Lunch seminar: Small Modular Reactors in the future Sustainable Electrical grid

Lina Bertling Tjernberg Professor in Power Grids

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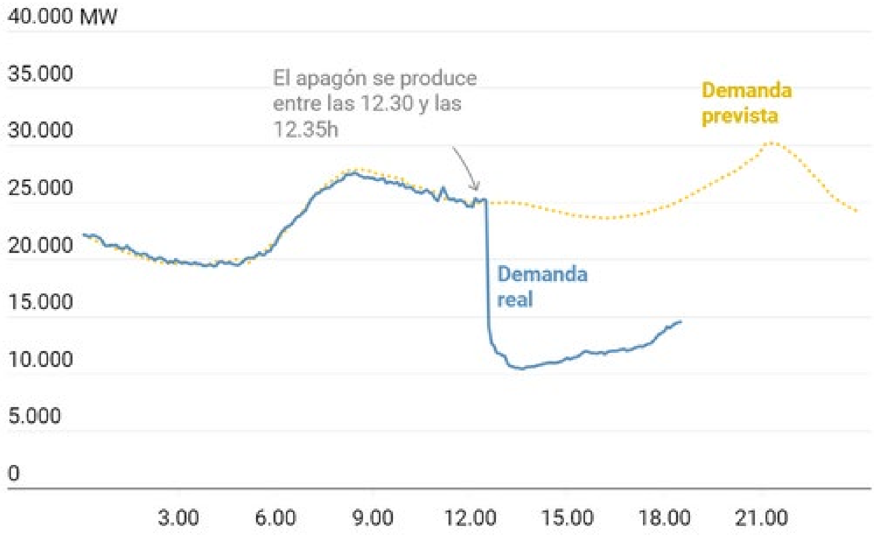
2025-05-07 KTH Library , Stockholm.

Monday 28 April 12-13– seminar 1 and blackout

2025 Iberian Peninsula blackout

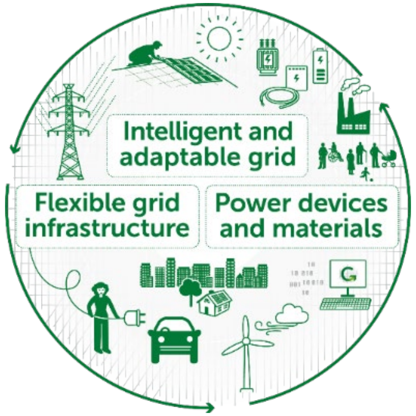
- On Monday 28 April 2025, at 12:33 CEST a major power blackout occurred across the Iberian Peninsula affecting mainland Portugal and peninsular Spain
- The power cut caused severe difficulties in telecommunications, transportation systems, and essential sectors such as emergency services.
- In 5 seconds 15 GW power were disconnected
- Much attention in media and society
- Restoring the power supply went successful and 90%

➢ An expert panel will investigate the incident.

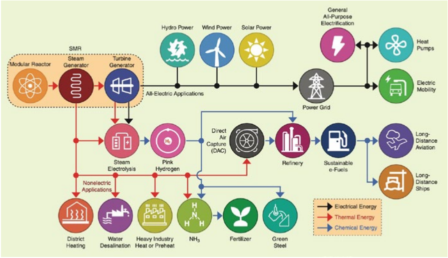


Key messages

- Thanks and Brief introductions and Energy book
- Global targets for sustainable development goals (SDGs) and EU binding agreements plan for green transition (Fit for 55) - transition towards fossil free electricity generation and sustainable fuels
- International Outlook - IEEE GridEdge SanDiego jan 25.
- Towards Sustainable and Resillient Power Supply - GreenGrids
  - need for flexibility
  - capacity shortage
  - market solutions with prosumer
  - circular economy



- Example GreenGrids - renewables, hydrogen, nuclear
  - Small Modular Reactors (SMR) list of papers from own work so far
  - First results on system benefits of SMR (IEEE ISGT Europe 2024)
- Welcome and contacts linab@kth.se www.kth.se/profile/linab



Welcome to KTH !

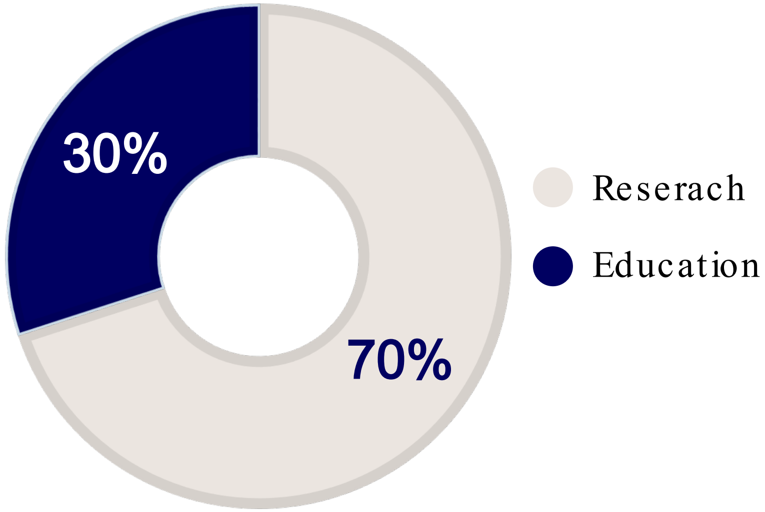
We take the lead for a sustainable society

KTH shapes the future through education, research and innovation. Situated in one of the world's most dynamic cities, we stand as a unifying force internationally to tackle global challenges.

- *We embrace diversity and attract talent from across the globe. Together we bring ideas to life.*
- *Our academic freedom and principles of openness and transparency are fundamental to democracy and the advancement of knowledge.*
- *We are bold, creative, and responsible, driven by our purpose to enable sustainable and gender-equal societies.*

KTH in brief

Sweden’s largest technical university



18,000
students

35%
women

2,300
International students

175,000
alumni in 100 countries

20
international alumni associations

4,000
staff (FTE)

336
professors

2,800
staff within research

1,700
doctoral students

KTH in brief

KTH is organized in five schools with departments

Architecture and the Built Environment

- Architecture
- Civil and Architectural Engineering
- Philosophy and History
- Real Estate and Construction Management
- Sustainable Development, Environmental Science and Engineering
- Urban Planning and Environment

Electrical Engineering and Computer Science

- Computer Science
- Electrical Engineering
- Human Centered Technology
- Intelligent Systems

Industrial Engineering and Management

- Energy Technology
- Industrial Economics and Management
- Learning in Engineering Sciences
- Engineering Design
- Materials Science and Engineering
- Production Engineering

Engineering Sciences in Chemistry, Biotechnology and Health

- Biomedical Engineering and Health Systems
- Chemistry
- Chemical Engineering
- Engineering Pedagogics
- Fibre and Polymer Technology
- Gene Technology
- Industrial Biotechnology
- Protein Science

Engineering Sciences

- Applied Physics
- Engineering Mechanics
- Mathematics
- Physics

Brief intro Lina Bertling Tjernberg

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@lina.bertling
www.kth.se/profile/linab

Professor in Power Grid Technology at KTH Royal Institute of Technology and Deputy Head of School of EECS with focus on Research & Impact

