Applications of a Reference System Architecture for the Energy Water Nexus

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LIINES LABORATORY FOR INTELLIGENT INTEGRATED NETWORKS OF ENGINEERING SYSTEMS EMPOWERING YOUR NETWORK

http://engineering.dartmouth.edu/liines

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Presentation Abstract

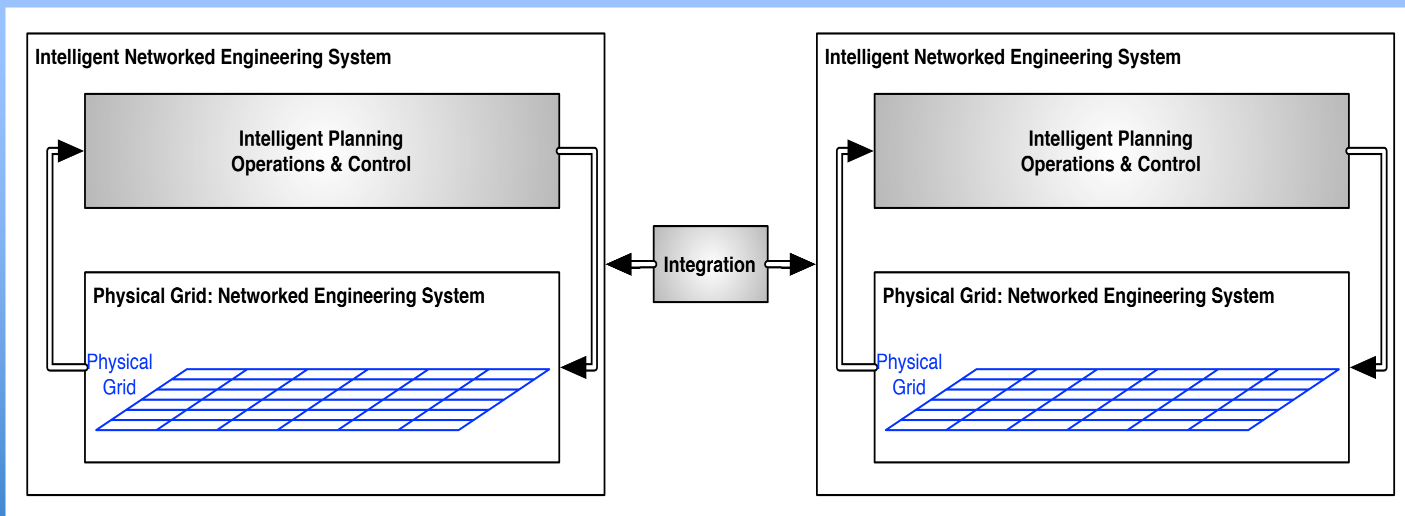
Electric power is required to produce, treat, distribute, and recycle water while water is required to generate and consume electricity. Naturally, this energy-water nexus is most evident in multi-utilities that provide electricity and water but still exists when the nexus has distinct organizations as owners and operators. Therefore, the sustainability question that arises from energy-water trade-offs and synergies is very much tied to the potential for economies of scope. Furthermore, in the hot and arid regions, multi-utilities are not only common, but also the nexus is particularly exacerbated by the high energy intensity of the water supply due to limited fresh water resources.

This presentation presents a reference system architecture for this purpose developed and presented with the Systems Modeling Language (SysML). Once instantiated, this architecture identifies and motivates several opportunities for integrated operations management and planning of the the energy-water nexus (EWN). First, an exposition of the EWN is given. This discussion focuses on the electric power, potable water, and wastewater distributions systems. Second, the paper shifts to opportunities in integrated operations management highlighted by an energy-water nexus supply-side economic dispatch illustration. Thirdly, the discussion shifts to planning opportunities for the energy-water nexus for the sustainable development of water and energy resources. A concluding section summarizes the policy implications of the identified opportunities.

LIINES Research: the Case for Engineering Systems

"Energy is physical, energy is economic, energy is political"

Political Context



Prof. Amro M. Farid

Smart Power Grids

Energy-Water Nexus

Electrified Transportation Systems

Industrial Energy Management

Integrated Smart City Infrastructures

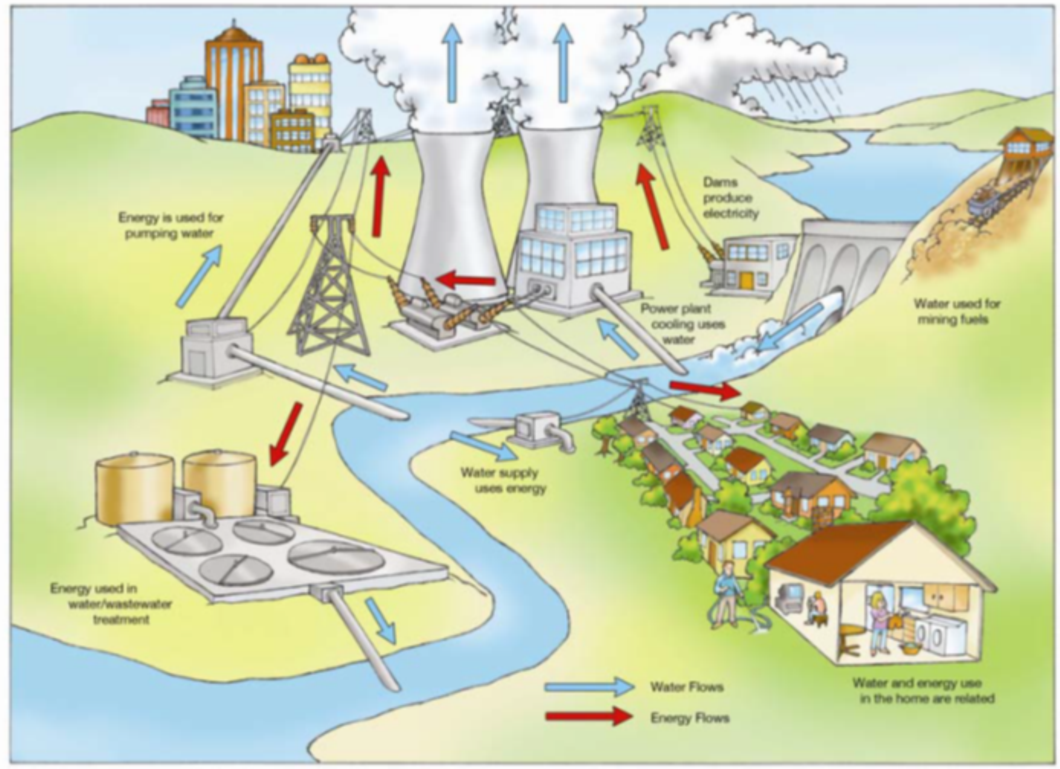
Presentation Outline

- An Energy-Water Nexus Introduction
- A Holistic View of the Energy-Water Infrastructure
- Optimized Operations in Integrated Energy-Water Utilities
- Opportunities for Integrated Planning & Operations
- Extensions to Agricultural, Industrial, Commercial & Residential End Uses

- **References can be found at (18 Publications)**:
- LIINES Energy-Water Nexus Webpage:
- http://engineering.dartmouth.edu/liines/research/EWN/index.php

Energy-Water Nexus: Overview

- Clean energy and water are two essential resources that any society must securely deliver in order to develop sustainably i.e. meets its economic, social, and environmental goals
- Water is required in energy generation & consumption
- Energy is required to produce, treat, distribute and recycle water

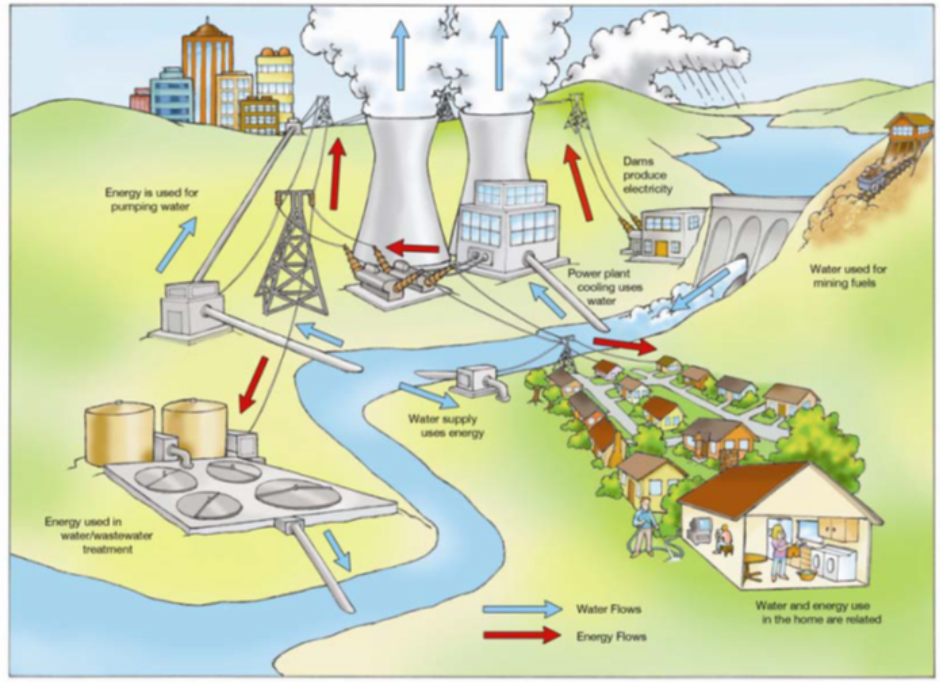


∴Individual coupling points are often studied

∴We seek an integrated energy-water approach to engineering design, operations management, and infrastructure planning

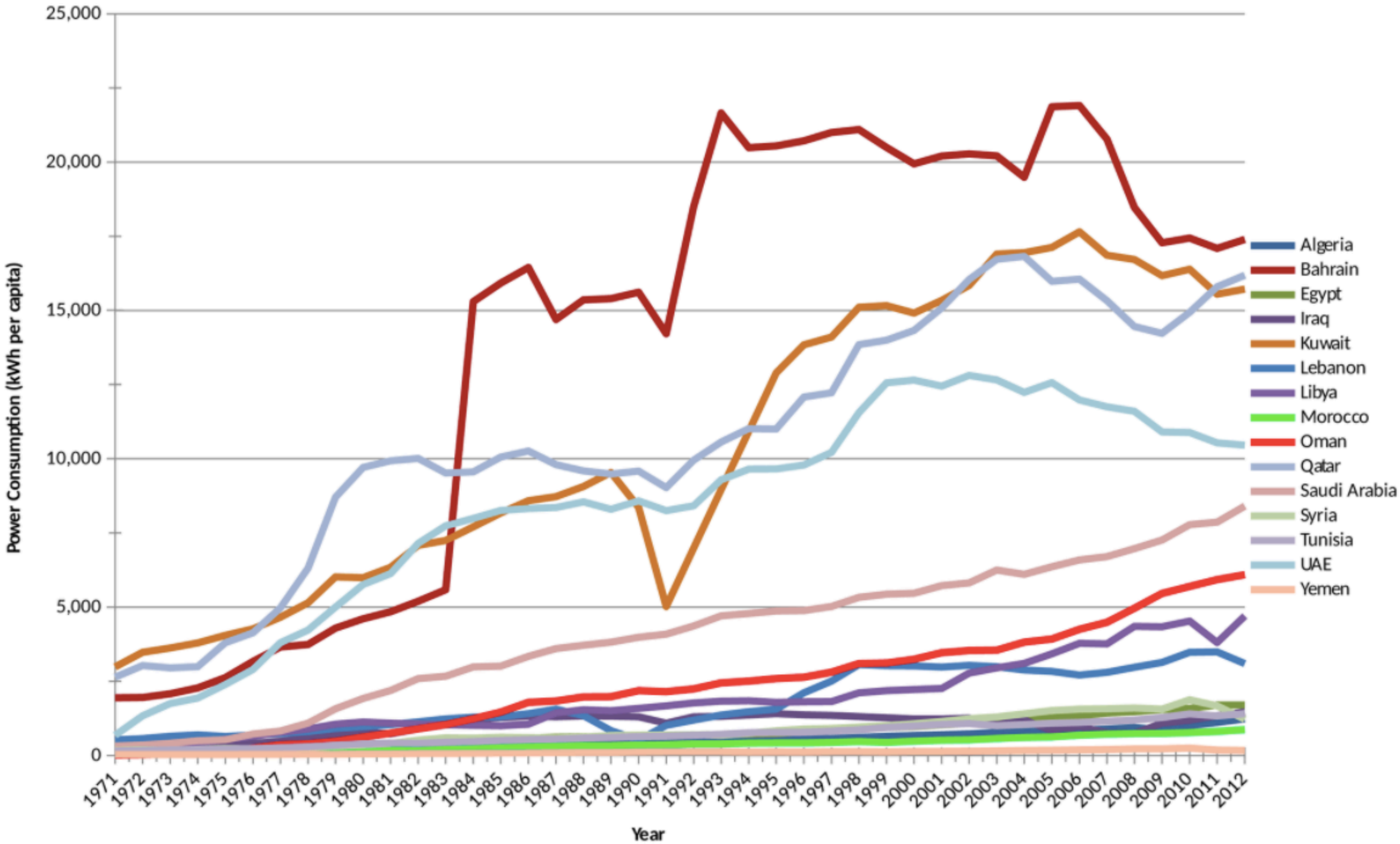
Energy Water Nexus in Dry and Arid Regions

