COMMUNICATION AND ENERGY SUPPLY SYSTEMS

Interlinking worlds caught in complexity

Friederich Kupzog
Head of Center for Energy

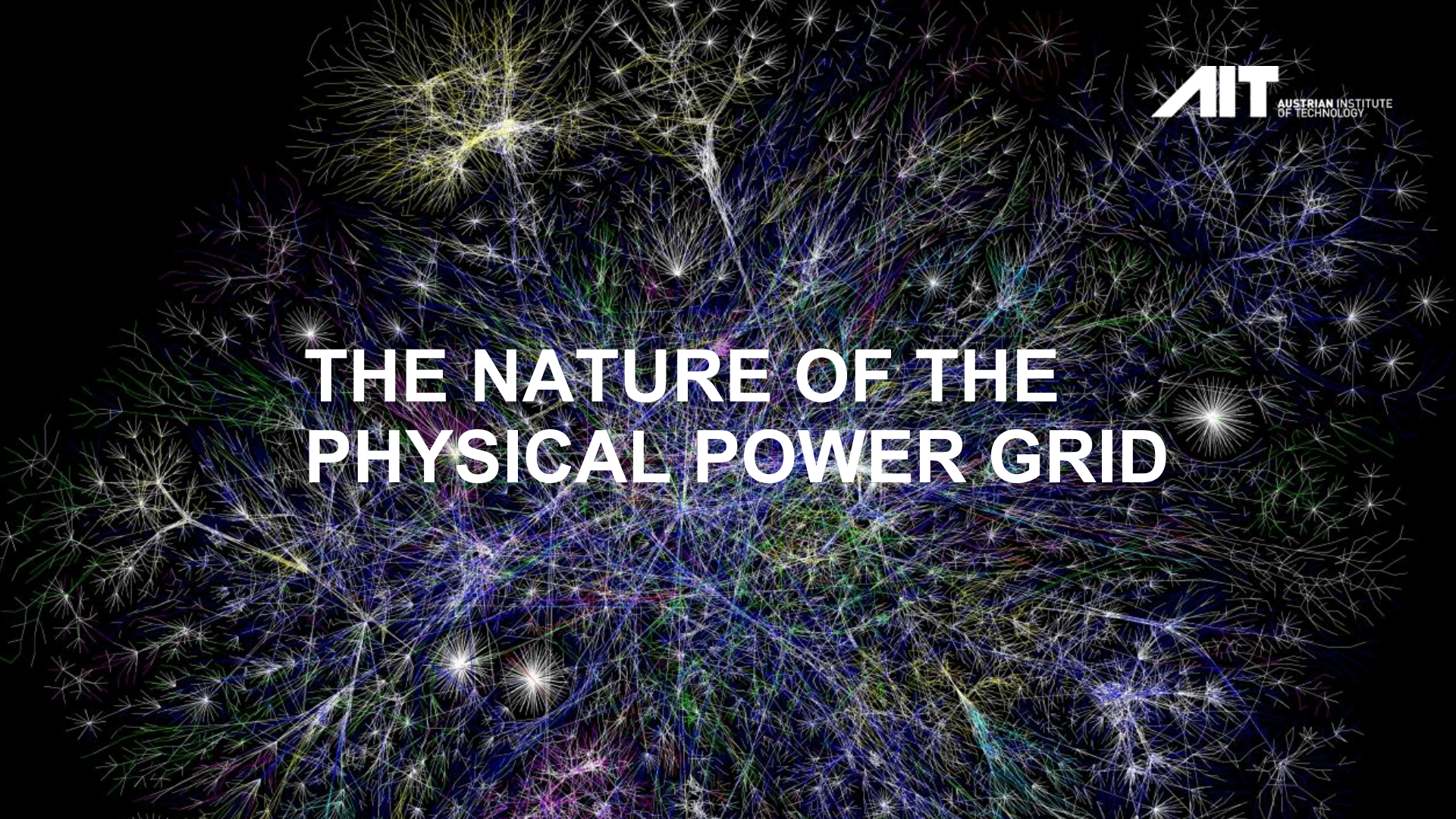
Agenda

The nature of the physical power grid

The nature of the digital power grid

Evolition pathways

Conclusion


AIT
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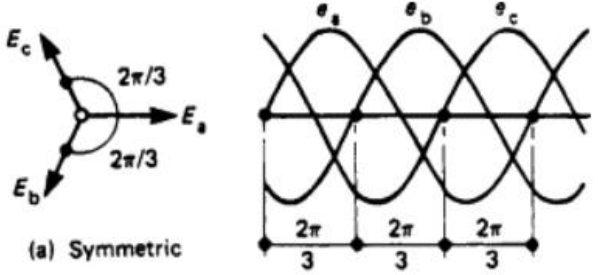
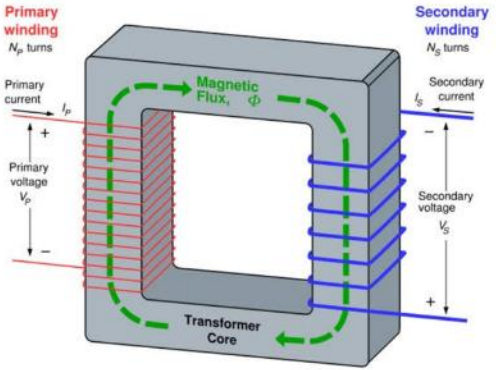
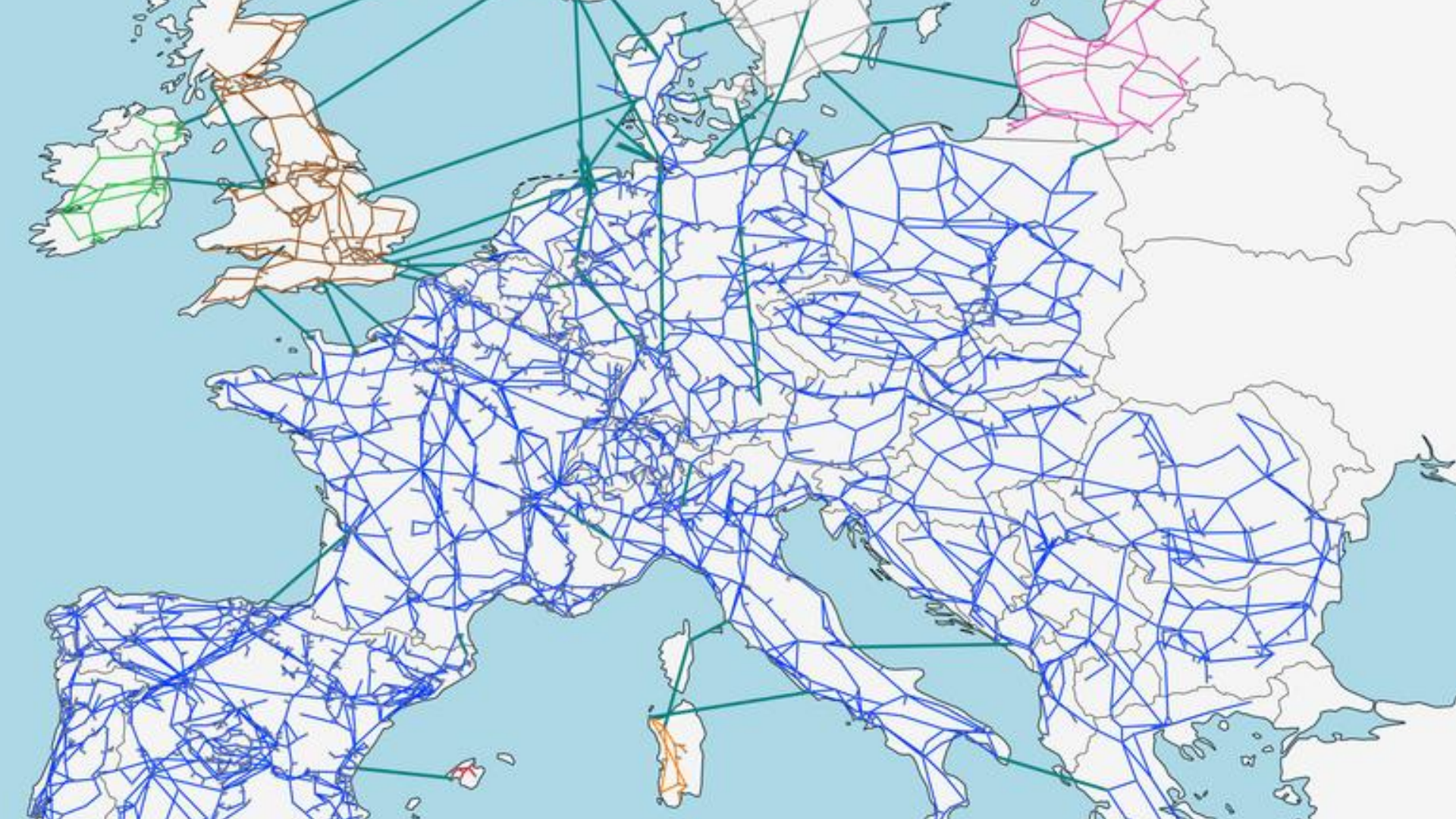
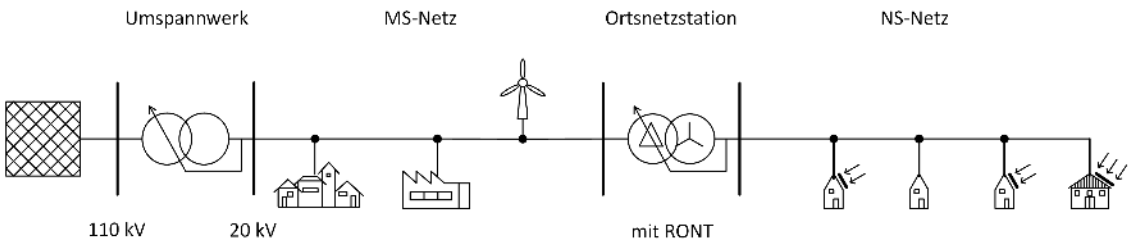
THE NATURE OF THE PHYSICAL POWER GRID

