

Clean and Renewable Energy-Driven Microgrid Planning for Integrated Power Systems

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Introduction: The Global Picture

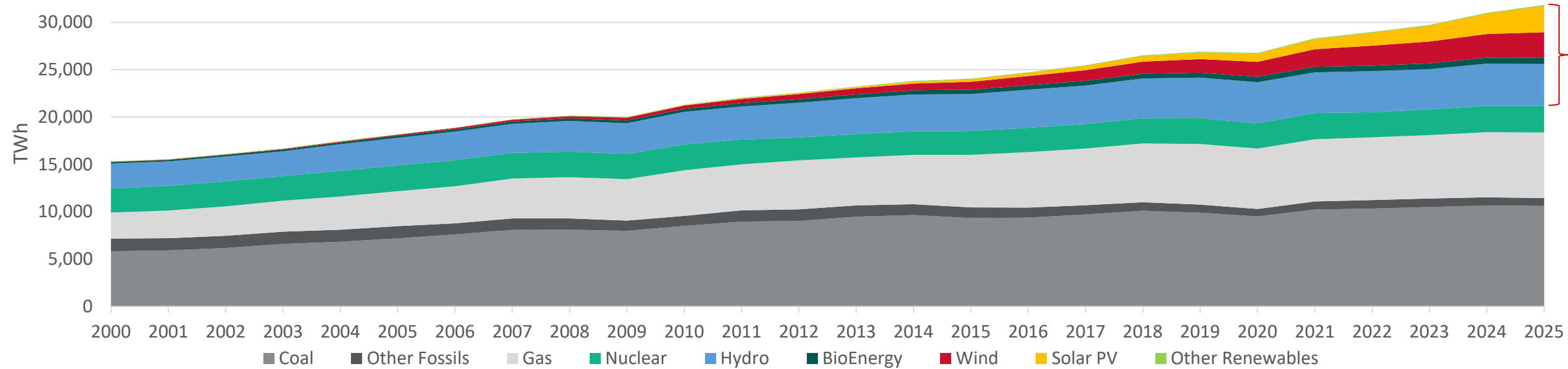


Fig.1.1 : Evolution of electricity generation sources globally since 2000

33.8%

of global electricity came from
renewables in 2025 ^[1]

85.6%

of new power capacity added in
2025 was renewable ^[2]

\$2.2T

of the \$3.3T invested in energy
went to clean energy ^[3]

945 TWh

Projected annual global datacenter
electricity consumption by
2030 ^[4.5]

The question is no longer whether to build clean and renewable infrastructure. It's how to plan it well.

Planning tools size each asset on its own and treat everything around it as fixed.



Isolated Microgrids

Renewables are intermittent, so the battery cycles constantly, every cycle degrades the battery.

TREATED AS FIXED

Battery degradation is a fixed cost

ACTUALLY DEPENDS ON

How often and how deeply it is charged and discharged



Wind farms

Wake losses range from a few percent to more than 20% of farm output.

TREATED AS FIXED

Every turbine gets the open wind, wake loss is a fixed percent

ACTUALLY DEPENDS ON

Upstream turbines, spacing and hub height



Water systems

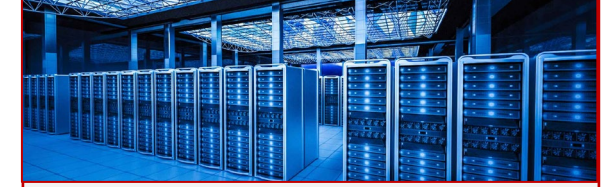
Drinking water and wastewater plants are often 30–40% of a municipality's energy use.

TREATED AS FIXED

Water treatment is a fixed electrical load

ACTUALLY DEPENDS ON

When treatment runs, and which storage can shift it



Datacenters

Every megawatt of computing becomes a megawatt of heat that has to be rejected.

TREATED AS FIXED

Cooling is a fixed share of IT load.

ACTUALLY DEPENDS ON

Chiller choice, weather, reactor heat and water

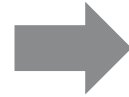
In every setting, one service depends on how another operates.

Research Question: What this research investigates

How should infrastructure be planned when one service depends on the operation of another?

Resources

-  Wind
(Ch.2 & 3)
-  Waves and tides
(Ch.2)
-  Sun
(Ch.2, 4 & 5)
-  Rain
(Ch.4 & 5)
-  Battery
(Ch. 2, 4 & 5)
-  Artificial Lake
(Ch.4 & 5)
-  Nuclear
(Ch. 5)
-  Water Treatment
(Ch. 4 & 5)



Planning decisions, made together

Capacity

what to build, and how big
(Ch.2, 3, 4 & 5)

Layout

where it goes
(Ch. 3)

Operation

how it runs, hour by hour
(Ch.2, 4 & 5)



Services people need

-  Electricity
(Ch.2, 3, 4 & 5)
-  Water
(Ch.4 & 5)
-  Cooling
(Ch.5)
-  Computation
(Ch.5)

	Previous research tells us...	...but we still don't clearly understand	To investigate these, I developed...
Chapter 2 REMO	Microgrids can be sized together with their dispatch (HOMER, REopt)	How use-based battery aging affects an offshore microgrid sizing	Multi-rating sizing with a neural-network battery-degradation loop ; tested against a benchmark
Chapter 3 WAKE-NET	Engineering wake models and 2D layout optimizers estimate and reduce wake loss	How 3D wakes, hub heights, land and cable trade off when the goal is profit	Layout, ratings, hub heights and cable under one profit objective with 3D wakes ; tested against wake-ignorant model
Chapter 4 WATTER-NEX	Coordinating water and power operation lowers cost in existing systems	How much battery capacity can water storage replace when both are sized together?	Joint sizing and hourly scheduling of six water and energy subsystems ; tested against a rule-based benchmark
Chapter 5 Hyperscale WATTER-NEX	Datacenter cooling, water footprint and workload shifting, each studied on its own	How reactor, heat, cooling, water and flexible IT work interact	One integrated model of power, cooling, water and IT workload; tested against three workload benchmark cases

Not new: joint sizing and dispatch, wake model, water-energy nexus. **New: which decisions sit inside the same optimization.**

It shows planners which interactions belong inside the model, and that keeping them changes the design of the infrastructure

Decisions last decades

Infrastructure is built once and run for 20 to 30 years, so a planning error is locked in for that long.

Trillions follow planning models

About \$2.2T goes to clean energy in 2025.
A model that misses a coupling sends capital to the wrong place.

Overbuilding has a footprint

An oversized battery, extra turbines or a bigger tank cost material, land, minerals and embodied carbon.

New loads couple everything

Datacenters and electrification tie power, cooling and water together, so planning one alone is harder to defend.

Stresses arrive together

A heat wave raises cooling load, lowers PV efficiency and can shrink the water supply, all at once.

Isolated systems have no margin

Platforms, remote communities and off-grid sites can't import power or water to cover a mistake.

REMO

Renewable Energy Microgrid Optimizer

GUIDING QUESTION

How should infrastructure be planned when one service depends on the operation of another?

By coupling...

1

generation with battery aging
REMO

2

turbines with their wakes
WAKE-NET

3

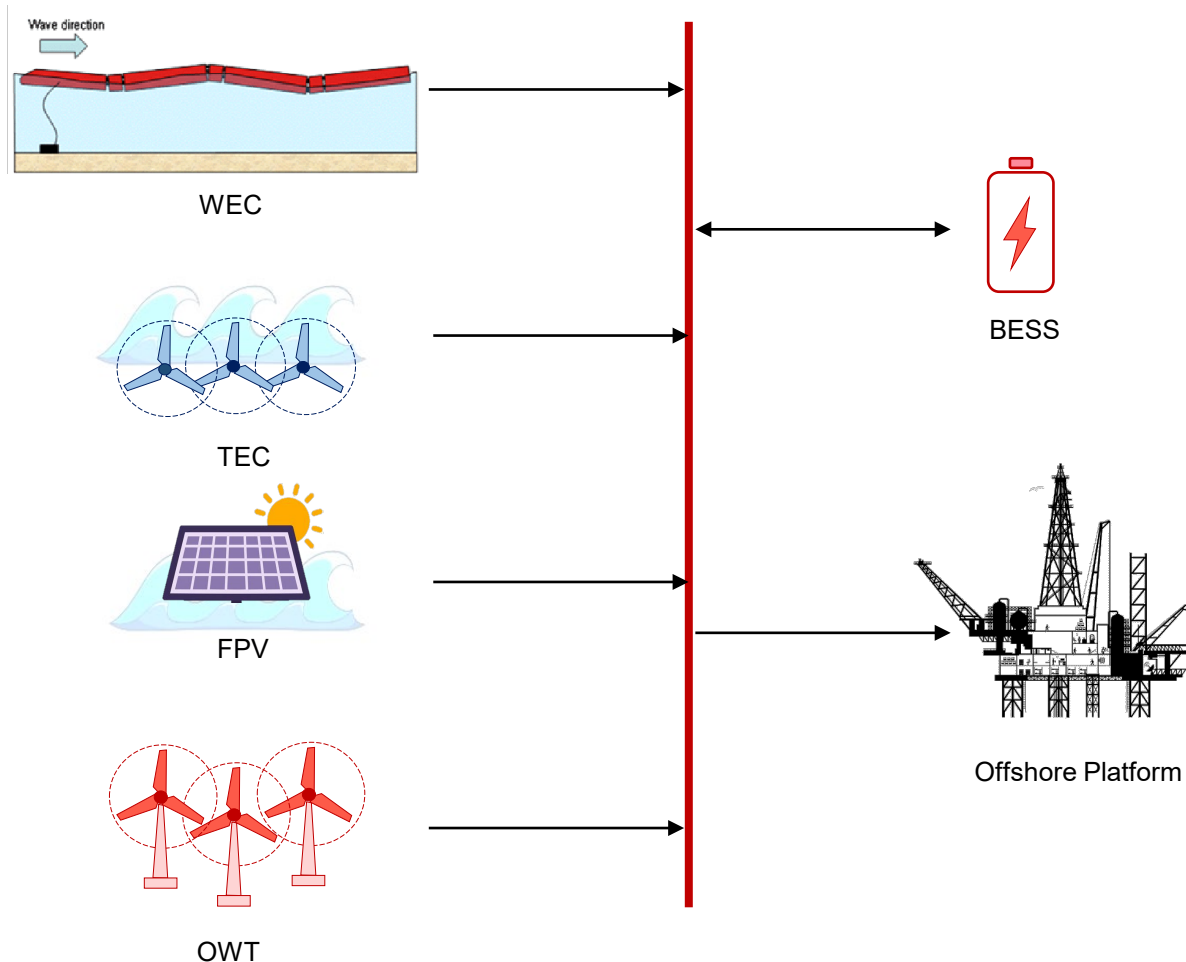
water with energy
WATTER-NEX

4

computing, cooling, water and energy
Hyperscale WATTER-NEX



Isolated offshore, coastal communities and platforms face electricity costs of 50–80¢/kWh ^[6] on diesel; 3–6× mainland rates ^[7].



Wave Energy Converters (WEC)

Floating line absorbers turn the motion of waves into power

Tidal Energy Converters (TEC)

Predictable tidal cycles; the most predictable resource.

