

Hidden battles over the control of future energy systems

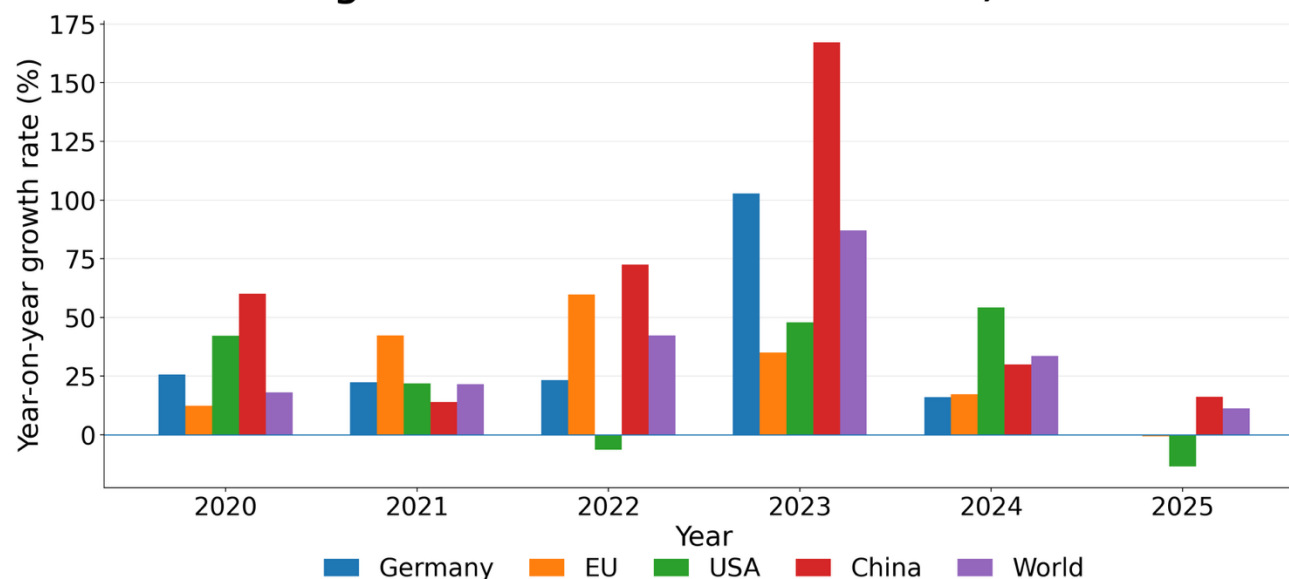
Ruggero Schleicher-Tappeser

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Are we stuck with the growth of renewables?

Annual growth of solar PV installations, 2020-2025

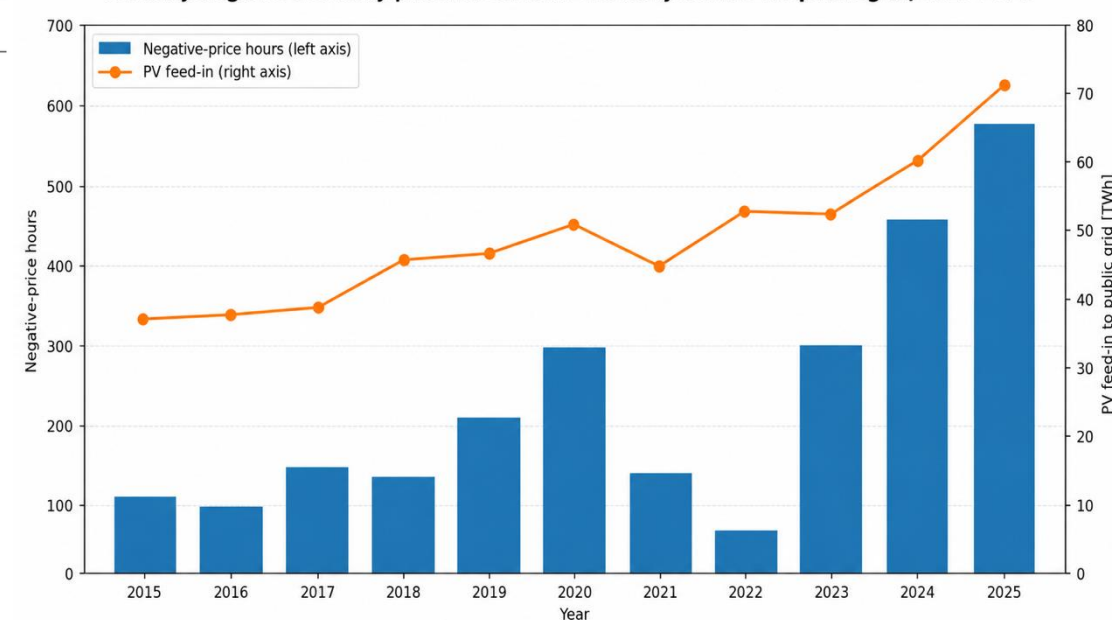


Source: SolarPower Europe (Global Market Outlook and EU Market Outlook series).

Solar growth rates are declining

System imbalance:
Increasing hours with negative power prices

Germany: negative electricity-price hours and PV electricity fed into the public grid, 2015-2025

