UNIVERSITY OF WESTERN MACEDONIA

COLUMBIA CLIMATE SCHOOL
Climate, Earth, and Society

# Energy System Integration for Resilience

Decision-Supporting Technologies for Flexible and Reliable Energy Systems

# Who We Are

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# Why Resilience in Energy System Integration (ESI) Matters

Renewable energy creates system challenges.

Climate change contributes to vulnerable energy systems.

Quantitative assessments to maximize energy security and sustainability are needed.

Rising energy system complexity requires better coordination.

# Case Study: Kozani as an Example

Prior dependence on lignite for electricity production

Major transformation:

- Closure of coal plants and mines
- Investment and growth of renewable energy projects
- Economic restructuring
- Workforce transition

Renewable energy integration, grid modernization
→ resilient energy planning

- Reducing wasted renewable generation
- Stabilizing energy supply
- Potentially enabling electricity exports to neighboring countries



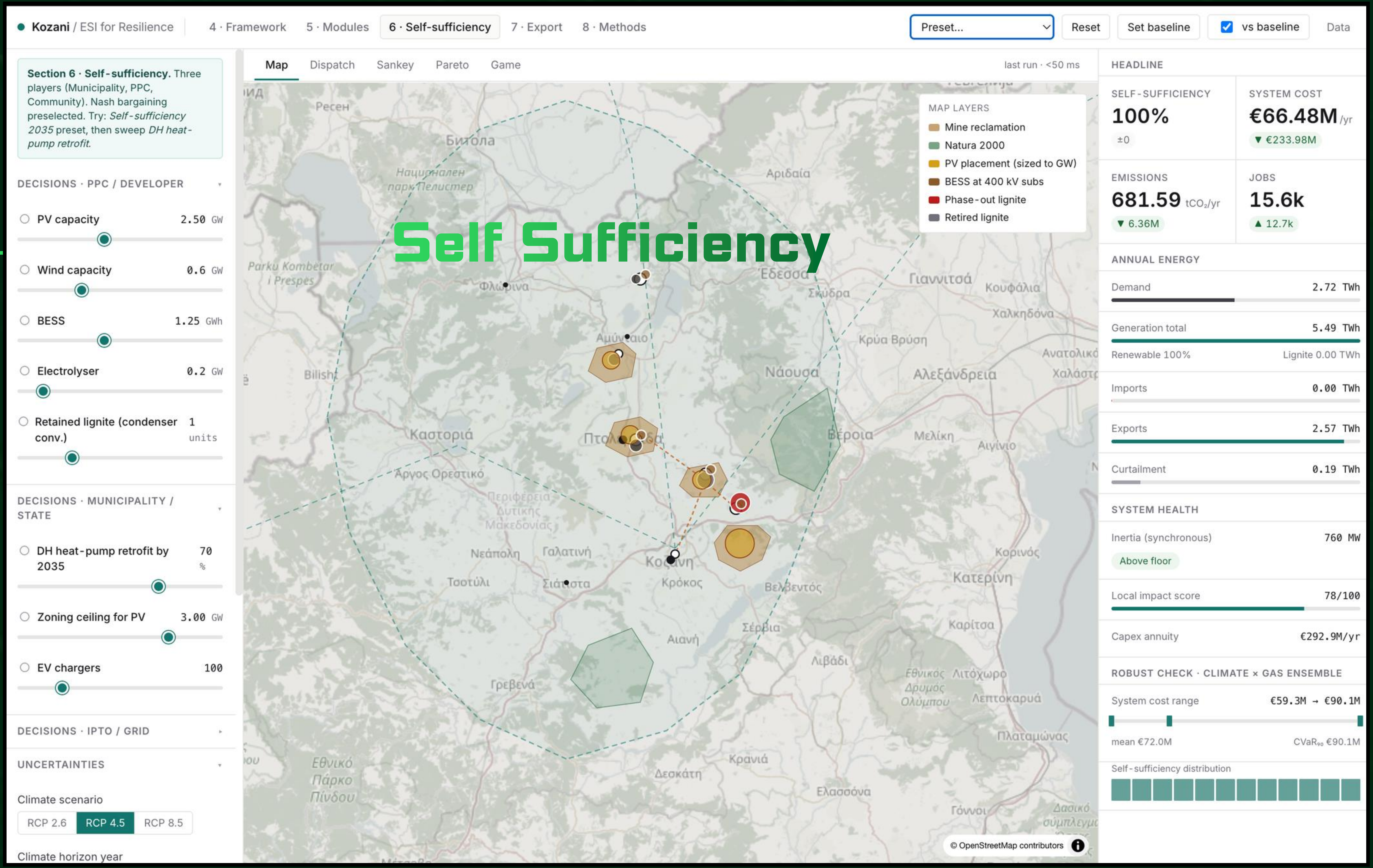
Farmaki, P., Tranoulidis, A., Kouletsos, T., Giourka, P., & Kataracha, A. (2021). Mining transition and hydropower energy in Greece—sustainable governance of water resources management in a post-lignite era: the case of western Macedonia, Greece. Water, 13(14), 1878.