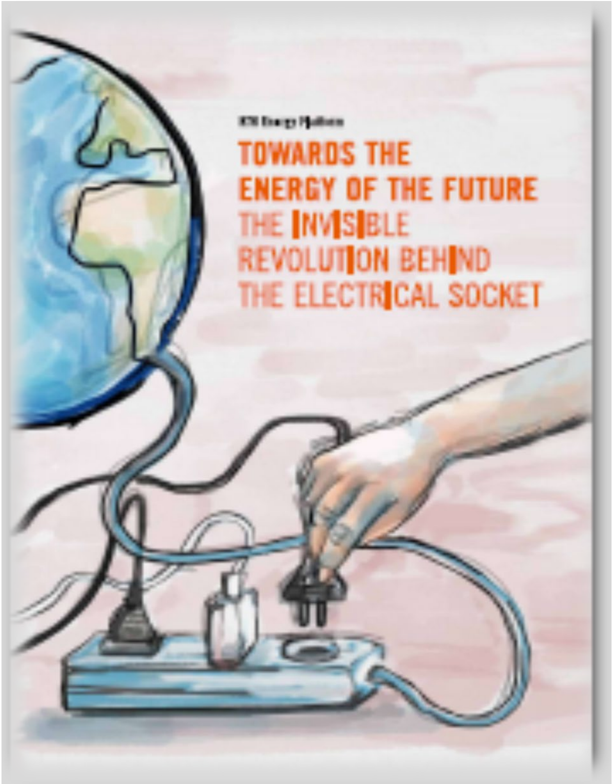
- Docent 2008, Ph.D. 2002 Electric Power Systems all at KTH.
- Masters Vehicle engineering (T92) Systems engineering KTH, Forsmark school energy.
- Fellow of the Royal Swedish Academy of Engineering IVA.
- IEEE Senior member, IEEE Power & Energy Society (PES) Distinguished lecturer.
- Previously with Chalmers Technical University 2009-2013, Swedish National Grid 2007-2009.
- Visiting with: Nanyang Technological University 2023, Stanford University 2014, University of Toronto 2002/2003 and University of Saskatchewan 2000.
- Expert for EU HORIZON EUROPE
- *Past:* IEEE PES board Treasure/Secretary (2012-2016), IEEE Sweden Chapter PE/PEL chair 2009-2019, Chair of the IEEE RRPA (2011-2013), Member of the Swedish Government Coordination Council for Smart Grid (2012-2014), Editor for the IEEE Smart Grid Transaction (2010-2015).
- *Author:* 150+ papers, 2 books, 9 chapters and the book on *Infrastructure Asset Management with Power System Examples, L. Bertling Tjernberg, CRC Press, 2018*

KTH Energy anthology

- Researchers at KTH have published an anthology focused on providing knowledge about the challenges and opportunities of energy.
  - [Popular new science anthology on energy set to become knowledge platform | KTH]
  - The book is available in Swedish and English and can be down loaded for free or can be bought in hard copy.

Parts of the energy anthology editorial team
September 2022, Vetenskap och allmänhet

- ✓ More information from here: [Anthology on energy - Vetenskap & Allmänhet (vetenskapallmanhet.se)]



Sustainable developments and EU climate laws

The United Nations adopted a resolution for sustainable development with 17 goals (sustainable development goals – SDG) to be achieved by 2030.

The European climate law makes reaching the EU's climate goal of reducing EU emissions by at least 55% by 2030 a legal obligation.

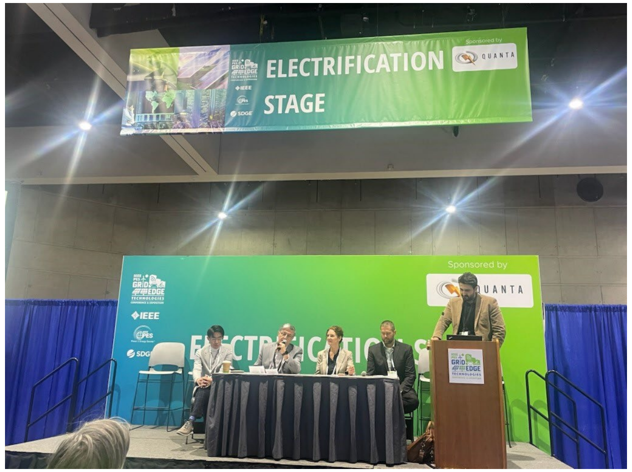
- EU countries are working on new legislation to achieve this goal and make the EU climate-neutral by 2050.
- The Fit for 55 package is a **set of proposals to revise and update EU legislation** and to with the aim of ensuring that EU policies are into line with the climate goals agreed by the Council and the European Parliament.

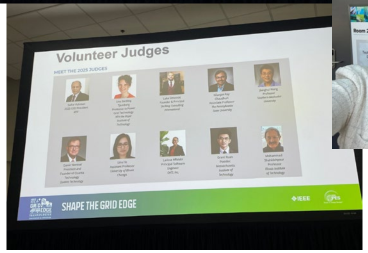
International Outlook

IEEE PES Grid Edge Technologies, SanDiego January 2025

- Technology stages
  1. Artificial Intelligence (AI)
  2. Electrification
  3. Distributed Energy Resources (DERs)
  4. Sustainability and Resiliency
  5. Startup and Innovation Showcase

- Some reflections
  - Increased needs from society and challenges e.g. wild fires
  - Availability to data is a key
  - Huge need for additional power supply e.g. data centers and several examples on planned investments in SMR





Power Grids: energy infrastructure

Fundamentals of power grids

- Electricity can be produced and consumed – prosumers do both
- The Power grid/electricity grid is the infrastructure that makes it possible to transport electrical energy, electricity, from producer to consumer.
- The future power grid is a mixture of traditional structure and new technologies including sector couplings – see GreenGrids Vision