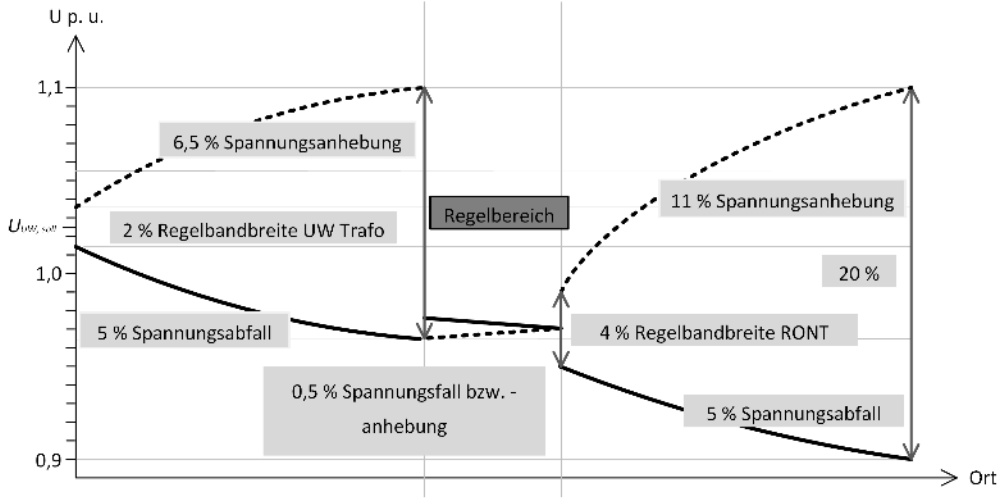

E_c
$2\pi/3$
E_a
$2\pi/3$
E_b
e_a
e_b
e_c
2π 3
2π 3
2π 3

(a) Symmetric


Primary winding
N_P turns
Secondary winding
N_S turns
Primary current
I_P
Magnetic Flux, Φ
Secondary current
I_S
+
Primary voltage
V_P
−
−
Secondary voltage
V_S
+
Transformer Core



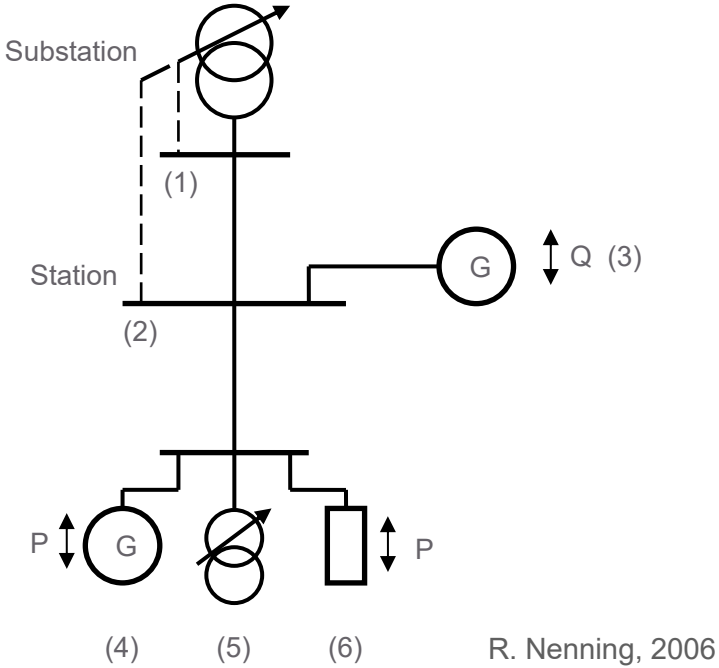




https://ront.info

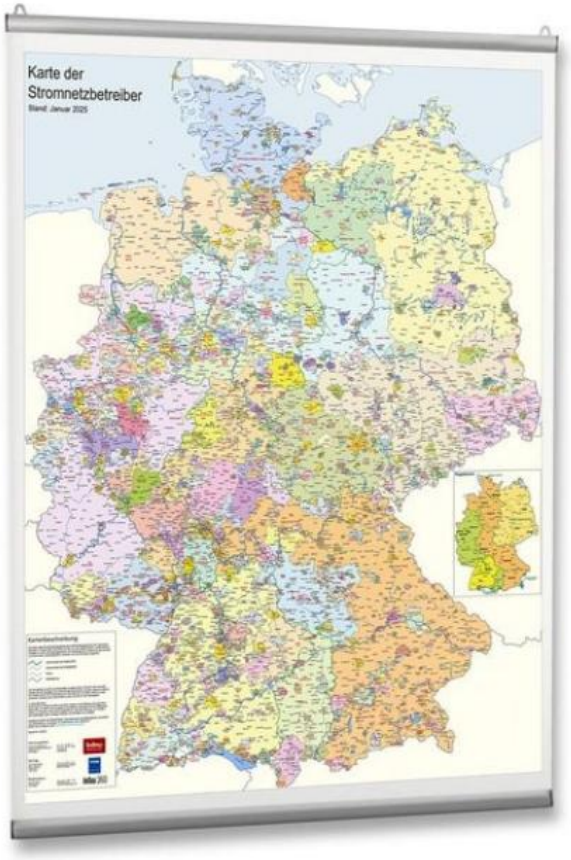
VOLTAGE ACTUATORS

- On-load tap changer (OLTC) (1)
- Generators (3, 4)
- Adjustable transformers (low voltage) (5)
- Demand side management (DSM) (6)

