loss of -SO3− end groups. Still from the viewpoint of methods development, cubic particles of platinum have been provided by Nanoscientifica with a narrow size distribution around 7 nm. These will be used to enable an identical location study of the morphological change of catalyst nanoparticles possibly induced by use in an operating fuel cell. Preliminary TEM images have been collected for these particles.

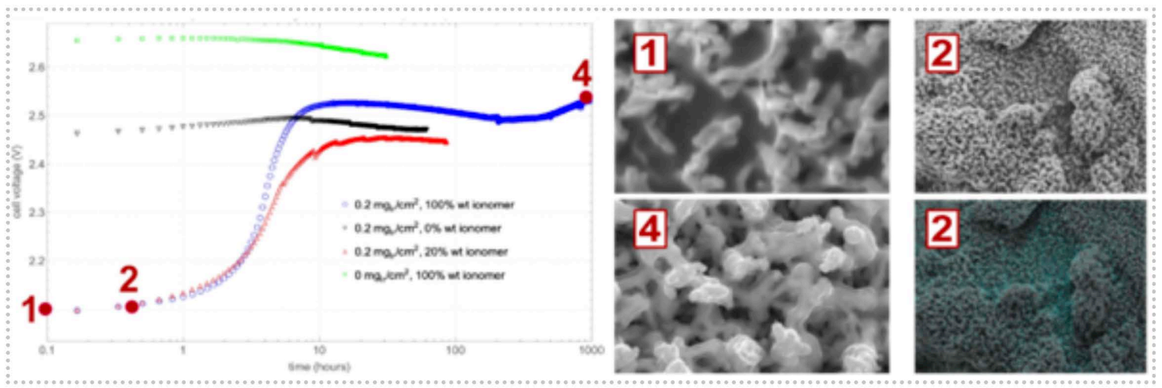
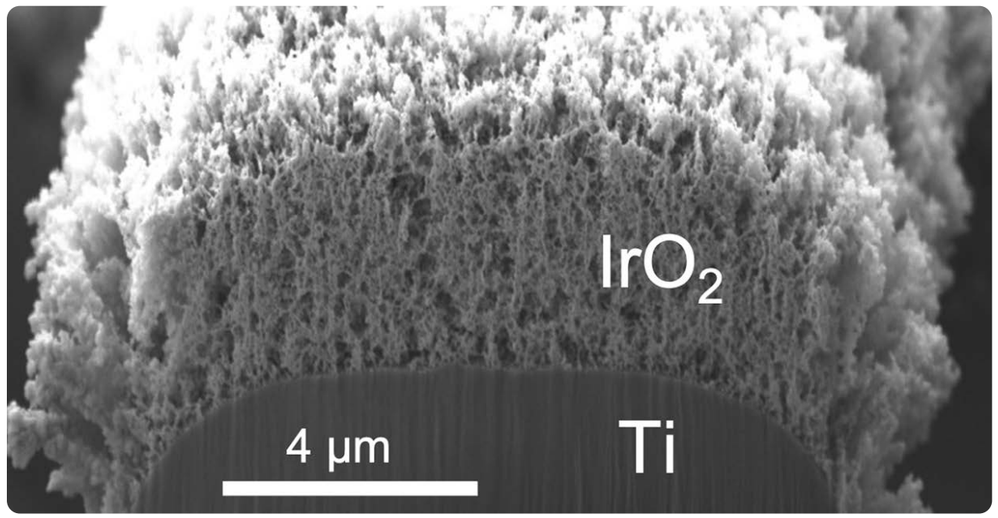


Figure 1. Left: polarization curve of a PEM electrolyser during a use time of 1000 hours. Right: SEM images of the anode materials at different time points of the curve. The bottom-right image shows the overlayed spatial mapping of fluorine (representative of the ionomer).

Publications 2024

Master thesis

S. B. Ravi Sankar "Comprehensive analysis of PTFE distribution in gas diffusion layers using advanced ex-situ and in-situ characterization techniques", Presented October 2024



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

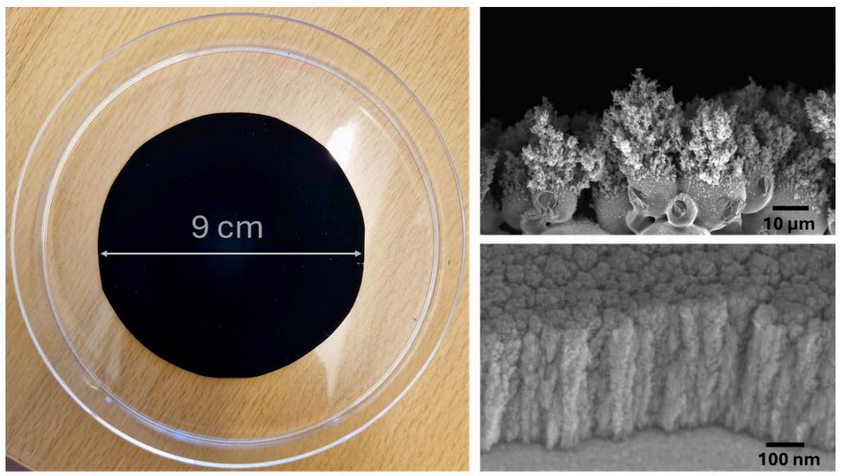
The experimental set-up is today suitable for production of test samples up to an active area of 150 cm2. In production samples are in the range of 3,000-10,000 cm2. Two approaches for scaling are now under development.

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



A coated PTL with an area of ~64 cm^2 deposited using hollow cathode sputtering (left) and Ir-O coatings with different porosity deposited using planar magnetron sputtering (right).

PROJECT RESULTS 2024

The focus this year have been to scale up the surface that can be covered by highly performing Ir-O catalyst for PEMWE.

