Silesian
University
of Technology

RESEARCH
UNIVERSITY
EXCELLENCE INITIATIVE
Ministry of Science
and Higher Education

KENER
Department of Power Electronics,
Electrical Drives and Robotics

ENERGY MANAGEMENT
FOR SUSTAINABLE ENERGY TRANSITION

Krzysztof Bodzek

Gliwice, 01.02.2023r.

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Europejskie
Wiedza Edukacja Rozwój

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Outline

- Introducing (electric power industry)
- Electroprosumerism
- RES source
- Energy management system
- Role of power converters
- Building electroprosumer resilience – Warsaw case study
- Conclusion

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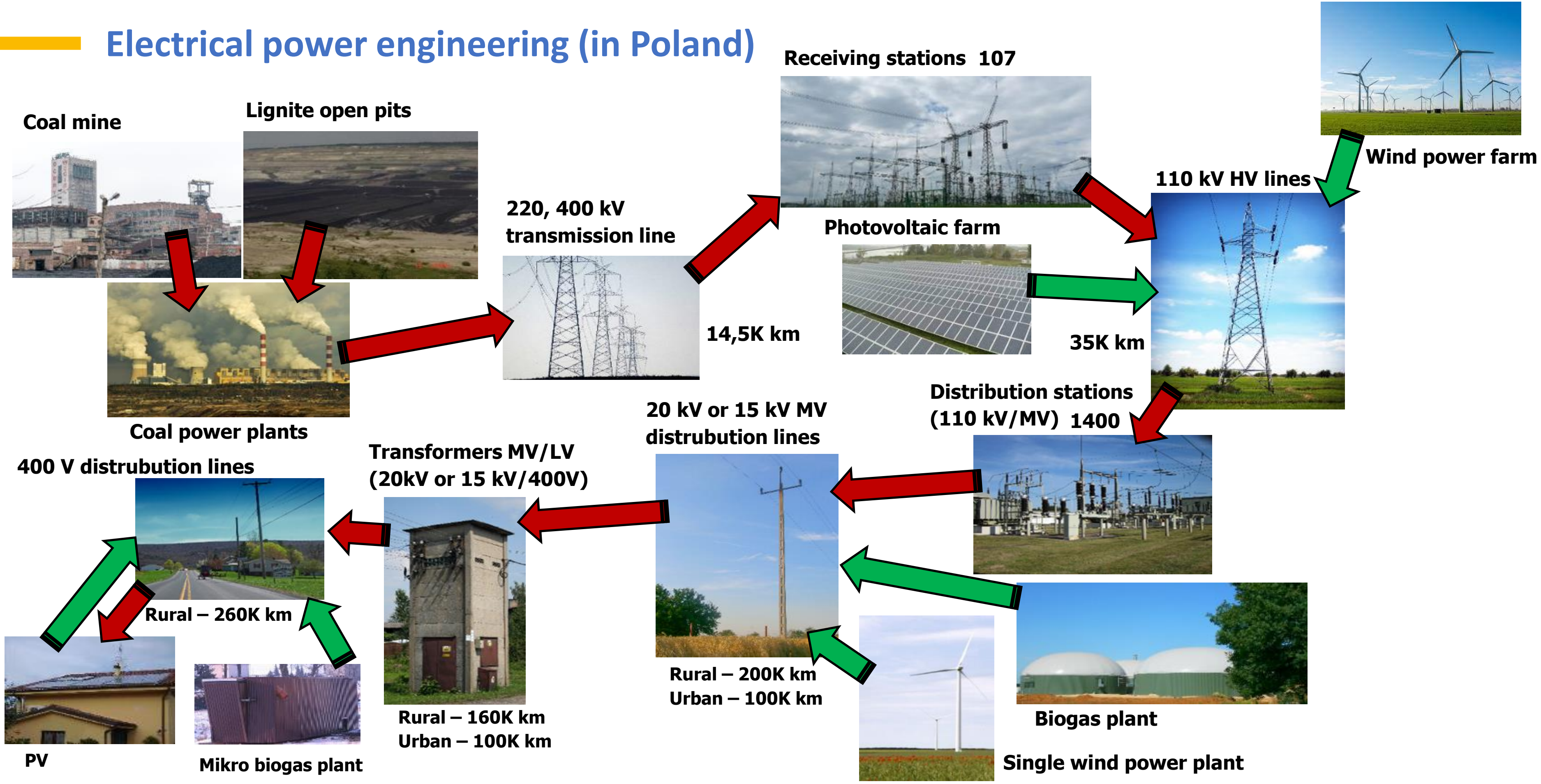
Electrical power engineering (in Poland)



Coal mine

Lignite open pits

Coal power plants

220, 400 kV transmission line

14,5K km

Receiving stations 107

Wind power farm

Photovoltaic farm

110 kV HV lines

35K km

Distribution stations (110 kV/MV) 1400

Biogas plant

Single wind power plant

20 kV or 15 kV MV distrubution lines

Rural – 200K km
Urban – 100K km

Transformers MV/LV (20kV or 15 kV/400V)

Rural – 160K km
Urban – 100K km

400 V distrubution lines

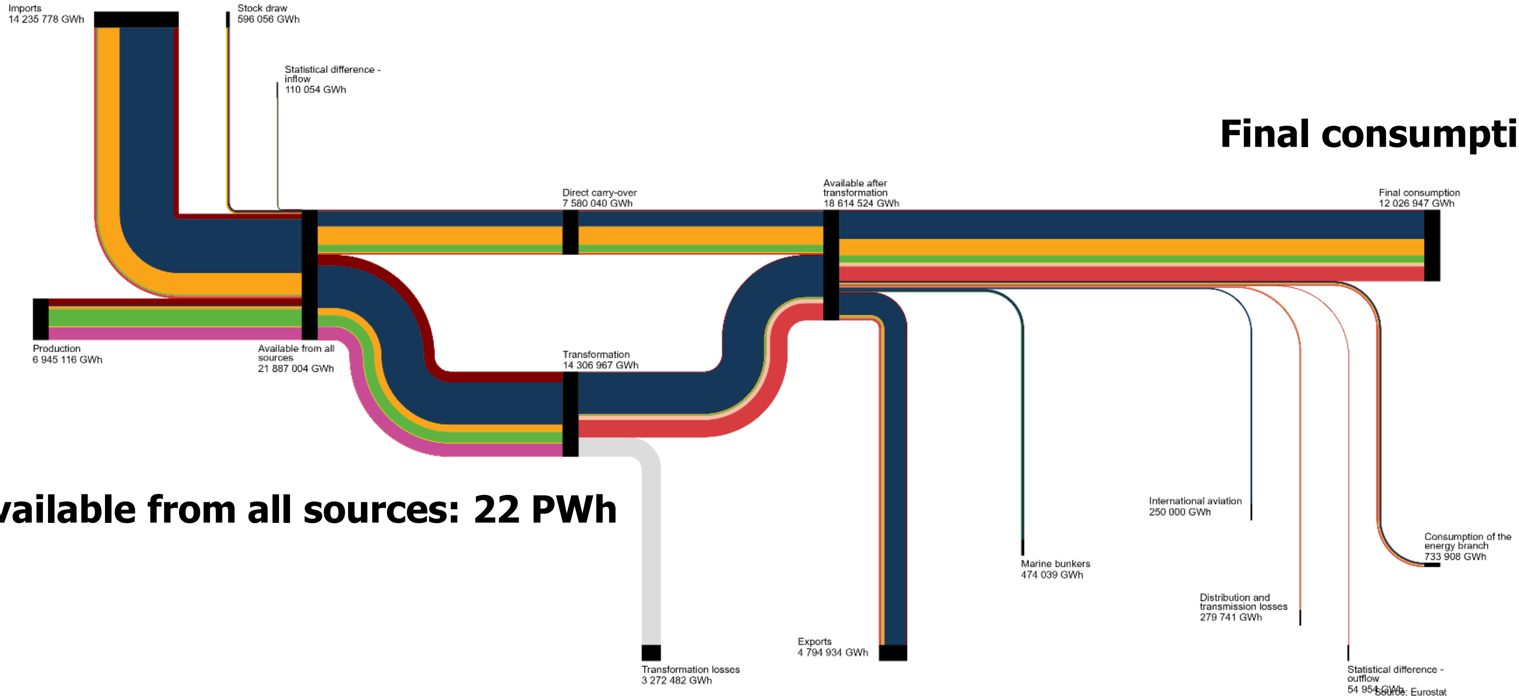
Rural – 260K km

PV

Mikro biogas plant

Energy balance flow for European Union (27 countries) 2021

Final consumption: 12 PWh



Source: Eurostat

Available from all sources: 22 PWh

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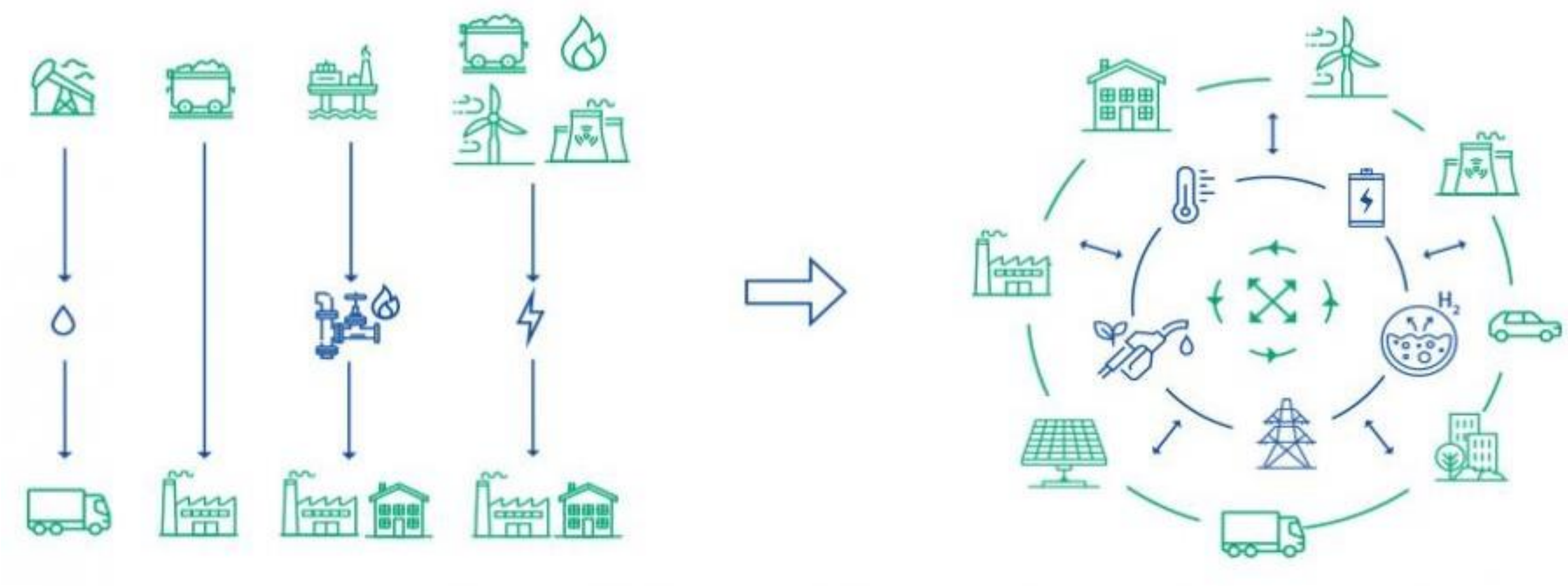
Transition requires energy management systems

The energy system today:
linear and wasteful flows of energy, in one direction only

Future integrated energy system:
energy flow between users and producers, reducing wasted resources and money



Sustainable energy transition

Thermo-Ecological Cost (TEC)
the influence of any production technology, including power technologies, on the depletion of resources

Takes into account:

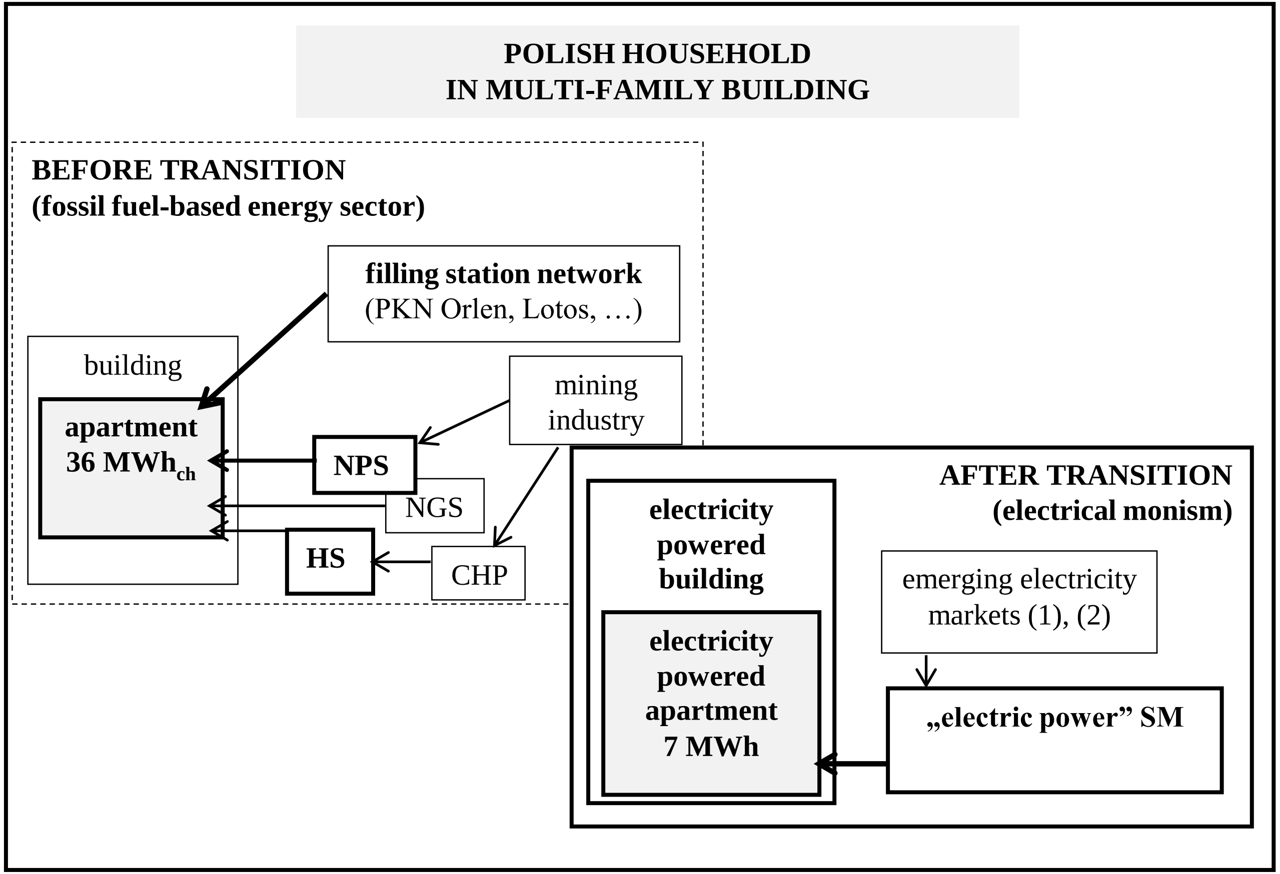
- whole cycle
- evaluate the resources quality
- influence on the depletion resulting from generation of wastes

Thermo-ecological cost (TEC)

	Type of technology	TEC MWh*/MWh	CO_2 footprint kg / MWh
1	Photovoltaic	0,294	41 (26 - 60)
2	Biogass plant	0,082	159 (-188 - 700)
2a	Biogas plant processing municipal waste	0,026	
2b	Biogas plant processing sewage sludge	0,021	
3	Wind onshore	0,029	7 (5 - 56)
4	Wind offshore	0,024	12 (8 - 35)
5	Vertical Axis Wind Turbine 2-6 kW	0,17	46
6	Modern coal-fired steam power plant	2,49	700
7	Lignite-fired steam power plant	3,18	900
8	Gas-steam power plant	1,74	490 (410 - 650)
9	Biomass steam power plant	0,27	230 (130 - 420)
10	Nuclear power plant	34	12 (4 - 110)

Transition idea

on the example of block of flats



POLISH HOUSEHOLD
IN MULTI-FAMILY BUILDING

BEFORE TRANSITION
(fossil fuel-based energy sector)

filling station network
(PKN Orlen, Lotos, …)

building

apartment
36 MWh$_{ch}$

mining
industry

NPS

NGS

HS

CHP

AFTER TRANSITION
(electrical monism)

electricity
powered
building

electricity
powered
apartment
7 MWh

emerging electricity
markets (1), (2)

