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**12th International Conference on “Energy, Sustainability and Climate Crisis”
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Developing a Sustainable Air Container Renting and Air Cargo Allocation Plan Under Dynamic Shipment Information

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Abstract—Air cargo forwarding plays an essential role in global trade, enabling the rapid transportation of goods across continents. The tremendous speed of air transportation and high frequency of scheduled flights to the majority of cities in the world have dramatically reduced transit time from weeks by sea to just one or two days by air. Although shipment size is still restricted by today's aircraft capacity, air cargoes that are mostly high-value goods make a significant contribution to the total value of global freight. However, the air transportation industry faces increasing pressure to adopt sustainable practices due to its significant impact on the environment and climate change. This research aims to develop a sustainable air container booking and air cargo allocation plan to minimize transportation costs while reducing environmental impact. Air forwarding companies are responsible for delivering air cargo from different origins to different destinations, managing key logistics functions such as cargo pickup, documentation for air shipment, cargo insurance, warehousing, and tracking. Among these, one of the most critical tasks is booking air containers, consolidating shipments, and allocating air cargo into air containers. Forwarding companies need to book air containers from airlines to ship air cargoes from different regions to various destinations. However, forwarders must book air containers in advance before they know accurate shipment information because urgent booking will incur a heavy penalty on top of the price of renting containers, and air containers may not be available. Additionally, the price of renting a container in advance not only depends on container types but also on the cargo weight inside the container. Therefore, forwarders need to make decisions about what quantities and types of containers are booked and how cargoes are loaded into containers. The problem becomes even more complex due to dynamic shipment demand, as forwarding companies must book air containers in advance without having accurate shipment information. Additionally, if there is a high demand for shipments, the booked containers may not be sufficient to accommodate all the cargo, requiring forwarding companies to determine the quantities and types of additional containers needed. On the other hand, if the shipment demand is low, the companies must decide on the quantities and types of containers to return. Any urgent requests for additional containers or cancellations incur penalties. In this research, an optimization model is formulated to develop an air container renting and air cargo allocation plan under dynamic information. It determines what the quantities and types of air containers are needed for booking, as well as urgent requirements for additional containers and cancellations for unwanted containers. The model can also determine which cargoes are loaded into which containers in dealing with the dynamic shipment information. Effectively utilizing containers not only reduces costs but also optimizes space, reducing the number of containers needed. This, in turn, helps decrease air

pollution and CO₂ emissions, contributing to a more sustainable air transportation industry.

Keywords—Air transportation; Decision making; Optimization

INTRODUCTION

Air transport is the fastest mode of delivering goods over long distances. Crabtree *et al.* (2014) exemplify that air cargo in the next two decades will grow, on average, 4.7% per year. They forecast that after 20 years the number of revenue tonne-kilometers (RTK) by air will reach more than twice the number reached in 2013. Yan *et al.* (2006) develop a model for cargo container loading plans by looking at the operations of the carrier FedEx. Airlines looking for the best possible baggage limit policy, whilst the goods were carried in the remaining aircraft belly space along with customers' luggage, has been identified as a new difficulty by Wong *et al.* (2009). Some of the challenges encountered during the loading and shipping of air cargoes include the cost of loading, which is pegged on the weight of the entire container, as well as the volume of packing (Feng *et al.*, 2015).

In this research, air cargo must be transported from various regions to different destinations via a hub where shipments are consolidated. Each cargo item has a specific weight and volume, and items are indivisible, meaning that each must be loaded entirely into a single container. Air freight forwarders are required to book containers for both the regions and the hub. At the hub, containers may come from three possible sources: (1) pre-used containers, which arrive from the regions and remain in use; (2) new containers, booked in advance; and (3) urgent containers, booked on the day of shipment. Notably, the use of pre-used containers at the hub is incentivized through a discount compared with booking new containers.

Air cargo forwarders must make decisions not only regarding the number of containers to use but also on how to load cargo into these containers to optimize space utilization and minimize total costs. Containers are typically booked one week before the shipping date to secure lower rental prices from airlines. However, the quantity of cargo provided by customers is uncertain. Forwarders prefer not to wait for the actual shipment information, as the cost of urgent container bookings or cancellations on the shipping day is significantly higher than the advance booking cost. Therefore, determining

how to book containers under uncertainty and how to efficiently load cargo into containers is critical for reducing both operational costs and associated air pollution.

The price of renting a container in advance depends on container types and the cargo weight inside the container. Before the time of rental, accurate information is not available, so the forwarders have to make a decision about the quantities and types of containers in all the regions and hub, along with how to use the pre-used containers in the hub. Then, after the realization of the uncertainty, if the containers that have been booked cannot hold all cargoes, additional containers are required with a high penalty cost. On the other hand, if too many containers have been ordered, redundant containers have to be returned to the airline with a penalty due to the breaking of a contract. Therefore, the rental cost consists of two parts: the cost of using the containers and the cost of penalties for urgent requirements or cancellation on the day of shipping. The cost of using a container is based on a fixed charge, plus a variable charge that depends on the total cargo weight that the container holds. The penalty cost includes the cost of renting the additional containers and the cost of returning the unused containers on the day of shipping.

AN OPTIMISATION MODEL

A. Renting cost

The cost of using a container consists of two components: a fixed cost and a variable cost. Once a container is selected, the fixed cost must be paid. If the weight of the cargo loaded into the container exceeds a specified threshold, an additional variable cost will be incurred. The variable cost is a piecewise function shown as follows (Wu, 2010):

$$c = \begin{cases} 0 & \sum_{j=1}^n w_j y_j \in (0, a_1] \\ \delta_2 (\sum_{j=1}^n w_j y_j - a_1) & \sum_{j=1}^n w_j y_j \in (a_1, a_2] \\ \delta_2 (a_2 - a_1) & \sum_{j=1}^n w_j y_j \in (a_2, a_3] \\ \delta_2 (a_2 - a_1) + \delta_4 (\sum_{j=1}^n w_j y_j - a_3) & \sum_{j=1}^n w_j y_j \in (a_3, a_4] \\ \delta_2 (a_2 - a_1) + \delta_4 (a_4 - a_3) & \sum_{j=1}^n w_j y_j \in (a_4, a_5] \\ \delta_2 (a_2 - a_1) + \delta_4 (a_4 - a_3) + \delta_6 (\sum_{j=1}^n w_j y_j - a_5) & \sum_{j=1}^n w_j y_j \in (a_5, a_6] \end{cases}$$

We can simplify the above formulation by adding two new variables g_k and z_k in the range $(a_{k-1}, a_k]$ in the container, $z_k = \begin{cases} 1 & \text{if } g_k > 0 \\ 0 & \text{otherwise} \end{cases}$. The variable cost can be converted into $\sum_{k=1}^K \delta_k g_k$ by adding the following constraints:

$$\sum_{k=1}^K g_k = \sum_{j=1}^n w_j y_j$$

$$g_k \leq z_k (a_k - a_{k-1}), \quad k = 1, 2, \dots, K$$

$$g_k \geq z_{k+1} (a_k - a_{k-1}), \quad k = 1, 2, \dots, K$$

B. Notation

Indices

i types of containers ($i = 1, 2, \dots, m$);

j types of cargoes ($j = 1, 2, \dots, n$);

r regions ($r = 1, 2, \dots, R$);

d destinations ($d = 1, 2, \dots, D$);

s scenarios ($s = 1, 2, \dots, S$);

k numbers of breaking-points for type i container ($k = 1, 2, \dots, K_i$);

l numbers of type i container ($l = 1, 2, \dots, L_i$).

Deterministic parameters

v_j volume of a type j cargo;

w_j weight of a type j cargo;

V_i volume limit of type i container;

W_i weight limit of type i container;

a_{ik} weight of type i container in breaking-points k ;

δ_{ik} the unit charge rate of type i container in the range $(a_{i(k-1)}, a_{ik}]$;

c_{ir}^0 fixed cost by renting a type i container in region r ;

c_i^{h0} fixed cost by renting a type i container in hub;

q_{jsr} type j cargo quantity in scenario s in region r ;

Decision variables

a_{ir} number of type i container for booking in region r ;

a_i^h number of type i container for booking in hub;

a_{isr}^- / a_{isr}^+ number of type i container required/returned in scenario s on shipping day in region r ;

a_{is}^- / a_{is}^+ number of type i container required/returned in scenario s on shipping day in hub;

a_i^{hc} number of type i pre-used container for booking to continue to use in the hub;

$x_{ilsr} = \begin{cases} 1 & \text{if the } l\text{th container of type } i \text{ is selected in scenario } s \text{ in region } r; \\ 0 & \text{otherwise} \end{cases}$;

p_s probability of scenario s ;

L_{ir} type i container available quantity in region r ;

L_i type i container available quantity in all regions, which means $L_i = \sum_{r=1}^R L_{ir}$;

L_i^h type i container available quantity in hub;

c_{ir}^- / c_{ir}^+ the unit penalty cost of requiring/returning type i containers on shipping day in region r ;

c_i^{h-} / c_i^{h+} the unit penalty cost of requiring/returning type i containers on shipping day in hub;

b_i the unit repacking cost of type i container in the hub;

θ the discount rate of fixed cost by using pre-used containers;

q_{jsd}^h quantity of type j cargo with destination d in scenario s in the hub.

y_{iljsrd} quantity of type j cargo with destination d loaded into the l th container of type i in sce s in region r ;

y_{iljsd}^h quantity of type j cargo with destination d loaded into the l th container of type i in sce s in hub;

g_{ilksr} cargo weight distributed in the range $(a_{i(k-1)}, a_{ik}]$ inside the l th container of type i in scenario s in region r ;

g_{ilksd}^h cargo weight distributed in the range $(a_{i(k-1)}, a_{ik}]$ inside the l th container of type i in scenario s with destination d in the hub;

$$z_{ilksr} = \begin{cases} 1 & \text{if } g_{ilksr} > 0 \\ 0 & \text{otherwise} \end{cases};$$

$$z_{ilksd}^h = \begin{cases} 1 & \text{if } g_{ilksd}^h > 0 \\ 0 & \text{otherwise} \end{cases};$$

$$x_{ilsd}^h = \begin{cases} 1 & \text{if the } l\text{th type } i \text{ container with destination } d \text{ is selected in scenario } s \text{ in hub} \\ 0 & \text{otherwise} \end{cases}$$

$$x_{ilsd}^{hc} = \begin{cases} 1 & \text{if } l\text{th type } i \text{ pre-used container with destination } d \text{ is selected in scenario } s \text{ in hub} \\ 0 & \text{otherwise} \end{cases}$$

y_{iljsd}^{hc} quantity of type j cargo with destination d loaded into the l th pre-used container of type i in scenario s in the hub;

g_{ilksd}^{hc} cargo weight distributed in the range $(a_{i(k-1)}, a_{ik}]$ inside the l th type i pre-used container with destination d in scenario s in the hub;

$$z_{ilksd}^{hc} = \begin{cases} 1 & \text{if } g_{ilksd}^{hc} > 0 \\ 0 & \text{otherwise} \end{cases}.$$

C. A robust optimisation model with model robustness

Model robustness for air cargo forwarding problems means that the air cargoes can be transported next week by adding penalty cost ω_j if it is profitable. The robust optimisation model with model robustness for air cargo forwarding problems is formatted as:

$$\begin{aligned} \min \sum_{r=1}^R (M_r + \sum_{i=1}^m \sum_{s=1}^S p_s c_{ir}^- o_{isr}^- + \sum_{i=1}^m \sum_{s=1}^S p_s c_{ir}^+ o_{isr}^+ + \sum_{d=1}^D \sum_{j=1}^n \sum_{s=1}^S p_s \omega_j e_{jsrd}) \\ + \sum_{r=1}^R \sum_{i=1}^m \sum_{l=1}^{L_{ir}} \sum_{s=1}^S b_{ilr} x_{ilsr} + \sum_{d=1}^D (N_d^c + N_d) + \sum_{i=1}^m \sum_{s=1}^S p_s c_i^{h-} o_{is}^{h-} \\ + \sum_{i=1}^m \sum_{s=1}^S p_s c_i^{h+} o_{is}^{h+} + \sum_{d=1}^D \sum_{j=1}^n \sum_{s=1}^S p_s \omega_j e_{jsd} \end{aligned}$$

subject to

$$M_r = \sum_{i=1}^m \sum_{l=1}^{L_{ir}} \sum_{s=1}^S p_s c_{ir}^0 x_{ilsr} + \sum_{i=1}^m \sum_{l=1}^{L_{ir}} \sum_{k=1}^{K_i} \sum_{s=1}^S p_s \delta_{ik} g_{ilksr}$$

$$N_d^c = \sum_{i=1}^m \sum_{l=1}^{L_i} \sum_{s=1}^S p_s \theta c_i^{h0} x_{ilsd}^{hc} + \sum_{i=1}^m \sum_{l=1}^{L_i} \sum_{k=1}^{K_i} \sum_{s=1}^S p_s \delta_{ik} g_{ilksd}^{hc}$$

$$N_d = \sum_{i=1}^m \sum_{l=1}^{L_i^h} \sum_{s=1}^S p_s c_i^{h0} x_{ilsd}^h + \sum_{i=1}^m \sum_{l=1}^{L_i^h} \sum_{k=1}^{K_i} \sum_{s=1}^S p_s \delta_{ik} g_{ilksd}^h$$

$$o_i^h = \sum_{l=1}^{L_i^h} \sum_{d=1}^D x_{ilsd}^h + o_{is}^{h+} - o_{is}^{h-} \quad i = 1, \dots, m, \quad s = 1, \dots, S$$

$$\sum_{l=1}^{L_i} \sum_{d=1}^D x_{ilsd}^{hc} \leq \sum_{r=1}^R \sum_{l=1}^{L_{ir}} x_{ilsr} \quad i = 1, \dots, m, \quad s = 1, \dots, S$$

$$\sum_{l=1}^{L_i^h} \sum_{d=1}^D x_{ilsd}^h \leq L_i^h$$

$$\sum_{l=1}^{L_i} \sum_{d=1}^D x_{ilsd}^{hc} = o_i^{hc}$$

$$\sum_{k=1}^{K_i} g_{ilksr} = \sum_{j=1}^n \sum_{d=1}^D w_j y_{iljsrd}$$

$$g_{ilksr} \leq z_{ilksr} (a_{ik} - a_{i(k-1)})$$

$$g_{ilksd}^h \geq z_{il(k-1)sd}^h (a_{ik} - a_{i(k-1)})$$

$$\sum_{k=1}^{K_i} g_{ilksd}^{hc} = \sum_{j=1}^n w_j y_{iljsd}^{hc}$$

$$g_{ilksd}^{hc} \leq z_{ilksd}^{hc} (a_{ik} - a_{i(k-1)})$$

$$g_{ilksd}^{hc} \geq z_{il(k-1)sd}^{hc} (a_{ik} - a_{i(k-1)})$$

$$\sum_{j=1}^n \sum_{d=1}^D v_j y_{iljsrd} \leq V_i x_{ilsr}$$

$$\sum_{j=1}^n \sum_{d=1}^D w_j y_{iljsrd} \leq W_i x_{ilsr}$$

$$\sum_{j=1}^n v_j y_{iljsd}^h \leq V_i x_{ilsd}^h$$

$$\sum_{j=1}^n w_j y_{iljsd}^h \leq W_i x_{ilsd}^h$$

$$\sum_{j=1}^n v_j y_{iljsd}^{hc} \leq V_i x_{ilsd}^{hc}$$

$$\sum_{j=1}^n w_j y_{iljsd}^{hc} \leq W_i x_{ilsd}^{hc}$$

$$\sum_{i=1}^m \sum_{d=1}^D \sum_{l=1}^{L_{ir}} y_{iljsrd} = q_{jsr} - e_{jsrd}$$

$$\sum_{i=1}^m \sum_{l=1}^{L_i^h} y_{iljsd}^h + \sum_{i=1}^m \sum_{l=1}^{L_i} y_{iljsd}^{hc} = q_{jsd}^h - \sum_{r=1}^R e_{jsrd} - e_{jsd}^h$$

$$o_{ir}, o_i^h, o_i^{hc}, o_{isr}^-, o_{isr}^+, o_{is}^h, o_{is}^+, y_{iljsrd}, y_{ilisd}, y_{ilisd}^h, g_{ilksr}, g_{ilksd}, g_{ilksd}^h \in \{0, 1, 2, \dots, 1\}$$

$$x_{ilsr}, x_{ilsd}^h, x_{ilsd}^{hc}, z_{ilksr}, z_{ilksd}^h, z_{ilksd}^{hc} \in \{0, 1\}$$

$$e_{jsrd}, e_{jsd}^h \in \{0, 1, 2, \dots, \inf\}$$

RESULTS

The practical case is described in greater detail in Wu (2010). In it, a logistics company in Hong Kong provides air transport services worldwide. It collects shipping information from its customers, including the characteristics of different types of cargoes, delivery dates, destinations, and uncertain demand. The air cargoes need to be transported from two regions, Mainland China (Region A) and Vietnam (Region B), to the hub in Hong Kong first. The cargoes are unloaded and consolidated in Hong Kong before they are sent to two destinations, the EU (Destination α) and North America (Destination β). There are three types of cargo: large, medium, and small, with volumes of 1500, 1200, and 1000 cubic decimeters and weights of 750, 600, and 500 kilograms. The containers in the regions and hub have the same characteristics. If the company decides to continue using the containers in the hub, which just come from the regions, it will get a 5% discount for the fixed cost.

The company contacts an airline to rent air containers in advance. There are seven types of containers, and currently there is only one of each type of container available in each region and hub. The airline provides container information in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.** and the unit penalty cost in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**

Table 1 Air container characteristics

Container type	1	2	3	4	5	6	7
Fixed cost	161617	105898	85207	74373	48713	46553	20695
Volume limit	6489	6300	5008	4882	3700	3150	1400
Weight limit	6800	5400	4200	4000	3900	3500	1200
Breaking point	α_{11}	3968	2600	2092	1826	1643	505
	α_{12}	4722	3050	2490	2173	1747	602
	α_{13}	5290	3467	2789	2434	1594	2000
	α_{14}	5976	3954	3149	2741	1825	2500
	α_{15}	6273	4111	3307	2886	1917	2591
	α_{16}	6800	5400	4200	4000	3900	3500
Charged rate	δ_{11}	0	0	0	0	0	0
	δ_{12}	32	32	32	32	32	32
	δ_{13}	0	0	0	0	0	0
	δ_{14}	29	29	29	29	29	29
	δ_{15}	0	0	0	0	0	0
	δ_{16}	25	25	25	25	25	25

Table 2. The unit penalty cost and unloading cost (\$)

Container type	Unit penalty cost for returning unused containers	Unit penalty cost for renting additional containers	Unloading cost
1	100000	200000	16000
2	70000	150000	10000
3	60000	120000	8000
4	50000	100000	7000
5	40000	80000	5000
6	35000	70000	4000
7	30000	60000	2000

In this study, we assume that uncertainty is characterized by three economic environments: good (s_1), fair (s_2), and bad (s_3). For example, in a good economic environment, the probabilities of high, medium, and low shipment demand scenarios are 80%, 10%, and 10%, respectively. In a fair economy, these probabilities change to 10%, 80%, and 10%, while in a bad economy, they become 10%, 10%, and 80%.

After running the robust model, we obtained the container booking plan in a good economic, shown in Table 3 and the unshipped cargo plan in Table 4. This results in total cost saving by not shipping all cargo. In turn, the company will spend less on container rentals, which also contributes to a reduction in air pollution.

Table 3. Container booking plan

Container type	1	2	3	4	5	6	7
Region	A			1	1	1	1
	B			1	1	1	1
Pre-used container				1	2	2	
Hub					1	1	

Table 4. Unshipped cargoes

Cargo	Scenario s_1			Scenario s_2			Scenario s_3		
	Large	Medium	Small	Large	Medium	Small	Large	Medium	Small
Region	A	2	1			2			
	B	2	1						
Hub									

Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.5 shows the computational results of the robust optimisation with different penalty cost of unshipping. In the tests, “L”, “M” and “S” means large, medium and small cargo respectively. When the penalty cost $\omega=0$, there is no penalty for unshipped cargoes which means all the cargoes can be considered in the next week. When the value of ω increases, the trend of expected infeasibility decreases, and the total cost increases. When ω increases by a large amount, the expected infeasibility becomes zero, which means that all cargoes should be loaded without delay due to the high cost of unshipment.

Table 5. Computational results of different penalty cost

$\omega_1 = \omega_1^h$		24000	26000	28000	30000	32000	34000
$\omega_2 = \omega_2^h$		20000	22000	24000	26000	28000	30000
$\omega_3 = \omega_3^h$		16000	18000	20000	22000	24000	26000
Expected cost in regions		0	216718	378606	423029	496214	599535
Expected cost in hub		0	225191	387870	428366	501181	606909
Unshipped cargoes in region A	scenario	s_1	4L 6M 5S	4L 3M 2S	4L 1M	3L 1M	3L 1S
		s_2	3L 5M 4S	3L 2M 1S	2L	2S	2S
		s_3	2L 4M 3S	1M 3S	0	0	0
Unshipped cargoes in region B	scenario	s_1	5L 4M 4S	5L 1M 1S	2L 2S	2L 1S	0
		s_2	2L 4M 3S	2L 1M	0	0	0
		s_3	2L 2M 3S	2S	0	0	0
Unshipped cargoes in hub	scenario	s_1	0	0	0	0	0
		s_2	0	0	0	0	0
		s_3	0	0	0	0	0
infeasibility cost (\$)		1040800	666800	382400	325600	201600	0
Total cost (\$)		1040800	1108709	1148876	1176995	1198995	1206444

CONCLUSION

In this research, we addressed the air cargo forwarding problem under uncertainty, where cargo must be transported from regions to destinations via a hub with inaccurate shipment information. Air forwarders are required not only to determine, in advance, the number of containers to book for each region and the hub before accurate shipment data becomes available, but also to decide on the number of additional containers to request or to return, as well as how to allocate and load cargo into containers in the hub and the regions.

The computational results demonstrate that the proposed robust model can generate a sustainable air container booking and cargo allocation plan under dynamic shipment information, effectively reducing container usage and, consequently, lowering levels of air pollution.

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Abstract— The islands face significant tourist pressure, leading to increased consumption of water and energy—two resources that are becoming scarcer and more impactful each year due to climate change. During peak seasons, most destinations exceed sustainability thresholds. In the Mediterranean islands, the summer months experience the highest tourist influx, coinciding with the period of greatest solar radiation and water scarcity. In the Balearic Islands, for example, the population doubles in high season, causing a sharp rise in water and energy consumption. It is estimated that hotels directly account for over 15% of annual energy consumption and 24% of water usage. This study analyzes available data on energy and water consumption in hotels across the Balearic Islands. Its main objective is to propose systems with zero impact—both in terms of CO₂ emissions and water consumption—that can be applied to other islands as well. A hotel equipped with rainwater storage and greywater recovery systems can reduce its reliance on the public water supply by more than 60%. When combined Solar Energy with a multi-effect vertical thermal seawater distiller or a reverse osmosis system, network energy and water consumption can be reduced to nearly zero.

Keywords— Renewable Energy; Sustainable Hotels; Heat recovery, desalination, water savings

INTRODUCTION

The tourist industry is amongst the most dynamic areas within the services sector, and this is especially the case in Southern Europe (France, Greece, Italy, Spain and Portugal) [2]. The Balearic Islands have historically been one of the primary tourist destinations; there are about half a million beds available, and it is the first destination for Spain, last year have arrived in the islands 18,7 million tourist, with a total of 205 million of night spends. Many successful hotel companies that have emerged during the last few years are now exporting their experience to other expanding destinations.