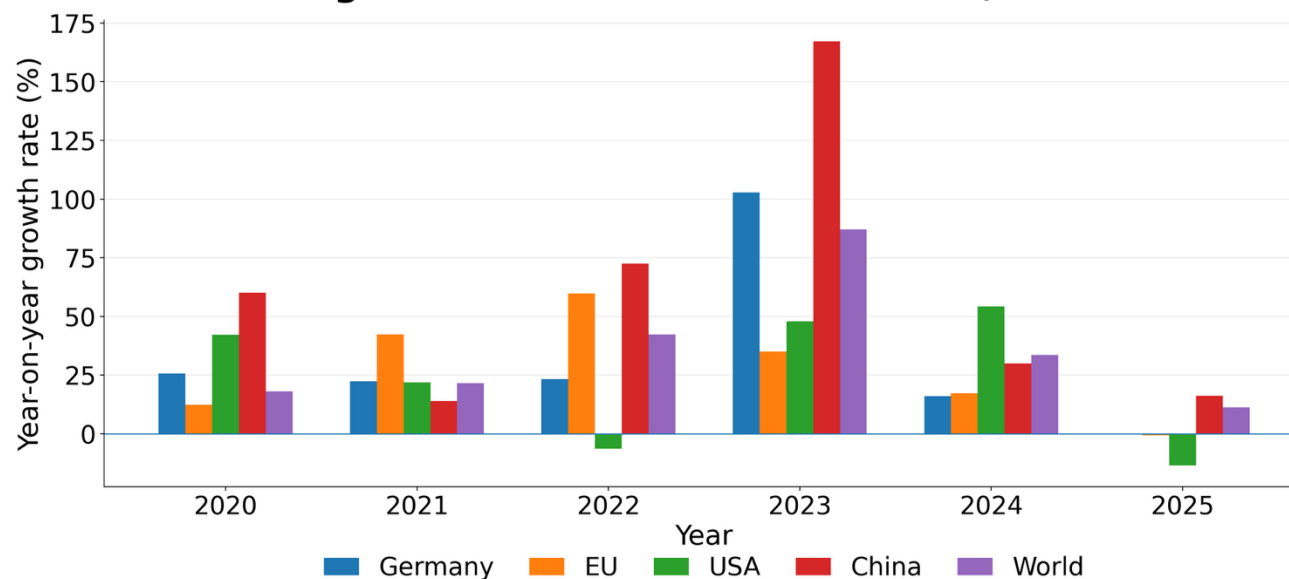


Sources: Negative-price hours: Fraunhofer ISE Energy-Charts (EPEX day-ahead); PV feed-in to public grid: Fraunhofer ISE annual electricity-generation summaries.

Are renewables stuck?

No – the whole system is transitioning

Annual growth of solar PV installations, 2020-2025



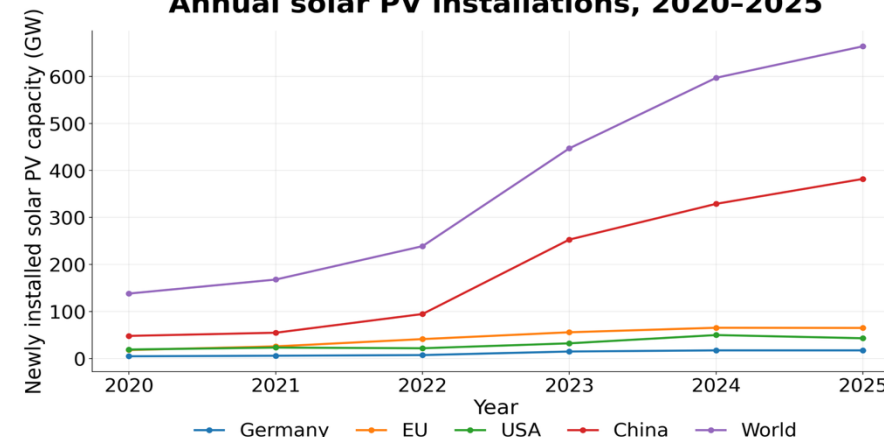
Source: SolarPower Europe (Global Market Outlook and EU Market Outlook series).

Solar growth rates are declining

But Battery installations are accelerating

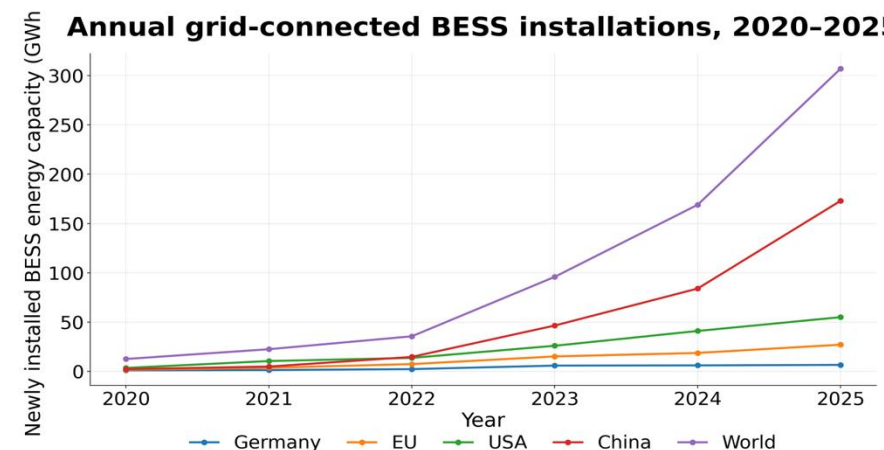
→ We need to look at the whole system!

Annual solar PV installations, 2020-2025



Source: SolarPower Europe (Global Market Outlook and EU Market Outlook series). Note: a stacked chart would be misleading because Germany is part of the EU and all regions are part of the World.

Annual grid-connected BESS installations, 2020-2025



Sources: IRENA/BloombergNEF; Wood Mackenzie/ACP; SolarPower Europe; RWTH Aachen/Battery Charts. Note: a stacked chart would be misleading because Germany is part of the EU and all regions are part of the World.

Understanding the Transformation

Powerful drivers of change

1. Security of energy supply

- Disruption of supply by conflicts and wars
- Hybrid attacks on energy infrastructure
- Increasing dependency on continuous supply of electricity
- Badly managed transition of complex systems

2. Climate change awareness

- Short time frame for substituting fossil fuels
- Climate change impacts energy needs and supply options (e.g. cooling, water availability, storms)

3. Energy costs

- Supply/price shocks. Shifts in competitiveness. Financing of upfront costs in transformation.

