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STRIDE Smart grid workshop

Lecture 3

Smart grid

Project co-funded by the Europen Union (ERDF, IPA).

Content

- Smart grid definition
- Smart meters
- Sensors
- Demand side management
- ICT
- Microgrids
- Artificial intelligence
- Blockchain
- Electric vehicles
- Energy storage systems

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Smart grid definitions (1)

- What Makes a Grid “Smart?”
  - In short, the digital technology that allows for **two-way communication between the utility** (producer, supplier, aggregator etc.) **and its customers**, and the sensing along the transmission lines is what makes the grid smart.
  - Like the Internet, the Smart Grid will consist of controls, computers, automation, and new technologies and equipment working together, but in this case, these technologies will **work with the electrical grid to respond digitally to our quickly changing electric demand.**

Project co-funded by the Europen Union (ERDF, IPA).

Smart grid definitions (2)

- What does a Smart Grid do?
  - The Smart Grid represents an unprecedented opportunity to move the energy industry into a **new era of reliability, availability, and efficiency** that will contribute to our economic and environmental health.
  - During the transition period, it will be critical to carry out testing, technology improvements, consumer education, development of standards and regulations, and information sharing between projects to ensure that the benefits we envision from the Smart Grid become a reality.

Project co-funded by the Europen Union (ERDF, IPA).

Smart grid definitions (3)

- The benefits associated with the Smart Grid include:
  - More efficient transmission of electricity
  - Quicker restoration of electricity after power disturbances
  - Reduced operations and management costs for utilities, and ultimately lower power costs for consumers
  - Reduced peak demand, which will also help lower electricity rates
  - Increased integration of large-scale renewable energy systems
  - Better integration of customer-owner power generation systems, including renewable energy systems, and
  - Improved security

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The Smart grid in cartoons

https://www.smartgrid.gov/the_smart_grid/smart_grid.html

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Smart grids

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From traditional … to the smart …

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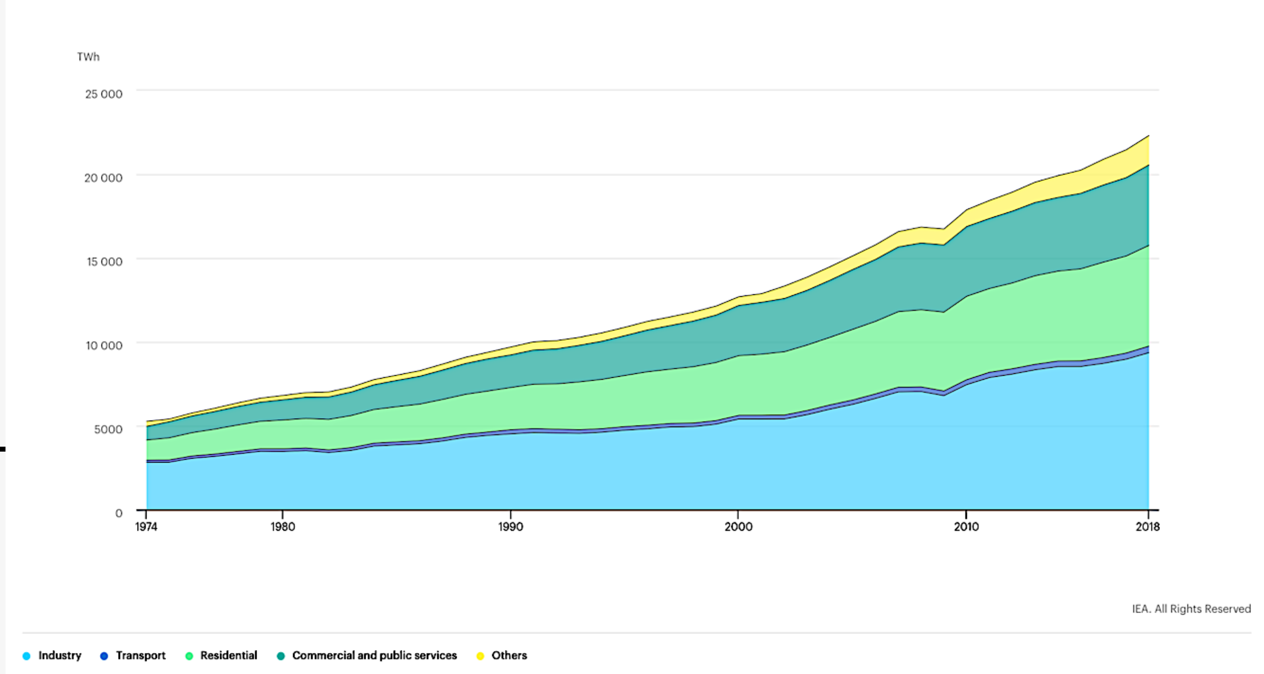
World electricity final consumption by sector 1974 - 2018

- Energy needs higher than ever
- Electricity in final energy consumption – 24% - 31%



Project co-funded by the Europen Union (ERDF, IPA).

Source: IEA, https://www.iea.org/data-and-statistics/charts/world-electricity-final-consumption-by-sector-1974-2018

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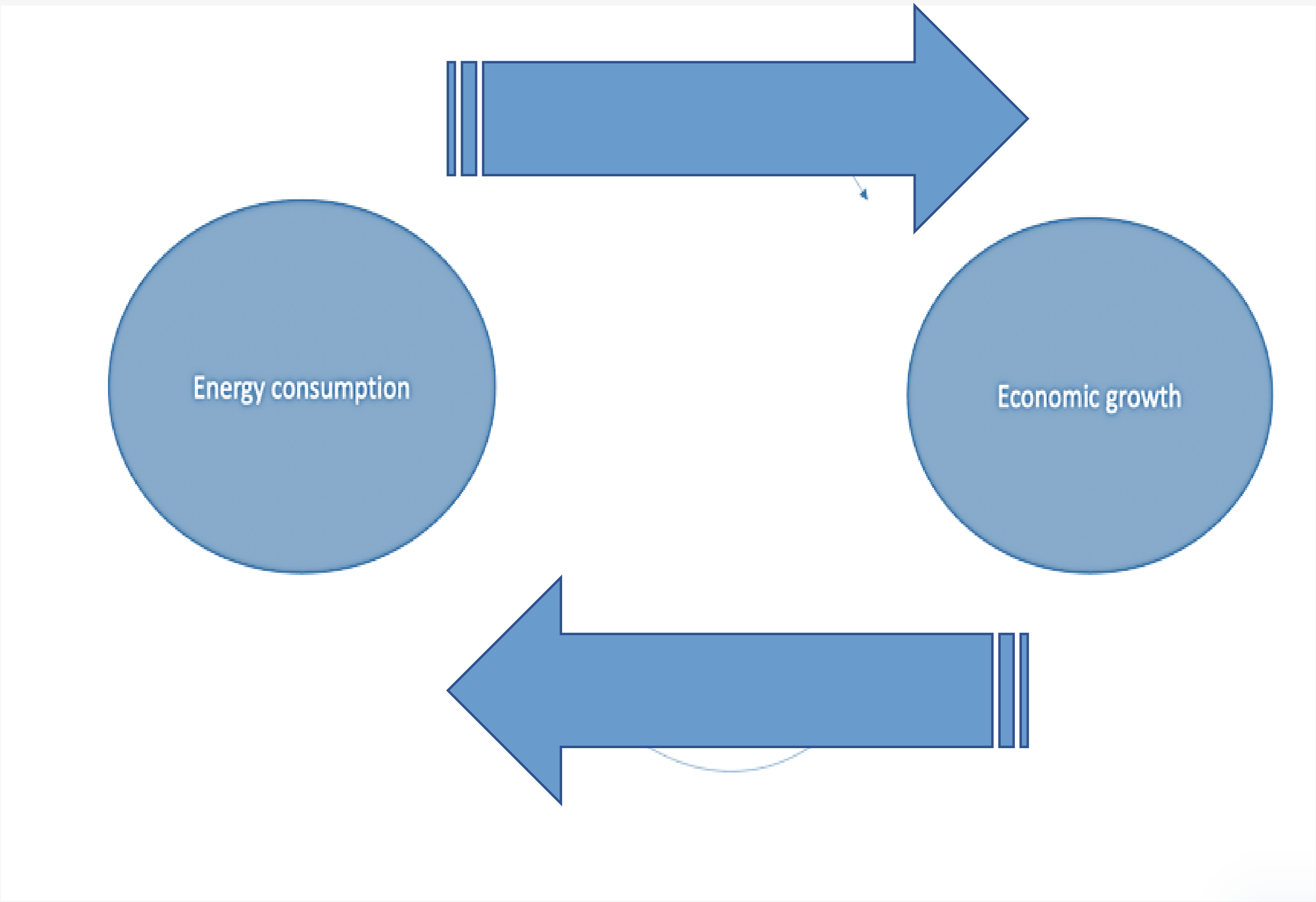
The relation between economic growth and energy consumption



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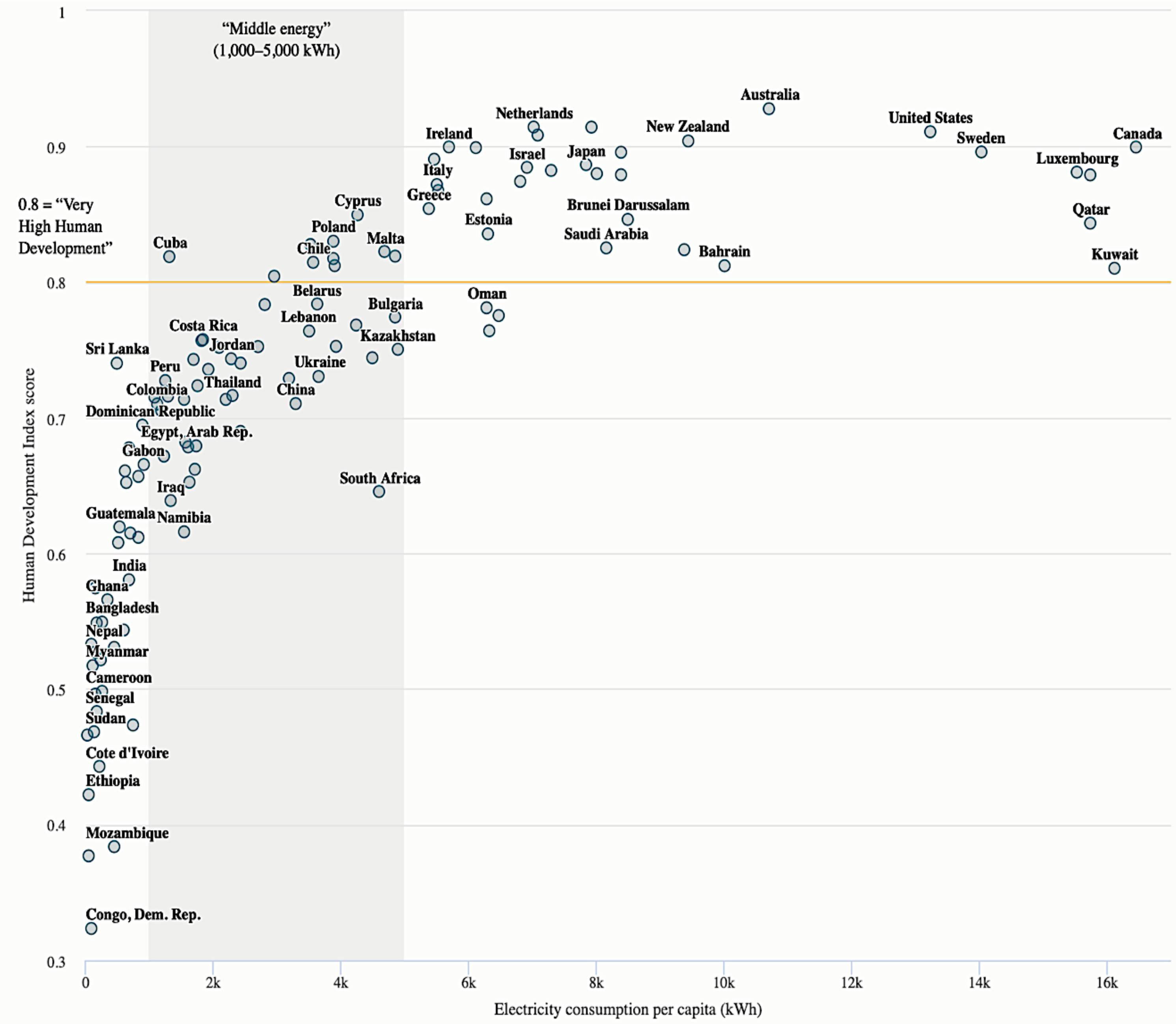
- The relation between **Human Development Index** (HDI) and **electricity** consumption
  - Life length and health
  - Education
  - Living standard



Source: https://www.cgdev.org/media/electricity-consumption-and-development-indicators

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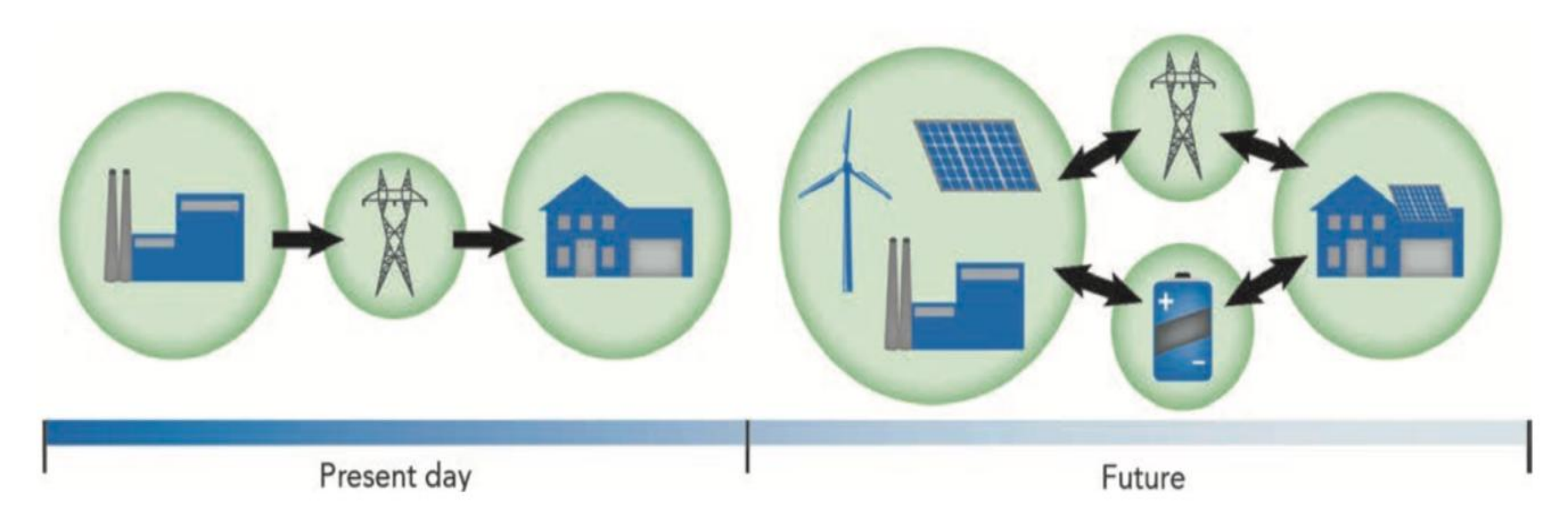
Smart Grid - Innovative solutions

- Two-way communication between consumer and provider
- Exchange of electricity and information
- Upgraded electricity network
- High flexibility
- Prosumers



Source: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2013/smart_grids.pdf

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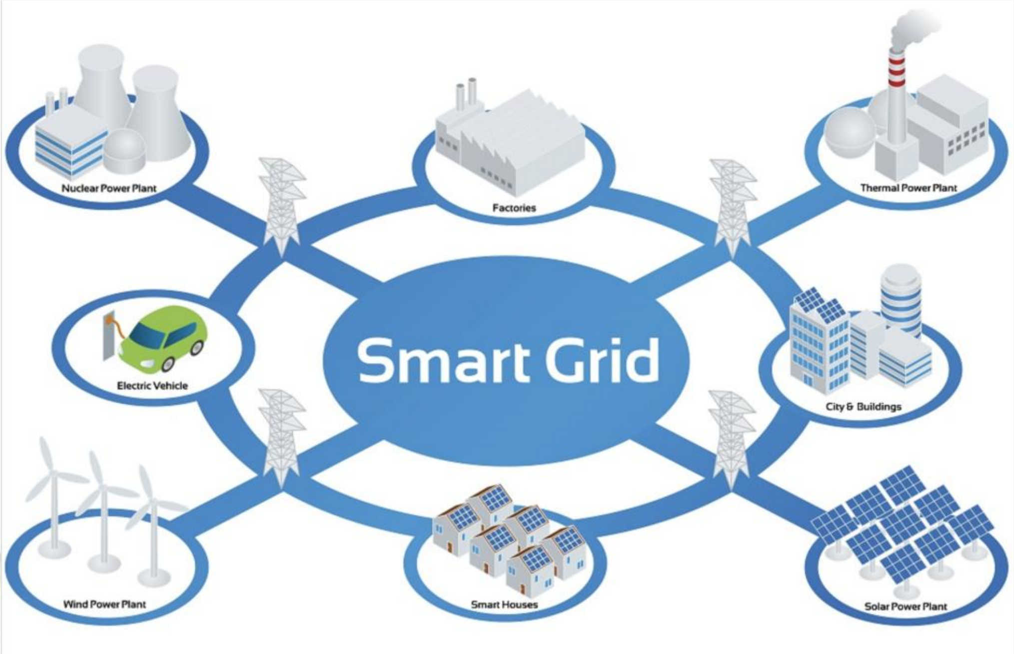
Elements of Smart Grid



- Change implementation over years and decades
- Long-term planning
- Policies and guidelines

Source: https://www.powerelectronicsnews.com/wp-content/uploads/sites/3/2017/05/NDavis2.png

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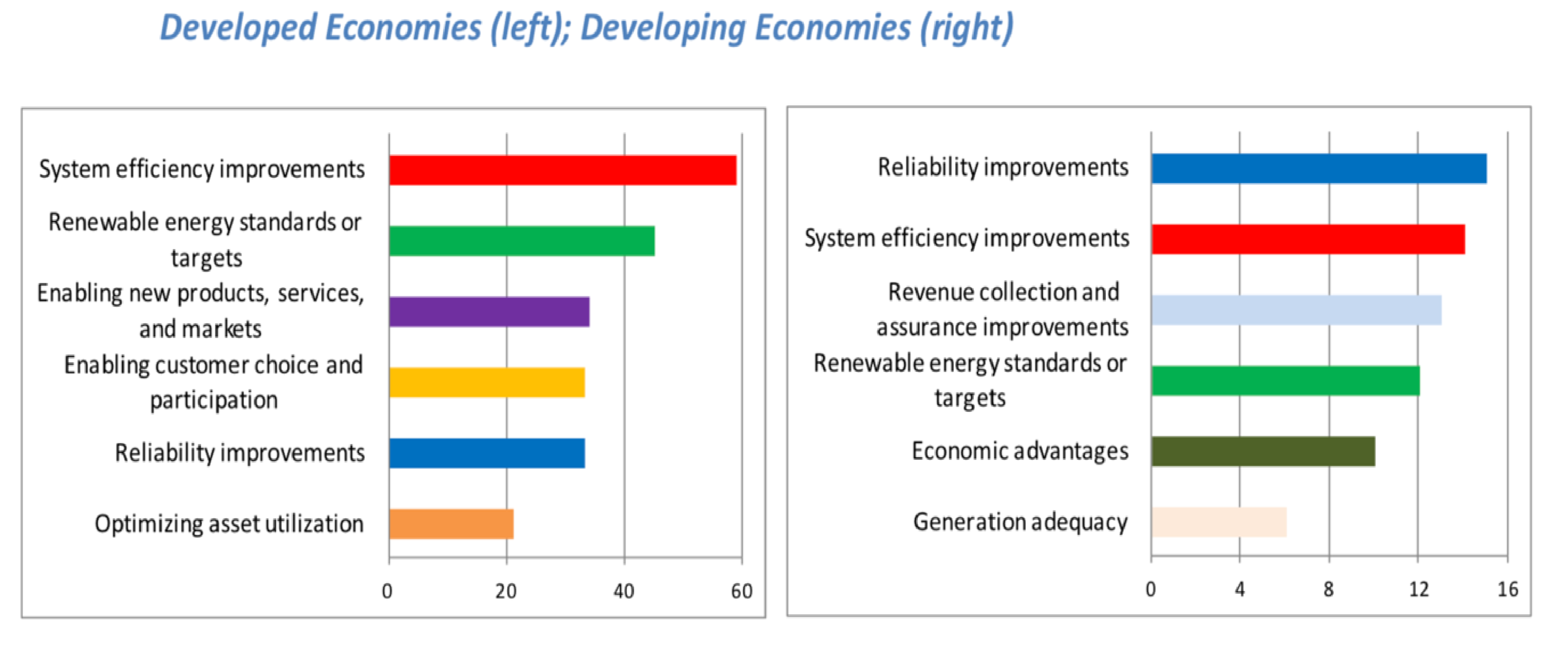
Smart Grid benefits and drivers

Top ranked motivating drivers by economies



Project co-funded by the Europen Union (ERDF, IPA).

Source: https://www.iea-isgan.org/wp-content/uploads/2018/02/ISGAN_Report_SGDriversAndTechnologies_2014.pdf

Smart Grid development drivers

Internal driving forces

end – user benefits

- lower energy costs
- less shortages
- better consumption awareness
- local energy generation
- income from DR

grid operator benefits

- greater flexibility
- greater supply security
- improved system security
- reduced management and operation costs

External driving forces

national benefits

- increasing electricity demand
- agreed upon international policies
- GHG emission goals
- renewable energy goals
- greater energy independence

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Smart Grid Technologies

1. Enable the grid to function in a "smart way"
2. Span different areas
3. Include existing and developing technologies

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Smart meters and Advanced Metering Infrastructure (AMI) (1)

- 1970s – start of smart metering development
  - Remote control and communication
  - Provide two-way communication
  - Measure electricity usage in real time
  - Can switch supply on/off

TYPES OF ELECTRICITY, HEAT, AND GAS METERS

<table>
<tr><th colspan="2">Type of meter</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td rowspan="2">Electricity meter</td><td>Electro-mechanical</td><td>• Reliable measurement</td><td>• Manually reading
• Electricity consumed by current coil is also registered on the meter
• Creep phenomenon</td></tr>
<tr><td>Electronic</td><td>• Measure more parameters besides energy consumption
• LCD/LED display
• Two-way communication
• Other functions of smart control</td><td>• Complex communication infrastructure required
• Periodic calibration routines are required
• Security issues with unencrypted communication</td></tr>
</table>

Source: https://ieeexplore.ieee.org/document/7365417

Smart meters and Advanced Metering Infrastructure (AMI) (2)

- Additional smart metering benefits:
  - Near real-time information on consumption
  - Energy usage management
  - Reducing costs and emissions
  - No more estimated billing
  - Easier supplier switching
  - Health monitoring

Project co-funded by the Europen Union (ERDF, IPA).