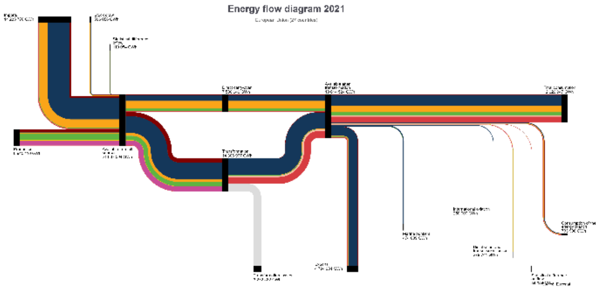
„electric power” SM

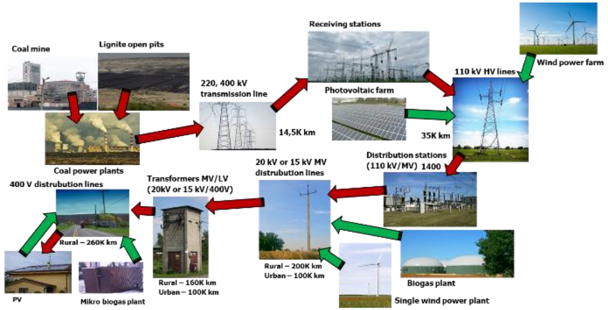
ENERGY TRANSITION

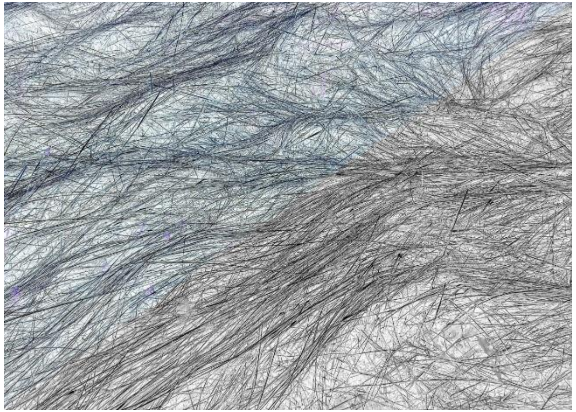
chaos, but with opportunities

A state (now)

we know







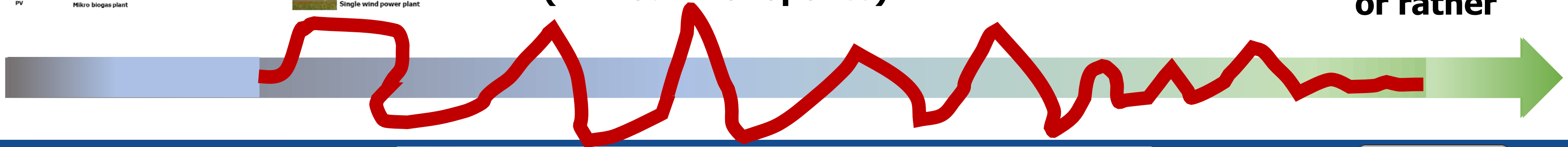
OK:
rational transition plan

PERFECT:
market energy transition (without monopolies)

B state (2050)

we expect:
European Green Deal

or rather



Prosumer is enough?

PRODUCER + **CONSUMER**

= **PROSUMER** + **ELECTRICITY**

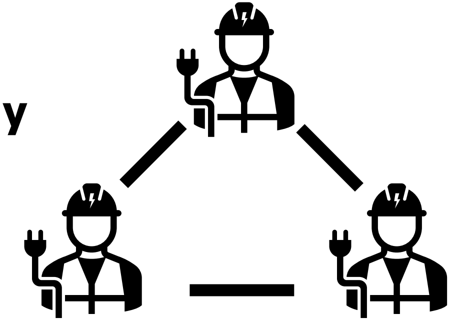
Exergy

= **ELECTROPROSUMER**

Electroprosumerism

United electropsumers create a democratic energy community (citizen/democracy energy) named:

Electroprosumerism



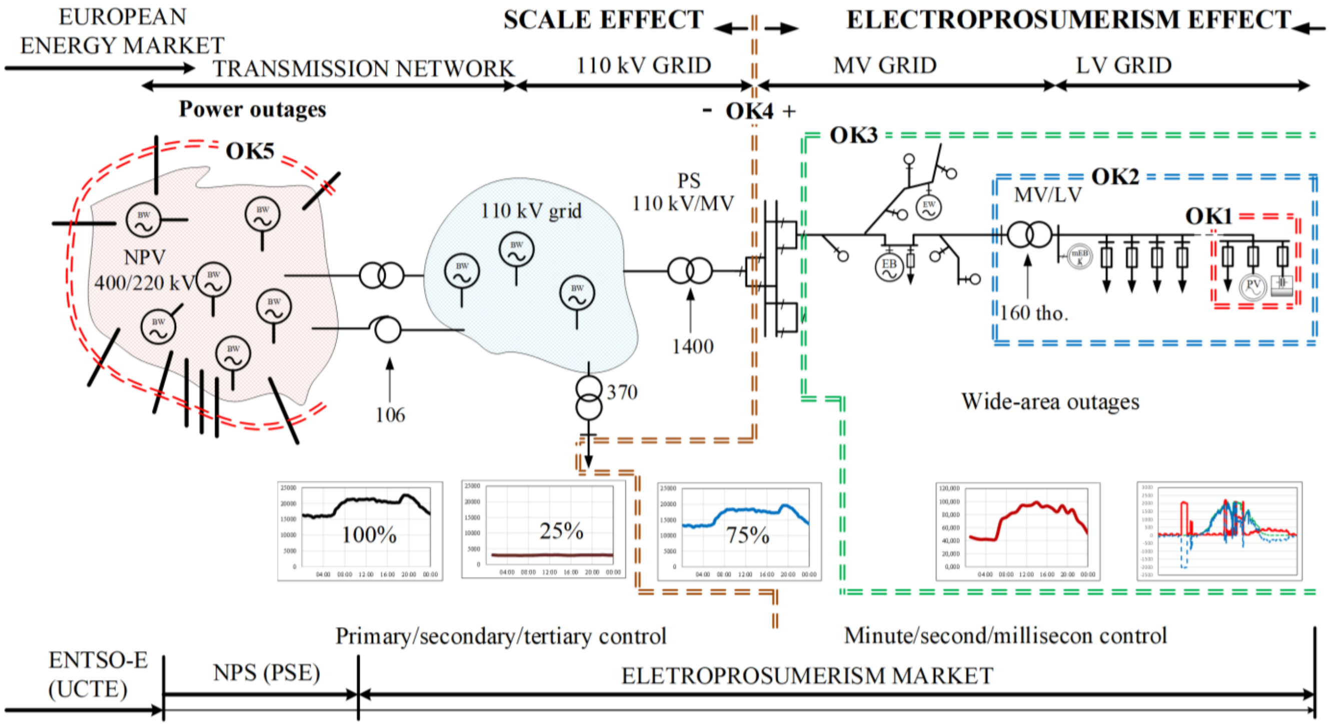
Electroprosumerism is the end state of transition to electrical monism.
It covers aspects of: technology, economic, environmental, and sociology.

Ranking the activities of electroprosumerism (in order of priority):

1. passivation of buildings,
2. electrification of heating industry,
3. electrification of transportation,
4. electricity use (flexibility) and electrotechnologies in the digital environment and circular economy,
5. RES re-electrification.

From the centralized (TSO, DNO) to the electroprosumerism

The management system should be in every control shield



OK1 – prosumer control shield - LV supply terminal

OK2 – control shield LV feeder bays of an MV/LV transformer substation (separating LV infrastructure supplied by the substation),

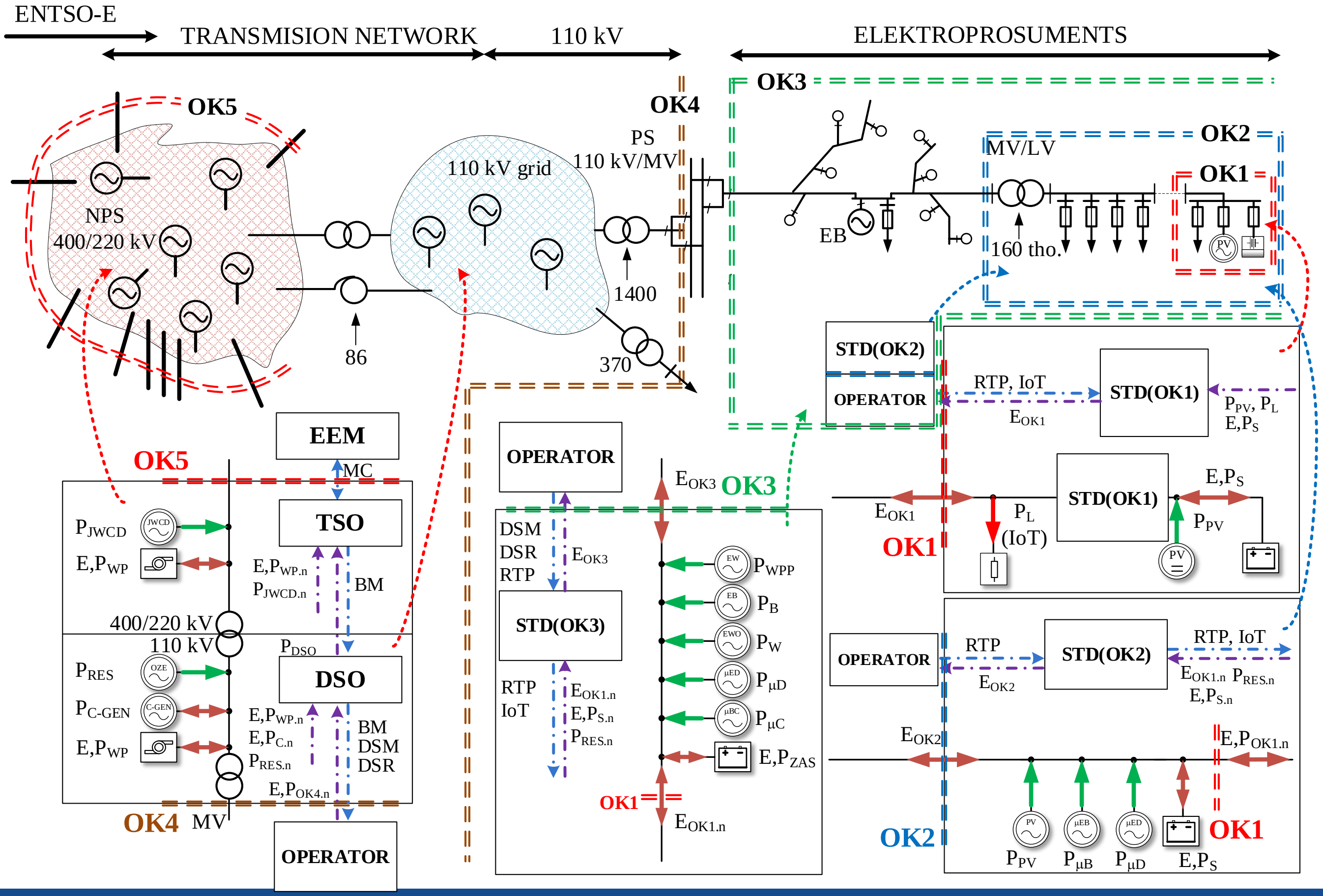
OK3 – control shield connecting bays (to MV/LV infrastructure) of sources and prosumers/consumers

OK4 – control shield MV feeder bays of 110 kV/MV transformer substation,

OK5 – control shield NPS cross-border connections with UCTE system

STD – Grid Aces Terminal (GAT)

Energy management structure for control shields



Electroprosumer Resilience

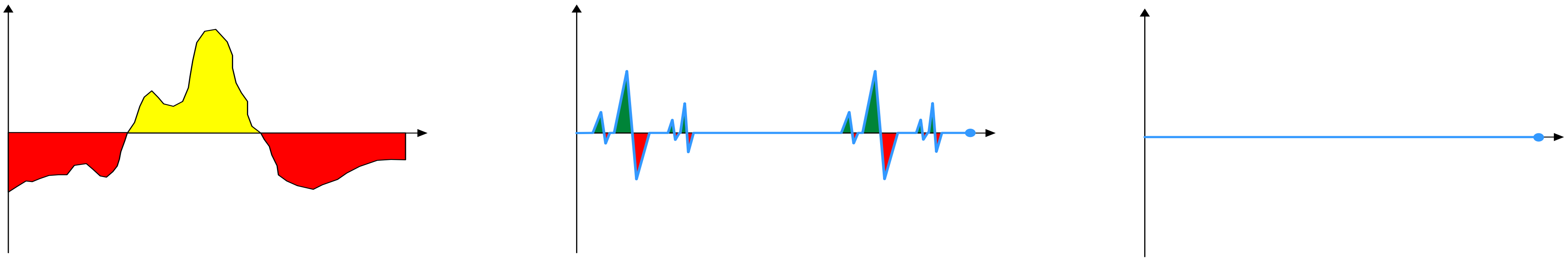
Final state of the process of building up one's energy independence to a reasonable (economically justified) level of energy self-sufficiency in sequence:

(on → on/off → off) grid

wherever it is possible.

Electroprosumer resilience includes the use of electricity as a driving energy, replacing all current fossil fuel markets. It is implemented in an environment of marginal cost and marginal efficiency.

on → on/off → off



Outline

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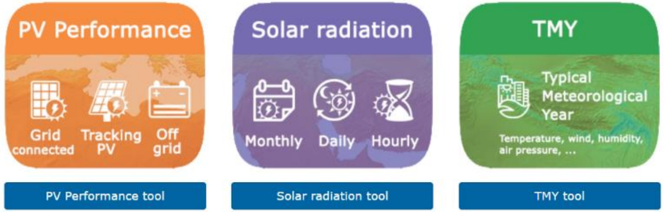
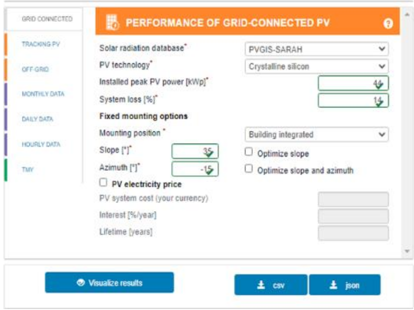
PV sources

Many tools to support design, both free and commercial

Production estimation based on historical data

Portal PVGIS Photovoltaic Geografical Information System: https://ec.europa.eu/jrc/en/pvgis



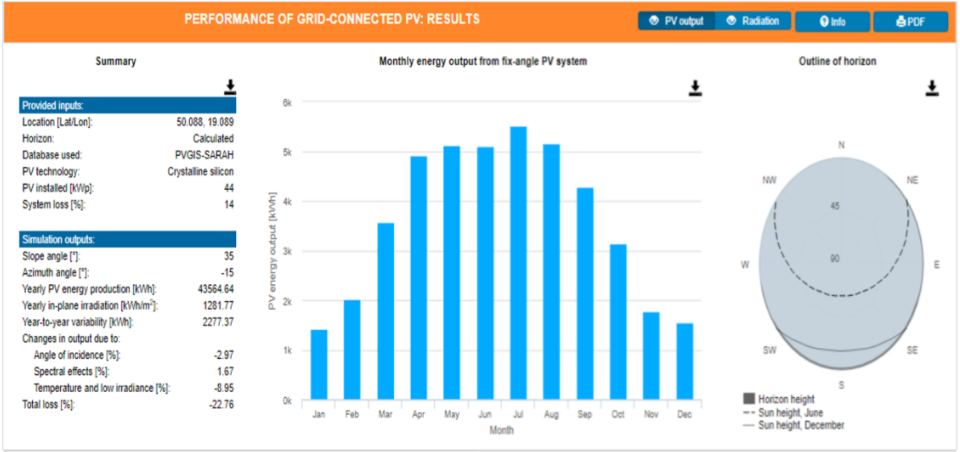


PERFORMANCE OF GRID-CONNECTED PV

Solar radiation database*: PVGIS-SARAH
PV technology*: Crystalline silicon
Installed peak PV power [kWp]*: 44
System loss [%]*: 14

Fixed mounting options

Mounting position *: Building integrated
Slope [°]*: 35
Azimuth [°]*: -15
☐ Optimize slope
☐ Optimize slope and azimuth
☐ **PV electricity price**
PV system cost (your currency)
Interest [%/year]
Lifetime [years]