4. Technological innovations

- Understanding nature's laws at the atomic scale, brings not only nuclear power but also a wide range of "electronic" technologies (based on the behaviour of electrons in the atom's shell, not on nuclear forces)
- They cover all stages of the energy value chain: sourcing, conversion and control, transport, storage, use
- Electricity is becoming the backbone of the energy system
- Electrification is mainly driven by game-changing improvements in four key technologies:

Nanosciences bring **DISRUPTIVE NEW ELECTRICITY TECHNOLOGIES**



Photovoltaics

Power generation

- Direct generation of electricity from sunlight
- >20 times more efficient than photosynthesis
- Lowest electricity costs
- Decentralised generation
- **Fluctuation with solar radiation**



Power Electronics

Power transformation, transport and control

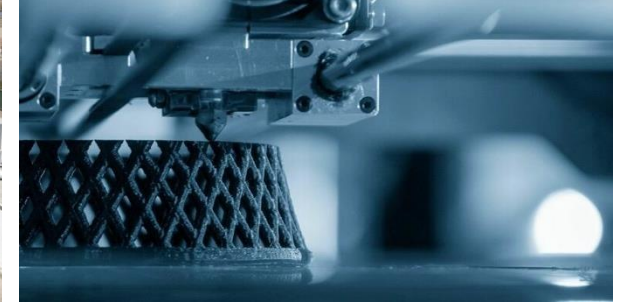
- Electricity converters
- Wind power to grid
- Digital control of electricity systems
- Efficient grids, HVDC, superconductors
- Digital frequency control → efficient e-motors



Batteries

Power storage

- High-density electro-chemical battery cells
- Flow batteries for longer-term-storage
- Strong density improvements and cost reduction
- Fuel cells
- Improved electrolyzers



Electricity → Radiation

Wikimedia Commons

Material processing & Light

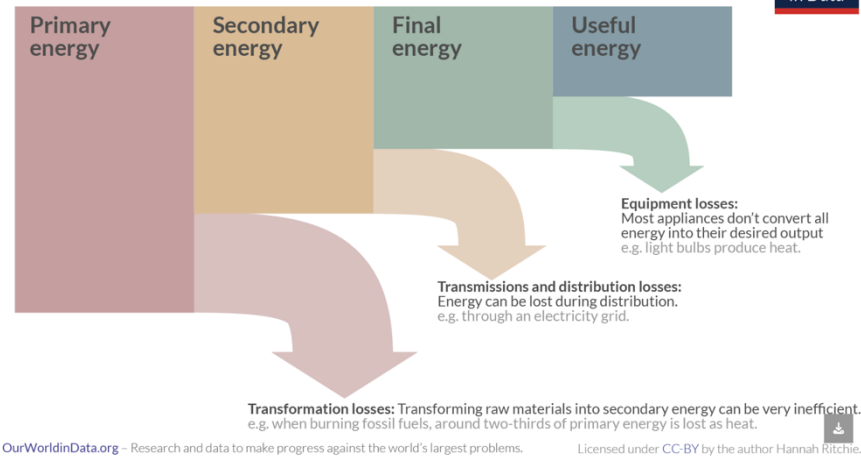
- LED, Laser, Microwave...
- 3D-printing: up to 75% material savings
- High life-cycle energy savings
- Efficient decentralised small series production

**Very rapid performance boost and cost reduction well above macroscopic process learning curves:
miniaturisation and speed/efficiency increase due to improved processes at nanoscale**

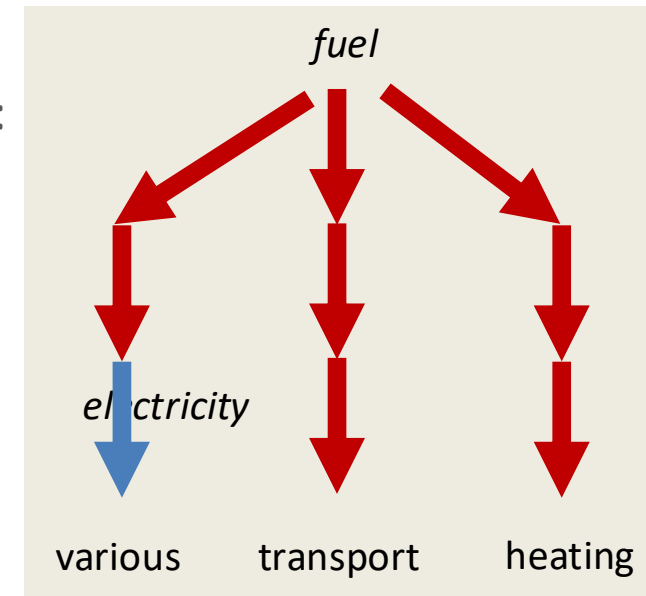
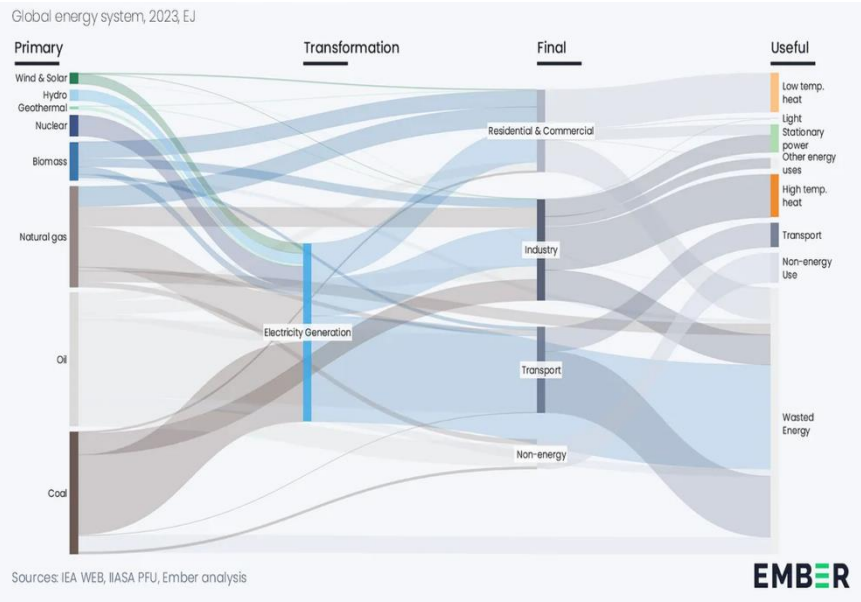
Understanding the “electronic” Transformation

The conventional energy system

Useful energy is just a fraction of primary energy



- From primary to useful energy: more than half of the energy is wasted
- 93% of primary energy yields **heat** (fossil + bio fuels, nuclear)
- 60% of the energy input into electricity comes from **fossil fuels**, 71% from heat
- Electricity, Heating and Transport are three largely **separate sectors**:
 - Final energy for transport: 1,5% electricity, 85% fossil fuels
 - Final energy for heating: 75% fossil, 13% trad biofuels
- In all three sectors: **top-down distribution system buffered by easy fossil fuel storage**