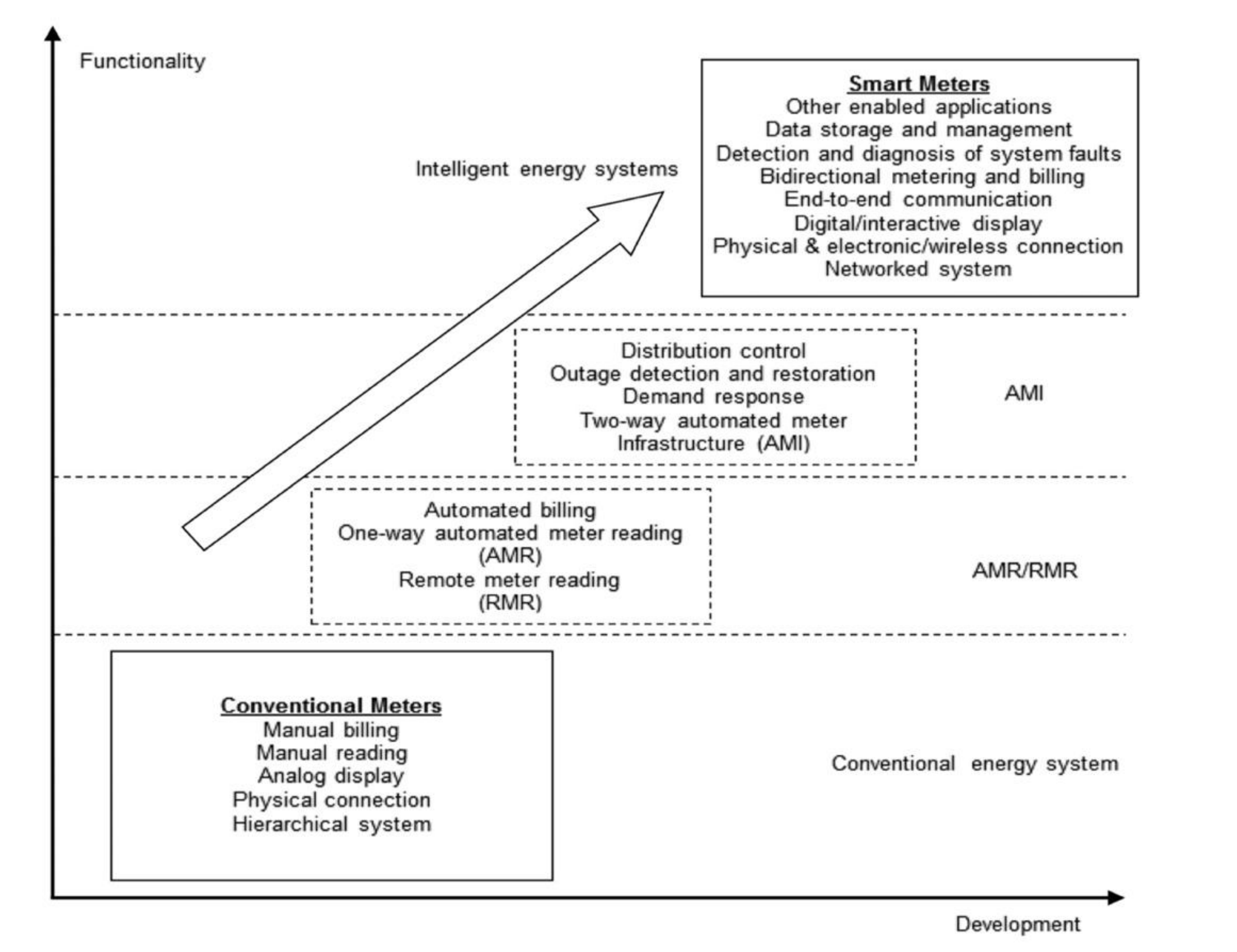
An older electromechanical Wh meter (left) and a modern smart meter (right)

- Croatian electricity meters provided by HEP Distribution System Operator (HEP DSO)

Source: https://hrvatska-danas.com/2021/04/11/akontacijska-struja-odlazi-u-povijest-iducih-10-godina-svi-bi-trebali-dobiti-pametna-brojila/

Project co-funded by the Europen Union (ERDF, IPA).

The development of smart energy meters and their functions



Source: https://ieeexplore.ieee.org/document/7365417

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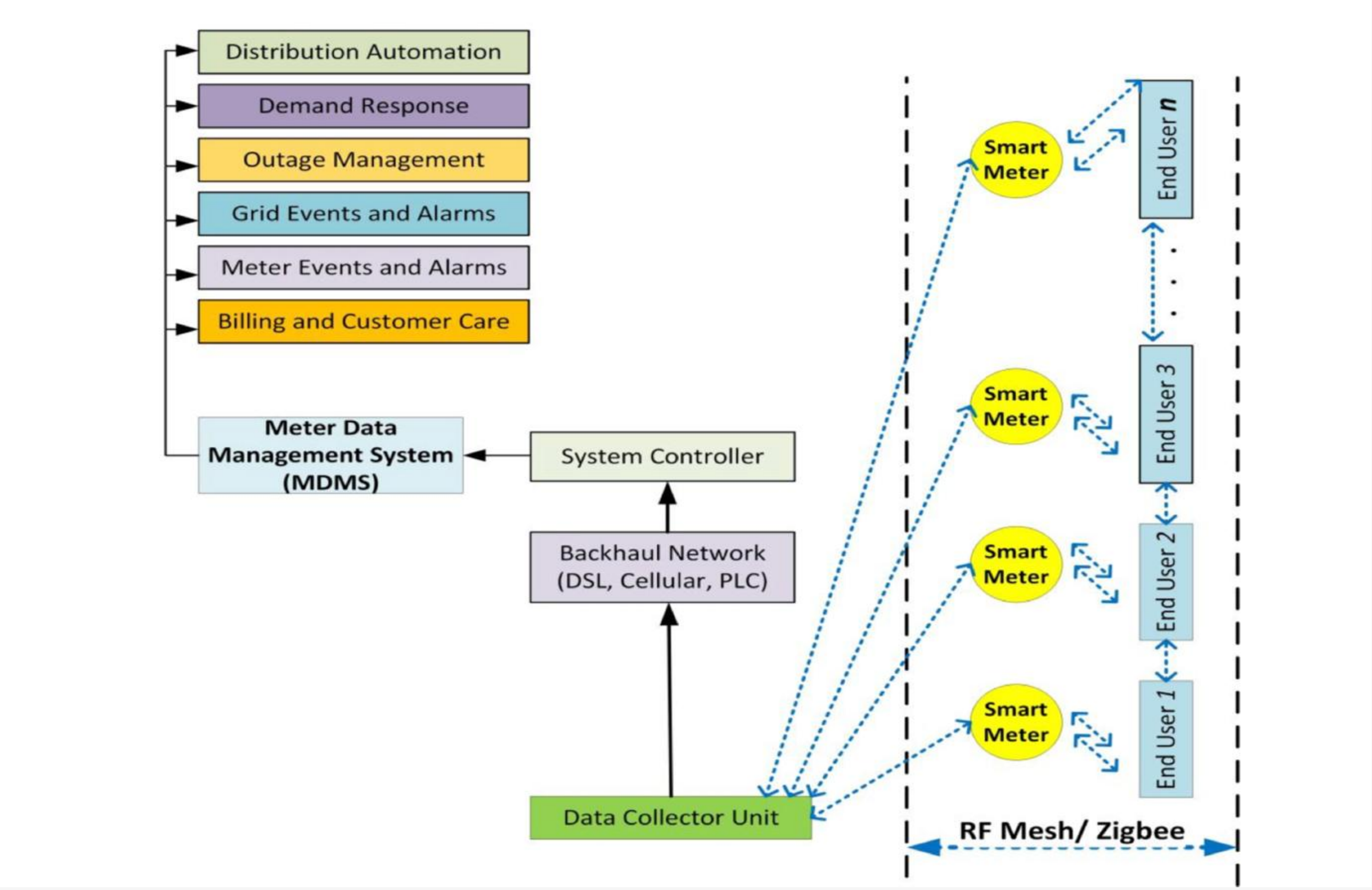
AMI infrastructure in a Smart Grid



Source: https://doi.org/10.1016/j.jnca.2016.10.003

Project co-funded by the Europen Union (ERDF, IPA).

AMI key applications

- Real time consumption data display
- More dynamic pricing schemes
- Net metering
- Faster services restoration
- Remote turn on and turn off

Source: https://www.smart-energy.com/regional-news/africa-middle-east/ericsson-bags-smart-meter-deal-in-india/

Project co-funded by the Europen Union (ERDF, IPA).

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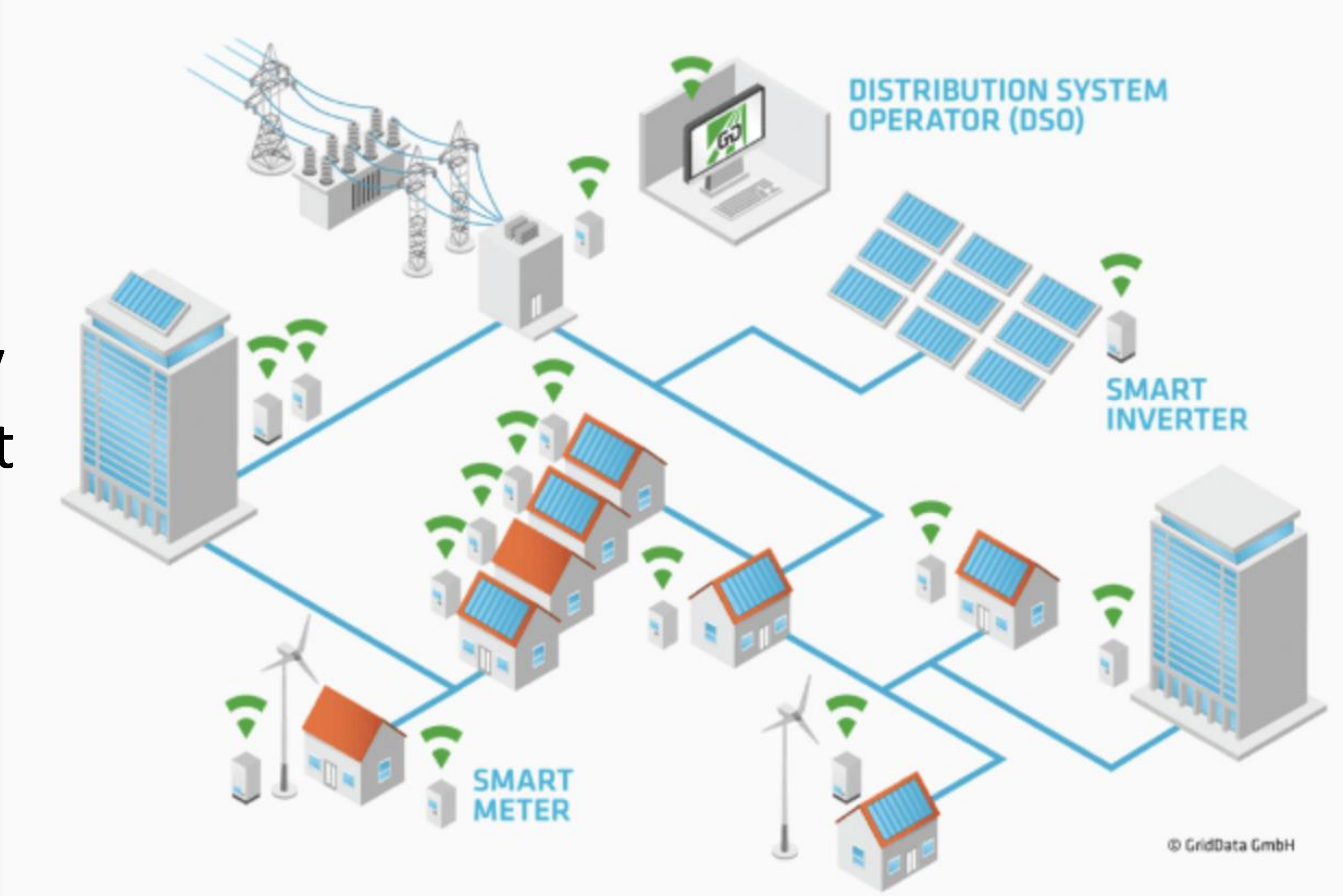
AMI key applications

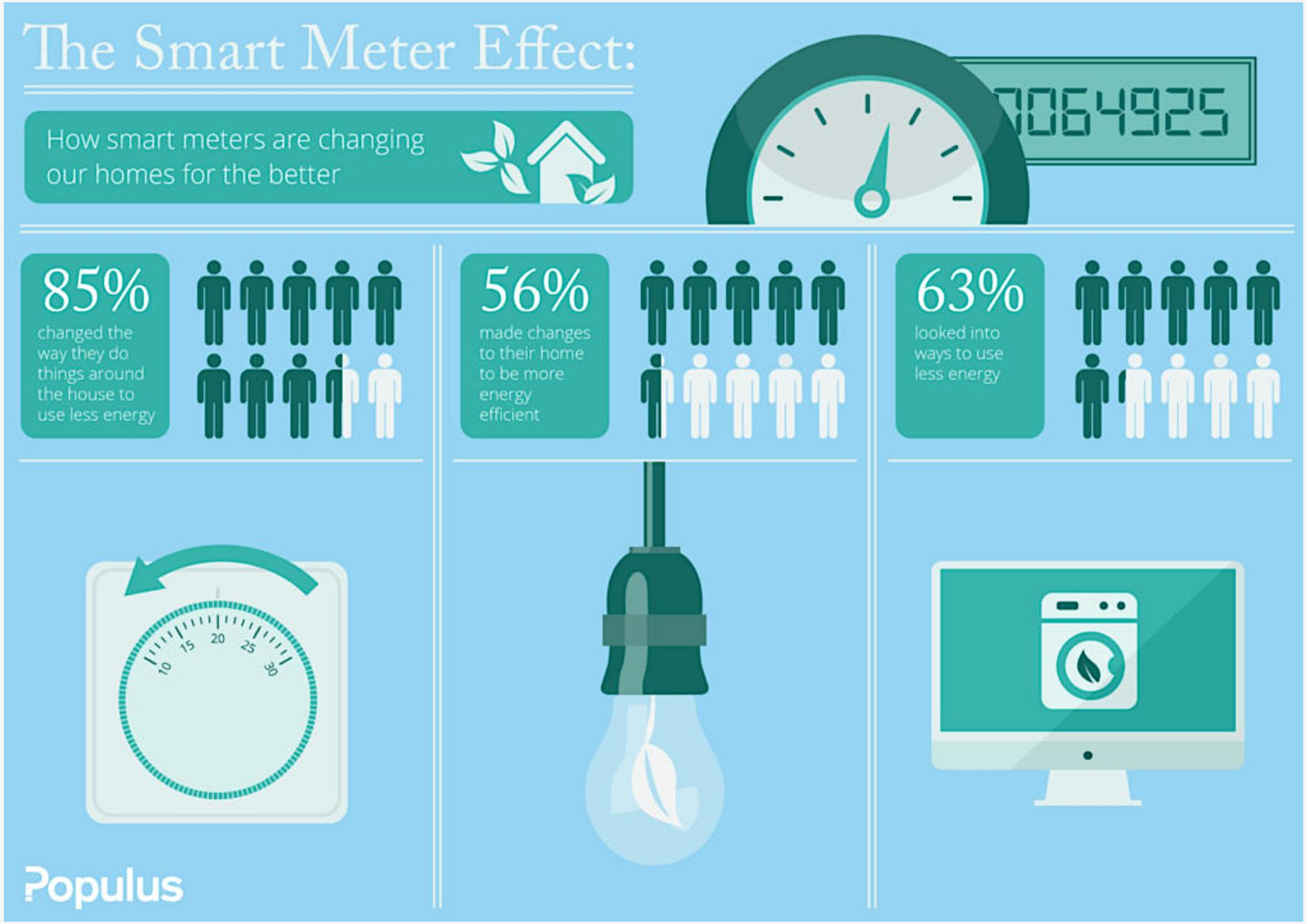
Power quality monitoring

- Energy prepayment
- Detection of energy tampering and theft
- More efficient EV use
- Customer convenience



Source: https://paktechpoint.com/advanced-metering-infrastructure-functional-requirements/

Project co-funded by the Europen Union (ERDF, IPA).



Source: https://alfakharco.com/utility-solutions/end-to-end-integrated-smart-metering/

Project co-funded by the Europen Union (ERDF, IPA).

AMI cost-benefit analysis

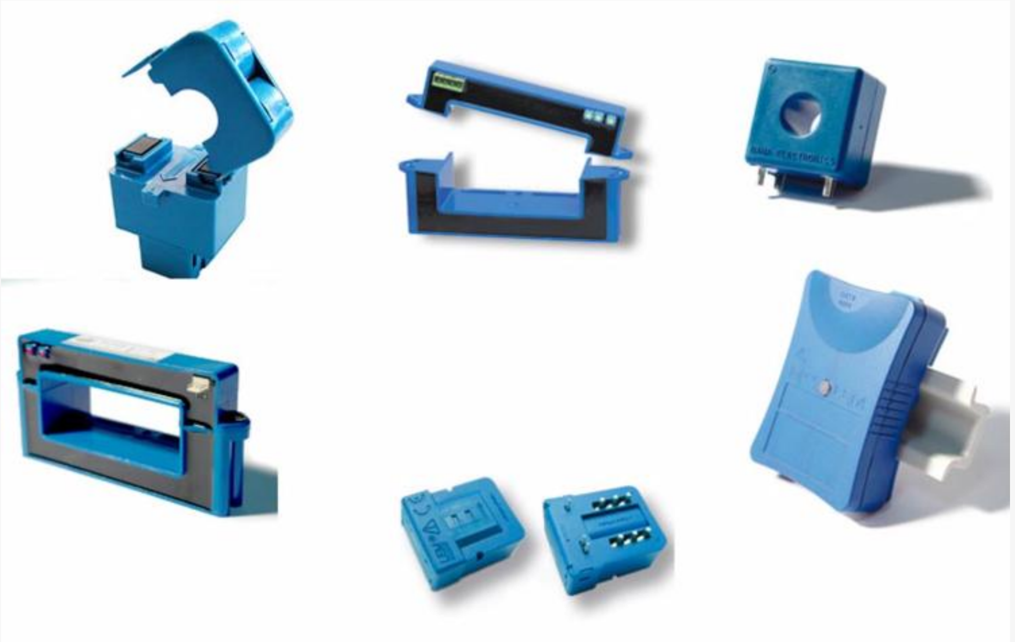
Costs	Benefits
▪ AMI Metering Equipment and Communications Infrastructure Implementation • AMI Meters & Installation • AMI Communications Network Hardware & Installation ▪ IT Systems and Integration: MDAS,MDM, storage system, data integration platform, analytics software ▪ Program Management ▪ AMI Operational Costs – Metering Operations (Maintenance, field servicing, inventory management) – Communications Operations ▪ Consumer Education	▪ Reduction in Meter Reading Costs ▪ Reduction in Field and Meter Services (Manual Disconnect/Reconnect of Meters, Manual Off-Cycle/Special Meter Reads) ▪ Theft/Tamper Detection and Reduction ▪ Efficiency Improvement in Billing and Customer Management ▪ Improved Capital Spend Efficiency – Distribution System Management – Asset Management Planning – Avoided Meter Purchases ▪ Improved Outage Management Efficiency

Source: https://www.nsgm.gov.in/sites/default/files/Smart-Grid-Training-Course-July-2016.pdf

Project co-funded by the Europen Union (ERDF, IPA).

Sensors

- Monitoring and measuring grid status
- Detecting mechanical failures in grids



Project co-funded by the Europen Union (ERDF, IPA).

Sources: http://www.metrycom.com, https://greentechlead.com/smart-grid/smart-grid-sensor-market-to-grow-ten-fold-by-2021-22459

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Demand Side Management (DSM)

- Demand response (DR) and energy efficiency (EE) programs
- Adapting the load to the available power
- Economic incentives
- Benefits for the environment
- Ensuring grid stability

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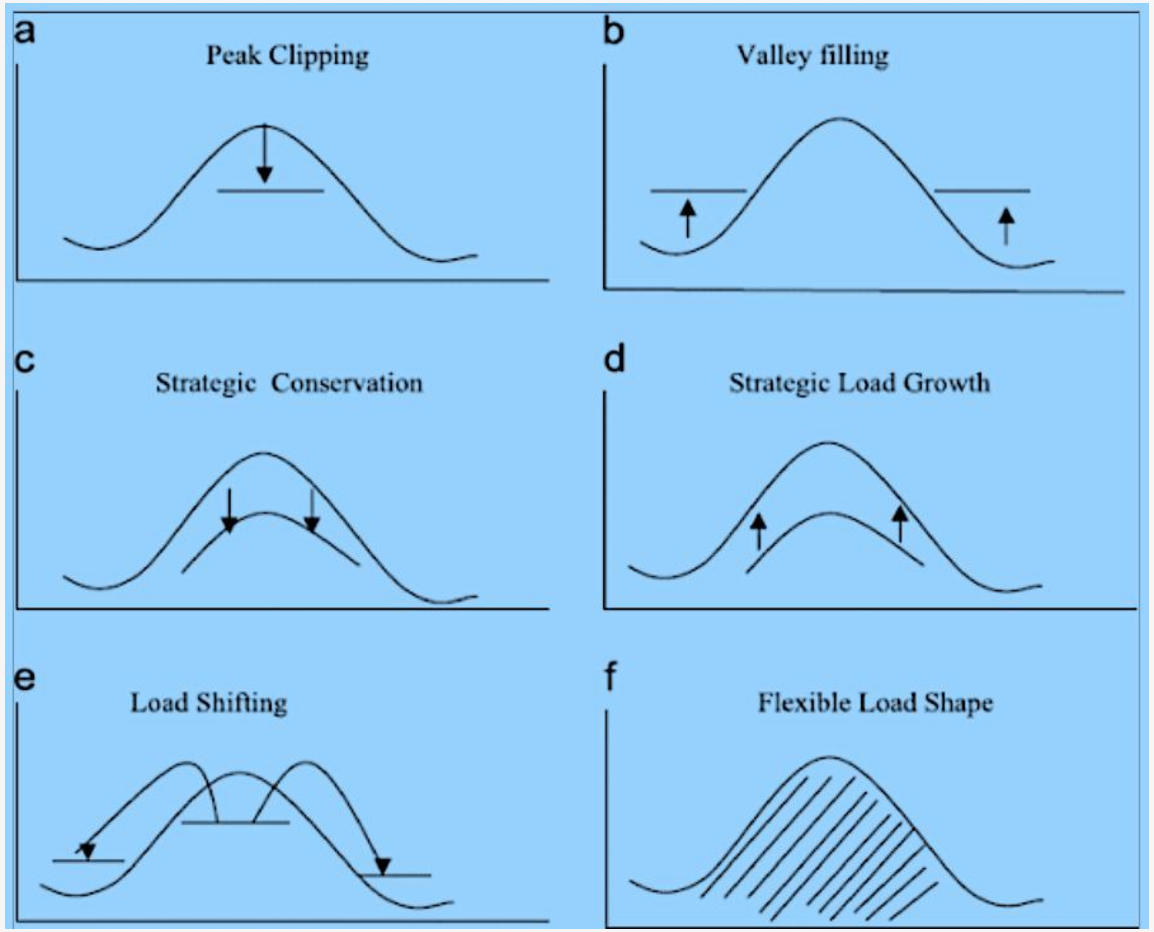
Typical load shape objectives that can be achieved through DSM



Source: https://ieeexplore.ieee.org/document/8038581

Types of Demand Response

- Implicit DR
  - DR pricing tariffs:
    - Flat rate tariff (FR)
    - Time of use pricing (TOU)
    - Real time pricing (RTP)
    - Critical peak pricing (CPP)
    - Critical peak rebate (CPR)
- Explicit DR