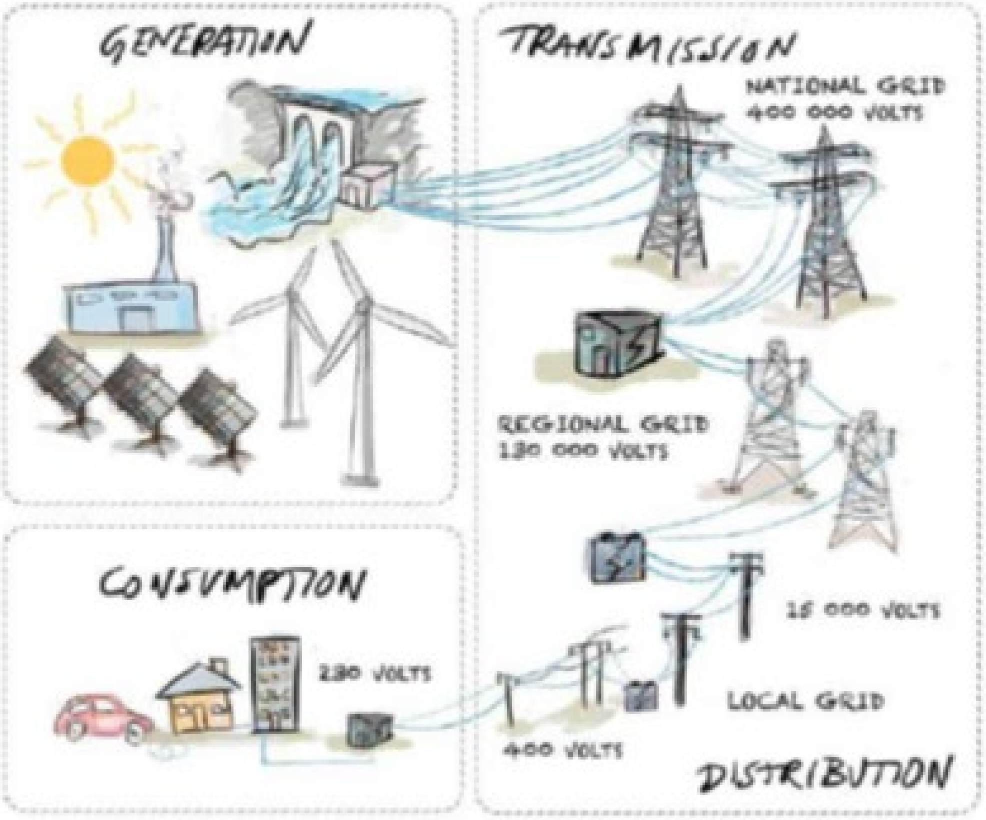


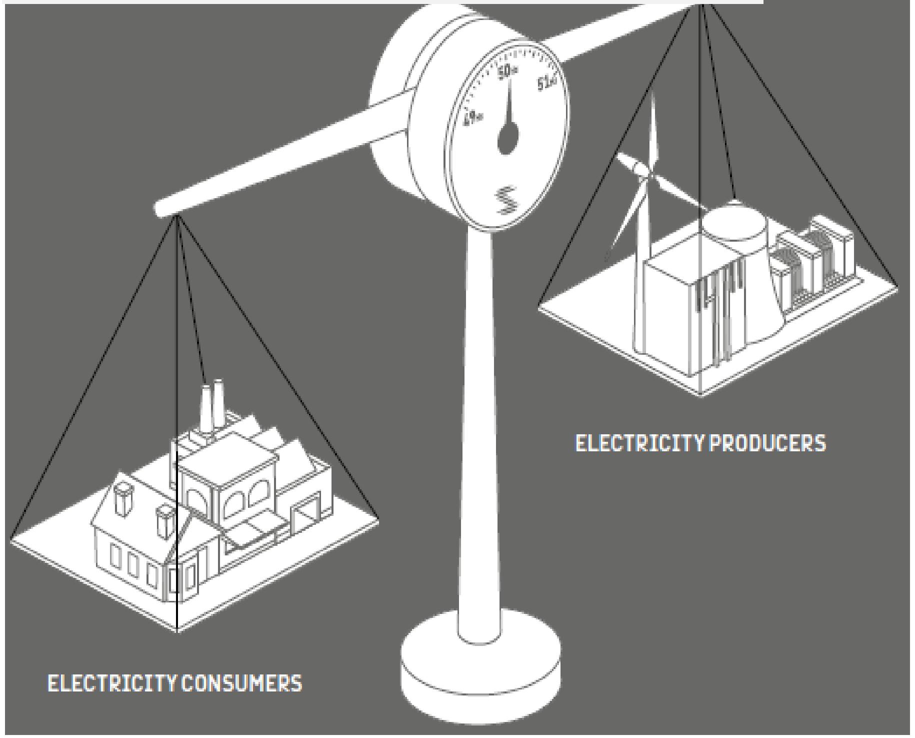
Figure 1: Schematic image of the electricity grid.

Bertling Tjernberg, L. (2022). Sustainable electricity grids – a prerequisite for the energy system of the future. In F. Brounéus & C. Duwig (Eds.), Towards the energy of the future – the invisible revolution behind the electrical socket.

Power Grids: energy infrastructure

Fundamental two technology challenges/constrains for a power grid

Balance in the power system



Grid Capacity

Source for figures: Swedish National Grid

Power Grids: energy infrastructure

Interconnected power grid in Europe

- ENTSO-E is the European association for the cooperation of transmission system operators (TSOs) for electricity
- A much deeper coordination between operators close to real-time is needed to integrate more renewables into the grid and reduce carbon emissions cost-effectively and in all security.

Source: figures ENTSO-E

- 16 March 2022 synchronisation of the Continental European Power System with the power systems of Ukraine and Moldova.

Power Grids: energy infrastructure

TYNDP 2024

- EU Regulation 2022/869 requires that the European Network of Transmission System Operators for Electricity (‘ENTSO-E’) and the European Network of Transmission System Operators for Gas (‘ENTSOG’) jointly develop scenarios for the future European energy system in the context of their respective Ten-Year Network Development (TYNDPs).

Download | ENTSOs TYNDP 2024 Scenarios

Source: : ENTSO-E

Power Grids: evolving for sustainability

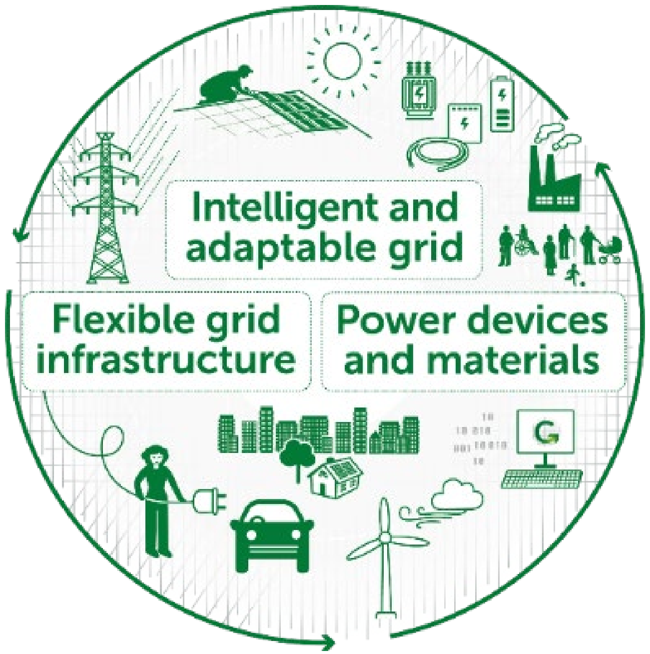
Trends for power grids evolving for sustainability (according to LB)

- ❑ Huge increase in electricity generated from wind and solar
- ❑ Smart grid technologies and integration of intermittent electricity generation
- ❑ Electrification of transportation sector and industrial processes
- ❑ Local electric generation and energy storage solutions (PV and EV batteries)
- ❑ Hydrogen solutions and sector couplings energy/transportation/industry
- ❑ Nuclear power and use of Small Modular Nuclear Reactors (SMR)

Example: PowerGrids

GreenGrids vision for a sustainable and resilient power supply

1. The intelligent and adaptable grid, which creates new values for electric power plants and electricity customers.
2. The flexible grid infrastructure, which integrates renewable energy sources and energy storage systems to even out variations in electricity generation.
3. Development of components, materials and environmentally friendly solutions with circular economy.