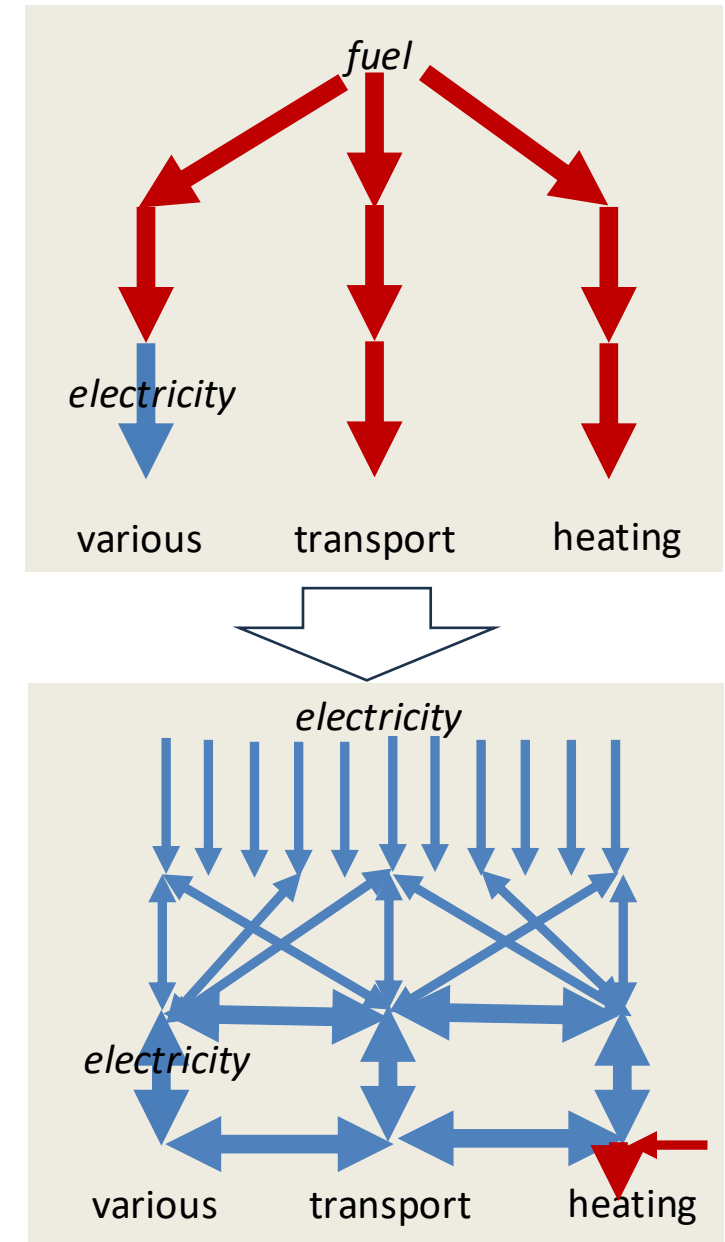


Understanding the “electronic” Transformation

The game changers: new converters and controllers

Industrial revolutions have been caused by new energy and information connections. Today, a wave of new connectors is again transforming the system:

- **Converters between different kinds of energy**
 - between radiation and electricity: photovoltaics, LEDs, lasers
 - between different kinds of electricity: power electronics
 - between electrical and mechanical energy: frequency variable drives
- **Conveyors across time**
 - New electrical batteries
- **Conveyors across space**
 - High voltage direct current HVDC
 - Superconductivity
- **Controlling energy flows with ICT and AI**
 - Power electronics allows remote control with digital information
 - AI allows autonomous decision-making at all system levels



Understanding the “electronic” Transformation

The game changers: Dramatic recent improvements

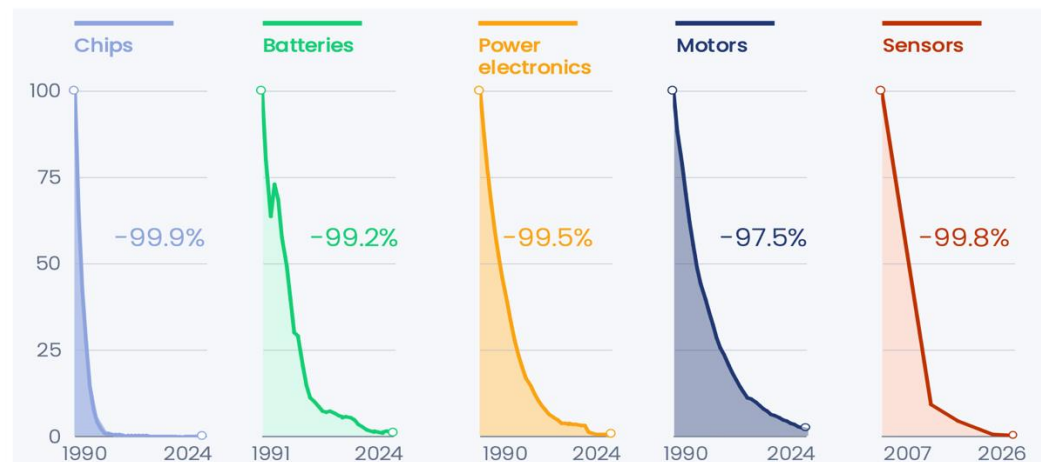
BESS (stationary battery energy storage systems)

2022-2025 costs: - 63%

installations (GW): +588%

(IEA)

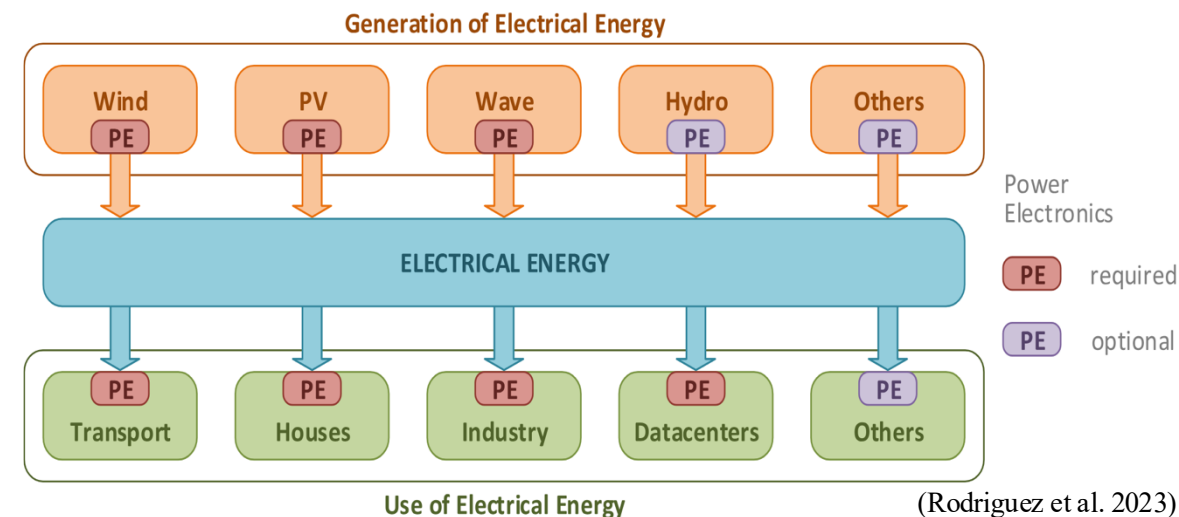
Game-changing cost reductions in recent decades