However, one problem of almost all the Islands, including the Balearic Islands the energy model is that it was based on imported fossil fuels [1], only the 3% of the energy is from Renewable Energies Sources (RES), from this the 16% of the electricity production is from RES. In 2019 was approved a

law in the same line of all the EU to reduce to zero emissions in 2050.

Water creates tensions with other economic and social sectors due to its scarcity causing network outages for residents. Formentera have to produce the 100% of the water with desalinization and Ibiza the 43 %, Mallorca and Minorca the desalinization is less than the 10% because they have more water resources and less density population. They use reverse osmosis systems that have a high energy consumption, between 3 to 6 kWh/m³. The desalination in Balearic Islands have about 162 GWh/year and near 96.892 tons of CO₂/year [3]. The cost of water from solar desalination systems decreases as production capacity increases.

Some Hotel companies that have the headquarters in the Islands and are present in all the world, they have start to reduce the CO₂ emissions and apply sustainable policy in the water management and waste recycling, they want to be zero emissions in 2030, but this could be applying in all the hotels at Balearic Islands by law in the next 20 years. In order to reduce waste generation some hotels have reached agreements with local farmers to implement the circular economy concept.

ENERGY CONSUMPTION

The average annual energy consumption in hotels is 154 kWh/m², with August averaging around 24 kWh/m², with a 50% of fossil fuels for thermal uses according [1], and another 30% for the rest of thermal uses with electricity (cooling, refrigeration, etc), the other 20% it's only electric consumption (elevators, lights, pumps,...). The usual design for the thermal demand of a hotel in the Islands is a Heat Pump (HP) with Heat Recover for cooling and freezing with electricity and support gas boiler Heating and produce the Domestic Hot Water (DHW), the use gas for kitchen devices.

Table 1: Energy consumption in Balearic Islands Hotels

Category	Number	Electric Consumption (MWh/year)	Thermal consumption (MWh/year)	Energy kWh/ m ² year
4* - 5*	368	133.353	109.107	377
3*	288	61.300	40.867	237
2*	105	7.539	4.059	158
Apartments	933	60.774	26.046	120
Other	25.073	195.569	130.380	65
TOTAL	26.767	458.535	310.459	154

The last years to increase the energy efficiency and reduce de fossil fuel consumption, hotels are changing the facilities design and are unifying the thermal systems - heating, cooling and hot water- in one by changing the conventional fossil fuel boiler by HP or using Biomass boiler, combined with solar photovoltaics (PV) and solar thermal (ST) systems.

From different energy audits we found that the average annual energy consumption may reach 1300-5000 kWh per bed. Installing between 1-2 kWp per bed (5 m²) and about 1 m² of Solar Thermal we could arrive to zero CO₂ emissions [1]. Actually, less than the 10 % of the Hotels in Balearic Islands have solar systems, PV or ST. In Mediterranean countries with solar thermal that could be very easy to cover the 70% of the energy consumption for hot water [2] and support heating systems. The main problem of the ST is the overheating when they have low occupation periods or at very high solar radiation, they must empty or use auxiliary cooling systems. Some thermal systems have been disabled or replace by the PV systems because they are more easy to maintain and with higher savings, with the big advantage that the over production could be sent to the grid. Using adsorption or absorption systems could be a way to use all the ST potential, another solution will be using the extra heat for desalination water system.

WATER CONSUMPTION IN HOTELS

The Island's hotels consume a lot of water, especially at summer when the occupation is higher, in some hotels the total consumption is higher than 500 liters'/person day, due to all the services; bathroom, restaurant, garden, pool, laundry... the average is near 356 l/person day, if we only count the room consumption [5]. A single room can consume between 60 m³ and 220 m³ per year. Usually, a hotel's garden can increase water consumption by around 50% compared to room use alone. A hotel without a garden may consume less than 200 litres per person per day, whereas one with a garden can exceed 350 litres per person per day [8]. In the Balearic Islands, hotels are legally required to have a water reservoir capable of storing three days' worth of total consumption.

Some hotels recycle greywater for toilet flushing or use reclaimed water supplied by the Council's Wastewater Treatment Facility (WTF). This can reduce water consumption by up to 50% [4] and generate significant economic savings, as reclaimed water is typically 4 to 10 times cheaper than domestic supply. In the beginning of the touristic period (60 and 70's) was usual that the Hotels have their own WTF, but nowadays almost all the tourist areas have central domestic water and WTF from the council, in Balearic Island's only some hotels in Mallorca, Formentera and in Menorca they still have WTF, but the rest have been integrated in the municipality system of WTF.

Table 2: Water consumption in Hotels vs. Residents

Water Consumption Hotels and residents			
Category	Max l/person day	Min l/person day	dam ³ /year
5*	550	180	1.790
4*	400	140	11.017
3*	340	130	5.268
1*-2*	280	120	477
Apartments	295	110	13.882
Residents	202	46	55.740

Some hotels have change the usual garden with grass to change a Mediterranean garden, with plants that can survive only with the rainwater, taking out almost all the grass and

other tropical plants from the gardens. Some of them have by municipal law a rainwater recovery and use wastewater recycling for the gardens, very common in the islands throughout centuries, due to the low water resource, but eventually this sustainable design was abandoned, and the local government has taken the responsibility. The rainwater in Balearic Islands with an average of 419 mm/year could cover more than the 30% of the annual consumption of a hotel or apartments, if they have the drainage and storage tank similar to the residential buildings, this water could be used with a few treatments (filter and chlorine) in the building like a drinkable water. The lowest water consumption of a hotel could be less than 120 l/person day applying all the water policies commented before. In the Balearic Islands about the 37% of the human consumption is due to the tourism, which has a direct impact in the total water consumption as we see in table 2. We can see the hotel consumption by category [5] which means a big difference in hotels with sustainable system or hotels without water management policy.

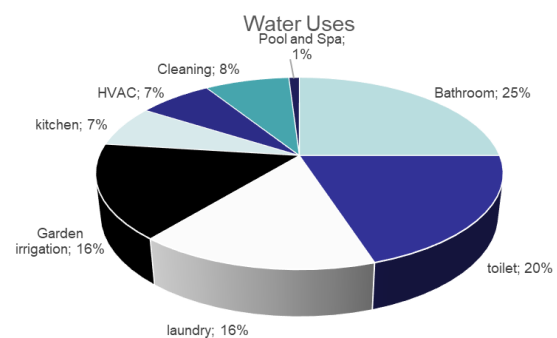


Figure 1: Water uses for a Hotel

SOLAR DESALINIZATION

Solar-powered seawater desalination was applied in some Island's in the Atlantic (Cape Verde) and Pacific (Samoa, Indonesia, Fiji, Vietnam, ...) has been installed the last century. They are especially effective for small island communities or off-grid settings, where traditional water infrastructure is lacking or too expensive to maintain. Some of them they have been changed by RO or hybrid systems. The solar desalination has evolved significantly from basic single-stage evaporation systems to advanced multi-effect technologies, some of them still in research stage. Early methods relied on simple solar stills, using sunlight to evaporate seawater and condense freshwater — a process with very low efficiency, typically around 10–20%, due to high thermal losses and limited output. Modern multi-effect distillation (MED) systems, often powered by solar thermal energy, use the latent heat of condensation in multiple stages, greatly increasing thermal efficiency. These systems can now achieve efficiencies of 50–70%, with much lower energy consumption per cubic meter of water produced. This evolution represents a major step forward in making solar desalination more viable, scalable, and sustainable.

The low price of the PV systems could open another system, with Reverse Osmosis (RO) systems that have higher efficiency (producing 30 to 100 liters per kWh), they require extensive maintenance and can only run on electricity. In contrast, the new MED systems offer great potential due to ability to utilize heat from the different sources (Solar Thermal, Heat Recovery, Biomass, Biogas,...).

HOTEL WATER-ENERGY ZERO IMPACT

Actually in Balearic Islands there are hotels which consume energy from 100% renewable sources (only with solar thermal, photovoltaic and biomass). The reduction of cost of some technologies (PV and Hydrogen technologies) could open other systems with 100% of solar energy. The hotels with only solar energy power will have to implement smart strategies, large thermal storage and small fraction with batteries or in other emerging technologies like Fuel Cell with Hydrogen (H₂) and Hydrolysis, in order to arrive to zero emissions systems [1]. Optimizing the energy mix of the hotels according to their demand and the available surface will be best scenario, using biomass or solar thermal with photovoltaics and small percentage of hydrogen in order to arrive to 100% of renewable energies. See at the table 3 some scenarios with renewable energies for the averaged hotels in Balearic Islands [1].

Table 3: potential of renewable energies in Hotels[1]

Category	Energy kWh/m ² year	Min. PV kWp/hotel	ST m ² /hotel
5*	377	1047	256
4*	237	564	138
3*	158	175	33
2*	120	148	23
1*	65	64	49
Average	191	400	100

We have studied the Best Available Techniques (BAT) in different hotels from the Balearic Islands and apply to a real Hotel with the information of the energy audit, with a bigger impact than the average for propose a new design, there are hotels with less occupancy, larger surface and open less months that will be easier to apply a good design to be zero impact. The studied Hotel has a high occupancy all the year (near 62 %), with 670 beds and 16.000 m² of total surface, located in Palma bay in Mallorca, is an area with a lot of tourist during all the year. In this case we have analyzed the water energy consumption of the hotel and increase to the global energy, with renewable energies a PV power of 1,5 kWp per bed and ST 1,8 m²/bed.

Table 4: Example of 4 stars Hotel 100% with RES

Characteristics of Study Case of 4 stars Hotel		
Nº of beds	670	Beds
Total Surface	16.000	m ²
Storage tank	500	m ³
Unitary water	196	l/person day
Water cons.	31.657	m ³ /year
PV	1.000	kWp
	4.000	m ²
ST	1.000	kWt
	1.206	m ²
Energy cons.	1.230.349	kWh
Unitary Energy	2.163	kWh/bed year
Energy Cons.	167	kWh/m ²

The Hotel will need to storage and collect all the rainwater, reuse gray water, reduce the water consumption of the garden, with only these will reduce more than the 50% of the water consumption. The building need a good design can use the energy from the Heat Recovery of the AC systems and overheating of the Solar Thermal system in some months to desalinate the sea water. Using all the heat with the new prototypes that are using multi-effect vertical (MED) solar distillers they have achieved efficiencies exceeding 400% [7].

These systems can produce 6 l/m² h and more than 5 liters of water per kWh and operate at temperatures between 40°C and 65°C, which are common in standard heat pumps with heat recovery or in most flat plate collectors (FPC) during 8 months. Reverse osmosis systems are already widely used in most hotels across the Balearic Islands to improve the quality of the poor tap water commonly found in many municipalities, which often contains high levels of calcium, salt, nitrites, phosphates, and other contaminants. Around 80% of municipalities in the Balearic Islands supply water that is either non-potable or contains substances exceeding the thresholds set by public health guidelines. In the proposed hotels, reverse osmosis could also be applied to treat wastewater or seawater, enhancing water reuse and sustainability. In contrast, the new VMED systems offer great potential due to their lower maintenance costs and ability to utilize thermal and waste heat from heating, ventilation, and air conditioning (HVAC) systems.

The hotel as well have to use all the waste water from the condensation of the HVAC system in order to increase the recycled water, and reduce the global impact.

We could have design a system in the Hotels that combine VMED and small fraction of RO in order to have more redundancy and reliability. The combined production of many products is advantageous both in terms of primary energy saving (less CO₂ emissions) and economical profitability [9]. The only bad impact of the RO is the amount of salt water they throw into the sea or the sewer, on the other hand, VMED evaporates all the water and only produces pure salt that can be used as a by-product to boost the local economy.

Other combinations could be made, like 100% with VMED and the HVAC systems only with Solar Thermal (absorption or adsorption), this has been analyzed in other studies have made combination of two solar polygeneration plants, consisted of thermally- and electrically-driven technologies for the production of freshwater, space heating and cooling, domestic hot water, and electricity. One combine PV and ST collectors, an absorption chiller, and a multi effect distillation unit. The other combine PV panels, heat pumps for space heating/cooling and DHW, and a reverse osmosis unit. The obtained primary energy savings, avoided CO₂ emissions, and simple payback period were equal to 32.2%, 27.8% and 12 years, respectively [6]. The study confirmed that, in the current energy market, PV panels coupled with electric driven HPs are more profitable than concentrating photovoltaic and thermal collectors coupled with thermally-driven technologies.

Another possible option in the future for Hotels will be for example, use biogas or green hydrogen (H₂) from the gas company or generate in the same hotel with a Hydrolyzer, and use a fuel cell to produce energy and water in the Hotels, will be a double system to decarbonizing the Islands and use the wasted water from the fuel cell to feed the water system. With Hydrogen a Hotel could generate the 100% of the energy consumption but only the 2% of the water consumption.

Actually in the Balearic Island's there are only a Hotel with green Hydrogen [1] and very few absorption plants, because they need a bigger investment and maintenance, the biggest advantage is they need lower surface due to the higher efficiency of the ST in front of the PV. The new system installed in all the hotels that are improving their facilities are Heat Pump combined with PV to cover all the thermal and electric demand (DHW, HVAC,..), in some hotels have a yearly positive balance of energy, with grid parity systems.

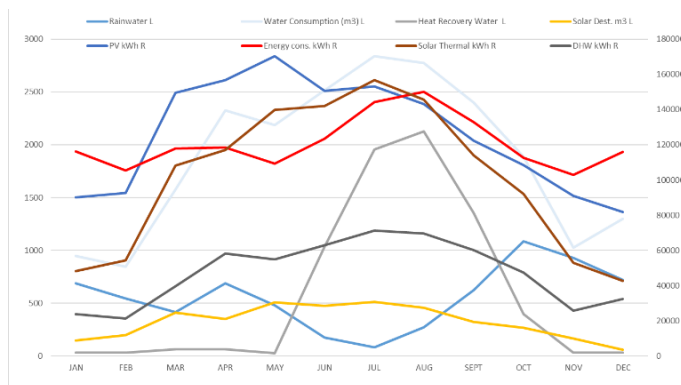


Figure 2: Monthly energy and water consumption-production for a Hotel with zero impact (left axis m³ right axis kWh)

To achieve zero impact in emissions and water, hotels would need around 8 m² of solar collectors (both photovoltaic and solar thermal) per bed, covering roughly 30% of their surface area. In Hotels with low surface available they could install PVT systems. The solar energy is covering almost the 100% of the energy consumption in some hotels, by installing solar thermal and photovoltaic systems and maximizing heat recovery from HVAC systems, hotels can meet all their energy needs while also using a portion of the recovered energy for seawater distillation.

Table 5: Example of a hotel with zero impact in water

Uses	m ³ / year	percentage	Energy (kWh)
Gray water	9.045	29%	13.568
Rainwater	6.704	21%	-
Solar Thermal distillation	3.877	12%	646.145
Heat Recovery distillation	7.153	23%	1.192.191
Condensation	678	2%	-
R.O.	4.201	13%	126.018
Total	31.657	100%	1.977.921

The studied hotel annually 9,045 m³ of wastewater could be recycled. So, the cost of reusing could be near 1.2 €/m³ that can be lower than the price of freshwater in our community (from 1 to 4 times bigger depending on consumption) [4].

The hotels could use as well all the recycled wastewater for the garden and other uses in order to reduce even more the impact of the water uses, and arrive to zero water consumption, and have positive water production for the Islands and the local farmers improving the circular economy.

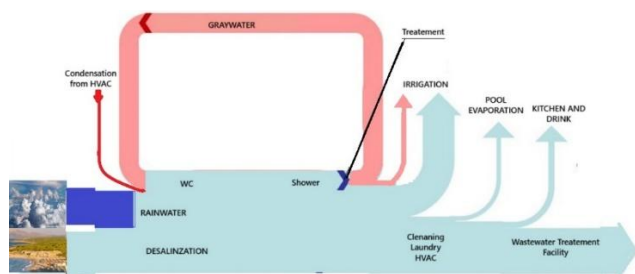


Figure 3: Sankey diagram of a Hotel with zero impact in water

CONCLUSIONS

Hotels can achieve zero or positive impact on water and energy by using 100% solar energy with currently available technologies. This would allow them to fully meet their energy demand and water consumption, significantly reducing

the environmental footprint of tourism and lowering the unit operating cost per bed. The Tourism could provide annually all the water that the residents needs with this designs. By adopting renewable energy solutions, tourist islands can become more competitive and sustainable. Achieving net-zero energy and water emissions by 2050 is now technically feasible, but it will require substantial investment, complete refurbishment, and a full redesign of hotels' energy and water systems.

Table 6: Future water-energy Hotels vs. Residents

Category	Water Consumption		Positive Energy
	Actual dam ³ /year	Future dam ³ /year	MWh/year
5*	1.790	586	155.600
4*	11.017	3.856	187.515
3*	5.268	2.169	40.658
1*-2*	478	205	238.557
Apartments	13.882	5.647	206.077
Total Tourism	32.435	12.463	828.406
Residents	55.738	12.693	2.506.216

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Innovative Application of Mulching and Smart Environmental Monitoring in Fire-Affected Forest Areas in Greece: From Restoration to Administrative Integration

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Abstract— The increasing extent of burned forests in Greece underscores the need for innovative restoration. This paper presents a mulching intervention in a 60-hectare area of Evia, where burned biomass is reused as a low-cost tool for soil stabilization and vegetation recovery. The approach follows circular economy principles and is supported by the ANTINERO program under the Recovery and Resilience Facility. A smart monitoring system with sensors, GIS, and field data evaluates effectiveness. Beyond technical aspects, mulching is framed within New Public Management, with indicators for efficiency, sustainability, and institutional readiness, including the Soil Conservation Factor. The Evia case illustrates both ecological and administrative innovation, offering a model for integrating mulching into national post-fire restoration and climate adaptation strategies.

Keywords: *Post-fire Management; Circular Economy; Biomass Utilization; Administrative Readiness; New Public Management*

INTRODUCTION

Wildfires in the Mediterranean cause severe ecological and socio-economic damage, making innovative restoration practices essential. In Greece, restoration is a legal and institutional obligation. Mulching reduces erosion and stabilizes soils, combining ecological effectiveness with administrative sustainability [1–3]. International experience underlines the need for institutional recognition, while KPIs and CSFs link ecological outcomes with governance. This study explores: (i) the link between mulching, NPM, and the circular economy, (ii) the role of institutional integration in resilience, and (iii) the contribution of international experience to Greek policy.

Mulching as Circular Economy Practice
Mulching, the coverage of burned areas with shredded biomass, is widely recognized as an effective post-fire

measure, reducing erosion and aiding regeneration [1–3]. Beyond its ecological role, it requires institutional recognition, linking it to efficiency and adaptability under New Public Management (NPM). From a circular economic perspective, mulching reuses biomass, cuts costs, and reduces reliance on external inputs, consistent with EU green transition guidelines [4]. Its effectiveness is assessed through Key Performance Indicators (KPIs) and Critical Success Factors (CSFs), connecting ecological outcomes with governance and administration [5–8].

NPM AND INSTITUTIONAL INTEGRATION IN POST-FIRE RESTORATION

Applying NPM principles to forest policy promotes efficiency and accountability through decentralization and performance measurement [9]. Post-fire restoration is framed as an administratively planned process, evaluated by efficiency, sustainability, and readiness indicators [10,11]. Evidence from the Iberian Peninsula and the United States shows that mulching succeeds with institutional integration and monitoring [12,13]. In Greece, where interventions remain fragmented, such integration is crucial for consistent adoption by the Forest Service.

APPLICATIONS OF MULCHING IN GREECE AND THE CASE OF EVIA

In Greece, mulching has been applied only sporadically in non-forest contexts, such as geotextiles in Olympia (2007) and plant residue coverings in Agia^[14,15]. This study presents the first organized forest application (Afrati, Evia, 60 ha), selected for its erosion risk, vegetation loss, and biomass availability. Biomass was shredded through the ANTINERO program, applied in a 3–5 cm layer, and

complemented by log barriers and check dams, emphasizing low cost and administrative integration. An innovation is smart monitoring with sensors, GIS data, and regeneration indicators, linking mulching to both ecological and administrative resilience.

BIBLIOMETRIC MAPPING OF THE RESEARCH DYNAMICS ON MULCHING

The Evia application gains significance when linked with international evidence. A bibliometric review (Scopus, VOSviewer) confirmed mulching’s rise as a post-fire restoration measure, with rapid growth after 2020, particularly in Mediterranean countries and the United States [16,17,12].

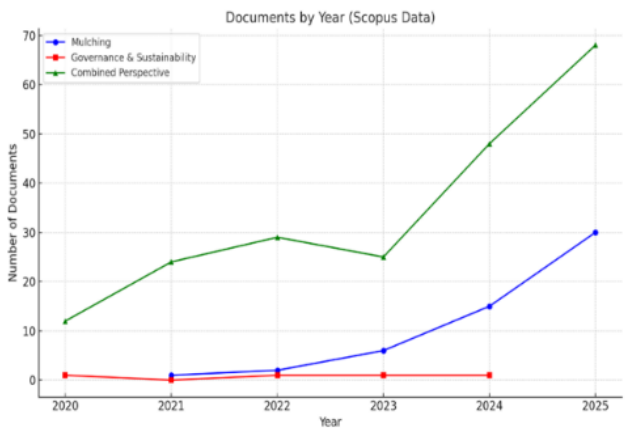


Figure 1: Annual evolution of publications on mulching, governance and sustainability (Scopus, 2020–2025)

The analysis revealed three dimensions: (i) technical—erosion control and hydrology, (ii) ecological—resilience and biodiversity, and (iii) administrative—governance, sustainability, circular economy, and NPM. Keyword mapping emphasized *post-fire rehabilitation*, *erosion control*, *resilience*, and *climate adaptation*, reflecting the global shift to sustainable restoration. Research is concentrated in the Iberian Peninsula and the United States, where mulching is systematically applied [13,19].

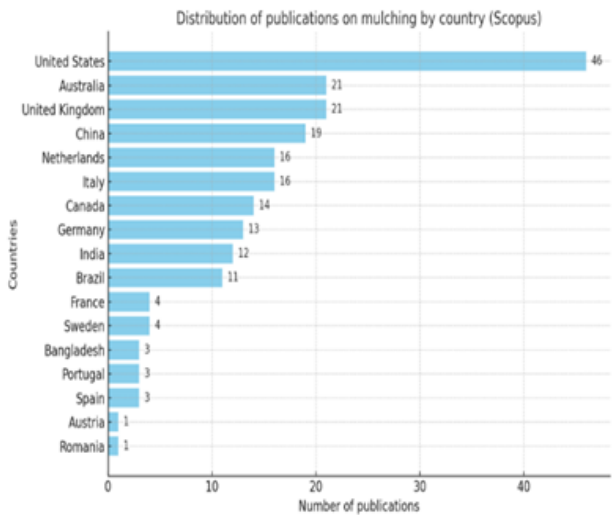


Figure 2: Geographic distribution of mulching-related publications (Scopus, 2000–2025).

In Greece, by contrast, documented forest applications are absent, with reliance on costlier, short-lived measures [15,20]. The review underlines the need to integrate mulching strategically into the Forest Service, supported by KPIs and sustainability indicators, to strengthen resilience under climate crisis conditions.

COMPOSITE EVALUATION INDICATORS

In the NPM framework, mulching is evaluated through composite indicators reflecting efficiency, sustainability, and institutional readiness [8,11,21]. These encompass three categories: (i) environmental—moisture retention, regeneration, runoff; (ii) administrative—cost-effectiveness, institutional integration, acceptance; and (iii) technological—smart monitoring via sensors and GIS. Their use links ecological results with governance, transparency, and strategic planning, reinforcing the need for institutional recognition.