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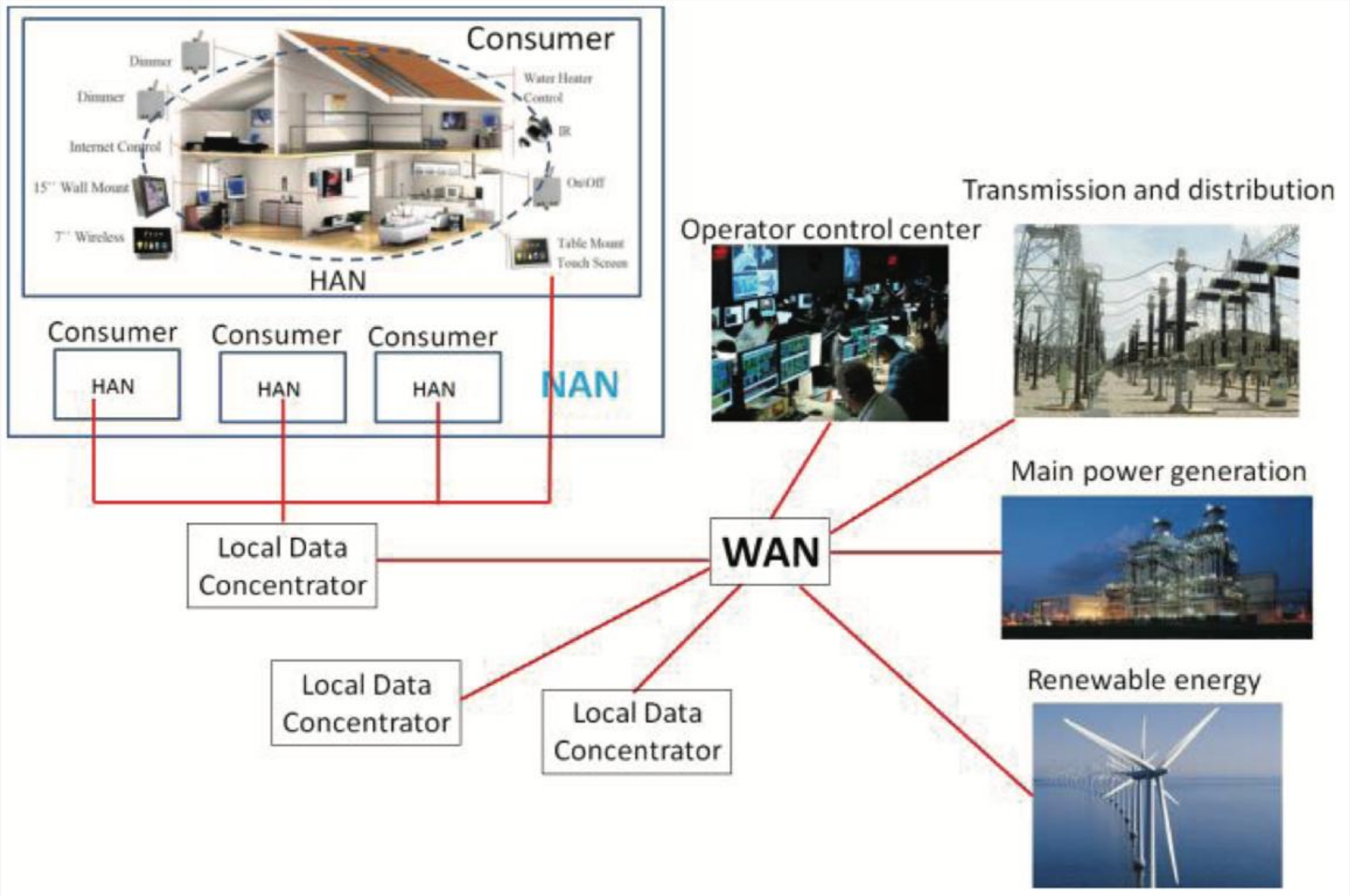
Information and Communication Technologies (ICT)



Source: https://ieeexplore.ieee.org/document/7526014

Project co-funded by the Europen Union (ERDF, IPA).

Microgrids

- SG can be divided into multiple integrated microgrids
- Part of the grid which can operate autonomously (off-grid)
- Consists of loads and power sources
- Switch for islanding

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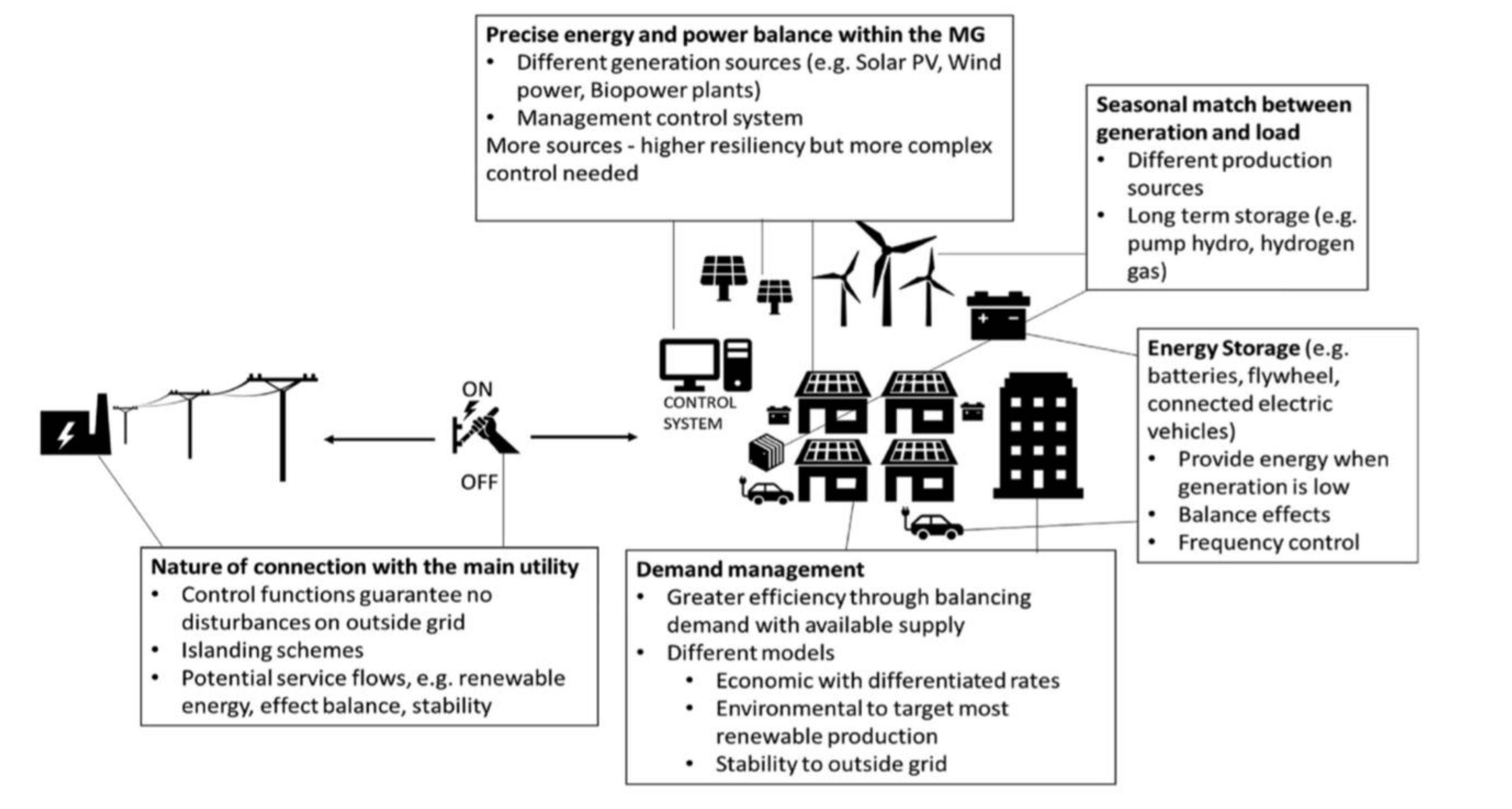
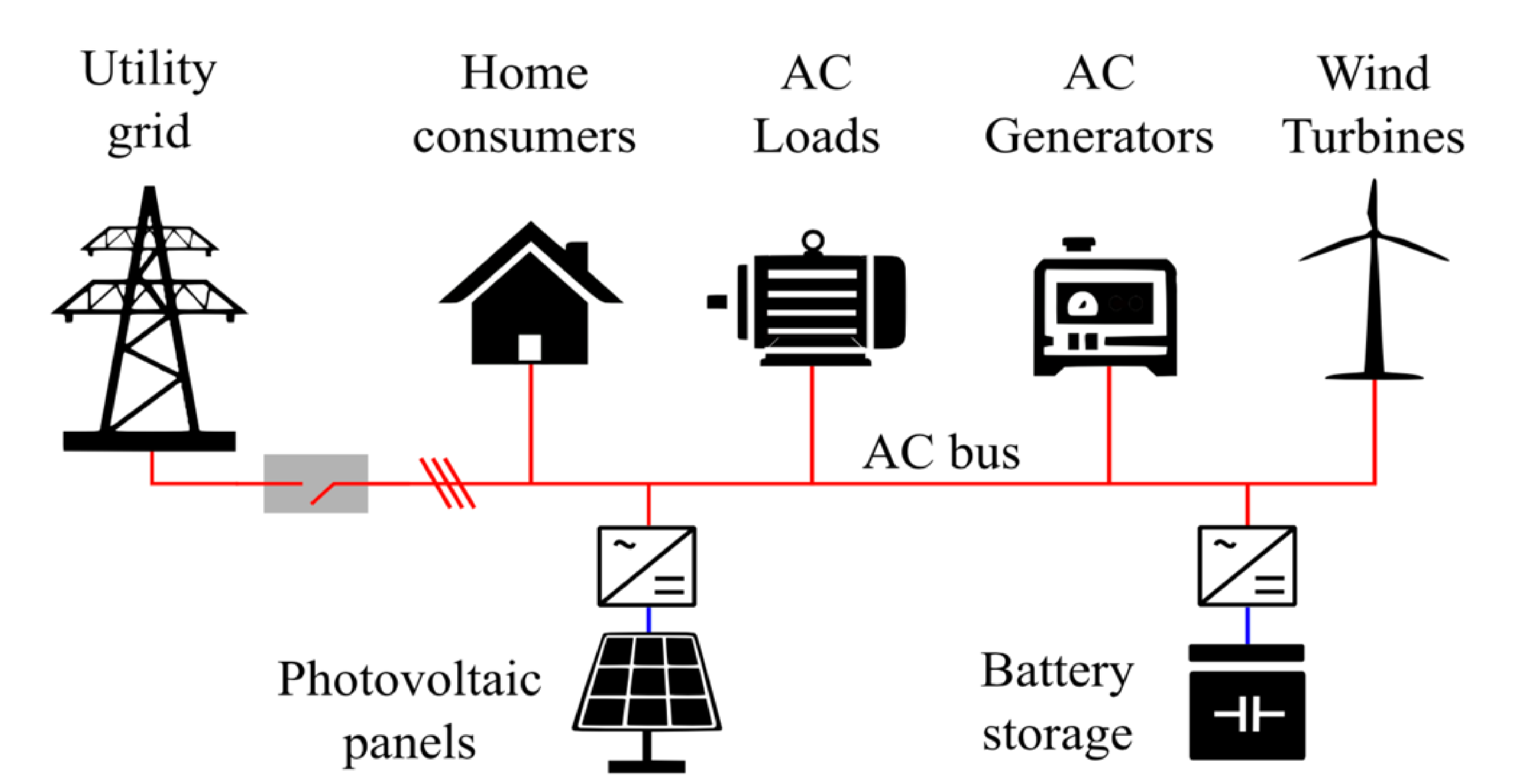
Conceptual scheme of a microgrid



Source: https://doi.org/10.1016/j.rser.2019.109690

Project co-funded by the Europen Union (ERDF, IPA).

AC microgrid structure



Source: https://ieeexplore.ieee.org/document/8282457

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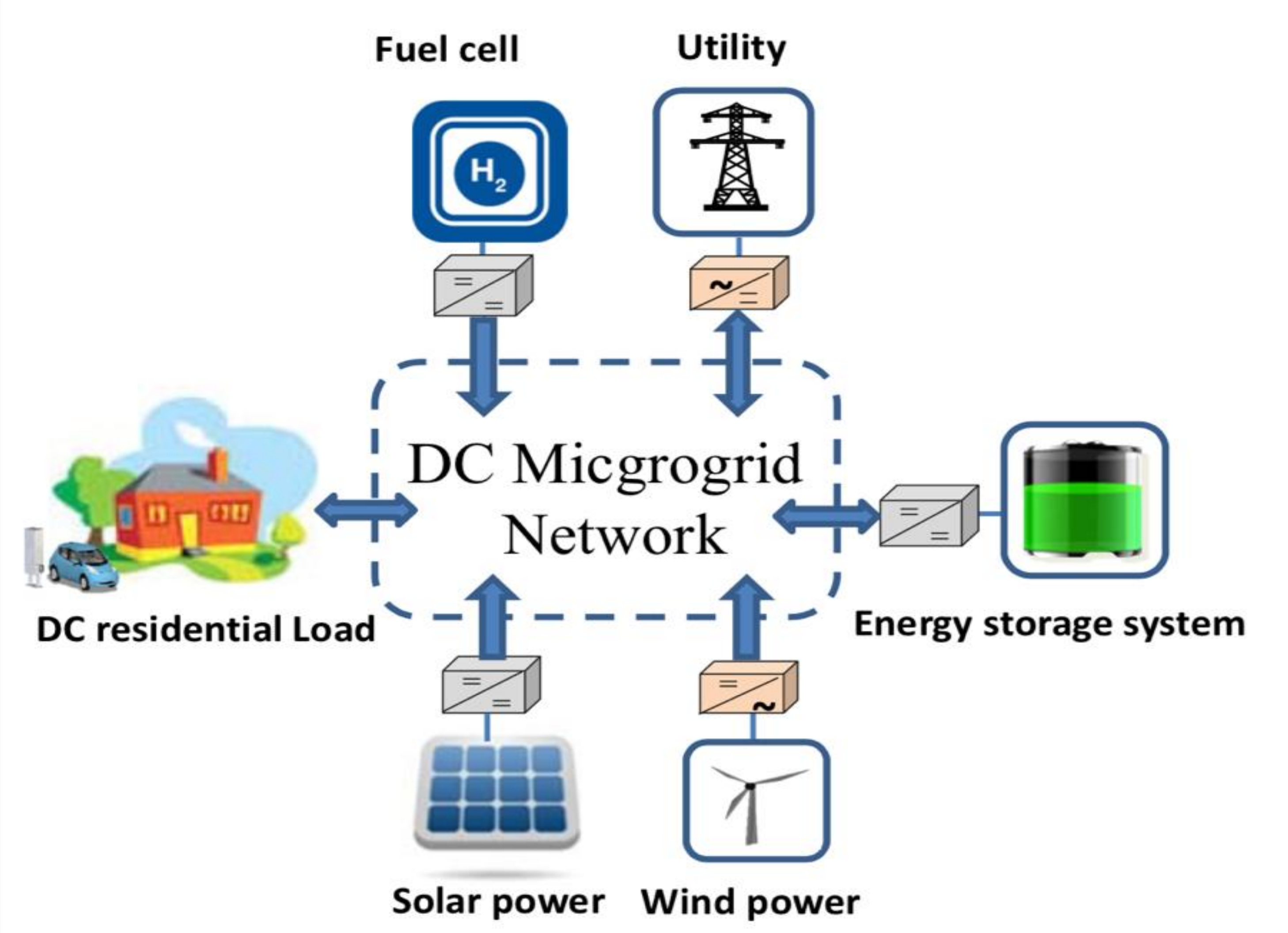
DC microgrid structure



Source: https://ieeexplore.ieee.org/document/7392709

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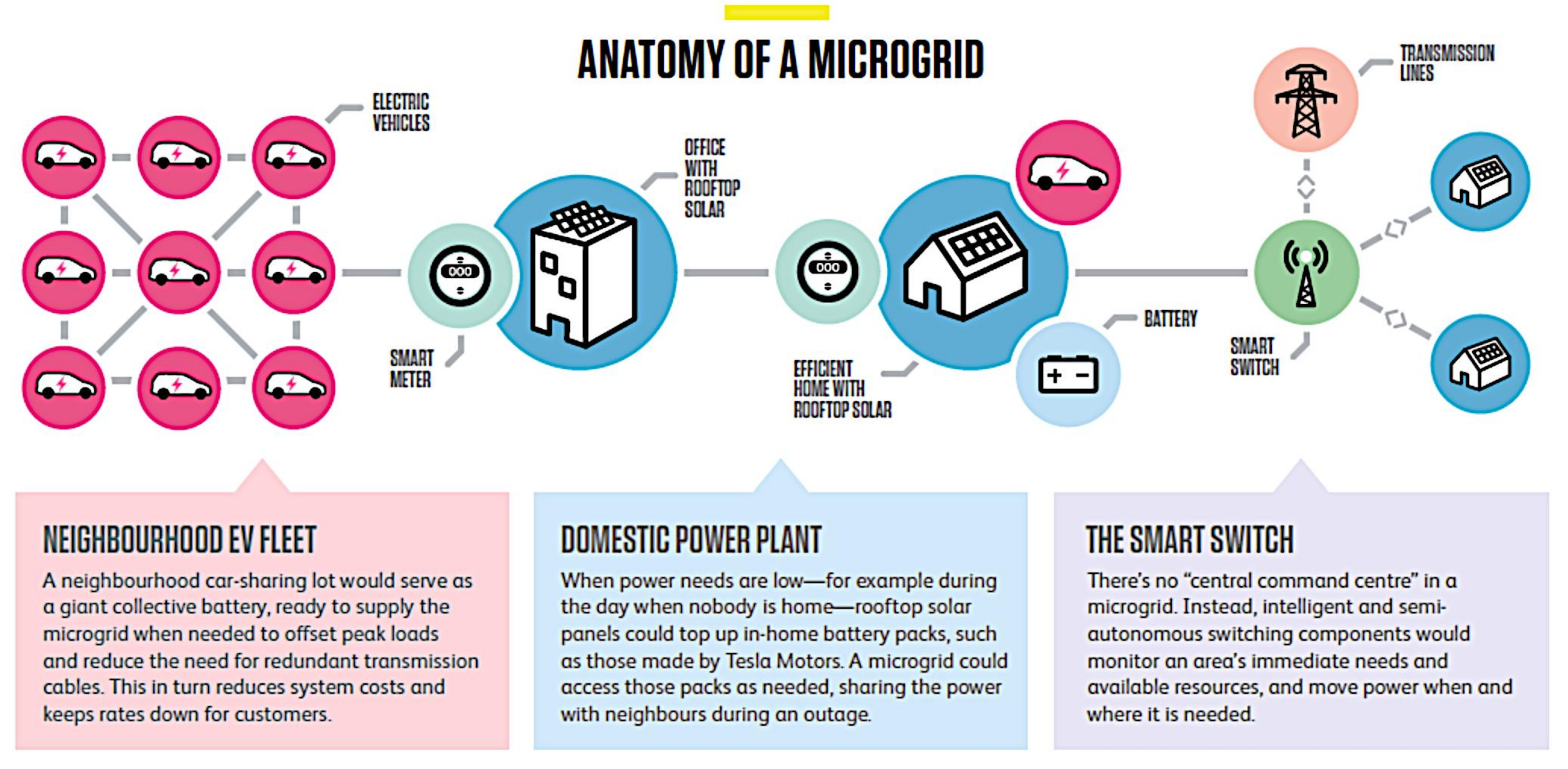
Smart microgrid



Source: https://cleanenergycanada.org/wp-content/uploads/2014/10/Anatomy-of-a-Microgrid.png

Project co-funded by the Europen Union (ERDF, IPA).

Artificial intelligence (AI)

- The science and engineering of building intelligent machines
  - Ways for machines to achieve AI:
    - Machine Learning (ML):
      - Deep Learning, and
      - Reinforcement Learning.
    - Rule-Based Programming
  - Artificial Neural Networks (ANN) – three layers

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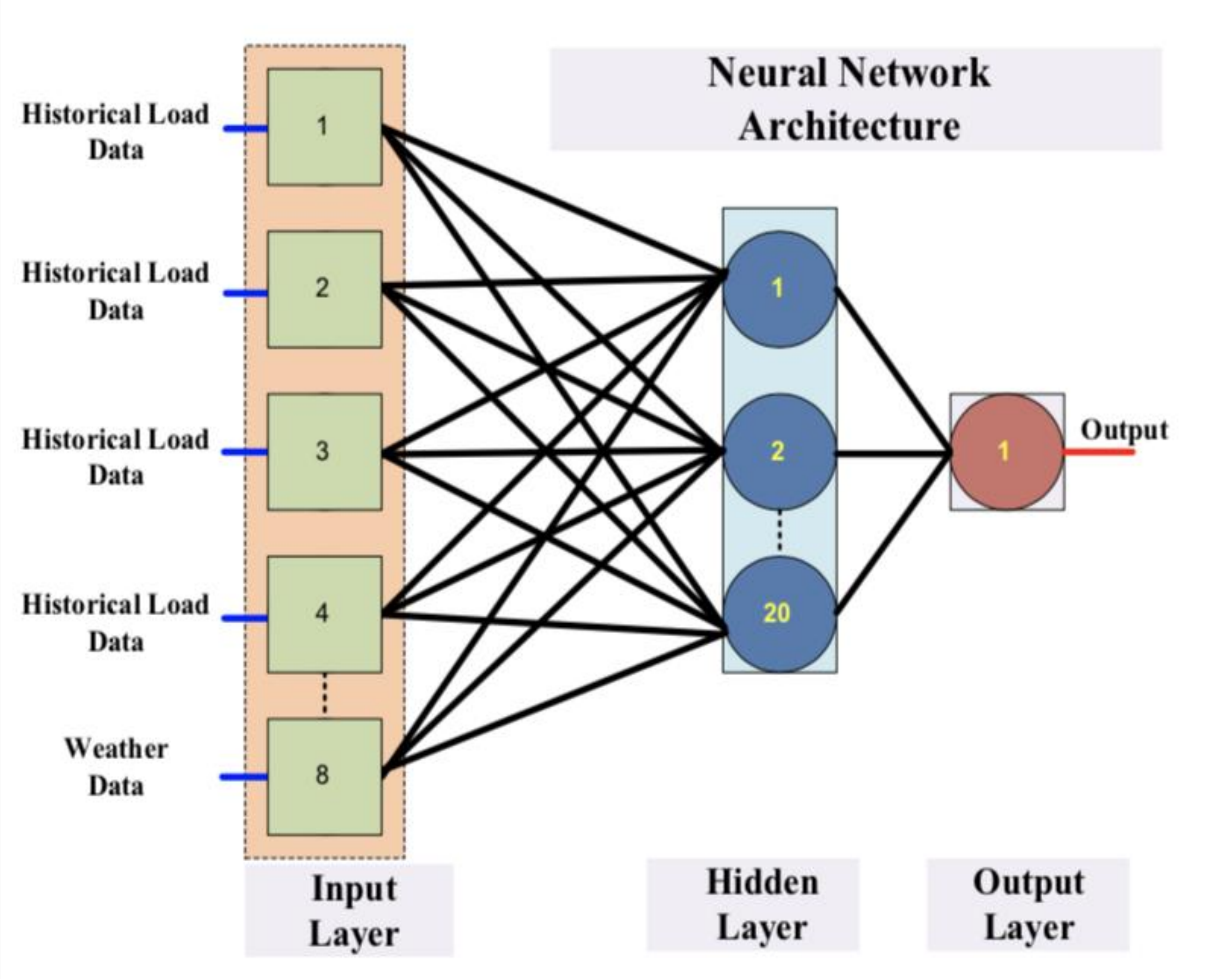
Architecture of an ANN used to predict future loads



Source: https://doi.org/10.1016/j.rser.2015.04.065

Project co-funded by the Europen Union (ERDF, IPA).