Sources: Not Boring (The Electric Slide); Our World in Data; Velodyne; Hesai; Thunder Said Energy; Ember analysis • Note: based on the following units: chips \$/DMIPS, batteries \$/kWh, power electronics \$/kW, motors \$/kW, sensors \$/LIDAR unit.

EMBER

Power Electronics is Everywhere



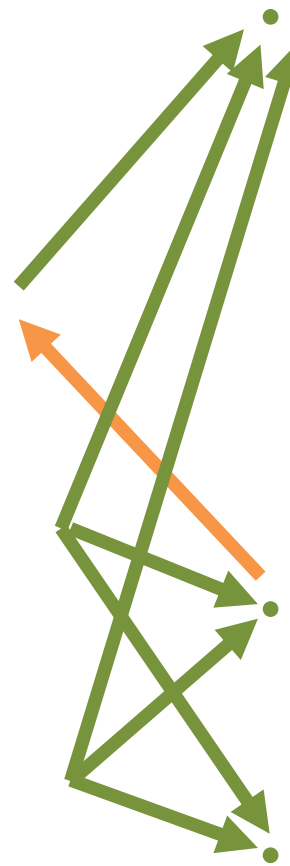
1990-2024, the power density of power electronics has increased by a factor of 1000

Understanding the “electronic” Transformation

Systemic advantages of meshed-grid electrification

Together, three technological drivers push for electrification:

1. Electricity can be generated directly from sunlight, wind, and waves
2. Electricity can be stored for several days at different scales
3. Electricity can be nearly losslessly converted and digitally controlled



EFFICIENCY is easy to measure, boosted by electrification: **x 2**

- Elimination of thermodynamically inevitable losses in the converting heat
- Gain of ambient heat in generating heat with heat pumps
- Far-reaching electrification would only double electricity consumption

FLEXIBILITY is a complex concept, depending on system levels and time frames

RESILIENCE relies on flexibility, variety of alternatives, depends on decision-making structure

Understanding the “electronic” Transformation

Energy sourcing becomes clean

Cheap renewable power triggers the transformation towards an electricity-based, decentralised system

- Photovoltaics + Batteries has become the cheapest power source around the clock

- **Firm clean power** costs 2025 according to IRENA

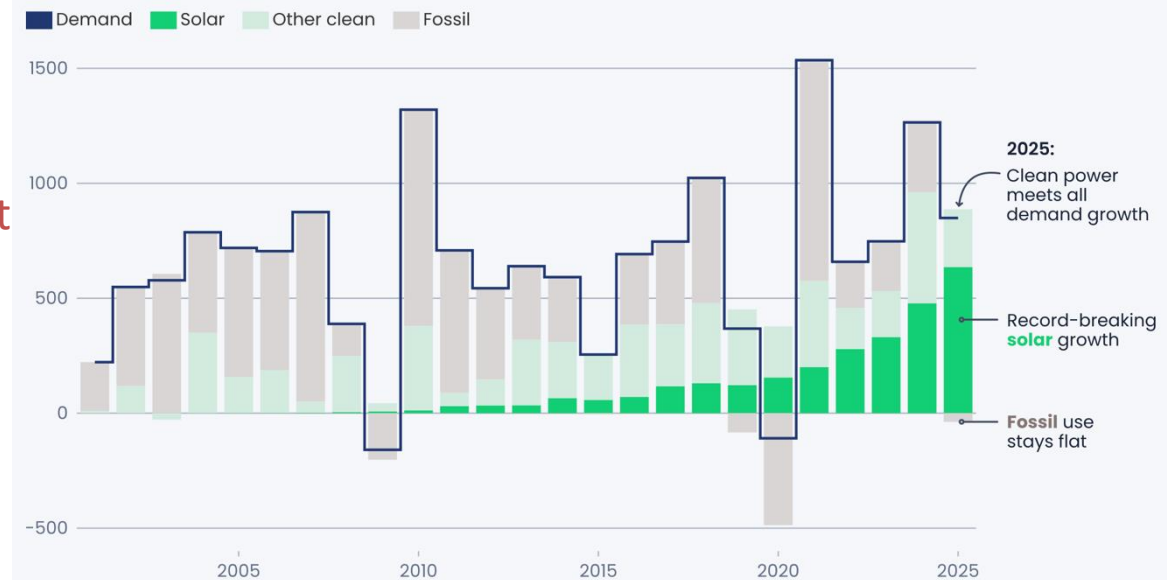
- PV Hebei, CN 5,4 ¢/kWh → 3,7 in 2030
- Wind Mongolia 5,9 ¢/kWh → 4,9
- PV Oman 6,9 ¢/kWh
- PV Andalusia, ES 9,1 ¢/kWh → 6,1
- Wind Schleswig, DE 9,1 ¢/kWh → 7,3

Hinkley Point
18 ¢/kWh

- In higher latitudes seasonal PV supply gaps persist. Mitigation strategies:
 - diversified portfolio (sun + wind + ??)
 - inter-regional links
 - long-term heat storage (sector coupling)
- Shift requires flexibility and brings decentralisation

Clean power growth exceeded the rise in global electricity demand in 2025, keeping fossil generation flat

Annual change in electricity generation (TWh)



Source: Yearly electricity data, Ember • 'Other clean' includes nuclear, wind, hydro, bioenergy and other renewables such as geothermal