# Introduction of the Decision Support Tool: GridWise

- Forecasting digitilization tool informs scenarios to produce excess electricity for export or meet local demand.
- The framework represents a multi-stakeholder, deeply-uncertain planning problem tunable in real time.
- Every slider feeds a simulation that re-runs in the browser.

- **Resources** – Solar/Wind/Lignite
- **Demand** – Electricity + Heat
- **Dispatch** - Balance against import/export/curtailment
- **Economics** – Jobs, Capex, Opex, Trade

# Scenario 01


Kozani / ESI for Resilience
4 · Framework
5 · Modules
6 · Self-sufficiency
7 · Export
8 · Methods
Preset...
Reset
Set baseline
vs baseline
Data
Section 6 · Self-sufficiency. Three players (Municipality, PPC, Community). Nash bargaining preselected. Try: Self-sufficiency 2035 preset, then sweep DH heat-pump retrofit.
DECISIONS · PPC / DEVELOPER
PV capacity 2.50 GW
Wind capacity 0.6 GW
BESS 1.25 GWh
Electrolyser 0.2 GW
Retained lignite (condenser conv.) 1 units
DECISIONS · MUNICIPALITY / STATE
DH heat-pump retrofit by 2035 70 %
Zoning ceiling for PV 3.00 GW
EV chargers 100
DECISIONS · IPTO / GRID
UNCERTAINTIES
Climate scenario
RCP 2.6
RCP 4.5
RCP 8.5
Climate horizon year
Map
Dispatch
Sankey
Pareto
Game
last run · <50 ms
Self Sufficiency
MAP LAYERS
Mine reclamation
Natura 2000
PV placement (sized to GW)
BESS at 400 kV subs
Phase-out lignite
Retired lignite
Битола
Καστοριά
Νάουσα
Αλεξάνδρεια
Βέροια
Έδεσσα
Γιαννιτσά
Κατερίνη
Γρεβενά
Κρόκος
Σέρβια
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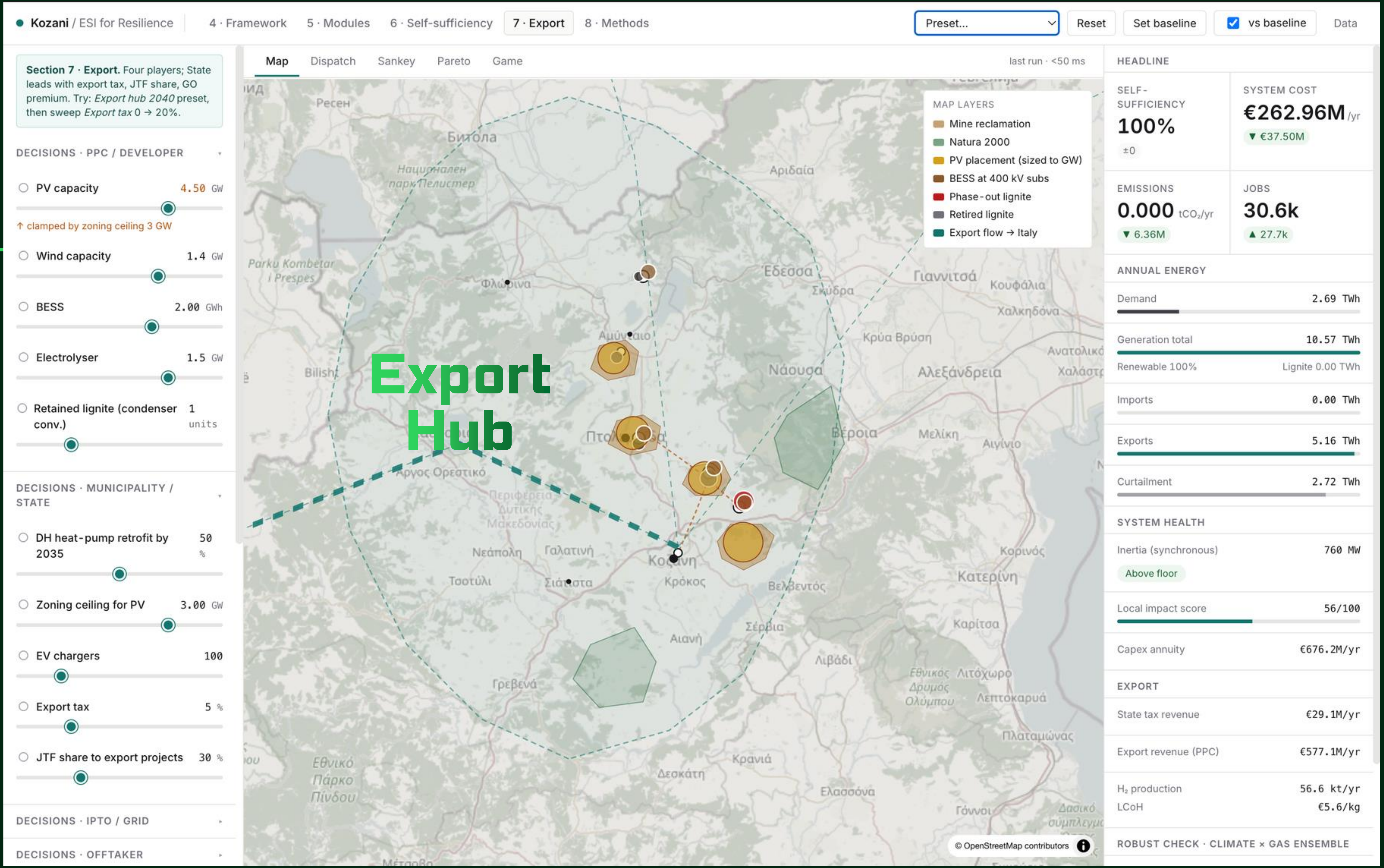
HEADLINE
SELF-SUFFICIENCY 100% ±0
SYSTEM COST €66.48M /yr ▼ €233.98M
EMISSIONS 681.59 tCO₂/yr ▼ 6.36M
JOBS 15.6k ▲ 12.7k
ANNUAL ENERGY
Demand 2.72 TWh
Generation total 5.49 TWh
Renewable 100% Lignite 0.00 TWh
Imports 0.00 TWh
Exports 2.57 TWh
Curtailment 0.19 TWh
SYSTEM HEALTH
Inertia (synchronous) 760 MW
Above floor
Local impact score 78/100
Capex annuity €292.9M/yr
ROBUST CHECK · CLIMATE × GAS ENSEMBLE
System cost range €59.3M → €90.1M
mean €72.0M CVaR₉₀ €90.1M
Self-sufficiency distribution