Floating PV (FPV)

Marine grade panels, cooled by water; improved efficiency

Offshore Wind Turbines (OWT)

The most mature of the four; steadier wind than on land

Battery (BESS)

Li-ion storage that shifts surplus energy to when it is needed

Fig.2.1 : Offshore hybrid renewable energy system (OHRES) supplying a platform

How existing tools approach microgrid sizing and where they fall short:

Tool / Approach	Primary Focus	Strengths	Key Limitations
HOMER Pro ^[8]	Identify the most cost-effective configuration of resources for a microgrid	Combines multiple energy resources	Limited modeling flexibility, Not an optimization solver, Black box structure
XENDEE ^[9]	grid integration and network-level performance	Co-optimization of planning and operation	Powerful but not user friendly
Sandia Microgrid Design Toolkit ^[10]	reliability , survivability , and mission-critical performance	Mission critical system focus, scenario based design approach	excellent for resilience-driven design, but weaker for cost-focused optimization
REopt ^[11]	cost-optimal and resilient planning , for grid-connected sites	Integrated economic + resilience analysis	site-level optimization rather than network-level analysis

Identified Gaps:

- (1) Cost does not account for overall lifetime cost;
- (2) Do not truly optimize across multiple discrete capacity classes within the same technology;
- (3) Battery degradation is simplified to a fixed cost share or replacement interval

Objective: $\min F(\text{Lifetime Cost}) = [f(C^{\text{Precom}}) + f(C^{\text{Capital}}) + \{f(C^{\text{O\&M}}) \times T_e\} + f(C^{\text{Decom}})] + f(C^{\text{BESS Deg}})$

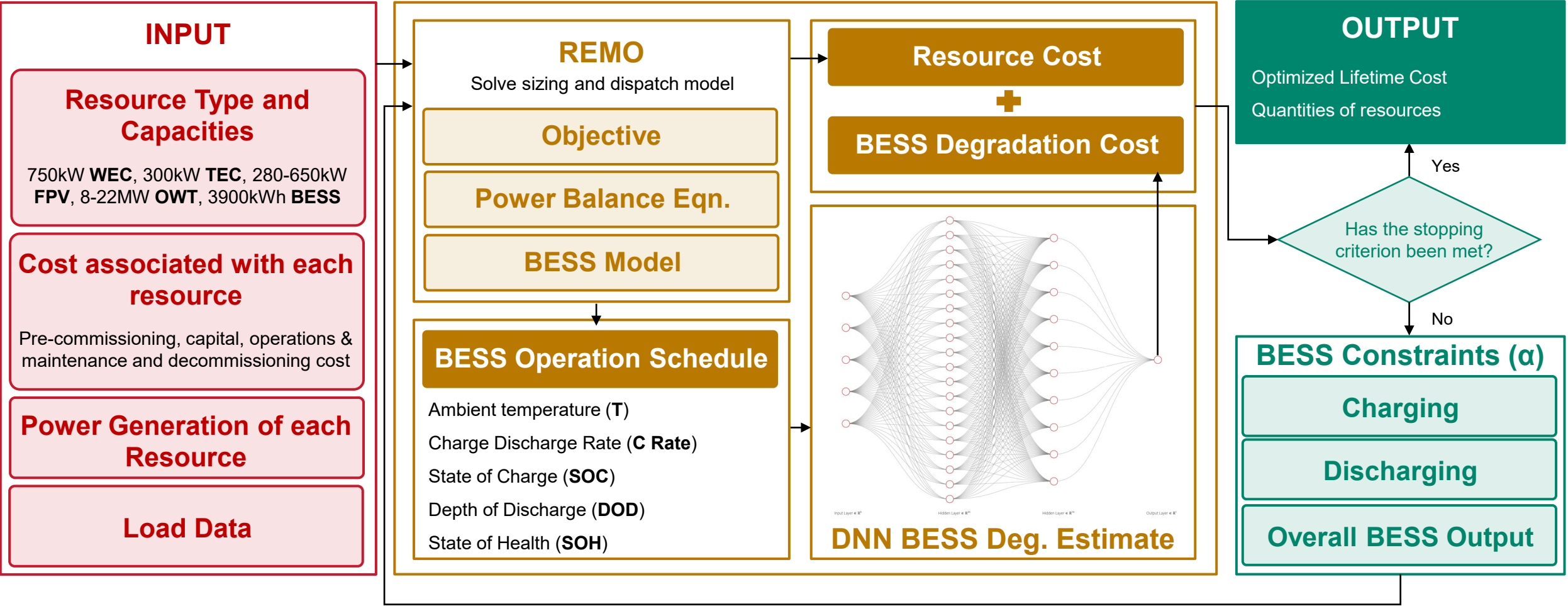


Fig.2.2 : REMO-DNN-BD Model



- Case 1: Texas
- Case 2: Alaska
- Case 3: California
- Case 4: Florida
- Case 5: Hawaii
- Case 6: New Jersey

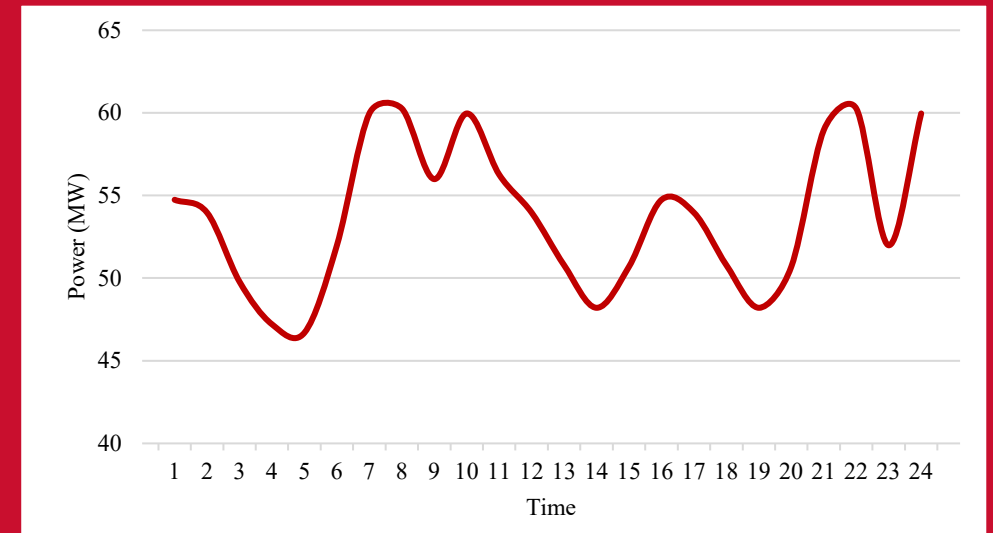


Fig. 2.3: Electricity Consumption Profile* for Offshore Platform
(Y-axis range 40-65 MW)

**the Electricity Consumption Profile for the offshore O&G rig is from a research paper*

The historical data taken to calculate the electrical power (electricity) that can be generated from the different energy conversion resources are from NDBC, NOAA and NREL

- Levelized Cost of Electricity (LCOE) is a measure of the average cost of generation of electricity from a generator over its lifetime.

$$LCOE = \frac{\text{Sum of Cost over a lifetime}}{\text{Sum of Electrical Energy Produced over a lifetime}}$$

Asset	Levelized Cost of Energy (¢/kWh)					
	TX	AK	CA	FL	HI	NJ
WEC	172.5	44.2	87.6	109.5	67.1	155.1
TEC	1653.3	448.7	-	83.2	3427.2	33527.0
OWT	6.3	4.5	6.2	6.0	5.2	5.7
FPV	7.8	12.4	7.3	8.1	7.7	9.0

Legend:

FPV : Floating Photovoltaics

OWT: Offshore Wind Turbines

TEC : Tidal Energy Converters

WEC : Wave Energy Converters

BESS: Battery Energy Storage Systems

LCOE: Levelized Cost of Electricity

Optimized lifetime cost and quantities of energy generation resources for offshore oil and gas platforms

- Offshore platform load: 1,290 MWh/day for 20 years.
- Wave and tidal: not selected in any region

Region	Lifetime cost	Wind turbines chosen	Floating PV	Battery
Texas	\$741.7M	1 × 8 MW + 6 × 16 MW	9 × 650 kW + 1 × 280 kW	171,600 kWh
Alaska	\$478.2M	1 × 8 MW + 4 × 16 MW	1 × 650 kW	74,100 kWh
California	\$647.2M	2 × 16 MW + 3 × 22 MW	1 × 650 kW + 1 × 280 kW	101,400 kWh
Florida	\$728.9M	5 × 22 MW	1 × 280 kW	97,500 kWh
Hawaii	\$592.1M	2 × 16 + 1 × 18 + 2 × 22 MW	—	66,300 kWh
New Jersey	\$724.3M	1 × 16 MW + 4 × 22 MW	22 × 280 kW	117,000 kWh

- No single design fits every site.
- The largest turbine isn't automatically chosen.
- The battery is sized by the variability left after the generation mix.

Savings - Texas Platform

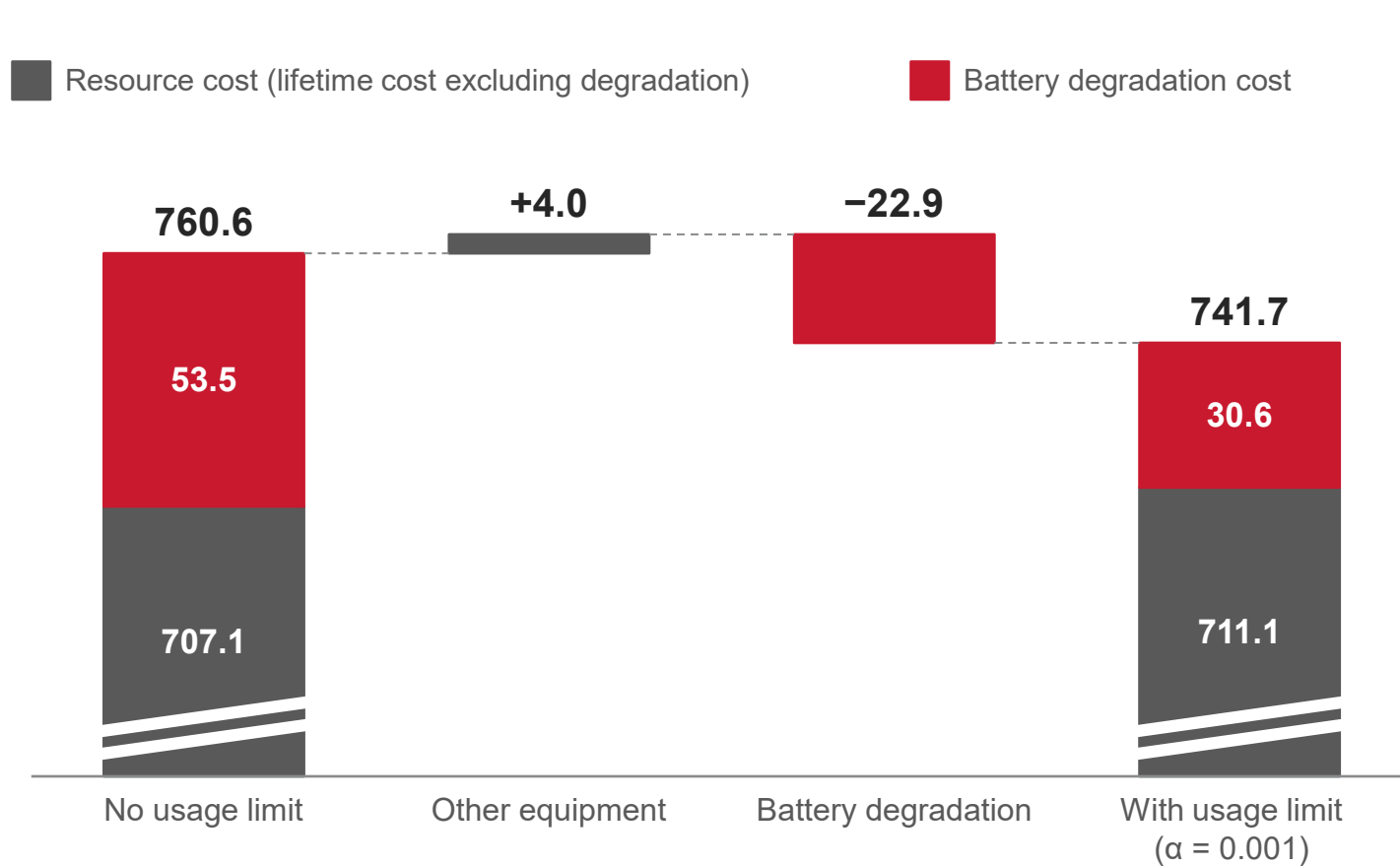


Fig.2.4: Texas platform lifetime cost with and without a battery-usage limit (\$M) y-axis starts at \$650M

Assets	No constraint
Lifetime Cost (M\$)	760.6
BESS Deg. Cost (M\$)	53.5
Resource Cost (M\$)	707.1
8MW OWT	1
11MW OWT	0
14MW OWT	0
16MW OWT	6
18MW OWT	0
22MW OWT	0
650kW FPV	7
280kW FPV	0
BESS (kWh)	171,600

By coupling generation with battery aging: degradation cost was reduced by 42.8% and lifetime cost decreased by \$18.9M

- ✓ Developed a **lifecycle cost optimization framework** that captures the full offshore microgrid cost from pre-commissioning and installation through operation, maintenance, replacement, and decommissioning.
- ✓ Enabled simultaneous optimization across **multiple discrete capacity** classes for four **marine renewable technologies** (WEC, TEC, OWT, and FPV) allowing both technology type and capacity size to be selected jointly.
- ✓ Integrated a **novel DNN-based battery degradation (DNN-BD) model** that captures five nonlinear aging factors, replacing simplified fixed degradation costs or predetermined replacement intervals.
- ✓ Demonstrated up to a **43% reduction in BESS degradation cost** through degradation-aware sizing and operation.
- ✓ **Validated the framework** across six diverse U.S. offshore regions, providing practical design insights for offshore platforms and coastal energy applications.