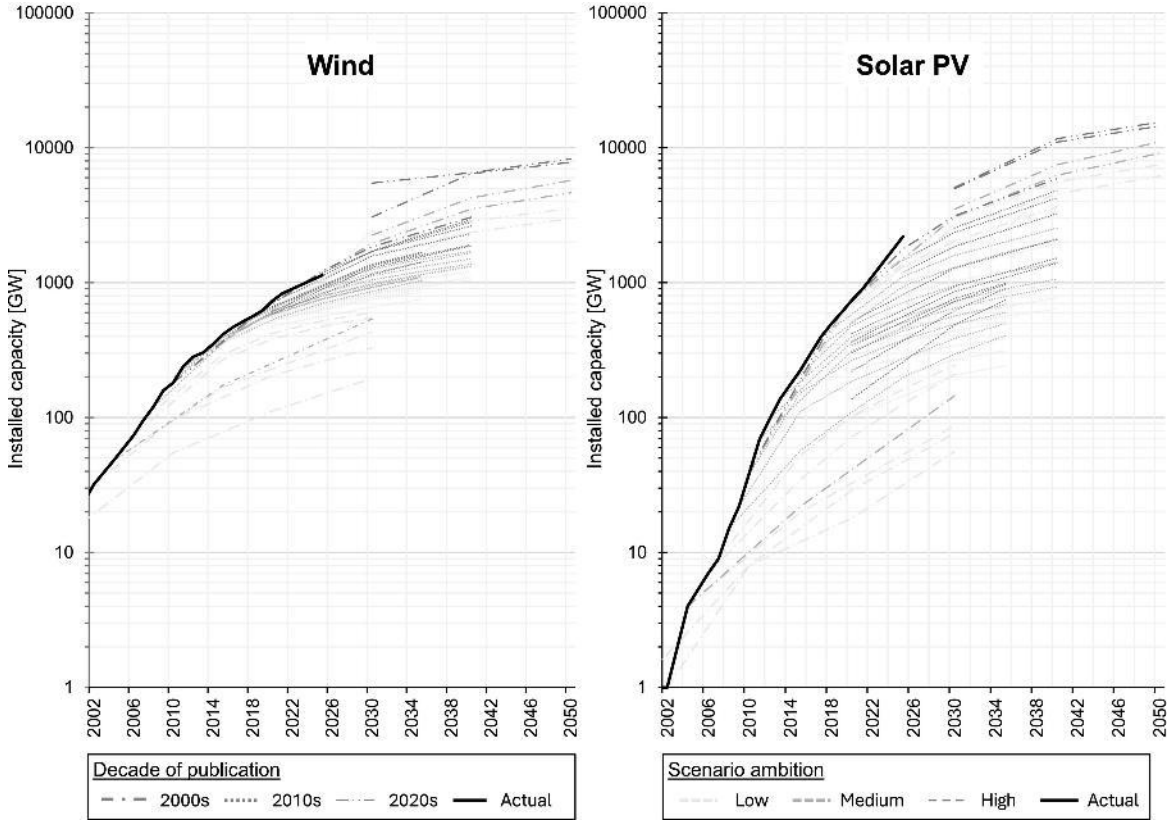


P: Active Power Q: Reactive Power

territorial fragmentation in Germany (1834, Schaumburg-Lippe)

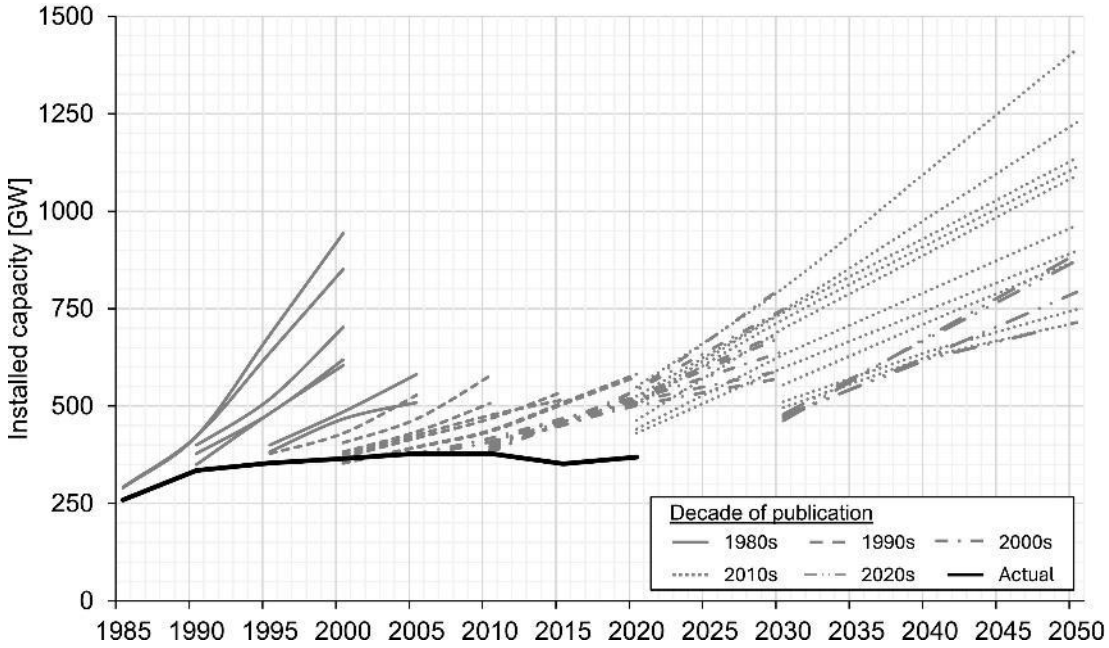


Distribution System Operators in Germany (ca. 2025)



Data from IEA

Fanny Böse, Alexander Wimmers, Björn Steigerwald, Christian von Hirschhausen, The “Nuclear Energy Paradox”- Investigating nuclear imaginaries in energy projections, Energy Research & Social Science, Volume 135, 2026, 104676, ISSN 2214-6296



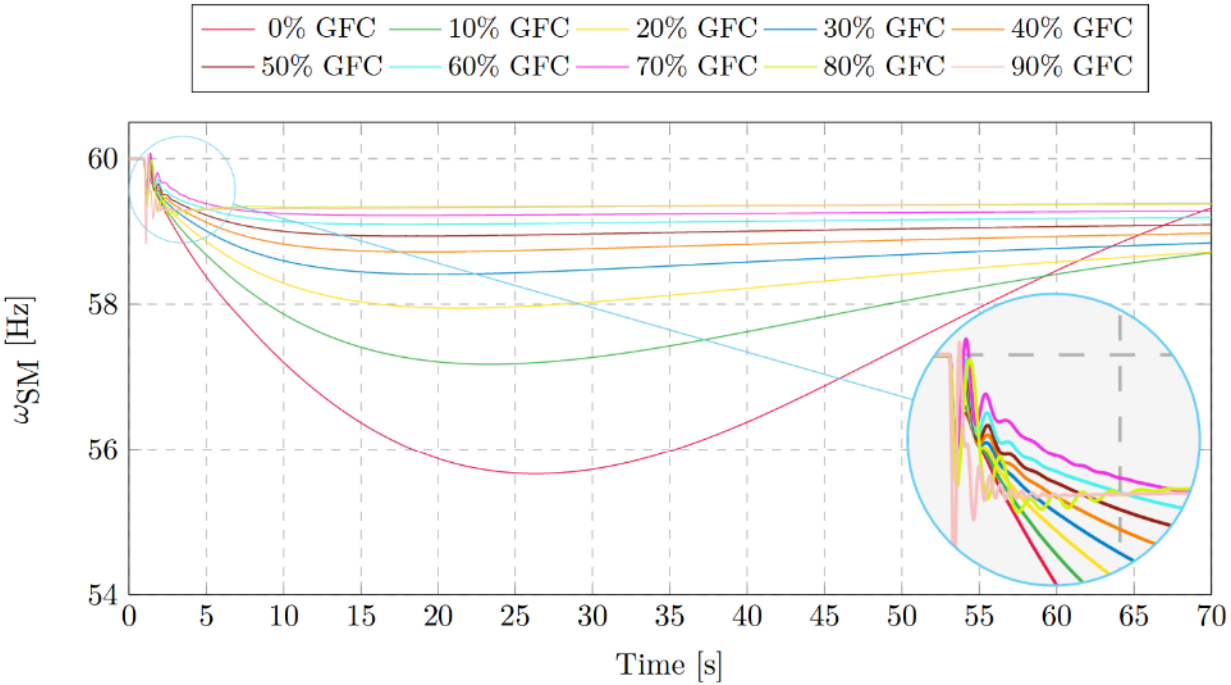
Data from IAEA

Fanny Böse, Alexander Wimmers, Björn Steigerwald, Christian von Hirschhausen, The “Nuclear Energy Paradox”- Investigating nuclear imaginaries in energy projections, Energy Research & Social Science, Volume 135, 2026, 104676, ISSN 2214-6296,