EMBER

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- Firm clean power costs 2025 according to IRENA
 - PV Hebei, CN 54 \$/MWh → 37 in 2030
 - Wind Mongolia 59 \$/MWh → 49
 - PV Oman 69 \$/MWh
 - PV Andalusia, ES 91 \$/MWh → 61
 - Wind Schleswig, DE 91 \$/MWh → 73
- In higher latitudes seasonal PV supply gaps persist. Mitigation strategies:
 - diversified portfolio (sun + wind + ??)
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Conflicts:

- This shift substitutes
 - Fossil, nuclear fuels
 - Fossil, nuclear power plants
 - Associated transport and maintenance
- Incumbent industries try to delay
 - Producers of fossil fuel
 - Producers of thermal power plants
 - Associated services
- China has cracked western oligopolies
 - Strong growth allows growing new industry without crippling old ones
 - Strategic planning and subsidies
 - Dominates world markets in PV and batteries
- Old structures in industrial countries resist
 - industrial countries have underestimated speed and importance. Old industries are still strong.
- **These conflicts are well understood**

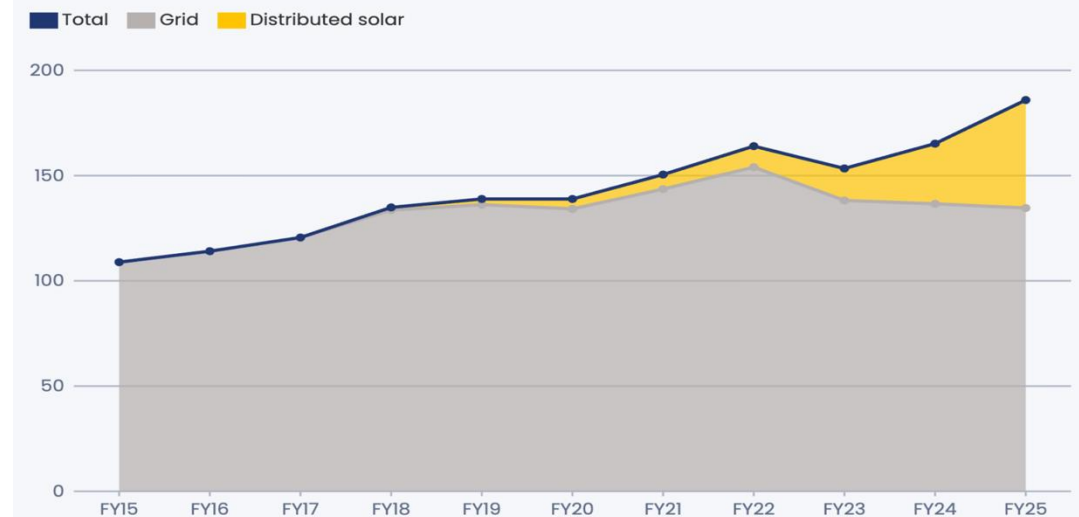
Understanding the “electronic” Transformation

PV + batteries: Revolution behind the meter

- **Nearly half of global PV capacity behind the meter**
 - Estimates: 43% cumulative, 41% added in 2025
 - Many countries do not track private behind-the-meter (b-t-m) installations, real numbers probably higher
 - New trend: balcony solar with battery, brings experience, pushes home energy management
- Percentages vary strongly:
 - China 36%
 - Germany 70%
 - USA 18%
 - Brazil 63%
- **Surge of distributed PV in emerging economies:**
In 2024 costs of PV+battery passed a tipping point
- Buildings matter: roof surface alone can globally provide 2x the present electricity generation

Pakistan's electricity demand surged 21% in the last two years, met entirely by distributed solar

Electricity generation, terawatt hours



Source: Grid generation from NEPRA; distributed solar generation calculated by Renewables First.

Pakistan's solar boom, from space

One neighbourhood in Islamabad, 2021 to 2025.

Islamabad
2021



Islamabad
2025



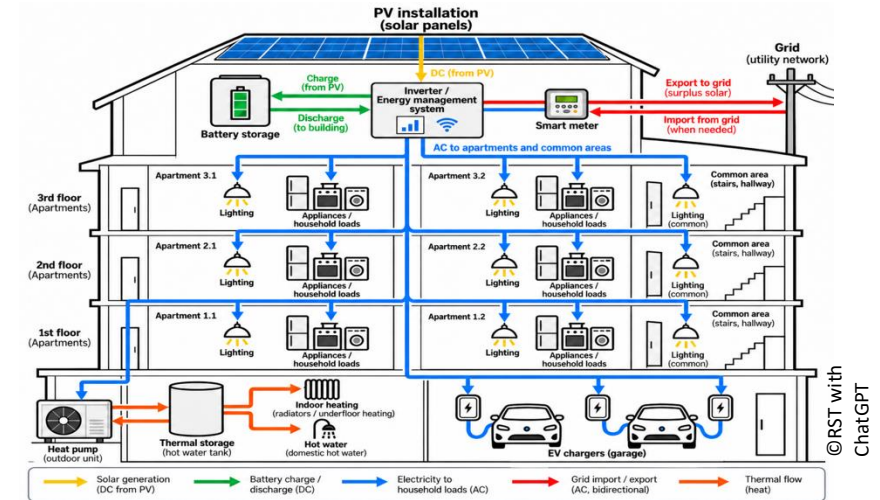
Understanding the “electronic” Transformation Revolution behind the meter

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 - Surge of distributed PV in developing countries
 - In 2024 costs of PV+battery passed tipping point
 - Buildings matter: roof surface alone can globally provide 2x the present electricity generation
- **Public system gets under pressure**
 - Utilities lose generation, increasingly become grid companies
 - Grid power competes with b-t-m generation,
 - Utilities have to push electrification to limit turnover losses
 - **Industrialised countries risk to fall back**
 - Leapfrogging in emerging economies
 - Delays result in higher power prices
 - China controls equipment supply