Publications

1. **A.M. Toms**, X. Li, K. Rajashekara — 'Optimal microgrid sizing of offshore renewable energy sources for offshore platforms and coastal communities,' *Sustainable Energy, Grids and Networks*, Vol. 44, 2025.
2. **A.M. Toms**, X. Li, K. Rajashekara — 'Optimal Sizing of On-Site Renewable Resources for Offshore Microgrids,' 2023 *North American Power Symposium (NAPS)*, Asheville, NC.

WAKE-NET

3D Wake Aware Wind Farm Optimizer

GUIDING QUESTION

How should infrastructure be planned when one service depends on the operation of another?

By coupling...

- 1 generation with battery aging
REMO
- 2 **turbines with their wakes**
WAKE-NET
- 3 water with energy
WATTER-NEX
- 4 computing, cooling, water and energy
Hyperscale WATTER-NEX



Air passing through a wind turbine loses speed, creating a turbulent, lower-speed airflow behind it - wake. This reduces the efficiency of downstream turbines

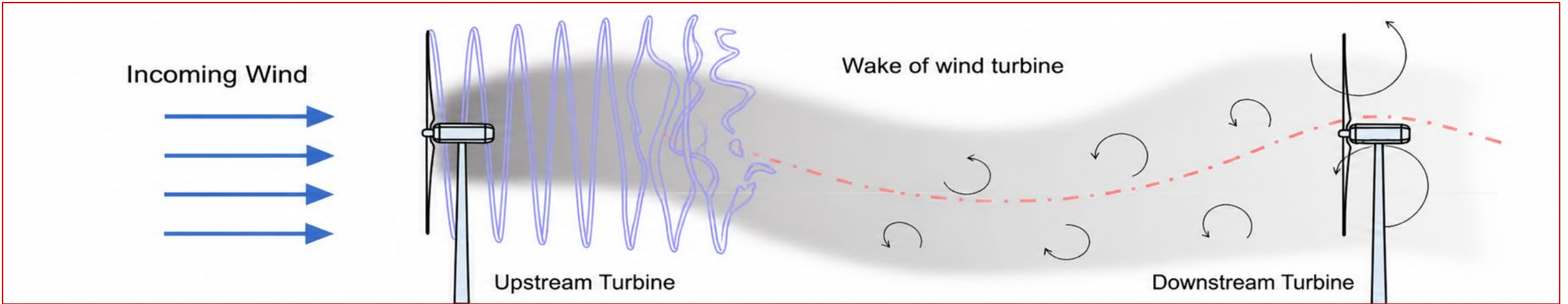


Fig.3.1 : Wake Effect on Downstream Turbine

What governs a wake

- Wind speed and direction
- turbulence intensity
- atmospheric stability
- Turbine spacing
- rotor diameter
- hub height

All are site-specific

Two ways to reduce wake loss

Turbine control: individual pitch control; wake steering (yawing turbines to deflect the wake)

Layout: spacing, and multiple hub heights that stagger turbines vertically (this chapter)

- How existing tools approach the wake aware wind farm layout optimization and where they fall short:

Tool / Approach	Primary Focus	Strengths	Key Limitations
WindSim ^[12]	CFD-based wind resource & AEP analysis	High-fidelity flow & terrain modeling; 3D wake	Computationally intensive
TOPFARM ^[13]	Economic wind farm layout optimization	Includes aeroelastic & cost-load trade-offs	Uses only flat homogeneous terrain, computationally intensive, 2D wake
WindFLO ^[14]	Fast layout optimization for AEP maximization	Computationally efficient, multi-model	Low-fidelity wake; no dynamic effects; 2D wake
Energy, Cost and Heuristic Layout Studies	Maximize power, minimize LCOE, search layouts with GA/PSO	Broad range of search methods (GA, PSO, gradient, greedy) that handle non-linear wakes	Count, rating or hub height fixed before the search; wakes checked after; economics secondary

Identified Gaps:

- (1) Reliance on simplified, steady-state 2D wake models
- (2) No unified framework optimizing layout, hub height, turbine mix, and electrical design together.

WAKE-NET: 3D Wake-aware wind farm optimizer

Objective: *max Profit = Revenue – annualized investment (turbines + land + cable)*

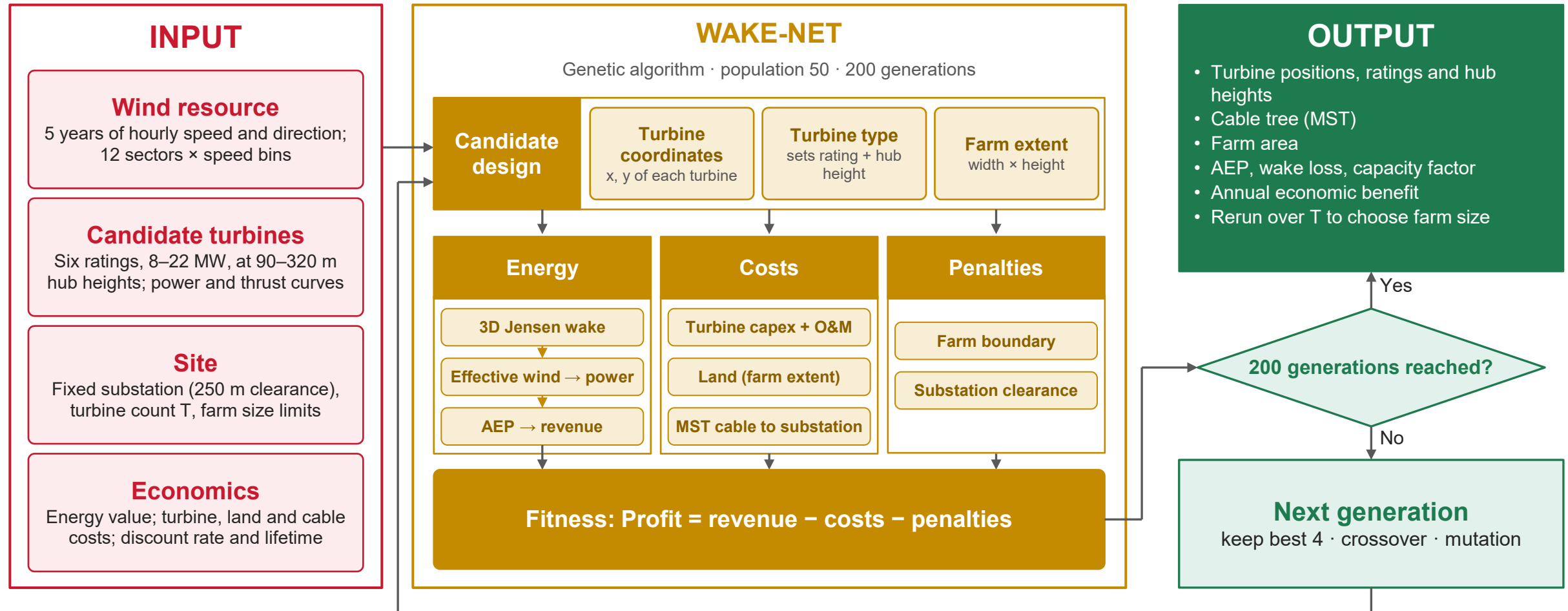


Fig.3.2 : WAKE-NET Model

Legend:

AEB : Annual Economic Benefit (Profit)

APB: Annual Production Benefit (Revenue)

AEP : Annual Energy Production



OFFSHORE

- Case 1: Alaska
- Case 2: Hawaii
- Case 3: Texas
- Case 4: California
- Case 5: New Jersey