Blockchain

- Decentralised technology
- Participants create, maintain and store chains of information blocks
- Every peer has a copy of the ledger
- Smart contracts – agreed upon in advance and executed when the terms are met
- Peer to peer (P2P) energy trading

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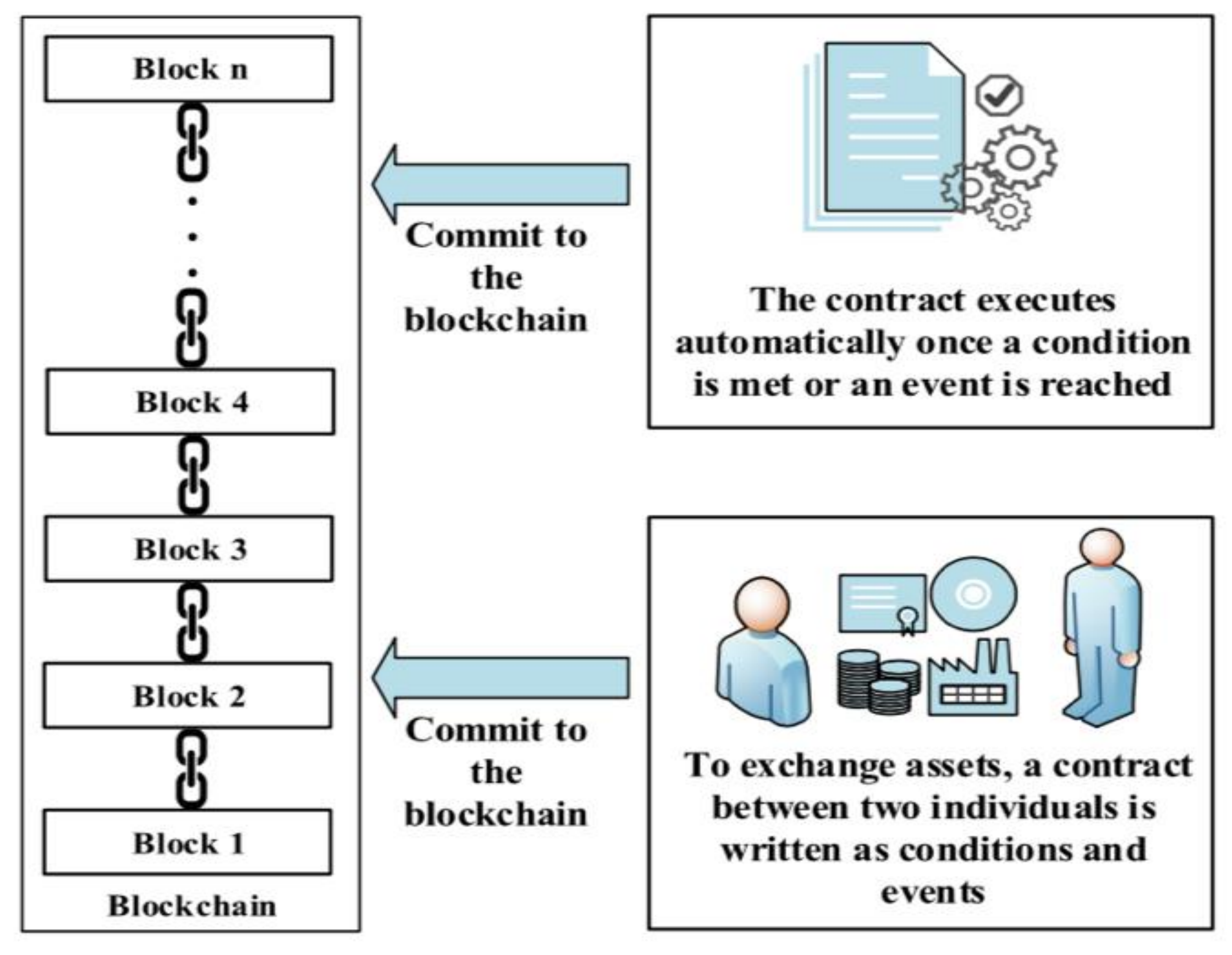
Depiction of Blockchain and the Smart Contract principle



Source: https://ieeexplore.ieee.org/document/9090812

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Electric vehicles

- Transport sector – 1/4 of Europe’s GHG emissions
- Noise pollution - high
- Internal Combustion Engines (ICEs) are highly inefficient (18% - 25%)

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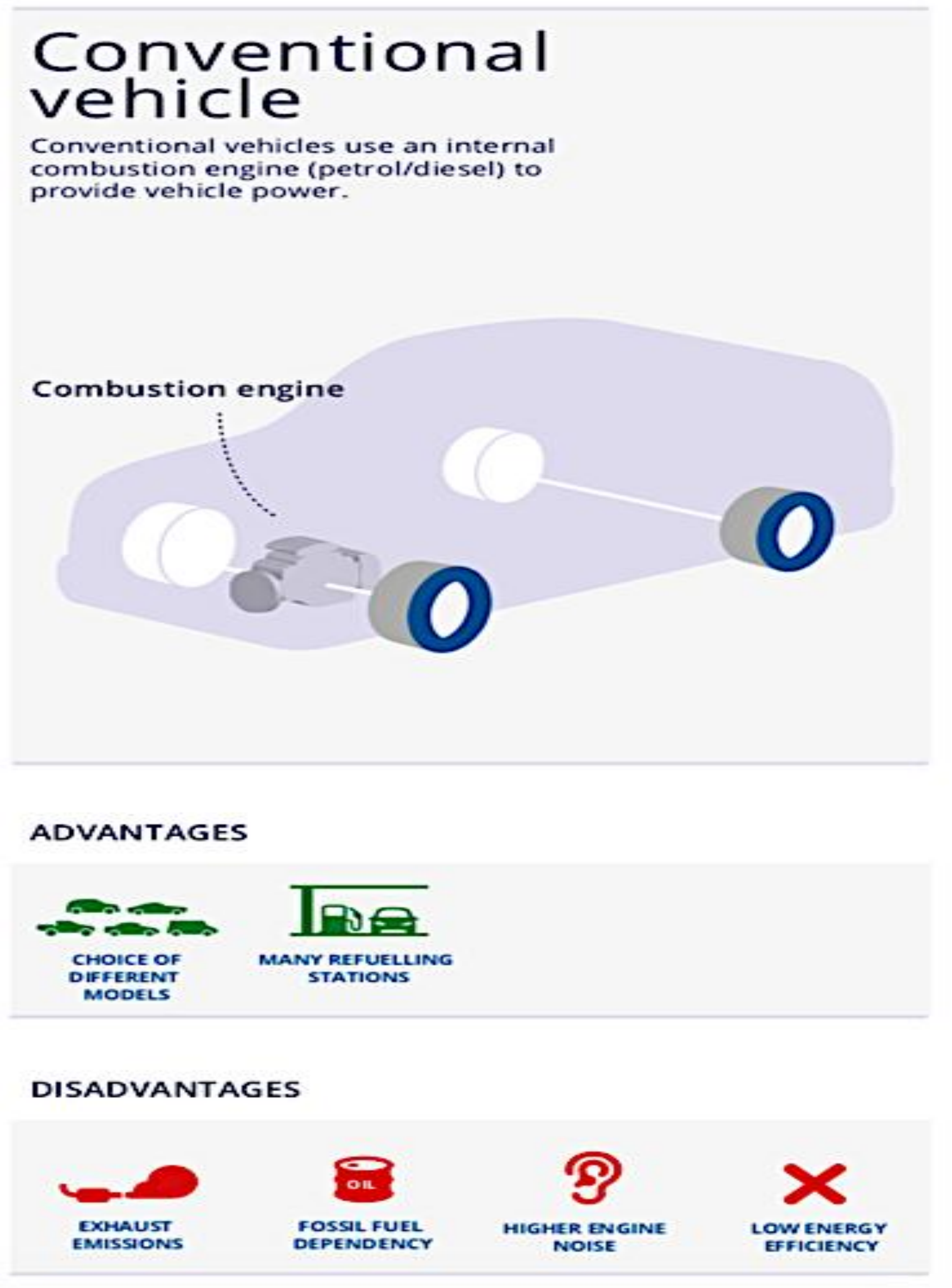
A conventional vehicle with an ICE, its advantages and disadvantages

Source: https://www.eea.europa.eu/publications/electric-vehicles-in-europe/at_download/file



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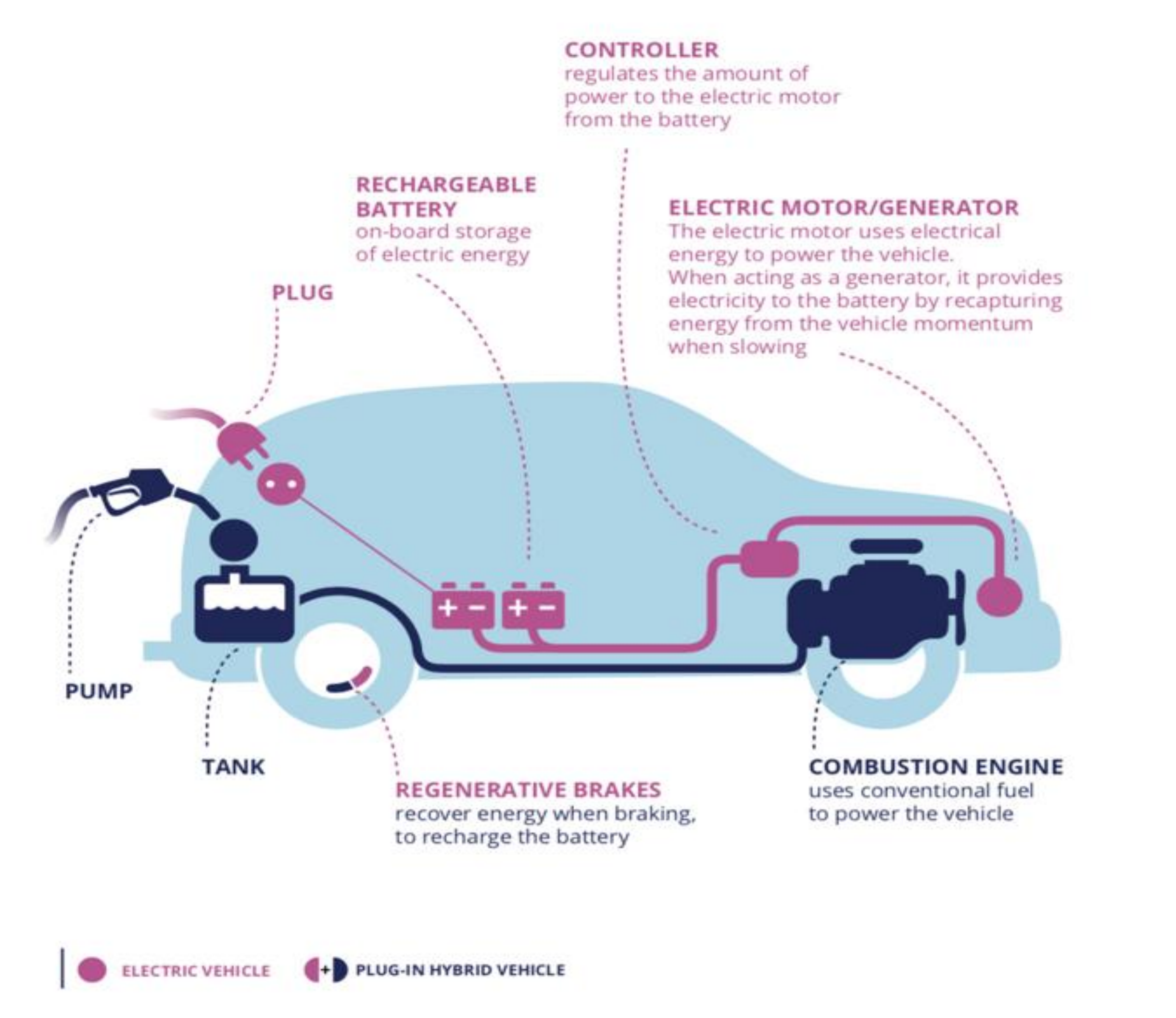
Main parts of an electric or hybrid vehicle



Source: https://www.eea.europa.eu/publications/electric-vehicles-in-europe/at_download/file

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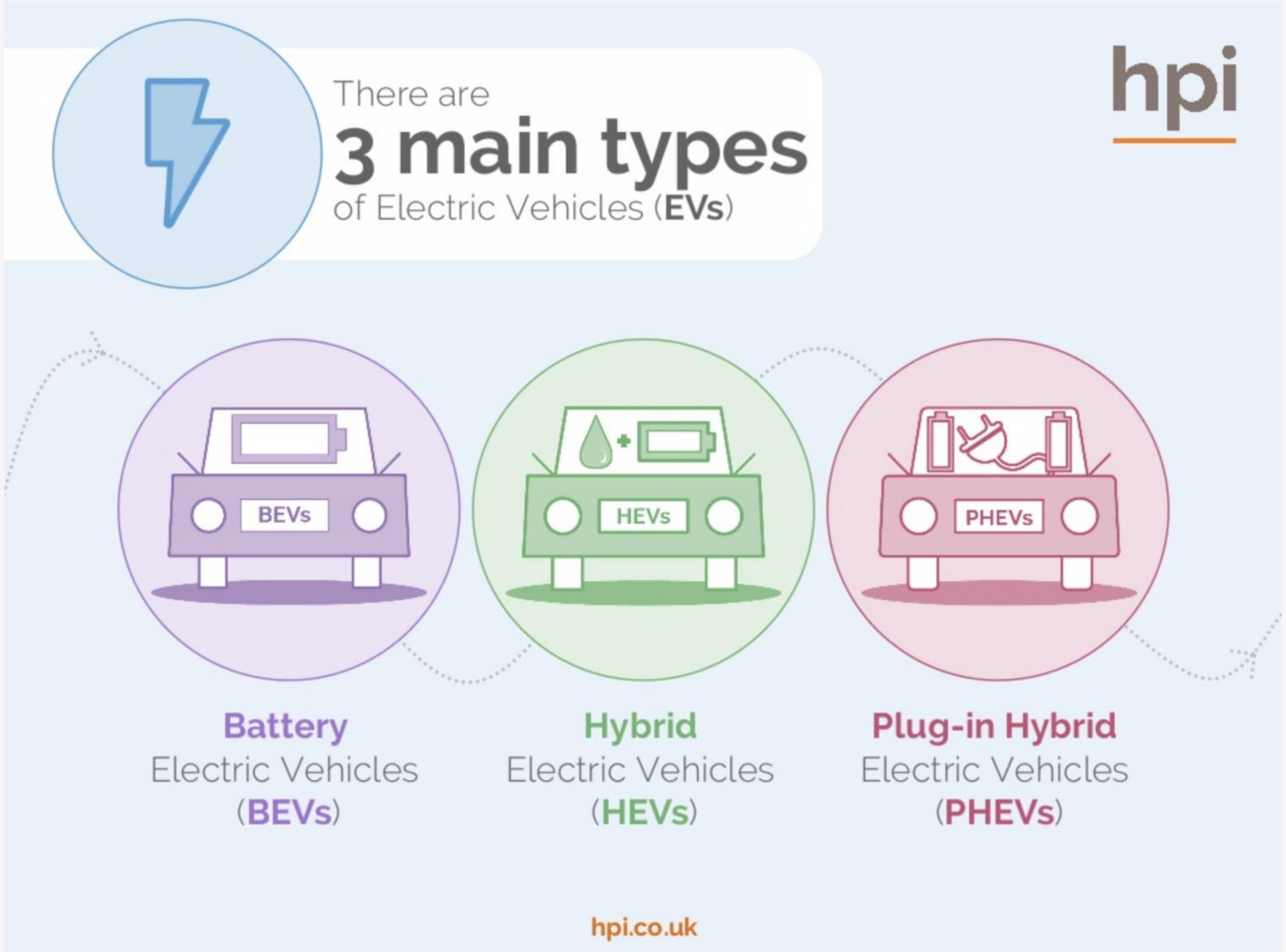
Types of EVs

- 3 main types
- 2 additional types



Source: https://www.hpi.co.uk/content/electric-cars-the-electric-era/electric-cars-different-types-electric-cars/

Project co-funded by the Europen Union (ERDF, IPA).

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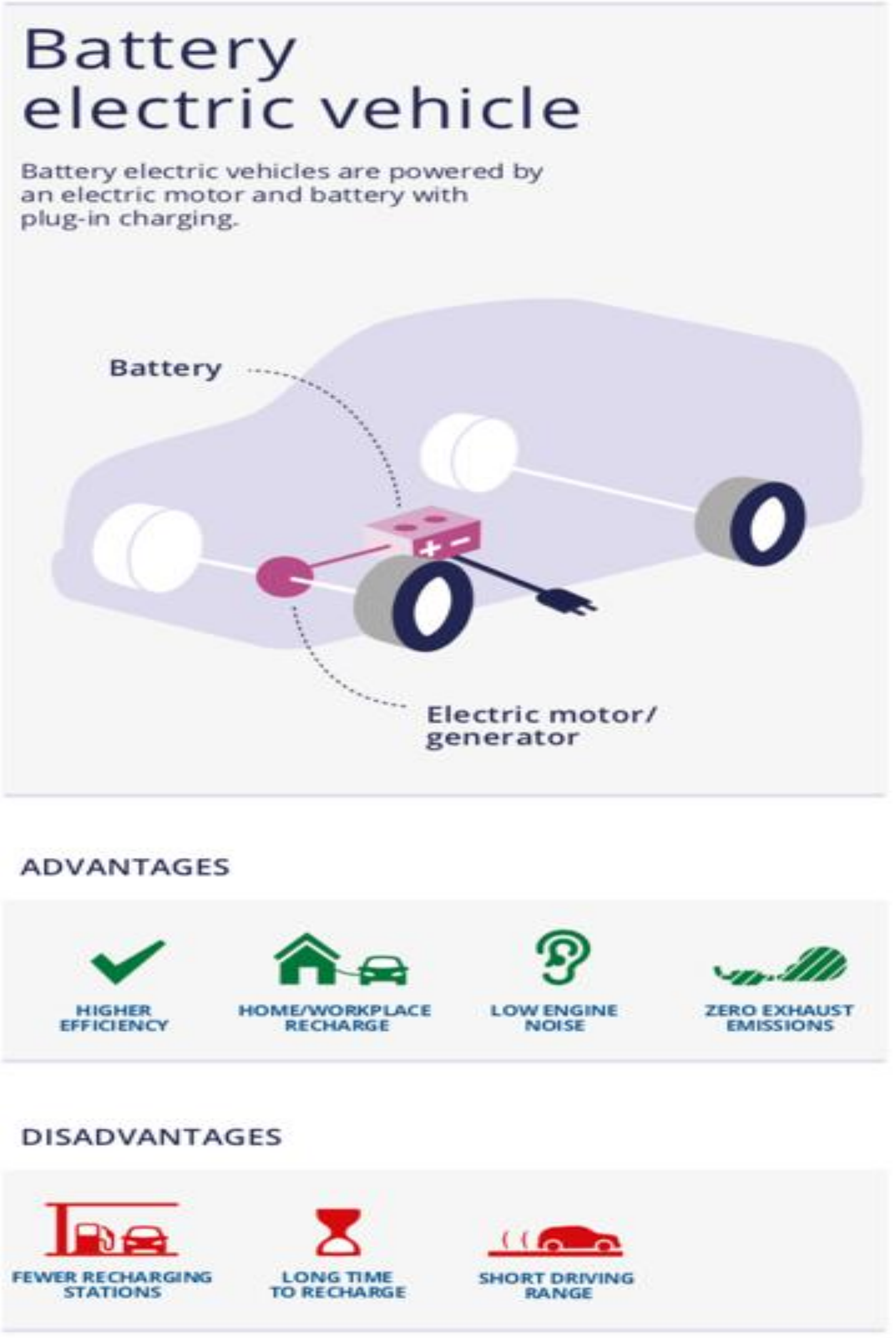
A battery electric vehicle (BEV), its advantages and disadvantages

Source: https://www.eea.europa.eu/publications/electric-vehicles-in-europe/at_download/file



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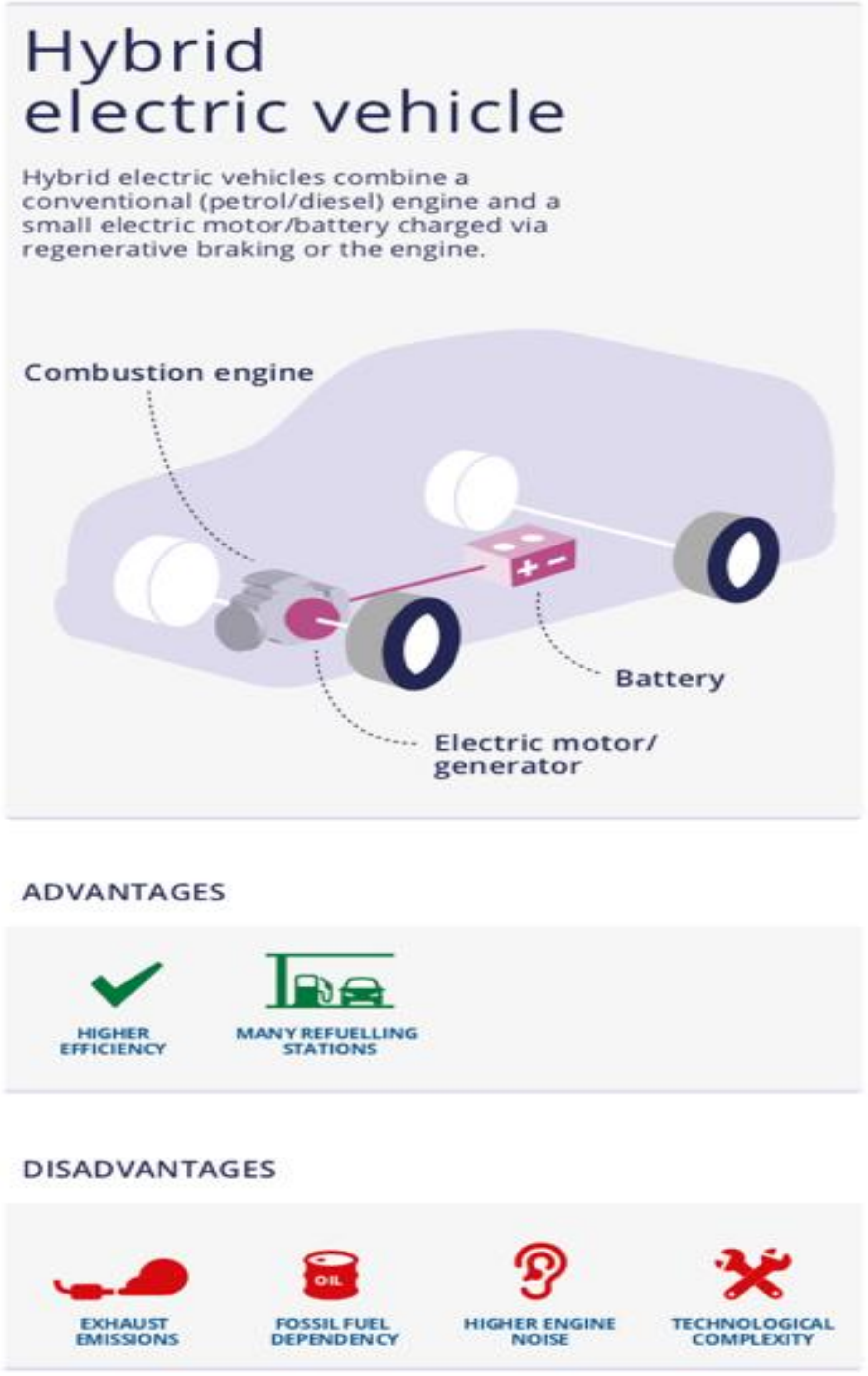
A hybrid electric vehicle (HEV), its advantages and disadvantages