RESULTS

This section combines bibliometric analysis, NPM indicators, and data from the Evia pilot, highlighting international trends and the potential for institutional integration in post-fire management. The KPIs—environmental, administrative, and technological—link technical effectiveness with sustainability and evidence-based decision-making. The bibliometric review (Scopus, 2020–2025) shows a sharp post-2020 rise in mulching research, concentrated in Spain, Portugal, and the United States. Keyword mapping emphasized *post-fire rehabilitation*, *erosion control*, *resilience*, and *climate adaptation*, while the absence of Greek forest applications underscores institutional and scientific gaps.

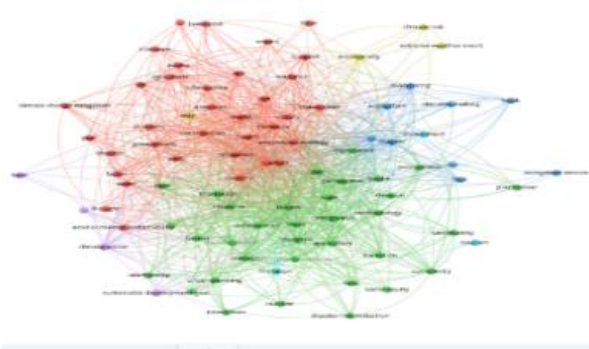


Figure 3: Keyword co-occurrence network on climate adaptation (clusters: sustainability, adaptation, risks, mitigation)

The absence of forest applications in Greece underscores institutional and scientific gaps.

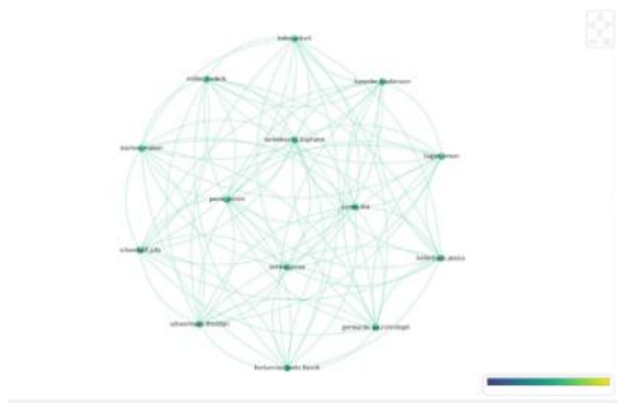


Figure 4: Author collaboration network in governance (main groups and interconnections).

OS viewer mapping revealed three main axes: (i) technical—erosion and hydrology, (ii) ecological—resilience and biodiversity, and (iii) administrative—governance, sustainability, circular economy, and NPM. This tripartite framework positions mulching as both an ecological and an institutional strategy.

SYNTHESIS OF BIBLIOMETRIC FINDINGS AND INDICATORS

The bibliometric analysis identified three clusters: (i) mulching and erosion control, (ii) ecological resilience and adaptation, and (iii) governance and sustainability. Correspondingly, three composite indicators are proposed: Efficiency, Sustainability, and Institutional Readiness, aligning with NPM principles and turning mulching into a measurable policy tool.

CALCULATION OF INDICATORS

Bibliometric analysis confirmed a surge in mulching research after 2020 [12, 16, 17], while in Greece, its lack of institutional integration reflects an administrative lag. To address this, three composite indicators are proposed: Efficiency Index (EI): Measures the impact of mulching on reducing runoff and erosion: $EI = [Q_c - Q_m / Q_c] * 100$, where Q_c = quantity of runoff/erosion in the control plot, and Q_m = quantity of runoff/erosion in the mulched plot.

Sustainability Index (SI): Evaluates long-term ecological improvement (e.g., organic matter, vegetation cover): $SI = [(V_t - V_0) / V_0] * 100$

where V_m = value of ecological parameter (e.g., organic matter, vegetation cover) in the mulched plot, and V_c = value of the same parameter in the control plot.

Institutional Readiness Index (IRI): Captures the level of administrative capacity and institutional integration of the technique: $IRI = (G + T + P) / 3$

where G = existence of standardized implementation guidelines (0–1),
 T = training of staff and crews (0–1),
 P = integration into policies and programs (0–1). Together, these indices link environmental performance, long-term sustainability, and administrative integration. International experience shows they act as “bridges” from pilot projects to institutionalized policy [10,11]. The Evia case can thus

serve as a model of ecological and administrative innovation if supported by monitoring and formal recognition.

PILOT APPLICATION IN EVIA

The 2024 wildfire in Afrati, Evia, provided the site for Greece’s first organized mulching pilot (60 ha), chosen for its erosion risk, soil loss, and biomass availability. Biomass was shredded and applied in a 3–5 cm layer, with log barriers along contours to reinforce erosion control. A smart monitoring system with soil sensors, GIS data, and regeneration indicators linked the intervention to efficiency, sustainability, and institutional readiness metrics. This pilot demonstrates mulching’s dual role as an ecological measure and an administrative innovation, offering a model for national forest policy.

CONCLUSIONS AND PERSPECTIVES

RESEARCH LIMITATIONS

The study is limited to Evia, short-term data, and early-stage institutional adoption. Broader applications, long-term monitoring, and standardized national procedures are needed.

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Risk Assessment of Flood-Prone Roads Using Digital Models

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Abstract— Climate change and extreme weather events constitute a major threat to traffic safety and to the integrity and the operability of every transportation system. Storm surges, wildfires, floods and hurricanes may produce unforeseeable damage to passengers, vehicles and goods, as well as, to the transport infrastructure.

Among these climate hazards, floods are the most damaging event. With respect to the road traffic and infrastructure, specifically, devastating floods occur frequently, ruining roadways and bridges and causing fatalities.

At international level, the concern about flood risk has gradually been amplified and respective action plans have been elaborated in Europe and elsewhere. Protection measures against flooding, implemented in various countries, are reported to have produced beneficial effects on the network integrity. However, it must be clearly stressed that the current situation in the industrialized world is far from being ideal or even significantly improved.

The hereby dual digital concept for flood risk assessment over road networks or road corridors has a proactive character and is meant for Road Operators willing to safeguard the infrastructure and to protect travelers. It consists of a digital flood-testing model and a digital twin model.

The digital flood-testing model makes possible a virtual inundation of the road corridor or the road network and the surroundings by rainfall water over a return period of 200 and 500 years. Every proactive measure or set of measures against flooding, to be potentially taken, can thus be tested and the respective outcome, in terms of flood impact alleviation, can be evaluated.

The digital twin model is an interactive tool providing real-time information, in case of flood. It follows constantly the rise of the flood water level and forecasts emergency situation.

By means of these digital tools, Road Operators can identify the most vulnerable and the safest Road Corridors, as well as, spot low-lying and flood-prone road segments along Critical Corridors. Accordingly, they will be able to plan actions to upgrade and reinforce the deficient infrastructure but also to elaborate suitable emergency plans in order to effectively face aggressive events of extreme severity.

The paper presents the layout of this dual digital concept and some measures to upgrade low-lying road segments by conventional and innovative techniques.

Keywords—road, infrastructure, flood, hazard, measure, digital, model

BACKGROUND

During the last decades, the frequency and the intensity of extreme weather events marked a net increase worldwide. Aggressive events, such as, floods, storm surges, wildfires and snowstorms, constitute a big threat to the integrity of the road transport system, since they can severely harm critical road assets and the infrastructure. The threat may become even more severe to drivers and travelers, unexpectedly obliged to face harsh weather events. In the field of road adaptation to climate hazards, multiple scientific approaches and protective

measures taken have not produced yet the expected results. The road transport sector still suffers from climatic hazards and undergoes severe deterioration in the advent of extreme weather events, often turning into disasters. The need for a method of reliable risk assessment leading to proactive and reactive measures with view to reinforcing the road infrastructure and to protecting travelers and vehicles still remains [1].

Among all climate hazards, flooding is certainly the most common and the most disastrous, since global temperature rise produces heavier and more frequent rainstorms. Consequently, devastating floods occur frequently worldwide. In 2024, disastrous floods were reported to have taken place in India, Bangladesh, Chad, Niger, Brazil [2], as well as in many European countries, namely in Spain, Germany, Belgium, Czech Republic, Poland and other. Such flood events produce severe damage, fatalities and a totally helpless situation. Recovery is always long and full of impediments.

Road infrastructure is typically designed to withstand high rainfall intensity. Road engineers take into account historical data on weather events, to design drainage assets, culverts and pipes of sufficient strength and capacity. However, it seems that, recently, the historical record on natural hazards is no longer a reliable predictor of future disasters [3]. Harsh events of extreme severity become more frequent and the rate of return for the design of drainage assets climbs from 50 to 100 and, possibly, to 200 years [4, 5, 6].

The serious concern about the vulnerability of roads and streets with regard to climate hazards has driven Road Authorities and Institutions to conduct research on the subject and to develop guidelines for the protection of road infrastructure [3, 6, 7, 8, 9, 10]. Moreover, individual scientists and researchers have proposed risk assessment methods and reinforcement measures to fight against climate threats [11, 12, 13]. Protection measures against flooding, implemented in various countries, United Kingdom, Denmark, France and other, are reported to have produced beneficial effects on the network integrity [14, 15].

However, it must be clearly stressed that the current situation in the industrialized world is far from being ideal, since incessantly and every year devastating floods occur worldwide ruining properties and causing fatalities. A method for flooding risk assessment on local scale and an emergency tool for timely alert about the oncoming flood are persistent challenges and fields for further research.

ROADS AND FLOODS

Climatic stressors are climatic factors of very high or very low values. Long and heavy precipitation, rainstorms, snowstorms, high temperature, tornados, storm surges and other, are climate stressors generating hazards of harmful impact on road infrastructure. Hazards associated with

climate stressors are floods, landslides, wildfires, droughts and sea level rise, which have multiple impact on roads, traffic and the environment. While it is very difficult to annihilate a climatic stressor, it is possible and mandatory to fight effectively against a hazard.

Plains, valleys and flat terrain may be submerged under heavy rain or rainstorm conditions if the runoff volume exceeds the discharge capacity of drainage assets. An extreme rainstorm is likely to generate a flash flood while a heavy and persistent rainfall will probably produce permanent flood. In either case, the road infrastructure risks to get inactive. A short- length segment being submerged may cut off an important road corridor of many kilometers [Fig.1].

In this regard, research institutions and scientists developed methods of flood risk assessment and proposed measures to fight against flood impact on roads.

The first operational European system monitoring and forecasting floods, across Europe, is the European Flood Awareness System (EFAS). According to its internet site, the aim of EFAS is to support preparatory measures before major flood events strike, particularly, in the large trans-national river basins and throughout Europe in general. Since 2012, EFAS is running fully operational as part of the Copernicus EMS [16]. Some international institutions strive to elaborate methods of proactive intervention to protect the road

infrastructure and assets [3, 7, 17, 18]. Most of them are of general character, that is, not specifically elaborated for each road or street network under consideration (Table 1). Nevertheless, these methods may be a powerful tool in the fight against flood hazards.



Figure 4: Sometimes an important Corridor gets inactive just because of a local submersion

Table 2: Flood Risk Assessment Methods and Models (from literature search)

Institution	Flood Risk Assessment of Roads	Area / Network	Proactive Measures		Reactive Measures
			General	Specific	
PIARC 2015 (All Hazards)	Assessment of impact severity and probability	Road network	Structural and green	Using algorithms	-
EU / Van Ginkel et al, 2021 (Floods)	Inundation maps and digital models	Region	-	-	-
AUTH 2020 / Mouratidis (All Hazards)	-	Road network	Structural, green and digital	-	-
FHWA 2024 / Leung (Floods)	Digital model + AI	Street network	-	-	-
EU ROADAPT 2016 (All Hazards)	Vulnerability assessment	TEN-T network	Structural and green	Using algorithms	-
WORLD BANK (All Hazards)	Vulnerability and road assessment	Road assets	-	-	Emergency planning
EFAS 2011 (Floods)	Forecast model	Post-event & precipitation maps	-	-	-
EEA 2017 (Floods)	-	Vulnerability by region	Structural and green	-	-
UK, Univ. of Huddersfield Mushtaq M. et al. 2024 (Floods)	-	Roads, streets pavements	Structural and green	-	-

FLOODS, TRAFFIC AND ROAD INFRASTRUCTURE

Floods may overflow a significant part of land, structures, habitations and the road infrastructure, namely roads and streets. constructed on low embankments or on the ground surface. Considering human life and health as the first priority in case of flooding, the road infrastructure has a very important role to play in a concerted public action for the safeguard of citizens and the safe movement of emergency vehicles on the transport network. Therefore, it is important to perceive, not only the risks to the integrity of road assets generated by flooding, but also the risks related to traffic safety during or in the aftermath of a flood event.

Several flood-induced risks, related to the integrity of the infrastructure (Table 2) and to traffic safety after excessive flooding (Table 3), are displayed and classified by level of severity.

Table 3: Flood -Induced Risks

High	Significant	Low
• Approach embankments • Abutments • Bridge piers • Wing walls	• Embankments (no surfacing on slopes) • Retaining walls • Earth shoulders • Gravity walls • Embankments on steep slopes	• Cutting sections • Natural slopes • Rigid pavements • Embankments with slope surfacing • Vegetated slopes

Table 4: Traffic Related Risks

High	Significant	Low
• Heavy trucks on saturated embankments • Heavy trucks on unstable bridges	• High-speed on littered / wet asphalt courses • Heavy trucks	• Traffic on road with weathered markings • Traffic on roadway at cutting sections after landslide

High	Significant	Low
• Unsuspended traffic before post-hazard inspection and placement of signage	on distressed pavements	debris removal

Engineering structures, including drainage systems, bridges and culverts, are designed to withstand flood conditions over a return period of 50 and rarely 100 years. However, recent catastrophic events all over the world proved that rainfall intensity and height may overrun these assumptions.

DIGITAL MODELS TO FIGHT AGAINST ROADWAY SUBMERSION AND TO MINIMIZE FLOOD IMPACT ON TRAFFIC

On a scale of a region or a town, it is very important to identify proactively the safest road corridors, as well as those of uncertain operability under flood conditions. By contrast to the general methods proposed by most research institutions and associations, what is really needed is the assessment of the submersion risk for the road/street network and of the effectiveness of some proactive measures. In this regard, low-cost engineering operations over unsafe road corridors, such as profile uplift or additional drainage systems, may prove beneficial, once these low-level segments are identified.

Moreover, the real-time observation of a flood event, with respect to the road/street network, may prove decisive in an emergency plan of evacuation and intervention. Roads need remain open and traffic must be directed to safe corridors.

The innovative hereby method consists of:

a) A digital flood-testing model, that is, of a Digital Ground Model (DGM), where the advent of a flood incident is investigated, in terms of road/ street corridors submersion. Moreover, every potential measure or set of measures is tested over the DGM and the respective outcome, in terms of flood impact alleviation, is evaluated. Thus, the beneficial impact of every measure or set of measures and the respective cost is recorded.

b) A digital twin model, consisting of a set of sensors, floating balls and CCTV, adequately placed on river banks, drainage pipes and culverts to identify the rate of groundwater rise and the probability of flooding, likely to affect the road and the street network.

THE DIGITAL FLOOD-TESTING MODEL

The development and implementation of the Digital Flood-Testing Model constitutes the first stage of the hereby outlined method. It consists of a digital ground model (DGM) of the area and the road/street network under investigation, where peak runoff volume, for different scenarios, over a return period of 200 or 500 years, risks to create full or partial submersion to the road and street corridors under investigation. Reasonably, the digital ground model must simulate realistic, conditions with regard to riverbed and banks, bridges, culverts and drainage systems.

The implementation of the Digital Flood-Testing Model aims at two distinct objectives:

1. Perform a Road / Street Vulnerability Assessment (risk of submersion) and classify road corridors by flooding susceptibility over different return periods
2. Determine Probable Engineering Intervention at Deficient / Low-Lying Road Segments (widening of riverbeds, new engineered canals and drainage

assets, red line uplift at short, low-lying, road segments)

The Digital Testing Concept is designed to provide answers to crucial questions regarding risk of flooding over road and street networks:

- Which corridors are at high risk of flooding?
- How deep and how long would this submersion be by corridor?
- What are the most effective engineering measures (widening riverbed, raise red line, artificial ponds, vertical wells) to prevent this submersion?
- What is the cost of these measures?

On a scale of a catchment area, it is important to examine and check on the impact of extreme rainfall events on the eventual submersion of the transport infrastructure. This may be carried out using digital ground models, simulating the terrain and the road corridors. For each increment of return period of rainfall, the runoff volume may be compared to the total discharge capacity. On a scale of a road corridor, the water level of a flooded area may be juxtaposed to the profile and the red line of the infrastructure, thus unveiling the parts/segments and the rate of submersion by corridor length. Since, extreme rainfall events are so frequent nowadays, this search and checking must attain, at least, a return period of 200 or 500 years.

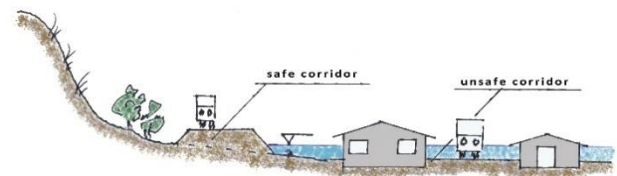


Figure 5: Sometimes an important Corridor gets inactive just because of a local submersion

THE DIGITAL-TWIN MODEL

The Digital-Twin Model is the reactive tool in the case of a potential flood event. It consists of physical indicators, namely, sensors, floating balls and CCTV, adequately placed on river and watercourse banks, culverts, bridge piers, sign posts and drainage systems (hardware of the Model) to provide real-time measurements of the water level.

The DT Model is equipped with a mathematical algorithm, able to interpret the water level measurements and to deduce the rate of water level rise. Reasonably, the time of concentration, gradual land saturation and other hydrological parameters must be taken into account for precise estimates. This mathematical process leads to an estimate of the remaining time for eventual submersion of each road or street corridor and provides the Competent Authorities with information about the time remaining to set forth actions directing traffic to safe road links.

In case of a flood emergency, Competent Authorities, local, regional or other, must proceed to the following actions:

- Inform drivers, travelers and individuals. A water height of 30cm renders a roadway unsafe.

- Suspend traffic and proceed to road closures, where water level is about to overflow road/street corridors
- Direct traffic to safe road links
- Evacuate residential areas risking submersion
- Launch auxiliary drainage measures (if any, retention basins, emergency water gates).

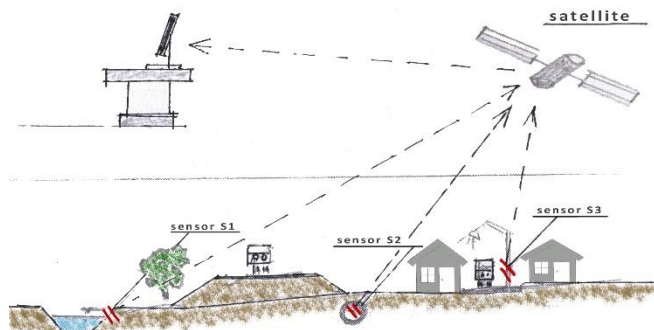


Figure 6: Sometimes an important Corridor gets inactive just because of a local submersion

PROACTIVE AND REACTIVE MEASURES

Setting in operation a strategic plan consisting of proactive and reactive measures to fight against flood hazards is the best option to protect individuals and properties, traffic and the road infrastructure. Even if, in many cases, this plan may prove partly ineffective, it is certain that a harder situation would turn up without proactive or reactive measures. Generally, measures can be classified into proactive and reactive, although, even reactive measures should be planned in advance.

Proactive measures are classified into two categories: a) preventive measures, aiming to reduce water runoff and to prevent submersion of the road structure (Table 4) and b) protection measures, intended to reinforce the road structure in case of upcoming inundation (Table 5).

Table 5: Preventive measures against flooding [19]

Preventive measures	Objective
Widen and deepen riverbed	Increase outflow discharge capacity
Construct additional culverts	Increase discharge capacity
Allow for enhanced vegetation uphill	Reduce runoff inflow
Drill vertical wells	Increase infiltration volume
Create small dams and artificial ponds uphill	Reduce runoff inflow
Artificial watercourses/channels	Increase outflow discharge capacity

Table 6: Protection measures against flooding [19]

Protection measures	Objective
Install lateral concrete barriers	Prevent roadway flooding
Lay Rip-rap on slopes	Protect road infrastructure
Deepen toe ditch	Prevent water level rise
Check drainage network	Enhance surface drainage
Raise roadway profile	Prevent roadway flooding
Remove debris from culvert inlets	Prevent erosion

On the other hand, reactive measures may be effective and crucial in case of a flood, especially these planned in advance (Table 6).

Table 7: Reactive measures during flooding

Reactive measures	Comment
Remove on-street parking	In the beginning of the flood event
Debris removal from culverts, inlets	Emergency patrols
Proceed to traffic diversion to safe corridors	Traffic management
Continuous check on bridges, overpasses	Structural integrity of piers, abutments
Divert (part of) rainwater runoff volume	Wherever possible
Install lateral barriers and pump the blocked runoff	Wherever possible

CONCLUSION

Flood-induced risks to the road infrastructure constitute a persistent challenge to road engineers and operators. Even more important are risks related to traffic on roads and streets, damaged by flood events, hereby presented. Protection measures, in this case, are obligatory and crucial.

The present approach, introducing two digital models for investigation and alertness, goes beyond the well-established methods of flood risk assessment for road networks. The objective is to identify the most suitable measures, specifically tailored for each road or street network, and to point out an effective emergency plan in case of a flood hazard.

The proactive checking on the effectiveness of measures can produce risk mitigation and save resources. It may be combined with green measures uphill which are meant to reduce runoff discharge downward.

Although, in several cases, the disaster produced by a flood event is immense and makes any measure seem pointless, this, in fact, is hardly true. Even in case of extreme hazards, engineering and green measures taken proactively may alleviate the impact of the disastrous event. They must observe the fundamental triptych of fighting against floods a) Reduce runoff water inflow, b) Increase discharge capacity, c) Protect vulnerable assets, and consider human life and survival as the utmost priority.

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Single-Diode Model Approach for Parametric Analysis of Photovoltaic Cells

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Abstract— In the face of increasing energy demand due to population growth, industrialization and economic developments, non-renewable energy resources are rapidly depleting. With this depletion, environmental problems occur. In recent years, because of these problems, the trend towards different energy sources has accelerated. At this point, solar energy from renewable energy sources comes to the fore with its sustainability, environmental friendliness and low cost. In order for the system performance to provide the best level of efficiency, it is necessary to track the maximum power point accurately. Various mathematical modeling methods are used to accurately analyze the performance of these systems. Accurate modeling of the electrical properties of photovoltaic panels is of great importance for system design, energy efficiency calculations and power generation predictions. This study focuses on the single diode circuit model for mathematical modeling of photovoltaic cells. The study presents a comprehensive simulation analysis of the electrical characteristics under different irradiance values and temperature conditions. In the study, the model reveals how the photovoltaic cell performance is affected by basic physical parameters. Thus, the presented model allows the analysis of cell output characteristics (power-voltage curves). The results show that environmental variables such as radiation and temperature have a decisive influence on PV cell output performance. It is concluded that despite the simplified structure of the single diode model, it can represent the practical operating conditions of PV cells with sufficient accuracy and provides an effective basis for performance analysis. In conclusion, this study validates the applicability and robustness of the single diode equivalent circuit model for PV system simulation and analysis.