ONSHORE

- Case 1: Texas
- Case 2: Kansas
- Case 3: Wyoming
- Case 4: Indiana

INPUT · THE WIND

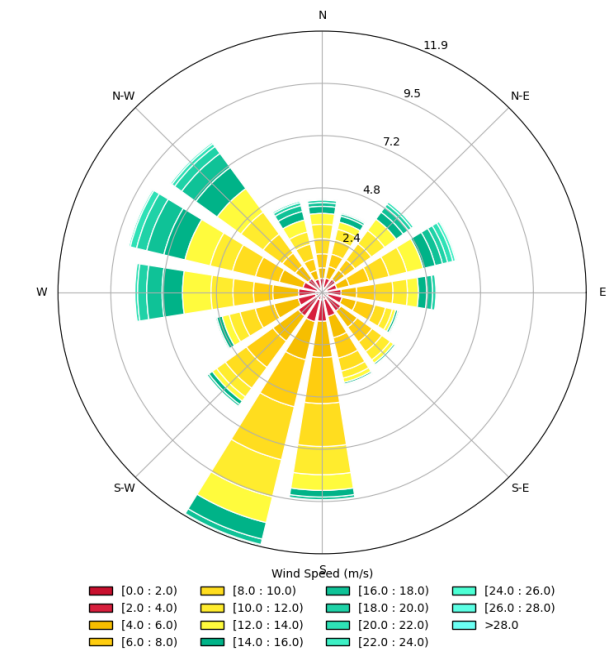


Fig.3.3 : Wind Rose

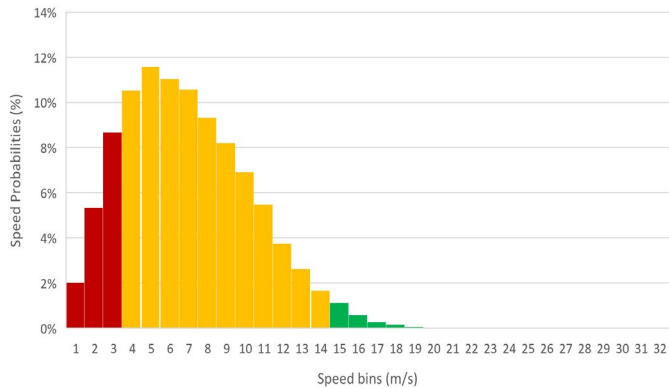


Fig.3.4 : Wind Speed Probability

OUTPUT · THE LAYOUT

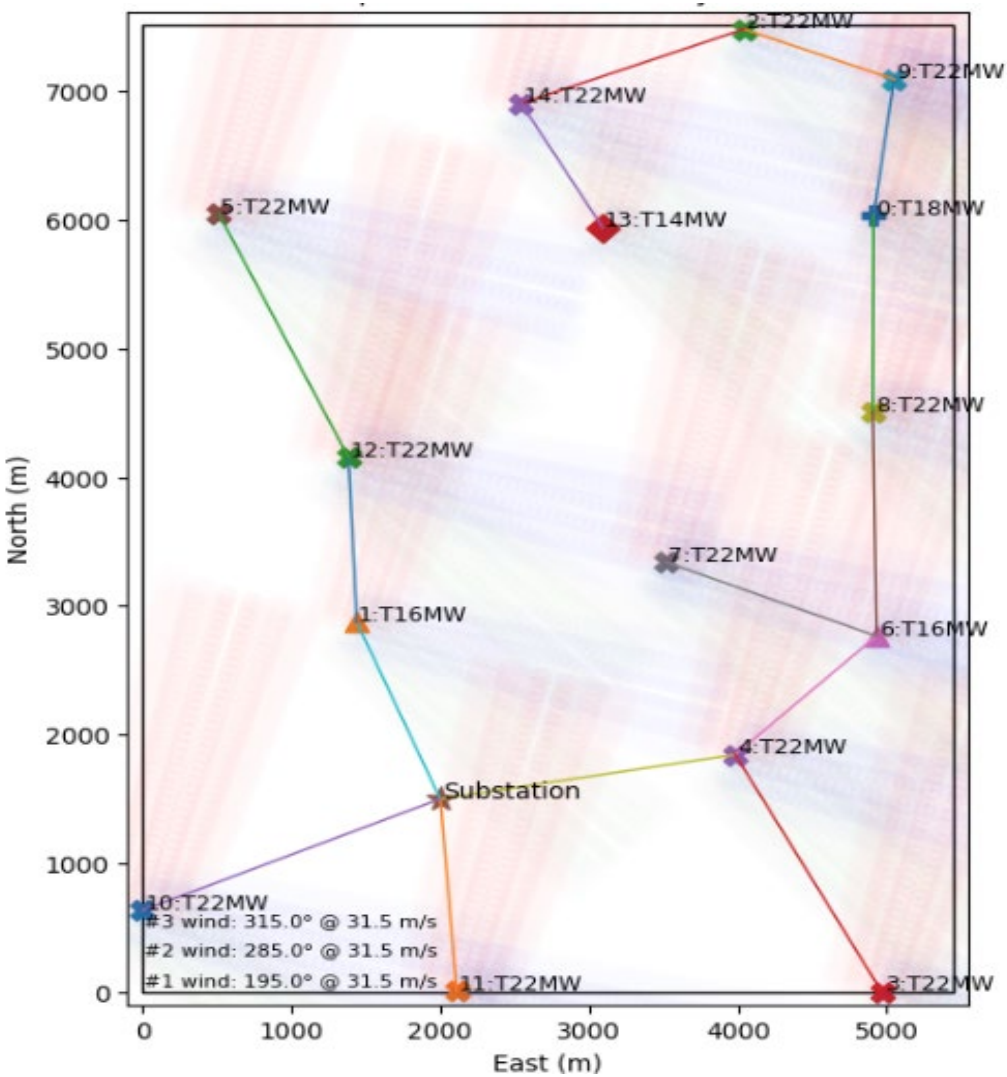


Fig.3.5 : Optimized 15 Turbine Layout

RESULTS

Parameter	New Jersey
Mean wind at 80 m	8.98 m/s
Turbines (count × MW)	11×22, 1×18, 2×16, 1×14
Capacity	306 MW
AEP	1,056.32 GWh/yr
Capacity factor	39.4%
Farm area	40.99 km ²
Cable length (MST)	23.61 km
Revenue (APB)	433.09 M\$/yr
Land cost	204.96 M\$/yr
Turbine cost (capex+O&M)	118.87 M\$/yr
Cable cost	0.67 M\$/yr
AEB = APB – costs	108.59 M\$/yr

What to notice

- Winds split between south-southwest and northwest, so no row lines up out of every wake
- High mean wind but lower most-frequent speeds: the optimizer mixes in 14–18 MW turbines

Optimized wind farm costs and capacities for offshore application UNIVERSITY OF HOUSTON

- 15 turbines at every site, the same six-rating menu and the same prices.

Site	Wind, 80 m (m/s)	Turbines (count × MW)	Capacity (MW)	AEP (GWh/yr)	Capacity factor	Farm area (km ²)	AEB (M\$/yr)
Alaska	11.05	14×22, 1×18	326	1,549.71	54.3%	39.13	313.25
Hawaii	9.27	12×22, 2×18, 1×16	316	1,197.53	43.3%	48.67	124.64
Texas	7.63	14×22, 1×18	326	1,139.34	39.9%	46.47	108.21
California	7.28	13×22, 1×18, 1×16	320	992.78	35.4%	46.20	51.59
New Jersey	8.98	11×22, 1×18, 2×16, 1×14	306	1,056.32	39.4%	40.99	108.59

Alaska

Strongest wind: 54% capacity factor and the highest benefit, on the smallest farm

Texas

The same capacity (326 MW), but a third of Alaska's profit

New Jersey

Higher mean wind than Texas, yet fewer large turbines: its most frequent speeds are lower

Legend:

AEB : Annual Economic Benefit (Profit)

APB: Annual Production Benefit (Revenue)

AEP : Annual Energy Production

Optimized wind farm costs and capacities for onshore application

- 15 turbines at every site, the same six-rating menu and the same prices.

Site	Wind, 80 m (m/s)	Turbines (count × MW)	Capacity (MW)	AEP (GWh/yr)	Capacity factor	Farm area (km ²)	AEB (M\$/yr)
Texas	7.28	11×22, 1×18, 1×14, 1×11, 1×8	293	823.18	32.1%	40.45	20.25
Kansas	7.09	9×22, 2×18, 4×16	298	803.78	30.8%	36.39	30.99
Wyoming	6.96	12×22, 1×16, 2×11	302	893.60	33.8%	44.25	27.04
Indiana	4.02	5×22, 1×18, 3×16, 1×11, 5×8	227	193.27	9.7%	37.11	−198.21

Wyoming

Lowest mean wind of the three profitable sites, yet the most energy (894 GWh/yr)

Kansas

Less energy, but the smallest site (36.4 km²) and shortest cable (19.2 km): the most profit

Indiana

4.02 m/s and a 9.7% capacity factor:
−\$198M/yr under the base assumptions

Legend:

AEB : Annual Economic Benefit (Profit)

APB: Annual Production Benefit (Revenue)

AEP : Annual Energy Production

What ignoring wake costs

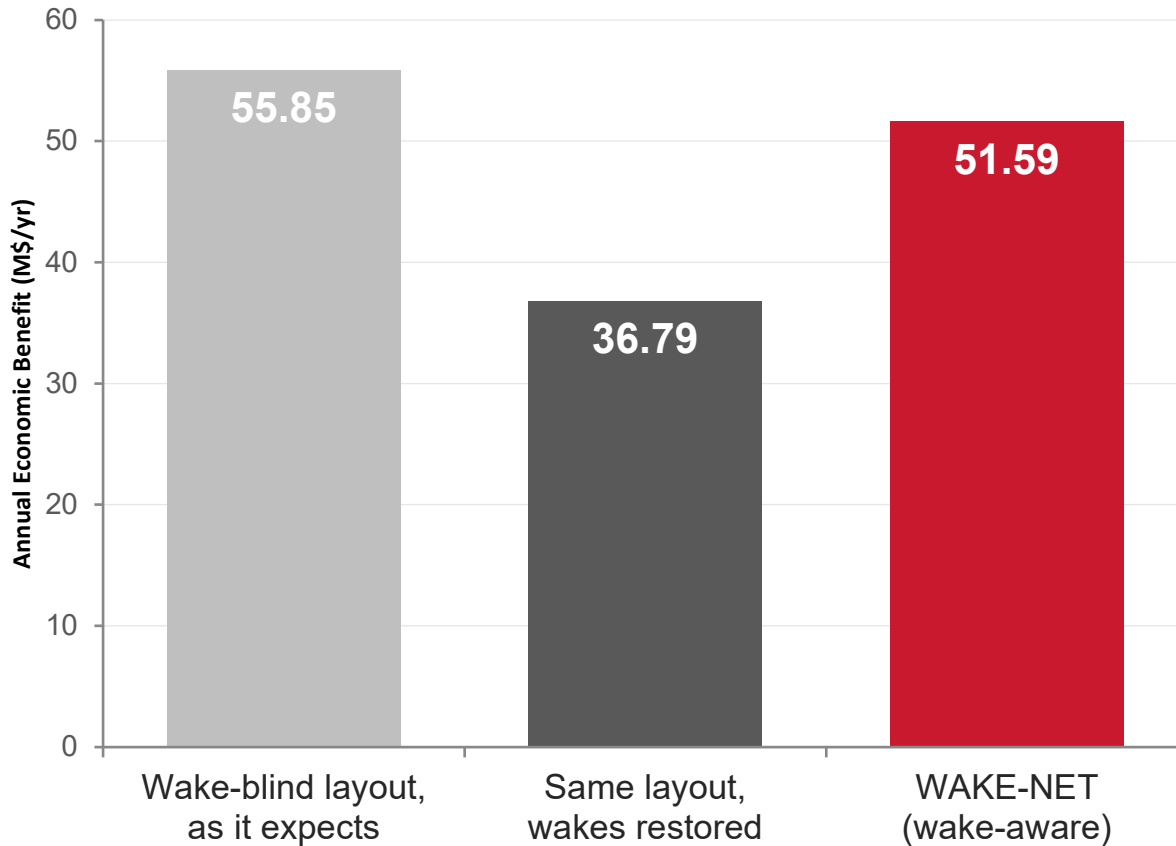


Fig.3.6: Comparison of wake aware and wake ignorant AEB in California

Parameter	Wake-aware (WAKE-NET)	Wake-ignorant	
		no wakes	Post optimization wake
AEP (GWh/yr)	992.78	972.98	926.50
APB (M\$/yr)	407.04	398.92	379.87
Farm capacity (MW)	320 13×22, 1×18, 1×16	304 10×22, 2×18, 3×16	
Capacity factor (%)	35.42	36.54	34.79
Farm area (km ²)	46.20	44.87	
Cable length (km)	24.48	19.99	
Land cost (M\$/yr)	230.99	224.33	
Cable cost (M\$/yr)	0.69	0.57	
Turbine cost (M\$/yr)	123.76	118.17	
AEB (M\$/yr)	51.59	55.85	36.79

WAKE-NET achieves 40.2% higher AEB per year than the wake-ignorant layout. Equivalent to approximately \$296M additional profit over a 20-year project lifetime

- ✓ **Jointly optimize** turbine layout, multi-hub-height selection, turbine capacity mix, and MST cable routing within a single profit-maximizing GA objective function
- ✓ **3D Jensen wake** incorporating hub-height differences; enabling vertical turbine staggering as a design variable
- ✓ Demonstrated **40.2% higher annual AEB** from wake-aware vs. wake-ignorant layout, equivalent to ~\$296M additional profit over a 20-year project lifetime in the California case

Publications

1. **A. M. Toms** and X. Li, “WAKE-NET: A 3D-wake-aware economic turbine layout and cabling optimization framework for multi-capacity multi-hub-height wind farms serving grid-scale and industrial power systems,” *Renewable Energy*, vol. 273, Oct. 2026, doi: 10.1016/j.renene.2026.126078.

WATTER-NEX

Community Scale Water-Energy Nexus
Microgrid Optimizer

GUIDING QUESTION

How should infrastructure be planned when one service depends on the operation of another?

By coupling...