PERFORMANCE OF GRID-CONNECTED PV: RESULTS

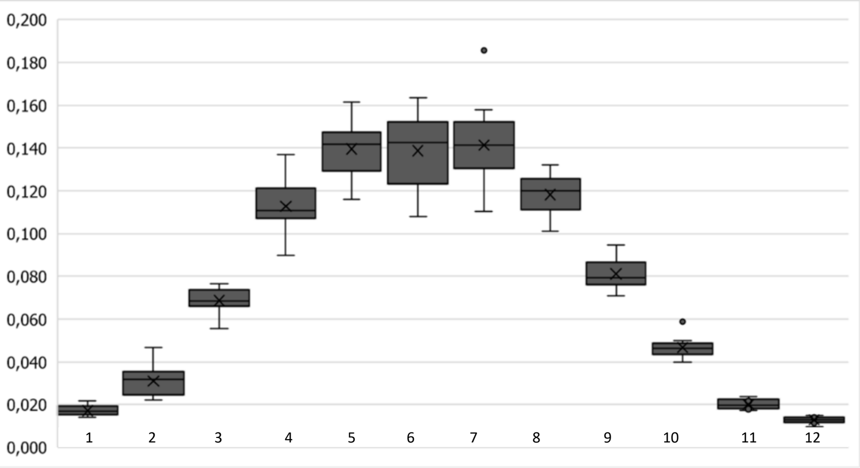
Summary

Monthly energy output from fix-angle PV system

Outline of horizon

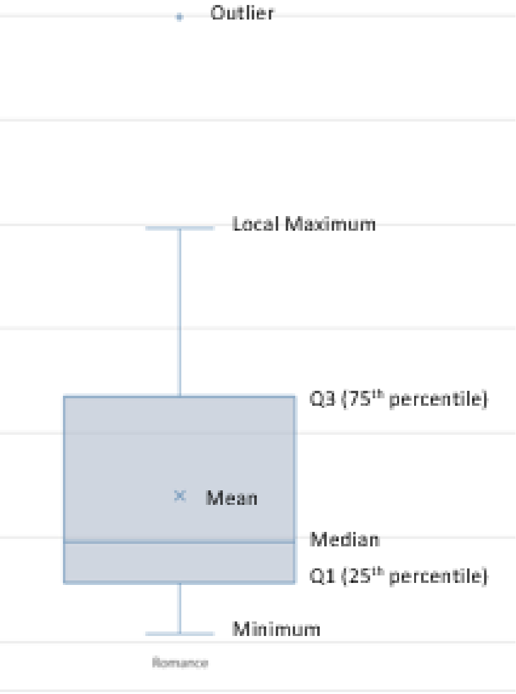
Provided inputs:	
Location [Lat/Lon]:	50.088, 19.089
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed [kWp]:	44
System loss [%]:	14
Simulation outputs:	
Slope angle [°]:	35
Azimuth angle [°]:	-15
Yearly PV energy production [kWh]:	43564.64
Yearly in-plane irradiation [kWh/m^2]:	1281.77
Year-to-year variability [kWh]:	2277.37
Changes in output due to:	
Angle of incidence [%]:	-2.97
Spectral effects [%]:	1.67
Temperature and low irradiance [%]:	-8.95
Total loss [%]:	-22.76

Probability of production

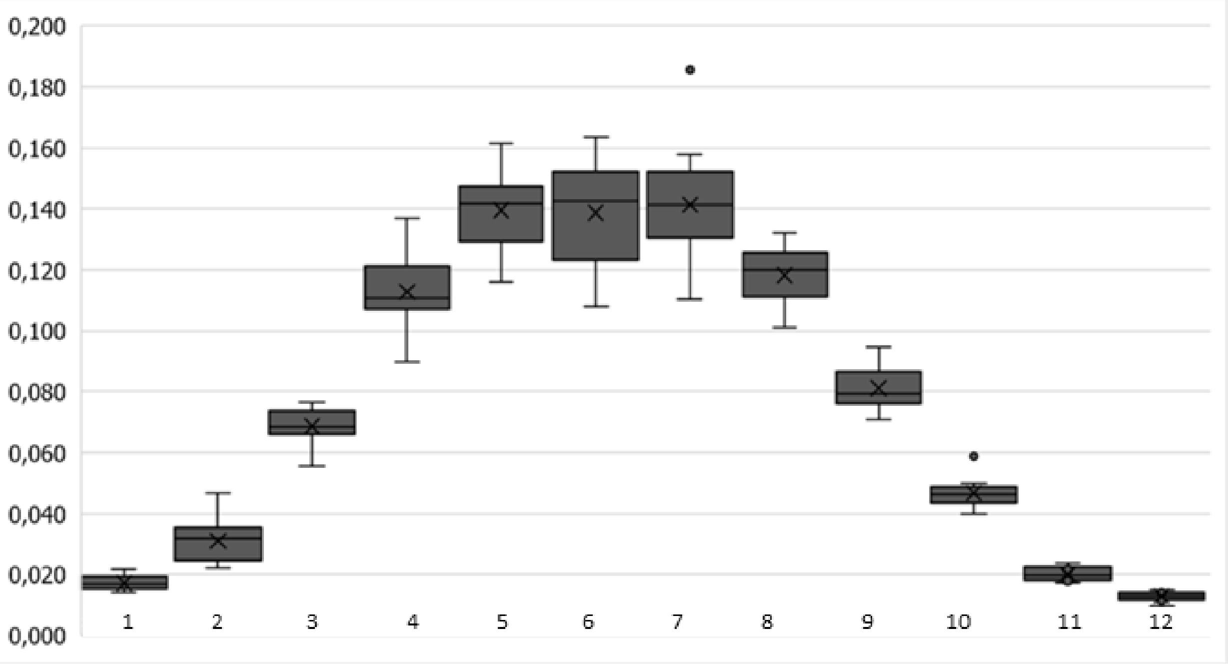


PV sources

Box & Whisker Plot

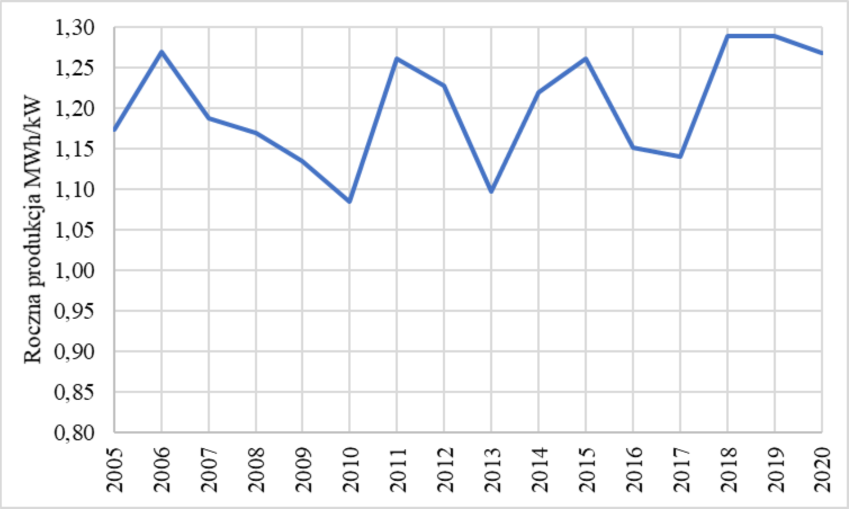


Normalized probability of production

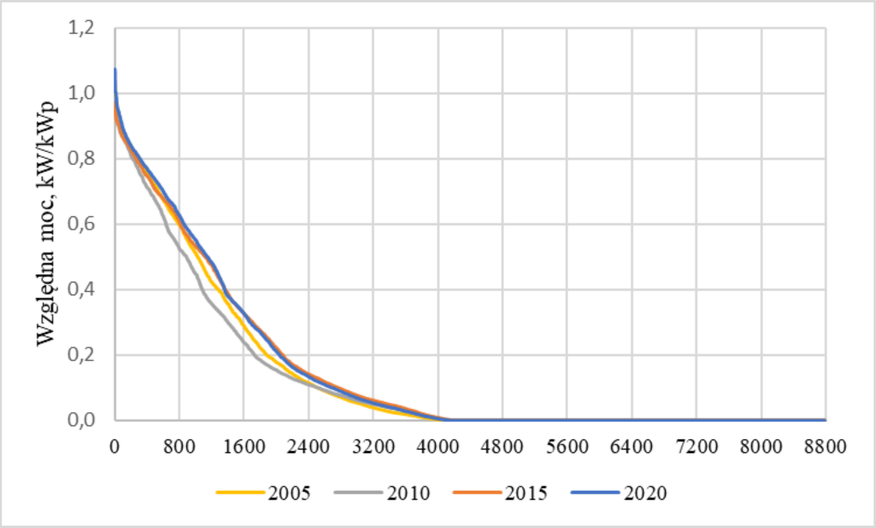


PV sources

Annual production MWh/kW
New installation (no losses in inverters)



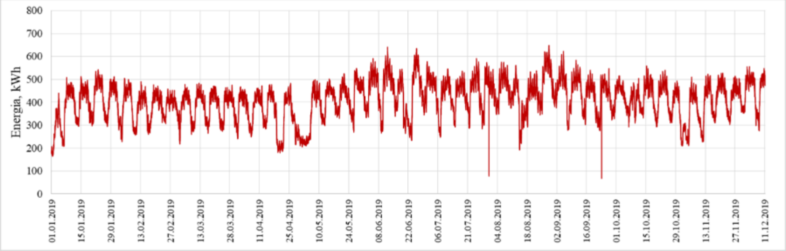
Ordered relative power of PV installations



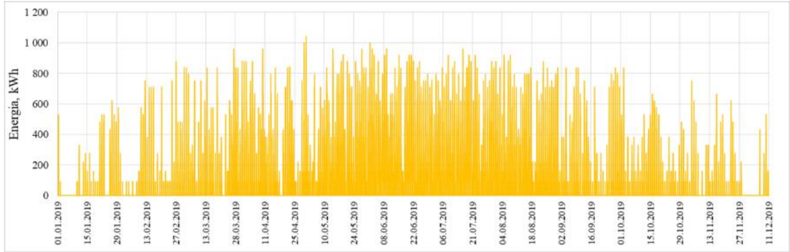
PV sources

Sources with forced production

Demand profile

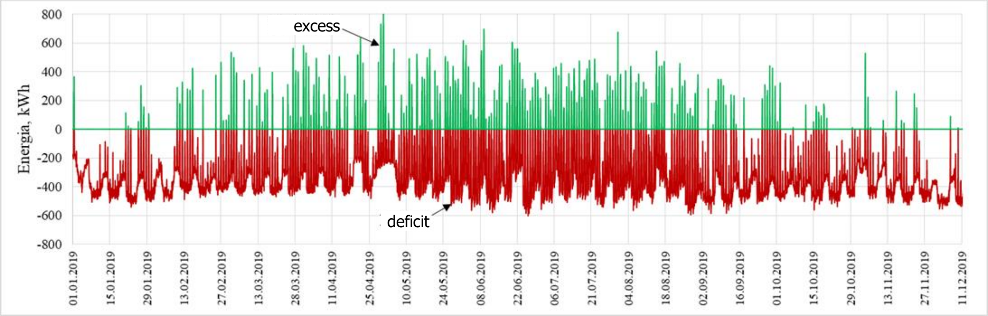


Production profile of PV sources



Energy balance

$$E = \sum E_G - \sum E_D$$



where:

E_G - generation

E_D - demand

Accumulator selection – without energy management

Off grid systems - case study

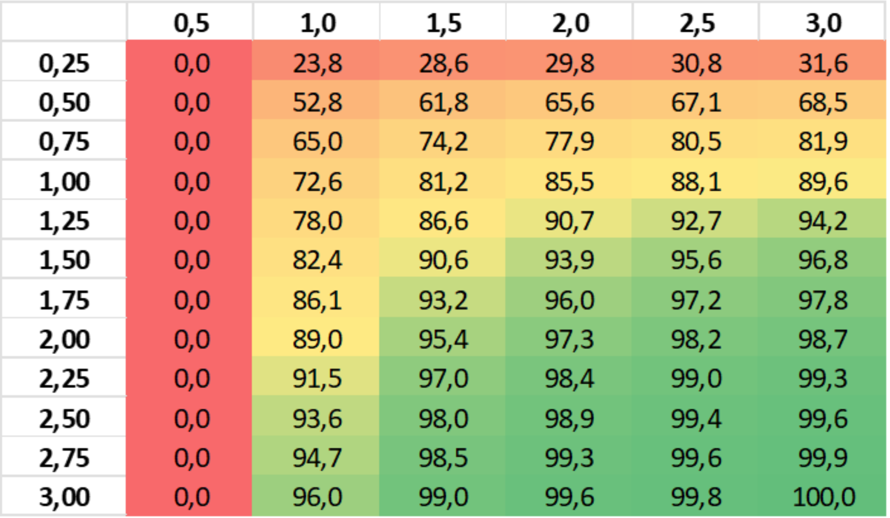
Assumptions:

- daily demand - 1 kWh
- selection based on profiles
- cost of acumulator - 3 thousand PLN/kWh
- cost of PV source - 4 thousand PLN/kW

Number of days with full coverage of demand, %

Accumulator capacity, kWh

Power of PV sources, kW

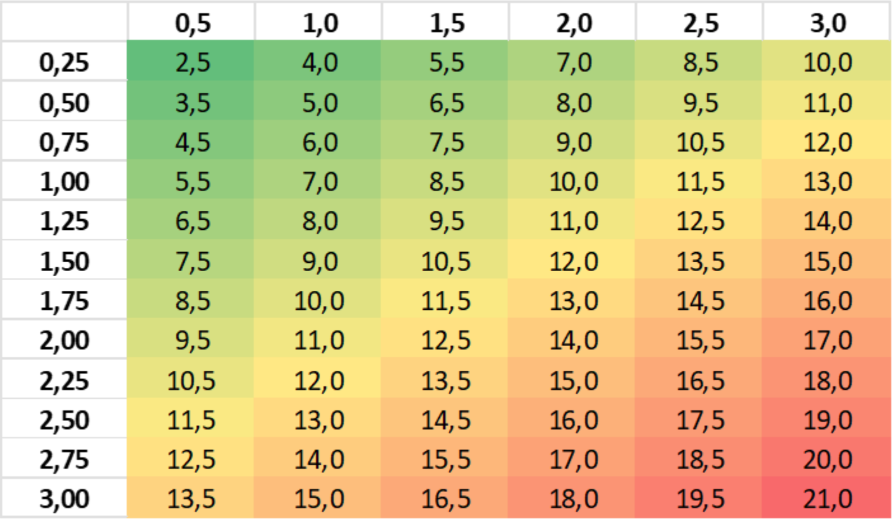


	0,5	1,0	1,5	2,0	2,5	3,0
0,25	0,0	23,8	28,6	29,8	30,8	31,6
0,50	0,0	52,8	61,8	65,6	67,1	68,5
0,75	0,0	65,0	74,2	77,9	80,5	81,9
1,00	0,0	72,6	81,2	85,5	88,1	89,6
1,25	0,0	78,0	86,6	90,7	92,7	94,2
1,50	0,0	82,4	90,6	93,9	95,6	96,8
1,75	0,0	86,1	93,2	96,0	97,2	97,8
2,00	0,0	89,0	95,4	97,3	98,2	98,7
2,25	0,0	91,5	97,0	98,4	99,0	99,3
2,50	0,0	93,6	98,0	98,9	99,4	99,6
2,75	0,0	94,7	98,5	99,3	99,6	99,9
3,00	0,0	96,0	99,0	99,6	99,8	100,0

Capital expenditure, PLN

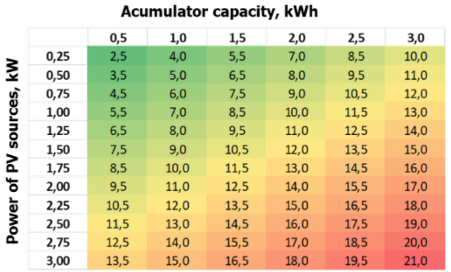
Accumulator capacity, kWh

Power of PV sources, kW



	0,5	1,0	1,5	2,0	2,5	3,0
0,25	2,5	4,0	5,5	7,0	8,5	10,0
0,50	3,5	5,0	6,5	8,0	9,5	11,0
0,75	4,5	6,0	7,5	9,0	10,5	12,0
1,00	5,5	7,0	8,5	10,0	11,5	13,0
1,25	6,5	8,0	9,5	11,0	12,5	14,0
1,50	7,5	9,0	10,5	12,0	13,5	15,0
1,75	8,5	10,0	11,5	13,0	14,5	16,0
2,00	9,5	11,0	12,5	14,0	15,5	17,0
2,25	10,5	12,0	13,5	15,0	16,5	18,0
2,50	11,5	13,0	14,5	16,0	17,5	19,0
2,75	12,5	14,0	15,5	17,0	18,5	20,0
3,00	13,5	15,0	16,5	18,0	19,5	21,0