- Energy-Water Nexus particularly aggravated in water-scarce regions with dry-arid-hot climates
- Examples: American South West, The Gulf Cooperation Council, Mediterranean, Australia, etc.
- Dependence on climate control technology
- Mega-Trends
  - ↑ water demand/capita
  - ↑ energy demand/capita
  - ↑ Population growth
  - ↑ Economic growth
  - ↑ Distortions of freshwater availability due to climate change
  - ↑ Water treatment standards, flue gas management, ageing infrastructure

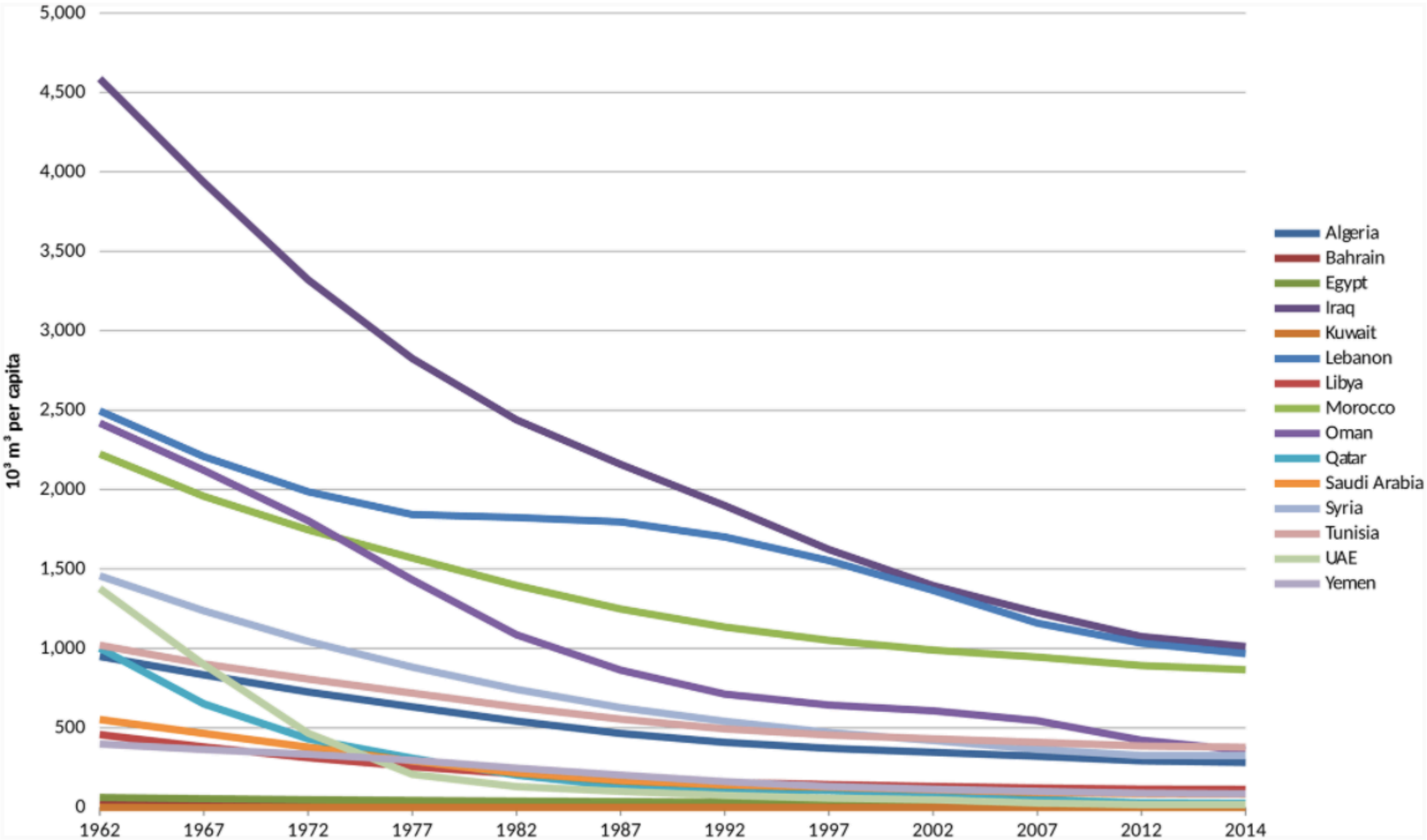


∴ The importance of any individual coupling depends by region!

Electric Power Consumption/capita in MENA region



Renewable Water Resources/Capita in MENA region



Water Use in the Electric Power System

- US: 49% of fresh water withdrawals are by power plants
  - Withdrawn and returned
  - Reliability concern

- US: 3% of fresh water consumption are by power plants
  - Withdrawn, but not returned
  - Sustainability concern

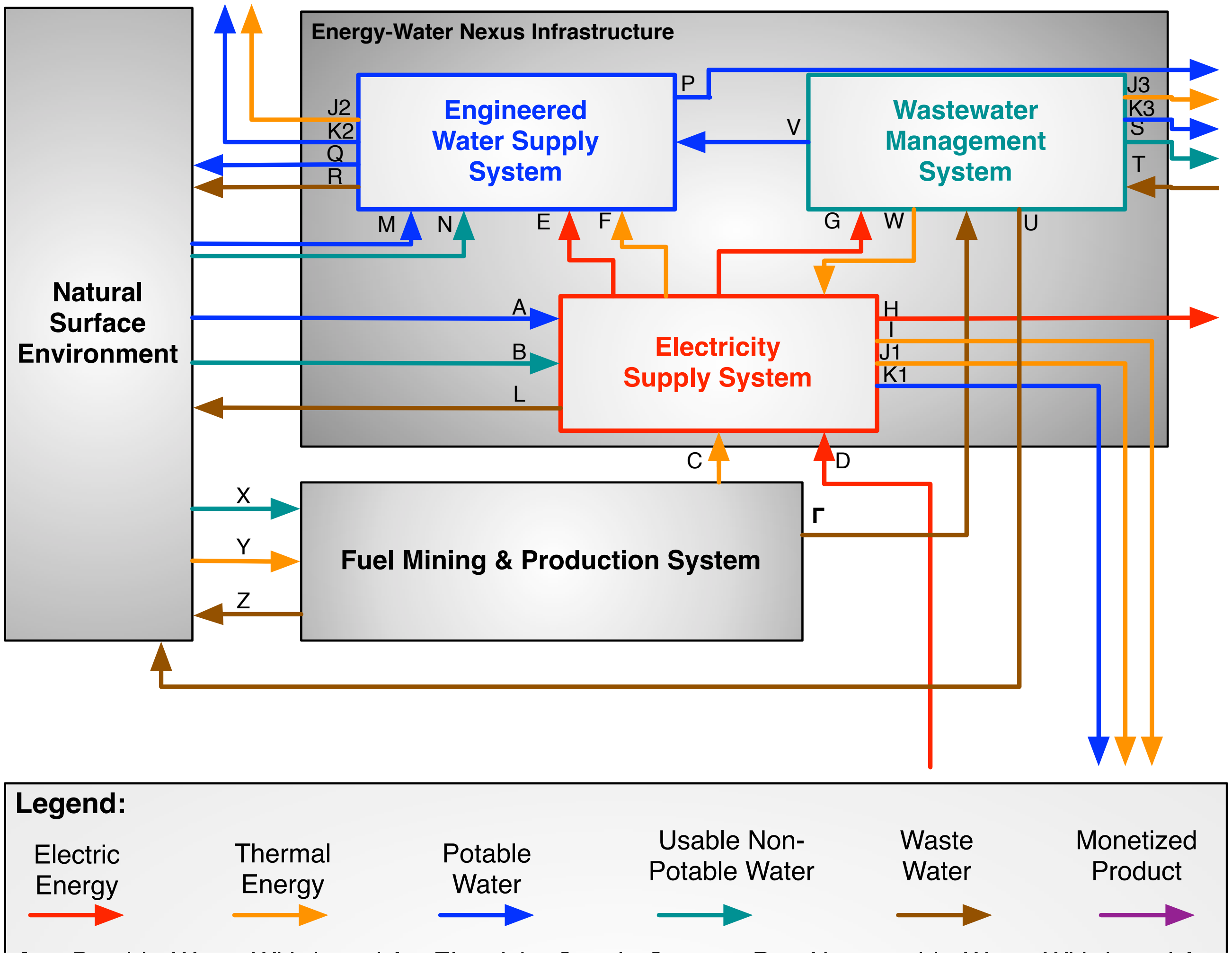
- But, aren't power plants built close to natural water resources? What's the problem?
  - France, 2003: power plant shut down, caused by a water shortage
  - Texas, 2011: again
- NREL: commissioned several studies to vulnerability of the power supply, especially focused on the Western US.

Electric Power Use in the Water System [3]

Water System Activity	Energy Intensity [kWh/MG]
Water Supply: • Gravity fed • Groundwater (GW) • Brackish GW • RO desalinated seawater • MSF desalinated seawater • Recycled water	 0 2,000 3,200 5,000 14,000 1,100
Water Treatment	100 – 16,000
Water Distribution	250 – 1,200
Wastewater Collection & Treatment	700 – 4,600
Wastewater discharge	0 – 400
Total:	**1,050 – 36,200**

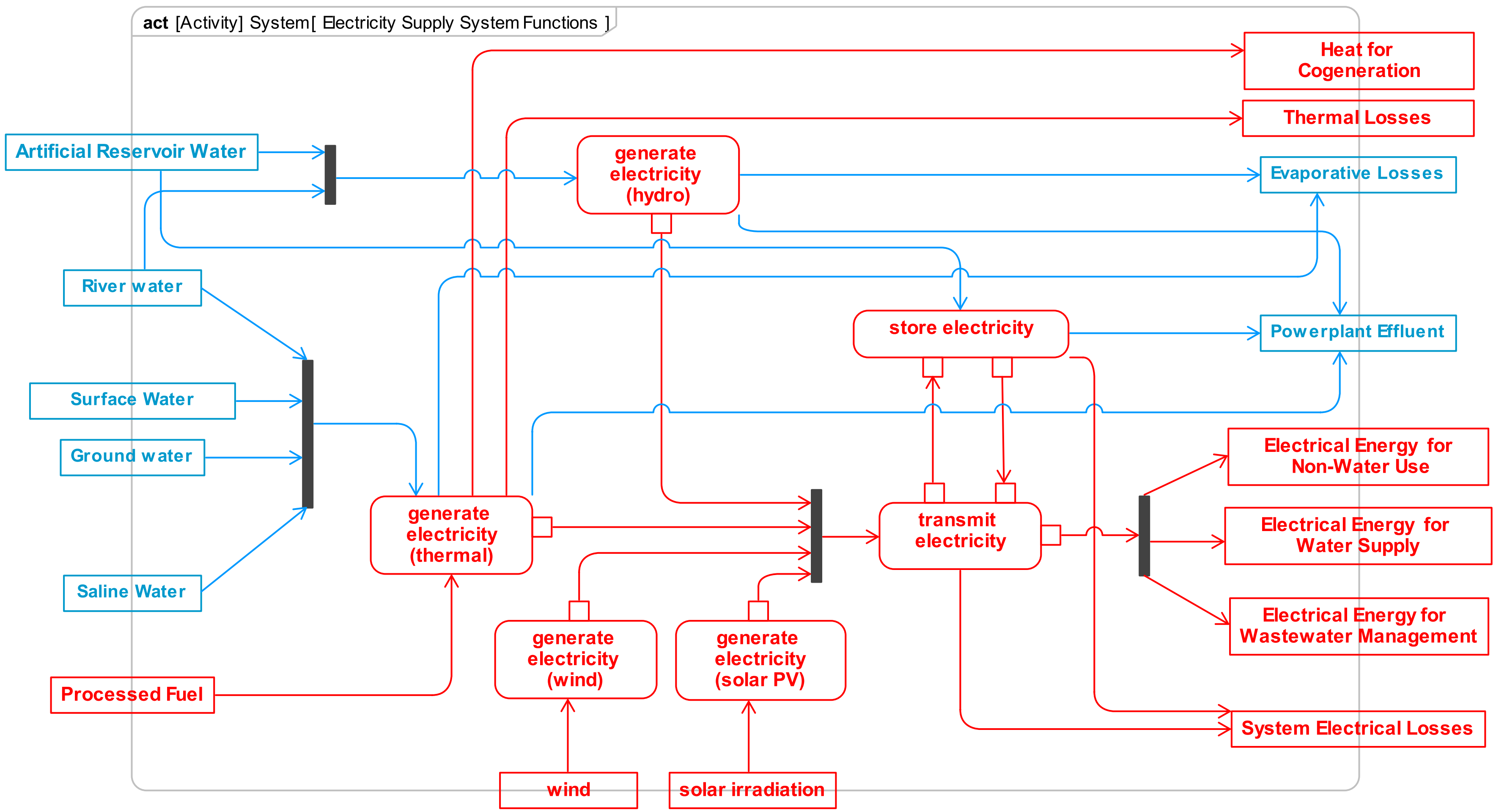
Treatment Type	Energy Intensity [kWh/m³]
Trickling filter	0.25
Activated Sludge	0.34
Advanced Treatment	0.4
Advanced Treatment w/ Nitrification	0.5
Surface Water Treatment	0.06
Ground Water Treatment	0.16
Reverse Osmosis	3-5
Multistage Flash Desalination	10-20

Systems Engineering of Energy Water Nexus (SEWN)