- 1 generation with battery aging
REMO
- 2 turbines with their wakes
WAKE-NET
- 3 **water with energy**
WATTER-NEX
- 4 computing, cooling, water and energy
Hyperscale WATTER-NEX



Water is needed to produce electricity; electricity is needed to produce water

**Off-grid communities
face double scarcity**

2.1 billion

people lacked safely managed drinking
water in 2024 ^[15]

730 million

people lacked electricity in 2024 ^[16]



Electricity for water

- Pumping, treatment, distribution and wastewater recovery are all electrical loads
- Treated water can be produced early and stored, so that load can move in time



Water for electricity

- Power plants need water for cooling
- Dust on PV panels cuts output, and cleaning them takes water and pumping energy

- How existing tools approach the water-energy nexus and where they fall short:

Tool / Approach	Primary Focus	Strengths	Key Limitations
Nexus Solutions Tool (NEST) ^[17]	Regional-scale Energy–Water–Land system planning	Integrated multi-sector, physics-informed optimization	Limited operational detail; linear; coarse resolution
WEF Nexus Tool 2.0 ^[18]	Scenario-based resource allocation assessment	Simple, intuitive, trade-off visualization	No optimization; no system level modeling
MicroWEF ^[19]	Community-scale integrated system design	Detailed, nonlinear co-optimization of Energy–Water–Food systems	Case-specific; limited scalability; community is linear

Identified Gaps:

- (1) Incomplete representation of interconnected water subsystems
- (2) lack of explicit bi-directional water–energy coupling
- (3) absence of high-resolution operational modeling
- (4) simplified water infrastructure cost behavior

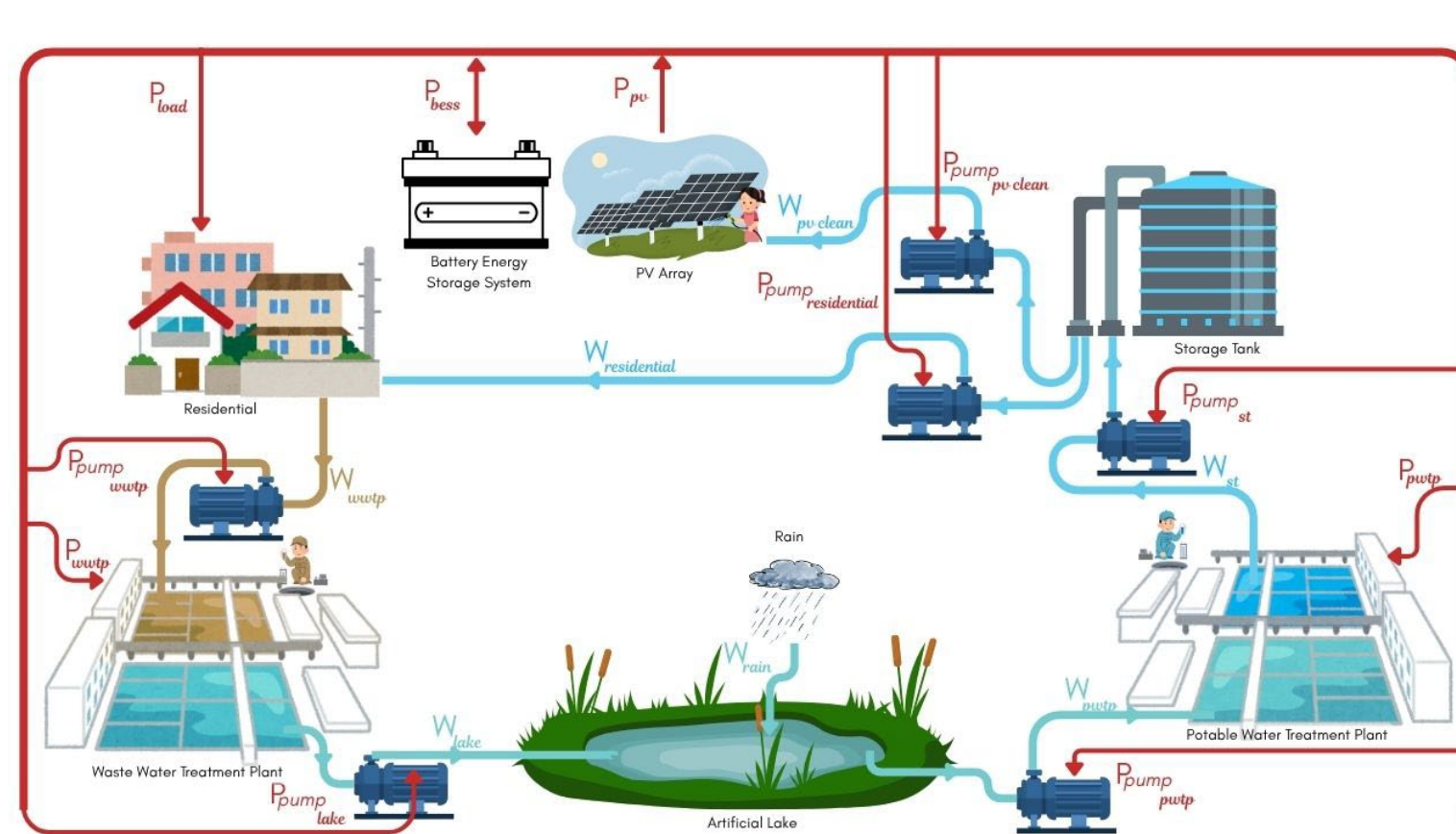


Fig. 4.1 Overall architecture of the WATTER-NEX framework

PV array

The only generator: powers homes and plants, and needs water for cleaning

Battery (BESS)

Shifts surplus solar electricity to the evening and night

Artificial lake

Collects rainfall and recovered wastewater, and holds raw water for dry spells

Potable water treatment plant (PWTP)

Treats raw water: a flexible electrical load that can run when the sun is up

Storage tank (ST)

Holds treated water, so production can be separated from consumption

Wastewater treatment plant (WWTP)

Treats residential wastewater and returns it to the lake

PV Array

Generates electricity from solar irradiance. Soiling accumulates dust over time reducing output. Cleaning events restore performance. Cleaning consumes water drawn from storage tank.

Role: Energy source; soiling couples energy to water demand

BESS

Stores excess PV energy; discharges to meet electrical load including all water pump demands.

Role: Energy buffer; cycling intensity driven by water pump load

Artificial Lake

Collects rainfall and overflow. Primary water source feeding PWTP. Water balance: inflow (rain, WWTP recirculation) vs. outflow (PWTP intake). Power required for pumping.

Role: Primary water reservoir; rain inflow is stochastic input

PWTP

Treats raw lake water to potable standard. Flow rate is a decision variable. Must meet residential and cleaning demand. Electrical power proportional to throughput.

Role: Potable water producer; major electricity consumer

Storage Tank

Buffers treated potable water between PWTP output and water demand. Sized to absorb hourly demand variability. Water balance enforced at each time step

Role: Decouples treatment timing from residential consumption

WWTP

Treats residential wastewater before discharge. Flow rate proportional to residential consumption. Electrical power demand from treatment process included in the power balance.

Role: Closes the water cycle; secondary electricity consumer

Objective: $\min \textit{lifetime cost} = C_{PV} + C_{BESS} + C_{lake} + C_{PWTP} + C_{ST} + C_{WWTP}$

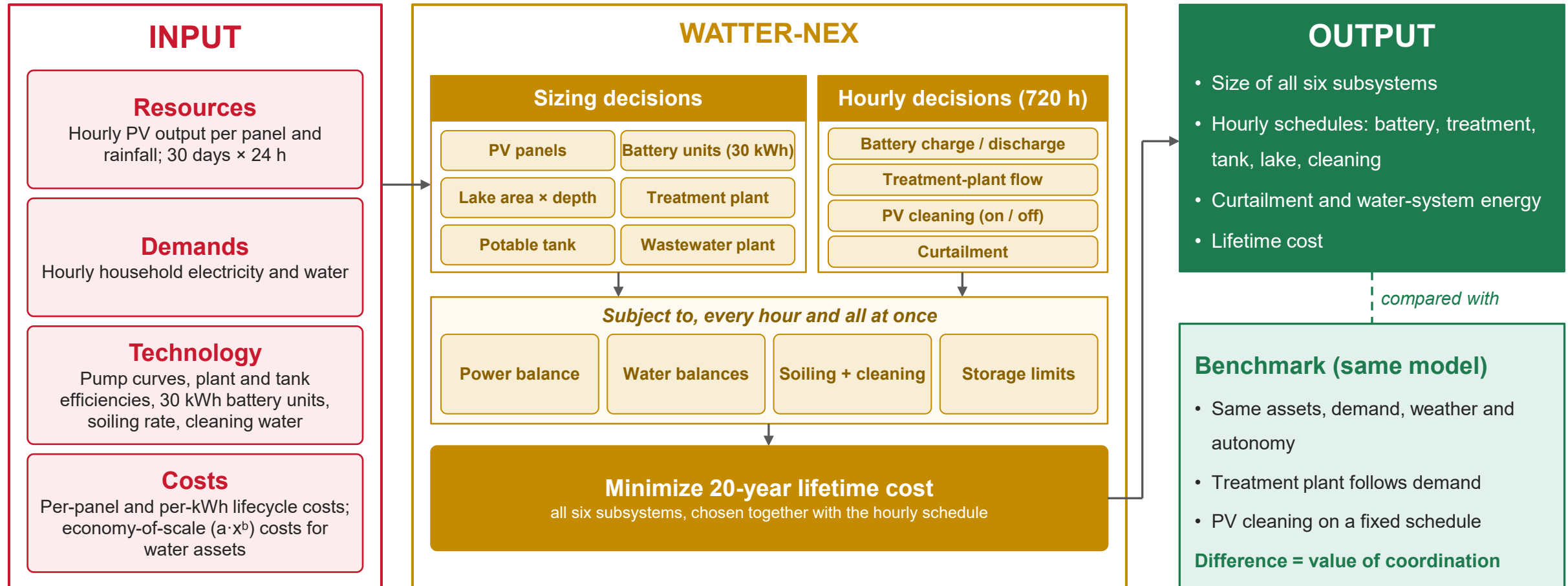


Fig.4.2 : WATTER-NEX Model

Legend:

PV: Photovoltaic Panel

BESS : Battery Energy Storage System

PWTP: Potable water treatment plant

ST: Storage Tank

lake: Artificial lake

WWTP : Waste Water Treatment Plant

Input and Results

Days 1–6 of the 30-day horizon

1 Sun and rain

— PV output per panel (kW)
-- Rain (mm/h)

2 Treatment and lake

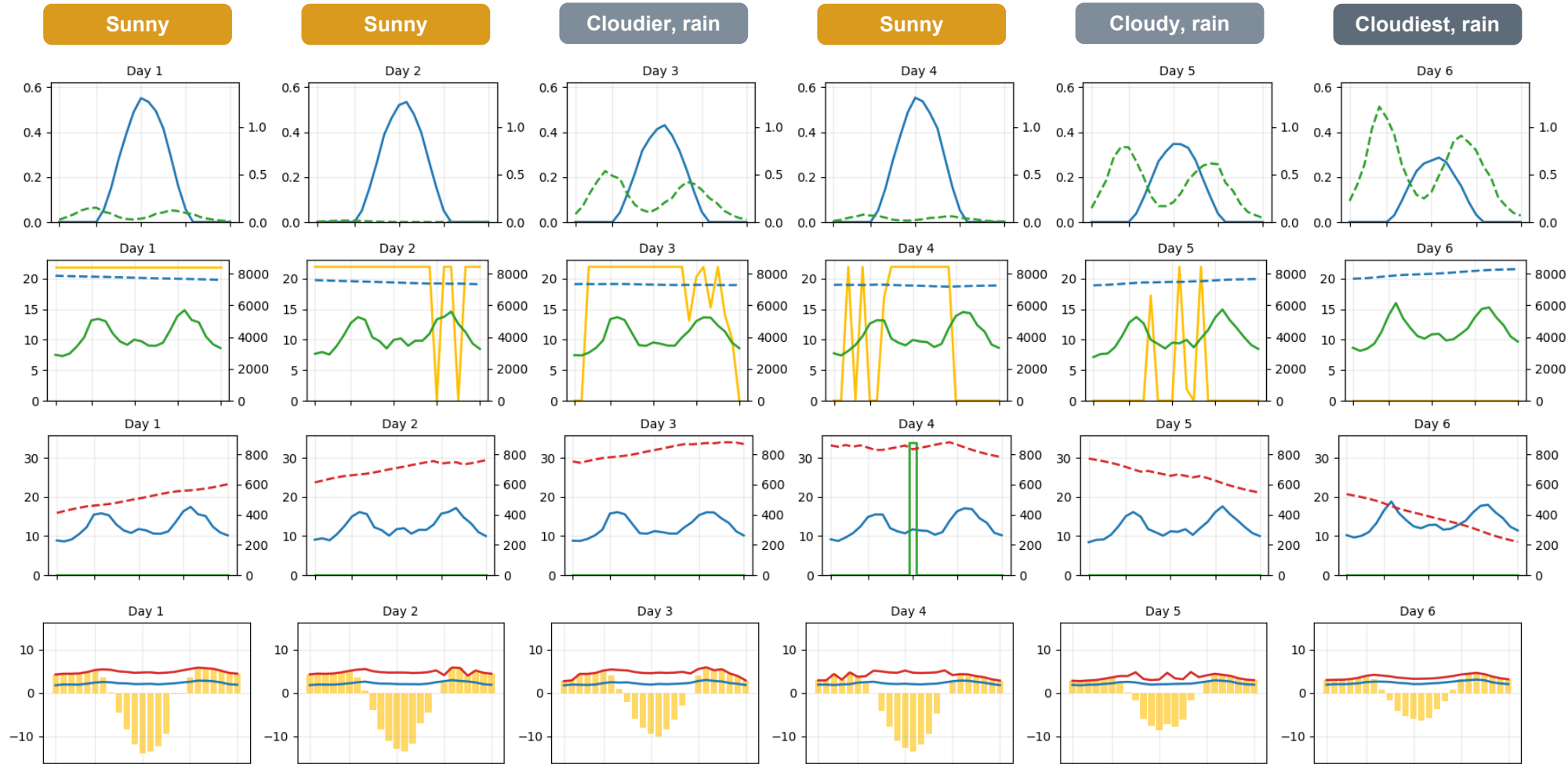
— Treatment plant (gal/h)
— Wastewater plant (gal/h)
-- Lake (gal, right axis)