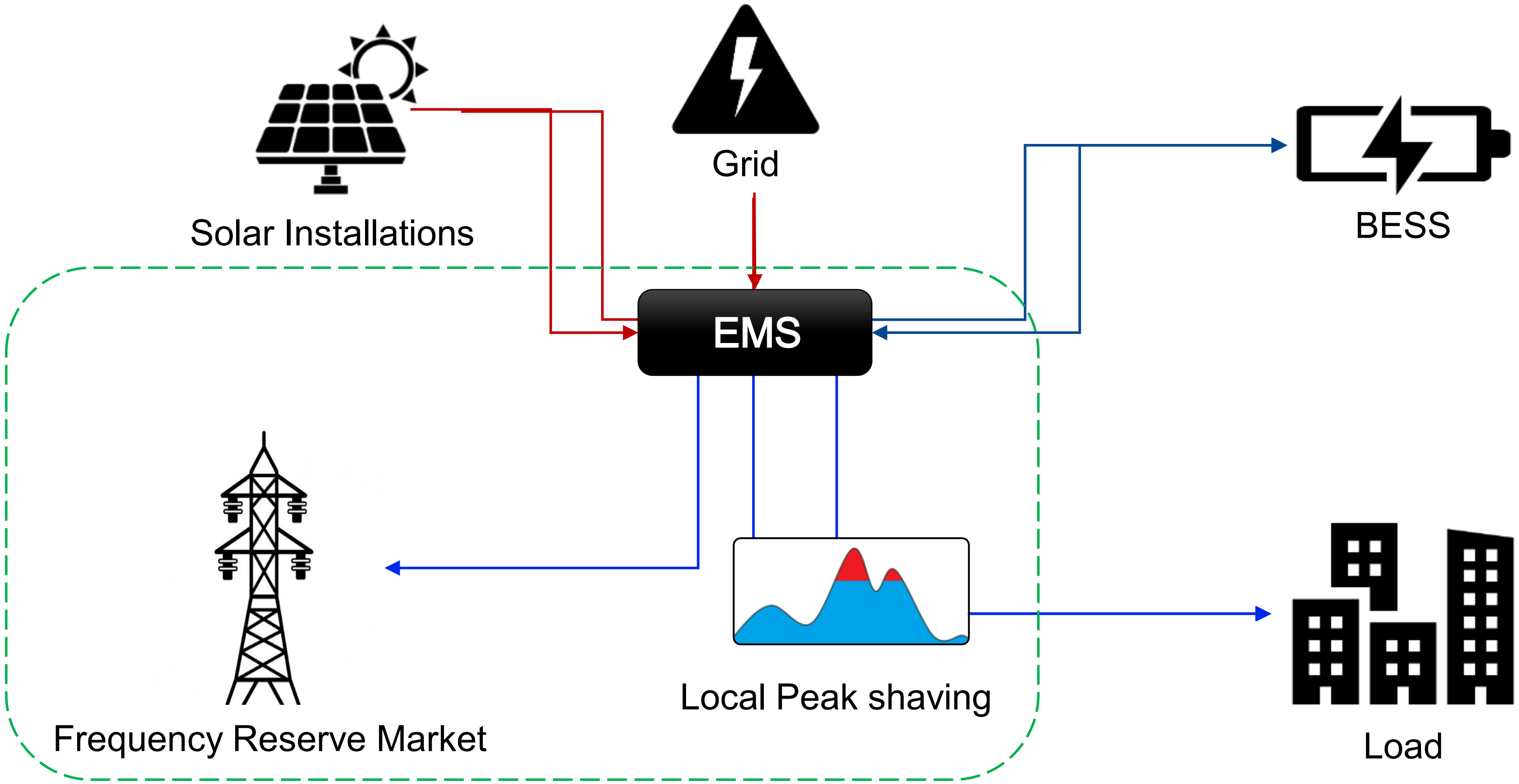


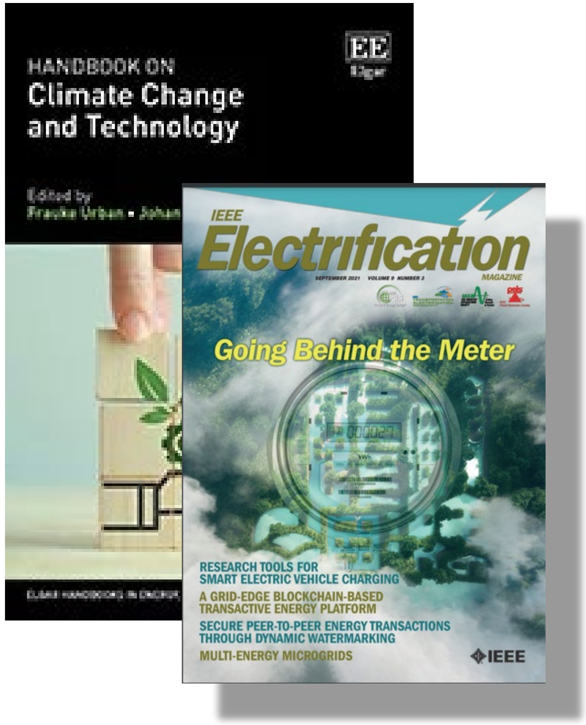
Bertling Tjernberg, L. (2022). Sustainable electricity grids – a prerequisite for the energy system of the future. In F. Brounéus & C. Duwig (Eds.), Towards the energy of the future – the invisible revolution behind the electrical socket.

L. Bertling Tjernberg, H. Shafique (2023), Chapter 17, In Urban F. and Nordensvärd J. (Eds) Handbook on Climate Change and Technology, Edward Elgar Publishing, https://doi.org/10.4337/9781800882119.00029 (pp 274-290), December 2023.

Example: PowerGrids - Flex

Example: local generation and battery storage 1(2)





***EMS:**
Energy Management System

***BESS:**
Battery Energy Storage System

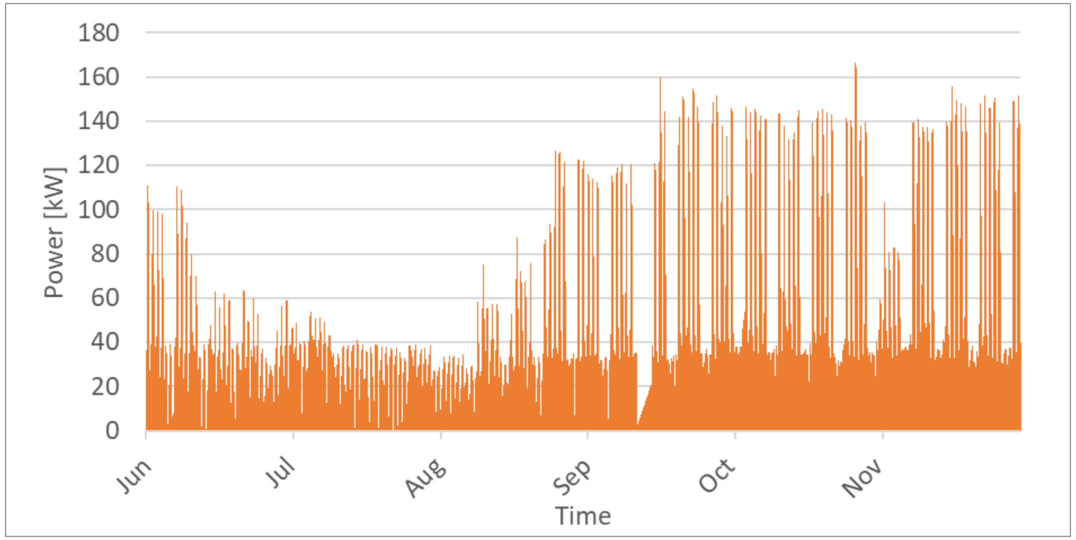
H. Shafique et al., Behind the Meter Strategies Energy management system with a Swedish case study, IEEE Electrification Magazine, vol. 9, no. 3, 2021.
Energy Management System (EMS) of Battery Energy Storage System (BESS) – Providing Ancillary Services, IEEE PowerTech, Madrid, 2021.

Example: PowerGrids - Flex

Example: local generation and battery storage 2(2)

Sinntorp school (400 students)

Real-time Hourly Average Power
(Jun-Nov 2021)



Solar PV peak power (DC) production
= 300 kW

Max Inverter rating
= 60 kW

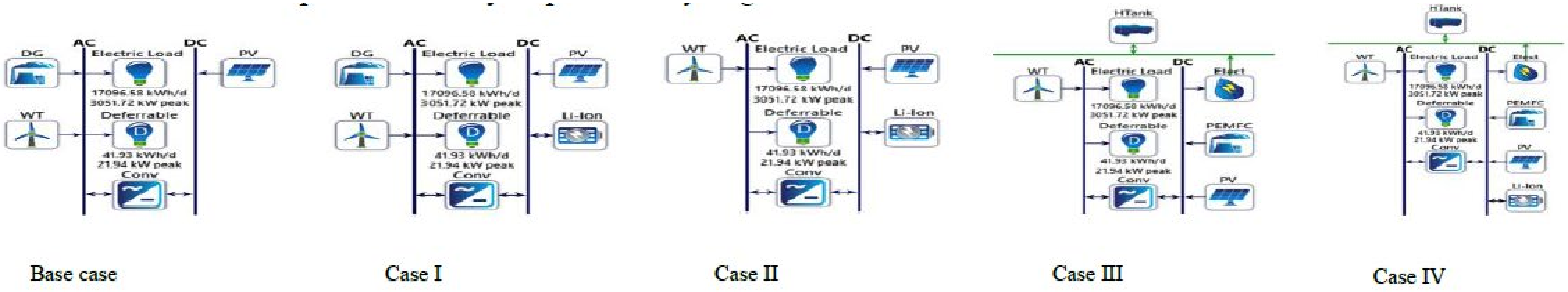
Useable BESS Capacity
= 75 kWh

H. Shafique, D.-E. Archer , R. Eriksson, L. B. Tjernberg, Real-time Operation Model for Energy Management System of Battery Energy Storage System - Case Study: The School of Sinntorp, In proceedings of the International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Manchester, UK, June 2022.

Example: PowerGrids - Flex

Fig. 1. Geographical location of Gara Botora-Kemisie

Example: Sustainable Off-grid Systems with Integration of Renewable Generation and Hydrogen-Fuel Cell