Understanding the “electronic” Transformation

Energy use systems electrify

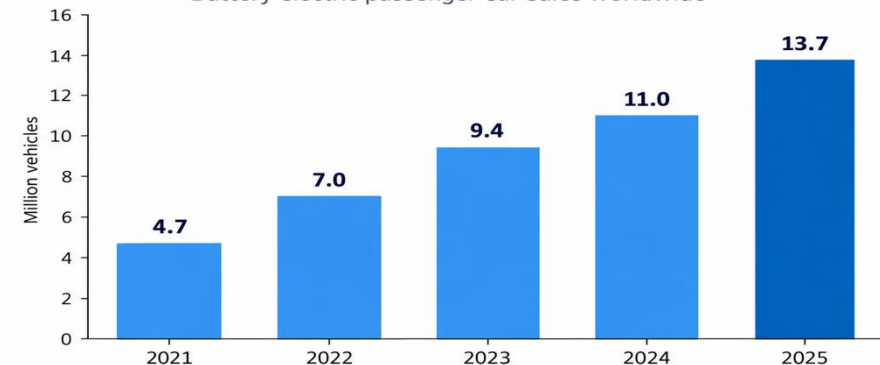
- **Buildings**
 - PV + batteries + heat pumps can satisfy a large share of energy needs behind the meter, including cars
 - Booming home energy management systems HEMS, optimize respecting prosumer preferences, using AI.
 - Heat storage can solve winter problem but needs multi-building systems as of now
- **Manufacturing**
 - Electrification is possible for most processes
 - Local generation + external power supply
 - Power-intensive industries will move south
- **Data centres (DCs)**
 - Hot debate, because of high concentration in the US
 - Data transport is cheap. Power-intensive uses migrate
 - DCs can contribute flexibility, prefer DC to AC supply
- **Transport**
 - Electrification is about to boom



- *Buildings can be fully electrified*
- *Using membranes & pumps instead of drying and distillation can save ¼ of US industrial energy*
- *electric car sales are strongly growing*

Global BEV sales, last five years

Battery electric passenger car sales worldwide



Source: IEA Global EV Outlook 2025 and 2026; 2021-2024 approximated from IEA chart, 2025 derived from 21 million electric car sales and 65% BEV share.

Understanding the “electronic” Transformation

Energy use systems electrify

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- **Power & gas utilities fear competition with behind the metre installations, try hard to**
 - delay change and complicate rules (esp. MFH)
 - conserve old market structures
 - keep control of local consumption / generation
- **Manufacturers try to monetize existing structures, push hard for:**
 - subsidies for fossil fuels, energy-intensive prod.
 - avoiding early investments into electrification
 - Increasingly ambivalent/ open
- **Data centre operators**
 - Try to get power where they can
 - Do not care much about power prices
 - Are potential innovators when obliged to
- **European and US car-makers**
 - Stuck in old habits, underestimated CN
 - Misjudged depth of change, still try to delay
 - Lack of long-term strategy

Understanding the “electronic” Transformation

Electricity grids struggle to manage dynamics

- **Slow change in trad. top-down electricity grids**
 - Transmission grids today are well monitored and digitally controlled, meshed and intensely used
 - Distribution grids are mostly dumb, not well monitored, utilisation rates only 20-50%
- **New challenges: from static to dynamic thinking**
 - Feed-in at low levels, flow inversions, local exchange alone would require considerable grid extension
 - Fluctuating generation requires more flexibility and dynamic management of storage and consumption
 - Limited grid capacity creates temporary bottlenecks
 - Uncontrolled loads (e-cars, heat pumps etc.) resist traditional treatment but offer flexibility options
- **Digitalised active grid management**
 - Optimised routing and battery buffering between grid nodes can boost grid capacity and flexibility
 - Fundamental problem at millions of handover points (meters): who controls consumption?
 - Centralised control of private appliances has not worked, does not meet acceptance
- **Electricity markets and rules are outdated**
 - In most places, new dynamic wholesale markets do not reflect varying local scarcities.
 - Utilities shield consumers/ prosumers from variations
 - Varying grid availability and generation costs are managed with complex administrative procedures



Solid state transformer by EATON

Understanding the “electronic” Transformation

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 - Utilities shield consumers/ prosumers from variations
 - Varying grid availability and generation costs are managed with complex administrative procedures
- **Conflicts between grid companies at all levels**
 - they want autonomy but control over lower levels
 - they fight over data access and control rights
 - they are reluctant to invest under uncertainty
 - **Conflicts over control of generation/ consumers**
 - untapped local flexibility
 - distribution grid optimisation delayed
 - **Political compromise: patches to old framework**
 - Increasingly complex administrative rules
 - Experimentation with market mechanisms

Understanding the “electronic” Transformation

The inescapable shift towards a new control paradigm

Fluctuating generation

- Dynamic management
- Need to exploit flexibilities in routing, storage, and use

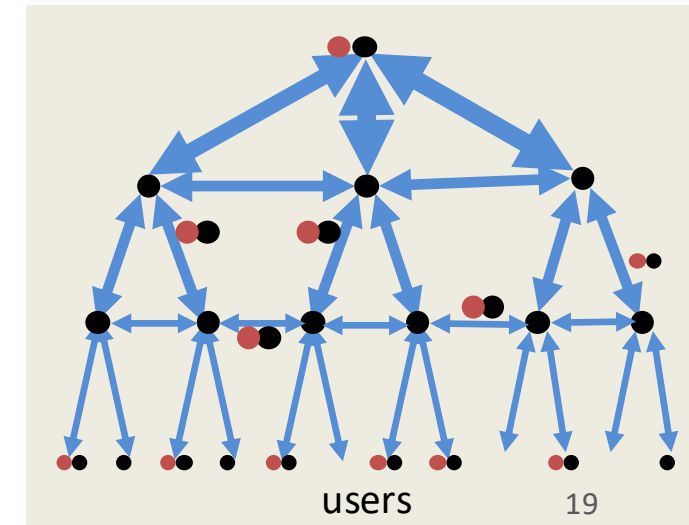
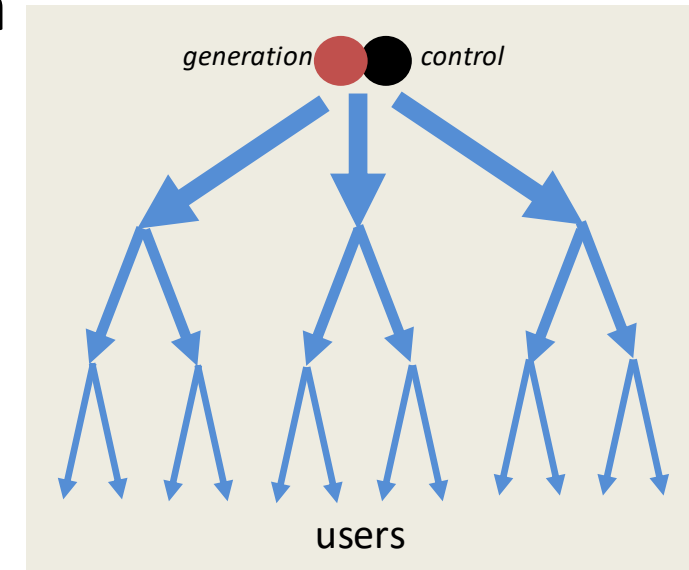
Distributed generation