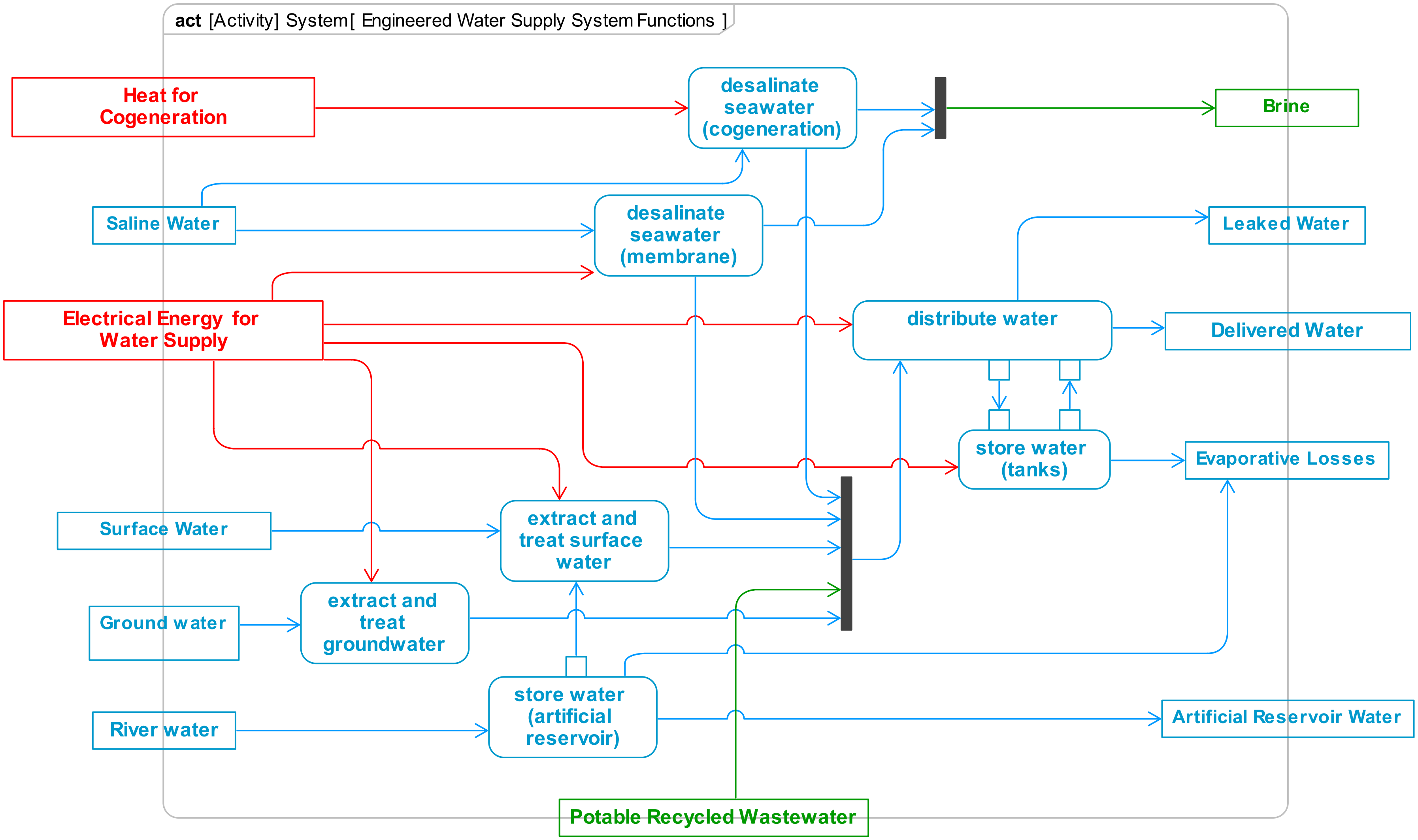
∴Judiciously choosen system boundary. Calculate energy-water infrastructure flows

Systems Engineering of Energy Water Nexus (SEWN)



∴ Electric supply system function illustrates activities and their interactions.

Systems Engineering of Energy Water Nexus (SEWN)



∴ Water supply system function illustrates activities and their interactions.

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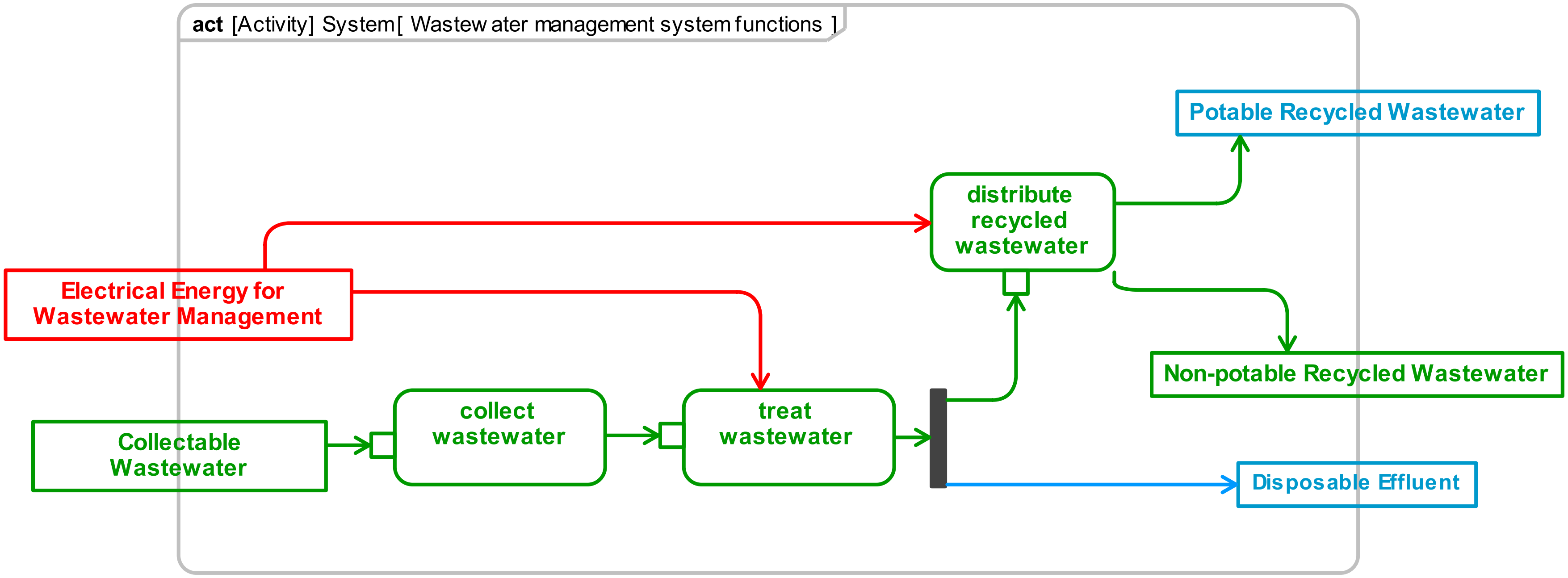
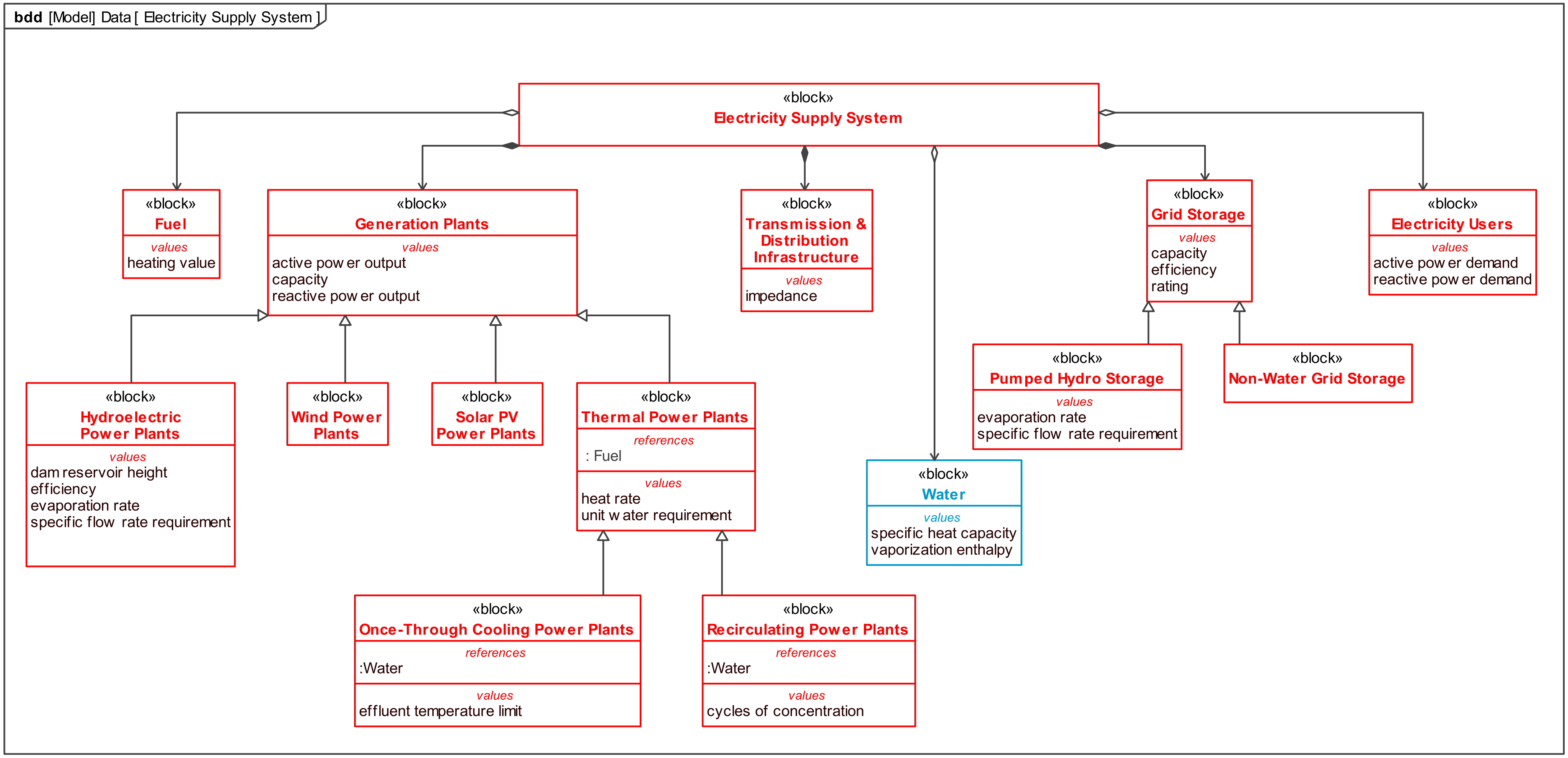
Systems Engineering of Energy Water Nexus (SEWN)



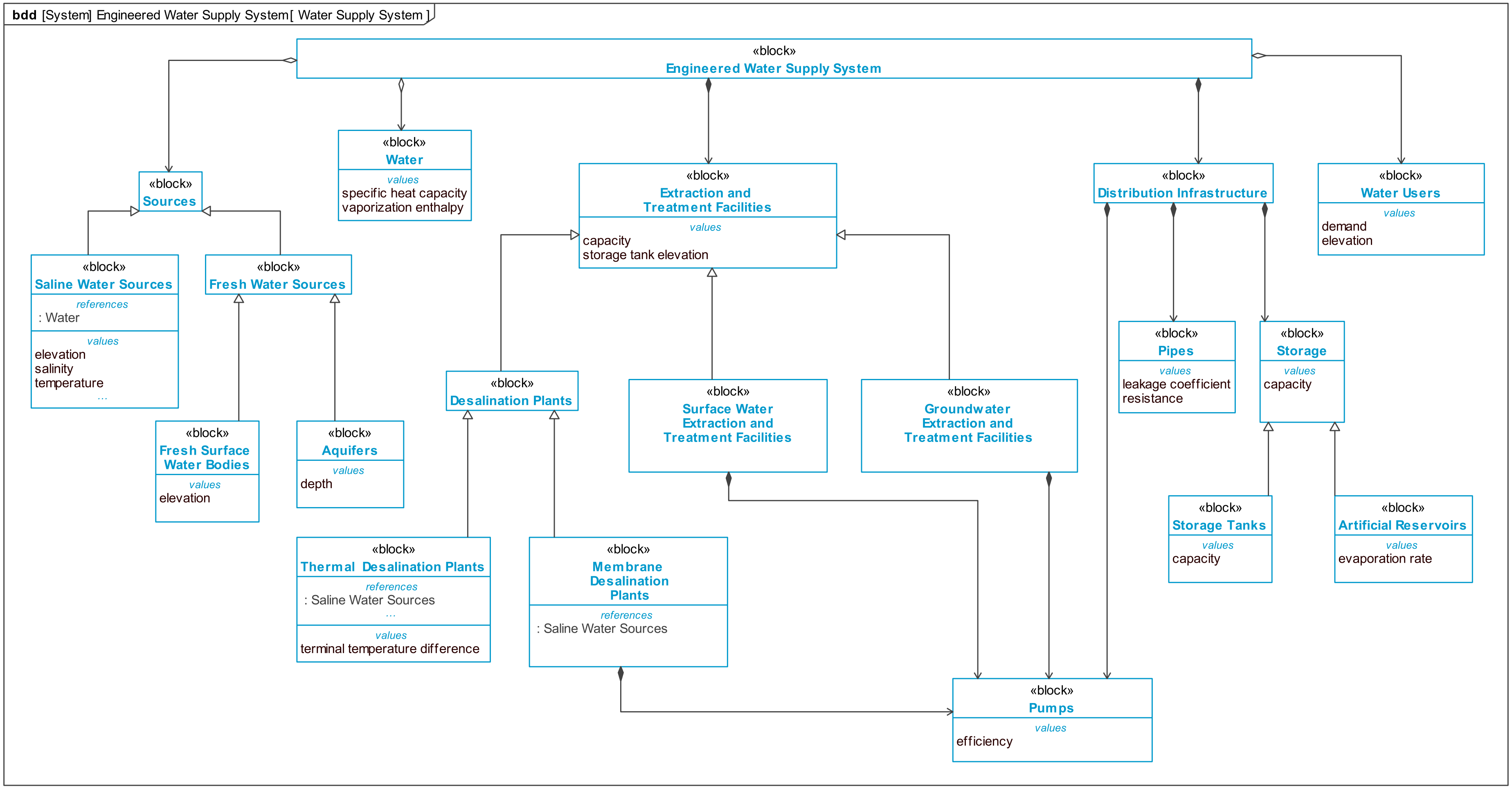
∴ Wastewater management system function illustrates activities and their interactions.