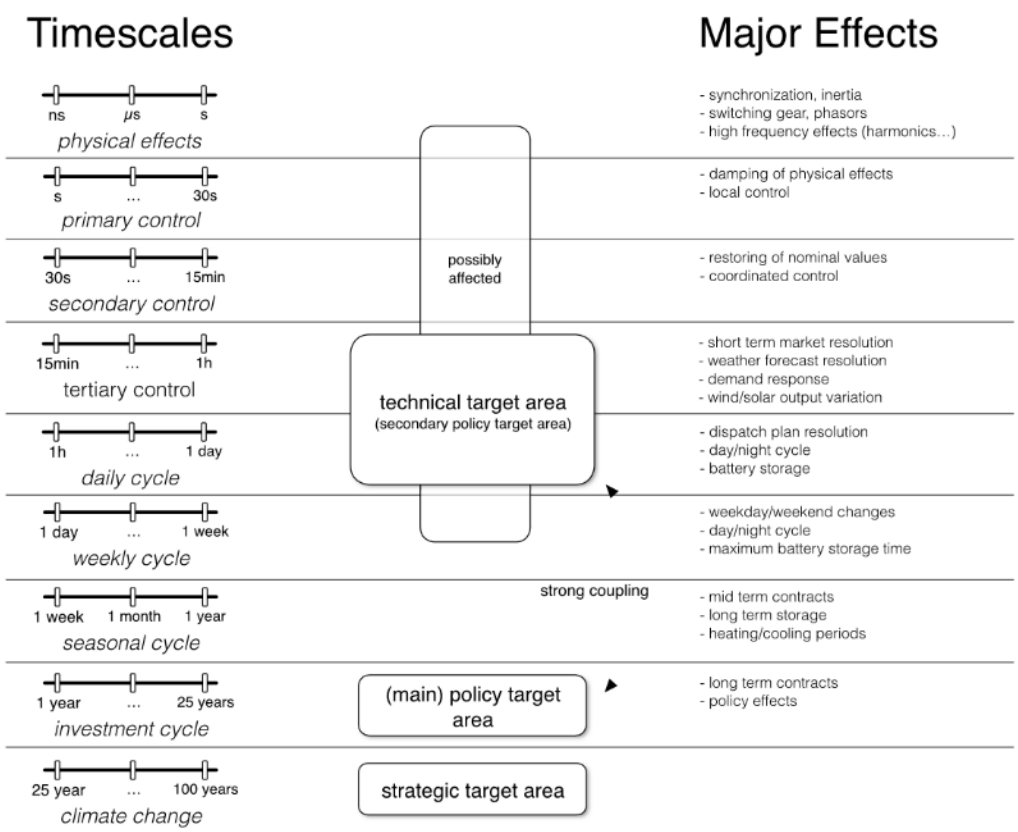
Beyond low-inertia systems: Massive integration of grid-forming power converters in transmission grids

Publisher: IEEE Cite This PDF

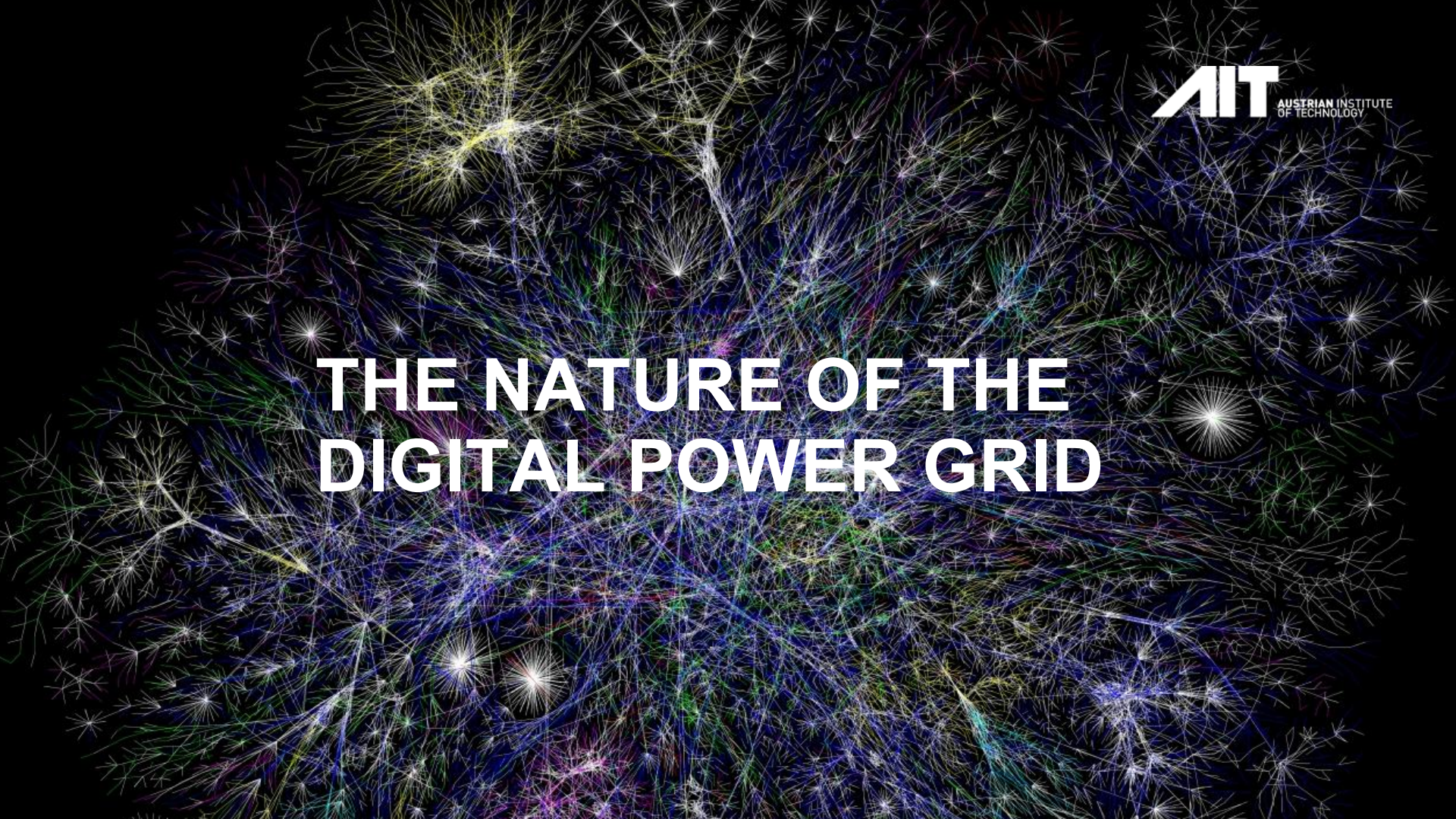
A. Crivellaro ; A. Tayyebi ; C. Gavriluta ; D. Groß ; A. Anta ; F. Kupzog All Authors