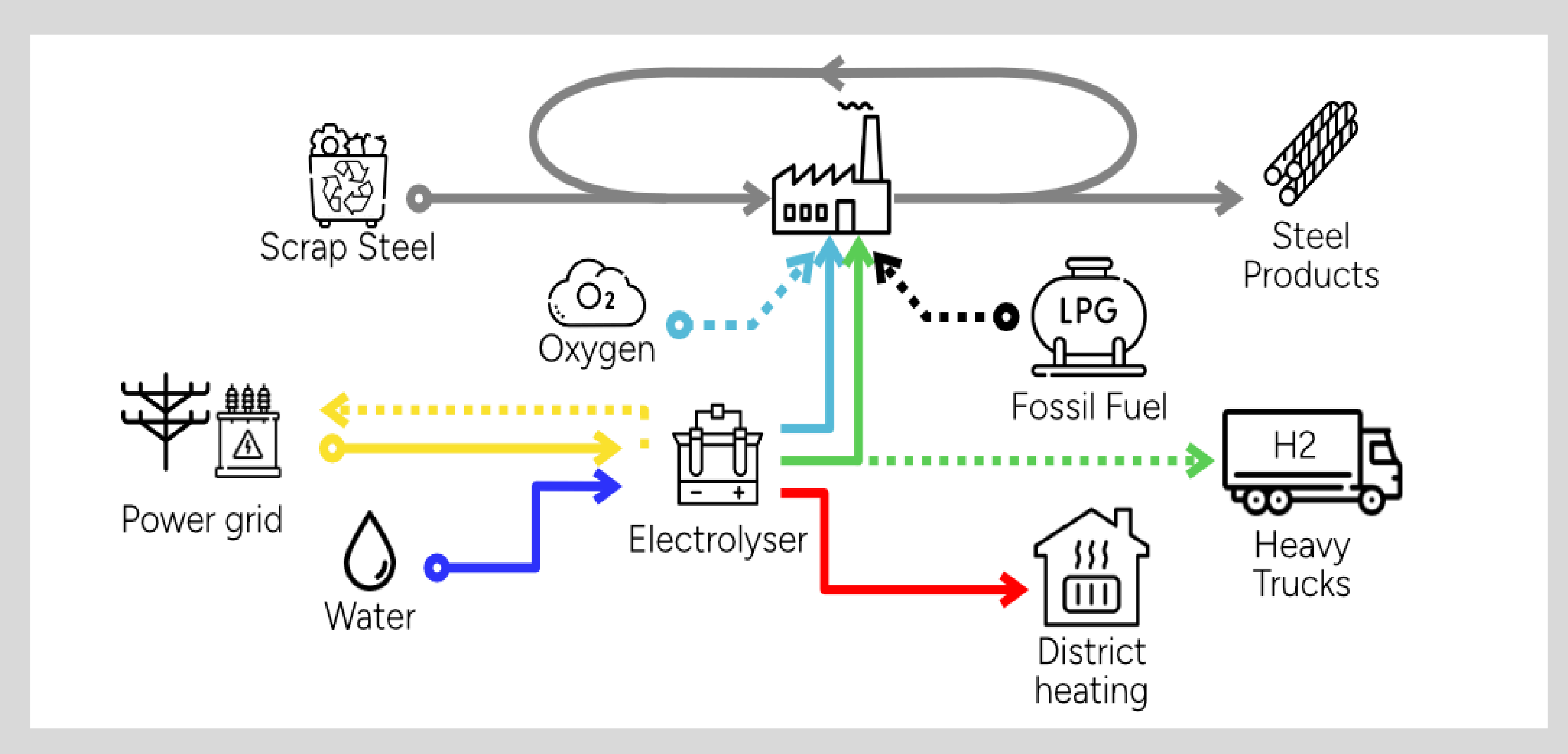
- ✓ The results of the simulation indicate that, even though the systems with diesel generators are more reliable, the high fuel cost and high emission content of these systems are the disadvantages. Absence of storage also leads to excess electricity curtailment in these systems. The system with diesel generator alone releases 2 848.4 t/yr of pollutants in which 98.52% of total pollutants is CO2.

Y. Bekele, G. Biru , L. Bertling Tjernberg , Sustainable Off-grid Systems with Integration of Renewable Generation and Hydrogen-Fuel Cell, Accepted to be published at the IEEE PES Innovative Smart Grid Technology Conference Europe, Serbia, October 2022.

Example: PowerGrids – Sector coupling

Example: Sector-coupling Green Hydrogen to Electrify Steel Production

- **A Case Study at Ovako Hofors**
- Vinnova project with partners:
  - ✓ Ovako
  - ✓ Volvo Technology
  - ✓ Hitachi Energy
  - ✓ KTH
- More information: https://www.kth.se/profile/linab/page/hydrogen-power-grid-technologies-and-transportation



T. Elmfeldt, Y. Arafat, L. Bertling Tjernberg, A. Lugnet, and G. Nyström, [Sector-coupling Green Hydrogen to Electrify Steel Production - A Case Study at Ovako Hofors,](#) Proceedings of the International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Auckland, June 2024.

Example: Nuclear power

Invited IEEE DLP talk and visit at a reactor in operation at the campus in Budapest

2025-04-03 , pictures @linabertling

Example: PowerGrids – new nuclear and SMR

Example: Small Nuclear Reactors (<= 300 MW) integrated with power grids

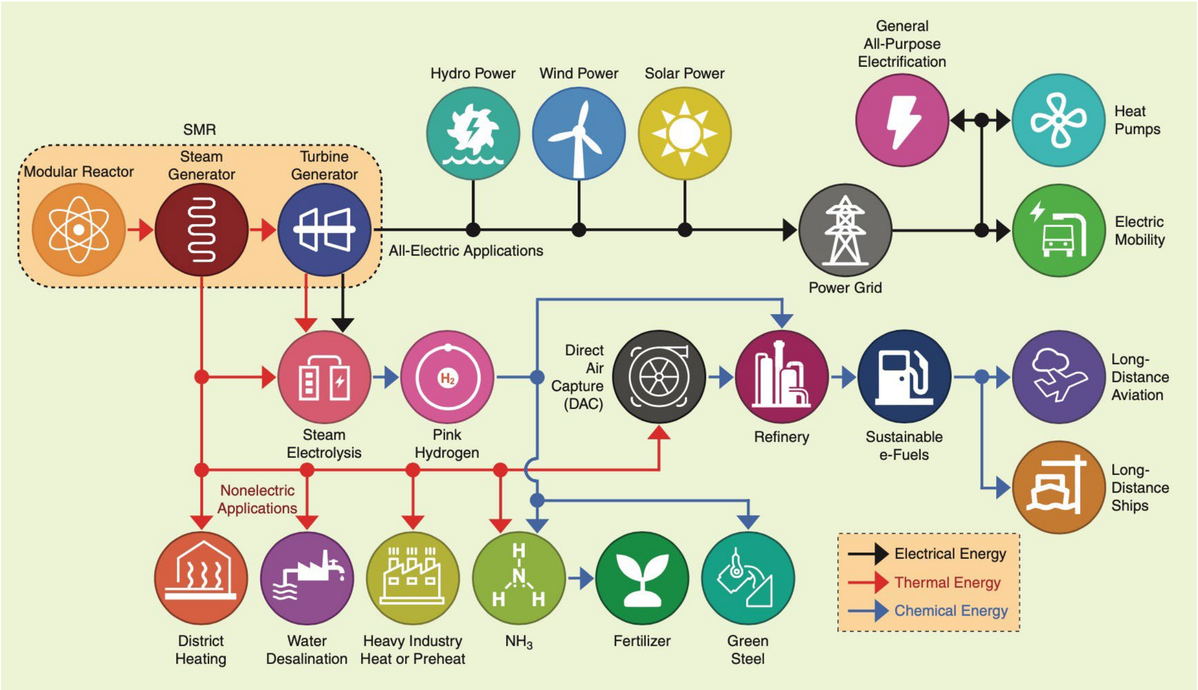


TABLE III
FLEXIBILITY SERVICES OFFERED BY SMRS BASED ON CONVENTIONAL NUCLEAR REACTOR TECHNOLOGIES [22]

SMR concept	Availability factor	Dispatch range	Ramping capability
GE-Hitachi BWRX-300	≥ 95 %	50–100 %	± 0.5 %/min
NuScale VOYGR	≥ 95 %	20–100 %	± 0.8 %/min
Candu Energy SMR	≥ 94 %	60–100 %	± 1 %/min
Rolls-Royce SMR	≥ 95 %	50–100 %	± 3–5 %/min
EDF NUWARD	≥ 90 %	20–100 %	± 5 %/min
KHNP/KAERI i-SMR	≥ 95 %	20–100 %	± 5 %/min
Mitsubishi IMR	≥ 97 %	0–100 %	± 5 %/min
Rosatom ABV-6E	n/a	20–100 %	± 6 %/min

J. K. Nøland, M. Hjelmeland, C. Hartmann, T. Øyvang, M. Korpås and L. B. Tjernberg, Running Renewable-Rich Power Grids With Small Modular Reactors: Their grid-forming role in the future power system, in IEEE Electrification Magazine, vol. 12, no. 4, pp. 20-29, Dec. 2024, doi: 10.1109/MELE.2024.3473130.
J. K. Nøland, M. N. Hjelmeland, C. Hartmann, L. B. Tjernberg and M. Korpås, Overview of Small Modular and Advanced Nuclear Reactors and Their Role in the Energy Transition, in IEEE Transactions on Energy Conversion, January 2025, doi: 10.1109/TEC.2025.3529616.