Systems Engineering of Energy Water Nexus (SEWN)



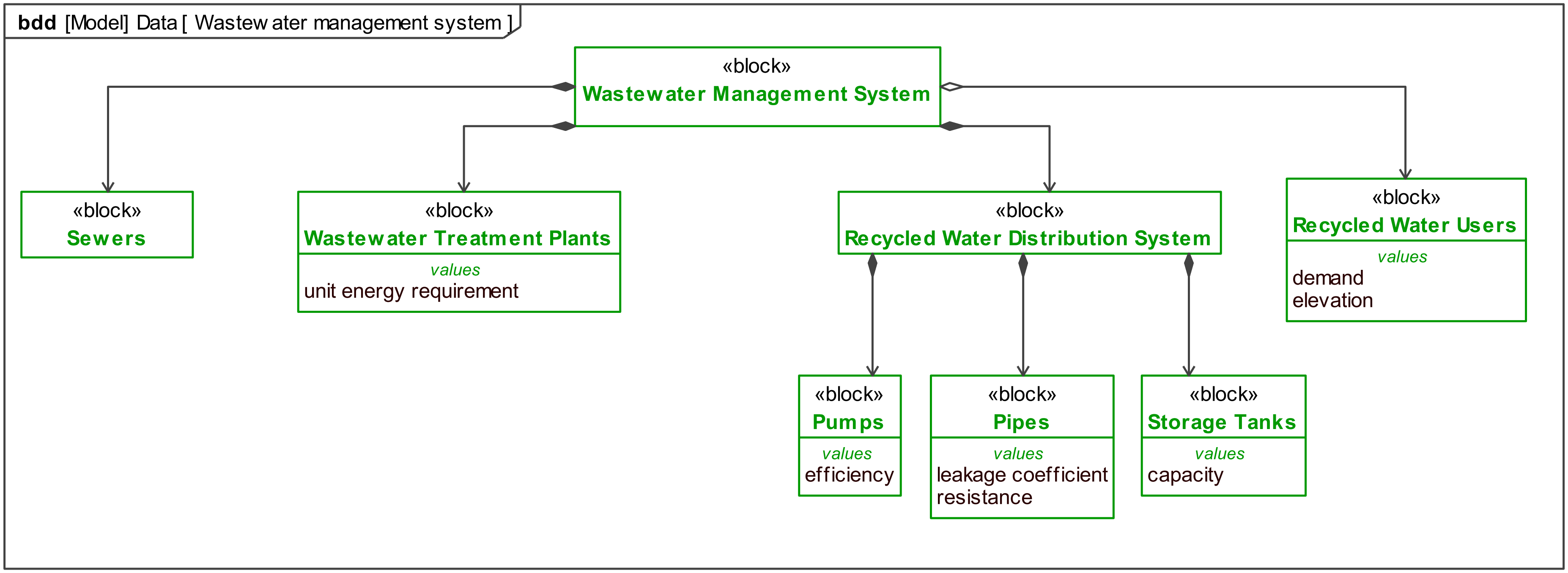
∴ Electric supply system form illustrates blocks and their relationships.

Systems Engineering of Energy Water Nexus (SEWN)



∴ Water supply system form illustrates blocks and their relationships.

Systems Engineering of Energy Water Nexus (SEWN)



∴ **Wastewater management system form illustrates blocks and their relationships.**

Systems Engineering of Energy Water Nexus (SEWN)

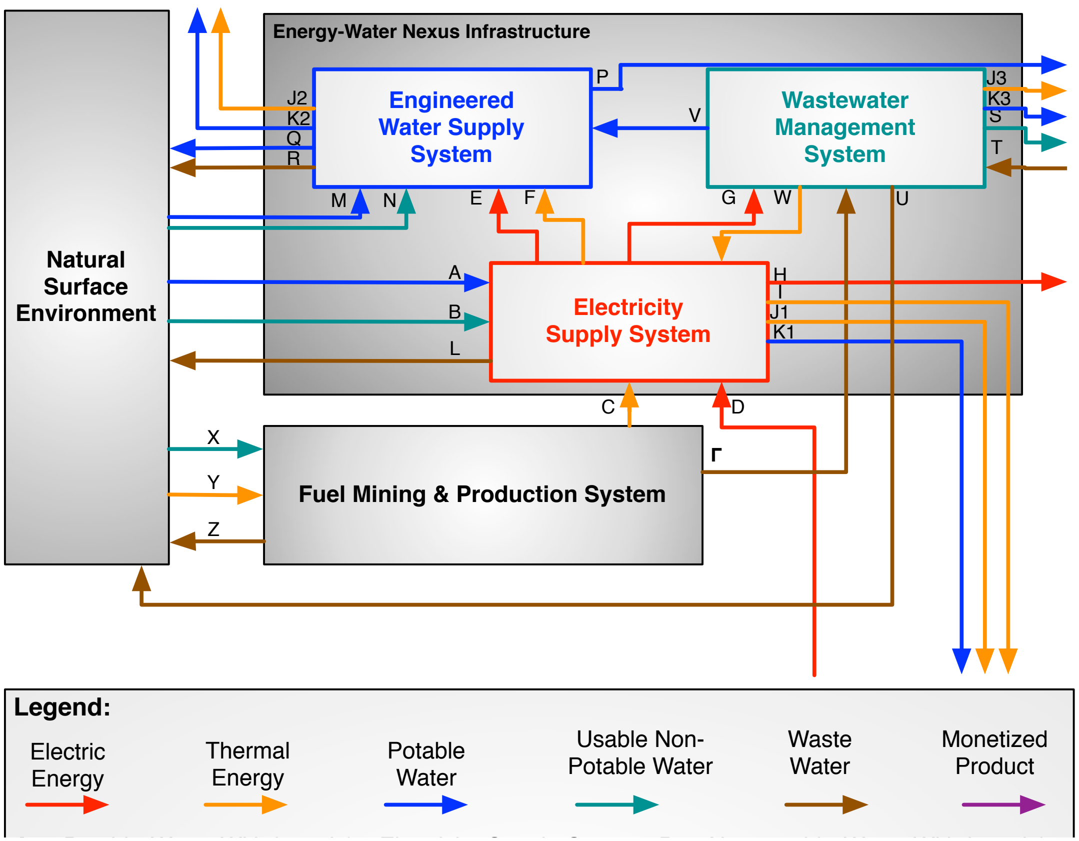
TABLE II
ELECTRICITY, WATER, AND WASTEWATER SYSTEMS KNOWLEDGE BASE

	HEP Plants	Thermal Power Plants	Solar PV Plants	Wind Power Plants	Non-Water Grid Storage	T& D Infrastructure	TDP	MDP	SWETP	GWETP	Pumped-Hydro Storage	Man-Made Lakes	Water Tanks	Municipal Water Users	Sewer Network	WWTP	Recycled Water Network
Generate Electricity from Water	x																
Generate Electricity from Fuel		x					x										
Generate Electricity from Solar Irradiation			x														
Generate Electricity from Wind				x													
Store Electricity					x						x						
Transmit Electricity						x											
Desalinate Seawater (cogeneration)							x										
Desalinate Seawater (osmosis)								x									
Extract & Treat Surface Water									x								
Extract & Treat Ground Water										x							
Store Water											x	x	x				
Use Water														x			
Collect Wastewater															x		
Treat Wastewater																x	
Distribute Recycle Wastewater																	x

(TDP=Thermal Desalination Plants, MDP= Membrane Desalination Plants,SWETP=Surface Water Extraction and Treatment Plants, GWETP = Groundwater Extraction and Treatment Plants, WWTP = Wastewater Treatment Plants)

∴ **System knowledge base shows the allocation of system function to system form.**

Systems Engineering of Energy Water Nexus (SEWN)



- Degree of coupling between the electricity and water systems:

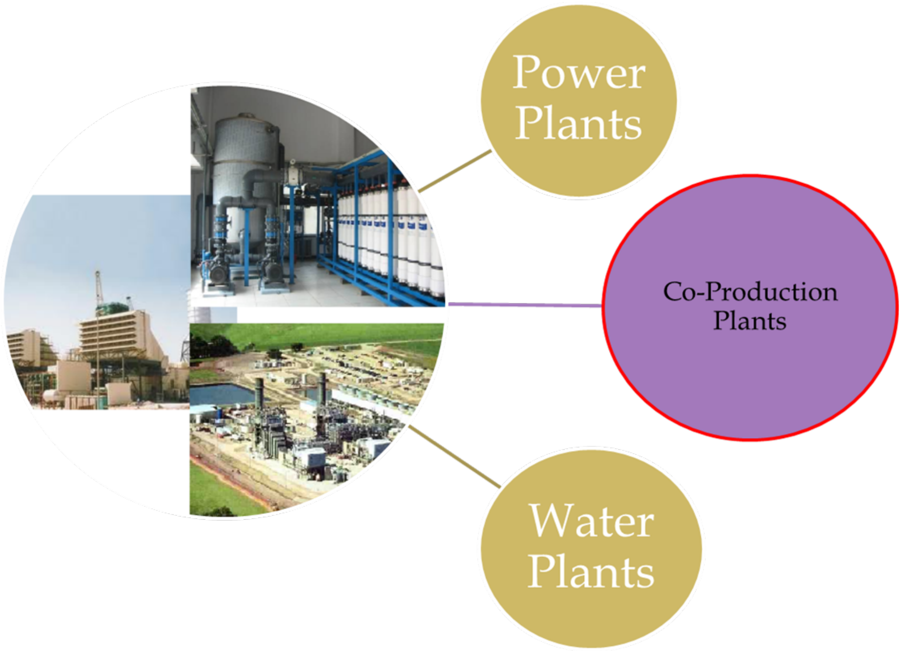
$$\frac{E+F+G-W}{E+F+G-W+H+I+J1}$$

- Water supply required to sustain the two engineered systems:
  - A+B+M+N-V
- Ratio of water displaced from its original source to total water withdrawn:
- (K+P-V)/(A+B+M+N-V)
- Proportion of water withdrawn that is returned with significantly altered quality
- (R+L+U)/(A+B+M+N-V)

∴ Judiciously choosen system boundary. Calculate energy-water infrastructure flows

Need for Integrated Energy Water Market Dispatch

- Multiple conversations w/ UAE utilities: need for co-dispatch of power & water
- Economic Dispatch of Power & Water
- Unit Commitment of Power & Water
- Role of Power & Water Storage and Ramping Rates in Co-Dispatch
- Role of Power & Water Transmission Constraints
- Synergistic Role of Renewable Energy Integration into the Energy-Water Nexus



∴ LIINES first to provide rigorous methods for power & water co-dispatch methods

IPPs, IWPs, and IWPPs in the MENA

- IPPs: Independent Power Producers
- IWPs: Independent Water Producers
- IWPPs: Integrated Water and Power Producers

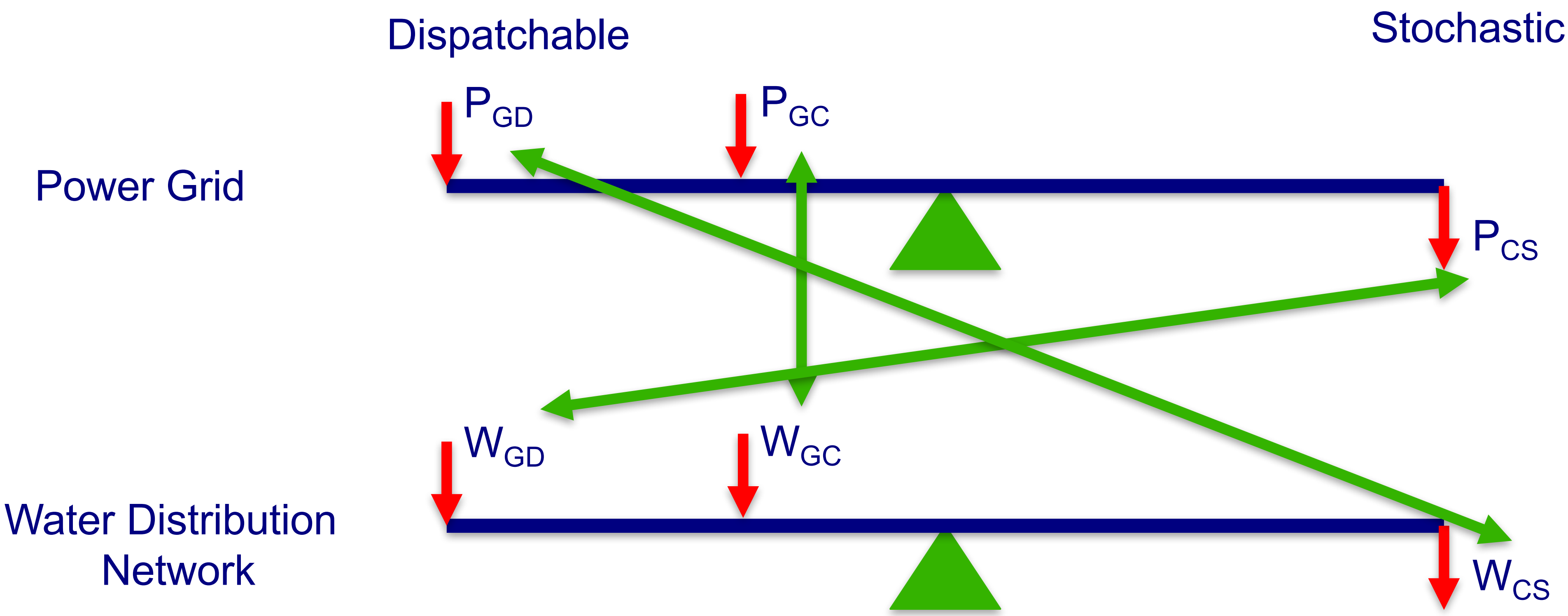
Contracts in MENA region:

- Fixed contracts for 20-25 years
- Contracts include water and power production level and fuel supply cost

Disadvantages:

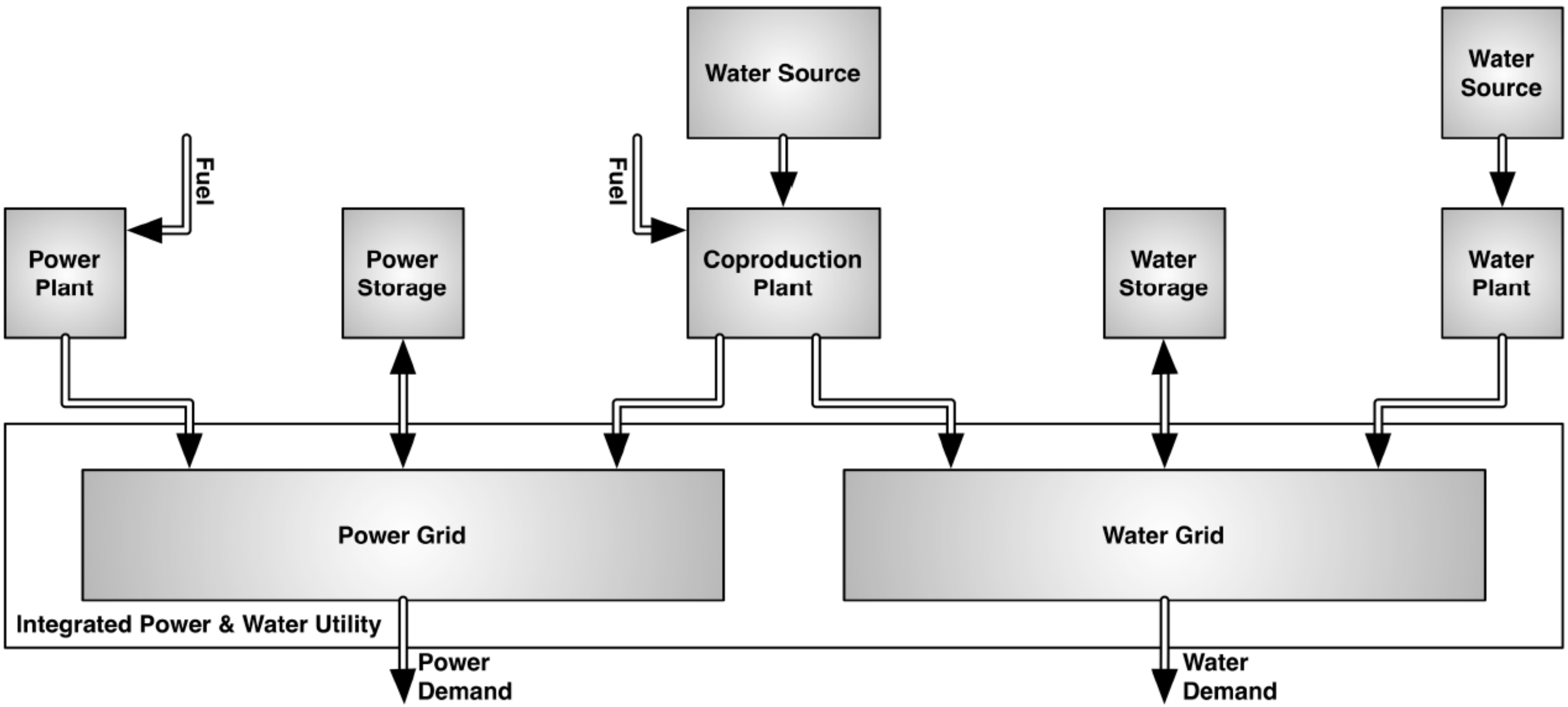
- No incentive for efficiency improvements
- May lead to overabundance of power in times of economic downturn
- Bids based on maximum capacity: bias towards baseload plants – not as flexible
- Baseload bias of independent operators may push government owned plants to the mid-load, inherently less efficient

Integrated Energy-Water Operations in the MENA Region



Conceptual Model [14-18]

Objective: To minimize cost of production in a multi-plant generation network which consists of power generation plants, water production plants and dual product plants



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Dispatch of Energy Water Nexus (DEWN)

$$min \;\; C_G(X_{pi}, X_{wj}, X_{ck}) = \sum_{i=1}^{n_{pp}} C_{pi}(X_{pi}) + \sum_{j=1}^{n_{wp}} C_{wj}(X_{wj}) + \sum_{k=1}^{n_{cp}} C_{wj}(X_{ck})$$

$$MinGenPP_i \leq X_{pi} \leq MaxGenPP_i \quad i = 1...n_{pp}$$
$$MinGenWP_i \leq X_{wj} \leq MaxGenWP_j \quad j = 1...n_{wp}$$
$$MinGenCP_k \leq X_{ck} \leq MaxGenCP_k \quad k = 1...n_{cp}$$

$$\sum_{i=1}^{n_{pp}} X_{pi} + \sum_{j=1}^{n_{wp}} X_{wj} + \sum_{k=1}^{n_{cp}} X_{ck} = D$$

$$r_k^{lower} \leq \frac{x_{cpk}}{x_{cwk}} \leq r_k^{upper} \forall k = 1..n_{cp}$$

$$C_{pi} = X_{pi}^T A_{pi} X_{pi} + B_{pi} X_{pi} + C_{pi}$$
$$C_{wj} = X_{wj}^T A_{wj} X_{wj} + B_{wj} X_{wj} + C_{wj}$$
$$C_{ck} = X_{ck}^T A_{ck} X_{ck} + B_{ck} X_{ck} + C_{ck}$$

$$X_{pi} = [x_{pi}, 0]^T$$
$$X_{wj} = [0, x_{wj}]^T$$
$$X_{ck} = [x_{cpk}, x_{cwk}]^T$$
$$D = [D_p, D_w]^T$$

∴ LIINES first to provide rigorous methods for power & water co-dispatch methods

Dispatch of Energy Water Nexus (DEWN)

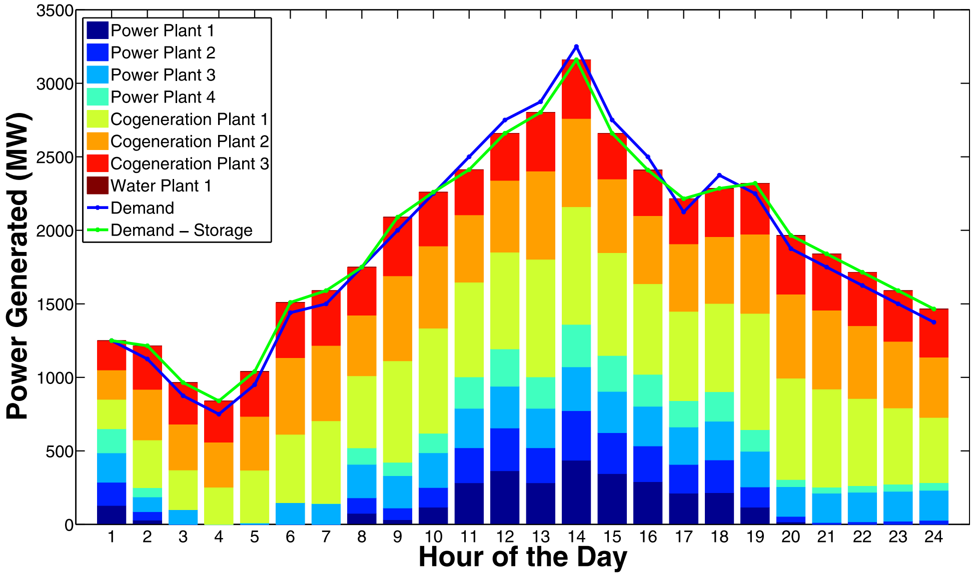


Fig. 2. Case 1: power generation and demand profile over 24 h period.

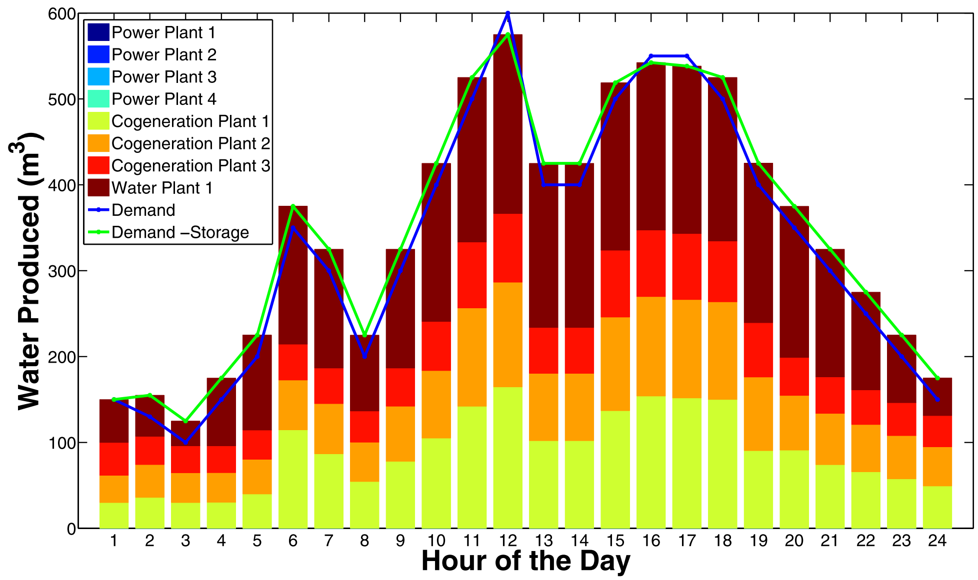


Fig. 3. Case 1: water production and demand profile over 24 h period.

∴Integrated Energy-Water Dispatch would solve many existing problems!

Integrated Demand Side Management

Opportunities

- Water can play a role as operating reserves for the power grid: water distribution accounts for 3%-5% of all power consumption
- Direct load control: thermal capacitance as electrical load displacement
- Wastewater treatment may generate methane, which can be used for peak generation

Challenges

- Increased operational complexity
- Lack of appropriate market structures
- Difficulty in fairly apportioning the costs and benefits of demand side management programs
- Municipal and wastewater systems are owned and operated at a municipal level

Integrated Energy Water Nexus Operation

- Give incentives to continuously improve cost efficiency of power and water
- Incentivize Integrated Water & Power Producers (e.g. in the GCC)
- More responsive to fluctuating daily and seasonable demand.
- Assessing technical and economic tradeoffs in power and water
- Allow for power demand side management of water infrastructure

∴ Integrated Energy-Water Dispatch would solve many existing problems!

Stabilizing Role of the Energy-Water Nexus in Electricity

- Hydro-electric facilities support renewable energy integration (e.g. Norway & Denmark)
- Water storage in integrated energy-water utilities alleviate ramping on co-production facilities (e.g. in GCC)
- Water storage in integrated energy-water utilities alleviate peak load growth.
- Water heater pilot (e.g. in PJM) & swimming pools (e.g. Florida utility) for regulation services.
- Pumping energy typically accounts for 5% of load ≈ % of operating reserves
- 32 billion m^3 of treated water per year globally. 20-40% typical water losses.
- District cooling can curb peak load growth. 35-65% reduction in electric power. (e.g. Palm Jumeira in Dubai provides 921MW of district cooling)
- Wastewater treatment can provide biogas electric power generation

∴Many opportunities to leverage water to alleviate electric power system reliability challenges!

Integrated Energy Water Nexus Planning

- Shfits towards renewable energy
- Shifts in desalination technology
- Optimization of water distribution networks and leaks
- Usage of alternative forms of water
- Integrated environmental Management & sustainable development

Table 5
Cross case comparison of cost, CO_2 emissions & water withdrawal by thermo-electric facilities.

Case	Cost (M$)	CO_2 (metric tons)	Water Withdrawal (m^3)
Case 1.1: Singapore with Solar PV	2.592	16,070	3,674,000
Case 1.2: Singapore without Solar PV	2.702	18,020	3,873,000
Case 2.1: Middle East with Solar PV	2.444	16,090	3,673,000
Case 2.2: Middle East without Solar PV	2.608	18,030	3,872,000

∴ **Holistic Thinking Enables Sustainable Development**

Shifts Towards Renewable Energy [13,14]

- Wind & Solar PV have negligible water footprint
- CSP has more but Shams 1 uses air cooling at the expense of lower efficiency
- Renewable Energy → Intermittency → Storage → Pumped Hydro → Evaporation
- If (wholesale) water were monetized, renewable energy would have an even stronger case

∴ Renewable energy can be more easily justified with monetized water

Shifts in Desalination Technology [13,14]

- RO significantly less energy-intensive than MSF
- But if you continuously need power than MSF co-production facilities remains a viable option. Requires careful analysis.
- Market drivers can bring incentives for new technology.