& Need to exploit flexibilities → Distributed decision-making, Millions of control points, millions of users with changing preferences

Distributed decision-making

& considerable storage costs → Coordination needed, with maximal privacy, minimal communication

→ User-owned real-time control, reacting to price signals and a minimum of rules



Understanding the “electronic” Transformation

An additional dimension: digital information networks

Real-time dynamic management

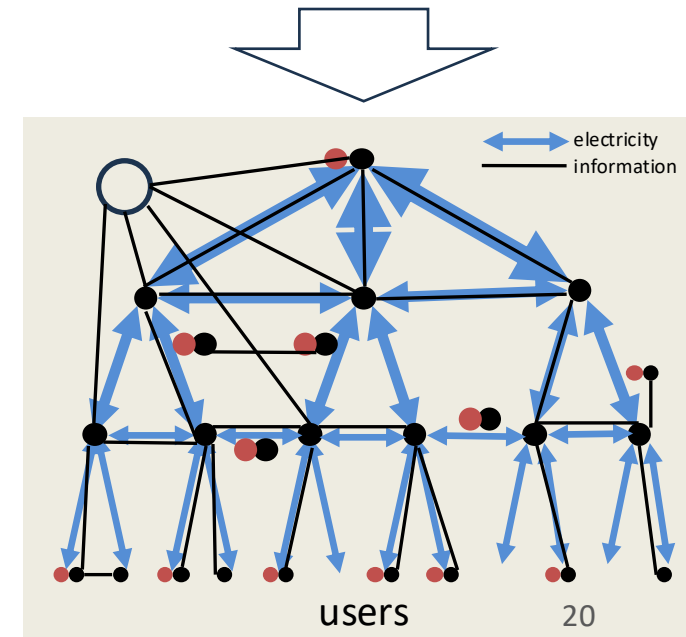
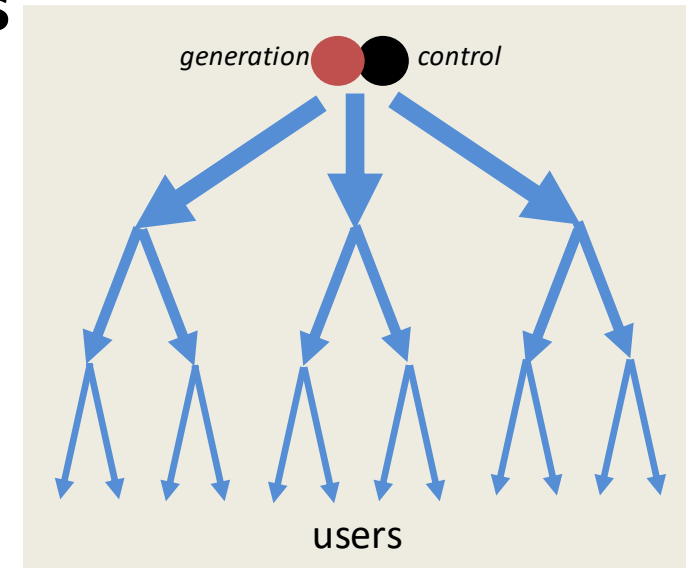
- Digitalisation, information links
 - between controllers
 - with human actors
 - with external data sources

Privacy concerns

- Consumers reluctant to allow control of their activities
- Preference for private HEMS, reacting only to price and emergency signals
- Clear distinction between public grid and behind the meter

Security concerns

- Information systems and links pose additional risk for external attacks
- Layered system with autonomous nodes is safer than centralised system



Power games

Main battles delaying transformation

BEHIND THE METRE INSTALLATIONS

Utilities fear losing control over consumers, losing part of the market. Risks in changing the system. New role as an enabler?

DRIVER: b-t-m is increasingly attractive and grows despite hurdles

FLEXIBILITY

ELECTRIFICATION

High upfront costs, lack of information, lack of interest, ideological wars in public politics. Across all industry sectors, private owners of cars and heating systems.

DRIVER: cost reduction, climate policy, increasing gas costs, security concerns

EFFICIENCY

FLEXIBILITY

RESILIENCE

STATIC PLANNING → DYNAMIC MANAGEMENT

Loss of commercial, administrative, political power. Long-established habits. Inadequate skills. Need for new procedures

- In the energy industry
- In politics / supervising agencies

DRIVER: dynamic management is unavoidable; patches bring instability

EFFICIENCY

FLEXIBILITY

RESILIENCE

LOCAL CONFLICTS: WIND TURBINES, POWER LINES, (DATA CENTRES)

Predominantly NIMBY conflicts, design problems, participation problems, ideological cultural wars.

DRIVER: public interest, cost reduction, climate policy, security concerns

EFFICIENCY

RESILIENCE

The risks of delaying change

Vulnerability in conflicts

Missing climate targets

High energy costs

Falling behind in international competition
(technology expertise, equipment production, location attractiveness)

Priorities for Europe

- **Europe needs determined joint action**
- **Legal framework**
 - Regional/nodal time of use pricing
 - Towards cellular grid management
 - Priority for market-based coordination
 - Public ownership of public grids
 - Strong European grid / interconnectors
- **Industry policy/ Investment support**
 - +++ Grid & charging infrastructure
 - +++ Own EU PV & battery industries
 - +++ **DC Technology**
 - +++ Public Transport
 - ++ Relocate energy-intensive industries N → S
 - - - Gas industry
- **Research & Development**
 - +++ Superconductivity, DC systems
 - +++ Heat storage, heat pumps
 - - Hydrogen
 - - - Fusion, Nuclear
- **Frontrunner regions programme**
 - Competitive application, special subsidies
 - Duration: 5y, prep. 1y, execution 4y
 - Ca. 5 M inhabitants, start with 3, each y more
 - Generation: ambitious PV + wind targets
 - Electrification: Heating, transport, industry
 - Grids: digitalisation, batteries, charging stations
 - Dismantling of gas, petrol, diesel infrastructure
 - Massive upgrading of public transport

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