GFC – Grid forming controllers



Nardelli, Pedro HJ, et al. "Energy internet via packetized management: Enabling technologies and deployment challenges." *IEEE Access* 7 (2019): 16909-16924.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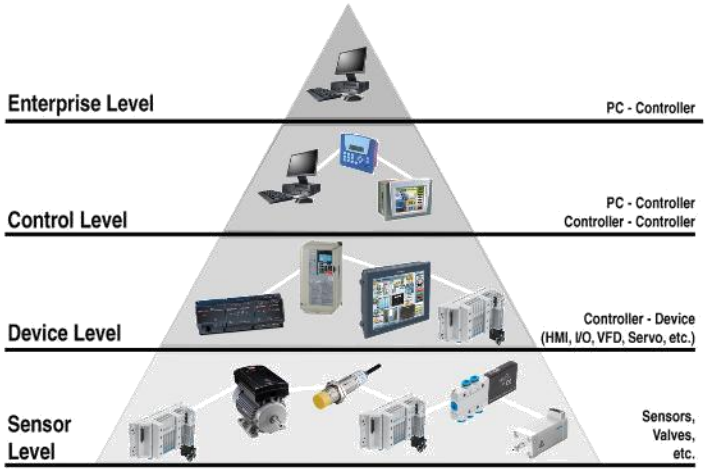
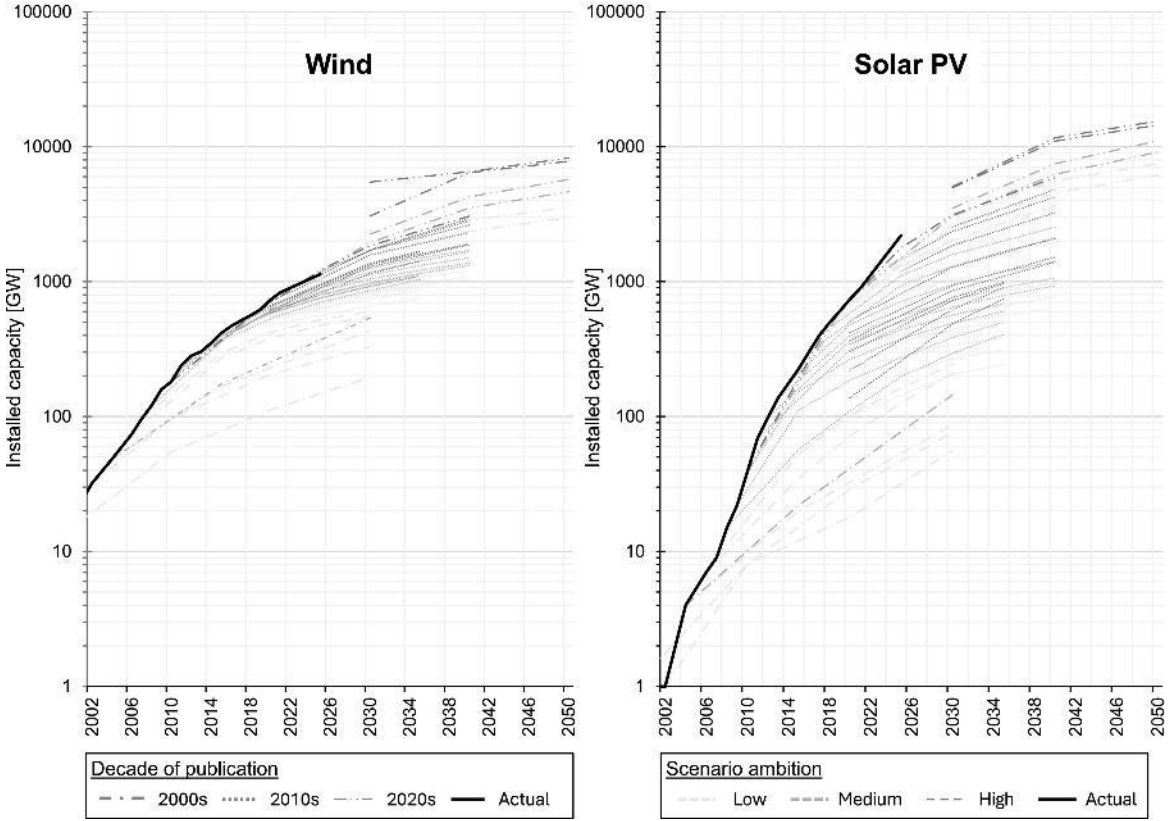
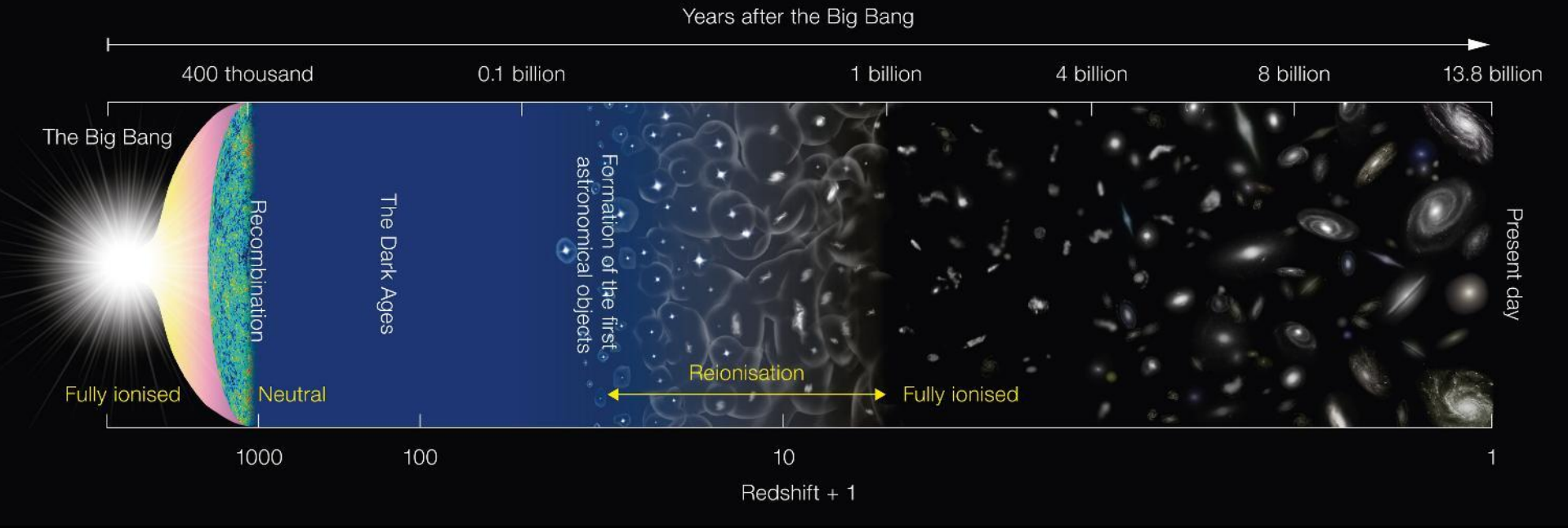
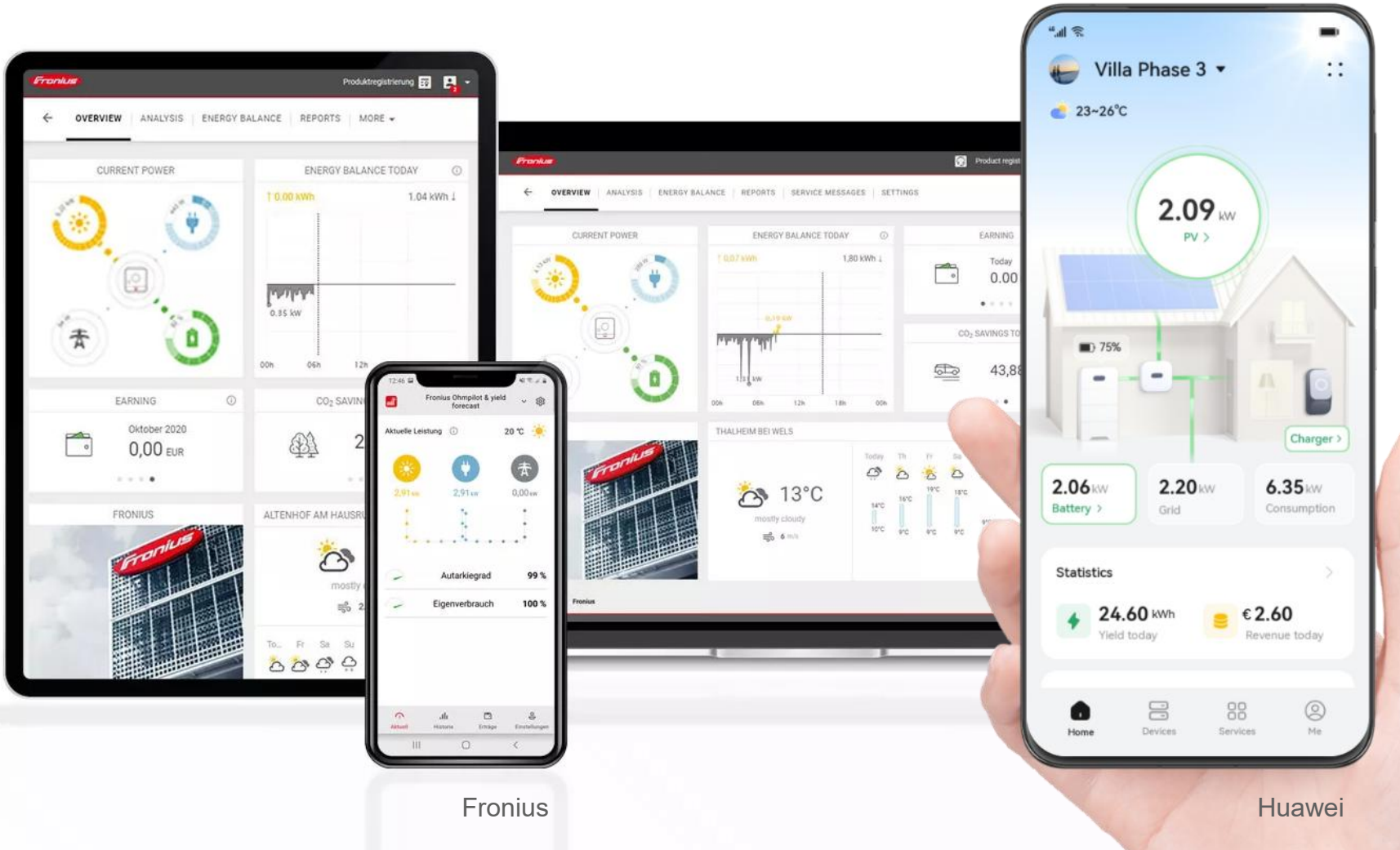
THE NATURE OF THE DIGITAL POWER GRID


Enterprise Level
PC - Controller
Control Level
PC - Controller
Controller - Controller
Device Level
Controller - Device
(HMI, I/O, VFD, Servo, etc.)
Sensor
Level
Sensors,
Valves,
etc.