This has been successful using our standard hollow cathode discharge process up to substrates 9 cm in diameter, as seen to the left in the figure. This is a sufficient surface area for serious testing by several of Ionautics industrial contacts. However, the industrial demand is to be able to deposit on significantly larger substrates. For this reason, we shifted in the middle of the year to using magneton sputtering sources, sources that are of industrial standard and scalable to any size. This shift in technology has been successful and we have reached a performance that is close to what was achieved with hollow cathodes. Further optimization is however needed since industrial demands are rather extreme, combining high mechanical strength of the catalyst layer with high porosity. To the right in the figure two different layers with different porosity are shown.

Publications 2024

No publications during 2024

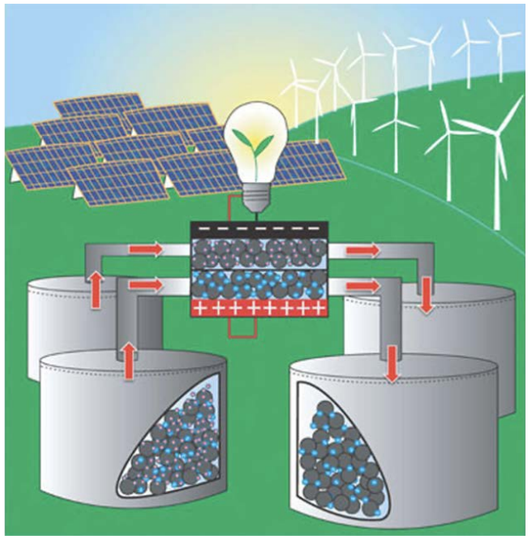
DESIGN OF THE NEXT GENERATION OF SLURRY FLOW CELLS FOR ELECTRICAL ENERGY STORAGE

We design new organic slurries for the charge storage in redox flow batteries. Those are made of conducting polymer or carbon conductor particles and other redox organic additives. We adapt the architecture of the redox flow cell to be appropriate to slurries and avoid obstruction phenomenon.

The global demand for electric energy is growing and cannot be stopped, which contributes to global warming. An increasing share of renewable energy sources can help curb CO2 emissions. However, wind flow and sunlight are intermittent, meaning power generation from windmills and solar panels is not always reliable. This obvious intermittency in renewable energy supply, along with fluctuations in demand, highlights the importance of stabilizing the electric power grid. It's important to note that grid stability involves more than just providing sufficient electricity to consumers on average—it also includes various parameters that must be managed over timescales ranging from milliseconds to hours.

Electrochemical devices store and release electric energy: batteries operate more slowly, while supercapacitors can respond very quickly. Both can contribute to grid stabilization, provided they are scalable. Scalability can be achieved when energy storage in large external tanks is decoupled from the charge/discharge cells, whose dimensions are determined by the physics and chemistry of the processes involved. In such flow devices, active materials are pumped between the tanks and the cell.

An emerging idea is to use, instead of solutions, suspensions or thicker slurries of energy-carrying materials in water with necessary additives. In this project, we propose to study the storage and transfer of electric energy using such flowable slurries made from organic, sustainable, non-toxic, and inexpensive materials. Depending on their composition, the behavior of these slurries can be adjusted to resemble either battery-like or capacitor-like systems. The challenge is to turn this promising idea into a practical solution by addressing several fundamental and engineering problems. These include, on one hand, physico-chemical tasks related to preparing and characterizing stable flowable slurries capable of delivering relevant power and energy, and on the other hand, designing flow cells and circuits adapted to the properties of these slurries.



Involved in the project

Viktor Gueskine, Penghui Ding, Jaywant Phopase, Pawel Wójcik, Peter Ringstad, Reverant Crispin

Partners

Linköping University, Redoxme, Linköping University, Ligna Energy, Swedish Energy Agency

MATERIALS AND DEVICES FOR ENERGY STORAGE

PROJECT RESULTS 2024

Synthesis of the Slurries
Posolyte and negolyte slurries were synthesized using redox-active conducting polymer nanoparticles. The posolyte consisted of lignin-conducting polymer (PEDOT) composite nanoparticles, synthesized via in-situ polymerization of EDOT in the presence of lignosulfonate. The negolyte followed a similar method but with polyaminoanthraquinone (PA) as the redox polymer. The resulting nanoparticles were dispersed in water to prepare slurries for further use.

Fabrication and Characterization of Static Organic Slurry-Based Battery Cell
A semi-solid battery concept was developed to decouple mechanical and electrochemical properties, enabling flexible energy storage. A stretchable poly-styrene-isobutylene-styrene (SIBS) membrane was designed to allow proton conductivity while preventing cross-over of active materials. Highly conductive stretchable current collectors were created using nanographite-polymer composites with a silver nanowire mesh. The active materials, PEDOT-lignin (PL) and PEDOT-PACA (PP), demonstrated shear-thinning behavior, allowing potential use in printed batteries. Electrochemical impedance spectroscopy showed an increase in conductivity with strain, attributed to improved charge transport networks. Galvanostatic charge-discharge (GCD) testing revealed that PL and PP achieved maximum volumetric capacities of 5.92 and 13.5 mAh/cm³, respectively, comparable to solid-state electrodes.

Full Cell Performance and Stretchability
A full cell was assembled and tested under varying mechanical strains. Cyclic voltammetry (CV) and GCD measurements indicated stable electrochemical performance, with capacity retention of 85.2% over 500 cycles at 1.9 mA/cm². Mechanical tests demonstrated increased capacity under strain due to enhanced ionic conductivity and reduced cell thickness. Even after 300 strain cycles at 30%, 65% capacity retention was observed. A practical demonstration powered an LED under mechanical deformation, confirming the feasibility of stretchable, fluid-based organic batteries.

Electrochemical Flow Cell Development
Initial tests with a flow cell using carbon particle-based slurries revealed an oxygen leakage issue, which could degrade organic redox polymers. To address this, Redoxme is redesigning the electrochemical flow cell to prevent gas leakage, with further updates expected in the next report.