Source: https://www.eea.europa.eu/publications/electric-vehicles-in-europe/at_download/file



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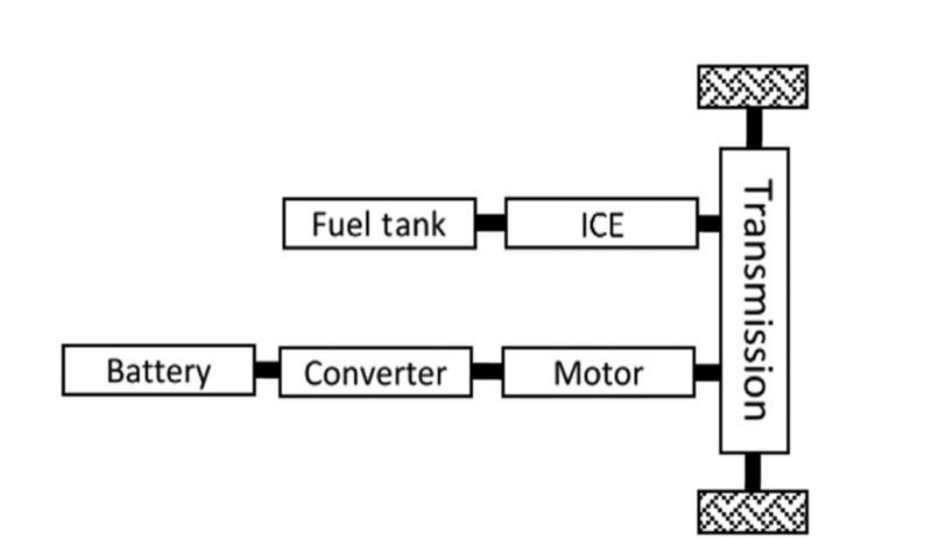
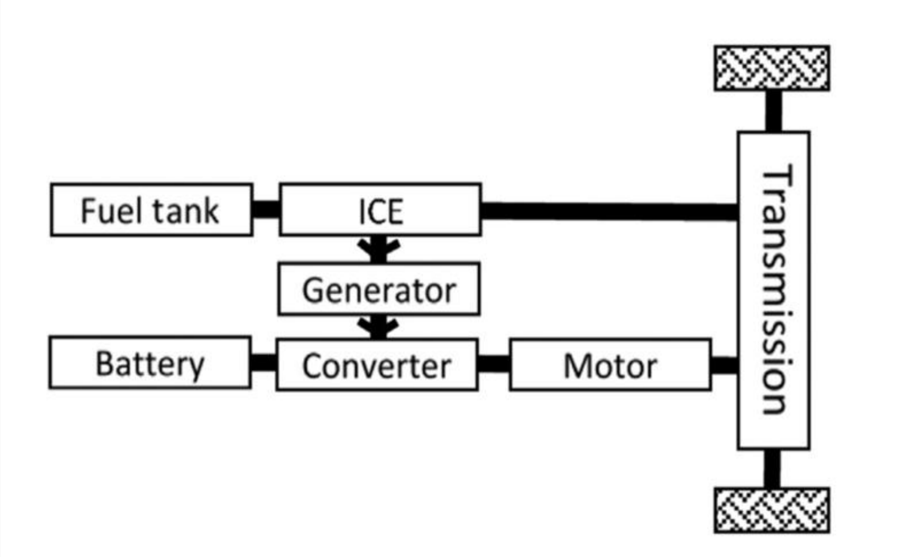
Types of HEVs

Parallel HEV



Series-parallel HEV



Source: https://www.elsevier.com/books/electric-vehicles-for-smart-cities/nanaki/978-0-12-815801-2

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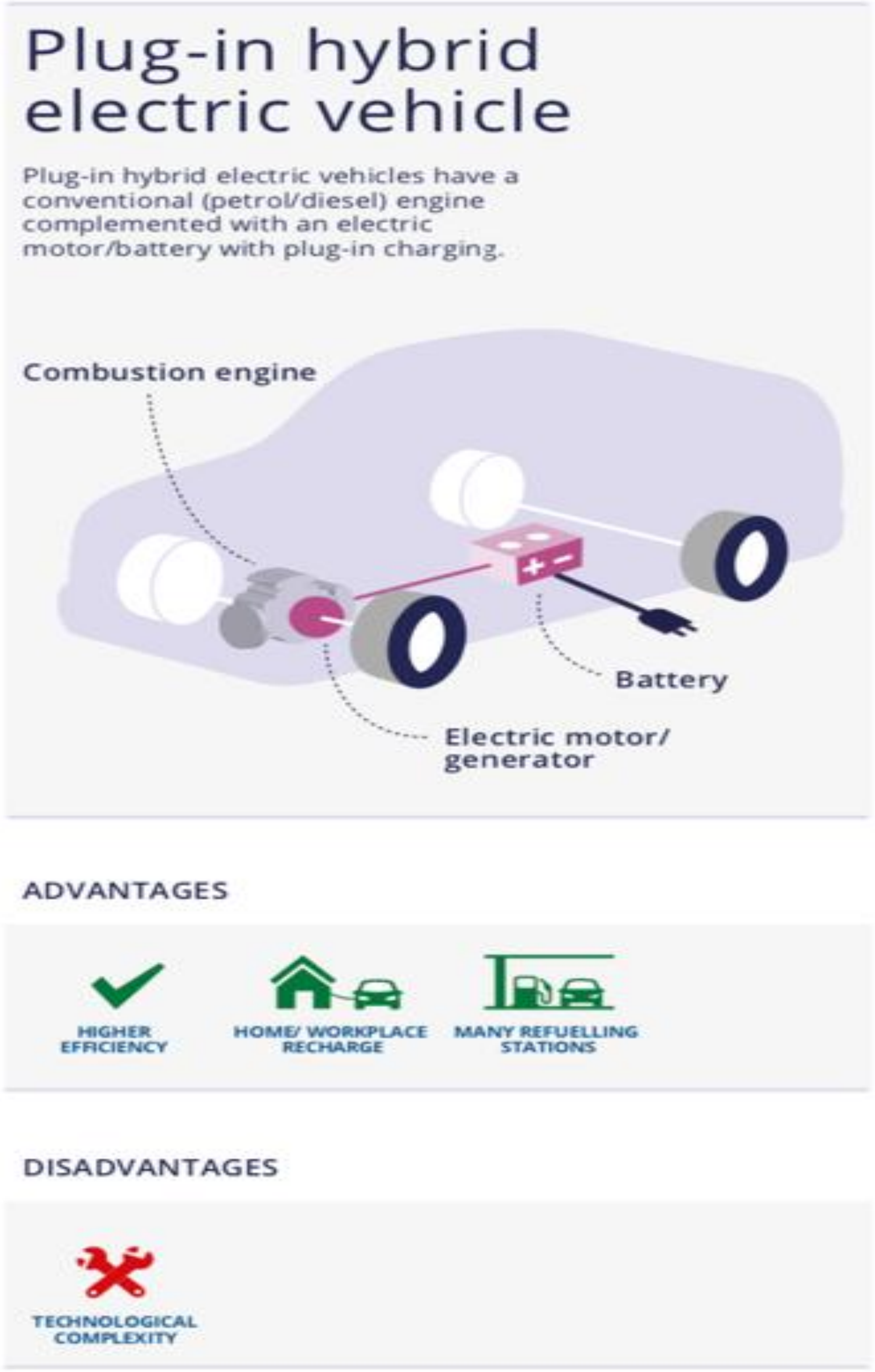
Plug-in hybrid electric vehicle, its advantages and disadvantages

Source: https://www.eea.europa.eu/publications/electric-vehicles-in-europe/at_download/file



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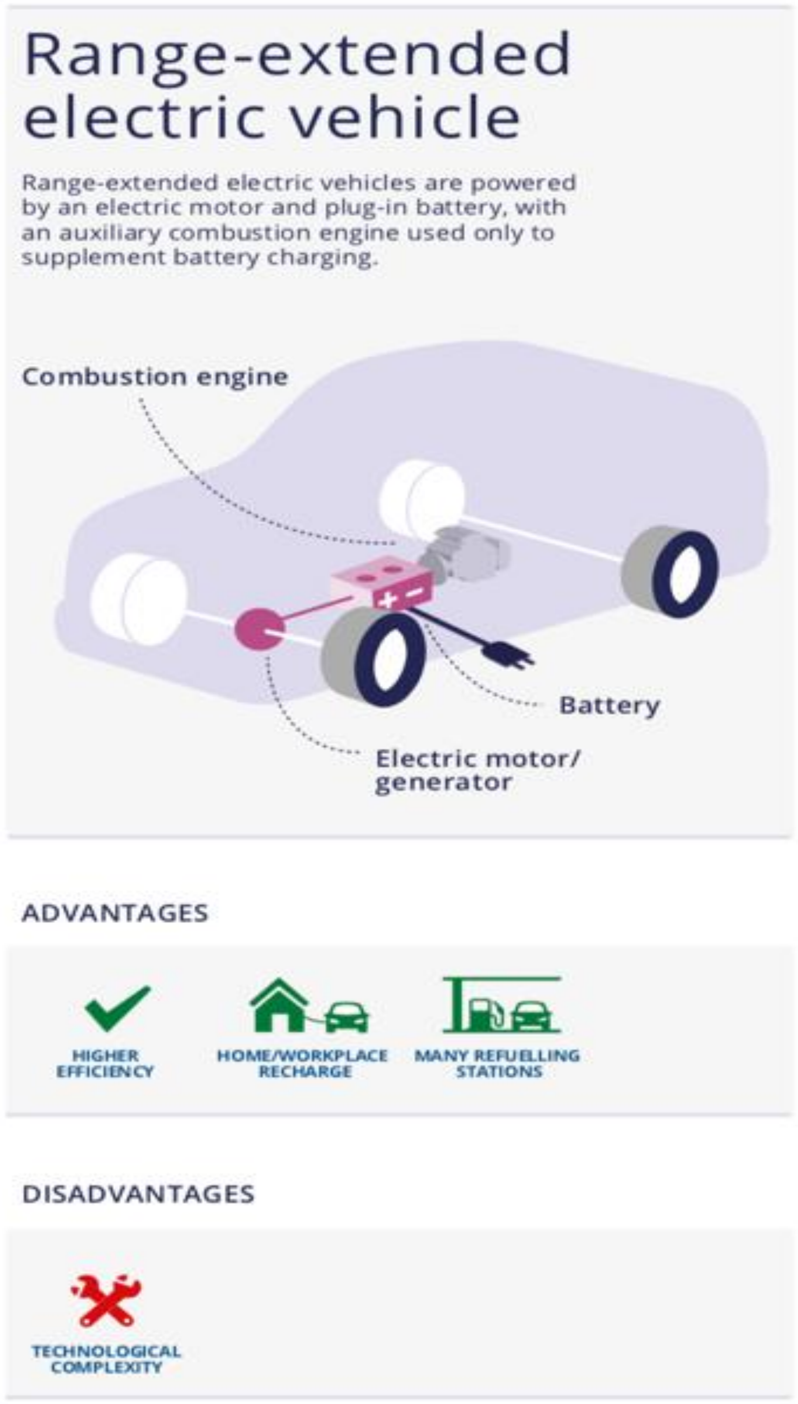
Range-extended electric vehicle (REEV), its advantages and disadvantages

Source: https://www.eea.europa.eu/publications/electric-vehicles-in-europe/at_download/file



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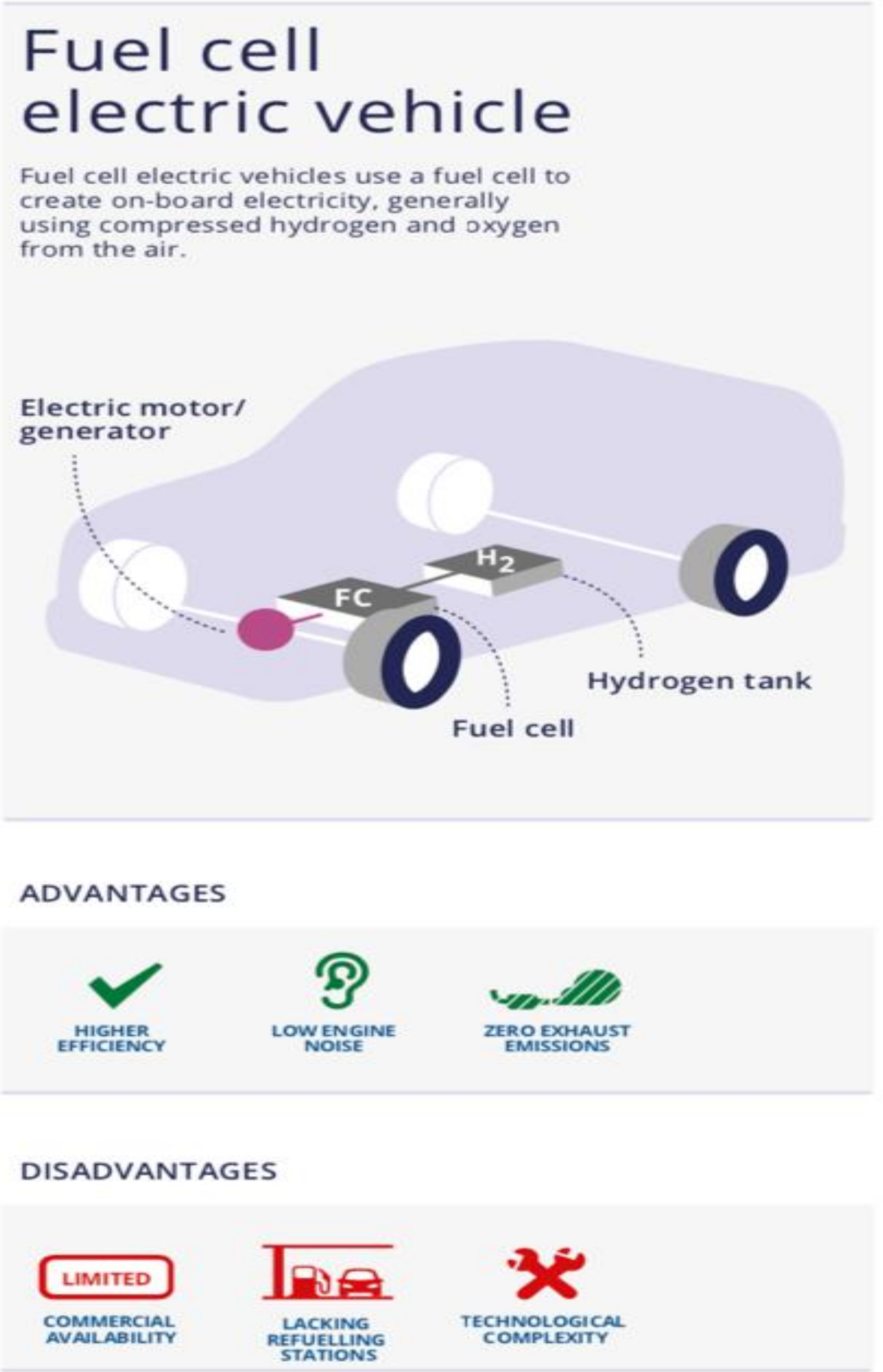
Fuel cell electric vehicle (FCEV), its advantages and disadvantages

Source: https://www.eea.europa.eu/publications/electric-vehicles-in-europe/at_download/file



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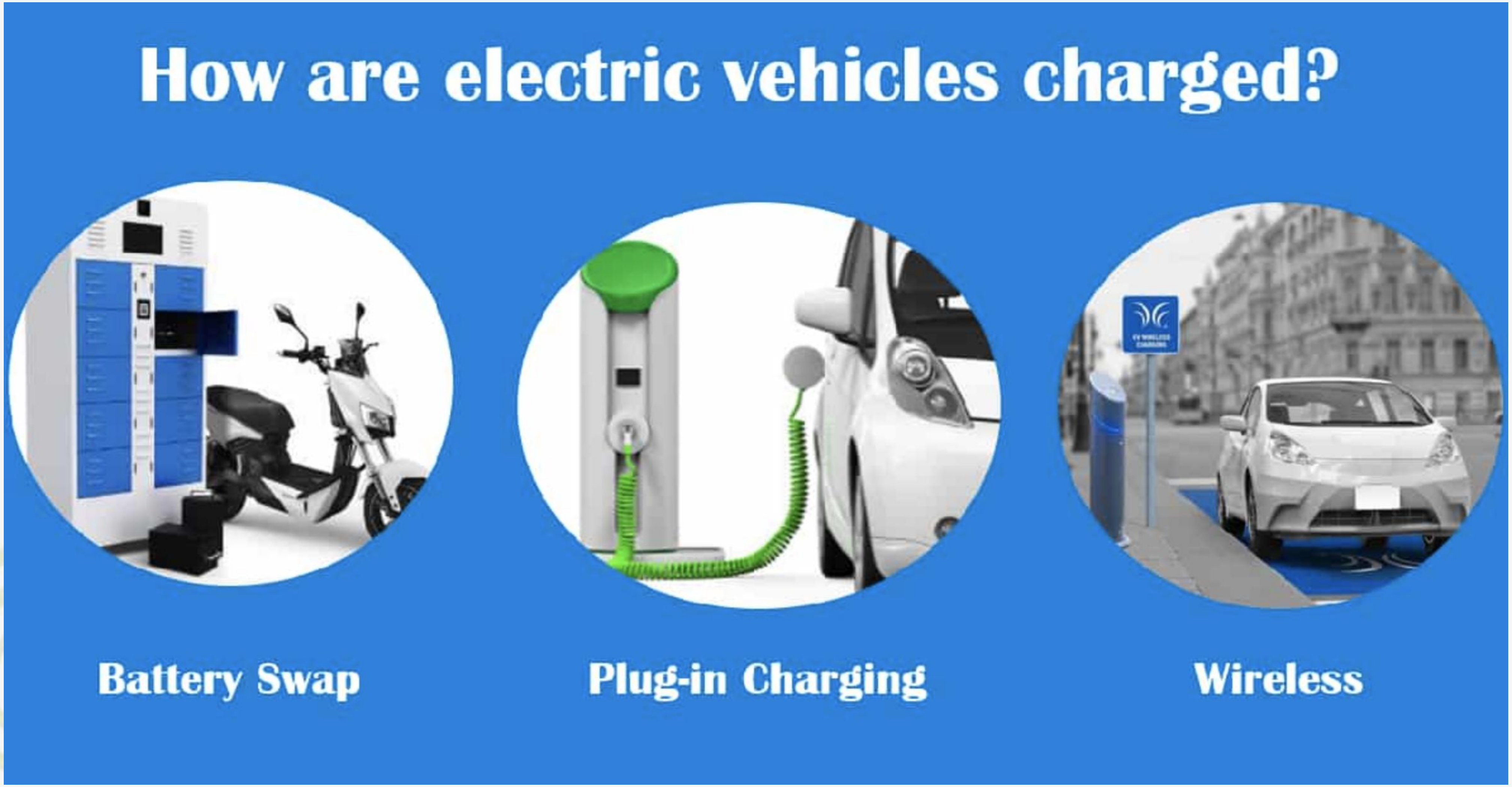
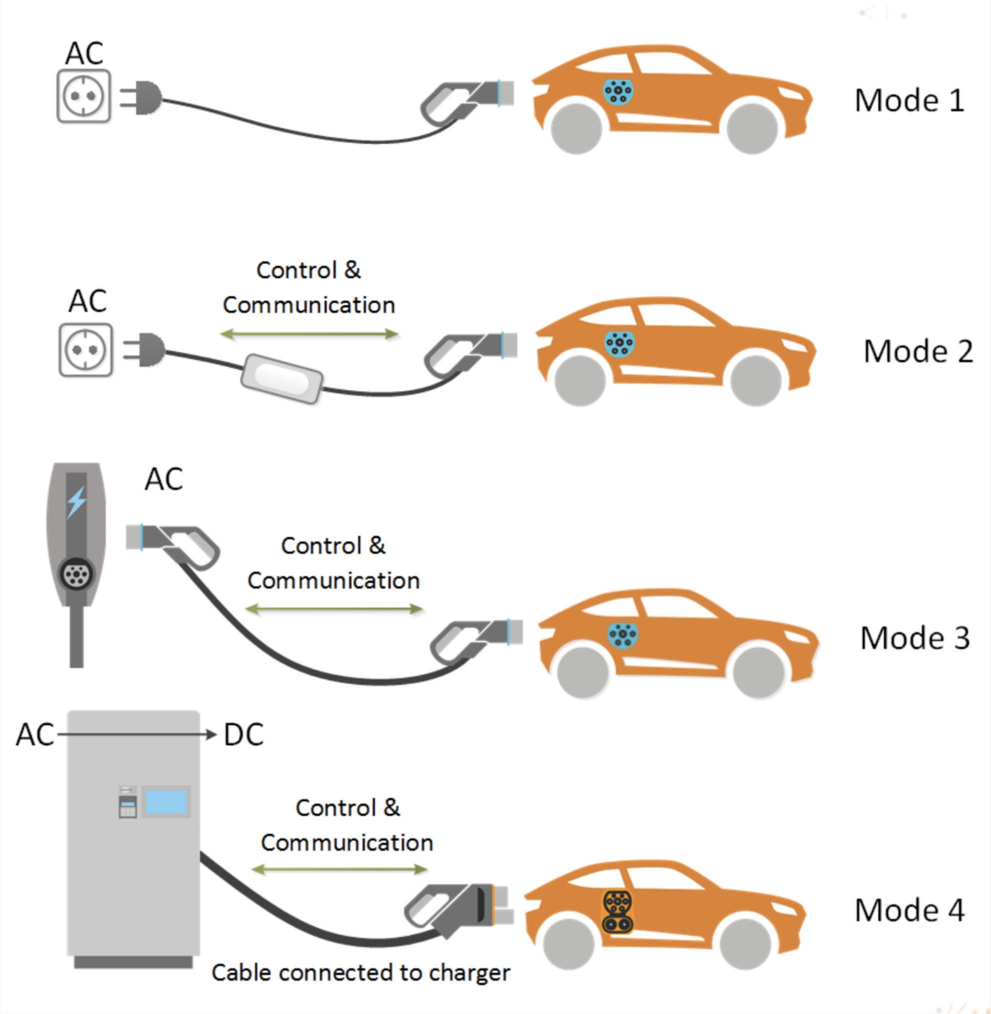


Source: https://www.emobilitysimplified.com/2020/03/how-to-charge-electric-vehicle-plug-in-battery-swap.html

Project co-funded by the Europen Union (ERDF, IPA).