∴Each desalination technology has its benefits. Long term planning required.

Optimization of Water Distribution Networks & Leaks [13,14]

- How can the water distribution network be planned to improve energy intensity?
- What are the ideal pressure setpoints?
- What is the energy-intensity of water leaks? How much does this costs the integrated power-water utility? Who pays for this?

∴ Energy intensity can benefit economic rationalization

Usage of Alternative Forms of Water [13,14]

- ASME workgroup is currently developing guidelines for the usage of alternative forms of water for multiple uses
  - Brackish, grey, recycled, sea water
  - Agricultural, industrial (many types), municipal, etc.
- What is the ideal network structure to support this? How many different types of water qualities need to be distributed?
- How does this match aspiration for the development of economic sectors (water intense or energy-intense sectors)

∴ Horses for Courses. One man's waste is another man's treasure.

Integrated Env. Management & Sustainability [13,14]

- Planning decisions should demonstrate clear scenarios in CO_2, water, and energy resource consumption
- Planning decisions should highlight where actions should be taken to make the biggest improvements in environmental impact & cost

∴ Holistic Thinking enable Sustainable Development

Challenges for Integrating Energy and Water Systems

Energy-Water Nexus corresponds with the definition of Engineering Systems:

"A class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes aimed at fulfilling important functions in society" – De Weck et al.

- Both technical and socio-economical
- Within technology: try to make disciplinary specialist speak to each other and reach a conclusion
- Existing modeling methods are specialized at disciplinary systems as well
- Location specific models: case study based research
- After modeling and designing: implementation
- Legacy infrastructure

∴ This is a shout-out to everyone in the room: Let's try to generalize our case specific models, so that we can reapply and compare methods

Opportunities for Integrated Energy-Water Systems

1. Shift towards renewable energy
   - *No water consumption in operation of Wind or Solar PV*
   - *Concentrated Solar: Rankine cycle may require water cooling*
   - *Pumped hydro storage: evaporative losses*
2. Shift in desalination technology
   - *Reverse Osmosis requires much less water than Multi-Stage Flash*
   - *Similar planning diligence for water resources as for power resources.*
3. Optimization of water distribution networks and leaks
   - *Track water flows <u>and</u> their energy intensity*
   - *Resolving leaks results in direct savings at the source*
4. Usage of alternative forms of water
   - *Use of separate water qualities to reduce energy density of water*
   - *New and advanced planning methods needed to plan and build such a system*
5. Integrated Environmental Management and Sustainable Development
   - *Include a wide variety of Key Performance Indicators to do the diverse and complex problem justice.*

Policy Implications for Integrated Energy-Water Nexus

Policy implication for operations:

"Shift towards integrated energy-water dispatch operation rather than addressing each product individually."

In three steps:

1. Existing approaches of energy and water dispatch need to be replaced by integrated energy-water dispatch
2. The regional trend towards IPPs, IWPs, and IWPPs should be supported
3. Carefully designed demand-side management schemes could improve coordination of energy-water coupling points

Policy Implications for Integrated Energy-Water Nexus

Policy implication for planning:

"An integrated approach to energy-water infrastructure modeling."

In four concrete planning opportunities:

1. Rationalize benefits of renewable energy <u>also</u> on the basis of reduced water consumption.
2. Water production planning should be rationalized using the "external effects" of the water treatment plants. RO is more efficient, but MSF can cogenerate
3. Reduction of water leakages should receive even more attention as a result of including the energy intensity of the water flows
4. Increased water recycling can reduce the environmental footprint of water production and support the need for new water resources.

Motivation for the End Use Architecture Extension [21]

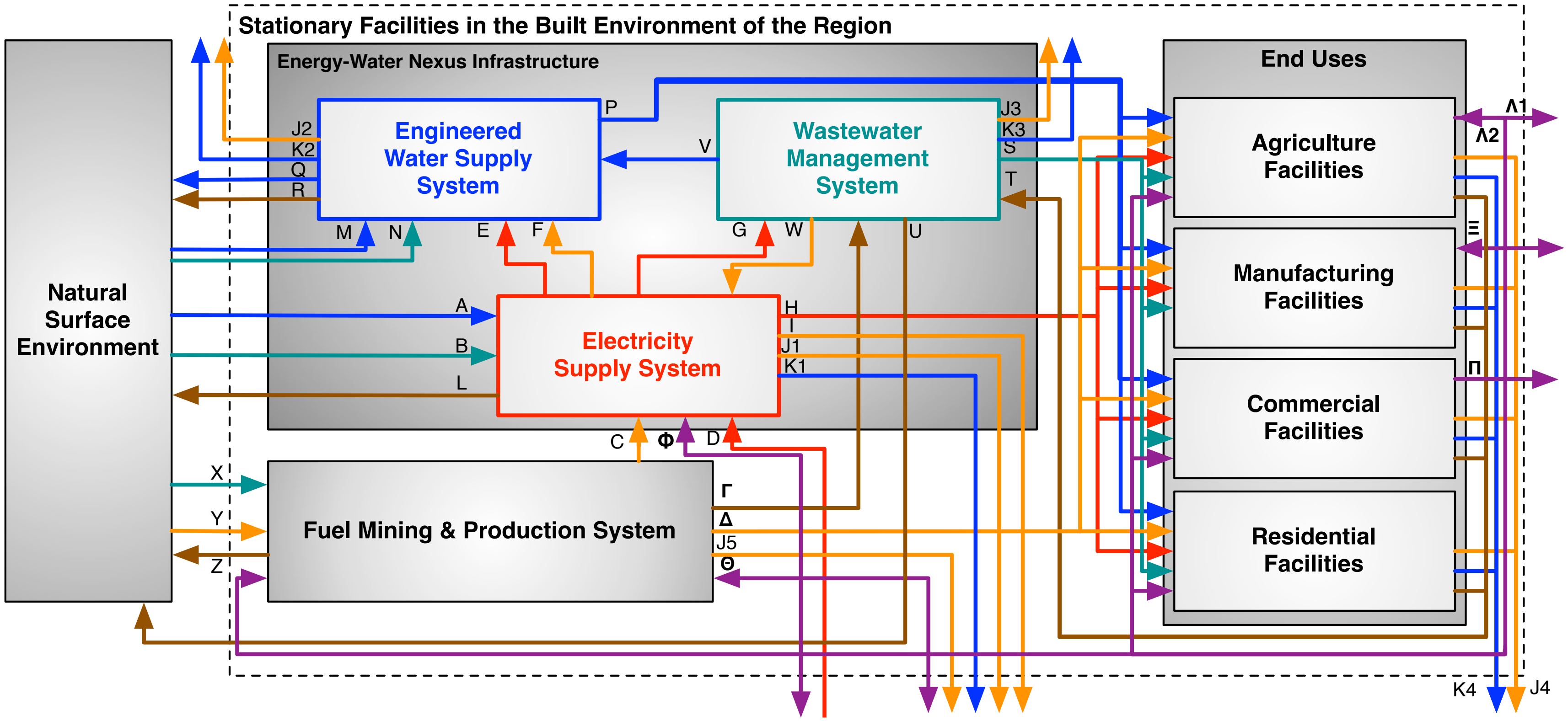
- Some end-uses use potable water when they only require non-potable water
- Some end-uses can choose between electricity & natural gas
- End-uses should be investigated to alleviate infrastructure constraints

Important Concerns:

- The degree to which the environment can sustain the associated resource consumption
- The degree to which the infrastructure can provide the right balance of inputs for the end use activities
- The degree to which end use processes and technologies efficiently produce these valuable products

∴ Relate the economic value of electricity, fuel, and agriculture, manufactured, and commercial products → input and waste streams of energy & water

EWN Reference Architecture End Use Extension [21]

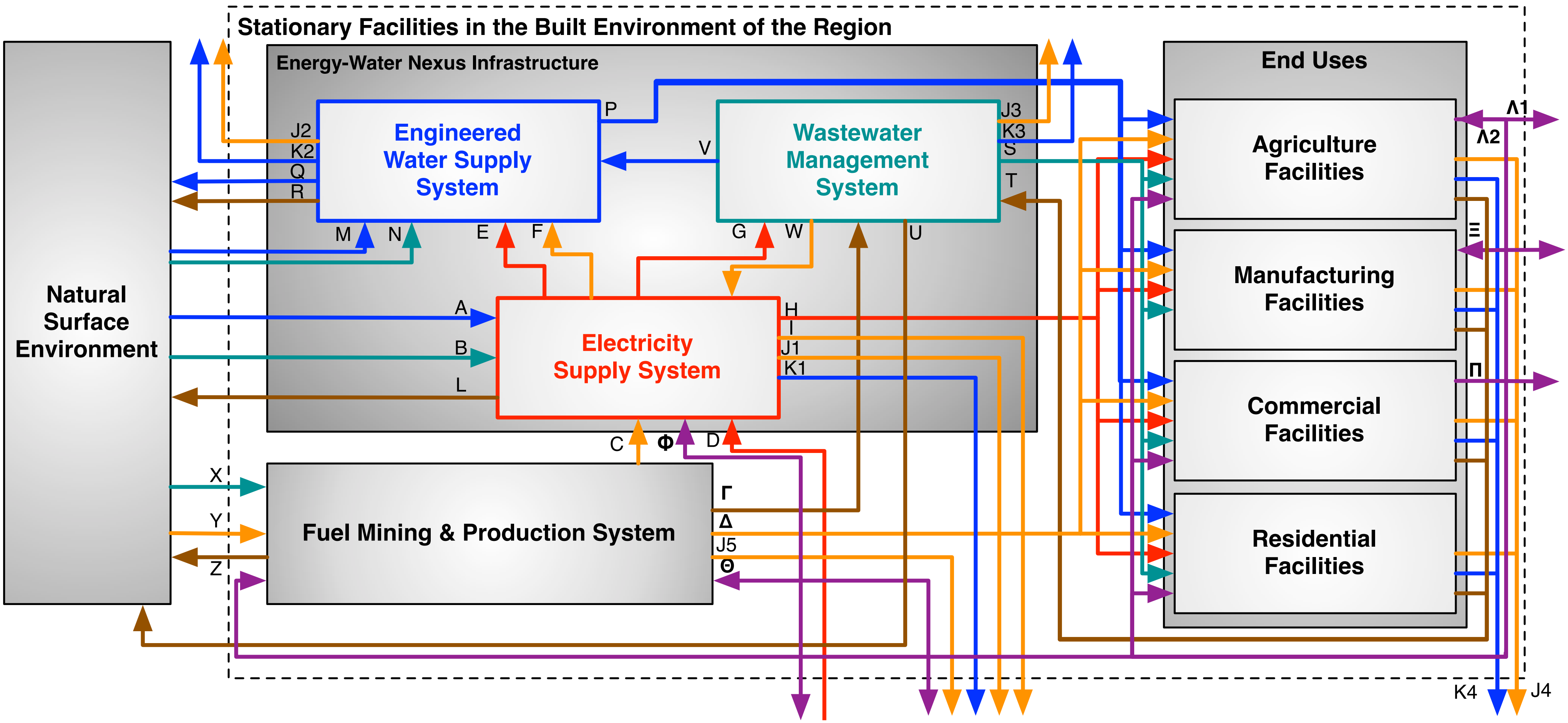


Legend:

Electric Energy | Thermal Energy | Potable Water | Usable Non-Potable Water | Waste Water | Monetized Product

A -- Potable Water Withdrawal for Electricity Supply System, **B** -- Non-potable Water Withdrawal for Electricity Supply System, **C** -- Processed Fuel, **D** -- Renewable Energy & Electricity Import/Export, **E** -- Electrical energy for Engineered Water Supply System, **F** -- Heat for Cogeneration, **G** -- Electrical Energy for Wastewater Management System, **H** -- Electrical Energy for End Use, **I** -- Electrical Losses, **J** -- Thermal Losses, **K** -- Evaporative Losses, **L** -- Power Plant Effluent, **M** -- Potable Water Withdrawal for Engineered Water Supply System, **N** -- Non-Potable Water Withdrawal for Engineered Water Supply System, **P** -- Potable Water for End Use, **Q** -- Leaked Potable Water, **R** -- Brine, **S** -- Recycled Waste Water for End Use, **T** -- Collectable Wastewater, **U** -- Effluent, Leaked Wastewater & Leaked, Recycled Water, **V** -- Recycled Potable Water, **W** -- Biogas, **X** -- Produced Water, **Y** -- Raw Fuel, **Z** -- Wasted Produced Water, **Φ** -- Electrical import/export, **Γ** -- Recycle Produced Water, **Δ** -- Fuel for End Use, **Θ** -- Fuel for Trade, **Λ** -- Agricultural Products, **Ξ** -- Manufactured Products, **Π** -- Value of Commercial Products.