# Scenario 02



Kozani / ESI for Resilience
4 · Framework
5 · Modules
6 · Self-sufficiency
7 · Export
8 · Methods
Preset...
Reset
Set baseline
vs baseline
Data
Section 7 · Export. Four players; State leads with export tax, JTF share, GO premium. Try: Export hub 2040 preset, then sweep Export tax 0 → 20%.
DECISIONS · PPC / DEVELOPER
PV capacity 4.50 GW
↑ clamped by zoning ceiling 3 GW
Wind capacity 1.4 GW
BESS 2.00 GWh
Electrolyser 1.5 GW
Retained lignite (condenser conv.) 1 units
DECISIONS · MUNICIPALITY / STATE
DH heat-pump retrofit by 2035 50 %
Zoning ceiling for PV 3.00 GW
EV chargers 100
Export tax 5 %
JTF share to export projects 30 %
DECISIONS · IPTO / GRID
DECISIONS · OFFTAKER
Map
Dispatch
Sankey
Pareto
Game
last run · <50 ms
MAP LAYERS
Mine reclamation
Natura 2000
PV placement (sized to GW)
BESS at 400 kV subs
Phase-out lignite
Retired lignite
Export flow → Italy
Export Hub
© OpenStreetMap contributors
HEADLINE
SELF-SUFFICIENCY
100%
±0
SYSTEM COST
€262.96M /yr
▼ €37.50M
EMISSIONS
0.000 tCO₂/yr
▼ 6.36M
JOBS
30.6k
▲ 27.7k
ANNUAL ENERGY
Demand 2.69 TWh
Generation total 10.57 TWh
Renewable 100% Lignite 0.00 TWh
Imports 0.00 TWh
Exports 5.16 TWh
Curtailment 2.72 TWh
SYSTEM HEALTH
Inertia (synchronous) 760 MW
Above floor
Local impact score 56/100
Capex annuity €676.2M/yr
EXPORT
State tax revenue €29.1M/yr
Export revenue (PPC) €577.1M/yr
H₂ production 56.6 kt/yr
LCoH €5.6/kg
ROBUST CHECK · CLIMATE × GAS ENSEMBLE

# Comparison of Scenarios

| | Status quo | Self-suf. 2035 | Export hub 2040 | Robust baseline |
|---|---|---|---|---|
| **System cost** | €228.79M/yr | **€40.82M/yr** | €213.98M/yr | €107.14M/yr |
| **Worst-case CVaR** | **€1.1B** | €66.4M | €227.7M | €207.6M |
| **Emissions** | 6.36M $tCO_2$ | 682k $tCO_2$ | **0** | 531k $tCO_2$ |
| **Jobs** | 2.9k | 15.6k | **30.6k** | 12.8k |
| **Local impact** | 44/100 | **78/100** | 61/100 | 70/100 |
| **Curtailment** | 0.00 TWh | 0.19 TWh | 2.72 TWh | **0.03 TWh** |
| **Key risks** | **Carbon/gas exposure** | **High capex** | **Zoning ceiling, curtailment** | **Moderate emissions remain** |

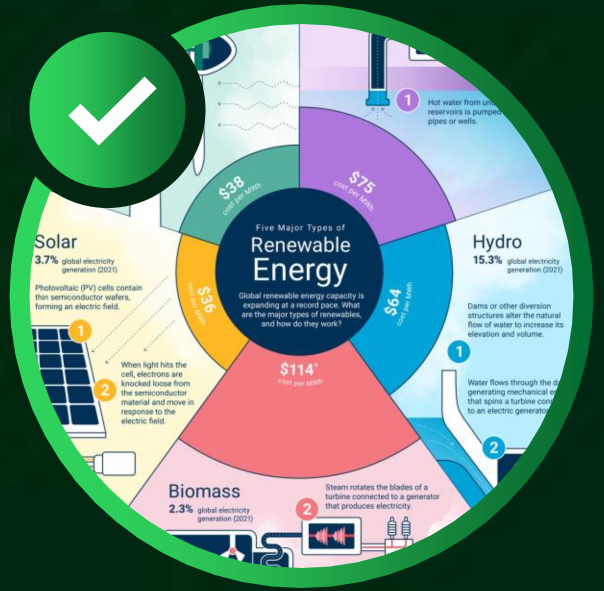
# Opportunities and Challenges

- Improved energy efficiency and security
- Regional economic diversification and workforce transition
- Technological innovation

- Variability and uncertainty of renewable energy
- Increased energy consumption
- Unequal access to technology and data complexicity

# Conclusion

Achieving a resilient energy future requires not only expanding renewable energy, but also developing **intelligent, flexible, and adaptive systems** capable of managing increasingly complex energy networks under climate, economic, and geopolitical uncertainty.




### Case Study in Kozani

- Flexibility
- Reliability
- Just transition

### Energy-system Resilience is Critical

- Resource variability and operational complexity
- Infrastructure vulnerability

### ESI Improves Resilience

- Coordination
- Monitoring
- Balancing

### Decision-supporting Technologies(GridWise)

- Resource
- Demand
- Dispatch
- Economics

# Thank You

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