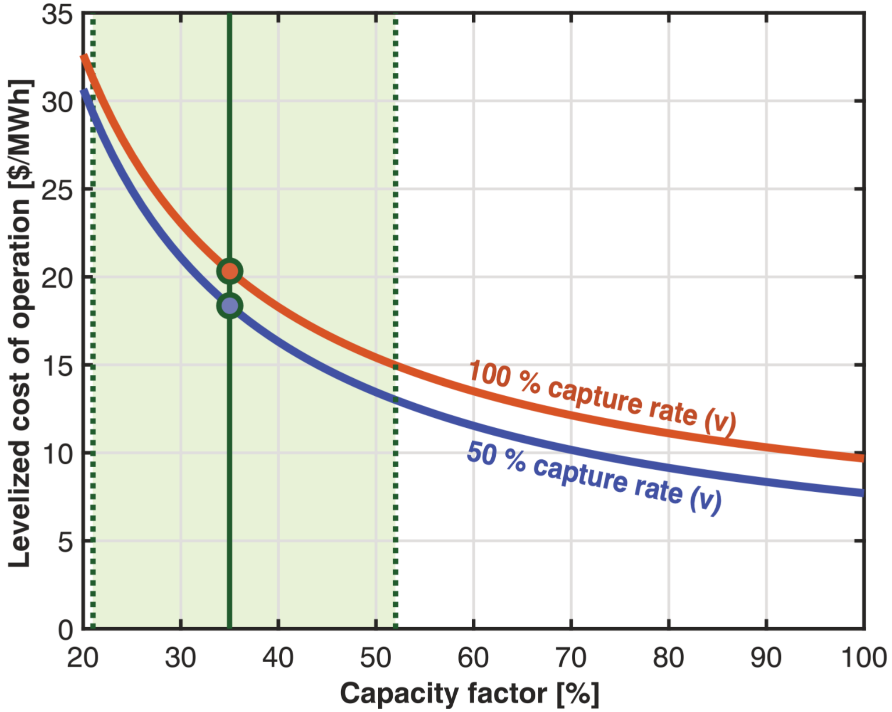
Example: PowerGrids – new nuclear and SMR

Example: The Potential of Small Modular Reactors to Provide System-Bearing Services in the Future Power Grid

- The operational cost of firming up inverter-based resources of a capacity factor of 35 % with synchronous consdensers (SCs) is approximately $20/MWh assuming lack of system-bearing services and SMRs.

SYNCHRONOUS CONDENSER ECONOMIC MODEL PARAMETERS

Parameter	Symbol	Value	Ref.
Capital expenditure (CAPEX) in 2024 $	c	$427/kVA	[24]
Operational expenditure (OPEX)	d	2 %	[25]
Capacity factor (utilization rate)	k	21–52 %	[26]
Power losses relative to nominal rating	σ	3 %	[27]
Wholesale electricity price	p	$127.2/MWh	[28]
Capture rate of electricity price	v	50–110 %	[29]
Weighted average cost of capital (WACC)	r	9.7 %	[30]
Expected lifetime in number of years	n	30	[24]



J. K. Nøland, M. Hjelmeland, M. Korpås, L. Bertling Tjernberg , The Potential of Small Modular Reactors to Provide System-Bearing Services in the Future Power Grid, In proceedings of IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe) 2024, Dubrovnik.

Example: PowerGrids – SMR

Research publications so far from research

- J. K. Nøland, M. N. Hjelmeland, C. Hartmann, L. B. Tjernberg and M. Korpås, Overview of Small Modular and Advanced Nuclear Reactors and Their Role in the Energy Transition, in *IEEE Transactions on Energy Conversion,* January 2025, doi: 10.1109/TEC.2025.3529616.
- J. K. Nøland, M. Hjelmeland, C. Hartmann, T. Øyvang, M. Korpås and L. B. Tjernberg, Running Renewable-Rich Power Grids With Small Modular Reactors: Their grid-forming role in the future power system, in *IEEE Electrification Magazine*, vol. 12, no. 4, pp. 20-29, Dec. 2024, doi: 10.1109/MELE.2024.3473130.

Example: PowerGrids – new nuclear

- J. K. Nøland, M. Hjelmeland, M. Korpås, L. Bertling Tjernberg , The Potential of Small Modular Reactors to Provide System-Bearing Services in the Future Power Grid, In proceedings of IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe) 2024, Dubrovnik.
- J. K. Nøland, M. Hjelmeland, L. B. Tjernberg and C. Hartmann, The Race to Realize Small Modular Reactors: Rapid Deployment of Clean Dispatchable Energy Sources, in *IEEE Power and Energy Magazine*, vol. 22, no. 3, pp. 90-103, May-June 2024, doi: 10.1109/MPE.2024.3357468.

IEEE PES ISGT Europe 2024 Conference

Dubrovnik, Croatia
October 14th - 17th

The Potential of Small Modular Reactors to Provide System-Bearing Services in the Future Power Grid

Jonas Kristiansen Nøland [a], Martin Hjelmeland [a], Magnus Korpås [a], and **Lina Bertling Tjernberg** [b]

[a] NTNU Norwegian University of Science and Technology

[b] KTH Royal Institute of Technology

Agenda

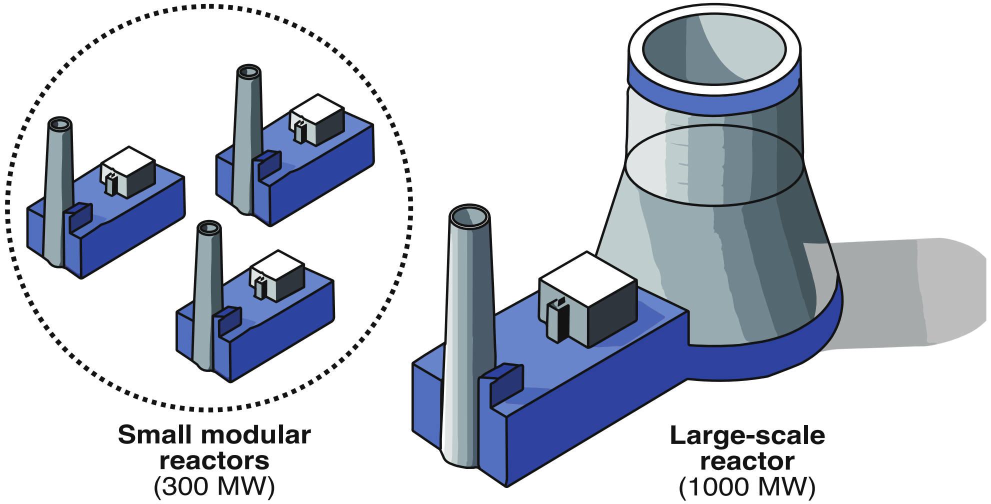
1. Small-scale vs. large-scale reactors
2. System-bearing ancillary services from small modular reactors (SMRs)
3. Intertial response and frequency regulation
4. Single-line grid equivalent of SMRs during short-circuits
5. Machine voltage and short-circuit strength comparison between SMRs and synchronous condensers (SCs)
6. SC economics as a reference for the value of SMRs
7. Conclusion

J. K. Nøland, M. Hjelmeland, L. B. Tjernberg and C. Hartmann, "The Race to Realize Small Modular Reactors: Rapid Deployment of Clean Dispatchable Energy Sources," in *IEEE Power and Energy Magazine*, vol. 22, no. 3, pp. 90-103, May 2024.

1. Small-scale vs. large-scale reactors

What are Small Modular Reactors?

- ❖**Small** physically a fraction of the size of a conventional nuclear power reactor.
- ❖**Modular** making it possible for systems and components to be factory-assembled and transported as a unit to a location for installation.
- ❖**Reactors** harnessing nuclear fission to generate heat to produce electricity.