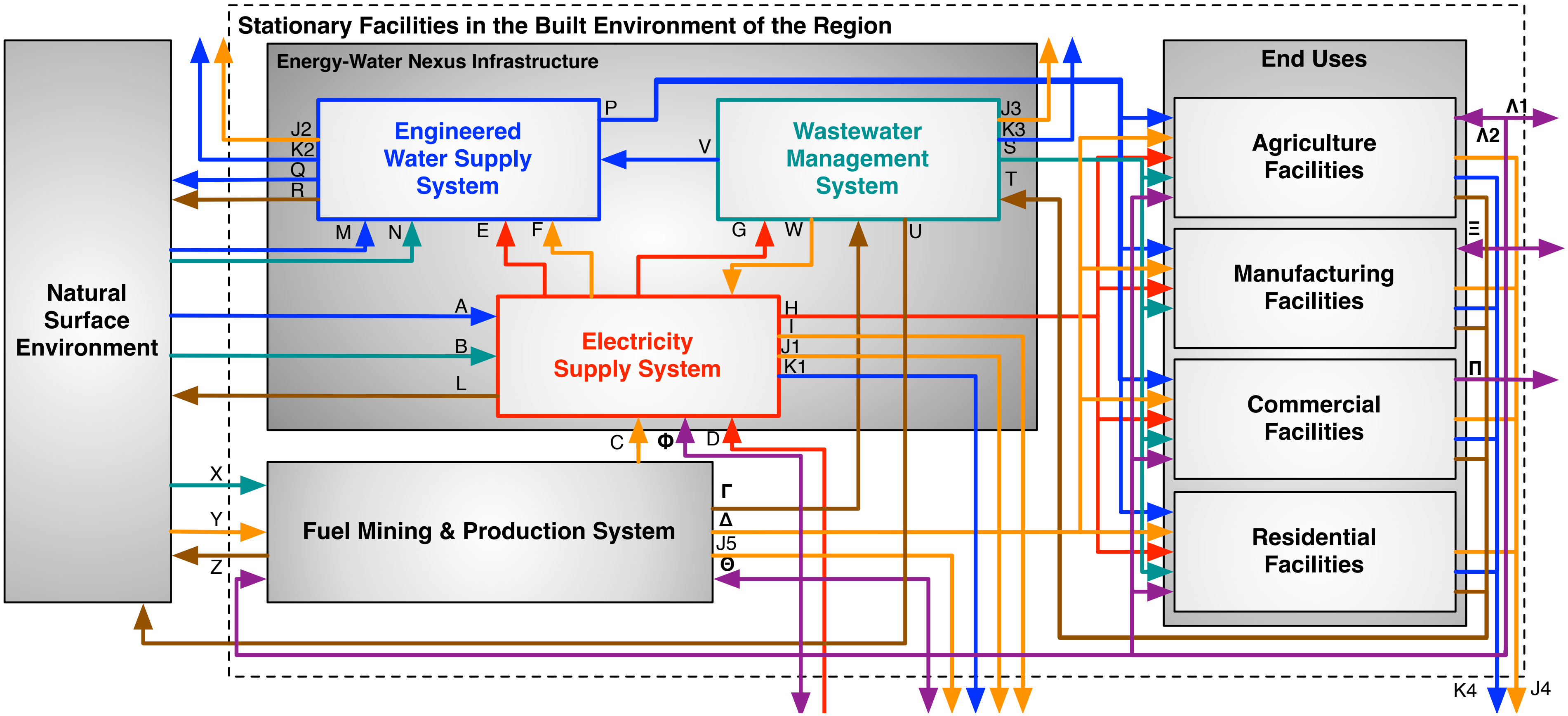
An Extension to Multiple End Use Sectors



∴ Long Term Infrastructure Design fit for Purpose:

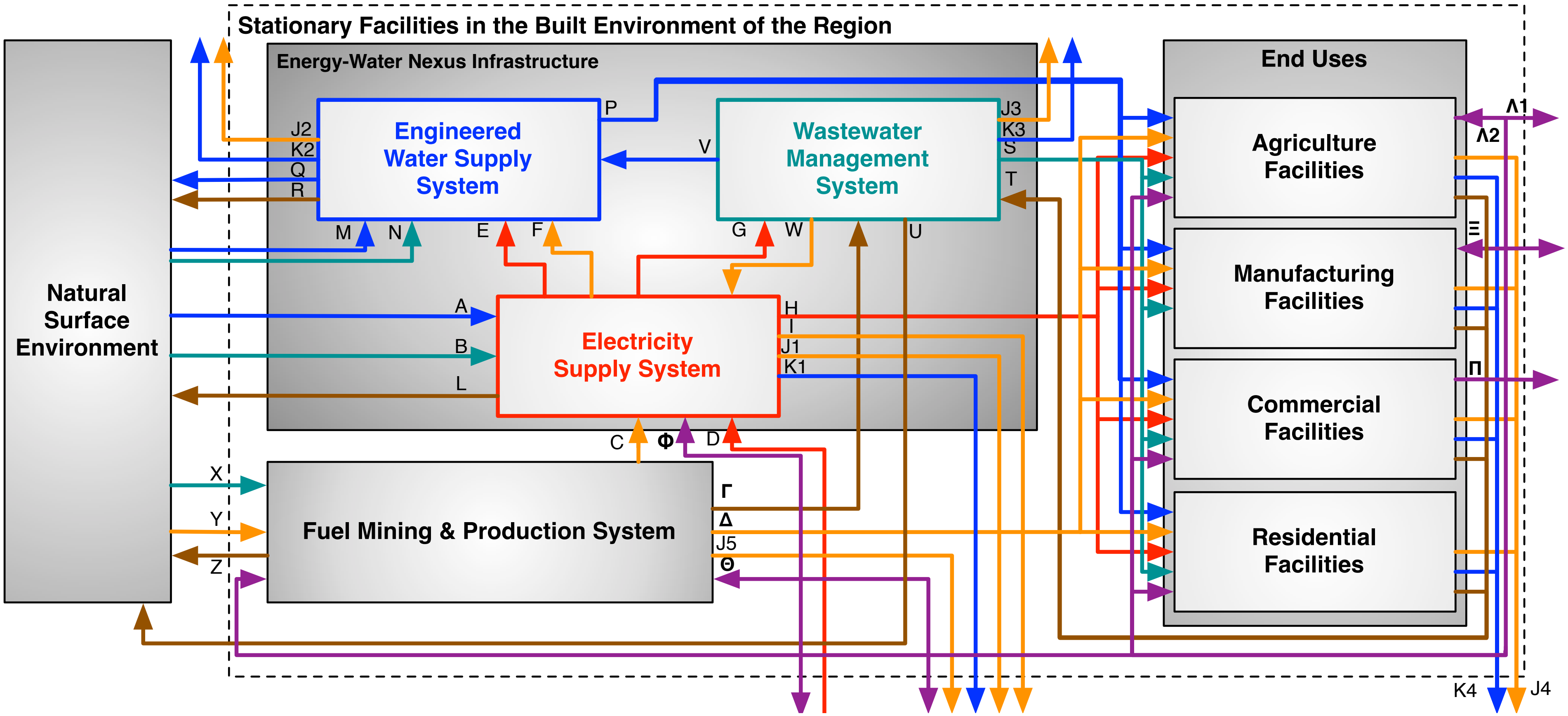
∴ Agriculture, Industrial, Commercial, & Residential Activities serve economics

EWN Ref. Arch: Fuel Mining & Production Systems [21]



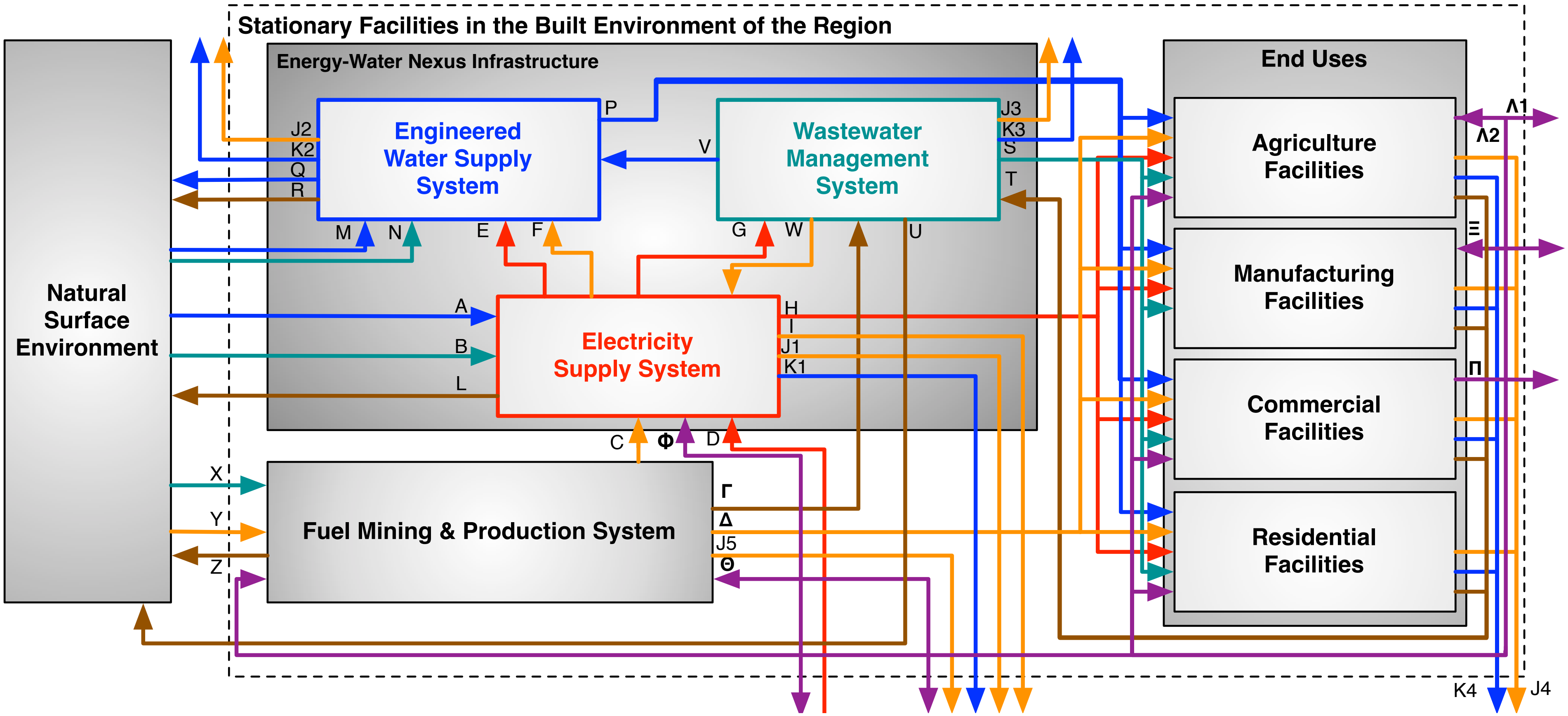
- Review of inputs/outputs
- Trade-Off Θ vs C vs Δ – Export vs Domestic Consumption
- Trade-Off Γ vs Z – Reuse of Produced Water

EWN Ref. Arch: Agriculture [21]



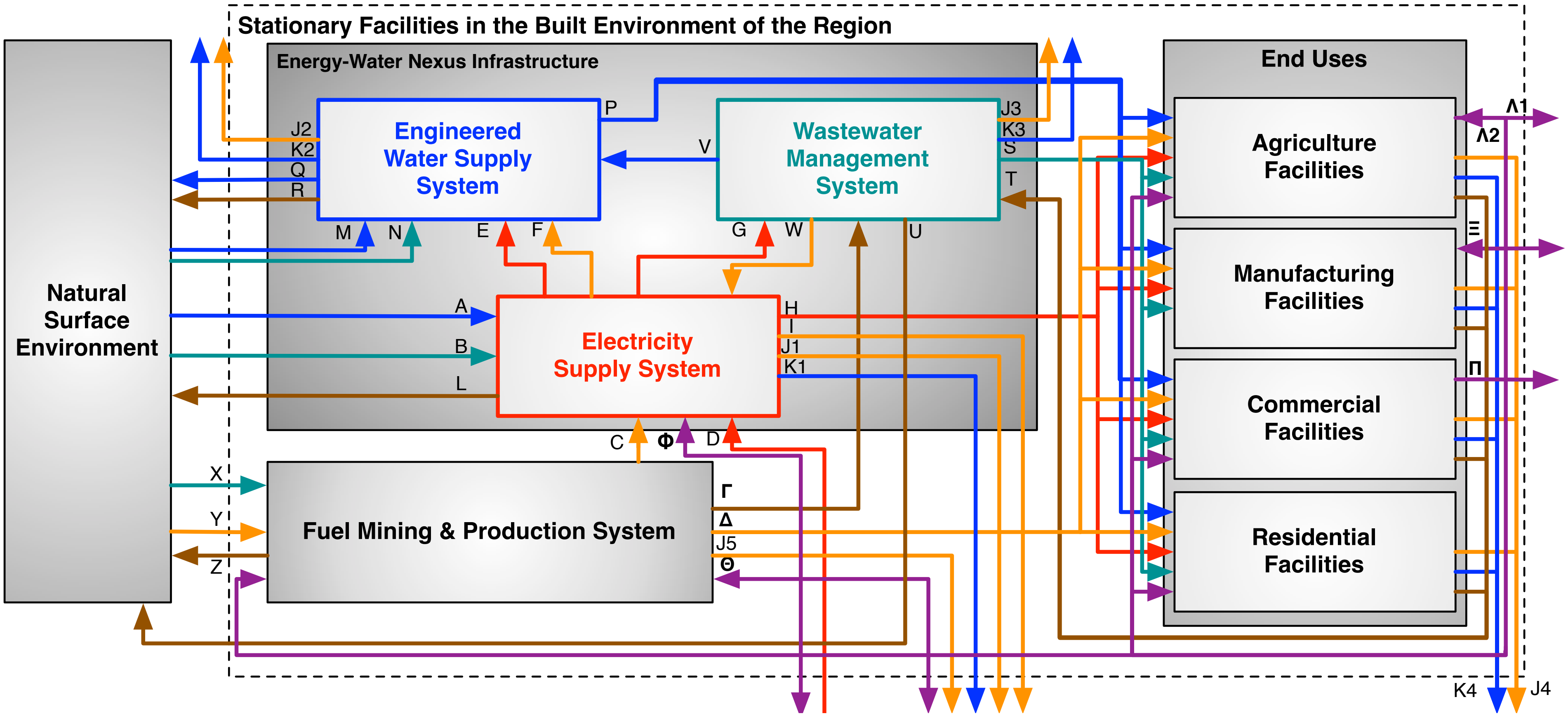
- Agricultural products have embedded water & energy
- Food energy intensity rationalizes supply chains
- Food water intensity rationalizes evaporative losses in farming
- Biofuel debate is well situated within energy-water food nexus