Publications 2024

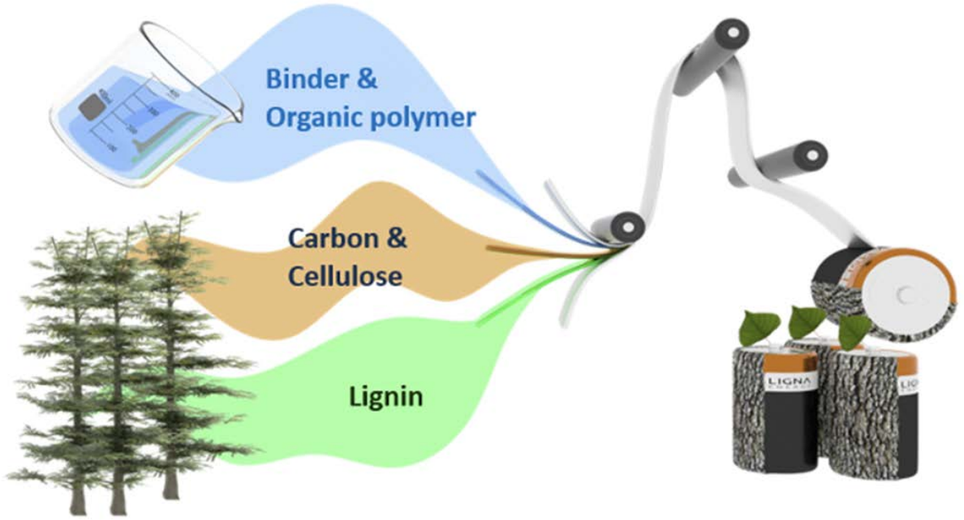
Journal paper

S. Mardi, U. Ail, M. Vagin, J. Phopase, R. Crispin, "On the Reversibility of Sustainable Symmetric Aqueous Organic Redox Flow Batteries," Advanced Energy and Sustainability Research, 2024 (https://doi.org/10.1002/aesr.202400324)

Publications under review 2024

Journal paper

M. Mohammadi, S. Mardi, J. Phopase, U. Ali, F. Wentz, J. Jibin, S. M. Berggren, R. Crispin, K. Tybrandt, A. Rahmanudin, "Stretchable organic redox-active fluid batteries," submitted.



NEW BIO-GEL ELECTROLYTES FOR ZN-LIGNIN BATTERIES

We propose a Zinc-Lignin battery as a new, low-cost energy storage solution using two of the most affordable electroactive materials: zinc and the biopolymer lignin, which makes up 30% of plants. To optimize its performance, we need to design an electrolyte that prevents dendritic growth, reduces hydrogen evolution, promotes zinc ion conductivity, and is compatible with lignin.

Aqueous Zn-ion batteries with aqueous electrolytes are promising due to their safety, low cost (36 SEK/kg), environmental friendliness, and high zinc abundance. The zinc anode offers a high theoretical capacity of 820 mAh/g, resulting in a low-cost capacity of 0.04 SEK/Ah. For the cathode, lignin, an abundant and inexpensive biopolymer (1-4 SEK/kg), is being considered. Combined with a conductor, lignin can form nanocomposites with a capacity of 80 mAh/g, making it a cost-effective battery material (0.01-0.04 SEK/Ah). Both materials are non-toxic, recyclable, and ideal for large-scale, stationary batteries with a cell voltage of 1.2V.

However, Zn-ion batteries face challenges like zinc dendrite formation, hydrogen gas evolution, and byproduct accumulation, limiting their commercial feasibility. While various strategies have been proposed to mitigate these issues, hydrogel electrolytes have recently emerged as a potential solution to improve stability. The aim of this project is to design low-cost Zinc-Lignin battery cells, focusing on the electrolyte. We propose using bio-gels, such as agarose, to develop Zn-ion aqueous gel electrolytes that prevent dendrite growth, promote Zn-ion transport, and limit hydrogen evolution. The project goals include: (i) Developing high-performance Zn-ion aqueous gel electrolytes. (ii) Characterizing ionic transport and electrochemical stability in “water-in-polymer salt” electrolytes. (iii) Integrating lignin electrodes from Ligna Energy with the new electrolyte to create safe, scalable, cost-effective Zinc-Lignin batteries.

Involved in the project

Reverant Crispin, Ziyauddin Khan, Peter Ringstad, Leandro R. Franco, Anna Martinelli, Moyses Araujo

Partners

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

MATERIALS AND DEVICES FOR ENERGY STORAGE

PROJECT RESULTS 2024

In recent years, the energy storage industry has seen a growing interest in the development of safe and efficient batteries. To address the limitations of traditional batteries, researchers have turned to new materials, such as lignin and carbon, as cathode materials in zinc batteries.

The use of water-in-polymer salt electrolytes (WiPSE) in these batteries offers additional advantages, including improved safety and stability, and the prevention of dendrite formation. This research explores the use of a WiPSE in zinc batteries with lignin and carbon as cathode materials. The findings of this study highlight the significant role of acrylate groups in the electrolyte in stabilizing the flux on the zinc electrode surface. This stabilization leads to a more uniform Zn deposition on the (002) plane, promoting parallel deposition and significantly reducing dendritic formation through vertical growth. The assembled sustainable Zn-lignin battery demonstrated impressive performance, delivering a maximum energy of 23 Wh/Kg and a maximum power of 610 W/kg with an exceptional 82% retention after 7000 cycles. With its improved environmental impact and cost-effectiveness, the Zn-lignin battery represents a promising space in the battery market.