Keywords— photovoltaic cells, single diode model, renewable energy, solar energy, simulation

INTRODUCTION

As a result of the increasing energy demand due to world population growth and economic developments and the rapid depletion of non-renewable energy sources such as coal, oil, natural gas and nuclear energy, we are faced with serious environmental problems such as excessive carbon emissions of fossil fuels, air pollution, radiation and waste disposal of nuclear energy [1]. As a result of these negativities, the tendency towards different energy sources has gained momentum. Sustainable and environmentally friendly renewable energy sources come to the forefront among these sources. Among the renewable energy sources, solar energy is gaining importance due to its sustainability and being a clean energy source [2]. Various mathematical modeling methods are used to correctly analyze the performance of solar energy systems. The methods used for photovoltaic (PV) system

modeling are generally divided into three main categories. These are physical-based, data-driven and hybrid models. Each of these methods is preferred according to their mathematical calculation, complex structure and accuracy levels. Equivalent circuit models are also included in physical-based models. These models are widely used to model the electrical behavior of photovoltaic cells [3]. In literature studies, physical models of photovoltaic cells; single diode model, two diode model and three diode model. Single diode model is the most commonly used method in literature studies [4-7]. It consists of a four and five parameter model. The internal parameters of the model with four parameters are photon current, diode leakage current, ideality factor and series resistance. Single diode model assumes that the parallel resistance is infinite. Thus, the open circuit voltage decreases. Five parameter model considers the effect of parallel resistances. The complexity of the model increases. Two diode model has a more complex structure compared to the single diode model because it has an extra diode [8-11]. In three diode model, leakage diode current is produced by three diodes [12-17]. As the number of parameters increases in three diode model, the model becomes more complex. The mentioned single, double and triple diode models contain four or five, seven and nine parameters respectively. Accurate modeling of electrical properties of photovoltaic panels is of great importance in terms of system design, energy efficiency calculations and power generation estimations. Maximum power point tracking (MPPT) is a technology that finds the highest power point of direct current electricity from solar panels and maximizes the power output. Photovoltaic panels can accurately track the maximum power point, thus improving the efficiency and performance of photovoltaic power generation systems [18]. MPPT control methods should be used to increase the accuracy of the model used in modeling and performance analysis of photovoltaic panels and to ensure the stability of the system. These maximum power tracking control methods include various techniques under the title of traditional MPPT methods such as switch and observe (P&O), incremental conductance (InC) and constant voltage (CV). In this study, the panel cell in a photovoltaic energy system was modeled. A single diode equivalent circuit model was used in the modeling. The panel model was simulated at different radiation and temperature values. The performance of the photovoltaic energy system under different operating conditions was examined in the model simulation results.

Photovoltaic Cell Model

In this study, the single diode model of the equivalent circuit of the photovoltaic cell was theoretically investigated in detail. Model parameters, effects of environmental factors on model performance, effects of environmental factors on model performance in photovoltaic systems were included in the study. The examined model is the basic model that defines the I-V characteristics of a photovoltaic cell. In the equivalent circuit of the photovoltaic cell in Figure 1, the photovoltaic cell acts as a current source. The generated current is directly proportional to solar radiation. When a photovoltaic cell is not excited by solar radiation, it acts as a standard p-n junction cell diode. For the equivalent circuit of a photovoltaic cell under ideal conditions, a diode and a diode-parallel current source were included. However, a series and a parallel resistor were added to the equivalent circuit to obtain realistic results from the model. As indicated, the four main circuit elements are shown in Figure 1. photovoltaic cell equivalent circuit.

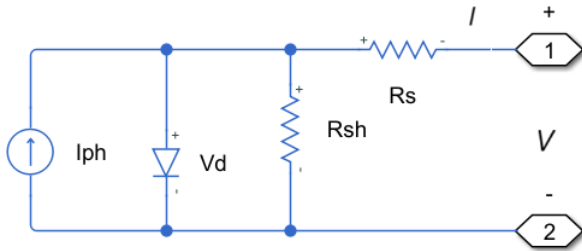


Figure 1: Photovoltaic cell equivalent circuit

In the photovoltaic cell equivalent circuit in Figure 1, I_{ph} is expressed as photon current. This current is the photon current is related to the potential to generate electrical energy from solar radiation. In the figure, V_d is the voltage across the parallel diode refers to the drop. The output I to be produced by the photovoltaic cell equivalent circuit shown in Figure 1 current is calculated by Equation (1).

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (1)$$

The variable “G” given in Equation (2) is the instantaneous radiation value (W/m^2), 1000 in the quotient process is the irradiance value accepted within the standard test conditions (STC). I_{sc} value short circuit current, K_i is the temperature coefficient and ΔT is the temperature difference. Unit of temperature coefficient A / °C or % / °C.

$$I_{ph} = \frac{G}{1000} (I_{sc} + K_i \Delta T) \quad (2)$$

I_d , given in Equation (3), is the diode current. I_0 is the leakage current. In the equation, T_c temperature (K), $q = 1.6 \times 10^{-19}$ C electron charge and $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant. In mathematical expression “A” is the ideality factor. The voltage drop across the parallel diode is expressed by Equation (4).

$$I_d = I_0 \left[\exp\left(\frac{qV_d}{AkT_c}\right) - 1 \right] \quad (3)$$

$$V_d = V_{pv} + IR_s \quad (4)$$

Photovoltaic cells are connected in series and parallel with each other to form modules and modules form arrays. The resulting arrays determine the current, voltage and power value of the system. Hence the photovoltaic cell numerical data for series-parallel connections are important in modeling. In series connection, the voltage (V) increases while the current (I) remains constant. In parallel connection, on the contrary the situation is realized. In other words, while the current increases, the voltage remains constant. The photovoltaic system, shown in Figure 2, obtains the output power obtained with temperature and irradiance inputs.

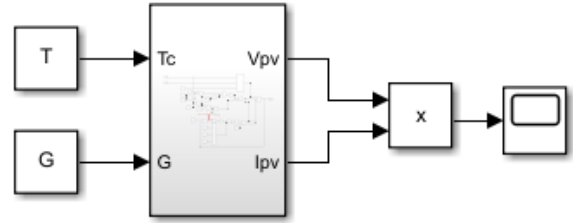


Figure 2: General simulation representation of the photovoltaic model

Modeling the Photon Current

In photovoltaic modeling, photon current (I_{ph}) is a fundamental parameter in equivalent circuit models. When the mathematical model of the photon current expressed by Equation (2) is examined, it is seen that temperature, radiation and the properties of the material used affect the photon current. I_{ph} , the main current in photovoltaic cells component and is directly proportional to sunlight. The mainstream is constructed as shown in Figure 3.

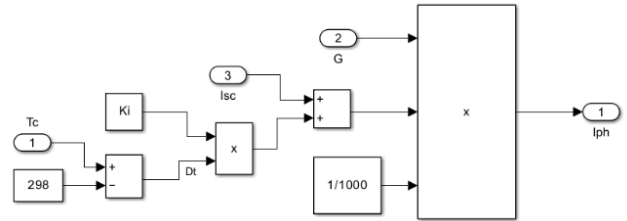


Figure 3: Photon current model

Modeling the Diode Current

The mathematical equation given in Equation (3) is used to calculate the diode current value. The leakage current I_0 , for a diode is calculated by the following Equation (5). Where T is the temperature and T_{ref} is the reference temperature under standard test conditions, which is taken as 298.15 K. E_g is the forbidden energy band gap value for the silicon cell, which is assumed to be 1.12 eV (for T= 300K). The equation expressed as VT in the equation is $VT = (k \cdot T)/q$.

$$I_0 = I_{on} \left[\frac{T}{T_{ref}} \right]^3 \exp \left[\frac{E_g}{AVT} \right] \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \quad (5)$$

Figure 4 shows the simulation modeling of the diode leakage current whose mathematical equation is given in Equation (5).

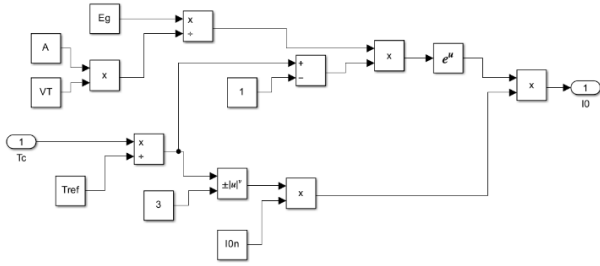


Figure 4: Diode leakage current model

Figure 5 shows the simulation modeling of the diode current whose mathematical equation is given in Equation (3).

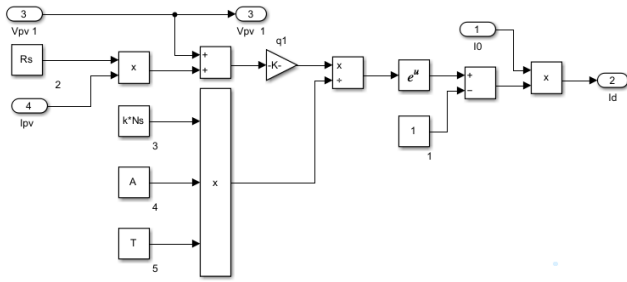


Figure 5: Diode current model

Modeling the Output Current

The output current of the photovoltaic cell equivalent circuit I_{pv} , which is expressed mathematically in Equation (1), is clearly shown in Equation (6).

$$I_{pv} = \frac{G}{1000} (I_{sc} + K_i \Delta T) - \left[I_{0n} \left[\frac{T}{T_{ref}} \right]^3 \exp \left[\frac{E_g}{AVT} \right] \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \left[\exp \left(\frac{qV_d}{AKTc} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (6)$$

The equivalent circuit of the photovoltaic cell expressed mathematically in Equation (6) is shown in Figure 6 with simulation.

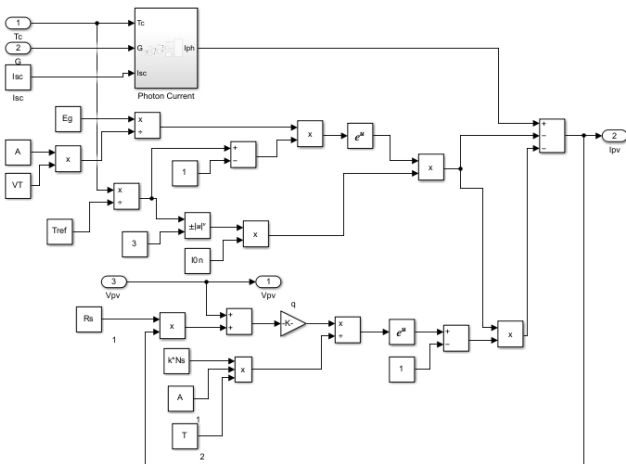
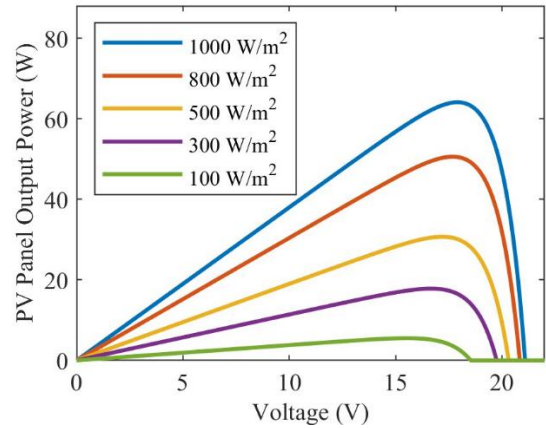


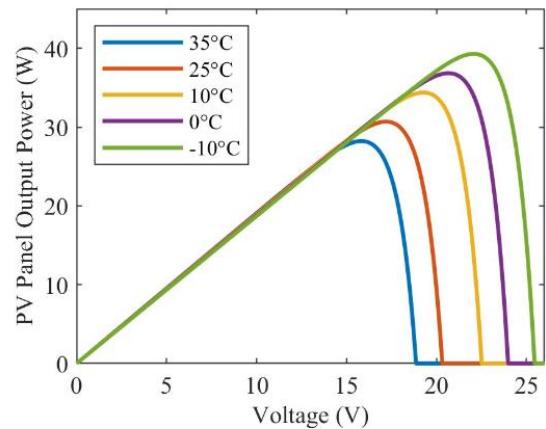
Figure 6: Photovoltaic cell output current

SIMULATION RESULTS

In this study, in the simulation of a single diode photovoltaic (PV) cell in software environment, different irradiance P-V characteristics of the photovoltaic cell at different values and temperature levels. Simulation applications, basic parameters of photovoltaic modules within the scope of the single diode model method of light current, diode leakage current, ideality factor, series resistance and parallel resistance. Figure 7.a the characteristic curves between the output power and voltage of a PV panel are shown. As the irradiance increases, the photovoltaic current generated per cell increases. Therefore, the output power increases. The maximum power point differs significantly for each irradiance level. shows. As the irradiance increases, this point is realized at higher voltage and power values. In particular, the maximum output power obtained at 1000 W/m² irradiance level is around 80 W, this value drops below 8 W at 100 W/m². It is noteworthy that the maximum power is that the voltage value corresponding to the point shows less variation than the irradiance variation increase. This suggests that voltage-oriented control algorithms may be more robust to irradiance conditions. These characteristic curves obtained will be used in PV systems MPPT algorithms are dynamically optimized to be sensitive to irradiance conditions update is necessary. Especially short-term radiation, such as suddenly changing cloud cover, the adaptive control capability of the system is of great importance. Thus, PV modeling is important for performance simulations of systems and field applications.



a. Constant temperature, different irradiance values



b. Constant irradiance, different temperature values

Figure 7. Simulation results of the photovoltaic system with different irradiance and temperature values

Figure 7.b shows the PV panel for varying temperature conditions under constant irradiation (from -10 °C to 35 °C). The relationship between output power and voltage is shown. The curves show that as the temperature increases, the maximum output power decreases and the voltage corresponding to the maximum power point drops significantly clearly reveals. The main reason for this behavior is that the temperature increase leads to an open circuit in PV cells. voltage of the semiconductor. This drop is due to the semiconductor is associated with a narrowing of the band gap of the material. Typically, with a temperature of about It decreases by 2 mV/°C. Although the current value increases slightly with temperature (approx. +0.05%/°C), Since it cannot compensate for the drop in voltage, there is a net reduction in the overall output power. For example, the output power and corresponding voltage value at -10 °C, compared to the values at 35 °C, they are considerably higher. This can be explained by the fact that at low temperatures modules operate more efficiently. At the same time, maximum power point monitoring tracker (MPPT) algorithms should be sensitive to temperature variations and temperature shows that a control strategy including compensation can improve performance. In conclusion, temperature increase is an important parameter that negatively affects PV system performance, system design and control algorithms should be optimized for this thermal effect. Also, high such as cooling strategies for PV systems operating under temperature conditions efficiency losses can be reduced through passive/active measures.

CONCLUSION

In this study, a single diode equivalent circuit model is mathematically investigated to observe the electrical behavior of photovoltaic (PV) cells. The mathematical modeling method allows for more accurate and reliable prediction of PV cell behavior. The model enables the analysis of cell output characteristics (power-voltage curves) by revealing how photovoltaic cell performance is shaped by fundamental physical parameters. The findings show that environmental variables such as irradiance and temperature have a decisive effect on PV cell output performance. The findings show that environmental variables such as irradiance and temperature have a decisive effect on PV cell output performance. Under constant temperature, the increase in irradiance led to a linear increase in short-circuit current, but a limited increase in open-circuit voltage. Conclusion the maximum power point is both increased and the general shape of the curve is preserved. On the other hand, the increase in temperature under constant irradiance leads to a significant reduction in maximum power generation, especially by lowering the open circuit voltage. It is concluded that despite the simplified structure of the single-diode model, it can represent the practical operating conditions of PV cells with sufficient accuracy and provides an effective basis for performance analysis. However, the model has some deviations at low irradiance levels or high temperatures. can show this, and therefore more advanced modeling approaches (such as the double diode model) conditions are considered to be preferable. Future studies can contribute to further development of PV system performance prediction and control strategies by focusing on parameter optimization of the single diode model, more accurate modeling of temperature and irradiance changes, and integration into real-time applications.

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Biomass Based Carbonized Material as Electrocatalyst Support

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Abstract— Carbon support materials ensure that the metallic catalyst is finely sized and consistently dispersed across the electrocatalyst layer in PEM technology. Carbonaceous materials derived from industrial tea waste biomass were investigated as the support material for electrocatalysts utilizing platinum nanoparticles (Pt/C). The physicochemical and electrochemical evaluation of Pt/C electrocatalysts was conducted. The electrochemical properties of the produced Pt/C electrocatalysts were examined by measuring the platinum mass-specific electrochemically active surface area (ECSA) in an acidic solution.

Keywords— biomass; carbonized material; Pt/C electrocatalyst; support

INTRODUCTION

The widespread adoption of technologies that make it simpler to generate alternative, sustainable, and clean energy is necessary in order to improve public, economic, and environmental health.

Proton Exchange Membrane (PEM) fuel cells as key enabling technology (KET) are capable of directly converting chemical energy into electricity with a high degree of efficiency, making them one of the most promising technologies for the generation of clean energy. A significant technological advancement in the process of transforming hydrogen, a source of clean energy, into electrical energy is the use of PEM fuel cells.

The widespread adoption of PEM fuel cell technology is contingent not only on the development of hydrogen production, storage, and transmission, but also on the enhancement of the durability of the electrocatalyst layers that form the heart of PEM fuel cells.

The common implementation of PEM fuel cell technology is contingent not only on the development of hydrogen production, storage, and transmission, but also improvement of the durability of the electrocatalyst layers that form the core of PEM equipment.

The electrocatalyst layer is the location where fundamental electrochemical reactions take place. It is composed of metallic electrocatalyst particles such as platinum that are placed on a carbon support material.

Carbon support is responsible for ensuring that the metallic catalyst is of a fine size and distributed uniformly throughout the electrocatalyst layer. This ultimately enhances the efficiency of the PEM fuel cell by increasing the availability of the metallic catalyst during electrochemical processes, while simultaneously facilitating a constant flow of electric current. At the same time, it enables a continuous flow of electronic current. The utilization of carbon support material

inhibits the sintering or agglomeration of Pt particles as well. Moreover, in contrast to bulk Pt catalysts, electrocatalysts distributed in carbon exhibit greater resistance to catalyst poisoning.

In commercial platinum/carbon (Pt/C) electrocatalysts, a wide variety of carbon materials are utilized as support materials. Vulcan or Ketjen Black are examples of the carbon support materials that are utilized the most frequently [1]. Pyrolysis or partial combustion of petroleum hydrocarbons, polymers, or acetylene gas are the processes that result in the production of these carbons.

When viewed from a different perspective, the combustion of fossil hydrocarbon sources has led to an increase in the pressure that is being placed on the commercial production of carbon and industries that are related to it. This is because of the fact that global warming and pollution of the environment have occurred.

In recent decades, research has been focusing on developing alternative, renewable, sustainable, and clean carbon materials that are derived from biomass to help overcome the limitations of carbon that is derived from fossil fuels. These materials have a high surface area, porosity and anchoring functional groups. Wu et al. [2] reviewed the recent progress in biomass-derived nano electrocatalysts for the sustainable energy development. The majority of research on carbon derived from biomass or carbonaceous materials as electrocatalysts for PEM fuel cells is focused on oxygen reduction reactions (ORR) or oxygen evolution reaction (OER) in alkali medium.

Cathodic ORR reactions are the ones that are accountable for rate determining step at the kinetics of these reactions which are extremely slow. Porous carbon derived from biomass, either doped or combined with metallic or non-metallic nanomaterials, has been produced to enhance the kinetics of the oxygen reduction reaction (ORR). Upskuvienė et al. [3] synthesized nitrogen doped activated carbon from wood residues and determined its ORR activity and have found that the synthesized carbon material is as effective as commercial 20% Pt/C electrocatalyst for ORR. Ding et al. [4] evaluated the electrocatalyst prepared by immobilizing Pt nanoparticles on a carbon support material obtained from the carbonization of eggplant peel biomass, in terms of its performance in the membrane electrode assembly (MEA) of PEM fuel cells and its ORR reaction performance. The catalyst's performance is found to be comparable to commercial electrocatalysts. Jalalah et al. [5] synthesized a nitrogen-doped Pt/C electrocatalyst using a carbon support material derived from bamboo biomass and determined its ORR performance in a 0.1 M KOH alkaline environment. The sensitized catalyst, as a metal-free electrocatalyst, provided

efficient charge and mass transfer and was reported as a promising catalyst.

Other PEM reactions, hydrogen evolution reaction (HER), hydrogen oxidation reaction (HOR), occur at the anode with the aid of a Pt/C electrocatalyst, and both at acidic and alkali conditions [6]. However, the challenges for acidic conditioned PEM reactions and acidic fuel cells still persist [7].

The studies on the Pt/C electrocatalysts synthesized with biomass based carbon support material are very limited. Particularly, studies on HER/HOR reactions with biomass-supported Pt/C in acidic conditions are scarce in the literature. Wu et al. [8] examined the carbon matrix obtained from bamboo fiber as supporting material for the immobilization of Pt nanoparticles. The robust association between Pt and pyrolytic N atoms enhances the electrocatalytic HER performance and underscores the potential of utilizing sustainable, biomass-derived materials to progress catalytic applications.

In this work, industrial tea waste biomass was converted to carbonized material by pyrolysis and used to prepare a carbon support material for synthesizing Pt/C electrocatalysts. The electrocatalytic activities of the synthesized Pt/C was investigated through measuring the Pt mass specific electrochemically active surface area (ECSA) in acidic medium.

EXPERIMENTAL

The industrial tea waste (TW) biomass from local tea factory in Rize (Türkiye) in the form of straw (<2.36 mm) was ground and sieved using from 0.5 mm sieve. Then, it was impregnated with the catalyst of FeCl_3 in 2:1 w/w ratio (TW: FeCl_3) that synthesis of graphitic carbon can be achieved by iron catalysed pyrolysis (Hunter). The impregnated sample was pyrolyzed at 850 °C, N_2 atmosphere, 1 h in a rotary oven (Protherm RTR 11/100/500). The obtained carbonized material was washed with 6 M HCl and 6 M HF to remove the impregnated metal-oxides and the other possible minerals biomass included to the sample of BC2.

Further, the sample BC2 subjected to second pyrolysis at various temperatures 300, 500 and 700 °C, at H_2/N_2 (5/95 v/v) atmosphere for 2 h with the aim of further structural improvement. The sample is nomenclature as BC2-H2-X (X is temperature).

The Pt/C electrocatalyst were synthesized by using ammonium hexachloroplatinate ($(\text{NH}_4)_2\text{PtCl}_6$) as the Pt precursor through microwave assisted polyol method [9] supported on the derived carbon samples BC2 and BC2-H2. The Pt precursor (40 mg, with the 20% target Pt ratio) is solved in an appropriate volume of ethylene glycol/water (MilliQ) (3:7 v/v) (15 ml) solution. The Pt concentration was checked before each synthesis by X-ray fluorescence (XRF) spectroscopy (Thermo Scientific Niton XL3t GOLDD+). After addition of the carbon sample (70 mg), the mixture was ultrasonicated for 1 min by an ultrasonic processor (Hielscher UP200St) to uniform dispersion and transferred into the reaction vessel. The microwave (MW) treatment was performed at a constant power output of 200 W by CEM Discovery SP MW synthesizer under constant magnetic stirring. The MW experimental setup was arranged in 100 °C max. temperature and 600 s duration time under the condenser cooled flux at 4 °C. After the MW treatment, the vessel was air cooled to room temperature. The samples were centrifuged, washed twice with ultrapure water, and dried at 80 °C in air. The supernatant was also analysed with the XRF

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to determine the concentration of Pt species and hence to calculate the degree of conversion of Pt^{4+} to Pt^0 . The commercial carbons of Ketjenblack EC 300J (C2) were utilized to synthesize Pt/C electrocatalysts as well. The synthesized electrocatalysts are Pt/C_{BC2}, Pt/C_{BC2-H2}, Pt/C_{C2}.