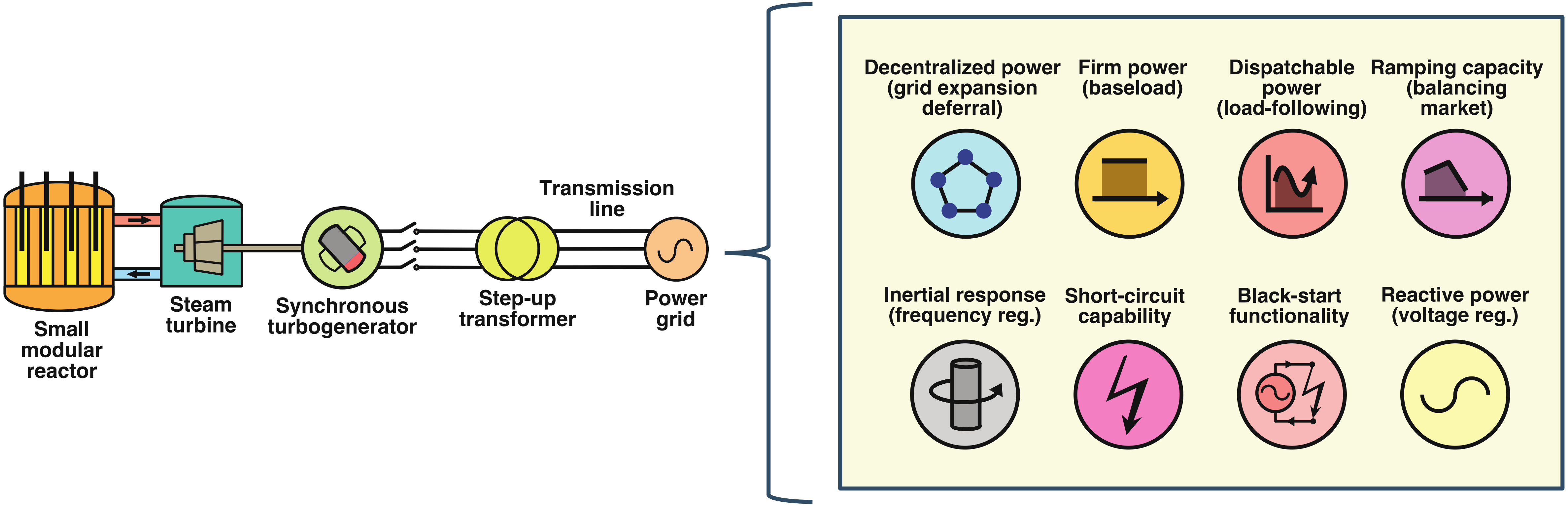


IAEA ELECTRICAL CAPACITY CLASSIFICATION [12]

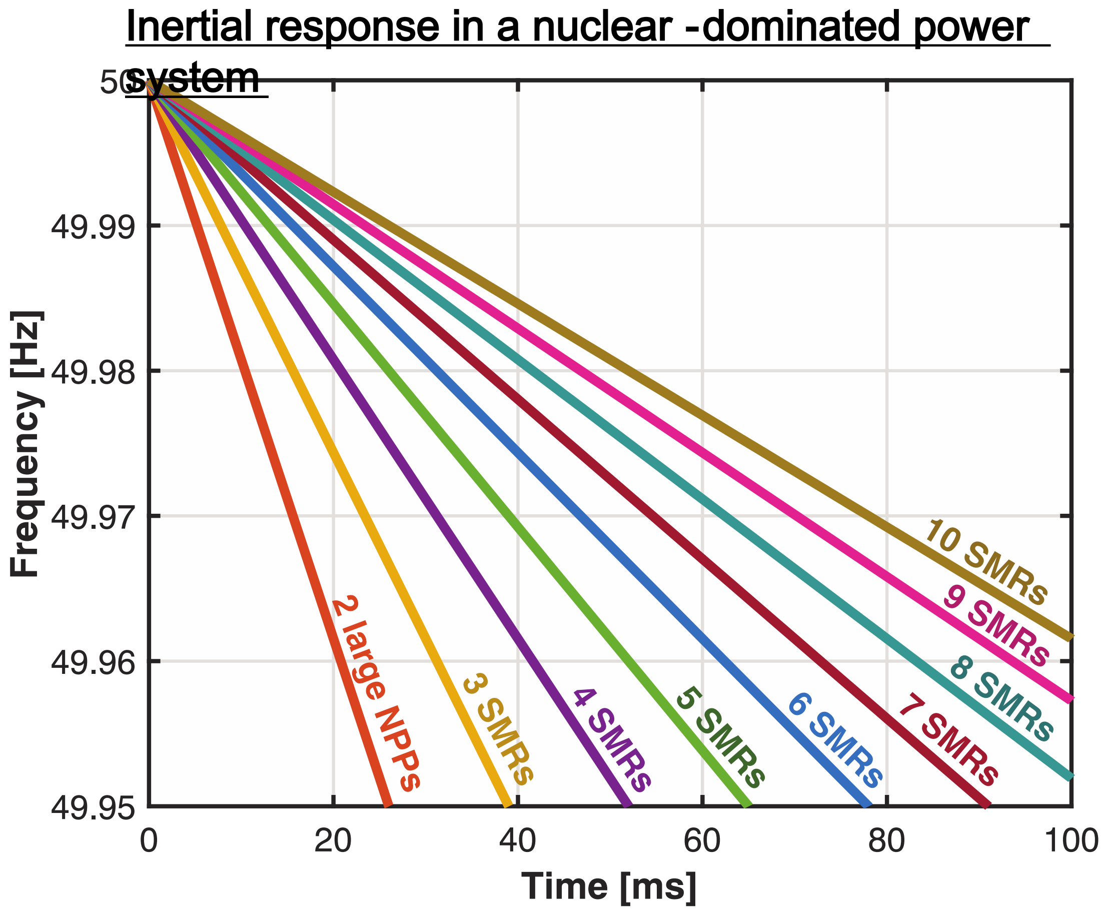
Type	Lower	Upper
Microreactor (MR)	0 MW	10 MW
Small modular reactor (SMR)	10 MW	300 MW
Medium-scale reactor (MSR)	300 MW	700 MW
Large-scale reactor (LSR)	700 MW	–

Source: What are Small Modular Reactors (SMRs)? | IAEA

2. System -bearing ancillary services from small modular reactors (SMRs)



3. Inertial response and frequency regulation

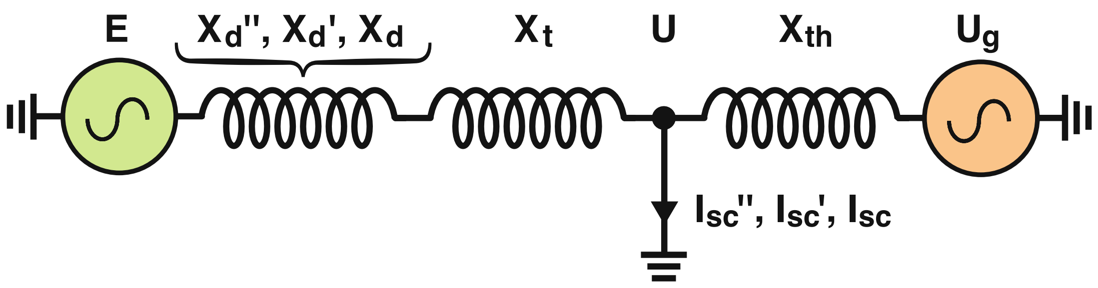


Assume one power unit falls out of the power system. What will be the intertial response depending on the number of SMR units?