3 Potable tank

— Household water (gal/h)
— PV cleaning water (gal/h)
-- Tank (gal, right axis)

4 Electricity

— Homes (kW)
— Total demand (kW)
■ Battery (kW; below 0 = charging)



Days 1–4, mostly sunny: the treatment plant runs hard and the tank fills to about 850 gal, its full size

Days 5–6, cloudy: the plant mostly rests; the tank drains to about 200 gal

Fig.4.3 : Day 1-6 of the 30 day horizon in the WATTER-NEX community

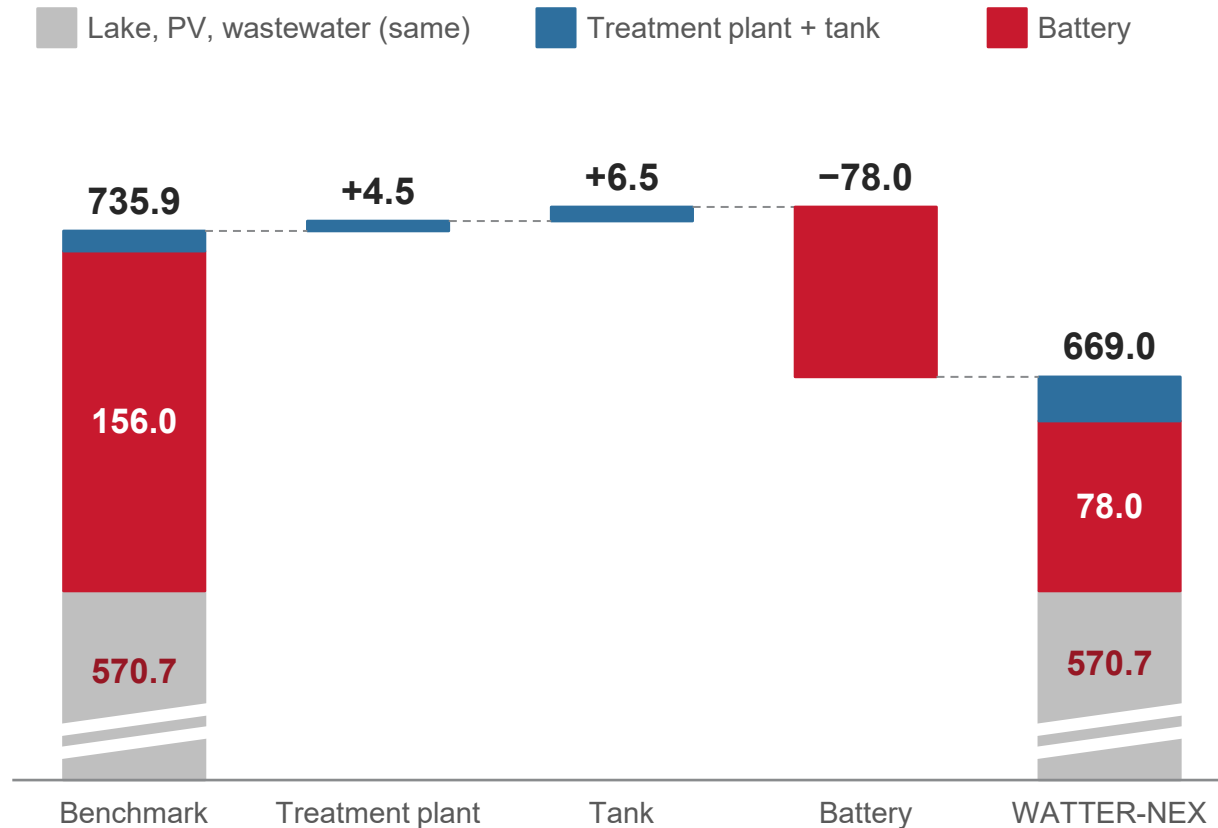


Fig.4.4 : Lifetime cost comparison (\$k); y-axis starts at \$500k

	Benchmark
Lifetime cost (\$)	735,941
PV panels	34
Battery (units / kWh)	8 / 240
Lake (gal)	66,840
Treatment plant, peak (gal/h)	13.39
Storage tank (gal)	80.61
Wastewater plant, peak (gal/h)	16.53
Curtailment (kWh/month)	95.18
Water-system energy (kWh)	1,532.48

WATTER-NEX achieves 9.1% lower lifetime investment cost than the benchmark. Equivalent to approximately \$67K saved over a 20-year project lifetime, with half the battery capacity.

- ✓ Developed an **integrated water-system representation** that jointly models rainfall collection, artificial lake storage, PWTP, ST, residential demand, WWTP, and water reuse within a single optimization framework.
- ✓ Established explicit **bi-directional water–energy coupling**, capturing both the electricity required to treat, store, and distribute water and the influence of water-system operation on optimal PV and BESS sizing and dispatch.
- ✓ Introduced **high-resolution operational co-optimization** of the power and water systems.
- ✓ Modeled **water infrastructure as optimizable design assets**, allowing treatment capacities and water-storage sizes to be jointly selected while accounting for their associated infrastructure costs rather than assuming fixed capacities.
- ✓ Demonstrated that **coordinated water treatment and storage** halve the required BESS capacity while maintaining the same PV capacity.

Publications

1. **A. M. Toms**, J. Silva-Rodriguez and X. Li, “WATTER-NEX: An Integrated Water-Energy Nexus Framework for Co-optimized Community Scale Renewable Microgrids and Water Infrastructure,” *Renewable Energy*, under review, 2026

Hyperscale WATTER-NEX

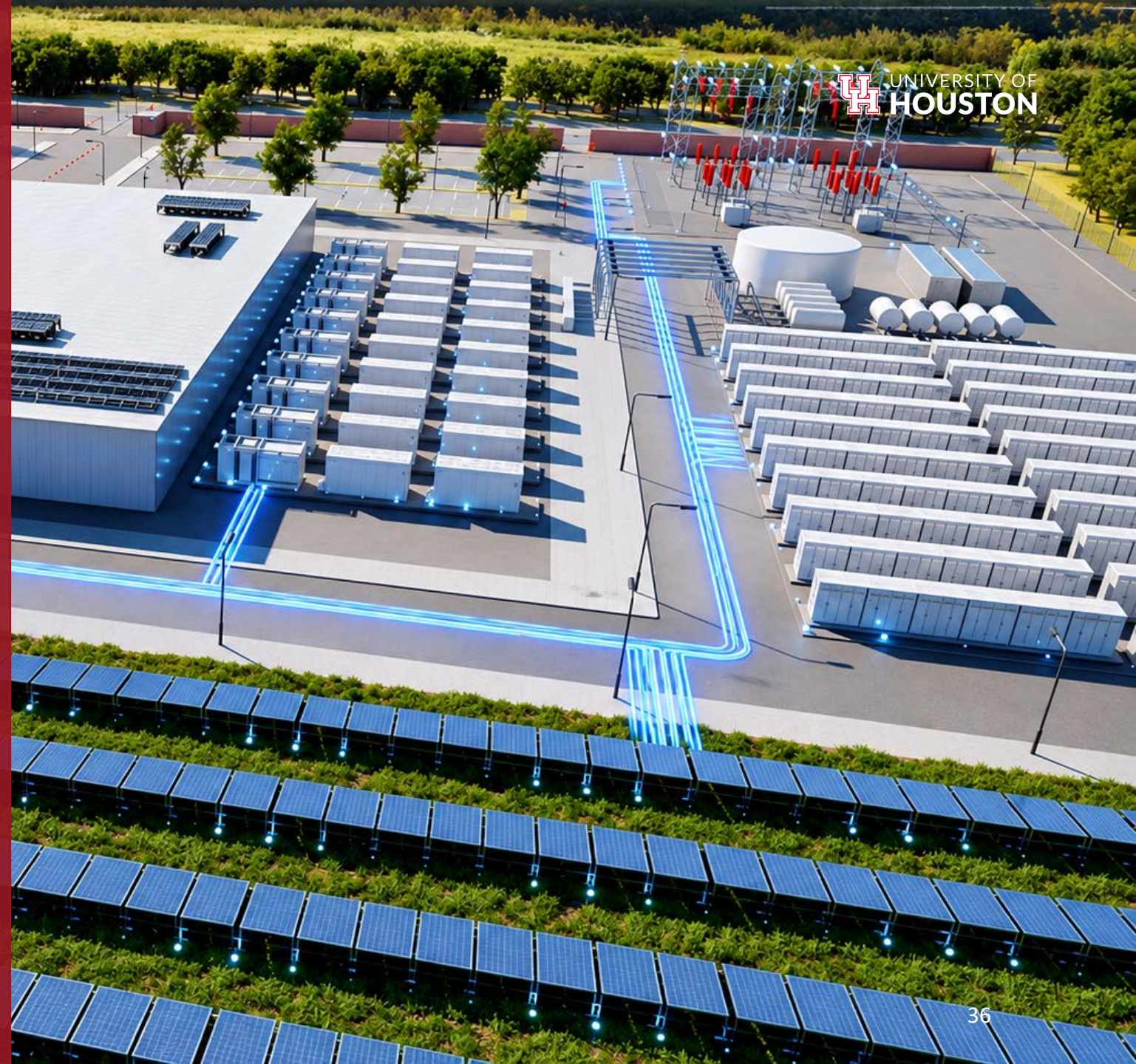
Hyperscale Datacenter Water-Energy-
Cooling-IT Nexus Microgrid Optimizer

GUIDING QUESTION

*How should infrastructure be planned when
one service depends on the operation of
another?*

By coupling...

- 1 generation with battery aging
REMO
- 2 turbines with their wakes
WAKE-NET
- 3 water with energy
WATTER-NEX
- 4 **computing, cooling, water and energy**
Hyperscale WATTER-NEX



In a hyperscale datacenter IT, power, cooling, and water are mutually dependent.

IT depends on power and cooling; power depends on water and cooling; cooling depends on power and water; and water depends on power.

**Growing fast, and hard
to supply**

4.4% → 6.7–12%

of US electricity, 2023 → 2028 ^[20]

Up to 5M gal/day

one large datacenter ≈ a town of 10k–50k
^[21]

IT workload

- Processing workloads need **power**.
- Almost every megawatt of IT power becomes **heat**.

Power

- Electricity powers all systems.
- On-site generation requires **cooling** and **water**.

Cooling

- Cooling removes heat generated.
- Cooling systems require **electricity** and may consume **water**.

Water

- Water treatment and distribution require **electricity**.