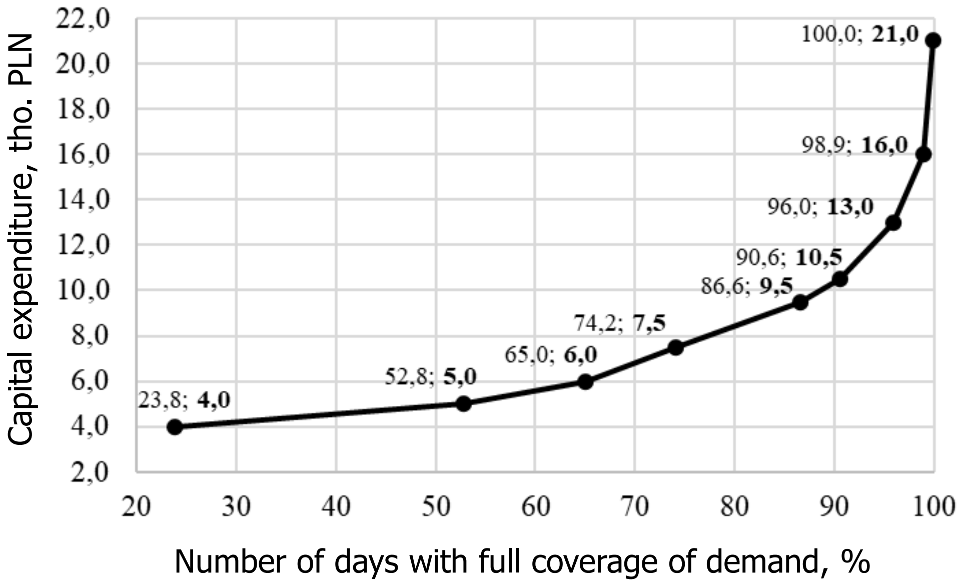
Accumulator selection – without energy management



	Acumulator capacity, kWh					
Power of PV sources, kW	0,5	1,0	1,5	2,0	2,5	3,0
0,25	2,5	4,0	5,5	7,0	8,5	10,0
0,50	3,5	5,0	6,5	8,0	9,5	11,0
0,75	4,5	6,0	7,5	9,0	10,5	12,0
1,00	5,5	7,0	8,5	10,0	11,5	13,0
1,25	6,5	8,0	9,5	11,0	12,5	14,0
1,50	7,5	9,0	10,5	12,0	13,5	15,0
1,75	8,5	10,0	11,5	13,0	14,5	16,0
2,00	9,5	11,0	12,5	14,0	15,5	17,0
2,25	10,5	12,0	13,5	15,0	16,5	18,0
2,50	11,5	13,0	14,5	16,0	17,5	19,0
2,75	12,5	14,0	15,5	17,0	18,5	20,0
3,00	13,5	15,0	16,5	18,0	19,5	21,0

Marginal cost of covering energy needs (days with full demand coverage, in %) as a function of capital expenditures for an installation with a PV source and an accumulator

The last 10% costs as much as the rest 90%



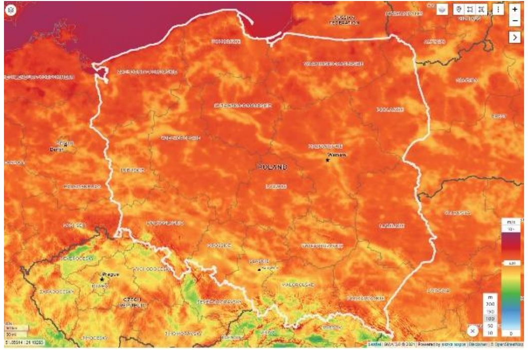
Energy management systems are needed, or the transition will cost us a lot

Wind power plant

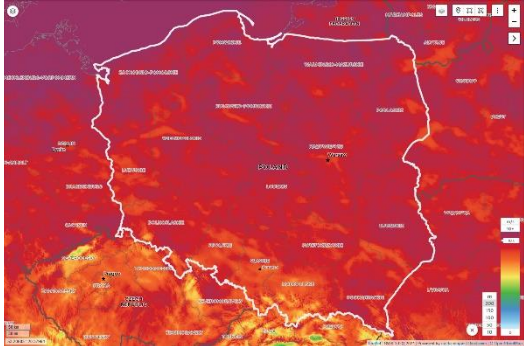
There are services, but access to data and tools is not so easy and requires more knowledge

Portal Global Wind Atlas: https://globalwindatlas.info/

Wind map of Poland - 100 m

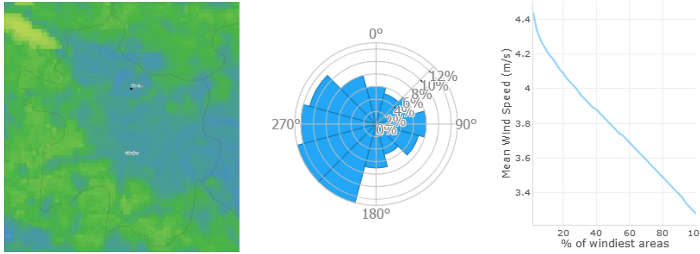


Wind map of Poland – 200 m

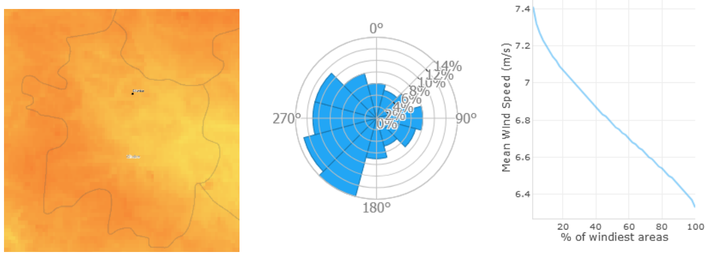


Wind map of Gliwice

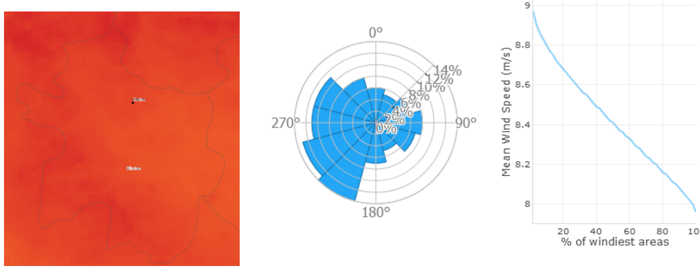
10 m

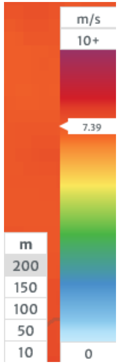


100 m



200 m

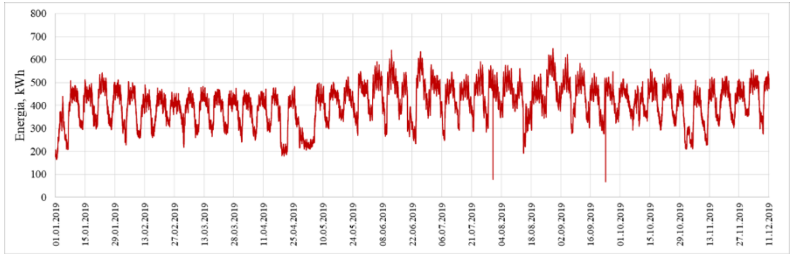




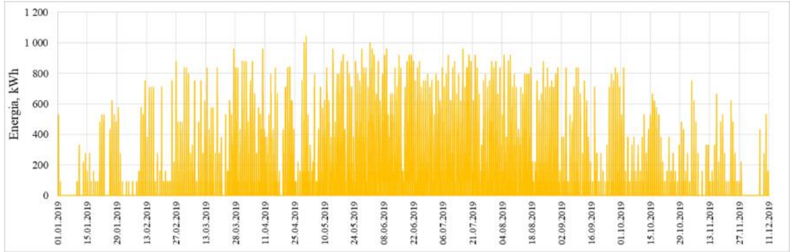
Wind power plant

Sources with forced production

Demand profile

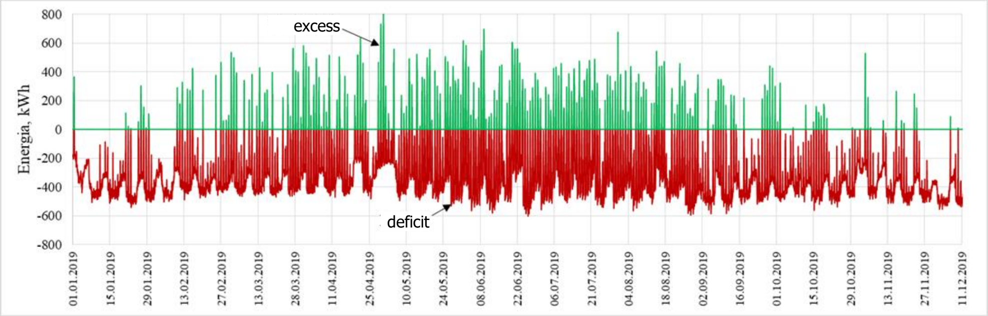


Production profile of PV sources

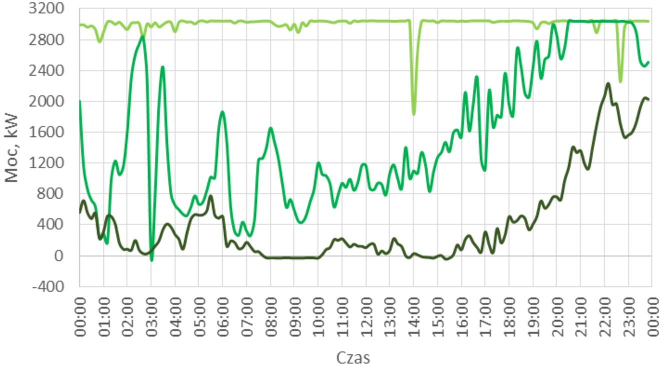


Energy balance

$$E = \sum E_G \pm \sum E_S - \sum E_D$$

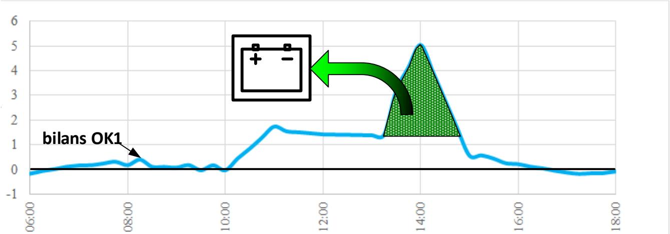


Production profile of wind farms

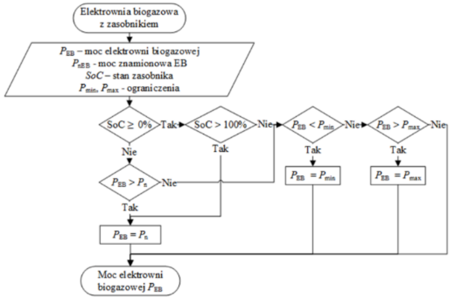


Regulating and balancing sources

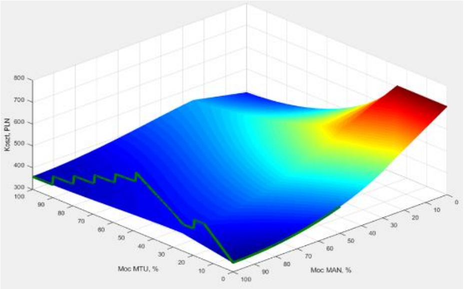
Battery management



Work algorithm of a biogas power plant



Characteristics of the cost of electricity generation with the control trajectory of aggregates in a biogas power plant



Load shifting

$$E_O\Big|_h = [E_O^1, E_O^2, \dots, E_O^{24}]$$ $E_O|_h$- hourly energy vector

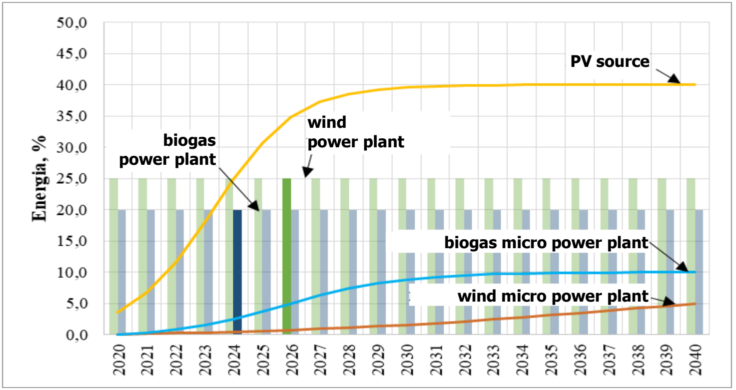
$$K = \sum_{h=1}^{24} K_h$$ **Minimizing energy costs while maximizing the comfort of use**

$$OZ_i = \frac{|t_z - t_{zr}|}{v}$$ **Minimize the on-delay**

$f(E_d) = f(t, O_i)$=min(K, OZ_i) **Objective function**

Transition trajectory analysis (S-curve)

$$E(t) = \frac{a}{1 + b \cdot e^{-ct}} + d$$



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Outline

- Introducing (electric power industry)
- Electroprosumerism
- RES source
- **Energy management system**
- Role of power converters
- Building electroprosumer resilience – Warsaw case study
- Conclusion

Fundamentals of flexibility

Energy balance equation

$$E_{OK}|_{t(s,min,h,d,m,r)} = \sum E_G|_{\ t(s,min,h,d,m,r)} \pm \sum E_S|_{\ t(s,min,h,d,m,r)} - \sum E_L|_{\ t(s,min,h,d,m,r)}$$

Energy generation

$$\sum E_G|_{\ t} = \sum E_{RES}|_{\ t} + \sum E_{RB}|_{\ t} + \sum E_{FF}|_{\ t}$$

E_{RES} - sources with forced production

E_{RB} - regulating and balancing sources

E_{FF} - fossil fuel sources

Energy storages

$$\sum E_S|_{\ t} = \sum E_{Se}|_{\ t} + \sum E_{Sch}|_{\ t} + \sum E_{Sc}|_{\ t}$$

E_{Se} - electricity storage

E_{Sch} - chemical energy storage (power to gas)

E_{Sc} - heat storage

Loads

$$\sum E_L|_{\ t} = \sum E_{CT}|_{\ t} + \sum E_{UC}|_{\ t} + \sum E_C|_{\ t}$$

E_{CT} - critical

E_{UC} - uncontrollable

E_C - controllable

Fundamentals of flexibility

Load shifting

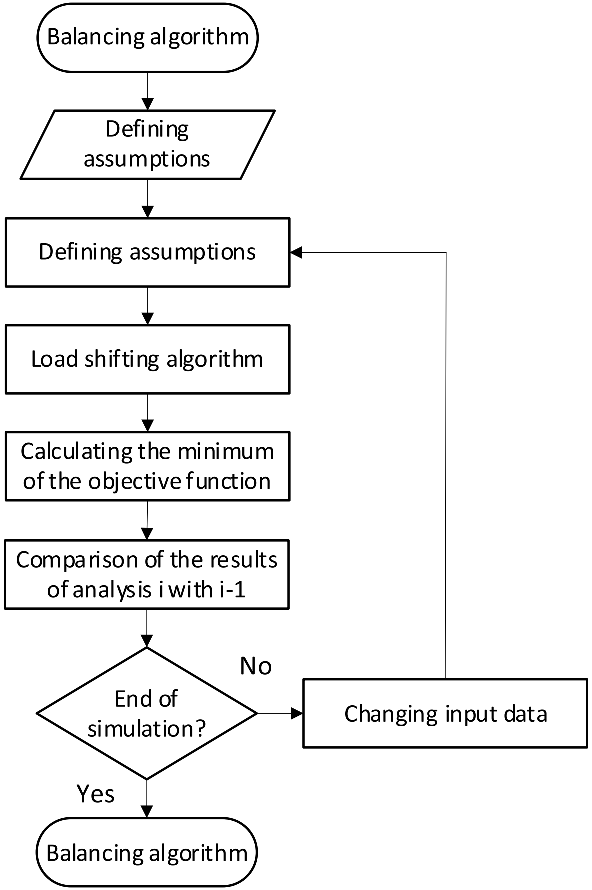
$E_O\Big|_h = [E_O^1, E_O^2, \dots, E_O^{24}]$ $E_O|_h$- hourly energy vector

$K = \sum_{h=1}^{24} K_h$ **Minimizing energy costs while maximizing the comfort of use**

$OZ_i = \frac{|t_z - t_{zr}|}{v}$ **Minimize the on-delay**

$f(E_d) = f(t, O_i)$=min(K, OZ_i) **Objective function**

General algorithm for minimizing deficits

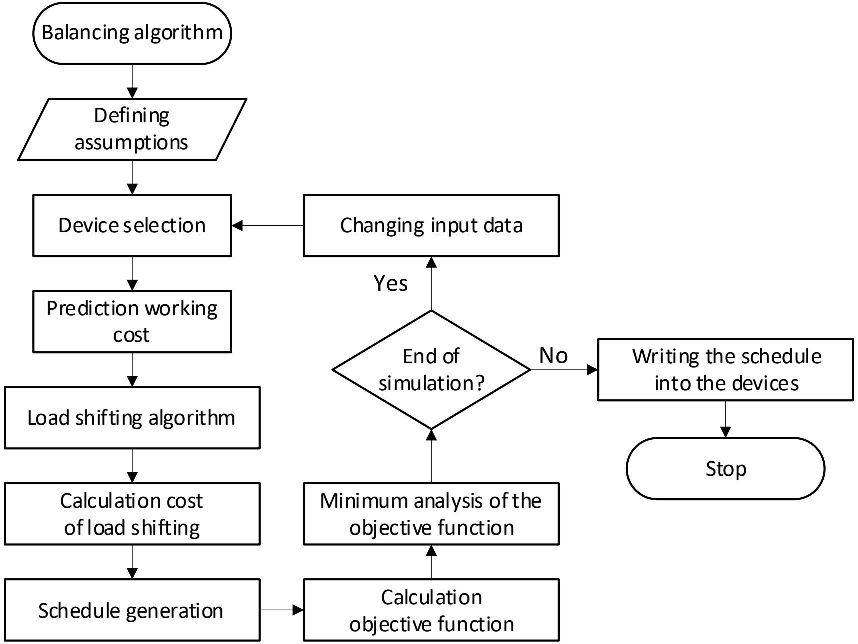


Minimize energy utility costs and maximize comfort of operation

Objective function

$$f(E_d) = f(t, O_i) = \min(K, OZ_i)$$

Algorithm of devices operation



Balancing algorithm

Defining assumptions

Device selection

Prediction working cost

Load shifting algorithm

Calculation cost of load shifting

Schedule generation

Calculation objective function

Minimum analysis of the objective function

End of simulation?