EWN Ref. Arch: Manufacturing [21]



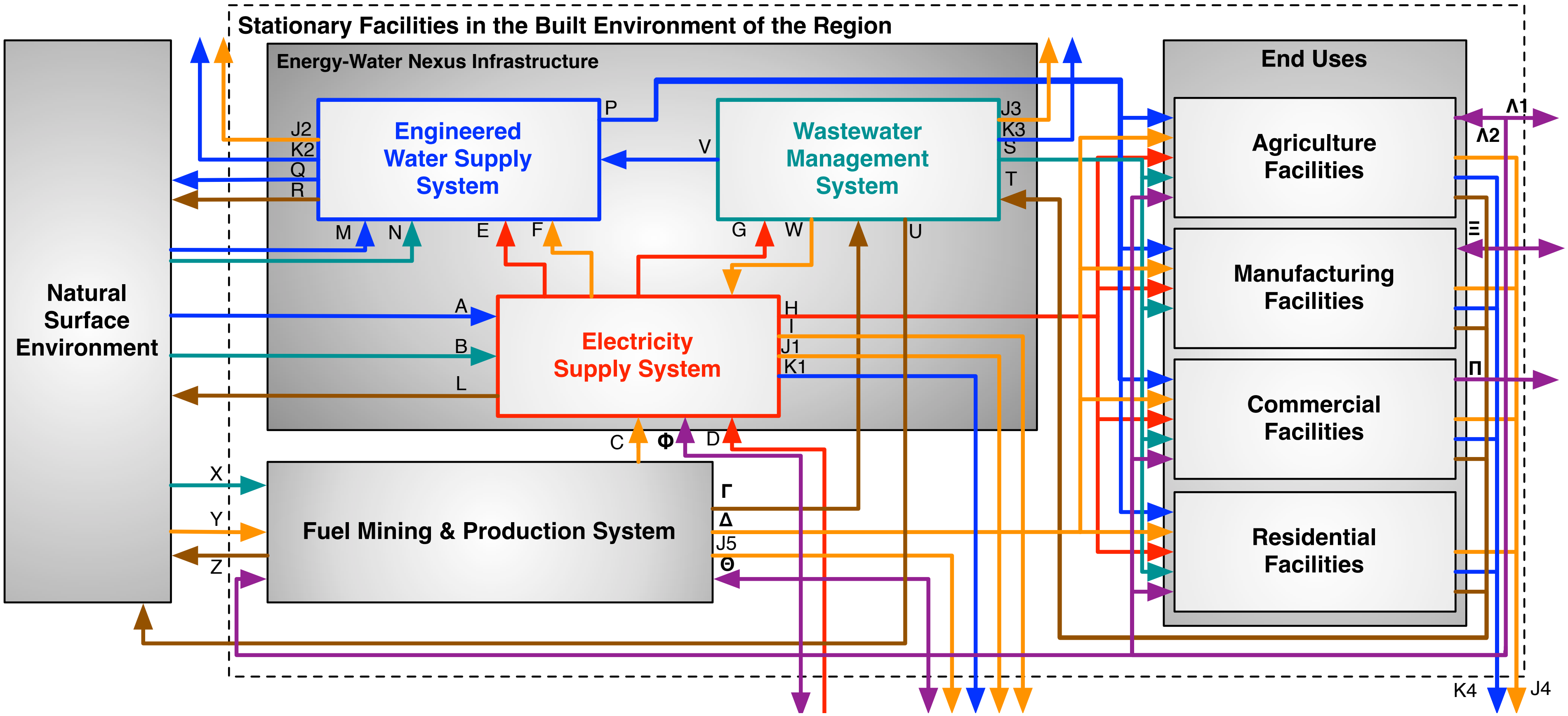
- Tremendous diversity in water & energy intensity of products
- Chemical & Metal products most energy intense
- Use of non-potable water a major opportunity
- Industrial energy management has tremendous potential

EWN Ref. Arch: Commercial & Residential Activities [21]



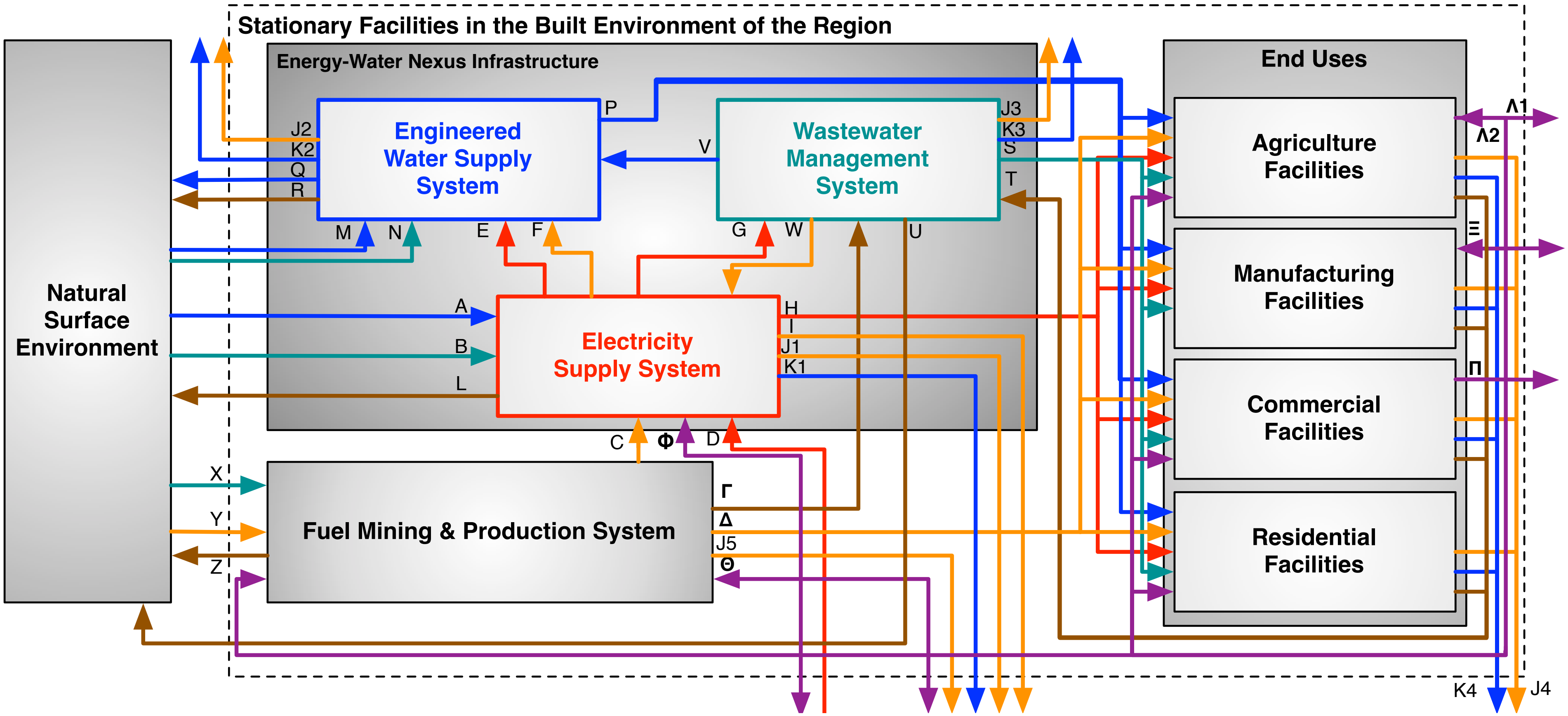
- Produced “monetized products”
- Energy – HVAC, lighting, water pumping, electronic products
- Can choose between NG and electricity
- Can choose between potable water vs grey water

EWN Ref. Arch: Role of Trade [21]



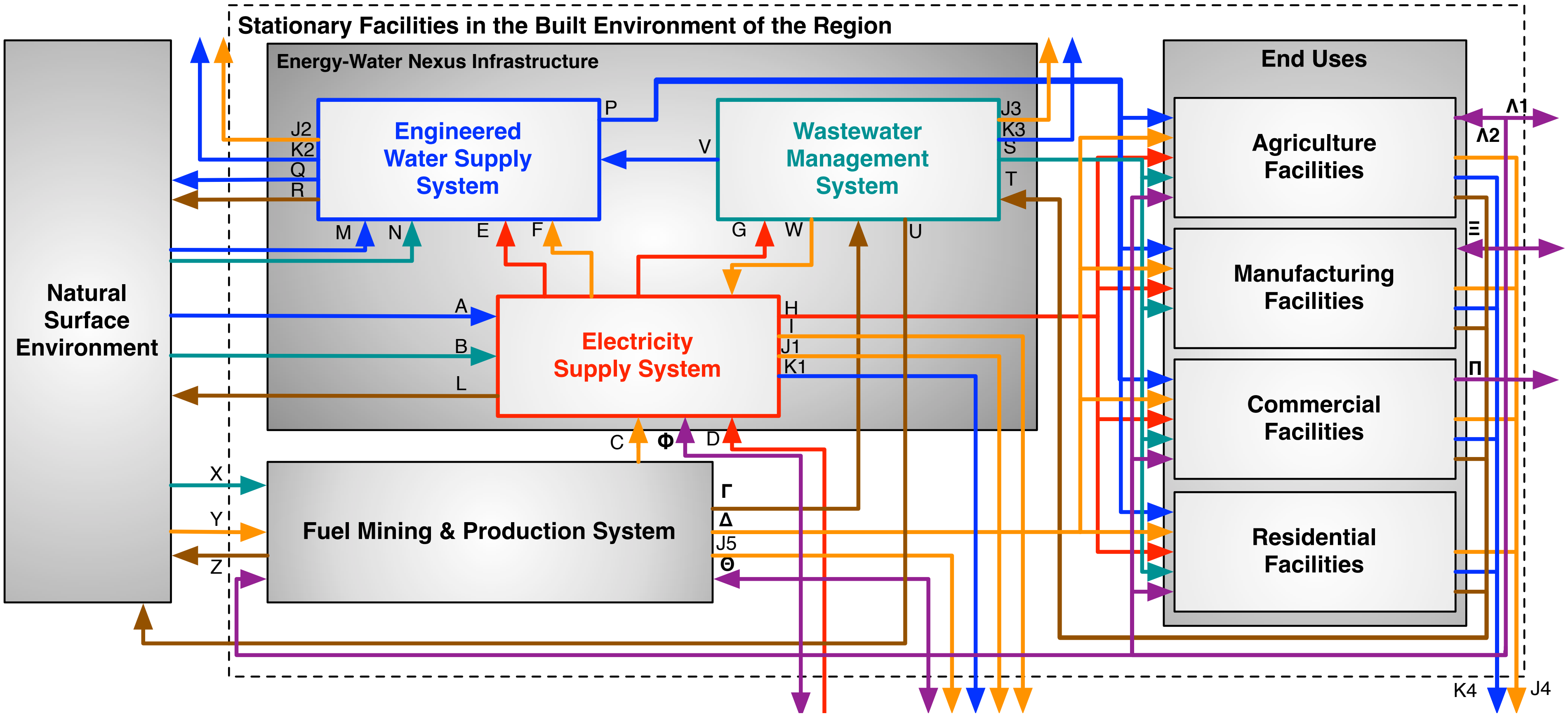
- Architecture is fundamentally an "open-system"
- Monetized products: electricity import/export Φ , fuel import/export Θ, agricultural products Λ, manufactured products Ξ, commercial products π

Conclusion [21]



- Energy-Water Nexus Reference Architecture useful for infrastructure Operators
- Now Seek to high level policy decision making -- Includes agricultural, industrial, commercial & residential activities

Conclusion [21]



- Relates economically valuable products (e.g. fossil fuels & agriculture) to energy & water streams
- Commitment to physical modeling supports infrastructure design

Discussion Topics

- Where do you see as the single greatest opportunity for making the energy-water nexus infrastructure more sustainable? *(answer: resource recovery of wastewater utilities)*
- Many regions are experiencing its greatest drought in decades, what lessons can be learned from energy-water nexus infrastructure in the GCC? *(answer: greater use & reuse of non-potable water for non-residential end-use)*
- What do you see as the role of information technology in making the energy-water nexus more sustainable (answer: need for greater IT integration to drive value in water & power)
- There is a worldwide shift towards reverse osmosis technology, does integrated energy-water planning suggest the same? (answer: depends)
- Can you elaborate on the potential for water utilities to participate in the demand side management of the future smart grid? (answer: water storage ~ energy storage)
- What role do you see for renewable energy in the energy-water nexus? (answer: renewable energy uses little water)

∴ **Holistic Thinking Enables Sustainable Development**