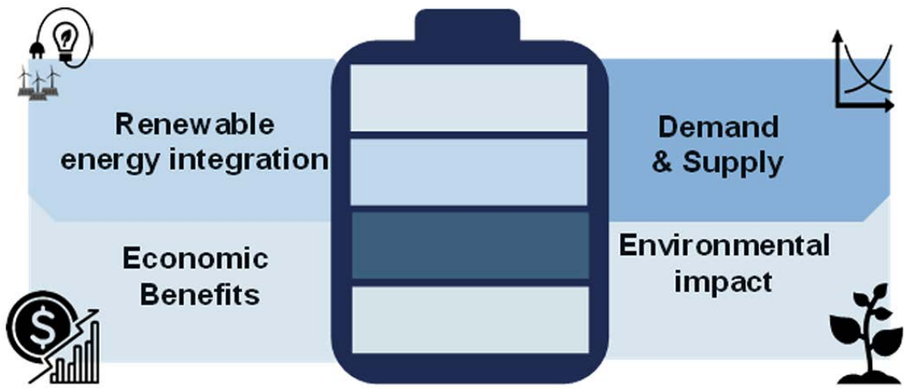
Publications 2024

Journal papers

U. Ail, J. Backe, Z. U. Khan, R. Shu, J. Phopase, M. Berggren and R. Crispin, “Safe and stable Zn-lignin batteries with a biopolymer based hydrogel electrolyte,” J. Mater. Chem. A, 2024

Z. Khan, D. Kumar, S. Lander, J. Phopase, R. Crispin, “Utilization of sulfonated cellulose membrane for Zn ion hybrid capacitors,” EcoEnergy. 2024; 2, 456-465.

D. Kumar, L.R. Franco, N. Abdou, R. Shu, A. Martinelli, C.M. Araujo, J. Gladisch, V. Gueskine, R. Crispin, Z. Khan, “Water-in-Polymer Salt Electrolyte for Long-Life Rechargeable Aqueous Zinc-Lignin Battery. Energy Environ,” 2024, Mater., 8: e12752.



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,

MATERIALS AND DEVICES FOR ENERGY STORAGE

PROJECT RESULTS 2024

This year one of the focus' was on Battery energy storage systems (BESS) providing frequency ancillary services, the aim was to determine the technical and economic implications of a BESS to participate in the Frequency Containment Reserve for Normal Operation (FCR-N) and Frequency Containment Reserve for Disturbances (FCR-D).

The power and energy requested by the grid was calculated and the state of energy was determined according to limited energy reservoir requirements. The economic results show that providing FCR-D up services was the most profitable one compared to FCR-N, FCR-D down or providing simultaneously both FCR-D services.

Another focus this year the focus was on developing a comprehensive battery model that provides insight into both the thermal and electrical performance of the battery, as well as an aging model to assess its long-term degradation. This detailed modelling approach enables a better understanding of battery efficiency, heat generation, and lifespan under various operating conditions. Additionally, a controller was designed to optimize battery operation for providing grid services such as frequency regulation.

Publications 2024

Conference papers

M. Ahouad, A. Sunjaq, E. Wikner, T. Thiringer, "Economic Assessment of Battery Energy Storage for Frequency Regulation in the Nordic Power Systems", International Conference on the European Energy Market, EEM. 2024

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.

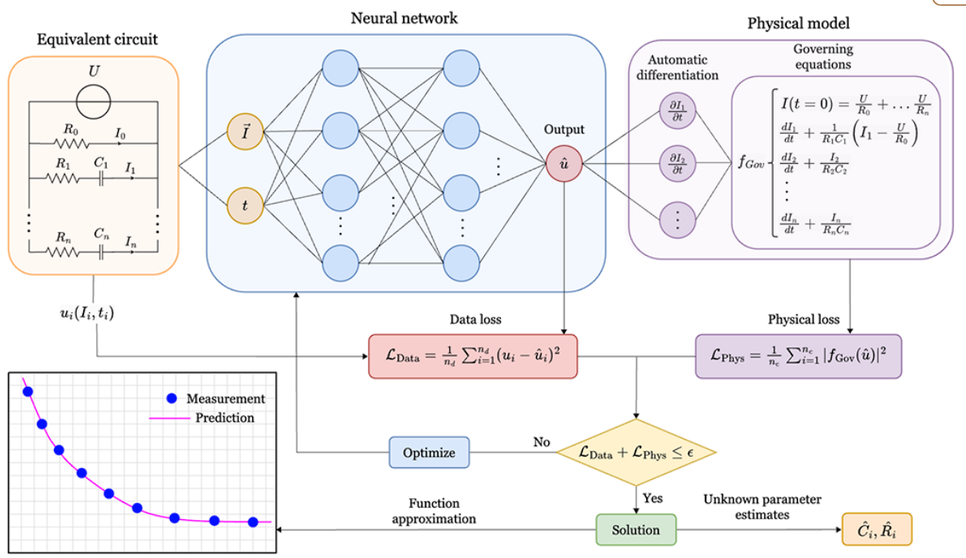
Involved in the project

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

Partners

Chalmers, Karlstad University, Linköping University, Hitachi Energy, Redox Me, Ligna Energy, Swedish Energy Agency

MATERIALS AND DEVICES FOR ENERGY STORAGE



PROJECT RESULTS 2024

The project started in September 2024 and since then focused on literature analysis and preliminary studies of ML methods applied to dielectric materials.

A working implementation of physics-informed neural networks for inverse equivalent circuit modeling of dielectric response data in time domain with positive results.

This is the first research focus of the PhD project and the results will be published to either a conference or a journal.

Publications 2024

No publications during 2024

Publications under review 2024

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," submitted to IEEE Conference on Electrical Insulation and Dielectric Phenomena CEIDP2025, Manchester, UK, September 2025.

ACTIVITIES 2024

SECOND ANNUAL SESBC CONFERENCE

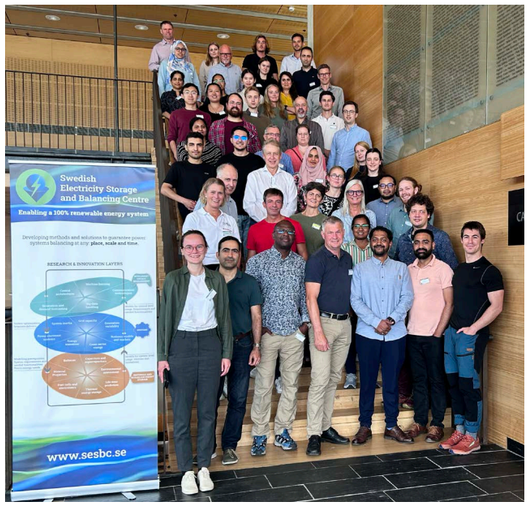
Swedish Electric Storage and Balancing Centre (SESBC) held its second annual conference 24-25 October. The event took place in the picturesque university city of Lund located in Sweden's most southern region, Skåne. The conference had about 65 attendees from academia, industry and agencies within the field of electricity storage and balancing.