EV charging modes

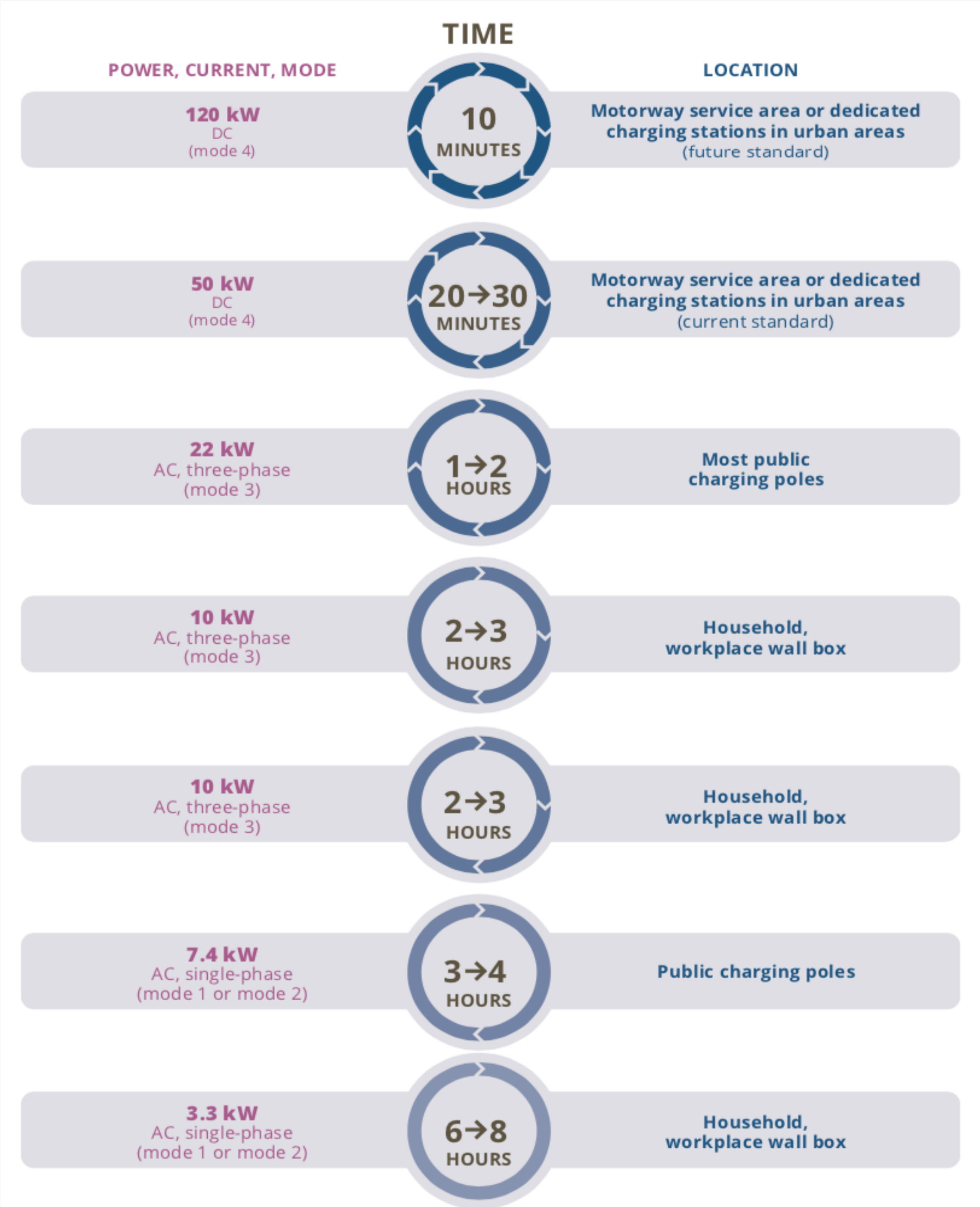
- 4 modes
- different speeds and uses



Source: https://deltrixchargers.com/about-emobility/charging-modes/

Project co-funded by the Europen Union (ERDF, IPA).

Charging times for 100km range provision



Source: https://www.eea.europa.eu/publications/electric-vehicles-in-europe/at_download/file

Project co-funded by the Europen Union (ERDF, IPA).

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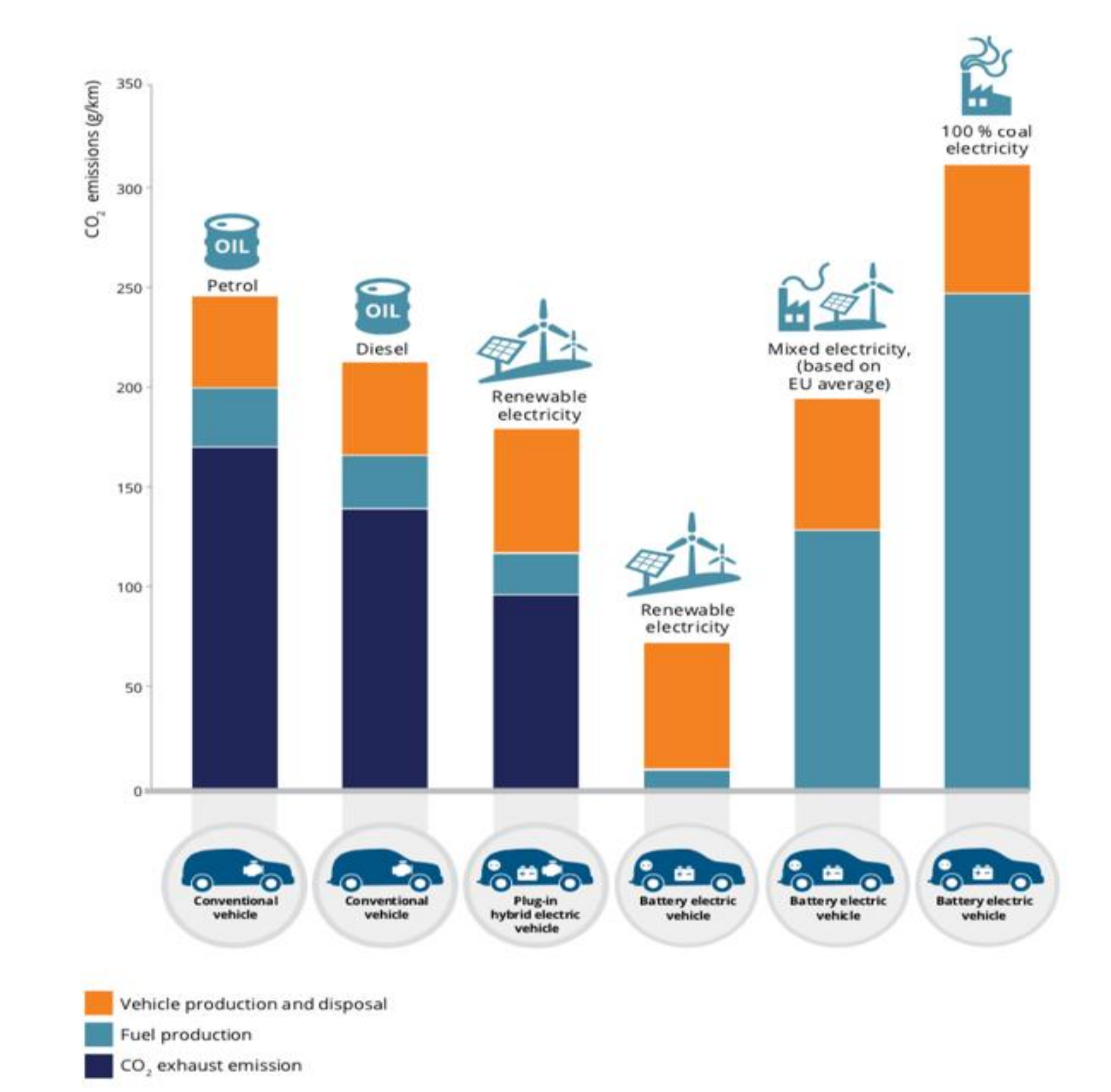
- Estimated life-cycle CO2 emissions for different vehicle and fuel types, based on an average mid-class vehicle that traverses 220.000km in its lifetime

Source: https://www.eea.europa.eu/publications/electric-vehicles-in-europe/at_download/file



Project co-funded by the Europen Union (ERDF, IPA).

EVs and Smart Grids

- Indirectly-controlled charging
- Grid-to-Vehicle (G2V) charging
- Smart charging:
  - Unidirectional controlled charging (V1G) – a type of G2V
  - Vehicle-to-Grid (V2G)
  - Vehicle-to-Home (V2H)
  - Vehicle-to-Vehicle (V2V)

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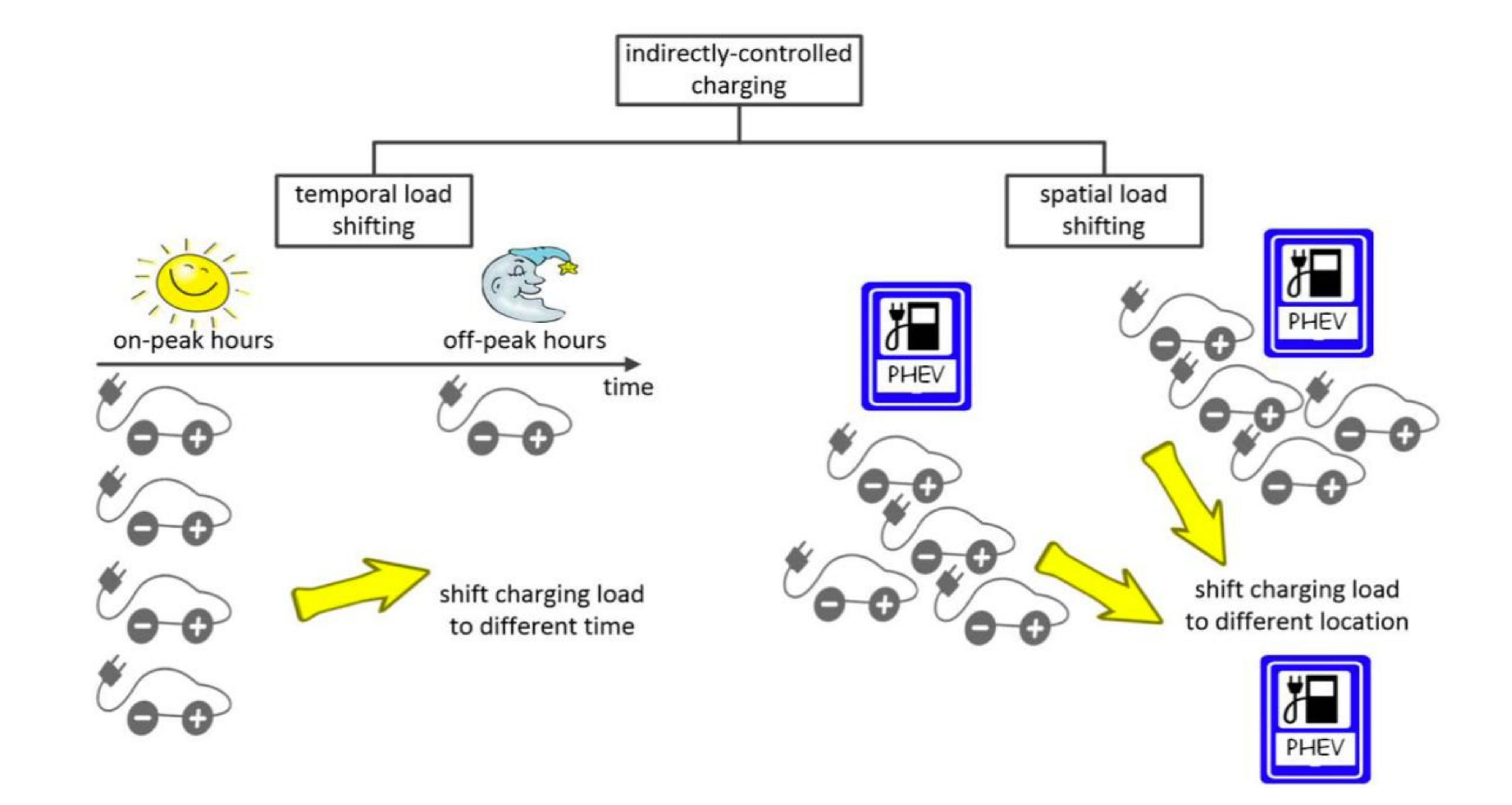
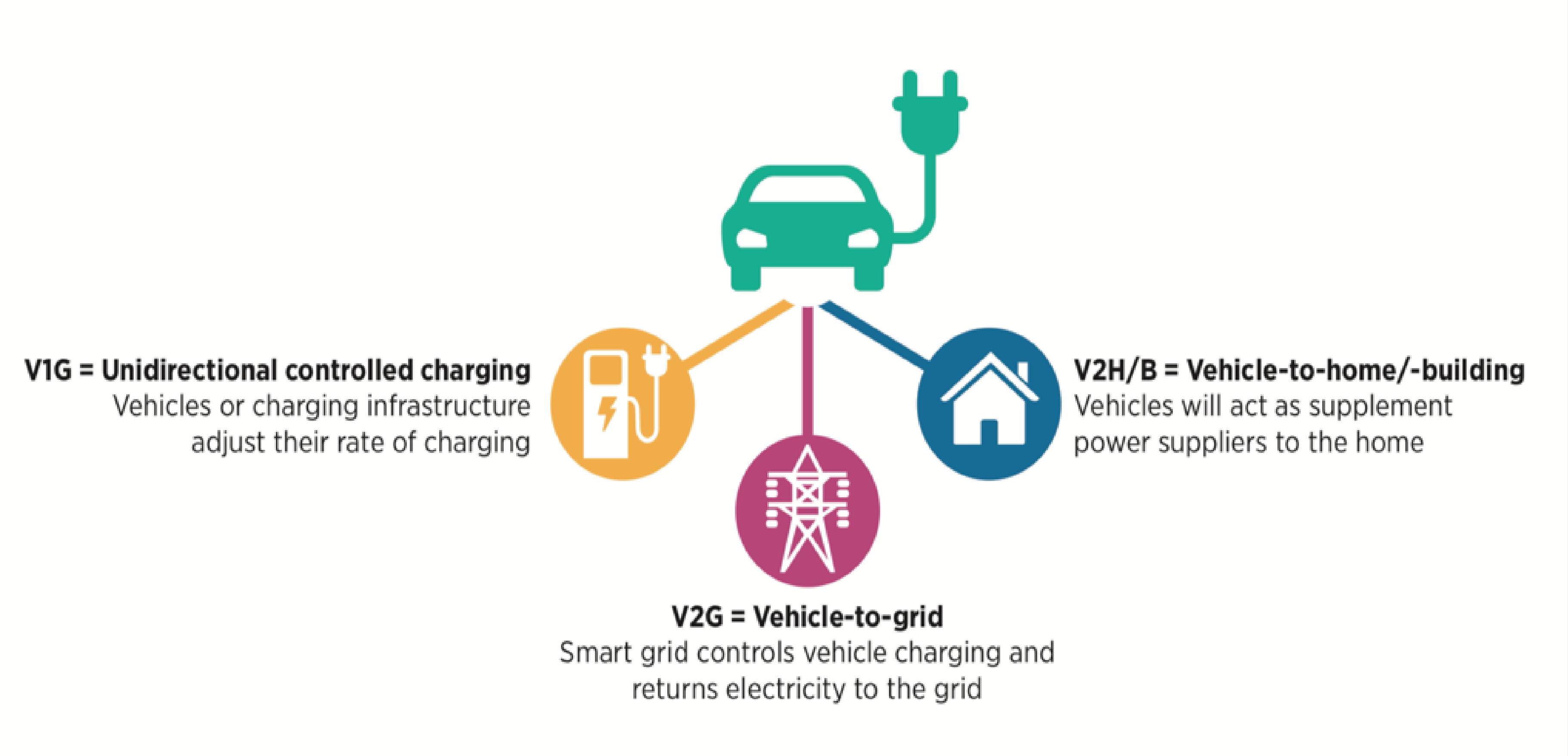
Price based indirectly controlled charging schemes



Source: https://ieeexplore.ieee.org/document/7586042

Project co-funded by the Europen Union (ERDF, IPA).

Smart charging forms



Source: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_EV_smart_charging_2019_summary.pdf?la=en&hash=8A4B9AB5BAB3F2341B366271DCA6FF7EE802AED4

Project co-funded by the Europen Union (ERDF, IPA).

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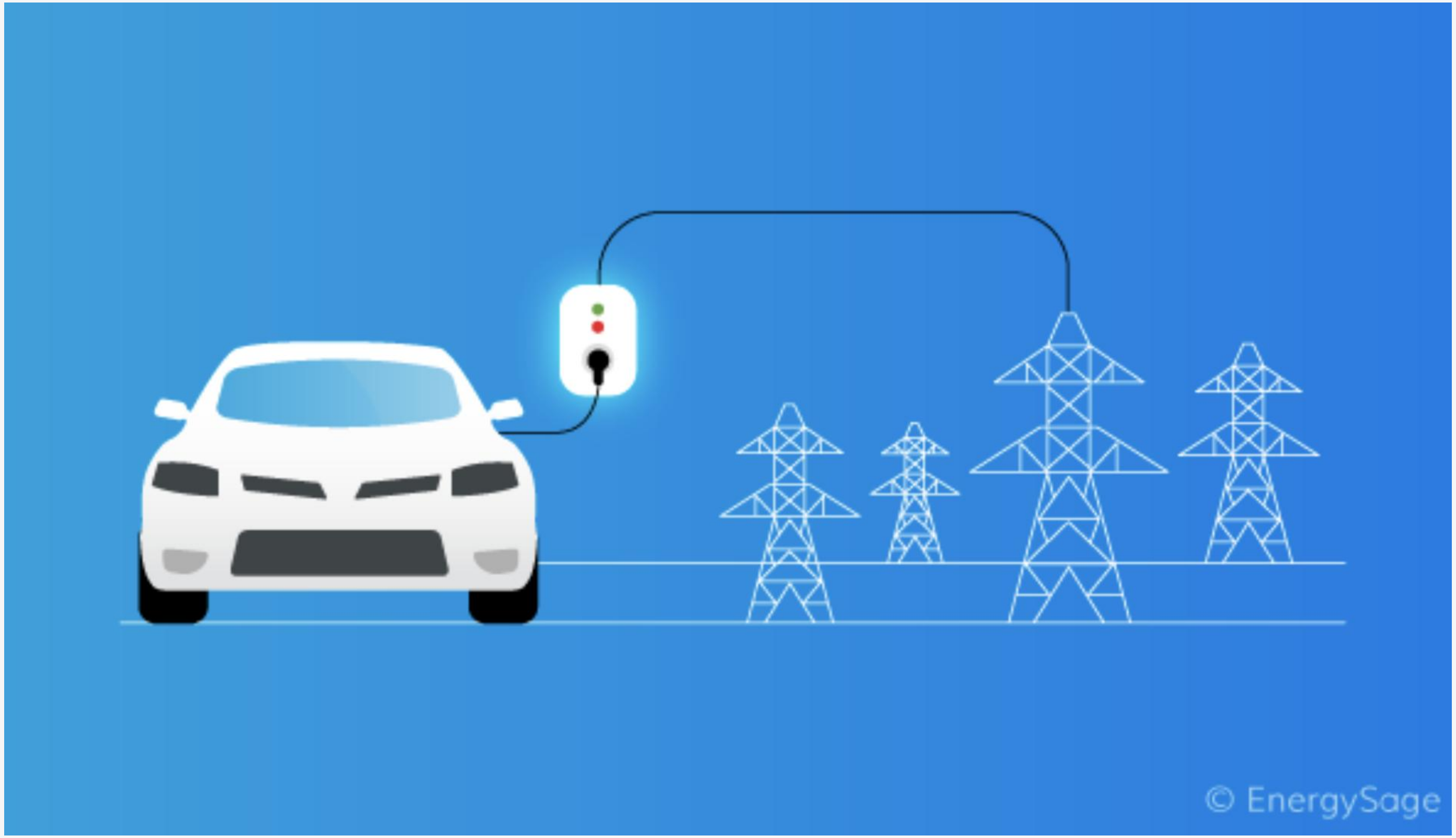
Grid-to-Vehicle (G2V) charging



Source: https://news.energysage.com/vehicle-to-grid-charging-what-you-need-to-know/

Project co-funded by the Europen Union (ERDF, IPA).

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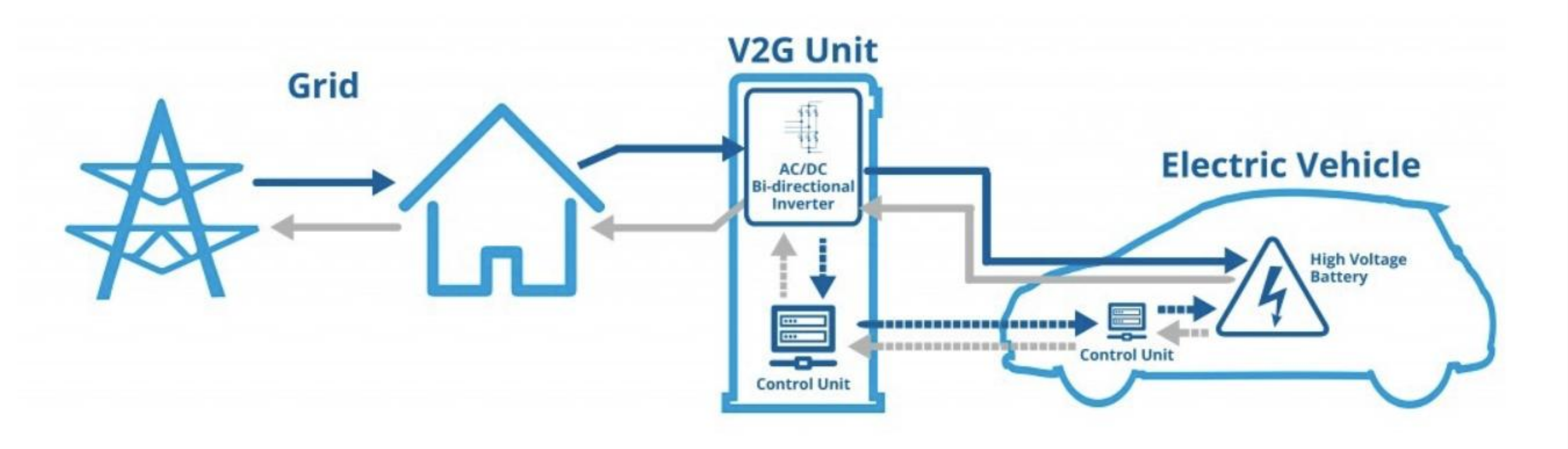
Vehicle-to-Grid (V2G) charging

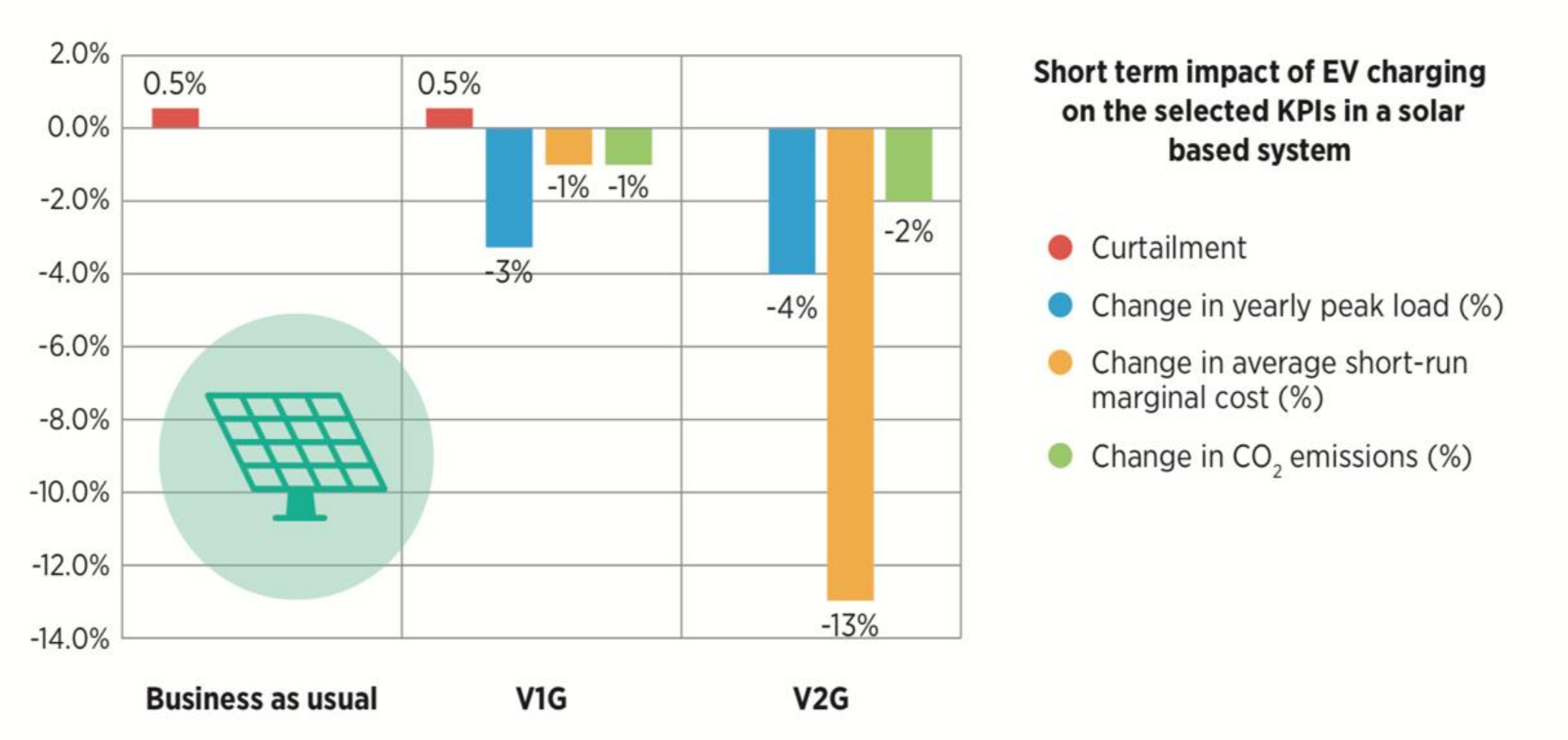


- controlled bi-directional electricity flow
- peak load management

Project co-funded by the Europen Union (ERDF, IPA).