Yes

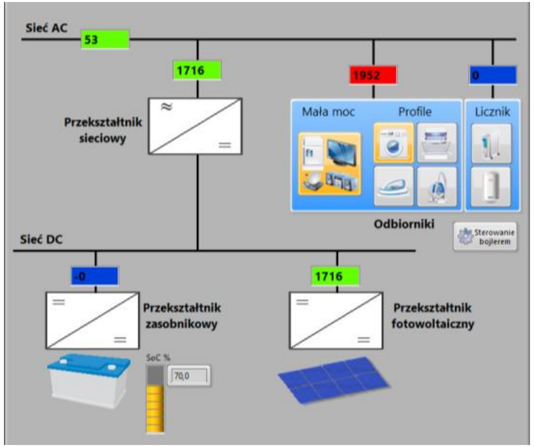
Changing input data

No

Writing the schedule into the devices

Stop

Modeling using a hybrid simulator

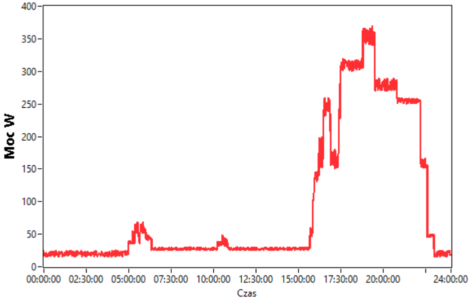


User application

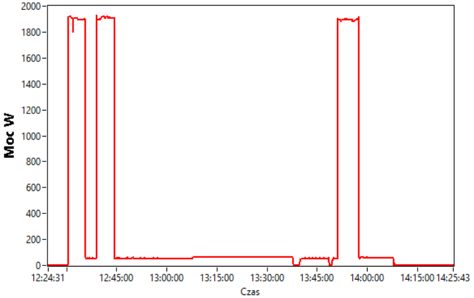
Minimize energy utility costs and maximize comfort of operation

Appliance profiles

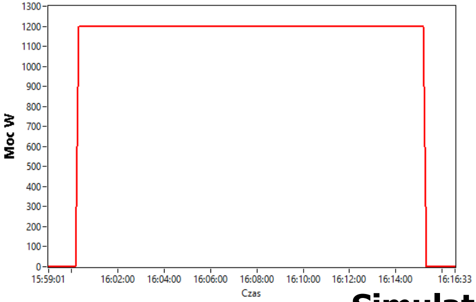
Uncontrollable devices - background profile



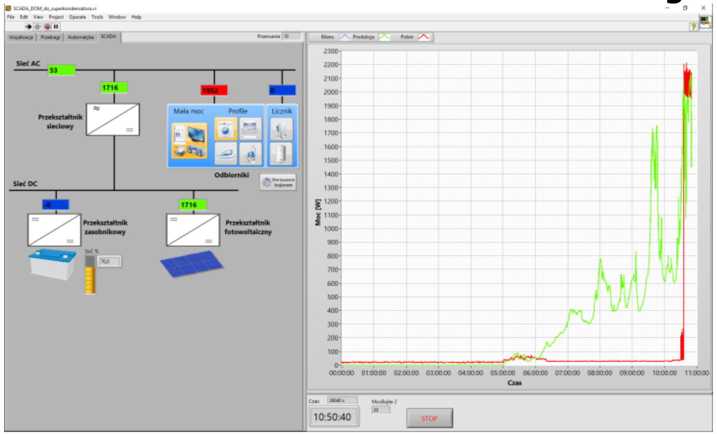
Dishwasher



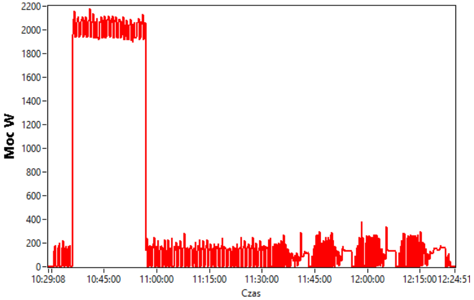
Vacuum cleaner



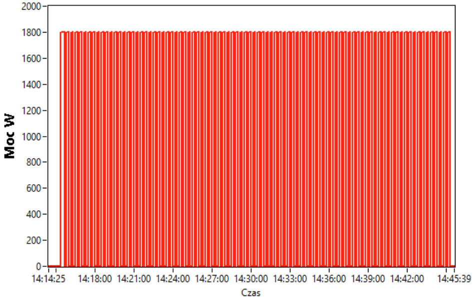
Simulation of device switching



Fridge



Iron



Maximizing the autoconsumption – case study

15-minute profiles

Configuration of loads selected for management

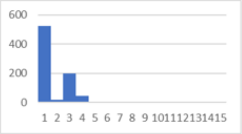
Household	Device number	Device type	Cycle consumption, Wh
1	1	Washing machine	792
	2	Dishwasher	520
	3	Drying machine	1880
	4	Oven	1550
	5	Vacuum cleaner	115
2	1	Washing machine	1135
	2	Dishwasher	725
	3	Vacuum cleaner	542
	4	Oven	737
3	1	Washing machine	945
	2	Dishwasher	1220
	3	Blender	25

Maximizing the autoconsumption – case study

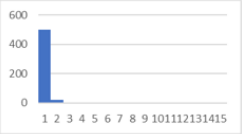
15-minute profiles of devices

Household 1

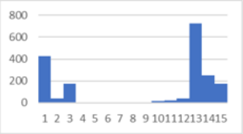
1)



2)

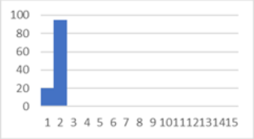


3)



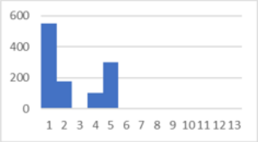
4)

5)

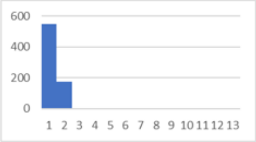


Household 2

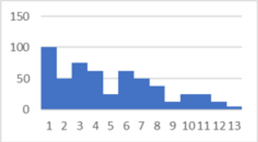
1)



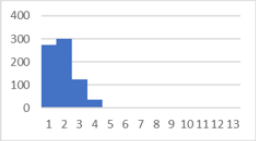
2)



3)

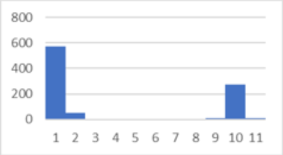


4)

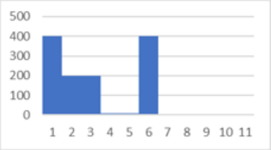


Household 3

1)



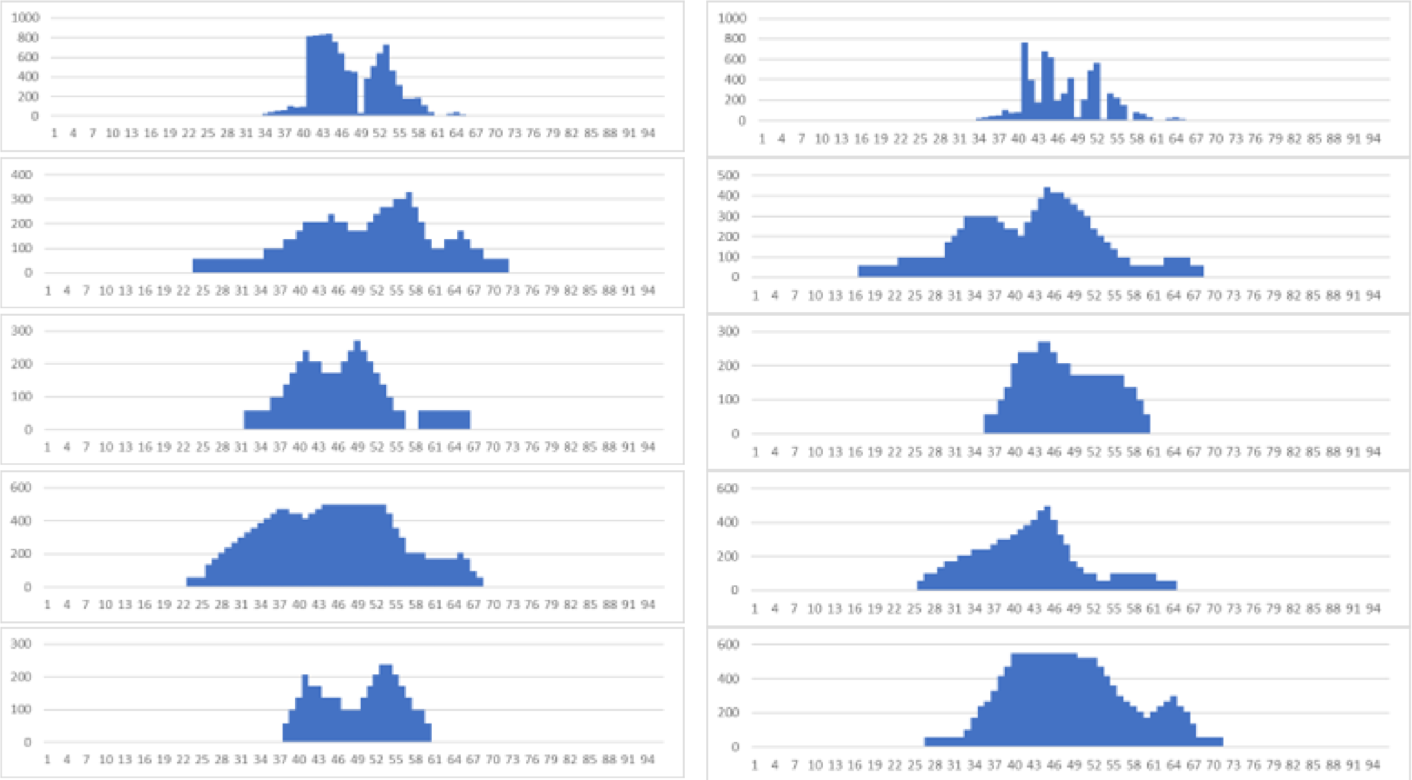
2)



3)

Maximizing the autoconsumption – case study

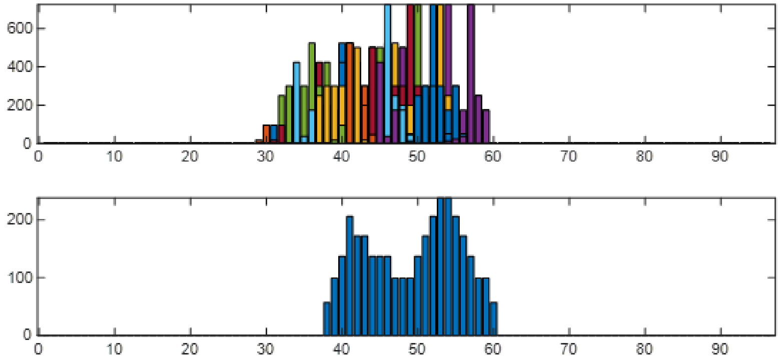
15-minute profiles of PV source – test profiles



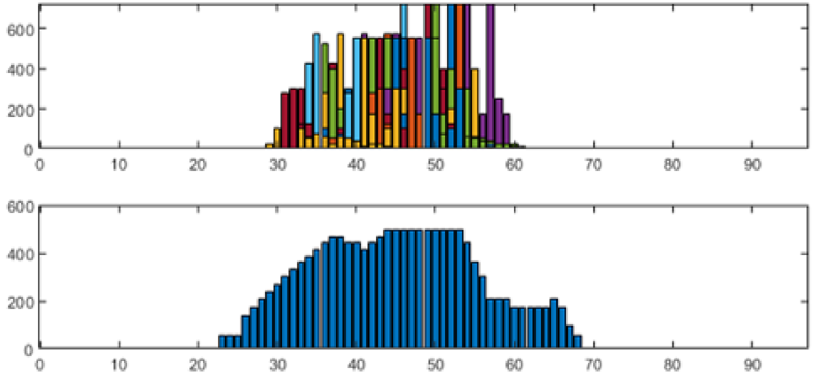
Maximizing the autoconsumption – case study

Results

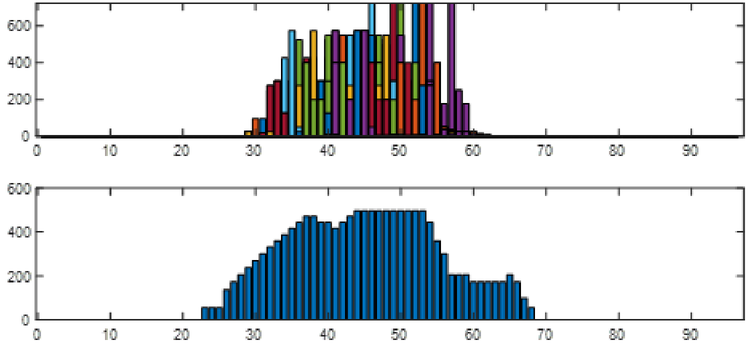
Household 1



Household 2



Household 3



Energy security in sustainable transition

Energy security - the state of the economy that allows covering the prospective demand of consumers for fuels and energy, in a technically and economically justified way, while maintaining the requirements of environmental protection

The Polish Energy Law Act

Three aspects:

- covering demand
- economically
- enviromental protection

Energy Security or Energy Resilience

Energy Resilience - ensuring that energy needs are covered with own resources (sources, storage facilities, ...) using local balancing, forecasts, converter functionalities, as well as using access to NPS resources when necessary, taking into account the ZWZ-NPS principle

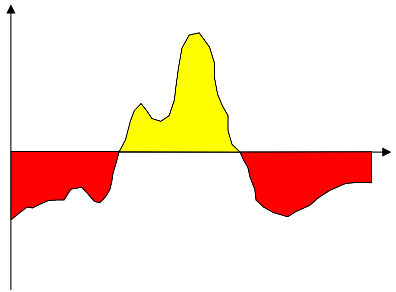
Proposal

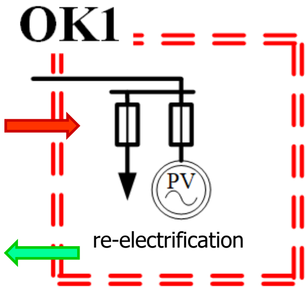
Building electroprosumer resilience in OK1 – case study