SESBC presence at international conferences

Researchers within SESBC have also attended several international conferences and symposiums during the year, presenting and sharing their work. Below are a few examples.

- International Meeting on Lithium Batteries, Hong-Kong
- 7th Symposium on Physics of Membrane Processes, Singapore
- International Society of Electrochemistry, Italy
- Prime ECS global conference, Honolulu
- RamanFest2024, France
- International Symposium on Beyond Li-Ion Batteries, Padua
- 2024 IEEE Energy Conversion Congress and Exposition (ECCE), USA
- ACM Principles of Distributed Computing, France
- 44th IEEE International Conference on Distributed Computing Systems (ICDCS), USA
- 5th IEEE International Conferenceon Dielectrics, ICD 2024, France
- International Conference on the European Energy Market, EEM, Turkey
- The 18th ACM International Conference on Distributed Event-Based Systems (DEBS 2024), France
- ACM/IFIP International Middleware Conference, China

PHD NETWORK



Summer school

The first SESBC Summer school had focus on temporary energy storage devices and their integration into the power systems. It took place in August at Chalmers University of Technology.

PhD network workshop

A much appreciated workshop about communicating through images, text and colors took place in Gothenburg the 23rd of February 2024.

The workshop was lead by Christel Kopp, lecturer at the Department of Journalism, Media and Communication at the University of Gothenburg. In addition, the group of PhD students and postdocs had the opportunity to visit SEEL, the Swedish Electricity Transport Laboratory in Säve, owned by Chalmers and RISE.

INDUSTRY FORUM

The Industry Forum was established during 2024. The purpose of the forum is to be 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. The Industry Forum is also a great opportunity to get to know each other.

"From these first meetings we have had there has been very positive feedback and many good ideas. There are many possible connections but to have projects across boundaries we have to get to know each other better. There is a need to understand how to utilize the centre, and also for other types of collaboration than just doctoral projects. The Industry Forum has great potential to help to solve these issues. A lot is happening now so it's very beneficial for academia to stay informed about the industry needs."

Chair, Mariliis Lehtveer

The Industry Forum's first on-location meeting was hosted by Port of Gothenburg.

SEMINARS & WORKSHOPS

Control of future power systems

Seminar introducing the R&I layer Intelligent Energy Management (IEM) and providing updates on ongoing projects

Materials, devices and diagnostics. New horizons at sight?

Workshop with the R&I layer Materials, devices and diagnostics and study visits.

Systems layer seminar

Seminar with R&I layer Systems. Discussions on cutting-edge developments in battery storage and power system resilience, and study visits.

Course in Power Systems Voltage Stability

Course held for power system engineers, PhD-students and lecturers in Nordic Universities

Online seminars

There have been six SESBC arranged online seminars. The topics have ranged from life cycle assesment, Li-metal batteries, grid monitoring, to national and international energy policies.

COLLABORATION

There have been several activities and collaborations both between SESBC partners and other actors. The collaborations involve industry partners, international academic institutions, and researchers. Some projects have come further, and others are initiating contacts.

Presenting ideas, research activities and industry needs combined with study visits and workshops are important tasks to understand how we can work together. Several initiatives with various activities such as interviews, reference groups, meetings and workshops have taken place during the year.

Industrial collaboration
The research projects have had regular reference group meetings with industrial partners. These meetings play an important part for sharing insights and results in various forms. There have also been several study visits during the year providing opportunities to further understand industry needs.

Academic collaboration
SESBC management has participated in the Swedish Energy Agency's "Leadership forum" to exchange knowledge and experience with other competence centres funded by the Swedish Energy Agency.

Associated projects
"Nätresiliens – Bostäders Möjligheter att Bidra till ett Mer Resilient Elnät", and "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.

International contacts
SESBC have several collaborations with international actors like Tampere University in Finland, NREL in USA, Tokyo Metropolitan University in Japan. Discussions have been initiated with DECHEMA-Forschungsinstitut in Germany, University of Bordeaux, the Marie Curie EU Doctoral Network, and an academic partner in Taiwan. SESBC International Scientific Advisory Board, has established a collaboration with University of Padova in Italy, and members of the International Scientific Advisory board have also been engaged giving SESBC webinars and participating in the Annual Conference. A memorandum of understanding has been signed between SESBC and INEGA, Spain and Horizon Power in Australia. There was also an international delegation from Mecklenburg-Vorpommern visiting Sweden to discuss commercialisation of energy technology. Further cooperation includes work with the European Battery Hub at the European Synchrotron Radiation Facility on interface characterization.

Other connections
There have been meetings with regional stakeholders, including Västra Götalandsregionen, RISE, and Energikontor Väst, that focused on presenting and refining the regional system model. Feedback from these discussions has supported the development of study cases and methodologies. Studies with Chalmers' Department of Chemistry and the Swedish NMR Centre on ion transport in innovative electrolyte formulations.

COMMUNICATION

In the end of 2023 the centre launched a website, a newsletter and a social media account on LinkedIn. These channels have developed well during 2024, and we believe that they will be a great asset for sharing information and gain awareness about the centre.

Newsletter
The SESBC Newsletter is sent out on a monthly basis to SESBC partners only. The main purpose is to inform about events and activities within the centre. It also contains information from external stakeholders that can be of interest.

Website
The website is the information hub where all the projects now are published. The aim is to further develop the platform with more relevant information that can also appeal to a wider audience.