In a different experiment, biomass derived carbon BC2 was combined with commercial carbon C2 in a range of different proportions (15-80 % w/w) in order to produce Pt/C_{Mix} electrocatalysts. The reason for choosing BC2 carbon is that it has a medium surface area, the Pt/C_{BC2} catalyst has a partially low ECSA value, and to observe the potential effects of commercial carbon on the Pt/C_{Mix} electrocatalysts. The catalysts are denoted as Pt/C_{Mix1} through Pt/C_{Mix5}. The final synthesized electrocatalyst Pt/C_{Mix6} was prepared by mixing pre-existing Pt/C_{BC2} and Pt/C_{C2} in 80/20 w/w, respectively.

The synthesized Pt/C electrocatalysts were used to prepare the ink for the next electrochemical characterizations according to a standard procedure [10]. In brief, around 10 mg solid sample was mixed with 5 ml 5% nafion (DuPont D521) solution consisting 2-propanol and water in the ratios of 0.4:20:79.6 (v/v), respectively. The mixture was ultrasonicated for 1 min and 10 μL of it was settled on the polished (by 0.5 μm and 0.05 μm alumina) glassy carbon (GC) electrode by drop-casting. The loaded Pt catalyst amount on the GC was estimated before and after the electrochemical measurements by the XRF analyser.

The electrochemical measurements were performed through cyclic voltammetry by ZahnerIM6e electrochemical workstation and a standard three-electrode setup of a Ag/AgCl reference electrode (RE), a platinum counter electrode (CE) and a GC ($\Phi = 5$ mm; Pine Instruments) as the working electrode (WE) coated with the synthesized Pt/C electrocatalyst. The sample on the GC was first activated by potential cycling for 20 cycles between 0.02 V and 1.2 V at a scan rate of 100 mVs⁻¹ in 1M H_2SO_4 (EMSURE grade, assay >95–97%, Merck) solution saturated with N_2 [20]. The ECSA values in m^2g^{-1} of the as-prepared electrocatalysts were determined by the accelerated stress test (AST) [11] through linear sweep potential cycling with a 1600 cycles between 0.4 V and 1.6 V at a scan rate of 1 Vs⁻¹ along with intermediate observational cycles between 1.2 V and 0.02 V at a scan rate of 10 mVs⁻¹ (2 cycles per observation). All the measurements were performed at room temperature. The ECSA of Pt/C electrocatalysts was calculated through the cathodic scan area under the H^+ adsorption region between 0.4 V and 0.02 V of CVs starting from the second peak [12]. The surface charge density for H^+ adsorption on polycrystalline Pt of 210 μCcm^{-2} was used.

A reference electrocatalyst with 20% Pt (BASF, rPt/C) was also subjected to electrochemical characterizations.

The structural characterizations of the samples were realized by surface area (BET, Quantachrome Autosorb 1C and Quantachrome Asi Qwin™), transmission electron microscope (TEM, Jeol JEM-2010F (200 kV)), the size distribution and agglomeration state of the Pt nanoparticles was evaluated by measuring individual 100 Pt nanoparticles from different TEM images through ImageJ software, X-ray Diffraction (XRD, Rigaku Miniflex 600 X-ray diffractometer (Cu $K\alpha$ ($\lambda = 1.5418$ Å) radiation), and X-ray photoelectron spectroscopy (XPS, Mg $K\alpha$ (1253.6 eV) radiation The SPECS® system equipped with a double anode X-ray source and a hemispherical analyzer). Survey and narrow scan spectra were collected at pass energy values of 50 eV and 25 eV, respectively, while the respective energy resolutions were

set to 2.5 eV and 0.1 eV [13]. XPSpeak 4.1 software package was used to analyze the data. The C 1s and O 1s peak components were plotted using a Linear background and Gaussian fitting.

The average crystallite size (L) for the Pt(111) was calculated using the Scherrer formula $L = (0.9 \times \lambda) / (\beta \times \cos \theta)$ where λ is the X-ray wavelength, β is the full width half maximum (FWHM), θ is the diffraction angle.

RESULTS AND DISCUSSION

Structural Characterizations of Raw Carbons

The surface areas of the derived samples of BC2, BC2-H2-300 and BC2-H2-700 and C2 are given in **Table 1**. The surface area for sample BC2-H2-500 was not determined because, as can be seen in the electrochemical measurements section, the ECSA values showed a directly proportional increase with increasing temperature. This also showed that the surface area values of the BC2-H2 samples obtained with applications at a minimum of 300 °C and a maximum of 700 °C could be sufficient for interpreting the results, and that the surface area of the BC2-H2-500 sample obtained at the intermediate temperature of 500 °C was less necessary. The surface area of C2 is taken from [1].

The biomass derived carbonaceous materials have comparable surface area with commercial carbon of C2. The surface areas increase from 580 m²/g for BC2 to 1056 m²/g with second pyrolysis at 700 °C and H₂/N₂ atmosphere.

Table 1. BET surface areas of the pristine samples

Sample	Surface area (m ² /g)
BC2	580
BC2-H2-300	696
BC2-H2-700	1056
C2	800 (Wang_16_progress in)

Since the surface area is widely acknowledged as one of the effective parameters for supercapacitor performance, further experiments were carried out with BC2-H2-700 and it will be referred as BC2-H2 shortly.

Figure 1 shows the XRD analysis of the carbonaceous samples of BC2, BC2-H2 and commercial carbon C2. The peaks reveal that all 3 samples possess an amorphous structure in general. The two main broad peaks at around 24° and 44° corresponding to the (002) and (101) reflections of carbon.

The XPS analyses displaying the survey spectra for both C 1s and O 1s of pristine carbon samples are presented in **Figure 2**. The elemental compositions of the samples directly on their surfaces are given in **Table 2**. The carbon content of C2 is 95% higher when compared to TW derived carbonaceous materials of BC2 and BC2-H2, which have 89 and 92 % C content, respectively. BC samples have a greater number of surface functional groups and a higher concentration of O and N than C2.

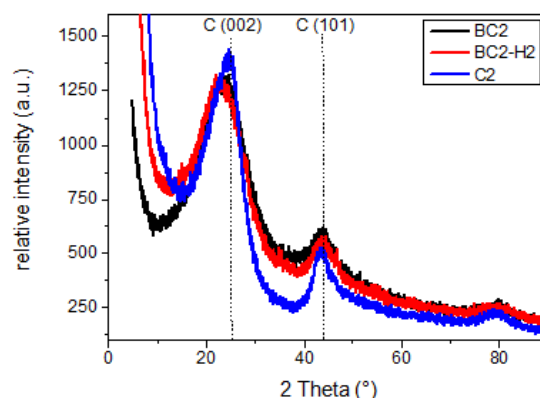


Figure 1. XRD of pristine samples

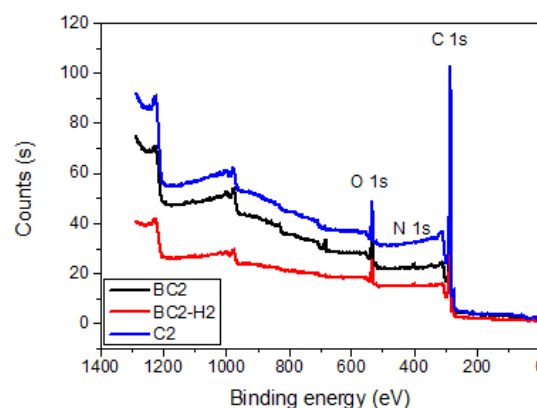


Figure 2. XPS analyses of pristine samples

Table 2. Elemental content of pristine samples

Sample	C (%)	O (%)	N (%)
BC2	89.0	9.5	1.5
BC2-H2	92.0	7.3	0.7
C2	95.0	5.0	-

Electrochemical Characterizations of Synthesized Electrocatalysts

The cyclic voltammograms (CVs) of the synthesized and reference electrocatalysts of Pt/C_{BC2}, Pt/C_{BC2-H2}, Pt/C_{C2} and rPt/C are presented in **Figure 3**. The ECSA values calculated from CVs, conversion ratios of synthesis, retention of electrocatalysts at the end of AST tests and Pt crystallite sizes in electrocatalysts are given in **Table 3**.

When considered the ECSA values, the electrocatalysts of reference, rPt/C, and synthesized one with commercial carbon, Pt/C_{C2}, demonstrate ECSA performance as 76.9 m²/g and 84.9 m²/g, respectively. Further, their retention ratios at the end of AST tests exceed 20%. On the other hand, the ECSA value of Pt/C_{BC2} electrocatalysts, was 41.9 m²/g, which is almost half the value of the reference electrocatalysts. This ECSA value of Pt/C_{BC2-H2}, developed to 89.8 m²/g by secondary pyrolysis of the same pristine material of BC2 at H₂/N₂ atmosphere. This advancement may be attributed to the increased surface area of BC2-H2. The electrocatalyst Pt/C_{BC2-H2} has a comparable ECSA with reference ones.

The retention values of BC electrocatalysts are less than 20% inferior to the reference values. This may also be

originate from abundance of their surface functional groups. Conversely, the Pt crystallinity and conversion rates are comparable and elevated for all synthesized electrocatalysts.

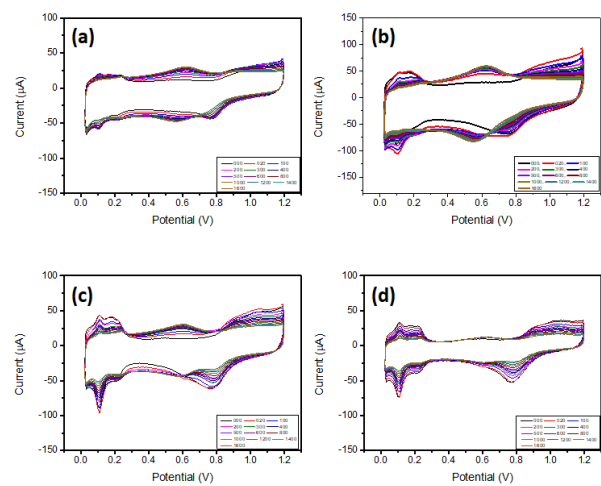


Figure 3. CVs of the electrocatalyst (a) Pt/C_{BC2}, (b) Pt/C_{BC2-H2}, (c) Pt/C_{C2}, (d) rPt/C

Table 3. Electrochemical parameters of the electrocatalysts .

Sample	ECSA	Retention	Conversion	Crystallite size
Unit	m ² g ⁻¹	%	%	nm
Pt/C _{BC2}	41.9	17.8	97.5	3.44
Pt/C _{BC2-H2}	89.8	3.1	99.5	3.90
Pt/C _{C2}	84.9	21.2	99.7	3.83
rPt/C	76.9	31.6	-	4.05

Here, when indicated in parentheses, the ECSA values of Pt/C_{BC2-H2}-300 and Pt/C_{BC2-H2}-500 are found to be 59.3 and 77.2 m²/g, respectively. These values are markedly inferior to the ECSA value of 89.6 m²/g for Pt/C_{BC2-H2}-700 (hence referred to as Pt/C_{BC2-H2}).

The CVs of Pt/C_{Mix} electrocatalysts are shown in **Figure 4**, and their electrochemical performance values are given in **Table 4**. The support carbon materials used in Pt/C_{Mix} electrocatalysts was prepared by mixing BC2 sample with C2 carbon in proportions ranging from 5% to 80%. The ECSA values of the Pt/C_{Mix} electrocatalysts, manufactured with a rising C2 ratio in the support material, increased from 69.7 m²/g to about 87 m²/g, achieving this equilibrium at a ratio below 50% (around 35%). (**Figure 5**). The ECSA performance of the Pt/C_{Mix6} electrocatalyst which is prepared by combining the as-prepared Pt/C_{C2} and PtC_{B2} electrocatalysts in 20%-80% ratio, respectively, was determined as 61.1 m²/g. Combining support carbons prior to the synthesis of electrocatalysts, instead of blending as-prepared electrocatalysts, seems to be more efficacious in attaining a superior ECSA value.

Ultimately, TEM images of the catalysts Pt/C_{BC2} and Pt/C_{Mix4} are presented in **Figure 6**. The nano Pt particles are significantly concentrated in some areas and are not evenly dispersed throughout the BC2 material. The irregular dispersion of Pt particles on the carbon support may lead to a reduces ECSA value for the electrocatalyst Pt/C_{BC2} although the crystallite sizes are comparable with Pt/C_{C2}.

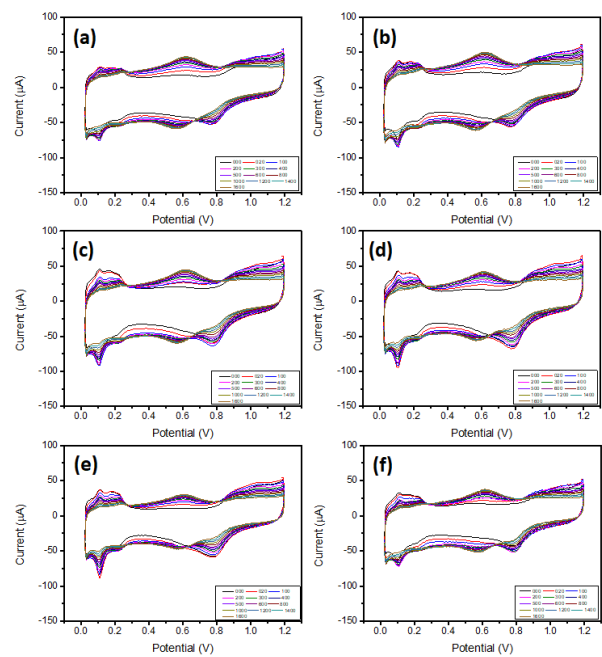


Figure 4. CVs of the electrocatalyst (a) Pt/C_{Mix1}, (b) Pt/C_{Mix2}, (c) Pt/C_{Mix3}, (d) Pt/C_{Mix4}, (e) Pt/C_{Mix5}, (f) Pt/C_{Mix6}

Table 4. Electrochemical performances of Pt/C_{Mix} electrocatalysts

Sample	Ratio of carbon C2	Ratio of BC2	ECSA	Retention	Conversion	Crystallite size
Unit	% w/w	% w/w	m ² g ⁻¹	%	%	nm
Pt/C _{Mix1}	5	95	69.7	17.4	100.0	4.51
Pt/C _{Mix2}	10	90	67.1	25.8	99.9	4.67
Pt/C _{Mix3}	20	80	83.4	20.4	100.0	3.24
Pt/C _{Mix4}	50	50	87.6	21.9	100.0	3.26
Pt/C _{Mix5}	80	20	86.9	19.5	99.9	3.23
Pt/C _{Mix6}	20*	80 [#]	61.1	19.0	-	3.70

* As prepared catalyst Pt/C_{C2}, [#] As prepared catalyst Pt/C_{B2}

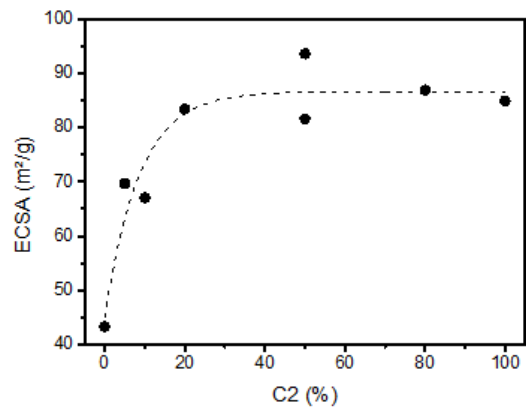


Figure 5. The ECSA changing synthesized electrocatalysts Pt/C_{Mix} by mixing BC2 and C2 carbons (fitted by basic asymptotic curve)

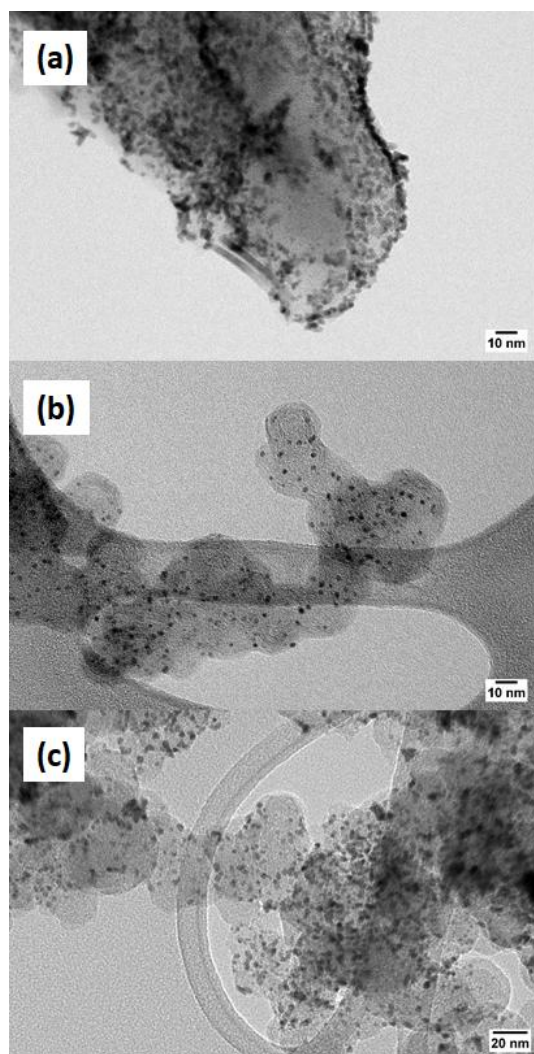


Figure 6. TEM image of the sample Pt/C_{BBC2} (a) and Pt/C_{Mix4} (b) and rPt/C (c)

CONCLUSION

TW derived carbonaceous materials were investigated as the support material for Pt/C electrocatalysts. The synthesized biomass based carbonaceous material supported Pt/C_{BBC2} electrocatalyst show a lower ECSA value compared to those of the reference electrocatalyst rPt/C and the commercial carbon supported electrocatalysts Pt/C_{C2}. Nonetheless, the partial reduction of surface oxygen groups through secondary pyrolysis of BC2 material at H₂/N₂ atmosphere markedly enhanced the ECSA value of the Pt/C_{BBC2-H2} electrocatalyst, rendering it similar to reference electrocatalysts. Additional structural optimization of the TW-derived carbons may be explored to achieve a high-performance carbon support that could enhance both PEM fuel cell technology and waste treatment in the tea business.

Electrocatalysts synthesized by mixing the carbonized material derived from biomass and the commercial carbon have demonstrated ECSA values comparable to those of commercial electrocatalysts. This outcome suggests that the reliance on petroleum-derived carbons as support materials in electrocatalysts can be diminished, allowing for the advancement of eco-friendly approaches in the fabrication of commercial electrocatalysts.

It is feasible to develop electrocatalysts that are renewable, sustainable, ecologically benign, and economically viable by utilizing the biomass based carbonized support materials. The

development of new technologies could constitute a step forward in the advancement of a circular economy for renewable and sustainable PEM fuel cell technology.

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Geospatial Analysis of Landslide Susceptibility using GIS and Remote Sensing: A Case Study in the Region of Thessaly.

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Abstract— Landslides are among the most frequent and destructive natural hazards in Greece, with significant consequences for human life, infrastructure, and the environment. Their occurrence depends on a complex interaction of conditioning factors such as lithology, slope, vegetation cover, and rainfall, combined with human interventions such as road construction or deforestation [1], [2]. The Thessaly Water District in Central Greece is a particularly vulnerable area due to its geomorphological diversity, combining the fertile Thessalian plain with surrounding mountainous terrain [3].

This study applies an integrated Geographic Information Systems (GIS) and Remote Sensing (RS) framework to evaluate landslide susceptibility in Thessaly. A combination of topographic, geological, environmental, and land-use datasets, including the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) [10], the CORINE Land Cover (CLC) database [9], lithological and soil maps [11], and multi-spectral Landsat 8 Operational Land Imager (OLI) imagery [12], were used to derive conditioning factors. These factors were weighted through the Analytic Hierarchy Process (AHP) [13] and integrated into a susceptibility model. The approach was further tested through two hazard scenarios and validated against observed landslide events triggered by the 2023 Daniel and Elias storms [14], [15].

Results highlight slope, fractured lithologies, and sparse vegetation as primary susceptibility factors [1], [8]. Inclusion of soil erodibility significantly expanded high-risk zones [11]. Case studies in Karditsa–Trikala and Drakeia (Pelion) confirmed the model's predictive ability. The study offers a spatial decision-support framework for landslide risk management in Central Greece.

Keywords— Landslide susceptibility, GIS, Remote Sensing, AHP, Landsat 8, Thessaly, Hazard mapping.

INTRODUCTION

Landslides constitute one of the most widespread natural hazards in mountainous environments, often leading to loss of life, property damage, and environmental degradation [4]. Their frequency is increasing globally due to climate change, urbanisation, and land use pressures [5]. In Greece, repeated

landslide events have impacted settlements, infrastructure, and agriculture, particularly in geomorphologically sensitive regions such as Thessaly [7].

The occurrence of landslides is controlled by a combination of natural and anthropogenic factors. Natural predisposition is shaped by slope, lithology, rainfall, and vegetation, while anthropogenic drivers such as road construction and deforestation frequently act as triggers [2], [6]. This complexity necessitates systematic approaches to susceptibility mapping.

Geographic Information Systems (GIS) provide a framework for integrating spatial datasets, while Remote Sensing (RS) delivers updated, multi-temporal Earth observations [9]. The Analytic Hierarchy Process (AHP) has been widely applied for multi-criteria evaluation in landslide studies [13].

The Thessaly Water District combines the extensive Thessalian plain with surrounding mountains, creating sharp contrasts in susceptibility. Recent extreme rainfall events, particularly storms Daniel and Elias in 2023, revealed the region's vulnerability [14], [15]. This study aims to systematically map landslide susceptibility through an integrated GIS–RS–AHP approach and to validate the results against observed events.

This work is part of a broader effort to support risk assessment and management in line with European and national disaster resilience strategies [16], [17].

STUDY AREA

The Thessaly Water District is located in Central Greece and encompasses both the Thessalian plain and surrounding mountainous areas, including parts of the Pindus, Olympus, Ossa, and Pelion ranges. The district is characterised by high geomorphological diversity:

- The Thessalian plain is the largest continuous plain in Greece, dominated by alluvial deposits and agricultural land use. It is less prone to landslides due to low slopes.

- Mountainous regions such as Pelion, Olympus, and Pindus consist of steep slopes and fractured lithologies, including schists, limestones, marbles, flysch, and ophiolites, which are highly susceptible to slope instability [8].

Hydrologically, the district is drained by the Pinios River and its tributaries, which frequently overflow after intense rainfall, exacerbating slope erosion and instability. Socio-economically, Thessaly is a key agricultural hub of Greece, meaning that slope instabilities have strong impacts on both rural livelihoods and critical infrastructure [15].

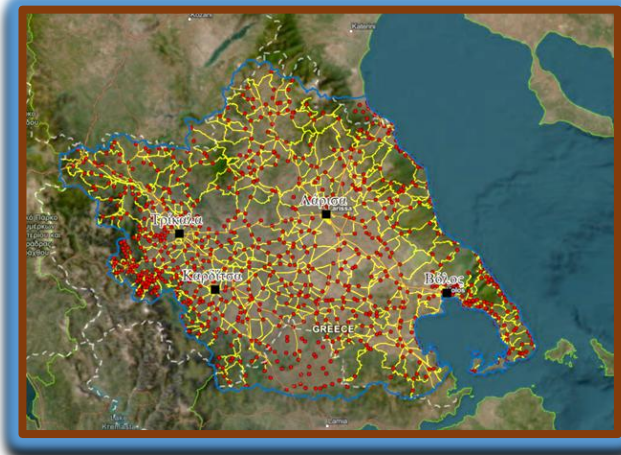


Figure 7. Map of the Thessaly Water District

STUDY FRAMEWORK [18]

A. Overall Framework

The research followed a structured framework consisting of four main stages:

1. Data collection: acquisition of DEM, Remote Sensing imagery, CORINE land cover, geological and soil data, and historical landslide records.
2. Preprocessing: harmonisation of projection and resolution, atmospheric correction of satellite data, derivation of slope and aspect, clipping to Thessaly's boundaries.
3. Factor analysis: identification of conditioning factors, preparation of thematic layers, and weight assignment using AHP.
4. Susceptibility mapping: integration of weighted layers, classification into risk zones, and validation against recorded landslides.