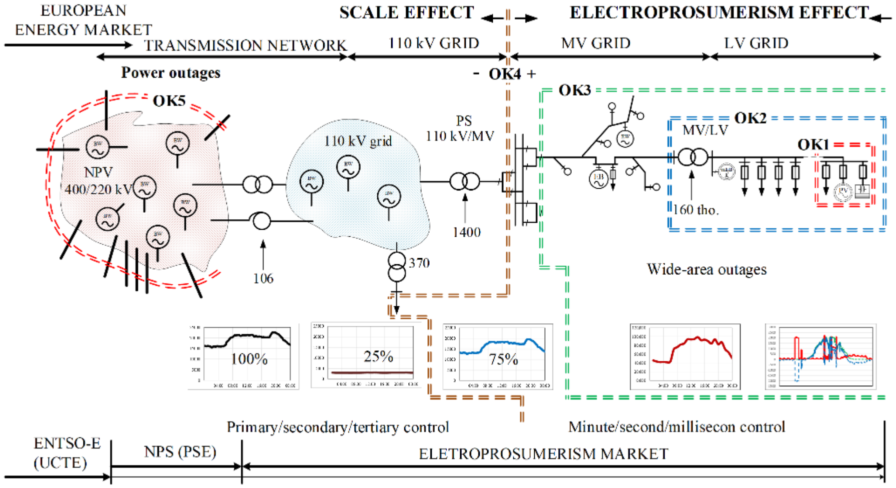
Now

Imbalance profile

- how the NPS sees the ~~electro~~prosumer







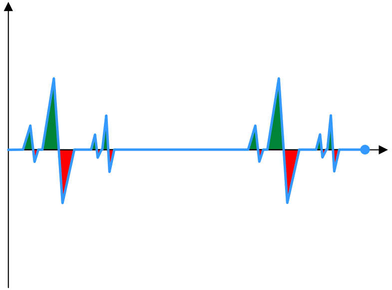
Building electroprosumer resilience in OK1 – case study

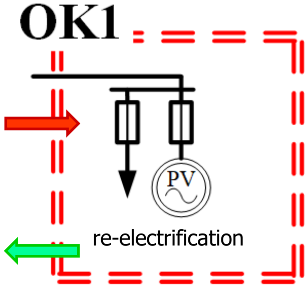
Energy transition

passivation

Imbalance profile

- how the NPS sees the "electroprosumer"





re-electrification

electrification of heating (HP)

electrification of transportation (EV)

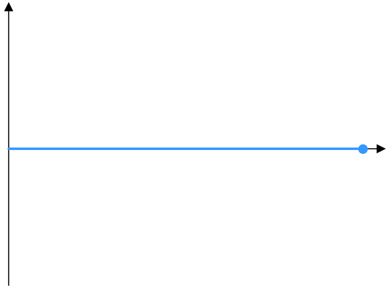
Building electroprosumer resilience in OK1 – case study

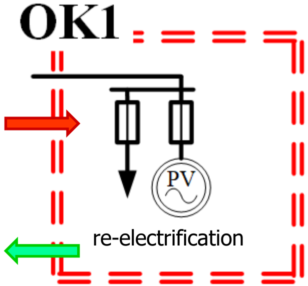
Electroprosumerism

passivation

Imbalance profile

- how the NPS sees the electroprosumer





electrification of heating (HP)

electricity use (flexibility) and electrotechnologies

electrification of transportation (EV)

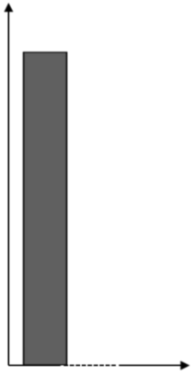
Ensuring rational (economic) electroprosumerism resilience

Changing thinking

- **I: <20%** (**level of electroprosumerism safety) -** critical state powered only critical consumers ensuring the safety of people and technical safety of buildings and technological installations
- **II**: **20%-100% (level of economic risk management) -** a state of deficit, requiring due to the strategy of energy management. The higher the energy deficit, the greater the measures taken to reduce it must be
- **III**: ≥**100% (environmental security level) -** a state of comfort, ensured full coverage of energy needs. No restrictions.

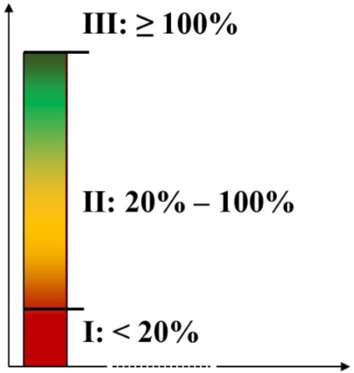
now

– without classification of load

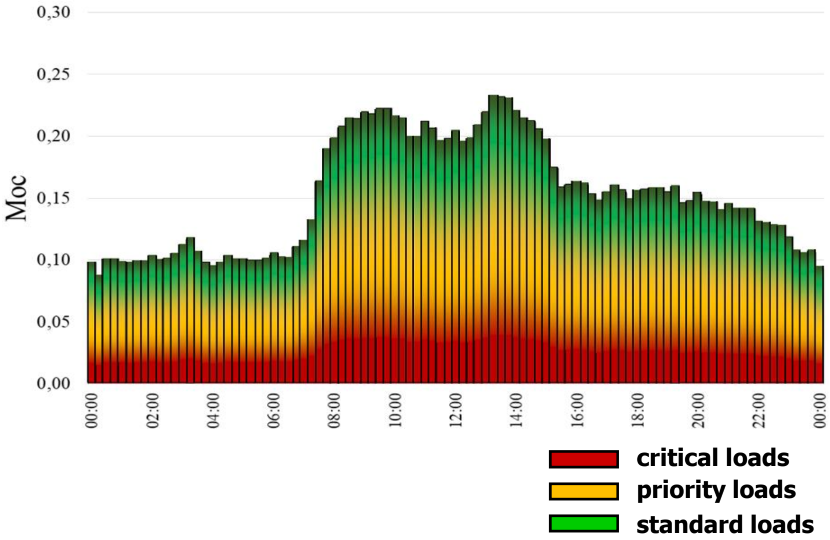


in electroprosumerism

- divided into critical,
priority and standard receipts



Relative profile by supply levels in industrial plant



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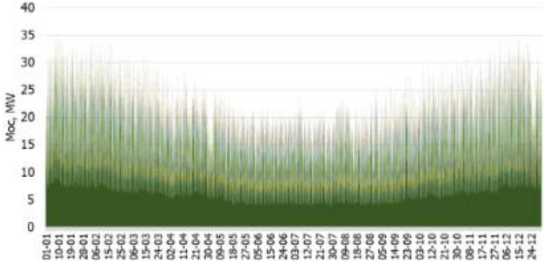
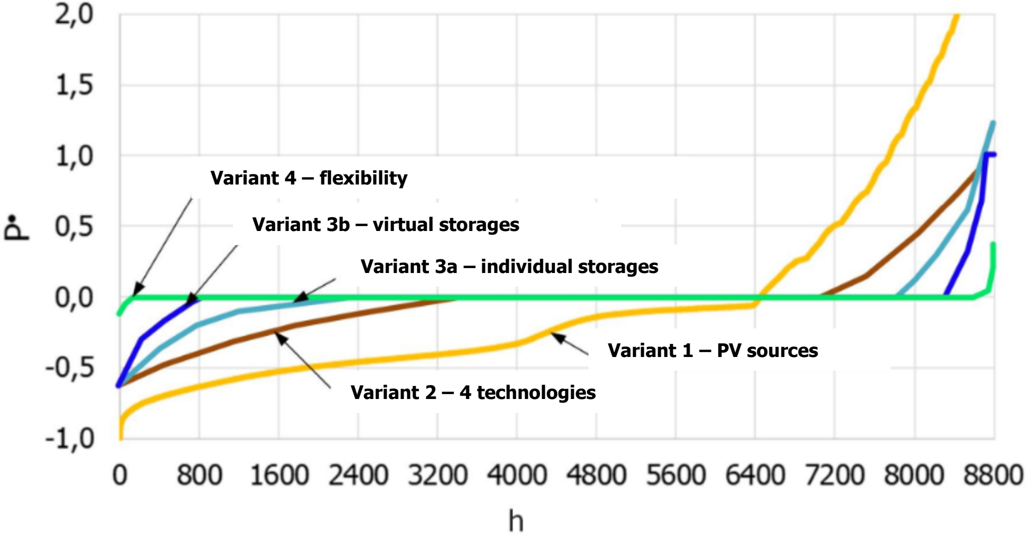
Building electroprosumer resilience

OK3 – energy cluster (MV – grid)

$$E^{\bullet} = \frac{E}{\max(E)|_{\sum E_P = 0}}; \; P^{\bullet} = \frac{P}{\max(P)|_{\sum E_P = 0}}$$



Relative ordered imbalance profiles - four variants



Variant 1 - use only PV sources.

Variant 2 - generation structure specific to rural-urban areas, including RES technologies such as PV sources, wind power plants (individual) and micro biogas and biogas plants.

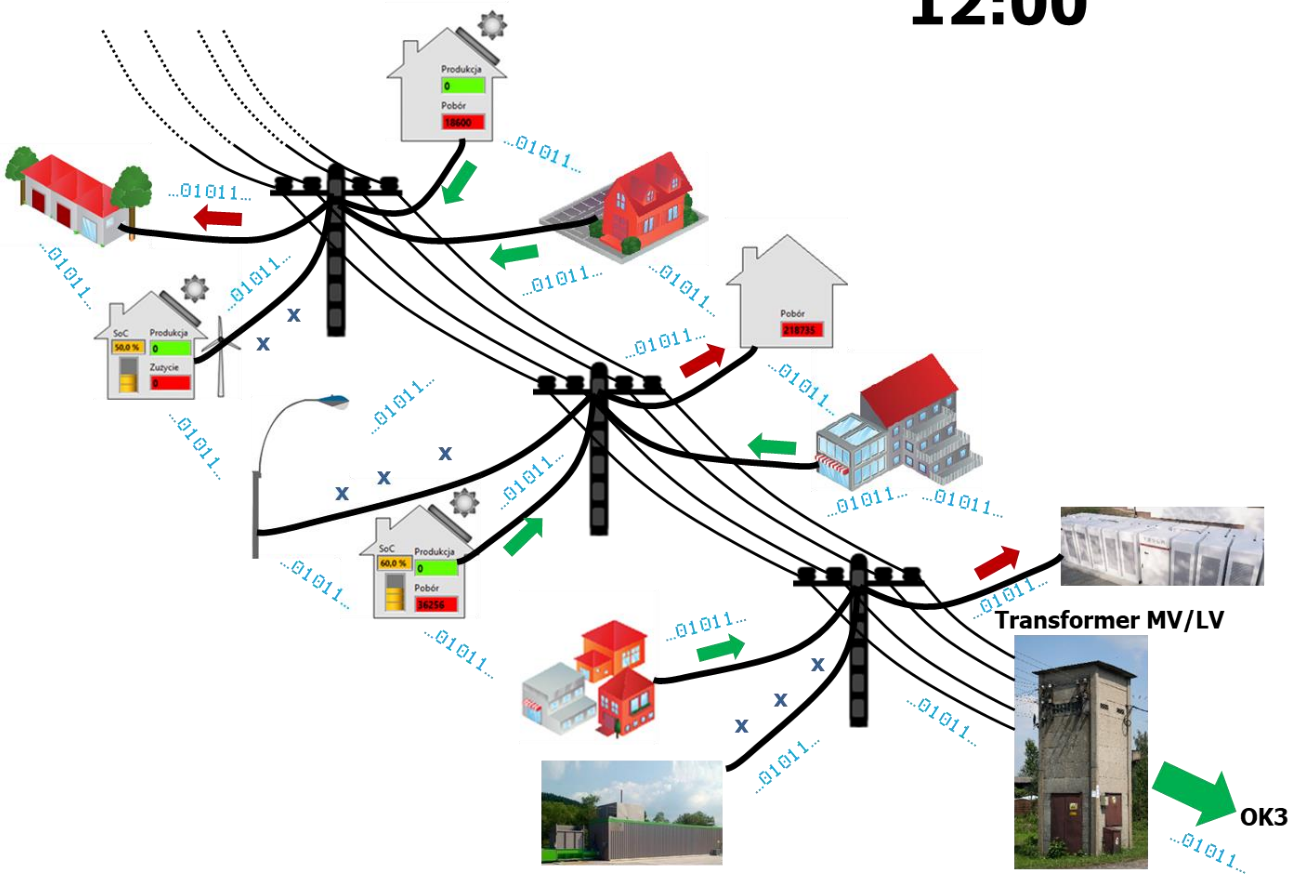
Variant 3a - use of energy storage (acumulator) - individual operation.

Variant 3b - use of energy storage (acumulator) - virtual storage

Variant 4 – flexibility (response to price signal)