LinkedIn
SESBC started a LinkedIn account in late 2023. It has grown fast during the year and has today about 1200 followers. Below is a screenshot from the most viewed post during 2024.

Robert Eriksson from Volvo Cars handing over the keys for an electric Volvo C40 to Torbjörn Thiringer from Chalmers.

MEDIA COVERAGE

Power supply and balancing are often being publicly debated by politicians and decision makers, with a high interest from a general audience. It is therefore important that the centre contributes with its expertise to have an informed public with fact based debates. Researchers within SESBC have been visible in media outlets and taken part on various platforms.

sverigesradio
ENERGI

Fyra experter om elsystemet: Hur nödvändig är kärnkraften?

14 min Dela

Publicerat söndag 13 oktober 2024 kl 09.42

Vad behövs för att Sveriges elsystem ska fungera bra framöver? Regeringen talar om behovet av mer planerbar el för att ha ett stabilt och leveranssäkert system, och vill satsa på att bygga ny kärnkraft. Därför processas just nu ett förslag om att satsa stora statliga pengar på det. Men hur nödvändigt är det med just kärnkraft för att ha ett stabilt elsystem? Vår reporter har ställt frågan till fyra experter på elsystem och elnät.

Daniel Karlsson and Lisa Göransson were interviewed in Swedish Radio "Godmorgon Världen". https://www.sverigesradio.se/artikel/fyra-experter-om-elsystemet-hur-nodvandig-ar-karnkraften

"Det är viktigt med ett stabilt elsystem och ny elproduktion, men det måste inte vara kärnkraft för att vi ska kunna upprätthålla ett stabilt kraftsystem på den tillförlitlighetsnivå som vi är vana vid, och som vi har idag. Det går att lösa med annan teknik," säger Daniel Karlsson.

Second Opinion

Stabilt kraftsystem både med och utan kärnkraft

Daniel Karlsson was interviewed in Second opinion. https://second-opinion.se/stabilt-kraftsystem-bade-med-och-utan-karnkraft/

– Den tröghet som de roterande generatorerna i kärnkraftverkens synkronmaskiner bidrar med kan åstadkommas på annat sätt, med känd teknik och till rimlig kostnad, säger Daniel Karlsson, senior chefsingenjör på DNV och adjungerad professor i elkraftssystem vid Chalmers.

sverigesradio

Behövs kärnkraft för den gröna omställningen?

6:42 min Dela

Publicerat tisdag 13 augusti 2024 kl 08.29

Björn Sandén is often visible in various media outlets. Here he was interviewed by Swedish Radio "P1 Morgon" regarding the government investigation on financing new nuclear energy. https://www.sverigesradio.se/artikel/behovs-karnkraft-for-den-grona-omstallningen

Björn Sandén, professor i innovation och hållbarhet på Chalmers tekniska högskola. Foto: Samuel Steén/TT

FINANCIAL REPORT

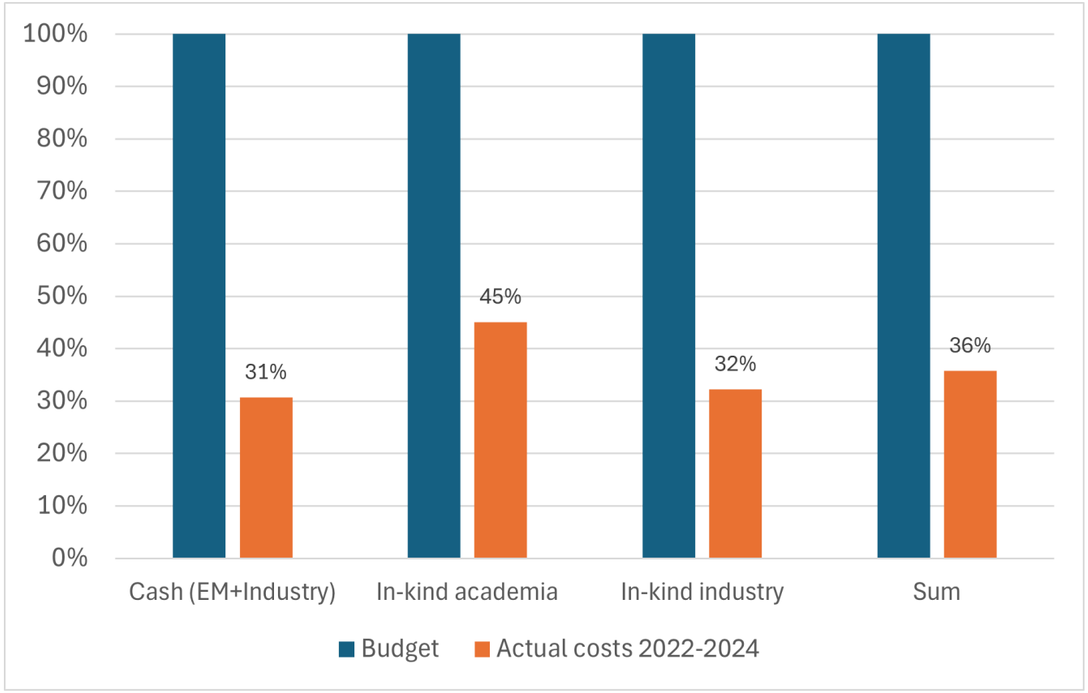
Up until 2024, the total costs within SESBC have been 59.1 MSEK, divided into a cash contribution of 22.8 MSEK from the Swedish Energy Agency and the industry partners, and 11.9 MSEK in-kind from academia and industry partners, respectively.

The total budget for the Centre is 165.4 MSEK as seen in Table 1, where more details can be found. Figure 1 displays how much of the budget for the different categories has been used. After the fourth call for projects, most of the cash from the Swedish Energy Agency and the industry partners has been allocated. Some in-kind from both academia and industry remains to be allocated for the upcoming activities. More details can be found in Figure 2.