B. Data Sources

Topographic information was obtained from the Shuttle Radar Topography Mission (SRTM) DEM at 30 m resolution [10], used to generate slope, aspect, and elevation layers. Land cover data were derived from CORINE Land Cover 2018 [9], providing detailed information on agricultural, urban, and natural environments. Remote Sensing inputs consisted of multi-spectral Landsat 8 OLI imagery (2019–2023), enabling the calculation of Normalized Difference Vegetation Index (NDVI) and temporal change detection [12]. Geological data were sourced from Institute of Geology and Mineral Exploration (IGME) lithological maps, while soil erodibility data were acquired from European Soil Data Center (ESDAC) [11]. Additional datasets included settlements, road networks,

and rivers from geodata.gov.gr. Together, these datasets created a robust basis for susceptibility assessment.

C. Preprocessing

The DEM was processed to derive slope, aspect, and elevation, which are primary topographic controls on landslide activity. Landsat imagery underwent atmospheric correction and noise reduction before NDVI indices were calculated. All datasets were harmonised in terms of projection and spatial resolution and clipped to the Thessaly Water District boundary to ensure a consistent analytical framework.

D. Factor Analysis

Conditioning factors were grouped into five categories: topographic (slope, aspect, elevation) [1]; geological (lithology, soil erodibility) [7], [11]; environmental (NDVI, rainfall triggers) [12], [16]; land-use (CORINE land cover) [9]; and proximity (distance to roads and rivers). Each was transformed into thematic GIS layers to be used in susceptibility analysis.



Figure 8. Derived maps from DEM, Corine and Landsat 8

E. AHP Weighting

The Analytic Hierarchy Process (AHP) was applied to determine factor weights [13]. Pairwise comparisons, based on literature and expert judgement, ranked slope and land cover as the most influential parameters, followed by lithology, with lower weights assigned to proximity factors. Consistency checks confirmed reliability, with all ratios <0.1.

F. Susceptibility Mapping

Weighted thematic layers were integrated using the GIS Weighted Overlay tool. The susceptibility index was classified into three categories: low susceptibility (mainly the Thessalian plain), moderate susceptibility (foothill areas), and high susceptibility (mountainous and coastal zones such as Pelion and Pindus) [7], [8].

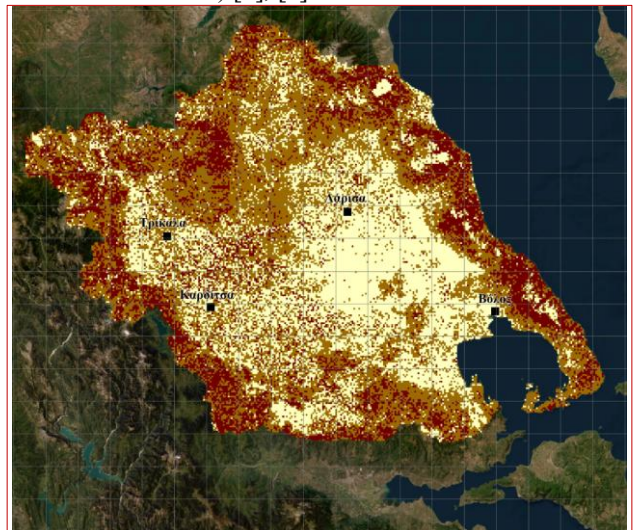


Figure 9. Landslide Susceptibility Map

A. Landslide Susceptibility Mapping

The susceptibility map revealed distinct spatial patterns. Low-susceptibility areas dominated the central plain, while moderate zones appeared in transitional foothills. High susceptibility was concentrated in Pelion, Olympus, Ossa, and the Pindus range. These findings align with previous regional studies.

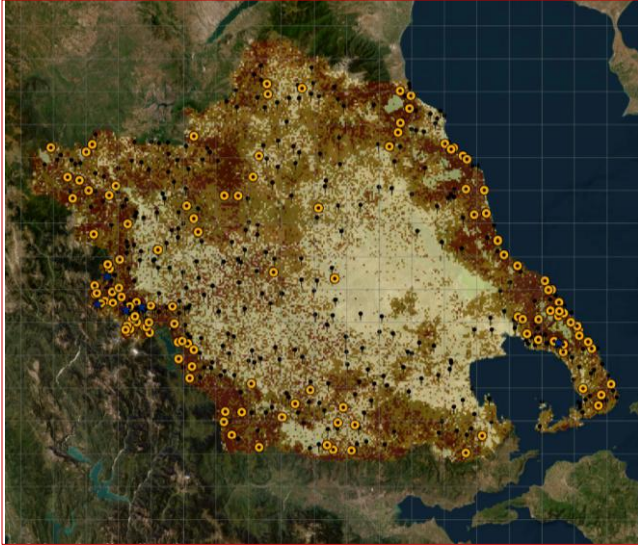


Figure 10. Landslide Susceptibility Map

B. Hazard Scenarios

Two hazard scenarios were examined to evaluate the influence of soil erodibility.

Scenario 1 included NDVI (25%), slope (25%), land use (35%), and elevation (15%). The results identified Larissa District with 42 high-risk settlements, followed by Magnesia with 16 and Trikala with 13.

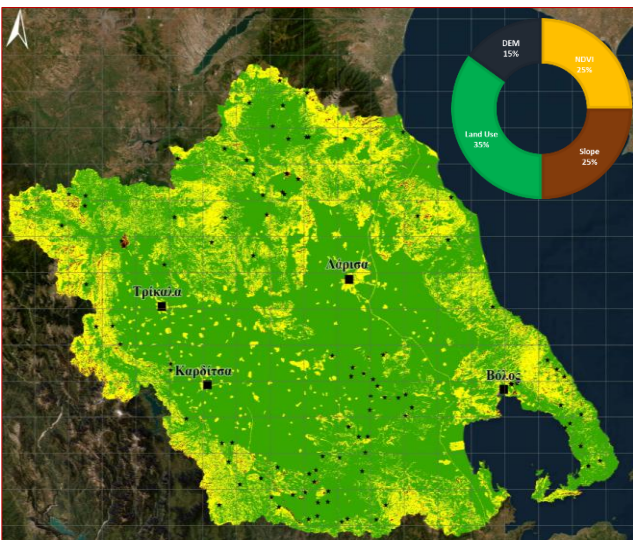


Figure 11. Scenario1, Landslide Hazard Map

Scenario 2 integrated soil erodibility (25%), with adjusted weights of NDVI (20%), slope (20%), land use (25%), and elevation (10%). High-risk areas expanded significantly, with Magnesia rising to 27 settlements, Larissa to 18, and Trikala to 16.

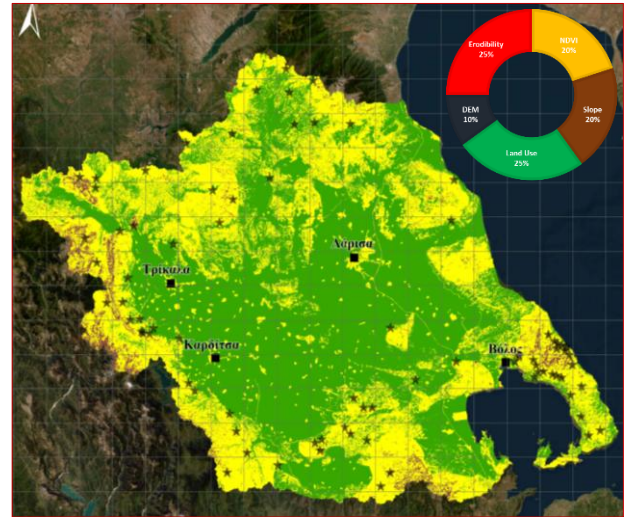


Figure 12. Scenario2, Landslide Hazard Map with erodibility

This comparison highlights how small variations in factor weighting can significantly shift susceptibility outcomes, with direct implications for planning.

C. Landslide Detection – Case Studies

In this stage of the study, landslide detection was performed across the Thessaly region by integrating ground-based information with satellite imagery. Reports from the Hellenic Survey of Geology and Mineral Exploration, combined with local newspaper articles, were first collected to establish the exact timing and location of landslide events. Based on these records, multi-temporal Landsat 8 imagery was selected, ensuring one image before and one image after each event. The pairs were processed to identify spectral differences and morphological changes, enabling accurate mapping of affected areas.

Two representative case studies are presented in detail:

Case 1: Karditsa–Trikala (June 2019 vs October 2023).

This case coincides with the extreme weather events of September 2023, when Thessaly was impacted first by storm Daniel and shortly after by storm Elias. The intense rainfall caused soil oversaturation, increased runoff, and widespread slope failures. The analysis revealed severe erosion near Lake Tavropos (Plastiras), accompanied by agricultural and urban land changes as well as damage to the road network. Although Lake Plastiras lies outside the official boundary of the Thessaly Water District, its surrounding environment experienced significant changes that contributed to slope instability and local land degradation. The affected areas overlapped with zones already classified as high susceptibility in the model, thereby confirming its reliability.

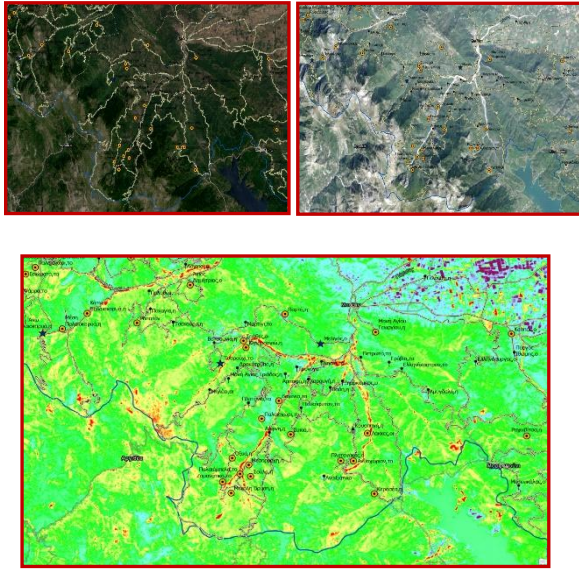


Figure 7. Case1: Details from Landslide Detection Map

Case 2: Drakeia, Mount Pelion (August 2022 vs October 2023).

This case focused on the village of Drakeia, which suffered intense slope instability during the 2023 storms. Post-event imagery highlighted vegetation loss, soil displacement, and the collapse of the Agrias–Drakeia road. Changes extended to adjacent slopes and drainage patterns, clearly demonstrating the cascading impact of extreme rainfall on mountainous terrain.

These case studies demonstrate how the integration of Remote Sensing change detection with ground-based information can effectively identify high-risk areas and provide valuable input for hazard prevention and management.

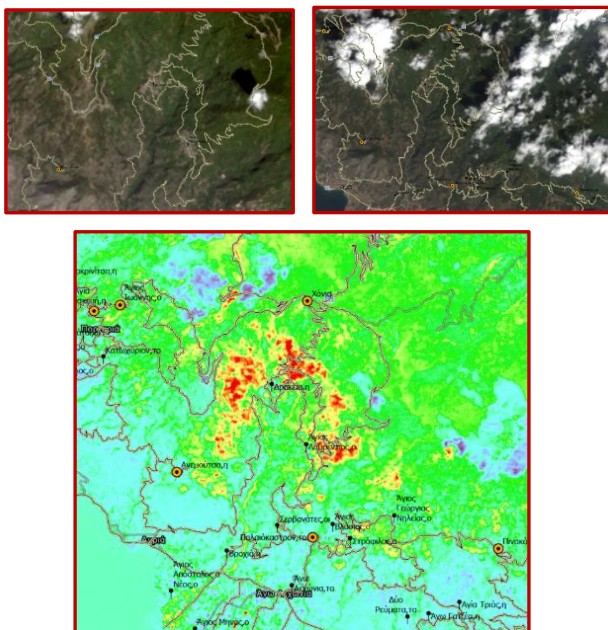


Figure 8. Case2 :Details from Landslide Detection Map Case 2

DISCUSSION AND LIMITATIONS

The findings of this study confirm that slope, lithology, vegetation cover, and soil erodibility are the dominant factors controlling landslide susceptibility in Thessaly [1], [7], [11]. The comparison of two hazard scenarios demonstrated the sensitivity of susceptibility outcomes to soil-related parameters [13], while case studies validated the predictive accuracy of the model against observed events [14], [15].

Despite these strengths, several limitations must be acknowledged. First, the analysis relied on medium-resolution datasets, such as the 30 m DEM and Landsat 8 imagery, which constrain the precision of the susceptibility maps. The inclusion of higher-resolution data (e.g., LiDAR or UAV imagery) would likely improve accuracy, particularly in steep mountainous areas [17]. Second, rainfall data were not integrated quantitatively into the model, even though storms Daniel and Elias clearly acted as critical triggers. Access to spatially explicit precipitation records would enhance the capacity to capture triggering conditions [14]. Third, field validation was limited, with most ground-truth information derived from reports and secondary sources. Systematic field surveys would strengthen the reliability of susceptibility assessment [17].

Future research should therefore focus on integrating high-resolution geospatial data, incorporating rainfall intensity and soil moisture parameters, and combining empirical methods with advanced machine learning approaches [5], [17].

CONCLUSIONS [18]

This study applied a GIS–RS–AHP framework to assess landslide susceptibility in Thessaly. Results identified mountainous zones as highly vulnerable, while scenario analysis highlighted the importance of soil erodibility. Validation through storms Daniel and Elias confirmed the reliability of the approach. The findings provide valuable input for regional hazard management and land-use planning in Central Greece.

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Smart Decision Support for Hybrid Hydropower Plants with PV and Hydrogen

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Abstract—This paper examines the hybridization of hydroelectric plants with hydrogen production systems to improve renewable energy integration and grid flexibility. Two scenarios are explored: a small-scale micro-hydro plant and a larger seasonal hydroelectric station, both combined with photovoltaic and hydrogen storage technologies. Through simulations using TRNSYS, the performance of these hybrid systems is evaluated under real-time market conditions. Results indicate that larger hydroelectric plants yield higher revenues and energy output, particularly when integrated with hydrogen storage, which enhances system flexibility and stability. This hybridization approach presents a promising solution for maximizing renewable energy usage and contributing to decarbonization goals.

Keywords— Smart Decision Support; Hydropower; Hybridization; Optimisation; Smart grids

INTRODUCTION

Electricity market operators increasingly demand flexibility from market agents to implement strategies in non-conventional market offerings. In the context of Smart Grids, hybrid systems provide the necessary control to balance loads. Specifically, hydroelectric plants and hydrogen generation and storage systems offer significant value in this paradigm, as they can intelligently manage energy storage—reservoirs for hydroelectric plants and hydrogen tanks—and power injection into the grid. Alongside virtual batteries [16] and other elements at various nodes, these systems form the framework of future energy networks. However, many hydroelectric plants currently operate below their nominal capacity due to hydrological, seasonal, or market regulation factors [19], presenting an opportunity to enhance their performance through hybridization with other renewable sources.

Hybrid systems exploit synergies between different technologies, maximizing resource utilization and mitigating limitations associated with the intermittency of solar and wind power [15]. The hybridization of hydroelectric plants with technologies like floating photovoltaic systems [19], batteries with advanced management systems [2], or hydrogen production systems [25] offers solutions to increase flexibility and stability in the electricity grid [18]. Looking ahead, hydroelectric plants are expected to become central nodes in large-scale hybrid energy systems, particularly in countries with abundant water resources [15].

Green hydrogen production, obtained via water electrolysis using renewable electricity, has emerged as a key energy vector for decarbonizing hard-to-electrify sectors such as transportation and certain industries [23, 8]. Advances in hydrogen production and storage technologies have enhanced its viability as a long-term, large-scale energy storage option [11], allowing it to store surplus renewable generation and release it when demand is high, acting as a buffer in the energy

system. The scientific community and industry are investing heavily in hydrogen as an essential component in the transition to sustainable energy systems, given its versatility and potential for integration across different sectors, making it strategic in achieving carbon neutrality goals.

Recent analyses of hydrogen production projects using hydroelectric energy in countries like Canada, Turkey, and China demonstrate that hydroelectric power offers a competitive solution for green hydrogen generation by enabling the production of both electricity and pure water at the same site [12, 25]. For instance, Turkey has developed a hydroelectric map to identify regions with high potential [1], and in Europe, projects like D-Hydroflex focus on the hybridization of hydroelectric plants to produce hydrogen, which could bring significant economic and technical benefits and support policy formulation to foster growth [4]. Implementing these renewable energy projects requires detailed economic analysis considering investment costs, operational expenses, and expected revenues. This analysis can be conducted using analytical models and dynamic energy simulation software. In this study, TRNSYS will be used to model hydroelectric plants and hydrogen systems, including electrolyzers, storage tanks, and PEM fuel cells [6], enabling simulations under different scenarios to assess system performance in response to variations in demand, operating conditions, and electricity markets.

HYBRIDIZATION

Scenarios

To assess the profitability of hybridizing a hydrogen system with a hydroelectric plant, two distinct scenarios have been considered. In both cases, the photovoltaic system and the hydrogen system remain constant in terms of size and production. The variation lies solely in the technologies of the selected hydroelectric plants. These scenarios represent two very different concepts of hydraulic production: a small-scale micro-hydropower plant and a large, seasonal hydroelectric station.

Small hydroelectric power plant (SCENARIO 1)

The first scenario is based on what could be a micro-hydropower[1] generation plant with a capacity of 35 kW, located in a water treatment facility (ETAP). This relatively novel installation integrates a pump operating as a turbine (PaT), allowing the recovery of energy that is currently dissipated through a pressure reduction valve (PRV) located at the inlet of the ETAP.

Since the water flow is constant and continuous due to the plant's operational nature, this system is expected to provide stable energy generation. This small-sized plant exemplifies how these types of turbines can be implemented in industrial sectors as an added value, optimizing resource use.

Seasonal hydroelectric power plant (SCENARIO 2)

The second scenario involves a 2.1 MW hydroelectric plant of the dam-peak type, with an average annual production of 2 GWh and a reservoir capacity of 102.6 hm³. Located in a dry tropical climate, the plant operates with a Francis turbine [14], handling flows between 0.8 and 4.8 m³/s with a nominal head of 56.5 meters.

This plant is ideal for exploring hybridization solutions due to its seasonal operation; the water released downstream is used for irrigation, an activity that occurs only during certain months of the year. Integration with hydrogen systems allows the plant to take advantage of periods of lower water demand or limitations in power injection into the grid, to store and produce energy.

Parameters and components

Turbine PaT

The first scenario uses a hydraulic pump used as a turbine from a mini-hydropower plant in Castilla y León (Spain). In order to obtain its power-flow generation curve, available data from its operation have been used. The curve describing the power generated by the turbine is defined by the following polynomial:

$$P = 957.417 \cdot Q^2 - 192.166 \cdot Q + 30.213 \quad (2)$$

where P is the power output of the turbine (in kW) and Q is the flow rate (in m³/s). The regression has been performed using a degree 2 polynomial. The degree of this polynomial is well adapted to the behavior of the pump used as a turbine, which has a minimum flow rate of 0.119 m³/s.

Turbine Francis

In the second scenario, a Francis turbine has been considered to obtain electricity in the hydropower plant. The Francis turbine is one of the most widely used turbines in the world, due to its high efficiency at high flow rates [14].

In order to model the behavior of the turbine, the power-flow curve was obtained from data provided by both Confederación Hidrográfica del Guadalquivir [3] and a company that operates hydropower plants in Andalucía (Spain). The method used to obtain the curve was ridge regression, using a degree 10 polynomial. The degree of the polynomial was chosen by comparing using the mean squared error metric the result obtained in the regression with the different degrees of the polynomial. Therefore, the curve obtained is expressed by the following polynomial:

$$\begin{aligned} P = & -0.510 \cdot Q^{10} + 9.761 \cdot Q^9 - 74.752 \cdot Q^8 \\ & + 284.478 \cdot Q^7 - 514.055 \cdot Q^6 \\ & + 193.680 \cdot Q^5 + 574.329 \cdot Q^4 \\ & - 188.815 \cdot Q^3 - 1067.230 \cdot Q^2 \\ & + 1036.870 \cdot Q + 1.539 \end{aligned} \quad (2)$$

As can be seen, the independent term of the equation is different from 0. This is expected, since the ridge regression, while fitting the actual measured data very well, is not exact. For this reason, we have added an additional rule to the equation so that when the flow rate is 0, the power is also 0. Both the regression methodology and the metrics used have been obtained from scikit-learn, a Python machine learning library [21]. The minimum flow rate of the Francis turbine has been limited to 0.8 m³/s.

Solar

For the sizing of the photovoltaic plant, a generation capacity of 500 kW has been selected, which is typical for a photovoltaic generation plant installed for self-consumption at an industrial facility in Spain [10,20] with an approximate

surface area of 4,500 m². This approach aims to represent a typical plant that could be installed by any industry or hydroelectric station on the roof of an industrial building or a small solar farm. In any case, for this study, the production and sale of solar energy should not constitute the primary activity of the industry in the case study.

The following values have been used in the modeling:

Table 8: Technical Specifications of the Photovoltaic Module and System Configuration

Photovoltaic Module Specifications		
Parameter	Value	Unit
Maximum Power	100.3	W
Voltage at Maximum Power Point	17	V
Current at Maximum Power Point	5.9	A
Open-Circuit Voltage	21.6	V
Short-Circuit Current	6.5	A
Module Efficiency	11.27	%
Temperature Coefficient of Voc	-0.079	V/K
Temperature Coefficient of Isc	0.02	A/K
NOCT	40	°C
Number of Cells in Module	36	-
Module Area	0.89	m ²
Tau-Alpha Product for Normal Incidence	0.95	-
Semiconductor Bandgap	1.12	eV
Module Series Resistance	0.3065	Ω
Module Temperature at NOCT	313	K
Ambient Temperature at NOCT	293	K
Insolation at NOCT	800	W/m ²
Installed Photovoltaic Power	500,000	W
Number of Modules in Series	16	-
Number of Modules in Parallel	333	Variable

H2

Electrolyzer System

In our virtual hybrid system, a high-pressure alkaline electrolyzer with a power capacity of 500 kW and a nominal production rate of 243.75 kg/h of H₂ will be modeled. This type of electrolyzer has been selected because, firstly, it is a sufficiently mature and reliable technology [9], capable of producing green hydrogen at relatively high pressures. This is particularly advantageous in systems where the intention is to store the hydrogen produced immediately after the electrolyzer, thereby reducing the operational and energy costs of subsequent compression.

Moreover, dimensionally, it is a medium-sized piece of equipment according to the current technological range, suitable for industrial applications. This size is appropriate as an intermediate point between the two study scenarios: the medium-sized hydroelectric plant (2.1 MW) and the micro-hydropower plant (35 kW), acting as a buffer to take advantage of surplus energy generation.