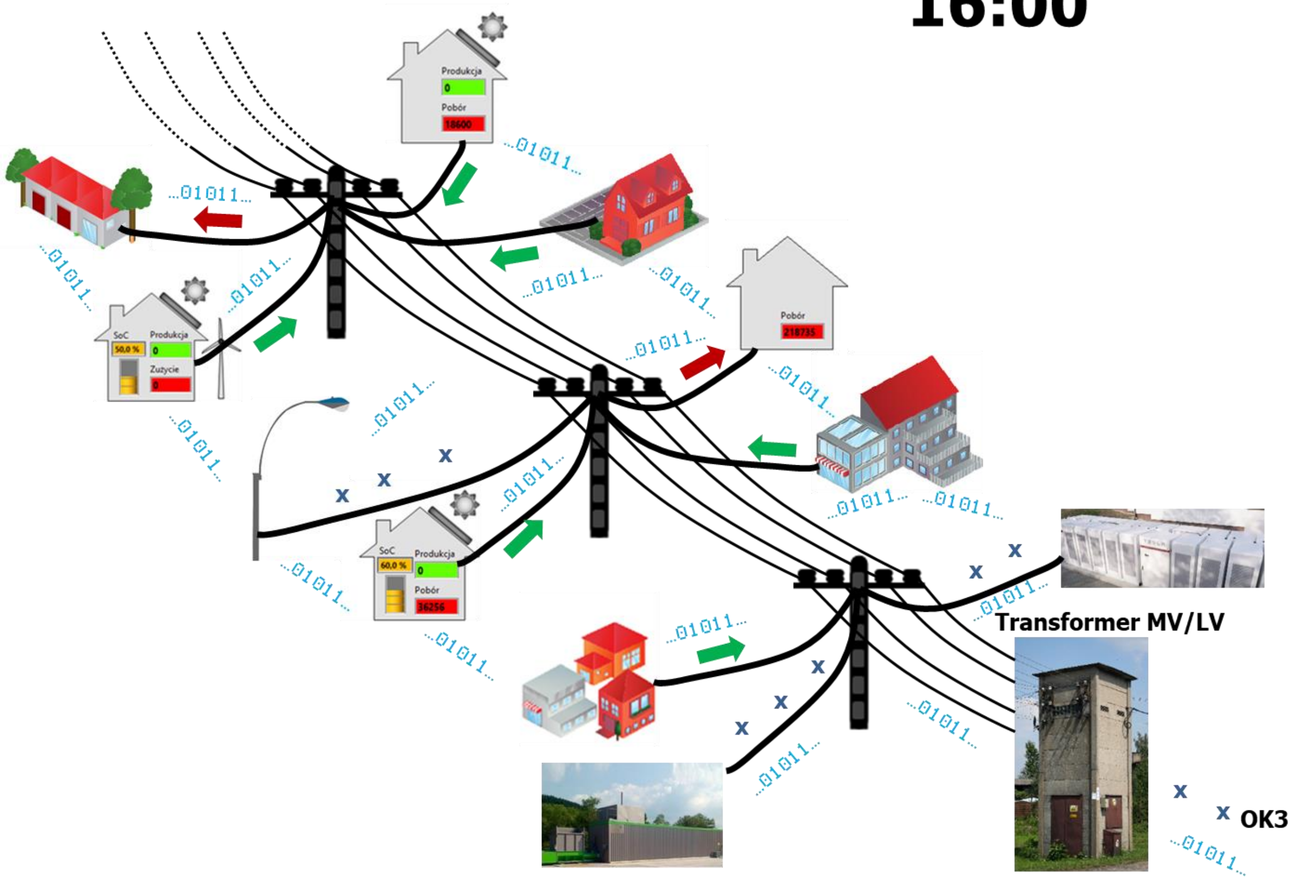
Electroprosumers (OK1) in OK2 – LV grid

12:00



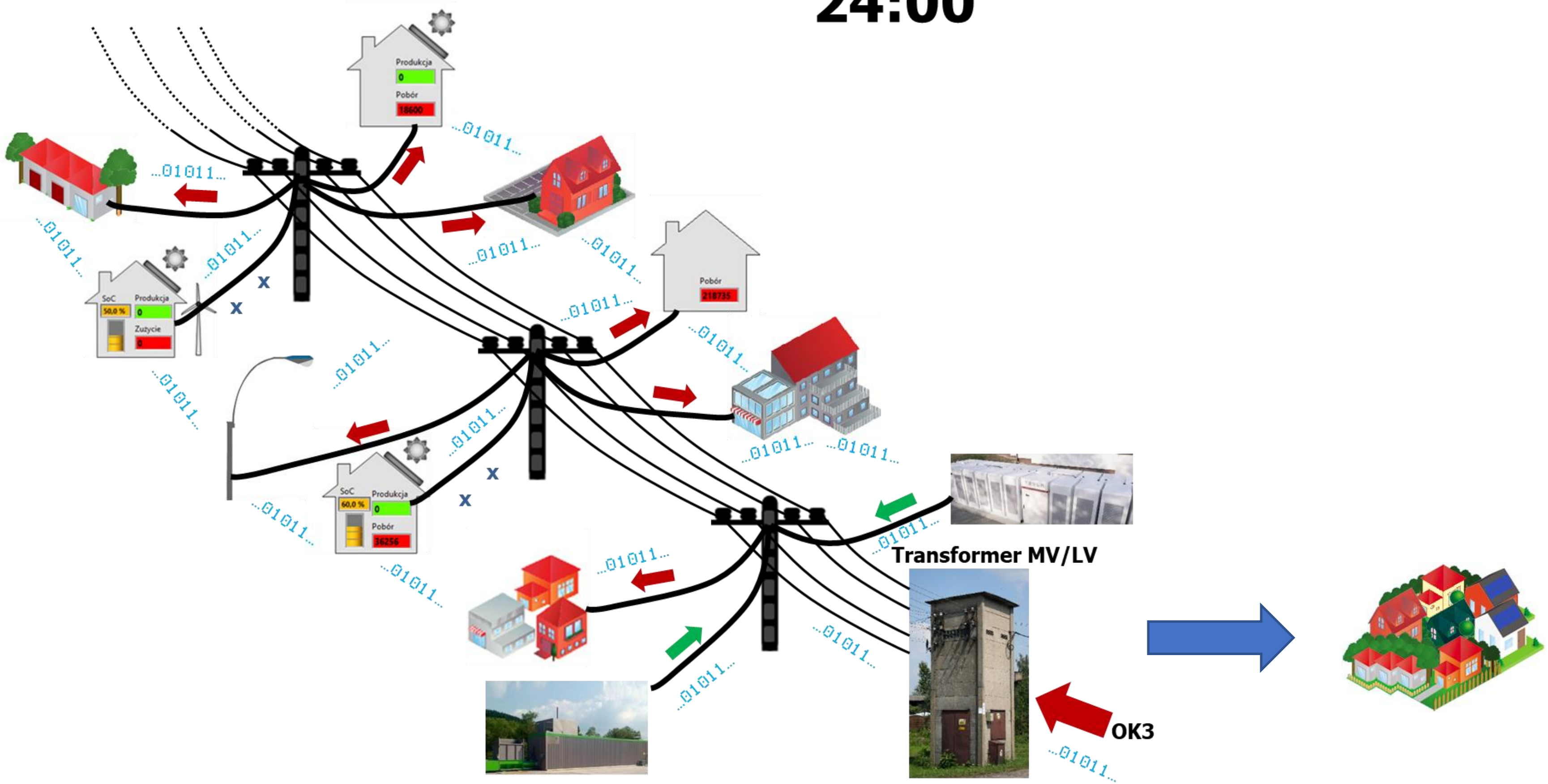
Electroprosumers (OK1) in OK2 – LV grid

16:00

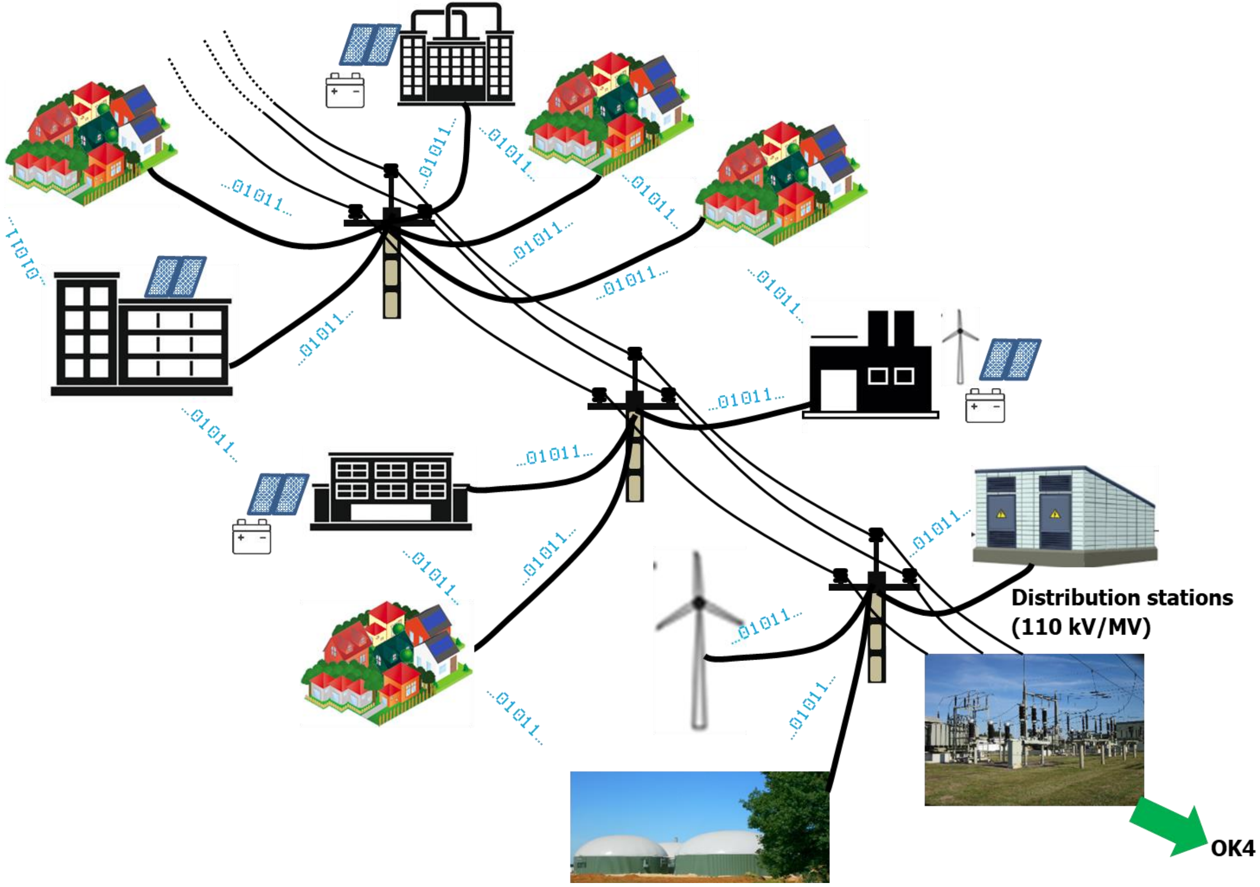


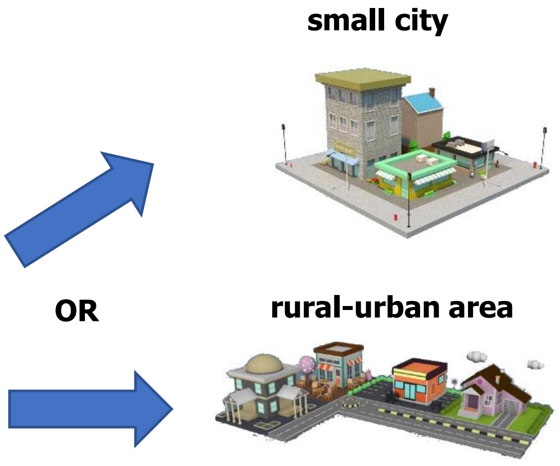
Electroprosumers (OK1) in OK2 – LV grid

24:00

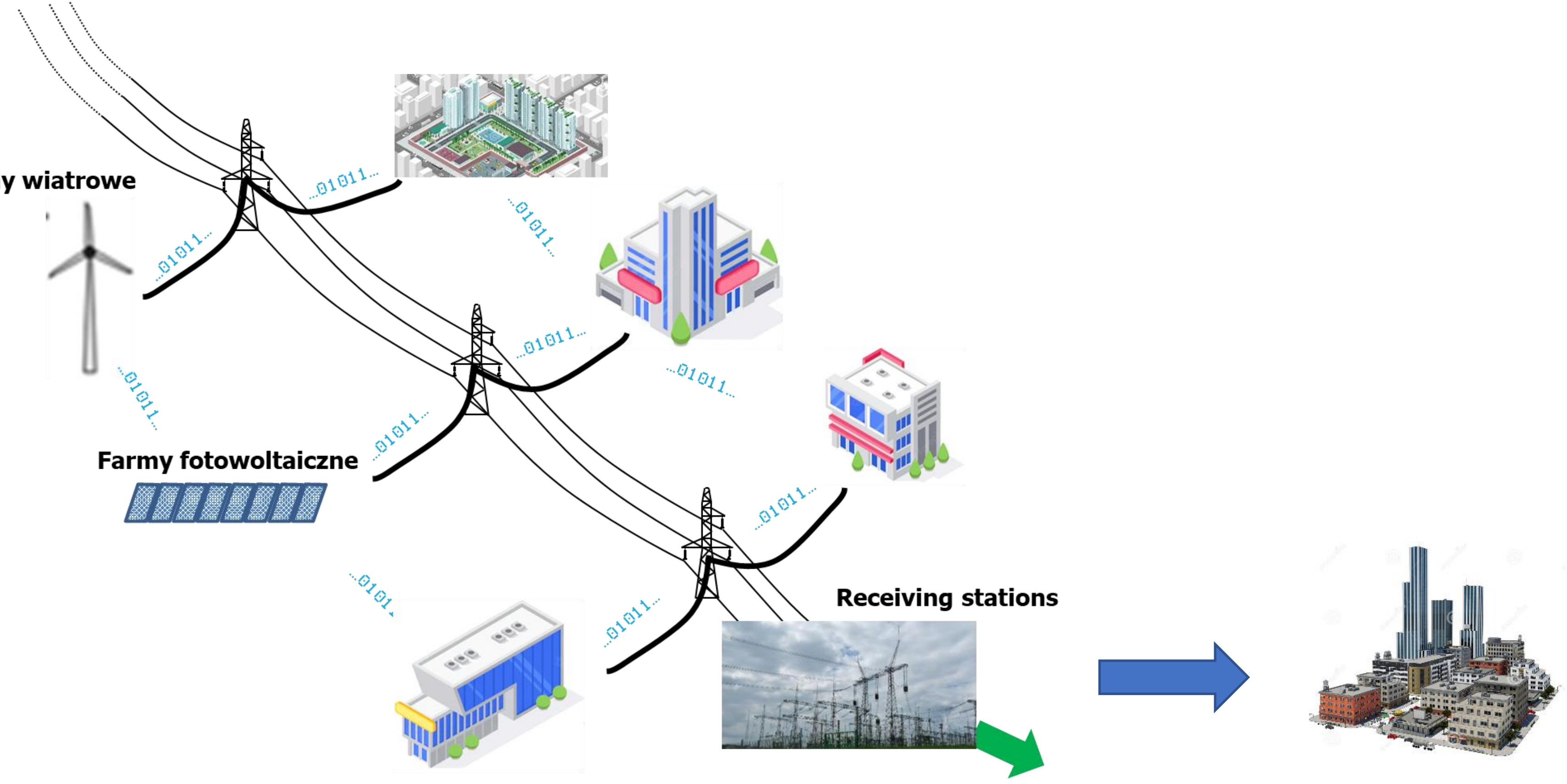


Electroprosumers (OK2) in OK3 – MV grid





Electroprosumers (OK3) in OK4 – 110 kV grid



Farmy wiatrowe

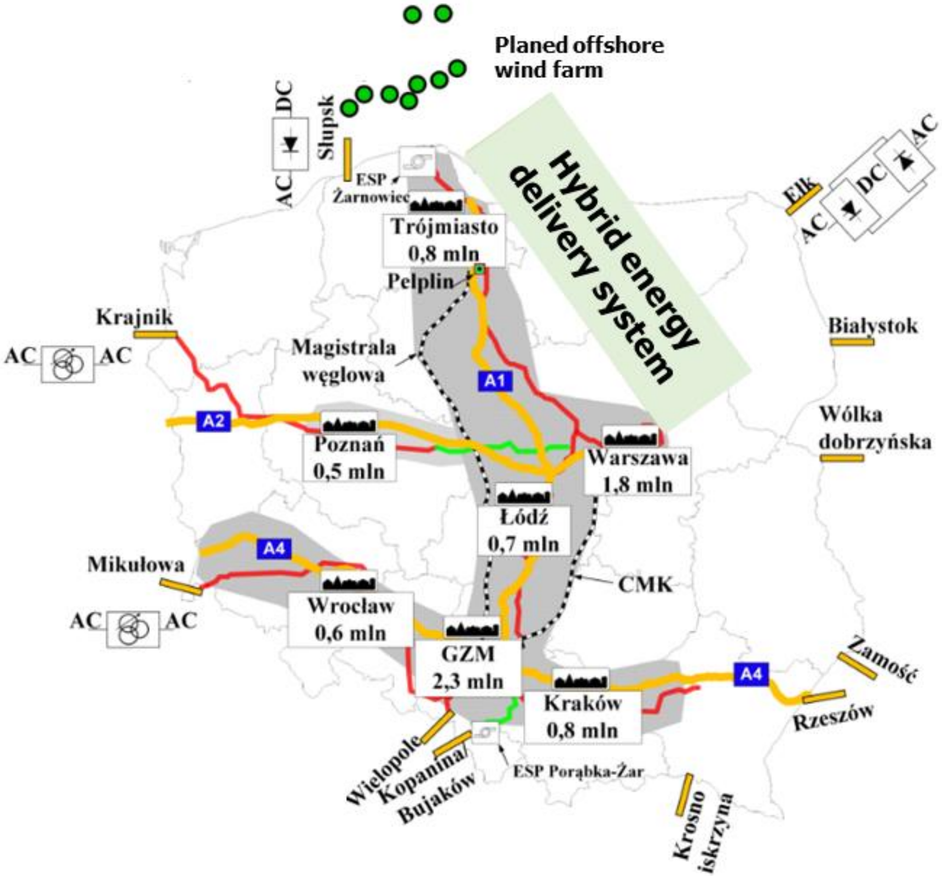
Farmy fotowoltaiczne

Receiving stations

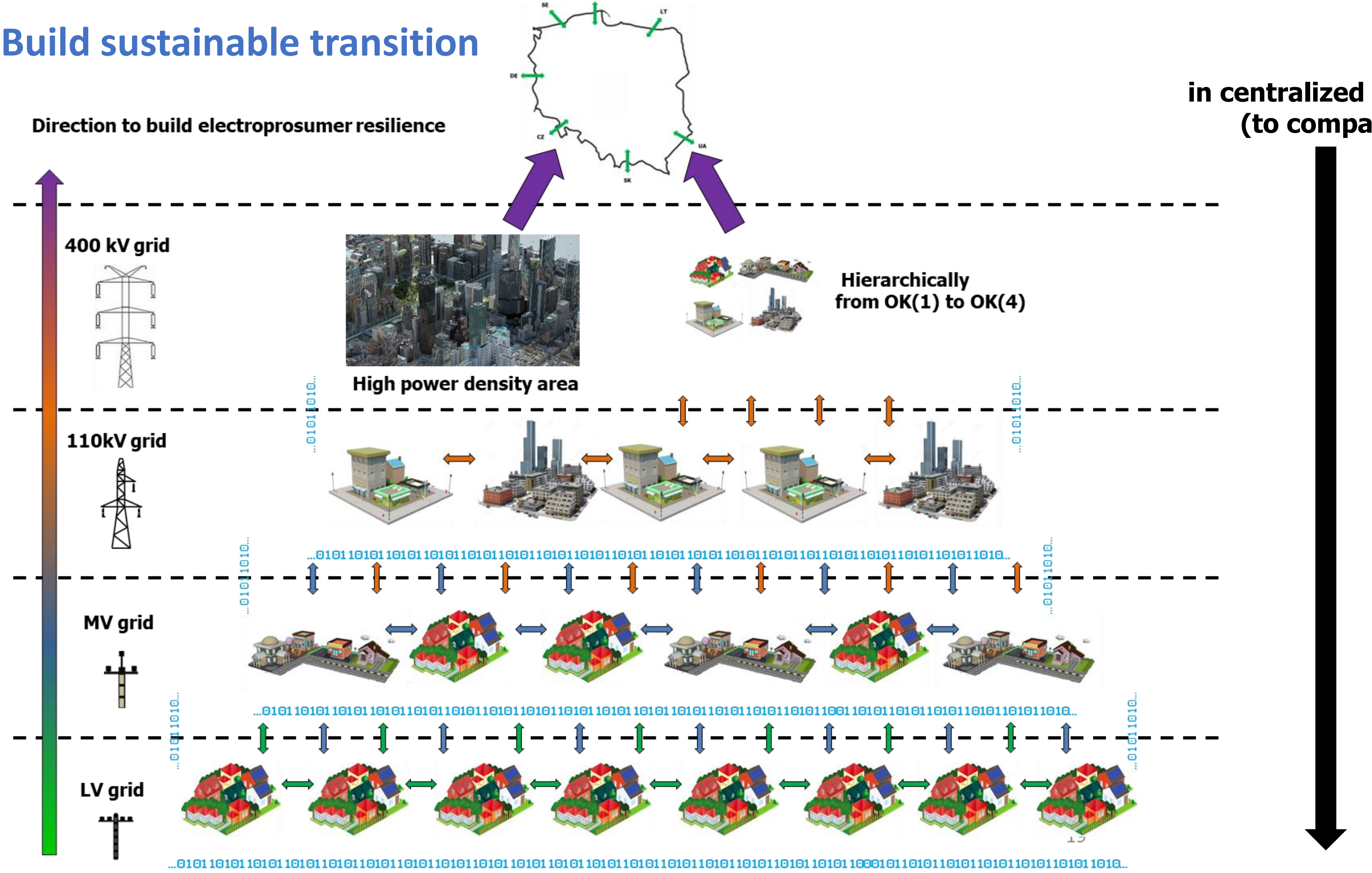
Transmission lines

Build sustainable transition

High power density area



Build sustainable transition



Direction to build electroprosumer resilience

in centralized system (to compare)