Table 1: Total centre budget

	Budget (kSEK)				Actual costs up until 2024 (kSEK)				Balance to be utilized in stage one (kSEK)			
	Cash (EM+In-dustry)	In-kind aca-demia	In-kind industry	Sum	Cash (EM+In-dustry)	In-kind aca-demia	In-kind industry	Sum	Cash (EM+In-dustry)	In-kind aca-demia	In-kind industry	Sum
Centre manage-ment	8 000	0	0	8 000	4 208			4 208	3 792	0	0	3 792
Projects	66 394	54 231	36 811	157 435	18 617	24 440	11 862	54 919	47 776	29 790	24 949	102 516
Sum	74 394	54 231	36 811	165 435	22 825	24 440	11 862	59 127	51 568	29 790	24 949	106 308

Figure 1: Budget & Actual costs



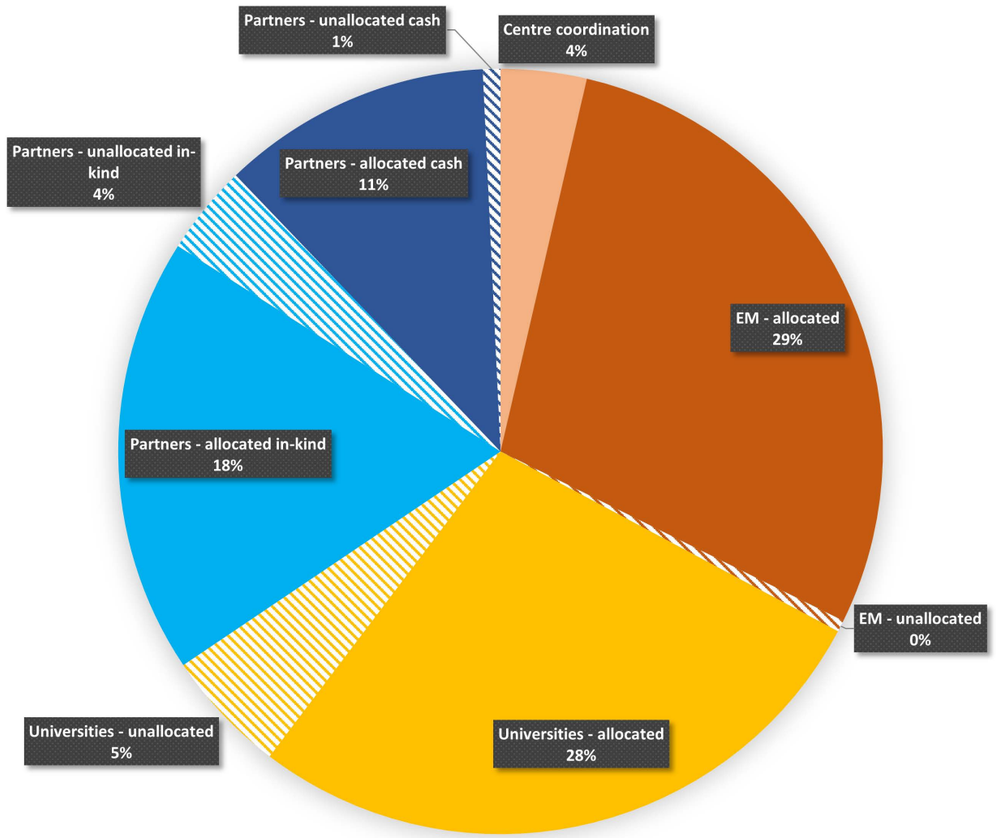


Figure 2: Total centre budget allocation

ORGANISATION

International Scientific Board
Paolo Mattavelli
University of Padova

Eleonora Riva Sanseverino
University of Palermo

Yaniv Gelbstein
Ben-Gurion University of the Negev

Magnus Hindsberger
Australian Energy Market Operator

Julia Matevosyan
Energy Systems Integration Group

Christina Roth
Universität Bayreuth

Christine Minke
Tu Clausthal

Silvia Muceli
Chalmers, IEEE WIE

Vice-chancellor of Chalmers

Program council

Centre Management

Operational board
Director and R&I layer leaders

R&I layer: Systems

Olof Samuelsson
Lund University

R&I layer: Materials and Devices for Energy Storage

Moyses Araujo
Karlstad University

R&I layer: Intelligent Energy Management

Tomas McKelvey
Chalmers

Reference groups

Program council

Niklas Thulin, Chair
Volvo Energy

Marina Oluic
Svenska Kraftnät

Sinisa Zubic
Hitachi Energy Research

Viktor Walter
Västra Götalandsregionen

Mariliis Lehtveer
Göteborg Energi

Ulf Helmersson
Linköpings universitet

Torbjörn Thiringer
Chalmers

Frida Lind (Jan–June)
Anna Dubois (July–Dec)
Chalmers

Sonja Lundmark
Chalmers

Marina Papatriantafilou
Chalmers

Centre Management

Massimo Bongiorno
Director

Anna Martinelli
Co-director

Sara Fogelström
Coordinator Projects

Johan Felix
Coordinator Industry

Marcus Folino
Communications Officer

Anna Abelius
Coordinator Events

Shruthi Murigayya Hiremath
Financial Officer

TIMELINE

The proposed timeline in the SESBC application

The proposed timeline in the SESBC application

6 months — Consortium agreement in place. Project portfolio decided.

1,5 years — First internal review of centre activities. Initiate centre´s training and utilization activities.

3 years — Second internal review of centre activities. New research projects granted.

5 years — Research projects finalized. Competence transfer.