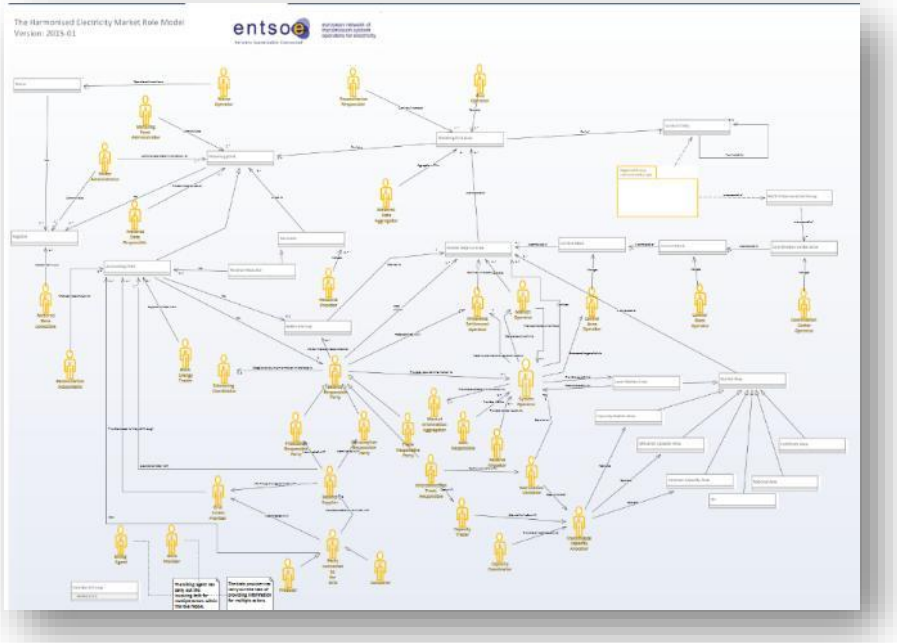

Wind
Solar PV
Installed capacity [GW]
100000
10000
1000
100
10
1
2002
2006
2010
2014
2018
2022
2026
2030
2034
2038
2042
2046
2050
Decade of publication
2000s
2010s
2020s
Actual
Scenario ambition
Low
Medium
High
Actual


Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Ages
Formation of the first astronomical objects
Present day
Fully ionised
Neutral
Reionisation
Fully ionised
1000
100
10
1
Redshift + 1

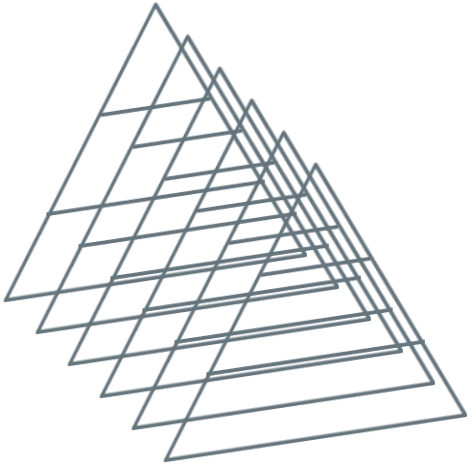


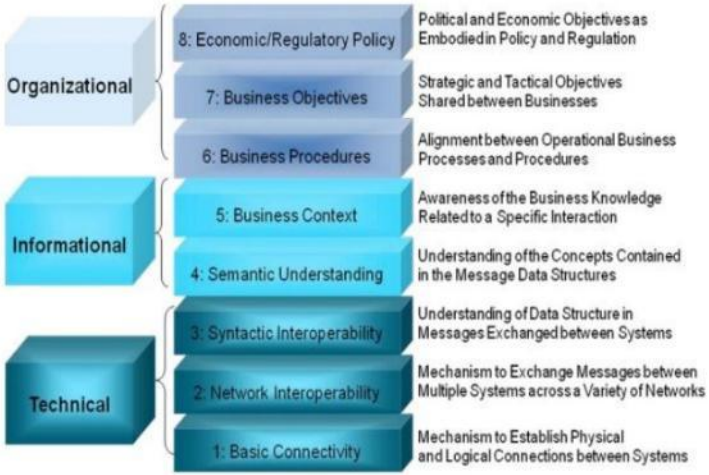
Fronius

Huawei



ENTSO-E Harmonized Electricity Market Role Model (2015)





GridWise Architecture Council (GWAC)

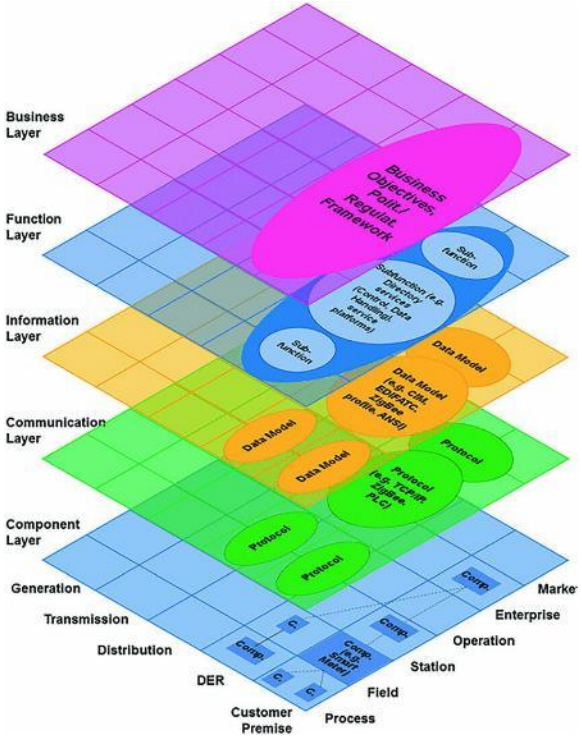
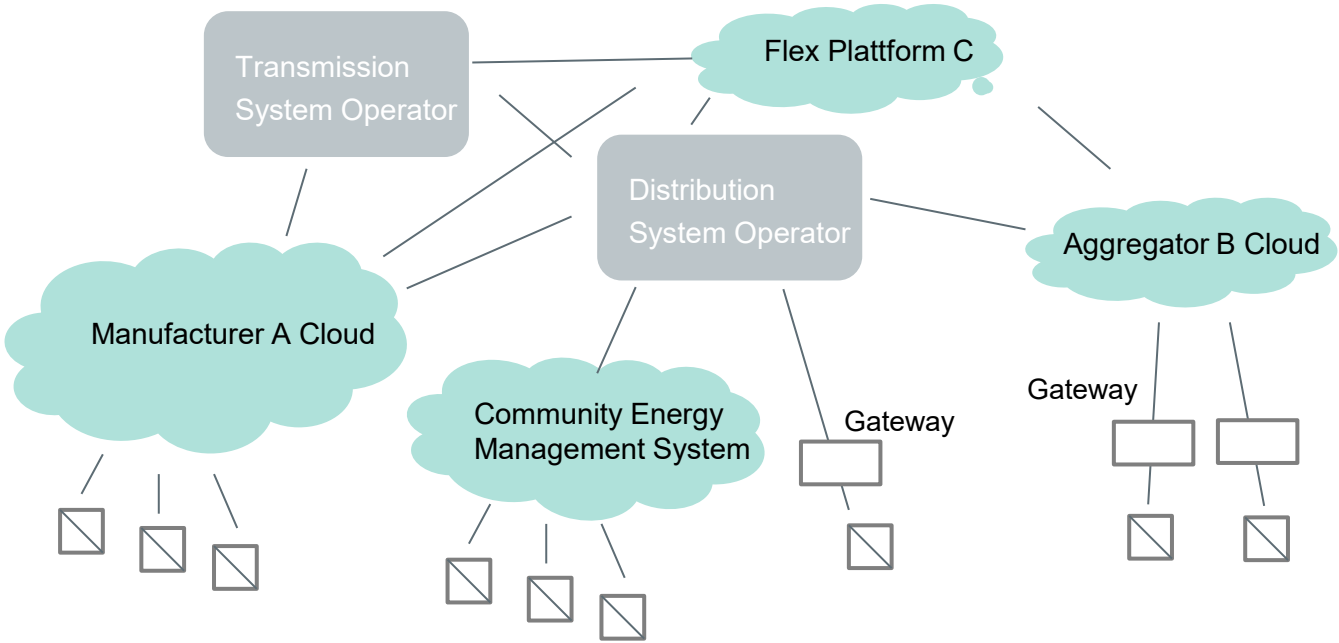


Image: Smart grid architecture model (SGAM).
Source: Gottschalk, Uslar, and Delfs (2017, p. 45).