400 kV grid

High power density area

Hierarchically from OK(1) to OK(4)

110kV grid

MV grid

LV grid

Outline

- Introducing (electric power industry)
- Electroprosumerism
- RES source
- Energy management system
- **Role of power converters**
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- Conclusion

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Role of power converters in management energy systems

Converters can offer services in energy management systems. These services can be synthesized into the following functions:

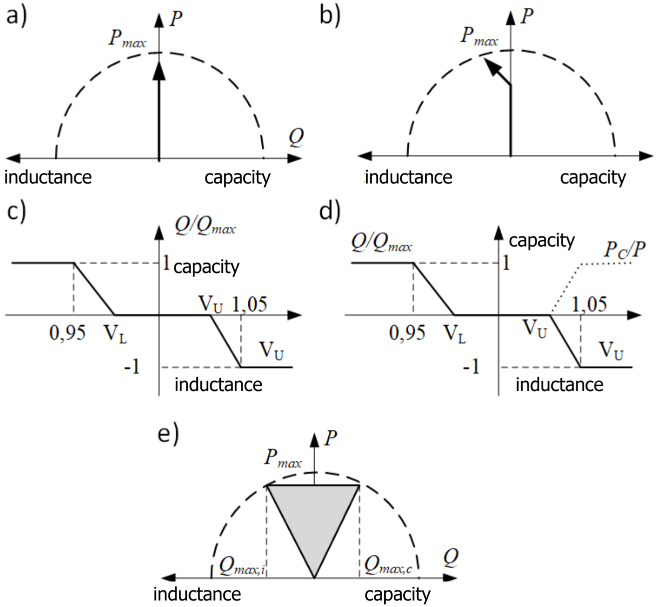
- **flow control,**
- **reactive power compensation,**
- **filtration of higher harmonics,**
- **voltage control,**
- **frequency control,**
- **interconnection (coupling) of networks,**
- **… .**

Often one device can provide multiple services

Flow control

- DC conversion
- direct

Operation diagrams of reactive power compensation in converters



Reactive power compensation

methods require active power generation to provide compensation

Reactive Power Control at Night

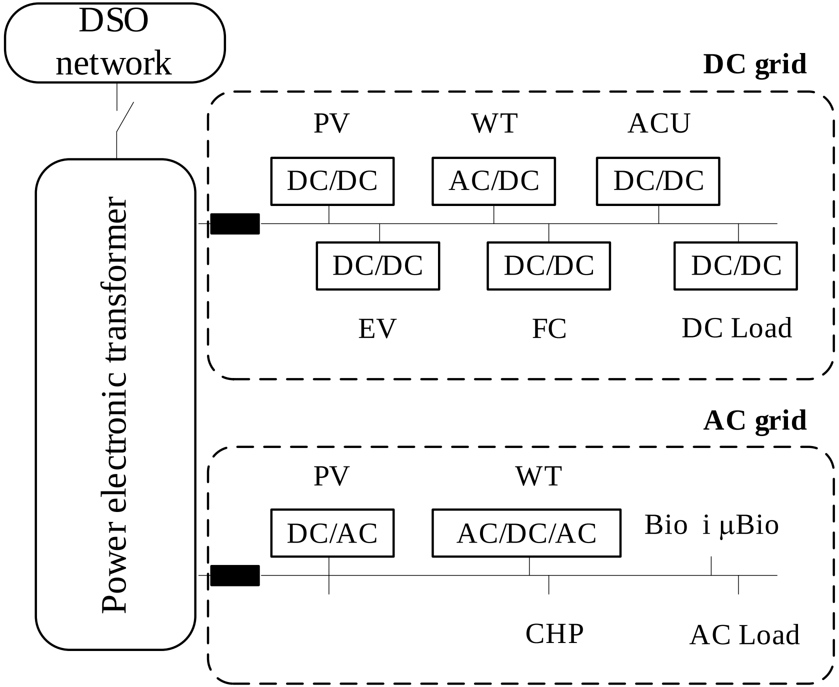
Role of power converters in management energy systems

Filtration of higher harmonics

Voltage control

Frequency control

Interconnection (coupling) of networks



Outline

- Introducing (electric power industry)
- Electroprosumerism
- RES source
- Energy management system
- Role of power converters
- **Building electroprosumer resilience – Warsaw case study**
- Conclusion

Building electroprosumer resilience – Warsaw case study

Structure of coverage of energy demand in electroprosumerism - horizon 2050

Technology	Model 1	Model 2	Model 3
RES Source			
PV, TWh	1,1	2,1	2,7
µWT, TWh	0,2	0,2	0,2
Onshore, TWh	0,0	1,9	2,1
Biogas, TWh	0,2	0,5	0,5
CE, TWh	0,0	0,5	0,5
Offshore, TWh	7,7	4,0	4,2
Fossil fuel			
CHP, TWh	1,0	1,0	0,3
UPS (diesel), TWh	0,4	0,3	0,0
Annual electricity balance			
Balance, TWh	10,6	10,6	10,6
Excess, %	1,0	1,0	1,0
Deficit, %	-1,0	-1,0	-1,0

Model 1

- Careful estimates of Warsaw's available local resources

Model 2

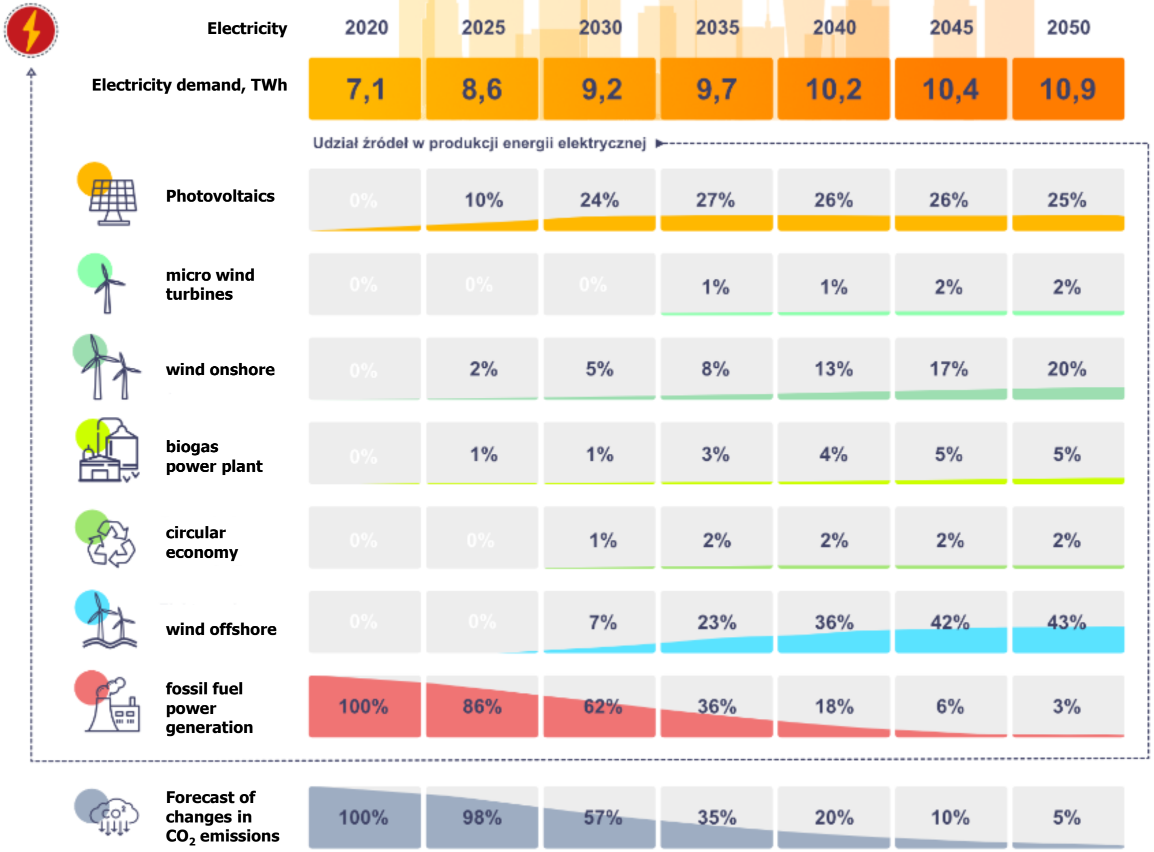
- Maximizing the use of local resources
- Energy from wind power plants located in areas surrounding Warsaw

Model 3

- Flexibility
- The key role of management

Building electroprosumer resilience – Warsaw case study

Energy model for the Warsaw in the 2050 perspective, taking into account conditions of electroprosumerism



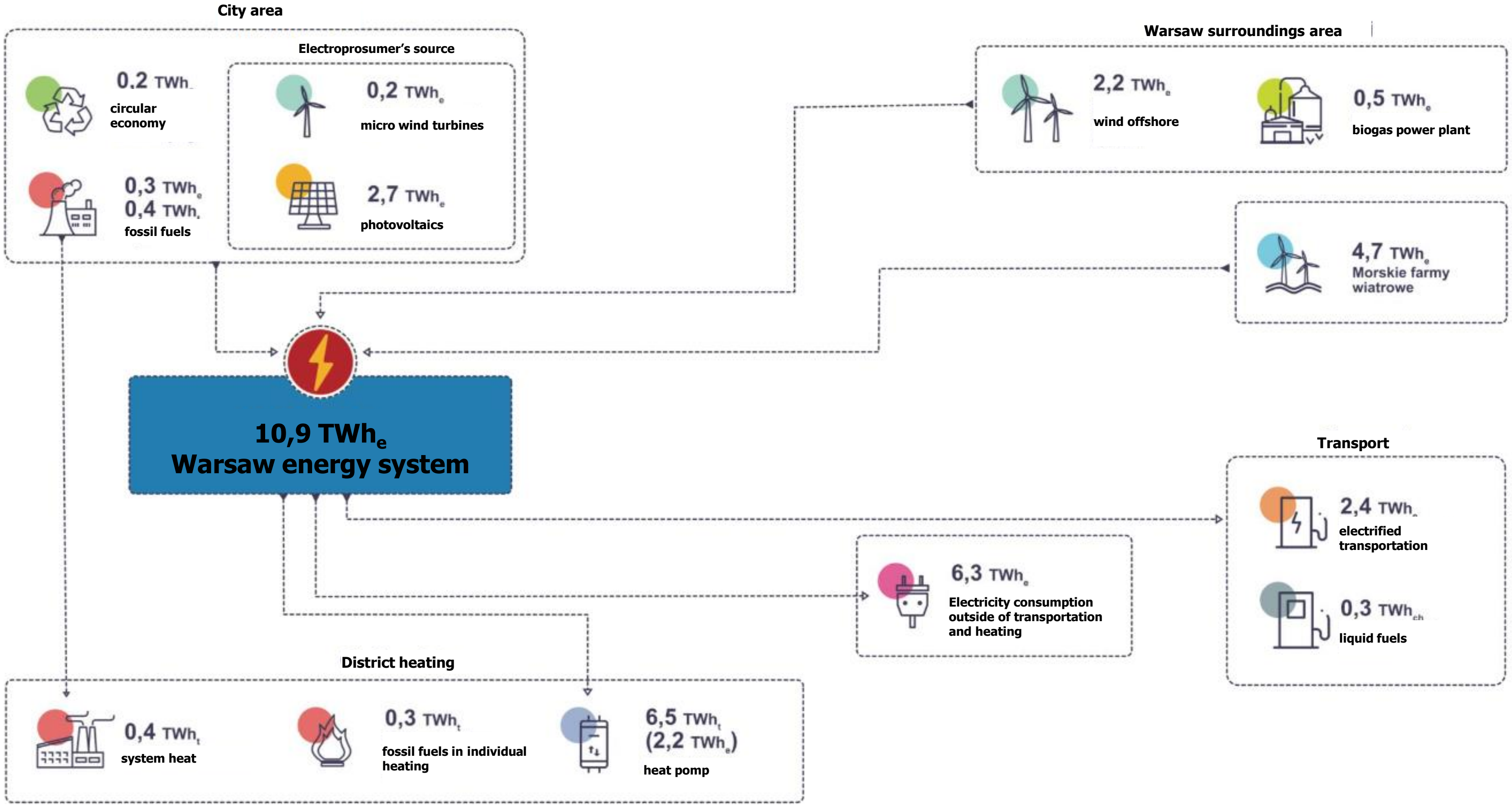
Electricity	2020	2025	2030	2035	2040	2045	2050
Electricity demand, TWh	7,1	8,6	9,2	9,7	10,2	10,4	10,9

Udział źródeł w produkcji energii elektrycznej

	2020	2025	2030	2035	2040	2045	2050
Photovoltaics	0%	10%	24%	27%	26%	26%	25%
micro wind turbines	0%	0%	0%	1%	1%	2%	2%
wind onshore	0%	2%	5%	8%	13%	17%	20%
biogas power plant	0%	1%	1%	3%	4%	5%	5%
circular economy	0%	0%	1%	2%	2%	2%	2%
wind offshore	0%	0%	7%	23%	36%	42%	43%
fossil fuel power generation	100%	86%	62%	36%	18%	6%	3%

	2020	2025	2030	2035	2040	2045	2050
Forecast of changes in CO_2 emissions	100%	98%	57%	35%	20%	10%	5%

Building electroprosumer resilience – Warsaw case study



City area

$0.2\ TWh$ circular economy

$0,3\ TWh_e$ $0,4\ TWh_t$ fossil fuels

Electroprosumer’s source

$0,2\ TWh_e$ micro wind turbines

$2,7\ TWh_e$ photovoltaics

Warsaw surroundings area

$2,2\ TWh_e$ wind offshore

$0,5\ TWh_e$ biogas power plant

$4,7\ TWh_e$ Morskie farmy wiatrowe

$10,9\ TWh_e$
Warsaw energy system

Transport

$2,4\ TWh_e$ electrified transportation

$0,3\ TWh_{ch}$ liquid fuels

$6,3\ TWh_e$ Electricity consumption outside of transportation and heating

District heating

$0,4\ TWh_t$ system heat

$0,3\ TWh_t$ fossil fuels in individual heating

$6,5\ TWh_t$ $(2,2\ TWh_e)$ heat pomp

Conclusion

In summary, a simple plan for sustainable energy transition:

clean up electricity (in global terms, TEC),
electrify everything,
manage available resources.