Source: https://www.cleantech.com/ev-charging-software-and-grid-services/

Short-term impact of EV charging



Project co-funded by the Europen Union (ERDF, IPA).

Source: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_EV_smart_charging_2019_summary.pdf?la=en&hash=8A4B9AB5BAB3F2341B366271DCA6FF7EE802AED4

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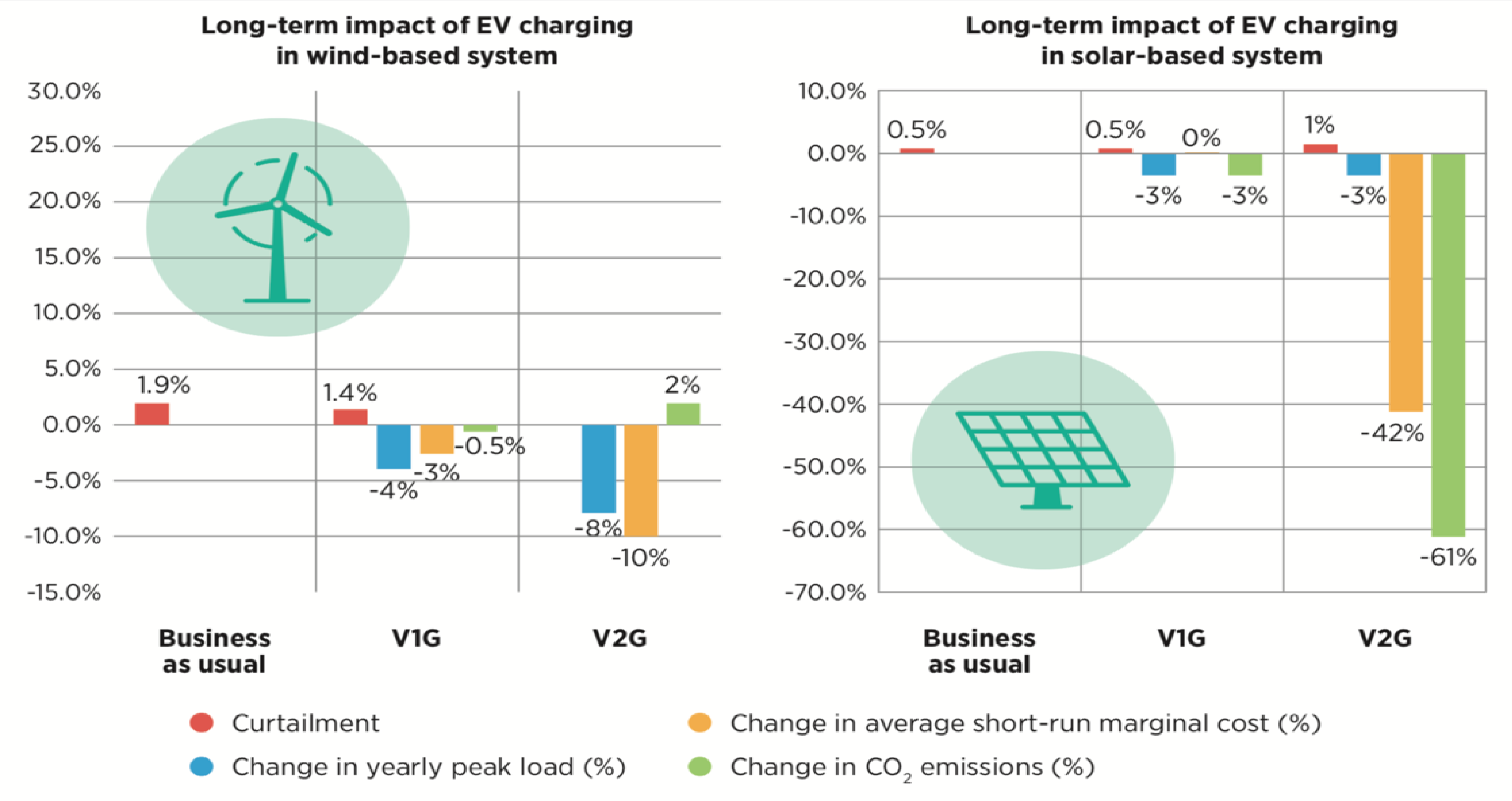
Long-term impact of EV charging



Source: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_EV_smart_charging_2019_summary.pdf?la=en&hash=8A4B9AB5BAB3F2341B366271DCA6FF7EE802AED4

Project co-funded by the Europen Union (ERDF, IPA).

Different scenario impacts on the power grid depending on EV charging technologies

Study	Scenario	Uncontrolled charging	Smart charging	
IRENA	**50%** penetration in an isolated system with 27% solar share	**↑9%** increase in peak load 0.5% solar curtailment	**↑5%** increase in peak load (V2G) Down to 0% curtailment	9% 5%
RMI, 2016	**23%** penetration US (California, Hawaii, Minnesota, New York, Texas)	**↑11%** increase in peak load	**↑1.3%** increase in peak load (V1G)	11% 1.3%
Taljegard, 2017	**100%** penetration Denmark, Germany, Norway & Sweden	**↑20%** increase in peak load	**↓7%** decrease in peak load (V2G)	20% -7%
McKenzie, 2016	**50%** penetration in Island of Oahu, Hawaii, US 23% VRE share	**10-23%** VRE curtailment without EVs	**8-13%** VRE curtailment with smart charging EVs	23% 13%
Chen and Wu, 2018	**1 MILLION** EVs in Guanzhou region, China	**↑15%** increase in peak load	**↓43-50%** reduction in valley/peak difference	

● Peak load with uncontrolled charging ● Curtailment in no EVs scenario
● Peak load with smart charging ● Curtailment with smart charging EVs

Source: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_EV_smart_charging_2019_summary.pdf?la=en&hash=8A4B9AB5BAB3F2341B366271DCA6FF7EE802AED4

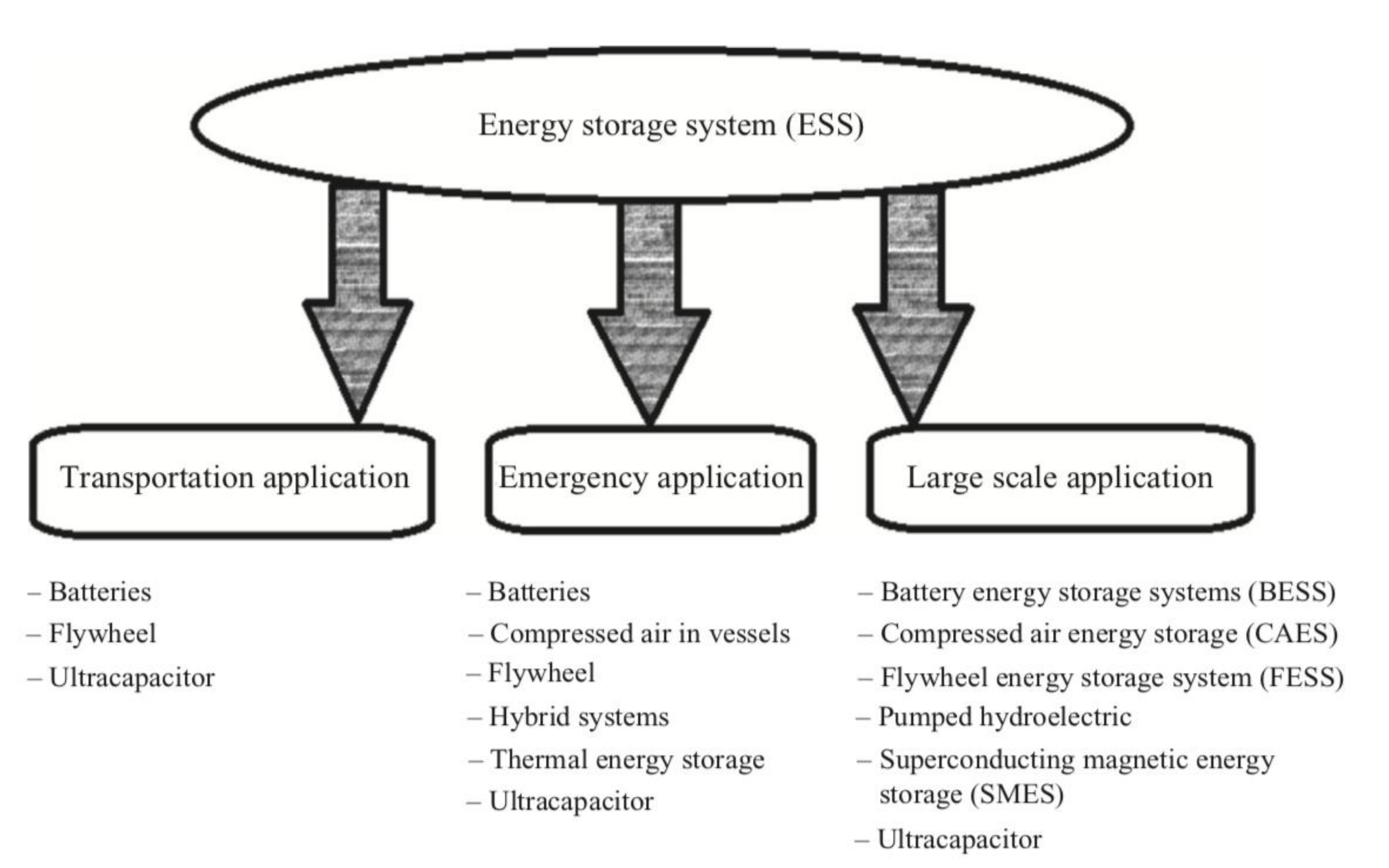
Project co-funded by the Europen Union (ERDF, IPA).

Energy storage systems

- Electromechanical storage technologies
  - Pumped-storage hydropower plants (PSH),
  - Compressed air energy storage (CAES) and
  - Flywheel energy storage
- Electrochemical storage technologies
  - Batteries and
  - Hydrogen fuel cells
- Electrostatic storages
  - Supercapacitors
- Electromagnetic storages
  - Superconducting magnetic energy storage (SMES)

Project co-funded by the Europen Union (ERDF, IPA).

Classification of the main energy storage systems based on their application



Source: https://www.sciencedirect.com/book/9780128042083/distributed-generation-systems

Project co-funded by the Europen Union (ERDF, IPA).

Energy storage technologies compared by their power, energy density, response time and efficiency

Technology	Power	Energy density	Response time	Efficiency
Pumped hydro	100 MW–2 GW	400 MWh–20 GWh	12 min	70–80%
CAES	110 MW–290 MW	1.16 GWh–3 GWh	12 min	90%
BESS	100 W–100 MW	1 kWh–200 MWh	Seconds	60–80%
Flywheels	5 kW–90 MW	5 kWh–200 kWh	12 min	80–95%
SMES	170 kW–100 MW	110 Wh–27 kWh	Milliseconds	95%
Super capacitors	<1 MW	1 Wh–1 kWh	Milliseconds	>95%

Project co-funded by the Europen Union (ERDF, IPA).

Source: https://www.sciencedirect.com/book/9780128042083/distributed-generation-systems

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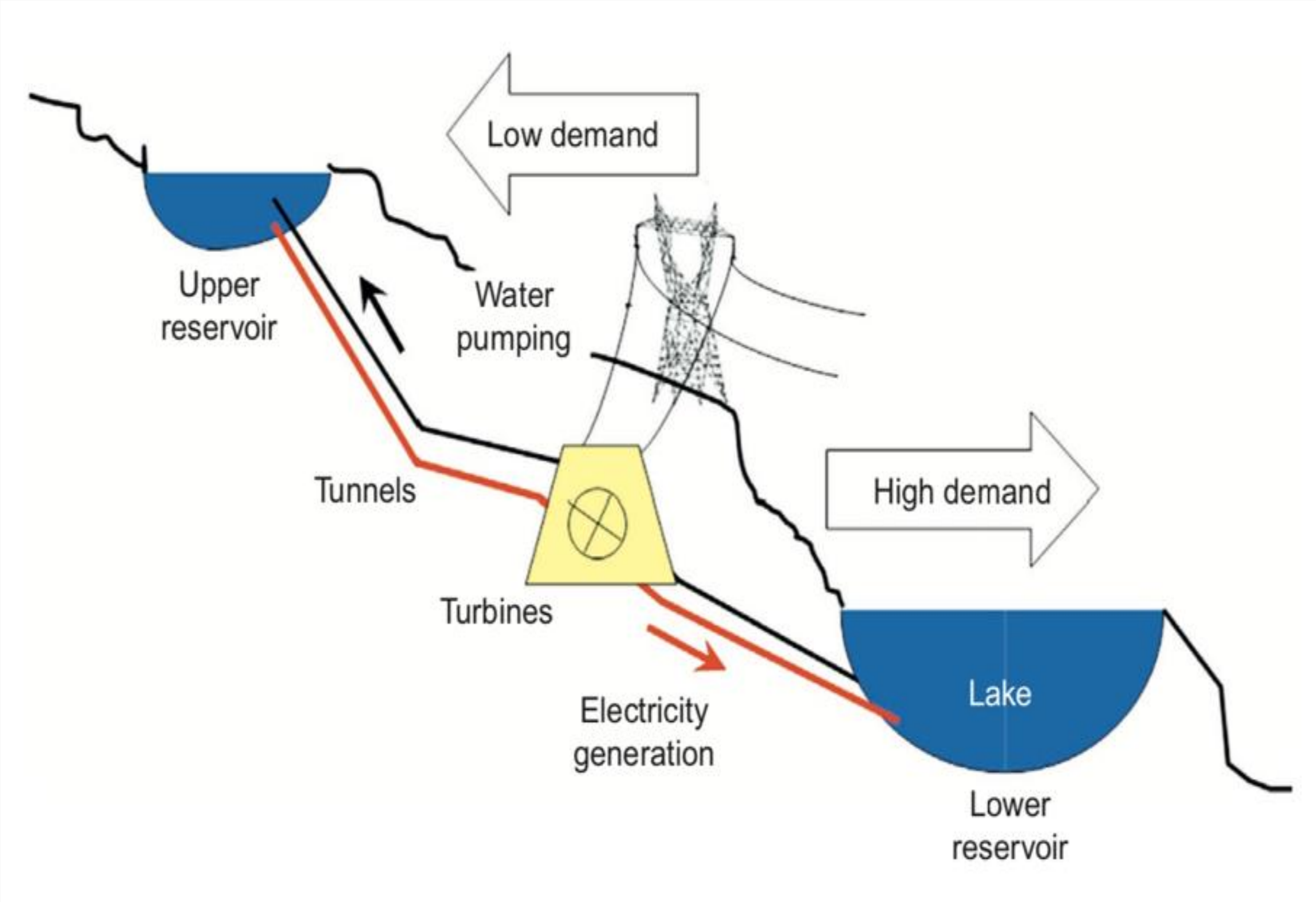
Pumped-storage hydropower plants

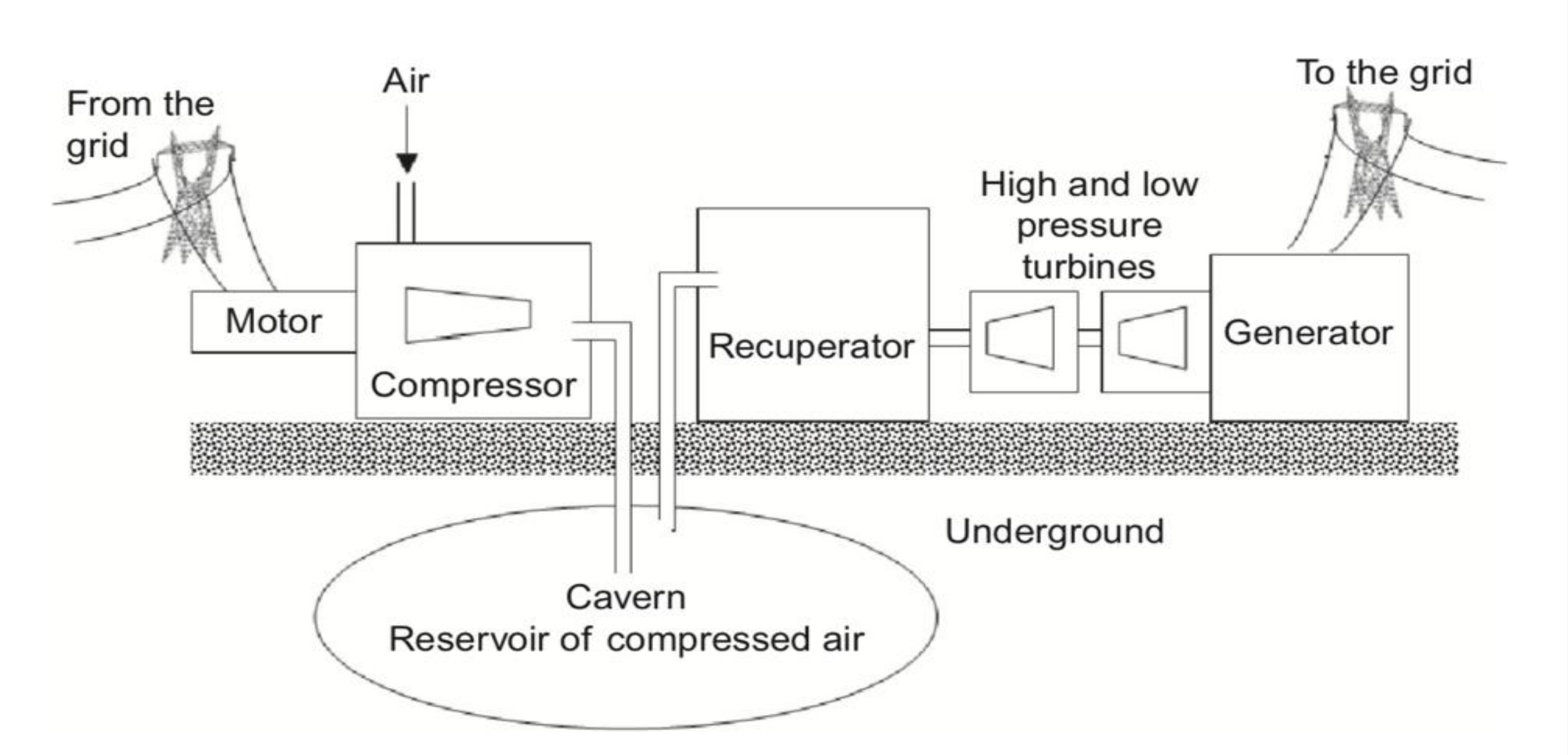
- Potential energy of water
- Largest capacity storage in today’s power system



Source: https://link.springer.com/chapter/10.1007%2F978-981-13-9409-6_286

Project co-funded by the Europen Union (ERDF, IPA).