M/490 Mandate: 2011


Transmission System Operator
Flex Plattform C
Distribution System Operator
Aggregator B Cloud
Manufacturer A Cloud
Community Energy Management System
Gateway
Gateway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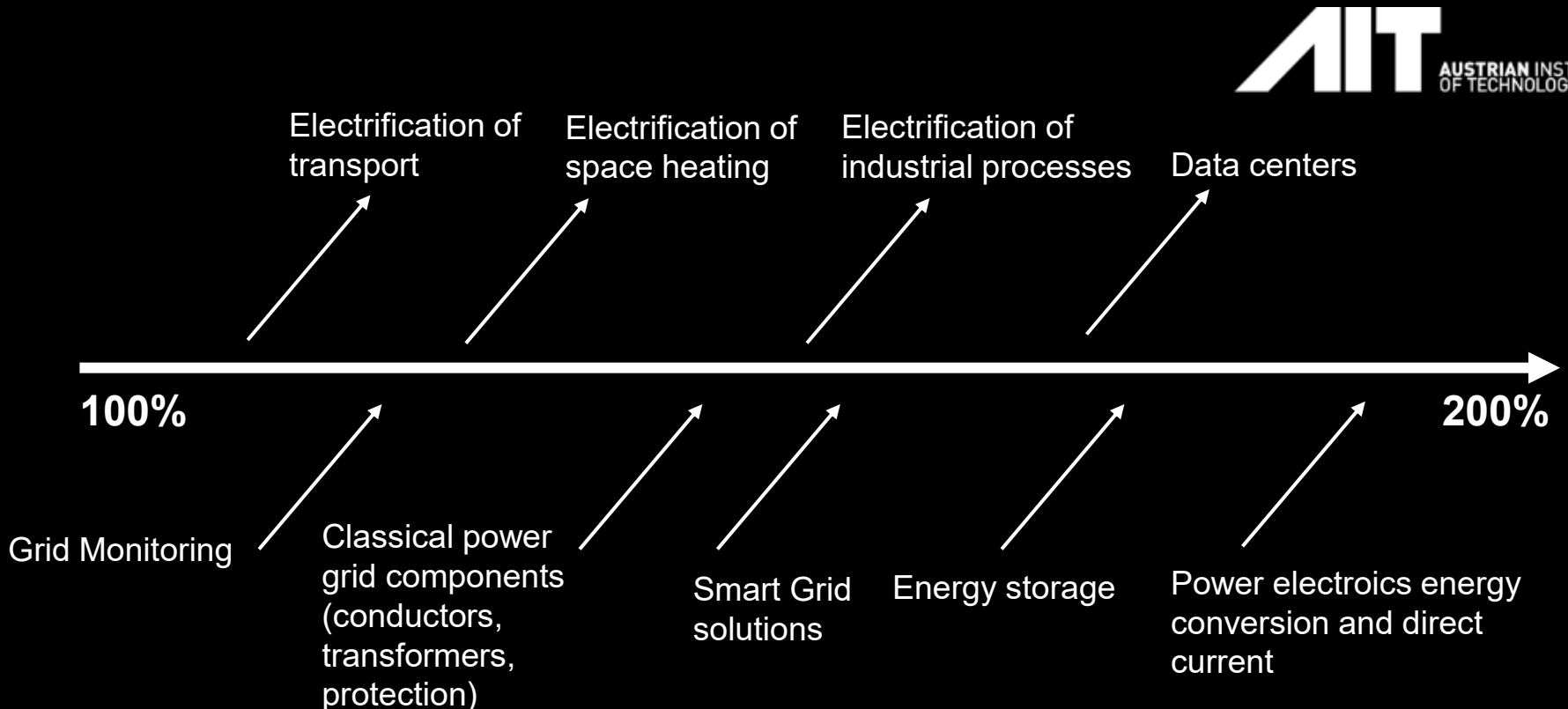
EVOLUTION
PATHWAYS


Electrification of transport
Electrification of space heating
Electrification of industrial processes
Data centers
100%
200%
Grid Monitoring
Classical power grid components (conductors, transformers, protection)
Smart Grid solutions
Energy storage
Power electroics energy conversion and direct current

EUROPEAN PLAN

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32%

ELECTRICITY SHARE TARGET

STATUS: 23%

1 200 BN €

INVESTMENTS IN POWER GRIDS UNTIL 2040

750 BN € DISTRIBUTION

450 BN € TRANSMISSION

240 BN €

INVESTMENT IN HYDROGEN GRIDS UNTIL 2040

1 600 BN €

INVESTMENTS IN ROADS UNTIL 2040 FOR COMPARISON

Sources:
https://energy.ec.europa.eu/news/eu-guidance-ensuring-electricity-grids-are-fit-future-2025-06-02_en
https://www.mckinsey.de/news/presse/2021-05-20-road-work-ahead
EU Grid Package Draft Version

COST REDUCTION BY ACTIVE GRID OPERATION

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Measure	Grid Level	Involved Actors			Cost reduction (%) based on total costs in base scenario	
		Grid Operator	Customer	Regulator	2030	2050
MV/LV controllable transformer and/or line coltage compensator	Low Voltage	×			5 – 10	5 – 10
Current-dependent Voltage Control in primary substation	Medium Voltage	×			10 – 20	5 – 15
Medium voltage line voltage compensator	Medium Voltage	×			5 – 15	5 – 15
70% clipping for PV infeed	Low + Medium Voltage		×	×	5 – 15	10 – 15
PV reactive power control Q(V)	Low + Medium Voltage	×	×		10 – 30	20 – 25
Smart EV charging (min. 50% charging power)	Low + Medium Voltage	×	×	×	5 – 25	5 – 15

Source: AIT, Projekt P567, Netzausbauszenarien für Österreich für gesamte Versorgungsgebiete bis auf Netzknotendetail, 2023

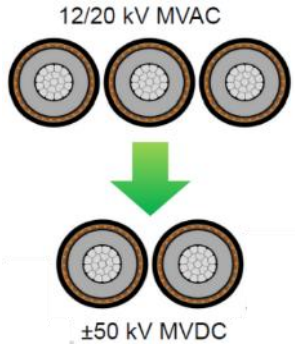
DIRECT CURRENT

Vimal Mahendru
Vice President IEC

“Medium Voltage DC will be the main development area of worldwide electricity supply“

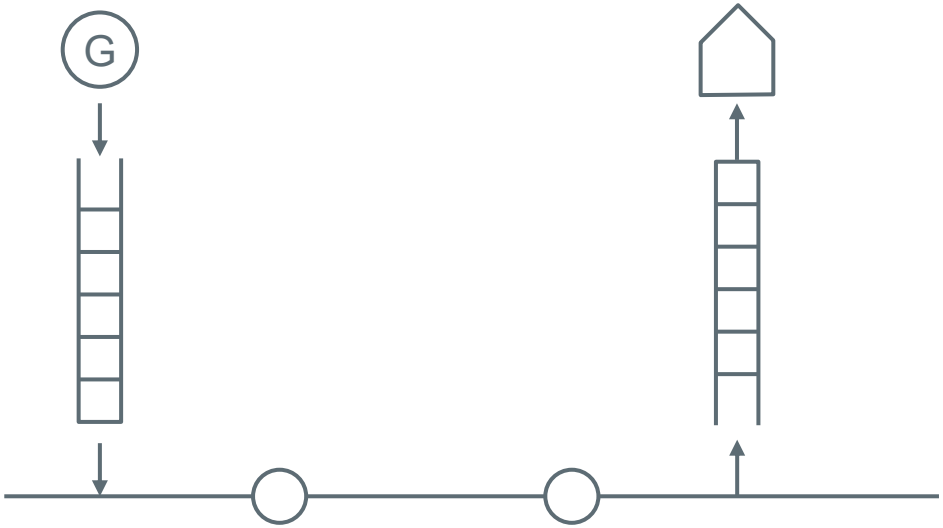
Keynote OVE Innovation Day, Vienna, 2025