Swing equation:

$$\mathrm{RoCoF} = \frac{\mathrm{df}}{\mathrm{dt}} \approx \frac{\mathrm{f_0}}{2\mathrm{H}} \cdot \frac{\mathrm{P_g} - \mathrm{P_l}}{\mathrm{S_b}}$$

4. Single-line grid-equivalent of SMRs during short-circuit



REPRESENTATIVE STANDARD PARAMETER VALUES FOR A GENERIC TURBOGENERATOR [18], [19]

Parameter	Symbol	Lower	Upper
Synchronous reactance	X_d	1.80 pu	2.00 pu
Transient reactance	X'_d	0.22 pu	0.30 pu
Subtransient reactance	X''_d	0.17 pu	0.25 pu
External reactance	X_t	0.10 pu	0.15 pu
Total inertia	H	6.50 s	8.70 s

Voltage behind

$$\mathbf{E} = U + \mathbf{j}(X_d + X_t)I\mathbf{e}^{-\mathbf{j}\varphi}$$

Stationary short-circuit current:

$$I_{sc} = \frac{|\mathbf{E}|}{X_d + X_t}$$

Transient short-circuit current:

$$I'_{sc} = \frac{|\mathbf{E}|}{X'_d + X_t}$$

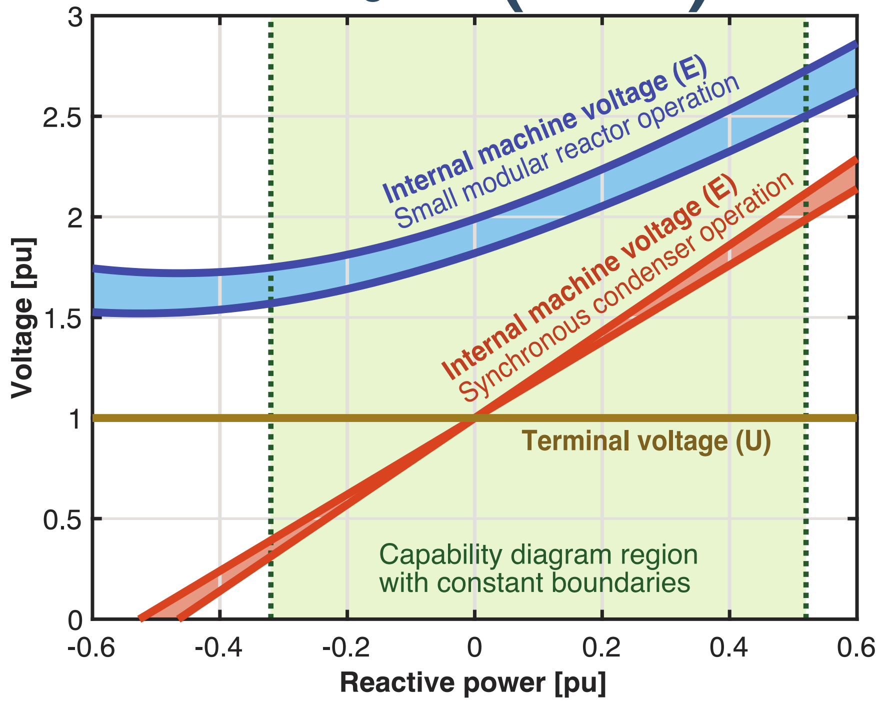
Subtransient short-circuit current:

$$I''_{sc} = \frac{|\mathbf{E}|}{X''_d + X_t}$$

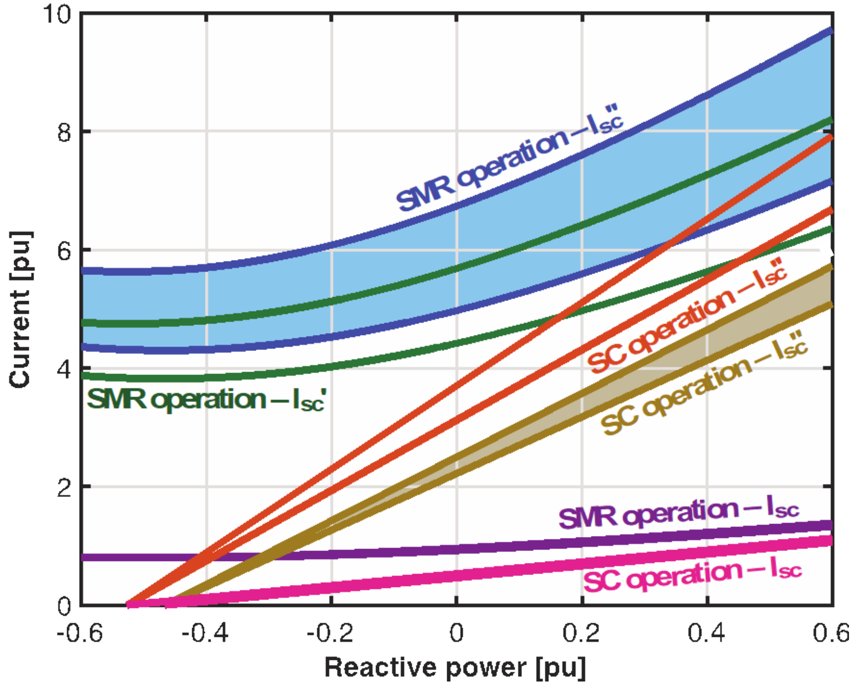
5. Machine voltage and short -circuit strength comparison between SMRs and synchronous condensers (SCs)

SMR operation yields higher machine voltage and higher short circuit grid strength as compared to synchronous condenser (SC) operation!

Voltage behind reactance



Short-circuit level



6. Synchronous condenser economics as a reference for the value of SMRs

The operational cost of firming up inverter -based resources of a capacity factor of 35 % with synchronous consdensers (SCs) is approximately $20/MWh assuming lack of system -bearing services and SMRs.

SYNCHRONOUS CONDENSER ECONOMIC MODEL PARAMETERS

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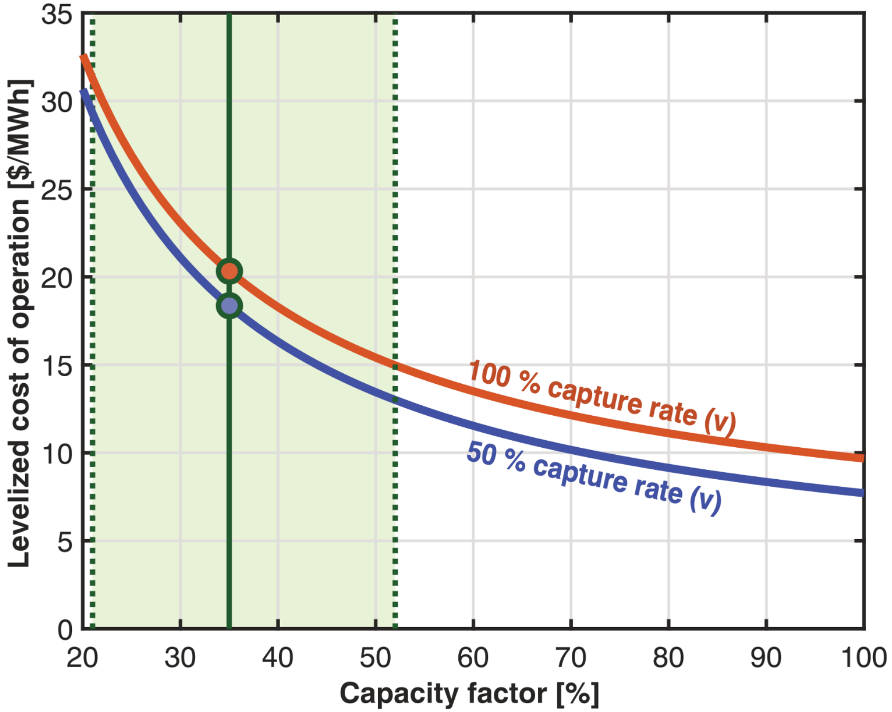

7. Conclusion

- Small modular reactors (SMRs) can provide a wide range of system-bearing ancillary services that can help support a renewable-rich power grid based on inverter-based resources (IBRs)
- Synchronous condensers (SCs) are the reference used in this work to emphasise the technical and economical benefits of SMRs
- If SMRs are deployed in the future power grid, they can reduce the additional cost of operation of IBRs by avoiding the need for SCs
- SMRs have been shown to positively impact the inertial response, implying that a power system consisting of SMRs might have less frequency regulation challenges

Thanks & Welcome: questions and contact!

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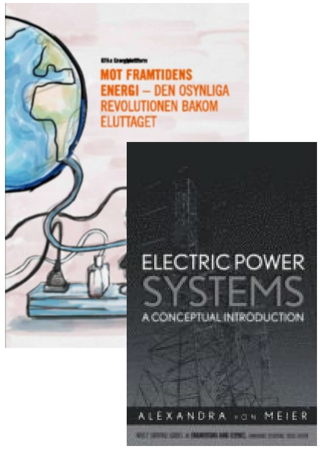
www.kth.se/profile/linab



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