Table 9: Technical Specifications of the Electrolyzer System

Electrolyzer Specifications		
Parameter	Value	Unit
Electrode Area	0.25	m ²
Number of Cells in Series	21	-
Number of Stacks in Parallel	1	-
Maximum Allowable Current Density	670	mA/cm ²
Maximum Allowable Operating Temperature	80	°C
Minimum Allowable Cell Voltage	1.229	V
Thermal Resistance	0.167	K/W
Lower SOC Limit	0.7	-
Upper SOC Limit	0.9	-
Idling Power	1,000	W
Nominal Power	600,000	W
Idling Constant	5.836×10^{-3}	-
Operating Voltage	2.06	V
Ohmic Constant	138.42	V ²
Electrolyzer Installed Power	500,000	W
Number of Electrolyzer Units	20	-
Hydrogen Production at Nominal Conditions	243.75	kg/h

Hydrogen Storage System

For the hydrogen storage system, a three-stage compressor has been sized to compress the hydrogen, directly at the output of the electrolyzer, into a 5 m³ tank with a maximum pressure of 200 bar. The storage system plays a fundamental role in hydrogen technologies. In our case, it serves as an energy storage solution until the control system decides to produce electricity, releasing the hydrogen into the fuel cell.

Table 10: Technical Specifications of the Hydrogen Storage System (Compressor and Tank)

Compressor Specifications		
Parameter	Value	Unit
Number of Parallel Compressors	1	-
Number of Compressor Stages	3	-
Maximum Pressure	200	bar
Tank Volume (VolTankH ₂)	5	m ³
Molar Weight of Gas	2.016	g/mol
Gas Critical Temperature	-240	°C
Gas Critical Pressure	12.9	bar

PEM Fuel Cell System

The final stage of our hydrogen system is a fuel cell. In our case, we have modeled a proton exchange membrane (PEM) fuel cell capable of producing 250 kW of electricity. This technology is highly mature and well-supported. Moreover, it offers a rapid response in terms of energy production, making it highly useful in our scenarios, as it would be able to inject energy into the grid [25] during intermittent periods when the selling price is high.

The following are the key characteristics used in the modeling:

Table 11: Technical Specifications of the PEM Fuel Cell System

PEM Fuel Cell Specifications		
Parameter	Value	Unit
Number of Cells in Series	21	-
Number of Stacks in Parallel	1	-
Minimum Cell Voltage	0.7	V
Maximum Current Density	1,629	mA/cm ²
Cell Active Area	441	cm ²
PEM Fuel Cell Installed Power	250,000	W
Number of PEM Units	125	-
Base Power per PEM Unit	2,000	W
Hydrogen Consumption at Nominal Conditions	243.75	kg/h
Maximum PEM Power Output	250,000	W
Minimum PEM Power Output	50,000	W
Total Active Area per PEM Unit	4,872	cm ²
Maximum Current per PEM Unit	79.34	A
Minimum Voltage per PEM Unit	14.7	V
Maximum PEM Power Output	250,000	W
Minimum PEM Power Output	50,000	W
Minimum Cell Voltage	0.7	V

Operational conditions

Electricity market

Our model aims to assess the technological and economic viability and profitability of hybridization. In the latter aspect, it is essential to accurately simulate real market conditions. In our study, and for both scenarios, we will use the SPOT prices in Spain [17], where we will collect hourly prices set in the wholesale energy market in real-time or with very little notice. The fluctuation of these prices will determine our control strategies and the relative operation of our production system.

Grid restrictions

The two scenarios have considered the existence of signals from the grid operator allowing or prohibiting the discharge of electrical power to the main grid. These prohibitions could be caused for different reasons:

excess of available renewable energy, insufficient demand, maintenance operations, etc. During the time the grid injection is prohibited, the system can produce hydrogen that can be converted into electricity in the future. The signal is transmitted hourly by using a binary variable.

In this paper, the grid restriction signals [17] that have been used were obtained from grid operator in Castilla y León (Spain).

Control Rules

The control design methodology is based on the following dynamics. Two price thresholds are set: a stop price of 60€/MWh for the sale of renewable electricity, at which point energy is no longer injected into the grid. At this moment, the energy production is used to produce and store hydrogen,

taking into account the tank capacity and min/max power restrictions. On the other hand, an activation price of 130 €/MWh is established for the PEM fuel cell, at which point the fuel cell is activated, consuming the previously stored hydrogen and generating electricity for direct sale.

Additionally, as explained in subsection 2) *Grid restrictions*, the control rules must ensure that no energy is injected into the grid when the operator imposes any restrictions. Taking all of this into account, the hybrid system operates all its components according to their respective dynamics to ensure the correct operation of each unit, aiming to maximize energy sales.

MODEL

The dynamic simulation tool TRNSYS has been used to model our system. Through this software, models have been created for our three main systems: the solar generation system, the hydraulic generation system with the two turbines used in the two case studies, and the hydrogen system. The control strategy defined, as described in subsection 3) *Control Rules*, is implemented through the different TYPES [24] of the software along with internal control equations. As for the variables and parameters used for the equipment, representative values of the case studies were employed, as compiled in Tables 1, 2, 3, and 4. Additionally, with future work in mind, the model configuration allows for parametric variation of critical design variables, such as hydrogen storage capacity, photovoltaic production capacity, string and array configuration of the solar field, or the number of electrolyzers, among others. This flexibility enables optimization of equipment performance according to different strategies.

The following are the TYPES used in each of the three systems described:

Hydraulic System:

The hydraulic subsystem was modeled using a CALCULATOR (turbine equations) and TYPE 9c (hourly flow data).

Photovoltaic System:

The PV subsystem includes TYPE 15 (weather data processor), TYPE 57 (unit conversion), and TYPE 190c (PV array with MPPT) to process meteorological inputs and simulate array performance with maximum power point tracking.

Hydrogen System:

The hydrogen subsystem was implemented with TYPE 100a (electrolyzer control), TYPE 175b (power conditioning unit), TYPE 160a (alkaline electrolyzer), TYPE 164b (compressed storage), TYPE 167 (compressor), and TYPE 170a (PEM fuel cell). Additional control calculators manage electrolyzer operation and hydrogen demand.

RESULTS

Simulation Results:

Turbine Performance Curve in Scenario 1 (PaT):

This graph shows the behavior of the pump operating as a turbine (PaT) in Scenario 1, based on the equations presented earlier, which are used to model the turbine.

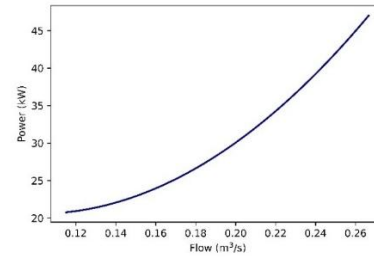


Figure 13: Turbine performance curve scenario 1

Turbine Performance Curve in Scenario 2 (Francis):

This graph details the power curve of the Francis turbine in Scenario 2. The relationship between flow rate and generated power is used to model the complete generation system of the hydroelectric plant as a "black box."

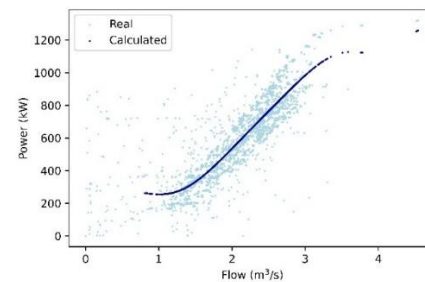


Figure 14: Turbine performance curve scenario 2

Comparison of Energy Sale Revenues in Both Scenarios:

This graph compares the revenues obtained from energy sales in the two scenarios (PaT and Francis). It highlights the influence of SPOT market prices on operational decisions and the profitability of each system, illustrating the economic differences between both hybridization approaches.

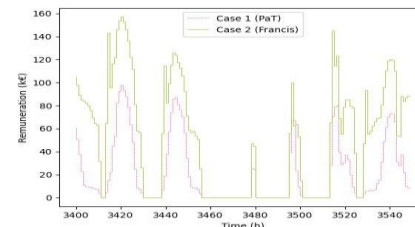


Figure 15: Comparison of revenue from energy sales in both scenarios.

Power Generation Curves in Scenario 1 (PaT):

This figure presents the power generation curves in Scenario 1, from both the photovoltaic plant (PV) and the micro-hydropower system (PaT), along with the hydrogen system (PEM). This graph helps to understand the operational dynamics of the micro-hydropower system, its variability, and its interaction with hydrogen storage.

Power Generation Curves in Scenario 2 (Francis):

This graph displays the power curves for Scenario 2, which include hydroelectric generation by the Francis turbine, photovoltaic generation (PV), and the hydrogen system (PEM). The figure illustrates the greater stability in hydraulic power generation due to the larger capacity and size of the plant compared to the first scenario.

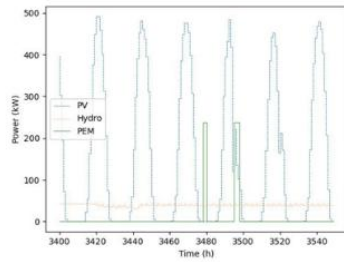


Figure 16: Power production curves case 1

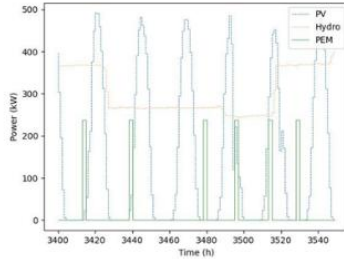


Figure 17: Power production curves case 2

Evaluation of Scenarios through Key Performance Indicators (KPIs)

To evaluate the two scenarios proposed in this study, a series of Key Performance Indicators (KPIs) have been defined. These KPIs will enable the analysis of both the energy performance and the economic viability of each configuration, facilitating a direct comparison between the two case studies. The following section describes how these KPIs will be used in the evaluation:

- **Energy Sold to the Grid:** This KPI measures the total amount of energy that each hybrid system exports to the electrical grid. It will be calculated by summing the energy generated by the hydroelectric plant and the photovoltaic plant, while also accounting for the energy converted into electricity through the PEM fuel cell powered by stored hydrogen. This indicator is crucial for determining the effective contribution of each system to the grid and its ability to utilize available energy resources efficiently.
- **Revenue from Energy Sales:** The economic revenue generated from energy sales will be calculated based on SPOT prices from the electricity market. For each scenario, the impact of price fluctuations throughout the day will be evaluated, optimizing energy dispatch when prices are highest. This KPI will help assess the economic profitability of each system, identifying which of the two scenarios generates higher income over the course of a year and under varying operational conditions.
- **Energy Sold vs. Potentially Generable Energy:** This KPI compares the energy that is effectively sold to the grid with the energy that could have been generated under ideal conditions (considering the maximum capacities of the hydroelectric and photovoltaic systems). It allows for an assessment of the operational efficiency of the system, identifying possible losses or limitations, whether due to technical restrictions, insufficient hydrogen storage, or operational decisions that affect overall performance.

- **Energy Distribution:** This indicator analyzes how the generated energy is distributed among different destinations: sale to the grid, self-consumption, or storage in the form of hydrogen. It will examine the operational decisions that determine whether the generated energy is used directly, stored, or sold depending on market conditions. This KPI will provide insights into how effectively each system manages energy resources to maximize its operational and economic efficiency.

Table 12: KPI COMPILATION

KPI	SCENARIO 1	SCENARIO 2
Energy sold to the grid (MWh)	1,098.78	2,243.17
Revenue from energy sales (K€)	171.68	337.24
Energy sold vs potentially generable energy	85.93%	88.27%
Renewable Energy Distribution - PV/Total Renewable	75%	38%
Renewable Energy Distribution - Hydro/Total Renewable	25%	62%
Energy consumed by electrolyzer / Renewable energy production	14%	9%

CONCLUSIONS

The scale of the hydroelectric plant significantly impacts the economic outcomes of hybridization with hydrogen systems. In Scenario 2, the larger capacity plant notably increases the energy sold and the revenues generated, demonstrating that larger hydroelectric facilities can better leverage the economic benefits of this integration. Both scenarios show high efficiency in the utilization of generated energy, reflecting effective optimization in the management and distribution of available energy resources. Moreover, hybridization facilitates the diversification and complementarity of renewable sources, adapting to the specific characteristics of each plant. In Scenario 1, photovoltaic energy complements the micro-hydropower system, while in Scenario 2, the seasonal hydroelectric plant benefits from the solar contribution, particularly during periods of low hydraulic generation. Hydrogen plays a key role by enabling surplus energy storage and adding flexibility to the system, thereby improving its stability and efficiency. This strategy is applicable across various contexts and scales, from small industrial installations to large energy infrastructures, contributing to environmental and social benefits by reducing greenhouse gas emissions and promoting sustainable development.

As the next steps in this research, a parametric optimization is proposed to determine the optimal sizes of the different technologies involved, considering both capital expenditures (CAPEX) and operational expenditures (OPEX) to maximize energy sales. Additionally, the use of various turbine technologies and types of hydroelectric plants will be explored to evaluate their impact on the efficiency and profitability of the hybridized system. Finally, the implementation of pilot projects is planned to validate the theoretical results obtained and adapt the models to real-world operating conditions.

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Adaptation of the Loss Distribution Approach in Climate Extreme Risk Analysis for Wind Farm Digital Twin Decision Support Systems

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Abstract—Extreme weather events pose significant operational risks to wind farms, yet analyzing these rare occurrences remains challenging for digital twin (DT) systems designed to mirror physical assets. The complexity of a wind farm (WF) energy production system only adds to the aforementioned challenge. This paper introduces a novel adaptation of the Loss Distribution Approach (LDA) to quantify and manage these risks within WF DTs being developed under the Horizon Europe-funded TWINVEST project.

The LDA is usually better known in the insurance and banking sectors as it is used in relevant advanced risk management practices for assessing Economic Capital requirements for operational risk. The LDA offers a methodological framework that is well-suited for modeling low-frequency, high-impact events. As such, it may be considered appropriate for accounting for extreme events and related consequences. Moreover, the proposed methodology is both flexible and adaptable to different configurations of wind farm and context setting, thus offering added value in the development of the wind farm DT. Nevertheless, its application in the WF sector necessitates careful understanding and examination of the underlying principles and assumptions. Our implementation addresses key challenges in transferring LDA from financial to renewable energy sectors, including parameter estimation from limited historical data and integration with existing wind farm monitoring systems. Key assumptions, and important advantages of the proposed approach in relation to other risk analysis approaches that have been considered in the WF sector are also discussed.

Indicative results based on synthetic field data showcase how the proposed approach may provide valuable insight to decision-making in the management of operational costs. This research contributes a methodological bridge between established financial risk practices and emerging DT applications in renewable energy, offering wind farm operators enhanced capabilities for resilience planning against increasingly volatile climate conditions.

Keywords—loss distribution model; operational risk analysis; wind farm digital twin.

INTRODUCTION

Wind farms (WFs) are complex energy production systems that pose significant operational risks and challenges for sustainable energy production. As renewable energy sources gain prominence in the global energy landscape, ensuring their resilience against climate extremes becomes crucial for energy security and sustainability goals. DTs, which provide a virtual representation of the real-world system for mirroring the behavior, performance and changes of their physical counterpart, offer promising solutions as WF simulation and decision support tools for monitoring, predicting, and optimizing WF performance for WF operators and decision makers. Accurate representation of the system's behavior in the form of Digital Twins (DTs) is challenging per se due to its complexity, moreover their effectiveness in managing risks from extreme weather events that are scarce by definition, often resulting in high-impacts can be further diminished.

The Loss Distribution Approach (LDA), originally developed in the banking sector for operational risk assessment under Basel regulation [1], offers a promising framework for addressing this gap. LDA provides a structured methodology for separately modeling the frequency and severity of risk events before combining them to estimate the total loss distribution. This approach is also applicable for rare events where empirical data may be limited.

Traditional risk assessment methods often fail to adequately capture the full risk profile of these low-frequency, high-severity events. Several applications of the Failure-Mode-Effect-(and Criticality)-Analysis FME(C)A exist in the literature (e.g. [2], [3]) often combined with Fault Tree Analysis (FTA – [3]), Risk-Priority-Number (RPN – [4], [5]) or Cost-Priority-Number (CPN – [3]) for identifying root causes and risk factors causing component failure and their associated cost. Other notable risk assessment methods include some combination of expert interviews (e.g. [6], [7], [8] for identifying critical risk factors, risk ratings and risk treatment options, with Structural Equation Modeling (SEM – e.g. [8]), SWOT analysis [9], indicator-based risk ratings [10] or Analytical

Hierarchy Process (AHP) risk factor ranking [7]. Thorough probabilistic approaches combined with structural modeling and resulting fragility functions [11], event tree methods with failure probabilities calculated by reliability methods [12], or Bayesian approaches [13] have also been proposed.

The majority of these methods focus on the wind turbine configuration or specific sub-assemblies at different settings (i.e. on-shore, off-shore). Often, these methods are tailored to the specific WF configuration and context that are applied, thus making their applicability not straightforward under a different context. As such, we argue that the level of detail, effort and relevant information needed for expanding these methods to the whole WF setting is extremely tedious for their practical application and integration in DTs. Furthermore, many of these methods depend significantly on expert judgment, which is not always easy to obtain, introduces subjectivity and increases the potential for uncertainty in the results. Other reliability and failure analysis approaches have been proposed, such as in e.g. [14] for condition-based maintenance cost optimization and [15] which combined it with Pareto analysis for prioritizing critical factors which caused failures of the system. However, a key limitation of these studies is that they did not differentiate failure rates across various wind turbine configurations and WF layouts. Additionally, they did not distinguish between failures occurring during normal operation versus those resulting from extreme weather events.

Stochastic financial approaches applying MC simulations to probabilistic cash flow analysis combined with risk modeling using financial indices based on macroeconomic data have also been proposed for the valuation of WF projects by accounting for the Capital and Operational Expenses (CAPEX and OPEX, respectively) [16], (Yildiz, Hemida, & Baniotopoulos, 2024). Such methods, however, lack the granularity necessary for risk attribution to extreme weather events.

Methods based on advanced statistical and stochastic concepts have also been proposed: the combined use of extreme value theory (EVT) methods with Copulas for simulating a WF composed of various wind turbines based on individual wind turbine failure rates and resulting downtime – direct cost from failure (i.e. spare parts, labor and repair logistics) and other major WF assemblies beyond the wind turbines were not considered [18]; [19] argued that, although tempting, instead of using the “... wind turbine as a generic entity and impose operational control from this perspective...”, instead “...maximum reliability can best be achieved through the use of the methodology described herein to allow treating the fleet as a data-compiling collective, and capture the similarities between turbines that exist on a statistical level, while acknowledging the uniqueness in their operational behavior.”. They proposed a multi-layered framework based on SCADA field data and Bayesian Gaussian mixture models (GMMs) as a clustering technique to relate loading conditions to operational zones within the WF. They acknowledged the limited availability of field data as the main limitation of their approach for evaluating a variety of different cases. In [20], a multivariate analysis using Copulas combined with indexed semi-Markov chain (ISMC) models and Monte Carlo (MC) simulations to reproduce the spatial dependencies of the WF system’s power generation.

These methods, although making use of advanced statistical concepts (i.e. EVT, Copulas, Bayesian Networks and Markov processes) are, arguably, more easily extendible and adaptable to the WF DT setting, including

major assemblies beyond the wind turbines already considered; we were thus guided by their reasoning in selecting our proposed use of the LDA.

Within the context of the TWINVEST project, which aims to develop DT technology for WFs, integrating robust quantitative risk assessment methods is crucial for supporting investment decisions and operational strategies. This paper presents an adaptation of the LDA framework specifically tailored to WF risk assessment, with a focus on extreme weather events and discusses the inherent assumptions, challenges and advantages for its applicability. Furthermore, it provides insight on how the LDA can be integrated into WF DTs to enhance decision support capabilities. In this respect, it must be mentioned that the resulting consequences for the failure events that were analyzed were considered only from the cost perspective; moreover, optimization of the maintenance process or the OPEX was not in the scope of our research.

The paper is structured as follows: Section 2 presents the research approach and methodology; Section 3 addresses data requirements and sources; Section 4 discusses the model implementation; Section 5 presents results and discussion; and Section 7 concludes with recommendations and future work.

METHODOLOGY

Research approach and methodological rationale

The selection of an appropriate risk assessment framework for WFs exposed to extreme weather events requires consideration of few major factors. First, the framework must handle the rare nature of extreme events while still providing reliable risk estimates. Second, it should accommodate the significant uncertainty in both the frequency and impact of these events. Finally, it must be able to support a DT architecture by being customizable in different context. Key criteria that support these factors are the following:

- The approach must be representative of WF operations without becoming overly complex, considering the intricate nature of the WF system.
- Flexibility is needed for accommodating different WF setting and context.
- Modularity is essential to allow for future adjustments without complete system redesign.
- Minimal data input to support user-friendliness.
- Support interoperability and data integration from the various WF assemblies.
- Obtain data from existing WF monitoring systems or records from existing databases to favor a fact-based approach over expert opinion, when available.
- The methodology needs to be scientifically sound, transparent, and traceable.

The LDA satisfies these criteria by providing a statistical framework that separately models the frequency and severity of failure events before combining them to estimate the total risk exposure. This approach is particularly well-suited for assessing weather hazard consequences studied from a cost perspective, similar to its application in the banking sector. At the very least, the LDA does not require more data than risk approaches discussed above; in fact, it requires significantly less data than most of those. Moreover, as we next argue, the data it requires may be more easily available or collected, if planned accordingly.

The Loss Distribution Approach framework

The LDA framework consists of three main components.

The Frequency distribution: Models how often failure events occur, typically using discrete probability distributions like Poisson or Negative Binomial (N-Bin).

The Severity distribution: Characterizes the financial impact when an event occurs, typically using continuous distributions such as Log-Normal, Weibull, or Generalized Pareto.

Aggregation method: Combines the frequency and severity distributions to estimate the total loss distribution, usually through MC simulation.

In the banking sector, assuming that indices i and j denote a given event type i and business line j , we may define the following:

Assuming that the number of events within a given timeframe is a discrete random variable $N(i,j)$ with probability mass function $p_{i,j}$, its Frequency Distribution $P_{i,j}$ is:

$$P_{i,j}(n) = \sum_{k=0}^n p_{i,j}(k) \quad (3)$$

Assuming that the resulting loss for one event occurrence is represented by a continuous random variable $s_{i,j}$ with Severity Distribution denoted $S_{i,j}$, then, the compound Loss Distribution $L_{i,j}$ may be provided by the following formula where $(*)$ indicates the n -fold convolution of S with itself:

$$L_{i,j}(n) = \begin{cases} \sum_{k=1}^{\infty} p_{i,j}(k) S_{i,j}^{n*}(x) & x > 0 \\ p_{i,j}(0) & x = 0 \end{cases} \quad (2)$$

Figure 1 depicts the aforementioned LDA distributions.

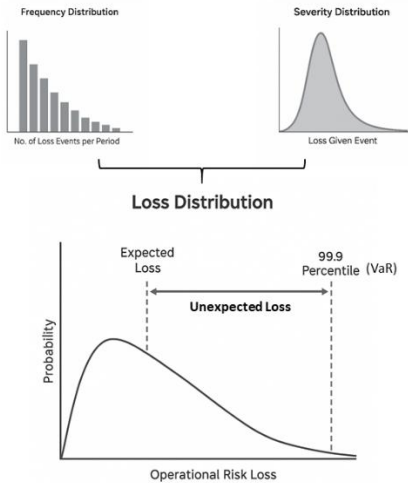


Figure 1: LDA distributions

The resulting Loss Distribution provides key risk insights, such as: a) *Expected Loss (EL)*: average loss over time; b) *Value at Risk (VaR)*: percentile measure representing the worst-case loss within a confidence level; c) *Unexpected Loss (UL)*: difference between VaR and EL. The LDA assumes:

- **Independence:** The frequency and severity are statistically independent.

- **Stationarity:** The statistical properties of the losses remain stable over time.
- **The occurrence of events follows a stochastic process.**

These assumptions must be carefully validated in the WF context, where dependencies between weather events may exist and where severity distributions may vary seasonally.