Kickoff

1st call

2nd call

3rd call

4th call

27 projects running

STAGE II

2022 | **2023** | **2024** | **2025** | **2026** | **2027**

Centre agreement in place

Website launched

Industry Forum launched

Initiating PhD network

1st Summer school

Diversity review started

e·on New partner

Strategic workshop 1 (gap analysis)

Strategic workshop 2 (intro new members)

Definition of activities for stage 2

Joint activity with other competence centres

First SESBC conference Norrköping

Second SESBC conference Lund

PUBLICATIONS 2024

Doctoral theses

P. Ding, ”Organic Materials-based Electrochemical Flow Cells for Energy Applications”, 1st March 2024, Linköping University

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D. Kumar, L.R. Franco, N. Abdou, R. Shu, A. Martinelli, C.M. Araujo, J. Gladisch, V. Gueskine, R. Crispin, Z. Khan, “Water-in-Polymer Salt Electrolyte for Long-Life Rechargeable Aqueous Zinc-Lignin Battery. Energy Environ,” (2024), Mater., 8: e12752.

P. Ding, M. Vagin, M.J Jafari, A.Y. Mehandzhiyski, V. Gueskine, T. Abrahamsson, I. Zozoulenko, T. Ederth, R. Crispin, “Migration-mitigated crossover of organic redox anion across proton-exchange membrane,” Sustainable Energy & Fuels, 2024, 8, 4882-4892

R. Duvignau, V. Gulisano, M. Papatriantafilou, and R. Klasing, “Geographical Peer Matching for P2P Energy Sharing,” IEEE Access 2024. https://doi.org/10.1109/ACCESS.2024.3524091

S. Mardi, U. Ail, M. Vagin, J. Phopase, R. Crispin, “On the Reversibility of Sustainable Symmetric Aqueous Organic Redox Flow Batteries,” Advanced Energy and Sustainability Research, 2025 (https://doi.org/10.1002/aesr.202400324)

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A. R. Zamani, M. Beza, M. Bongiorno, A. Narula and J. R. Svensson, “Impact of the Reactive Behavior of Grid-Connected Converters on Resonance Stability,” 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 4781-4787, doi: 10.1109/ECCE55643.2024.10861535

B. Havers, M. Papatriantafilou and V. Gulisano. “Research Summary: Enhancing Localization, Selection, and Processing of Data in Vehicular Cyber-Physical Systems. Advanced tools, programming languages, and PLatforms for Implementing and Evaluating algorithms for Distributed systems, (ApPLIED), in conjunction with PODC,” 2024, https://doi.org/10.1145/3663338.3663680

B. Havers, M. Papatriantafilou, V. Gulisano, “Nona: A Framework for Elastic Stream Processing,” 44th IEEE International Conference on Distributed Computing Systems (ICDCS), 2024, https://doi.org/10.1109/ICDCS60910.2024.00071

C. Ge, B. Sandén, “Mapping the global distribution of supply chains using customs data,” SETAC Europe 26th LCA Symposium, Göteborg, October 2024

D. Svensson, T. Hammarström, X, Xu, O. Hjortstam, Y. Serdyuk, “Evaluation of Data AcquisitionSystems for Dielectric Frequency Response Measurements,” Proc. 5th IEEE International Conferenceon Dielectrics, ICD 2024, Toulouse, France, June 30 – July 4, 2024, doi: 10.1109/ICD59037.2024.10613244.

M. Ahouad, A. Sunjaq, E. Wikner, T. Thiringer, “Economic Assessment of Battery Energy Storage for Frequency Regulation in the Nordic Power Systems”, International Conference on the European Energy Market, EEM. 2024

K. Kamalinejad, A. Narula, M. Bongiorno, M. Beza and J. R. Svensson, "Investigation of Control Parameters' Impact on Damping Property of Grid-Forming Converters," 2024 IEEE Energy Conversion Congress and Exposition (ECCE)

C. Kimbrell, F. Lind & A. Dubois, “At the transport and energy interface. Swedish transportation research conference (STRC),” Chalmers, 16-17 October, 2024

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V. Gulisano, A. Margara, M. Papatriantafilou. “On the Semantic Overlap of Operators in Stream Processing Engines,” ACM/IFIP International Middleware Conference. 2024. https://doi.org/10.1145/3652892.3654790

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V. Q. Ngo, M. Papatriantafilou, “Cuckoo Heavy Keeper and the balancing act of maintaining heavy-hitters in stream processing,” CoRR abs/2412.12873, 2024, https://doi.org/10.48550/arXiv.2412.12873

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M. Scaccabarozzi [in collaboration with Göteborg Energi] “Empirical Assessment of Energy Consumption Forecast Techniques for Monitoring Systems,” 2024

S. B. Ravi Sankar “Comprehensive analysis of PTFE distribution in gas diffusion layers using advanced ex-situ and in-situ characterization techniques”, 2024

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C. Ge, A. Nordelöf, and B.A. Sandén, “Monitoring spatial and temporal flexibility in electricity systems,” submitted for publication in Energy conversion and management: X, (2024)

J. Liu, V. Gulisano, “On-demand Memory Compression of Stream Aggregates through Reinforcement Learning,” ACM/SPEC ICPE 2025.

M. Mohammadi, S. Mardi, J. Phopase, U. Ali, F. Wentz, J. Jibin, S. M. Berggren, R. Crispin, K. Tybrandt, A. Rahmanudin, “Stretchable organic redox-active fluid batteries,” submitted.

V. Joseph, R. Crispin, Z. Khan, “Wood-Derived Hard Carbon in Sodium and Potassium Ion Batteries: Mechanisms, Challenges, and Future Directions”

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C. Kimbrell, “Who delivers on the promise of community energy? Evaluating niche–regime interactions in Swedish energy communities,” submitted to ECPR General Conference, 26-29 August, 2025

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,” submitted to the IMP Conference, 20-22 August, 2025

D. Svensson, T. Hammarström, X, Xu, O. Hjortstam, Y. Serdyuk, “Comparison of Various Types of Electrodes for Dielectric Frequency Response Measurements on Thin Films,” submitted to IEEE Conference on Electrical Insulation and Dielectric Phenomena CEIDP2025, Manchester, UK, September 2025.

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L. Govik, C. Kimbrell, & F. Lind, “Sharing resources across boundaries: Cases of batteries and charging applications of a Vehicle OEM,” submitted to the IMP Conference, 20-22 August, 2025

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