400 V AC ±5 kV LVDC



Source: TU Graz, Schichler

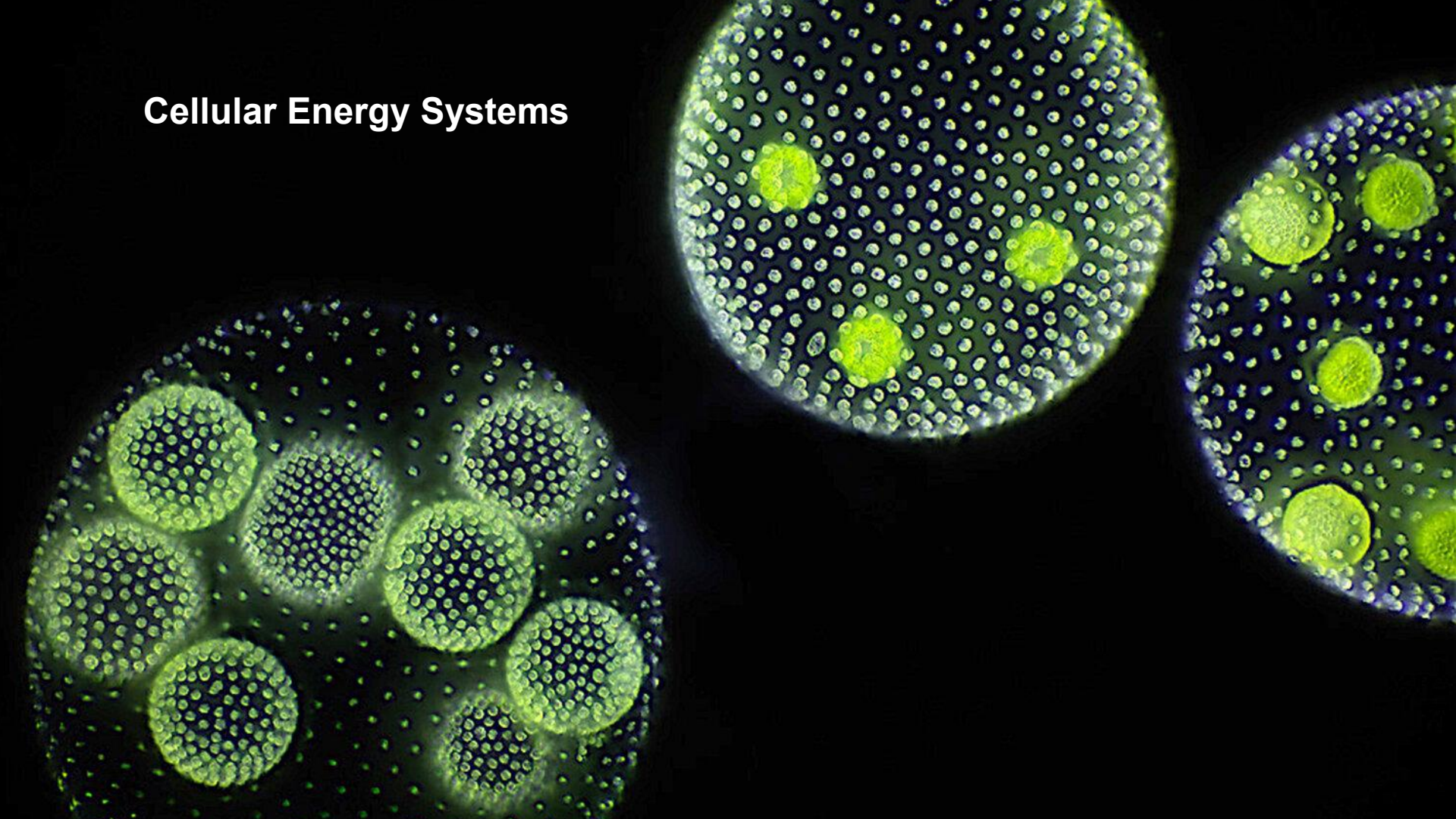
Packet-switched energy systems



Rojas-Cessa, R.; Wong, C.-K.; Jiang, Z.; Shah, H.; Grebel, H.; Mohamed, A., IEEE iThings 2018

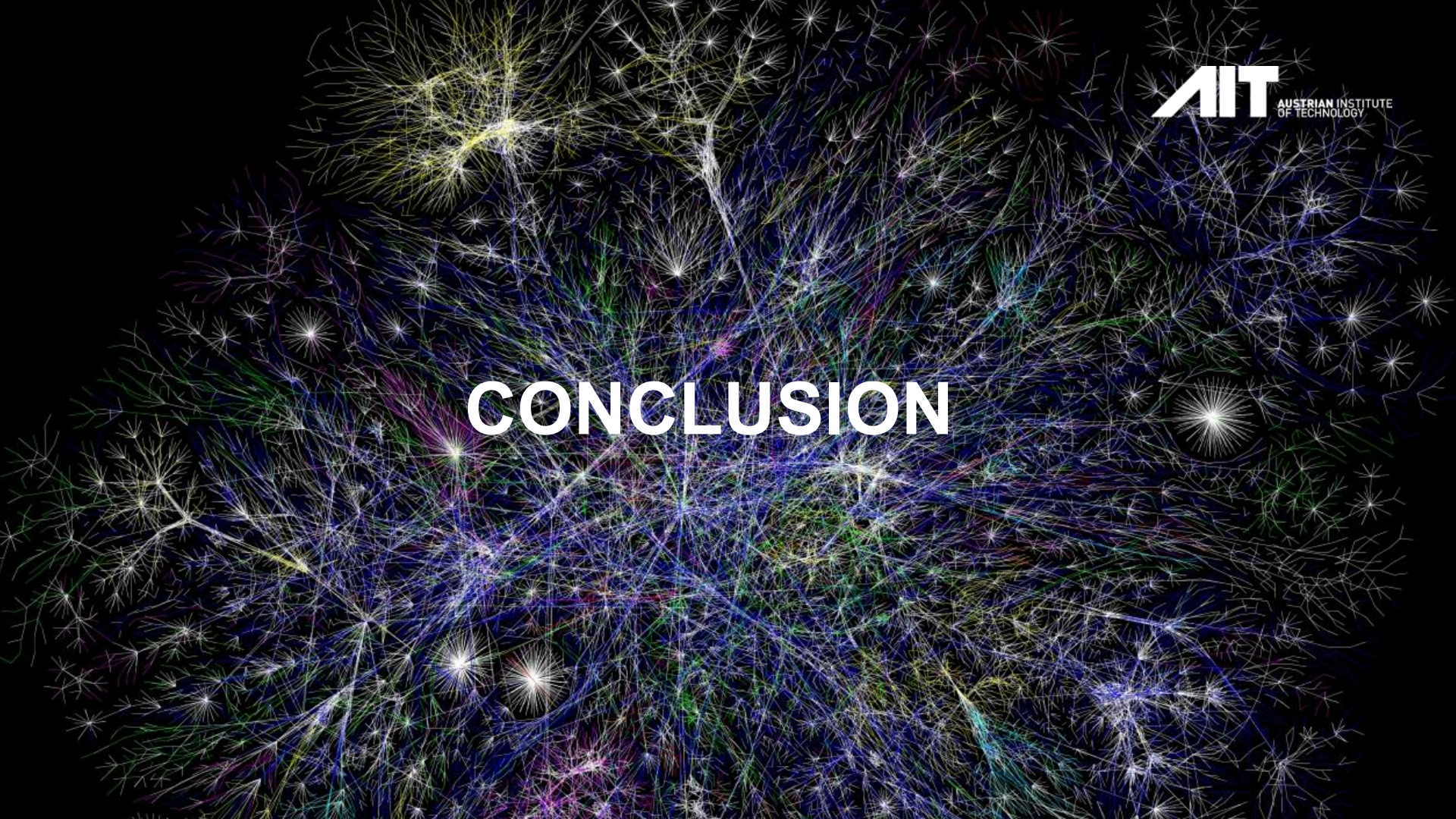
Nardelli, P.H.J. et al., IEEE Access, Vol. 7, 2019, S. 16909–16924. DOI: 10.1109/ACCESS.2019.2896281

Cellular Energy Systems



Energy Hubs

nhev.in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CONCLUSION

1. Ambitioned vision required
2. No single solution but hybrid system designs
3. Implementation roadmap and transition pathsways
4. Economy of scale solutions
5. Avoid fragmentation