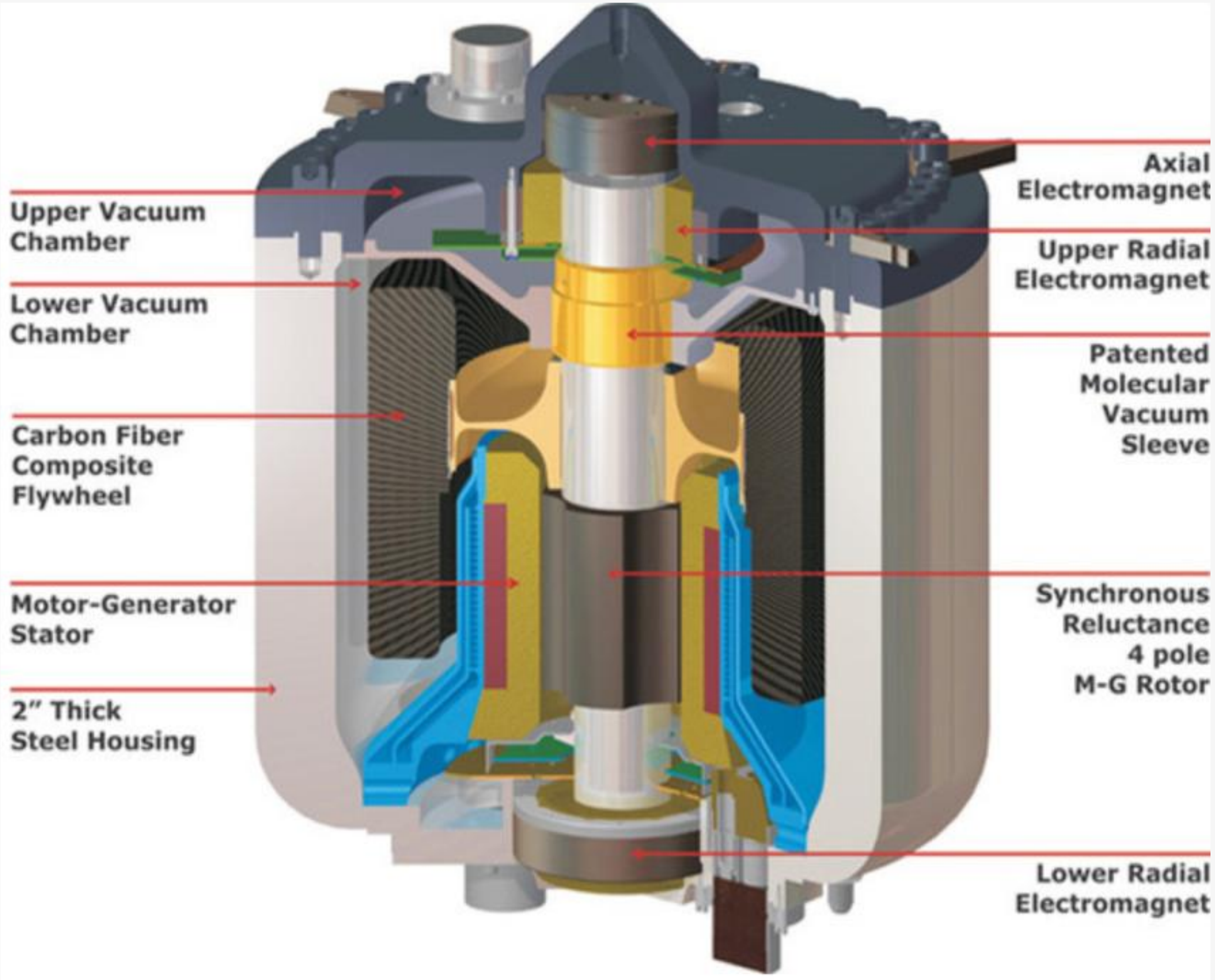
Compressed Air Energy Storage (CAES)



Source: https://link.springer.com/chapter/10.1007%2F978-981-13-9409-6_286

Flywheel energy storage

- Simple mechanical storage
- Heavy rotating disk stores angular momentum in a vacuum

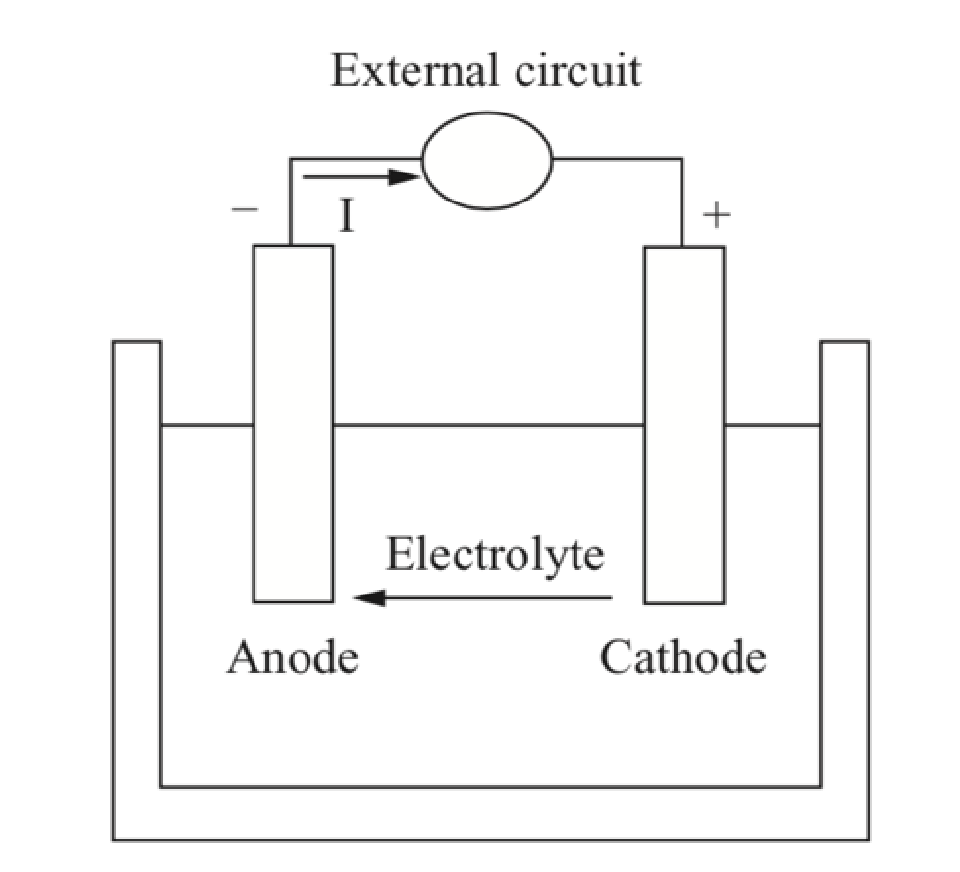


Source: https://www.betterworldsolutions.eu/smart-grid-energy-storage-flywheels/

Project co-funded by the Europen Union (ERDF, IPA).

Electrochemical batteries

- Two electrodes submerged into an electrolyte solution
- Non-rechargeable or rechargeable

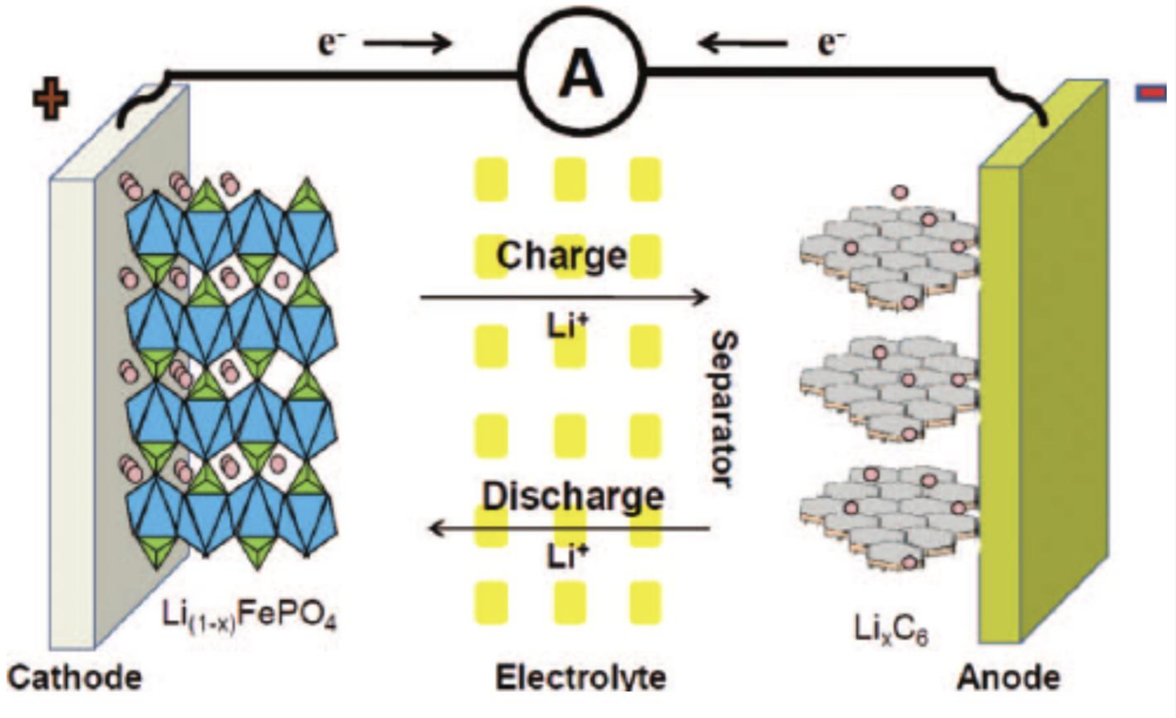


Source: https://www.sciencedirect.com/book/9780128042083/distributed-generation-systems

Project co-funded by the Europen Union (ERDF, IPA).

Basic parts of a battery (1)

- The positive electrode ≠ cathode
- The negative electrode ≠ anode
- The electrolyte
- The external circuit

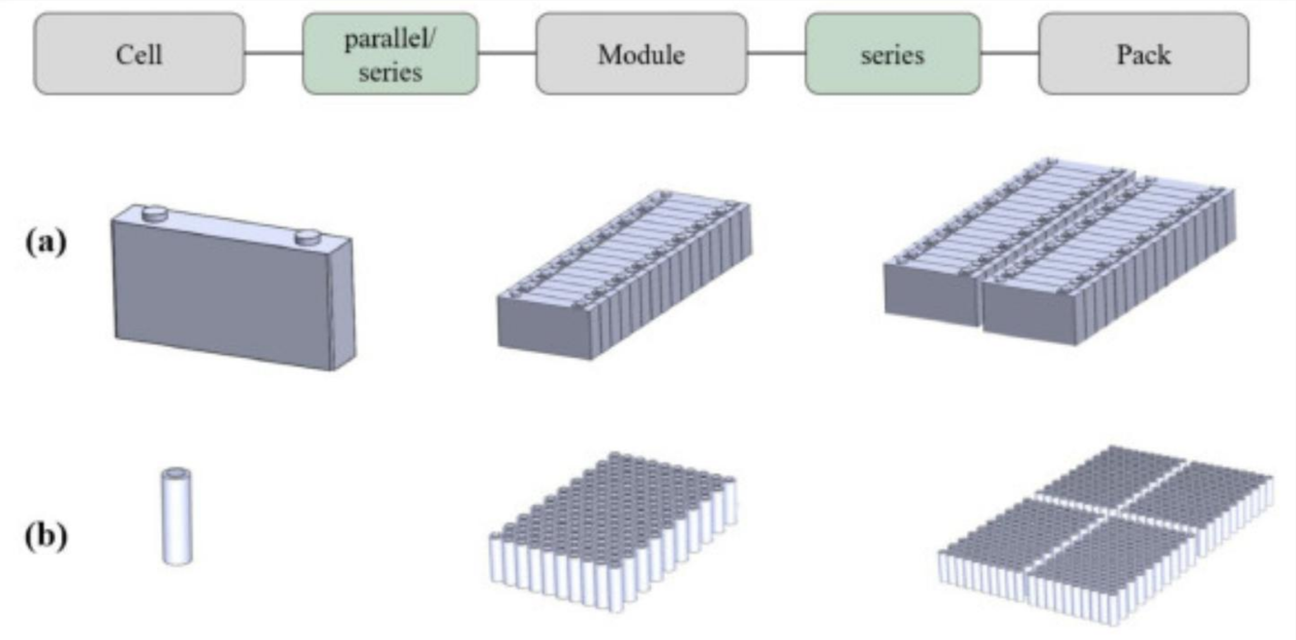


Project co-funded by the Europen Union (ERDF, IPA).

Source: https://www.researchgate.net/figure/Schematic-of-a-lithium-ion-battery-Each-lithium-ion-battery-consists-of-an-anode-and-a_fig1_233107188

Basic parts of a battery (2)

- Self-discharge rate
- Solution – 3rd type of batteries – reserve batteries
- Battery cells – battery modules – battery packs



Source: https://www.sciencedirect.com/science/article/pii/S2666330920300157#fig0002

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Battery cell types

- Alkaline (zinc-manganese dioxide)
- Lead acid
- Nickel cadmium (Ni-Cd)
- Lithium (lithium-copper oxide) Li-CuO
- Nickel-metal hydride (NiMH)
- Lithium (lithium-iron disulfide) LiFe S2
- Lithium-ion (Li-Ion)
- Lithium-ion polymer
- Nickel oxyhydroxide
- Zinc-Chloride
- Lithium (lithium-manganese dioxide) LiMn O2
- Zinc-Air
- Silver-oxide (Silver-Zinc)

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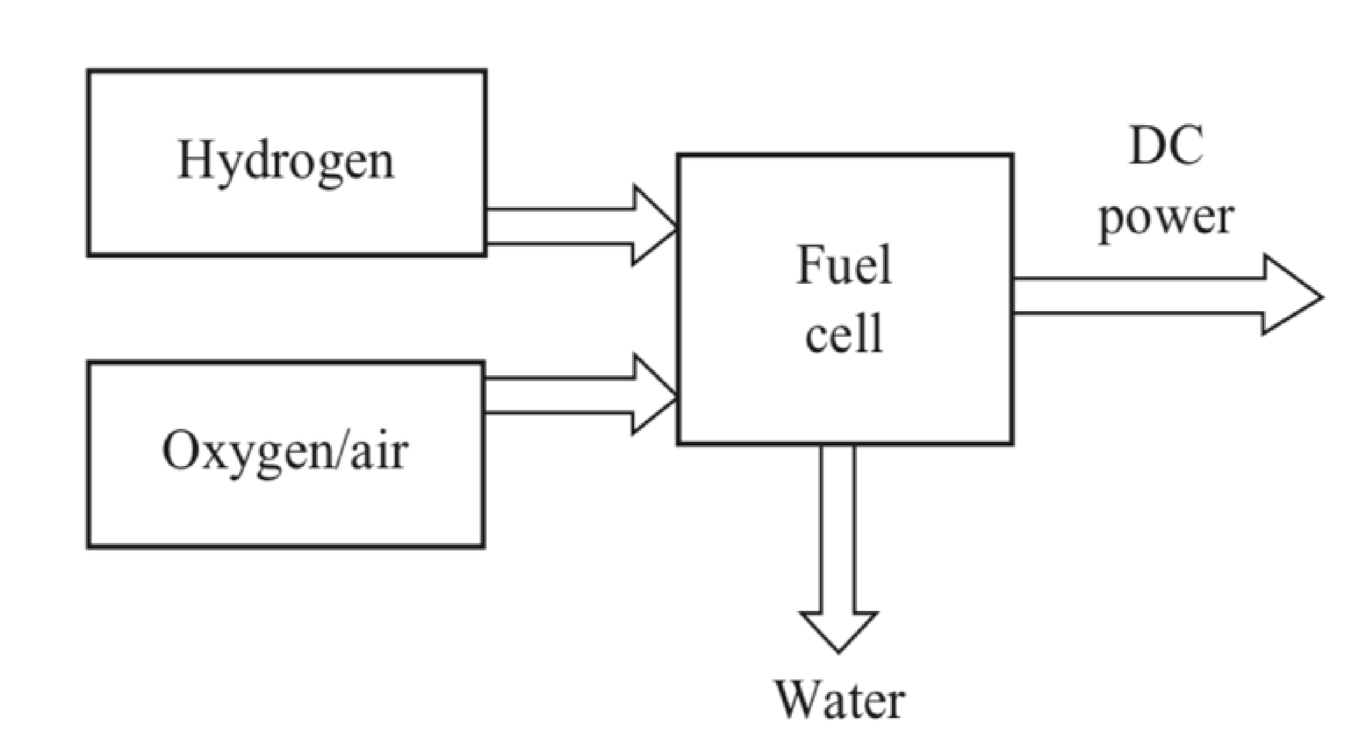
Hydrogen fuel cells

- Hydrogen or natural gas fuel cells
- Hydrogen + oxygen – generate DC current



Source: https://www.sciencedirect.com/book/9780128042083/distributed-generation-systems

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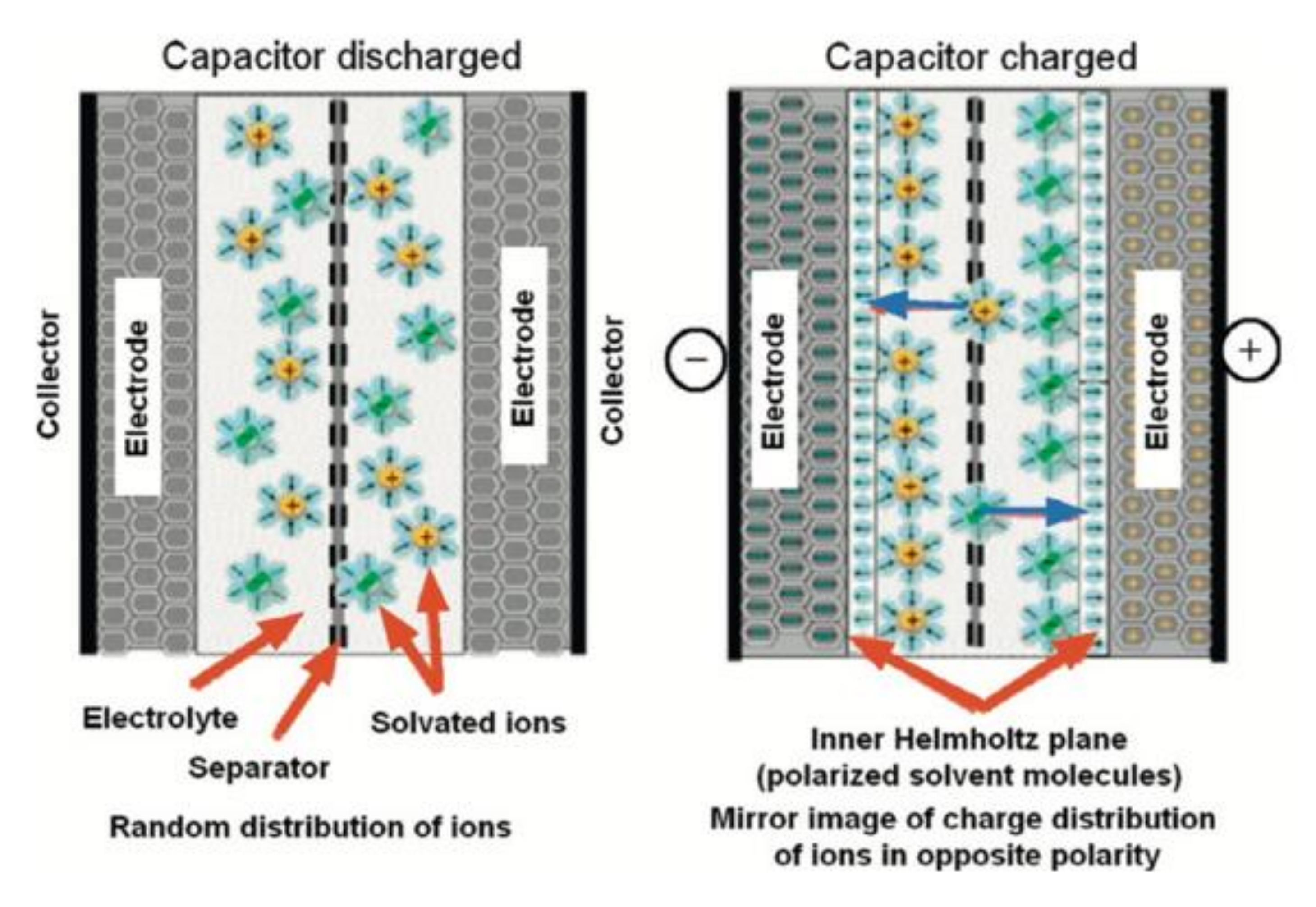
Supercapacitors

- High power output
- High cost
- High self-discharge rate



Source: https://link.springer.com/chapter/10.1007%2F978-981-13-9409-6_286

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- Key storage system characteristics with particular applications in the energy system

Source: https://www.iea.org/reports/technology-roadmap-energy-storage

Application	Output (electricity, thermal)	Size (MW)	Discharge duration	Cycles (typical)	Response time
Seasonal storage	e,t	500 to 2 000	Days to months	1 to 5 per year	day
Arbitrage	e	100 to 2 000	8 hours to 24 hours	0.25 to 1 per day	>1 hour
Frequency regulation	e	1 to 2 000	1 minute to 15 minutes	20 to 40 per day	1min
Load following	e,t	1 to 2 000	15 minutes to 1 day	1 to 29 per day	<15min
Voltage support	e	1 to 40	1 second to 1 minute	10 to 100 per day	millisecond to second
Black start	e	0.1 to 400	1 hour to 4 hours	< 1 per year	<1 hour
Transmission and Distribution (T&D) congestion relief	e,t	10 to 500	2 hours to 4 hours	0.14 to 1.25 per day	>1hour
T&D infrastructure investment deferral	e,t	1 to 500	2 hours to 5 hours	0.75 to 1.25 per day	>1hour
Demand shifting and peak reduction	e,t	0.001 to 1	Minutes to hours	1 to 29 per day	<15 min
Off-grid	e,t	0.001 to 0.01	3 hours to 5 hours	0.75 to 1.5 per day	<1hour
Variable supply resource integration	e,t	1 to 400	1 minute to hours	0.5 to 2 per day	<15 min
Waste heat utilisation	t	1 to 10	1 hour to 1 day	1 to 20 per day	< 10 min
Combined heat and power	t	1 to 5	Minutes to hours	1 to 10 per day	< 15 min
Spinning reserve	e	10 to 2 000	15 minutes to 2 hours	0.5 to 2 per day	<15 min
Non-spinning reserve	e	10 to 2 000	15 minutes to 2 hours	0.5 to 2 per day	<15 min

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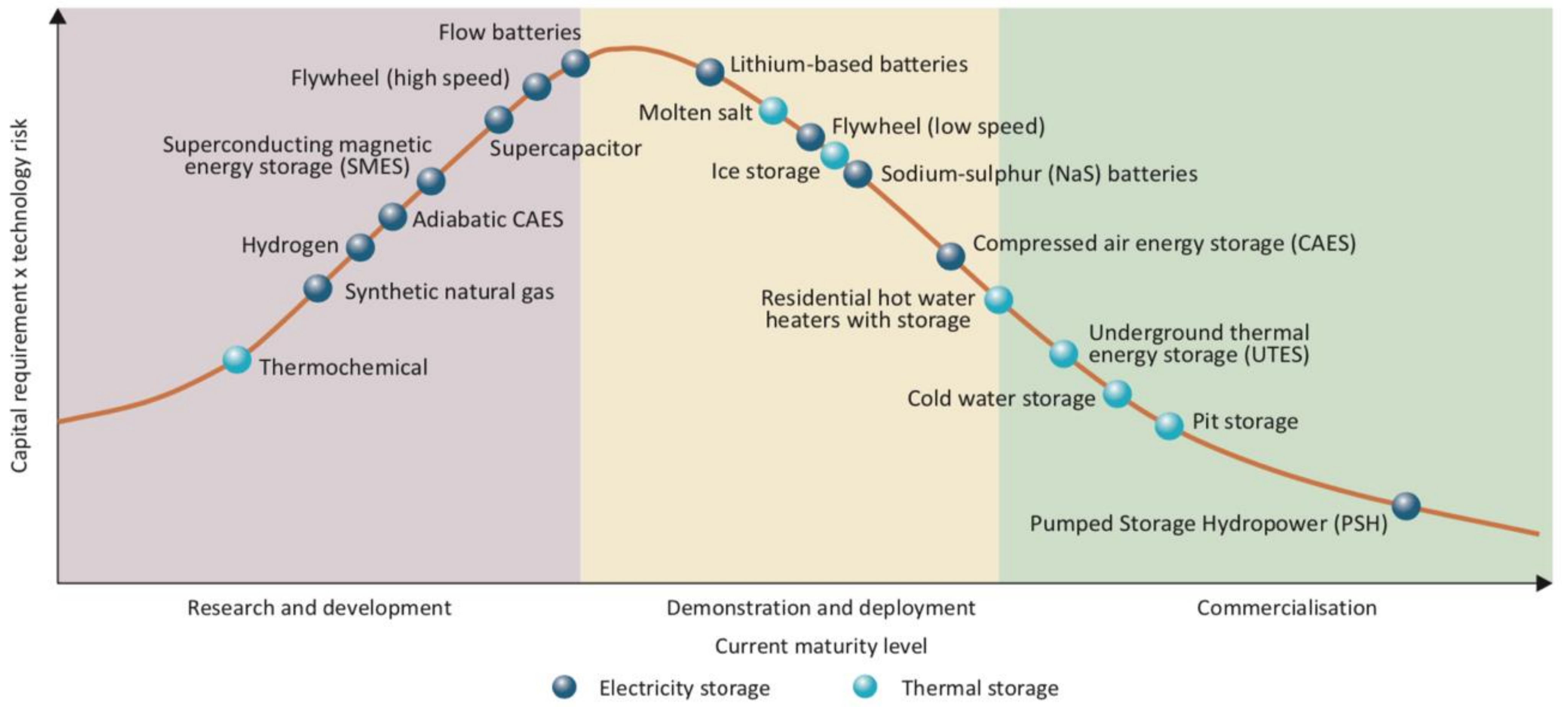
Hype curve - Energy storage technologies' maturity levels



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