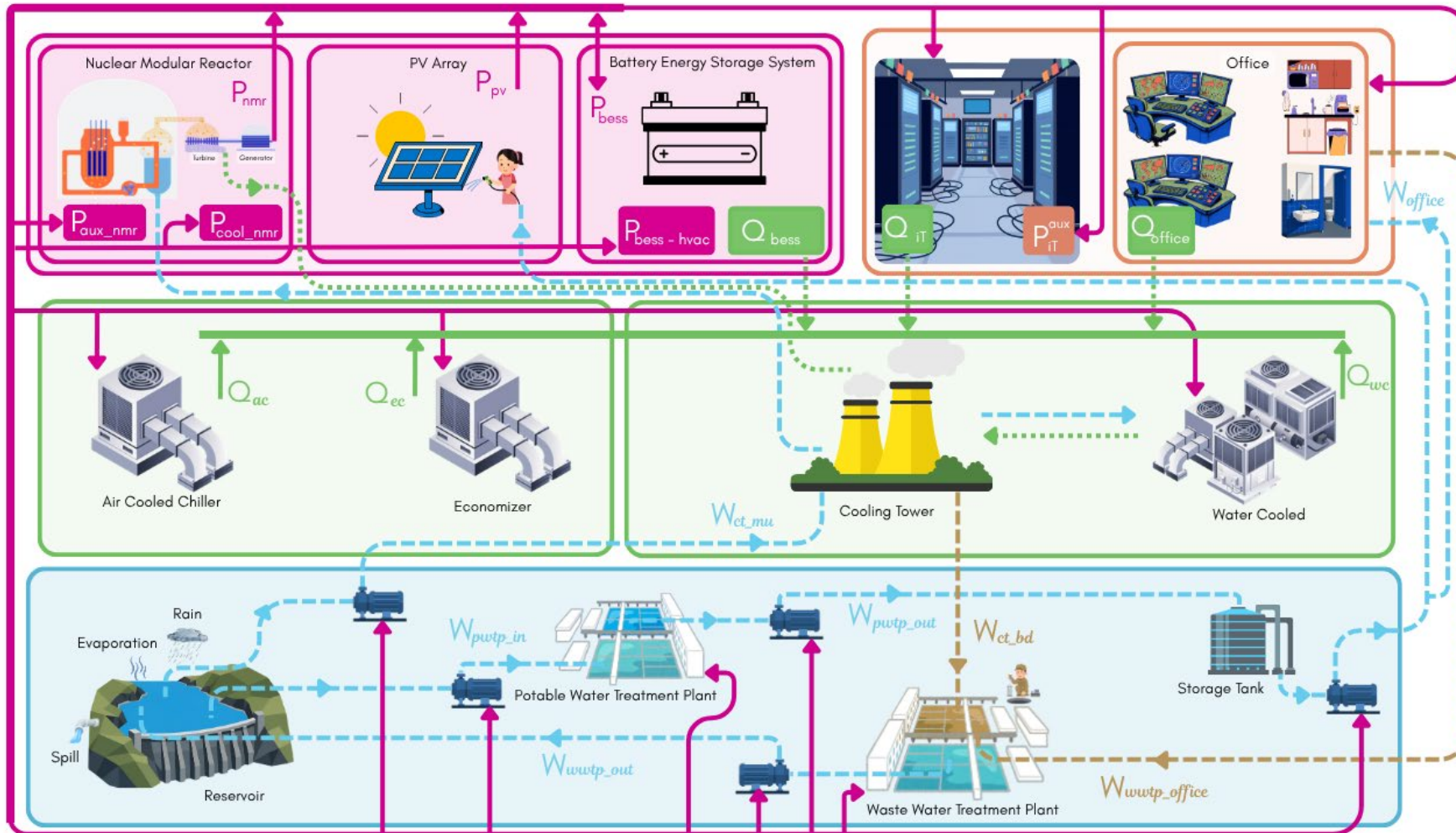
How existing work approaches datacenter energy, cooling, water and workload, and where it falls short

Tool / Approach	Primary Focus	Strengths	Key Limitations
Energy-efficient datacenter design ^[22]	IT, air management, cooling and electrical systems as connected design choices	Integrated facility view with practical metrics	Facility-level and grid-connected; generation and water not sized
Datacenter water-footprint studies ^[23,24]	Direct on-site and indirect (power-sector) water use	Separates site water from electricity-embedded water	Accounting, not design: no operating schedule or capacity choices
Carbon-aware computing ^[25]	Shift flexible work in time within completion limits	Demonstrated at fleet scale	Grid-connected; infrastructure fixed; no cooling or water

Identified Gaps:

- (1) No formulation for integrated IT–power–cooling–water optimization framework
- (2) Insufficient modeling of autonomous datacenters
- (3) Limited joint optimization of infrastructure sizing and hourly operations

Hyperscale WATTER-NEX Architecture



Electricity

Nuclear modules (77 MWe, 250 MWth), PV, candidate batteries

Cooling

Water-cooled chillers, air-cooled chillers, economizers

Heat rejection

Shared cooling towers: reactor heat + chiller heat

Water

Reservoir with rain catchment, treatment, tank, recovery

Work

Fixed, or flexible within 24 hours

Fig.5.1 : Hyperscale WATTER-NEX Architecture

Hyperscale WATTER-NEX Architecture

Nuclear modules (NMR)

77 MWe modules (250 MWth, 30.8% efficient); the optimizer picks 0–8. Each runs between 40% and full load, with ramp and start / stop limits. About 70% of the reactor heat is waste heat, rejected through the wet cooling towers.

Role: Firm power; its waste heat shares the towers with the chillers

PV array

Panel count is a decision. Output falls as dust builds up; heavy rain or a manual cleaning restores it. Manual cleanings are at least 48 h apart and draw water from the treated-water tank. Surplus can be curtailed.

Role: Daytime energy; soiling couples it to water demand

BESS

4-hour units of 2.958 MWh / 0.74 MW. Each hour it charges or discharges, never both, within 10–90% state of charge. Its losses and ambient heat must be removed by local HVAC or the central chillers.

Role: Energy buffer; adds its own cooling load

IT workload

Fixed work runs when it arrives; flexible work can run any time within 24 h of arriving. Processing is capped at 150 work-units/h and 155 MW. All IT power, plus 5% for auxiliaries, becomes heat for the cooling plant.

Role: The main load; flexible work is a scheduling decision

Chillers + economizers

Remove IT, office and battery heat. Water-cooled chillers (COP $\approx$ 6) send their heat to the towers; air-cooled chillers (COP $\approx$ 3) use more electricity but no tower water; economizers use outside air when the weather allows.

Role: Heat removal; the chiller choice trades electricity for water

Cooling towers

Reject heat from the water-cooled chillers and the reactors. Water is lost to evaporation, drift and blowdown and made up from the reservoir; blowdown goes to the wastewater plant. Fans and pumps add electrical load.

Role: Shared heat sink; where cooling turns into water use

Reservoir + catchment

Volume is a decision (8 ft deep); the rain catchment is five times its surface area. In: rain and treated wastewater. Out: tower makeup, treatment-plant intake, evaporation and spill. Keeps a 10% reserve and ends the year where it began.

Role: Main water store; rainfall is the only new water

PWTP, tank + WWTP

The treatment plant makes potable water for the office and panel cleaning; the tank buffers it. The wastewater plant treats office wastewater and tower blowdown and returns it to the reservoir. Capacities are decisions.

Role: Close the water loop; secondary electricity loads

Objective: $\min F(\text{Lifetime Cost}) = \text{nuclear} + \text{PV} + \text{BESS} + \text{cooling} + \text{water assets}$

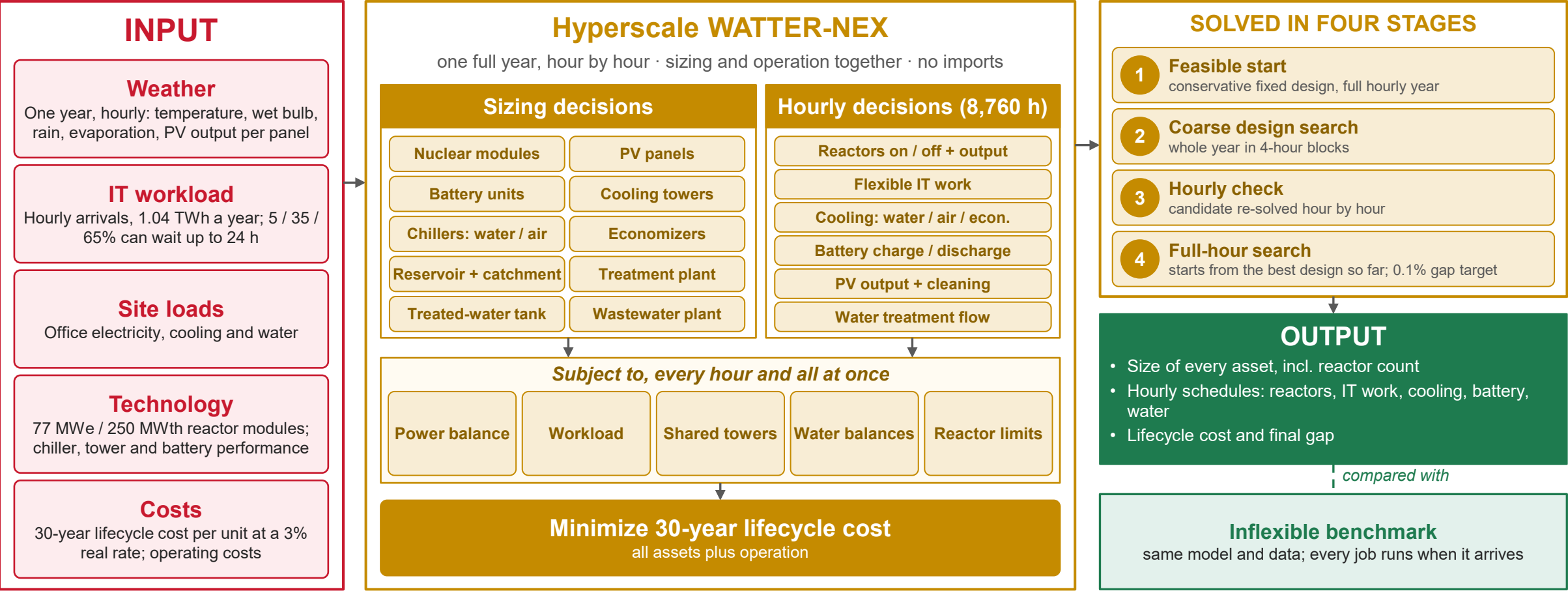


Fig.5.2 : Hyperscale WATTER-NEX Framework

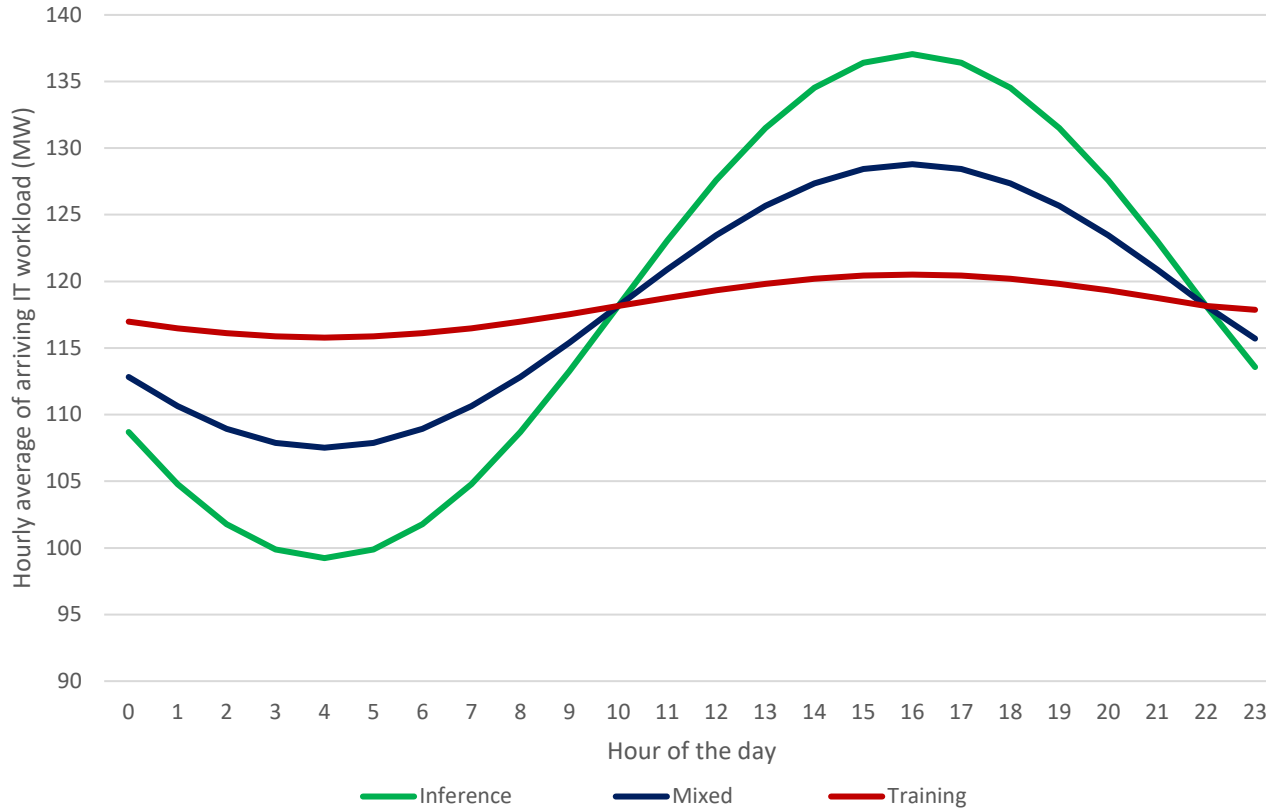


Fig.5.3 : Mean arriving IT workload by hour

5% flexible

Inference: peaky, almost nothing can wait

35% flexible

Mixed: in between

65% flexible

Training: flat, most of it can wait

Each case: 1.04 TWh of IT work a year (mean 118.5 MW), the same synthetic warm-humid year, the same prices.

Lifecycle cost (\$M)	Inference · 5%	Mixed · 35%	Training · 65%
Nuclear assets	2,393 3 modules	1,595 2 modules	1,595 2 modules
PV assets	0 no PV	115 110k panels (51 MW)	217 208k panels (97 MW)
Cooling assets	206 140 AC · 215 CT	209 126 WC · 20 AC · 224 CT	209 134 WC · 24 AC · 217 CT
Water assets	52 reservoir 574M gal	61 reservoir 679M gal	59 reservoir 642M gal
Variable operation	636 mostly reactor O&M	537 mostly reactor O&M	497 mostly reactor O&M
Total	3,287	2,517	2,577

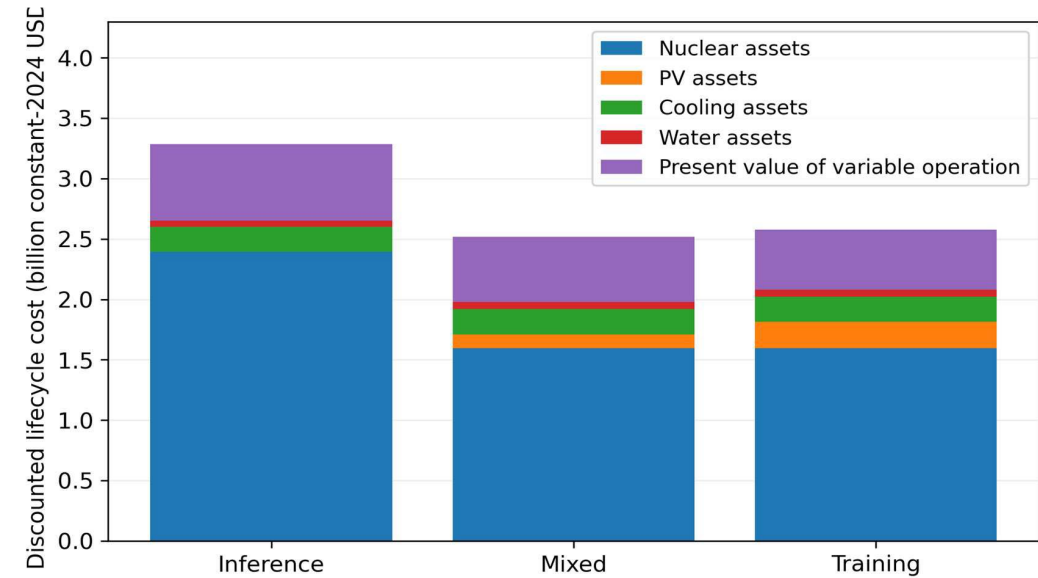
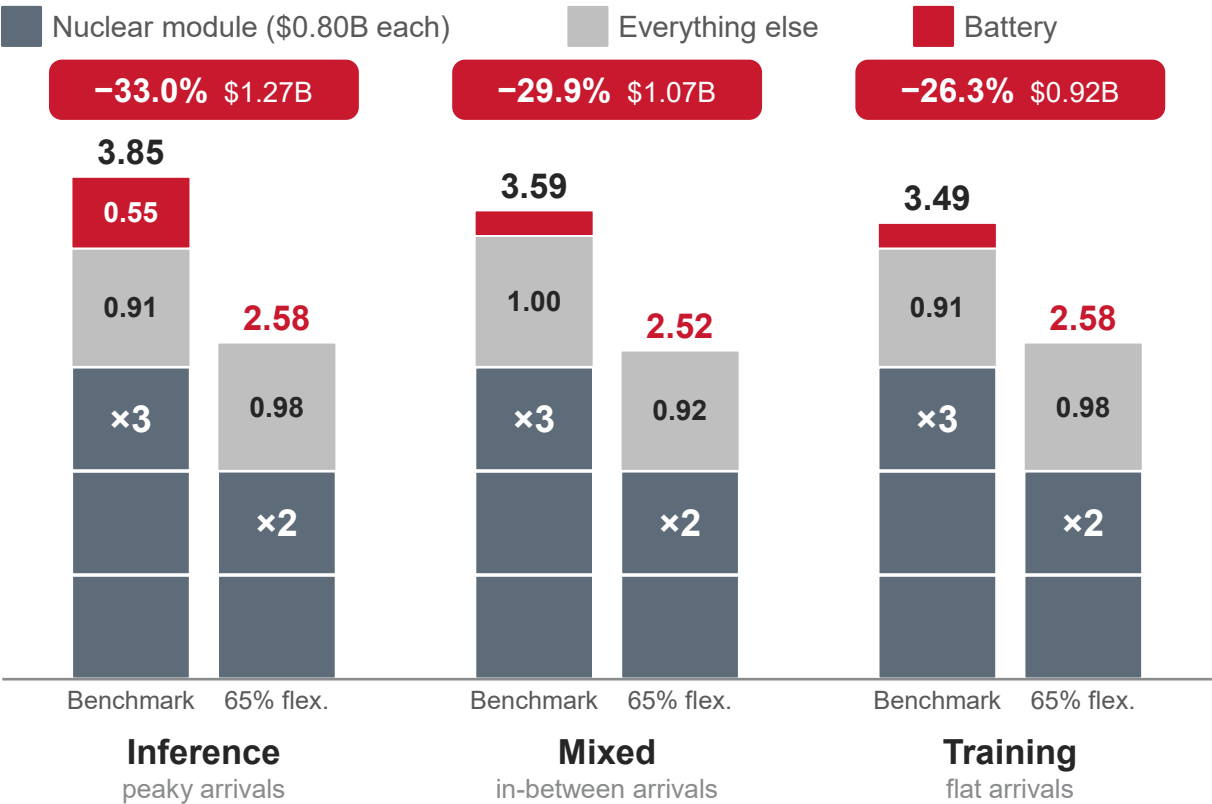


Fig.5.4 : lifecycle cost by asset

Greater IT flexibility enables higher PV penetration, reduces nuclear capacity requirements, and lowers lifecycle costs by up to 23%.



- ✓ Developed an **integrated IT–power–cooling–water optimization framework** that captures facility efficiency, workload timing, energy use, cooling demand, and water consumption within one model.
- ✓ **Modeled a fully autonomous off-grid data center**, forcing the system to internally absorb hourly imbalances through generation, storage, cooling, and water infrastructure.
- ✓ Introduced **shared heat-rejection modeling** where reactor and chiller heat are handled through the same cooling-tower system.
- ✓ **Demonstrated the value of operational flexibility**, showing that flexible workloads can reduce required hardware capacity and overall lifecycle cost.

Publications

1. **A.M. Toms**, X. Li, et al. — “Hyperscale WATTER-NEX: An Integrated Water–Energy–Cooling–IT Nexus Framework for Co-optimized Autonomous Hyperscale Data Centers,” *under preparation*, Oct. 2026.

Conclusions

& Future Works

What do the four projects add up to?

MAIN CONCLUSION

Plan dependent services together: keep the coupling inside the optimization. In all four settings it changed what to build and how to run it, for lower lifetime cost or higher profit.

REMO

1

Offshore microgrid

THE SIMPLER MODEL ASSUMED

Aging is a fixed share of battery cost

MY CONTRIBUTION

Multi-rating offshore sizing with a neural-network, use-based battery-aging loop

WHAT CHANGED

**Degradation cost -42.8%,
lifetime cost -\$18.9M (Texas)**

WAKE-NET

2

Wind farm

THE SIMPLER MODEL ASSUMED

Turbines don't affect each other's wind, post opt. wake

MY CONTRIBUTION

3D wake-aware optimizer that places and sizes turbines, with land and cable priced in

WHAT CHANGED

**+40.2% annual profit vs the wake-ignorant layout
(+\$14.8M a year)**

WATTER-NEX

3

Self-sufficient community

THE SIMPLER MODEL ASSUMED

The water plant runs on its own schedule

MY CONTRIBUTION

Joint sizing and hourly scheduling of six water and energy subsystems

WHAT CHANGED

Battery halved (240 → 120 kWh), lifetime cost -9.1%

Hyperscale WATTER-NEX

4

Off-grid datacenter

THE SIMPLER MODEL ASSUMED

Every job runs the moment it arrives

MY CONTRIBUTION

Full-year hourly model of reactors, PV, cooling, water and deadline-bound IT work

WHAT CHANGED

**No battery, one fewer reactor,
lifecycle cost -26% to -33%**

- ✓ **Outages and N-1:** Reactor outages, N-1 security and spare cooling margin in Hyperscale WATTER-NEX, where a battery may earn its keep.
- ✓ **A full IT load flexibility sweep:** Vary the deferrable share from 0 to 99% for every workload, with the arrival shape held fixed.
- ✓ **Planning under uncertainty:** Multi-year weather, droughts and forecast error, with stochastic or robust optimization
- ✓ **Grid Connected Networks:** Link sites through power and water networks, and shift work across a fleet of datacenters
- ✓ **Shift from planning to operation:** Rolling-horizon control with forecasts, in place of perfect foresight

GUIDING QUESTION

How should infrastructure be planned when one service depends on the operation of another?

Plan them together.

Each asset is worth what the system around it lets it do.

The most important decision in a planning model is made before you solve anything.
It's which couplings you let the model see, where you draw the boundary.

Journal - Published

A.M. Toms, X. Li, K. Rajashekara — “Optimal microgrid sizing of offshore renewable energy sources for offshore platforms and coastal communities,” *Sustainable Energy, Grids and Networks*, Vol. 44, 2025.

Conference - Published

A.M. Toms, X. Li, K. Rajashekara — “Optimal Sizing of On-Site Renewable Resources for Offshore Microgrids,” *2023 North American Power Symposium (NAPS)*, Asheville, NC.

Journal - Published

A. M. Toms and X. Li, “WAKE-NET: A 3D-wake-aware economic turbine layout and cabling optimization framework for multi-capacity multi-hub-height wind farms serving grid-scale and industrial power systems,” *Renewable Energy*, vol. 273, Oct. 2026, doi: 10.1016/j.renene.2026.126078.

Journal – Under Review

A. M. Toms, J. Silva-Rodriguez and X. Li, “WATTER-NEX: An Integrated Water-Energy Nexus Framework for Co-optimized Community Scale Renewable Microgrids and Water Infrastructure,” *Renewable Energy*, under review, 2026.

Journal – In preparation

A.M. Toms, X. Li, et al— “Hyperscale WATTER-NEX: An Integrated Water–Energy–Cooling–IT Nexus Framework for Co-optimized Autonomous Hyperscale Data Centers,” under preparation, Oct. 2026.

Thank You

Questions & Discussion

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Advisor: Dr. Xingpeng Li

REMO · WAKE-NET · WATTER-NEX · HYPERSCALE WATTER-NEX