Wind farm system decomposition; definition and classification of extreme weather events

Identifying key assemblies and sub-assemblies in a WF that are largely independent of each other, meaning that failure in one of these does not automatically trigger failures in others, is the first, but important (as extreme weather events often affect multiple systems simultaneously), step in applying the LDA. This decomposition allows for targeted risk assessment by identifying which assemblies are most vulnerable to specific weather hazards.

The second step is to follow a structured approach for attributing failures to specific extreme weather events by making use of recorded field information. The questions to address in this regard is what constitutes a weather *extreme* for the WF operation and how to consider a failure event as being due to the occurrence of the extreme event. We propose to adopt a threshold-based approach that can be applied to the different sub-assemblies of the WF. This approach offers both flexibility for the WF operator to consider different operational limits and allows for considering different WF location and assembly setting, attributes that are both desired towards the development of a DT.

The threshold may be defined based either historical meteorological data, WF assembly / sub-assembly design specifications, operational limits or some combination of these. Evidently, “one-off” failures, such as those occurring because of a lightning strike or an earthquake do not need thresholds, just the actual record of the occurrence. To be able to distinguish failures that occurred due to extreme weather versus those arising from normal wear, we propose to adopt a time-window around the occurrence of the event that exceeds the respective threshold; if a failure is recorded within this time-window, then it is attributed to the occurrence of the event, all other failures are attributed to normal wear.

As such, following a literature search and information obtained from WF assembly manufacturers, operational thresholds were proposed for the different weather events considered in relation to the WF discretization. Table 1 shows a proposed WF discretization into the major assemblies and sub-assemblies with the respective thresholds for wind, ice and lightning. Of course, these thresholds are only a convention and may be modified, as needed.

Table 13: Wind Farm (WF) discretization & used thresholds

WF main assembly	Subassembly	Used threshold for failure to be attributed to extreme event		
		Wind	Icing (Low T.)	Lightning
Wind Turbine (WT)	Generator	90% max V ^a	T < -15°C ^b	N/A
	Gearbox	90% max V ^a	T < -15°C ^b	N/A
	Pitch & Blades	90% max V ^a	T < -1°C RH > 80% ^c V: 1-15m/s T < -10°C (std. WT) T < -30°C (LTC WT) ^d	Recorded event

WF main assembly	Subassembly	Used threshold for failure to be attributed to extreme event		
		Wind	Icing (Low T.)	Lightning
	Yaw	90% max V ^a	T < -15°C ^b	N/A
Grid connection	Transmission lines & WT cables	90% max V ^a	T < -1°C RH > 80% V: 1-15 m/s	Recorded event
	Trans-former	90% max V ^a	T < -15°C ^b	Recorded event
Electrical system (WT)	Transfor-mers (WT)	90% max V ^a	T < -15°C ^b	Recorded event
	Inverter/Converter	90% max V ^a	T < -15°C ^b	Recorded event
Control System non-rotational	SCADA, Sensors & Communication System	90% max V ^a	T < -10°C (for downtime) T < -30°C (for failure)	Recorded event
	Lightning & earthing system	N/A	N/A	Recorded event
Other	(e.g. WT Tower, Foundation, Grid connection substation)	90% max V ^{a,c}	N/A	N/A

^a Depends on the max V for the operation of the WT recommended by the manufacturer (18–25 m/s). In all cases used, it is assumed that high wind velocity may induce damage.

^b High oil/hydraulic fluid viscosity when no mechanism for oil heating or oils suitable for cold are used for the relevant system.

^c Icing event at the rotor; for Temperatures ranging between -10°C and -15°C, only downtime may be considered as an (indirect) cost consequence of the occurrence of the “extreme” event due to the management decision. Recorded failures will however be considered as due to regular operation.

^d Manufacturers Operation Limit for Standard and Low Temperature Climate (LTC) WT.

^e Only if Tower damage is reported, N/A for others.

DATA REQUIREMENTS AND SOURCES

Data categories and requirements

The LDA implementation requires two primary data categories:

Failure frequency data: Recorded number of failures for each sub-assembly of the WF during the selected timeframe (equal to one year in the banking sector) for multiple timeframes (no less than three). A frequency distribution may then be fitted to the data for each WF sub-assembly or for each WF assembly by adding the respective frequencies.

Severity data: cost information that is related to the specific failure. Such cost may be the sum of direct (e.g. part replacement cost, personnel cost, crew and part transportation logistics cost) and indirect (e.g. revenue losses from downtime; other secondary losses, e.g. from contractual grid penalties) cost.

This data enables the derivation of a Loss Distribution for the specified timeframe, independent of the failure's cause. However, to determine whether a specific failure resulted from an extreme event or regular wear, it is also necessary to consider the weather conditions near the time of the event, particularly in relation to the relevant threshold values. Based on Table 1, such data may include according to the weather hazards that are to be analyzed: the time of the failure occurrence, records of failures because of a direct hit (e.g. lightning), wind velocity ambient temperature and relative humidity.

Data sourcing hierarchy

For the LDA to be data-driven and reflect to the best possible extent the particularities of the WF setting we

propose the following prioritization for data-sourcing, in decreasing order of relevance:

Field data: WF monitoring systems, such as SCADA, provide high-resolution operational data, including environmental conditions and assembly status. In absence of such information from the WF, relevant meteorological records provided by locally available instrumentation or satellite measurements may act as substitutes. Maintenance logs may offer detailed information on failure modes repair activities, and associated costs.

Industry databases: there are various databases, accessible for a fee or open, that can provide data relevant to WF assemblies (e.g. database produced by [21]; the Gearbox Reliability Database - <https://grd.nrel.gov/>).

Expert opinion: When field data is insufficient or unavailable, structured expert elicitation methods (e.g. Focus Group; Delphi method) may be employed to obtain relevant estimates from industry specialists.

Assumptions: In case access to all previous options is unavailable, the literature and engineering judgment may provide relevant information with justification.

Data challenges and solutions

Obtaining failure data is fairly straightforward, however cost data are more difficult to access. Cost data are not easily shared by WF operators as such information is considered sensitive. Cost may also be composed from different elements, direct (e.g. replacement part, labor, transportation) and indirect (e.g. energy production loss due to downtime), hence it is important for WF operators to keep detailed logs of the cost resulting from a failure event or from inspection/monitoring activities. In the context of DTs, interoperability of modules that keep track of downtime with those calculating energy production loss is important for assessing indirect cost. Integration with the DT platform requires standardized data formats and interfaces to connect risk assessment outputs with other modules.

Extreme event data scarcity poses another challenge in LDA implementation but other RA methods also suffer from this. Solutions may include use of EVT statistical methods for extrapolating the tail of distributions, bootstrapping or pooling of data across similar WFs accounting for site-specific factors, and data normalization to account for differences in assembly characteristics (e.g. size, age, technology) to ensure comparability across sources. Use of Bayesian updating as new data becomes available could also be applied.

With regard to satisfying the key assumptions the WF context offers another important challenge. A single extreme weather (risk) event, such as a strong wind, may result in multiple failures. These may be within a single subassembly (e.g. generators of multiple wind turbines failing) or across subassemblies (e.g. multiple generators and inverters). We note that the failure of one subassembly does not directly cause the failure of another subassembly, nevertheless, it is possible that are both attributable to the same underlying risk event. This triggering of multiple simultaneous failures, although not attributable to a cascading effect, introduces dependence in the LDA process as failures of subassemblies are not statistically independent. An extreme event increases the likelihood of multiple subassembly failures.

For weather events for which the occurrence of an event may result to only a single failure, such as lightning, the LDA may be implemented by fitting failure frequency and

cost severity distributions for each relevant combination of subassembly / event type. However, the adaptation of the LDA in the case of an event (e.g. strong wind / earthquake) that may cause multiple failures within and/or across subassemblies simultaneously must follow one of the following modifications:

Aggregate loss model (ALM): each extreme weather event that results to a failure is treated as one event. The frequency distribution still models how often the event occurs, however the severity distribution models the aggregate loss per event occurrence from all affected subassemblies (i.e. the total sum of cost from all failures that resulted due to the event). This approach is simpler to implement and models directly the systemic risk. It is the only that can be applied when records of total losses are only available. However, it loses the granularity and subsequently the ability to gain insight with respect to the contribution of different subassemblies which may be useful when trying to assess different configurations.

Use of a Compound Event Process (CEP): the use of a CEP would allow to model the event occurrence separately from the modeling of the subassembly failures conditional on the event's occurrence. If a Poisson distribution is used for both processes, this is known as the Compound Poisson Process. However, different distributions may be used for each process. This option is a more refined and granular version of the aggregate loss model. This approach ignores shared causality unless correlation is added through the use of copulas.

Use of Copulas: the use of copulas may allow to model the spatial or dependence structure between subassembly failures by looking at their correlations. In case we would apply the LDA by treating subassembly failures as separate events, two main pitfalls would result: a) we would be over counting the events and b) we would be splitting the total loss that would have resulted from an actual weather event into several smaller losses. This could skew the resulting the Loss Distribution and underestimate its tail in the case of rare but high-severity events, in particular for extremely heavy-tailed or skewed severity distributions. In such case, risk metrics may be used only for providing lower bound estimates of possible capital to allocate but these would be insufficient to properly model or assist decision making in relation to insurance structuring or actual financial impact.

MODEL IMPLEMENTATION

We showcase the LDA model implementation for the case of a small 8 MW onshore WF and recorded data that span a 5-year time period. Weather data were obtained from SCADA records. Such data were useful in differentiating between failures due to extreme events according to the relevant threshold. Next, adaptation of the LDA followed the ALM approach and compared it to the case for which fitting of failure occurrence is performed instead of the fitting of events with aggregate costs per event.

Distribution selection and fitting for failures and costs

Failures were identified from the maintenance and event logs. All failures were due to the effect of high winds. Furthermore, all failures were generator-type of failures. As such, we considered one-subassembly type WF system and one extreme event, i.e. high wind. Table 2 shows the failure

distribution over the 5-year period for events that exceeded the threshold.

The event occurrence was modeled by fitting a Poisson distribution to the failure events. Two cases were considered: a) the occurrence of total events per year, and b) the total failures observed per year. Case a) is consistent with the ALM approach whereas case b) fits individual failures.

Table 2: Recorded failures per wind event above threshold

Year	Total Events	Recorded failures per event occurrence					
		1	2	3	4	5	6
1	2	4	5				
2	3	3	2	1			
3	6	4	8	3	5	4	3
4	3	4	3	4			
5	2	3	5				

In relation to the severity, as the cost of failures had not been recorded, each failure was assigned a relevant cost that was randomly generated from a Log-Normal distribution with mean = 10.5 and standard deviation = 0.7. As such, 61 cost values were assigned in total, one for each failure. Three distributions, the Log-Normal, the Generalized Pareto and the Weibull were tested for the data set of resulting cost values. Parameters for these distributions were estimated using the Stats library of Python and maximum likelihood estimation. It is important to note that the fitted cost values are different for each case. In case a) (i.e. the ALM) cost is the sum of the cost that is assigned to the total failures that were recorded for the specific event; in case b) the cost is the value obtained from the aforementioned random application of the Log-Normal distribution.

Simulation framework

The LDA was implemented via MC simulations as following: 1. Random numbers representing events (case a) or failures (case b) were generated from the fitted frequency distribution. 2. For each event, a sampling from the fitted severity distribution returned the respective cost. 3. Aggregation of the sampled severities (i.e. costs) returned the total loss for the specific event. This process was repeated for 1,000,000 times.

The simulation was implemented in Python environment, by developing scripts that asked for user to designate the fitted frequency and severity distributions and input the relevant parameters. We resorted to specialized statistical libraries (i.e. Stats) for generating random numbers from the fitted statistical distributions. Modularity and vectorization were applied in coding for obtaining computational efficiency; overall the simulation took a few seconds on a 16GB RAM PC with an Intel(R) Xeon(R) CPU E5-1620 0 @ 3.60GHz processor.

RESULTS AND DISCUSSION

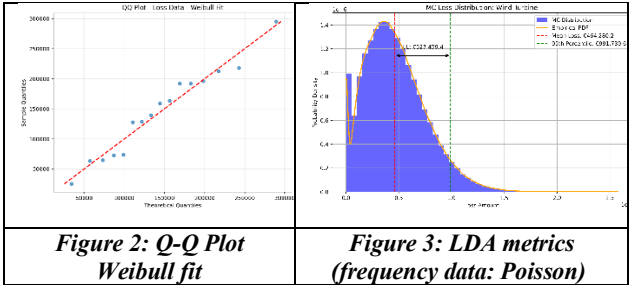
Next, the results obtained for each case are detailed and discussed.

Case a): LDA - Event modeling (ALM)

Fitting¹ of the Poisson distribution to the failure-causing event occurrence returned an estimated parameter λ

¹ The fitting of various distributions follows the distribution definition and parameterization of Python's library [Stats](#)

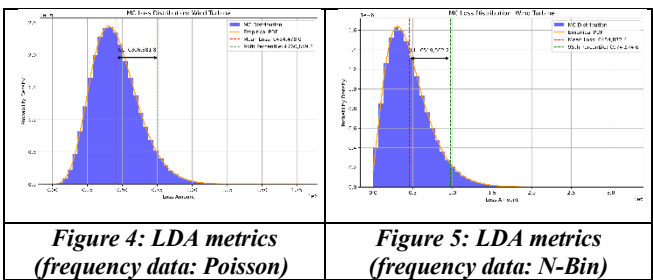
(average annual frequency) of events equal to 3.2 events/year. For the severity distribution the Weibull performed the best fitting with parameters α (shape) and ξ (scale) (standard deviation) equal to 2.19 and 163,901.08 respectively. Figure 2 shows the Q-Q plot of the Weibull fit. The Anderson-Darling (A-D) test value was equal to 0.3798 and smaller than the A-D critical value equal to 0.608. Figure 3 depicts the resulting LDA and the respective metrics from the MC process for 1,000,000 frequency distribution simulations.



The EL was equal to €464,280 and the 95% VaR equal to €991,740 which exceeds the EL by a factor of 2.14, resulting in an UL equal to €527,460 and highlighting the importance of using a probabilistic approach in risk management.

Case b): LDA – Individual failure modeling

Fitting of the Poisson distribution to the failure occurrence returned an estimated parameter λ (average annual frequency) of failures equal to 12.2 failures/year. However, exploratory analysis of failures yielded a variance equal to 71.7 failures/year. The higher by a factor of six variance indicates that the N-Bin may be a more appropriate fit than the Poisson for this process. The resulting parameters for the N-Bin were: size (n) = 4.4284 and probability (p) = 0.2663. For the severity distribution the Log-Normal, performed the best fitting, as expected since the cost values were derived from a Log-Normal, with parameters μ (mean) and σ (standard deviation) equal to 10.26 and 0.73 respectively. The Anderson-Darling (A-D) test value was equal to 0.4335 and smaller than the A-D critical value equal to 1.0807. For comparison purposes, the MC process was run both for the fitted Poisson and the N-Bin. The resulting LDA metrics are shown in Figures 4 and 5.



The EL for the N-Bin fitting was equal to €454,872 and the 95% VaR equal to €974,375 which exceeds the EL by a factor of 2.14 resulting in an UL equal to €509,503. The respective numbers for the Poisson fitting were €454,478 (EL), €760,860 (95% VaR) with a factor equal to 1.67 and an UL equal to €306,482.

Comparative analysis

The aforementioned results reveal some important features: First, we notice that the ALM may result in different fitted distributions both for the frequency and the severity data compared to case b). This may have important implications, in particular for the VaR metric, which is often

used for insurance purposes. Next, we can observe that when Poisson is used to fit the frequency data for both cases, the ALM UL is 1.72 times greater than the UL resulting from the individual failure modeling. This can be explained by the fact that the tail of the fitted distribution is more accurately captured by the ALM. An interesting finding is the similarity of results between the ALM with case b) when the N-Bin is used to fit the frequency data. This may be attributed in part to the fact that the N-Bin captures better the overdispersed failure data of case b) than the Poisson, which in turn results in a heavier tail Loss Distribution, and the absence of heavy-tailed severity distribution; nevertheless the key LDA assumptions are better satisfied by the ALM.

The analysis also reveals the importance of threshold definitions, which is a conventional measure for determining which weather events are considered extreme. It can be expected that selection of different thresholds will also affect the fitted distribution parameters, hence further analysis is warranted for exploring such impact on the resulting LDA metrics. The LDA approach may also highlight the importance that limited data may have on resulting metrics. For example, for the ALM case varying the average number of event occurrences (i.e. Poisson λ) per year $\pm 50\%$, i.e. from 1.6 to 4.8, while keeping the same severity distribution, results in EL varying from €232,294 (-50%) to €696,494 ($+50\%$), the 95% VaR from €619,883 (-37.5%) to €1,331,753 ($+34.3\%$) and the resulting UL from €387,589 (-26.5%) to €635,259 ($+20.4\%$), thus emphasizing the importance of availability of historical data for robust parameter estimation.

Pros and cons of the LDA

The aforementioned results provide some insight on the potential advantages of the LDA in the context of WF DT setting, in particular in comparison to the traditional risk assessment methods. Nevertheless, its thorough application raises also some challenges. Table 3 summarizes these.

Table 3: Main advantages and challenges for the use of LDA

Advantages	Challenges
Flexible approach: can accommodate different WF configuration, setting and weather conditions → appropriate for DT	Computationally-expensive requiring MC simulations.
Risk control and segregation: enhances understanding of risk exposure across WF assemblies	Requires some experience in fitting distributions, particularly when data are limited
Risk attribution: able to allocate risk to different hazards and differentiate from regular operation	Use of Copulas needed to account for complex interrelationships / dependencies of WF assemblies / hazards
Probabilistic approach: facilitates risk-based decision making	Requires thorough understanding of the underlying assumptions
Adaptable: easily modifiable input to allow for stress and scenario testing; allows to study the implications of different contingency measures	Applying the LDA for modeling of multiple failures due to the same event increases the modeling complexity
Ease of applicability: requires minimum amount of data in relation to other RA methods	
Field data-driven approach: field data usually readily available to WF operators (SCADA, maintenance / event logs)	
Applicable to extremes & possibility for insurance modelling: used in the banking and insurance sectors	

In short, the LDA offers the flexibility and adaptability needed in extreme weather risk assessment in DT setting

using field-based data and supporting risk-based decision making. However, obtaining sufficient granularity for the different sub-assemblies may call for advanced statistical methods and increased model complexity.

CONCLUSIONS AND FUTURE WORK

The LDA provides a statistically robust framework for quantifying risks through MC simulations. This study discussed the novel adaptation of LDA from the financial sector to WF operations and its suitability for integration in DTs.

Key findings indicate that the generation of probabilistic risk metrics (EL, VaR, UL) may provide valuable insight for informed, risk-based decision-making. The sensitivity of results to distribution selection and parameter fitting underscores the importance of high quality input data, understanding of the underlying assumptions and choice of threshold. This is even more important in the context of rare, catastrophic weather events for capturing the tail behavior of the Loss Distribution.

The flexibility and adaptability of the LDA in different context combined with its compatibility with data collected from SCADA systems and maintenance logs offer the following practical implications and benefits:

For WF operators, the LDA facilitates cost-based risk quantification, underpinning budget contingencies (resilience / preventive maintenance / assembly upgrade priorities), insurance-structuring, and record-keeping. Enhancing maintenance logs with granular cost details and field weather data tied to specific thresholds will improve and refine the deployment of the LDA.

From a DT perspective, the modular and data-driven design of the LDA makes it well-suited for integration into DT platforms, enabling scenario analysis while also supporting interoperability with field measurement systems for dynamically updating risk profiles.

Limitations include assumptions of statistical independence and event stationarity, dependence on sparse historical/cost data in a changing climate context and increase of modeling complexity when accounting for dependent or compound failures or for dependencies between different weather hazards.

Future research should explore the use of more sophisticated dependency structures such as CEPs and Copulas to model dependencies among simultaneous failures by considering multiple WF assemblies/subassemblies. Incorporating climate change projections into the frequency models or integrate the LDA to maintenance or OPEX optimization are also potential research avenues.

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Integrated Strategic and Tactical Transport Planning in the Charging Station Location Problem for Electric Buses

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Abstract—Electrifying bus fleets is a critical step toward sustainable urban mobility and the modernization of public transport systems. Yet, the deployment of charging infrastructure remains a major challenge, particularly in determining charger locations that balance operational efficiency with economic feasibility. This paper presents a planning model that identifies the optimal locations for charging stations that support the daily operation of an electric bus fleet. Focusing on the Charging Station Location Problem for Electric Buses (EB-CSLP), the model integrates tactical transport planning decisions, most notably charging scheduling, within a strategic planning framework that involves setting up an optimal charging stations network. The primary aim of this article is to demonstrate the impact of explicitly incorporating the charging scheduling component, as opposed to strategic planning approaches that omit it. Formulated as a single-objective mixed-integer linear program (MILP), the model minimizes monetary costs associated with deadheading distances, installation costs of the chargers, as well as daily energy consumption costs. The model's application to New York City data highlights its ability to generate practical insights for planners and transport authorities.

Keywords—electric buses, charging scheduling, charging station location problem, mixed-integer linear programming

INTRODUCTION

The electrification of public transport fleets is a key strategy for reducing greenhouse gas emissions and mitigating urban air pollution. With buses at the center of this transition, public transport services operators face the challenge of deploying adequate charging infrastructure while maintaining reliable and cost-effective services.

Mathematical programming models, such as the one proposed here for the Electric Bus Charging Station Location Problem (EB-CSLP), offer a valuable framework for tackling these challenges. By integrating decisions on charger placement and charging schedules, such models can help operators minimize operational costs, reduce deadheading distances, and align charging demand with grid constraints. Although mathematical programming approaches are not yet widely adopted in practice, they have the potential to support transport authorities and operators in planning efficient and sustainable electric bus networks.

LITERATURE REVIEW

The EB-CSLP has been studied in recent years to a considerable degree, with proposed mathematical models varying in their objectives, planning horizons, and constraints. Early contributions, such as An[1] laid the

foundation by integrating charging scheduling constraints, which made it possible to consider this aspect of the problem. However, the state of research at that point in time, did not account for disaggregate-level constraints that consider the charging scheduling of individual buses to specific time slots throughout the day. Later studies expanded the scope of the problem: Foda and Mohamed [2] examined flexible charger placement in dense urban settings and introduced deadhead times as recovery periods between trips, while Gairola and Nezamuddin [3] emphasized the inclusion of Time-of-Use (ToU) tariffs and peak demand charges in multi-objective models. Wang et al. [4] also proposed an exact MILP formulation that accounts for deadheading distances and ToU tariffs, though their framework did not consider the effects of multiple charger types or maximum demand charges.

Recent studies increasingly focus on disaggregate-level charging schedules and the integration of energy system interactions. Liu et al. [5], [6] advanced the field by incorporating detailed bus-to-charger assignments, specific charger types, and operational costs such as peak demand charges. Their research highlights the importance of capturing the operational complexities that arise when charging schedules are linked directly to fleet operations. In parallel, other studies such as He et al. [7] developed bi-objective models that analyze the trade-off between costs and deadheading distances, yet they do not fully address the charging scheduling sub-problem or validate results using large-scale data.

Taken together, this brief literature demonstrates a clear trend toward integrating tactical and operational dimensions into strategic planning for electric bus fleets. However, few studies provide experiments and specific comparisons between problems formulations that use charging scheduling constraints for the EB-CSLP and problem formulations that don't. This gap motivates the present study, which contributes by explicitly modeling disaggregate-level charging scheduling and by applying the approach to real-world data from Manhattan, New York.

METHODOLOGY

Problem Parameters and Decision Variables

The mathematical formulation presented in this article follows the nomenclature of the recently published research by Gkiotsalitis et al. [8] and Rizopoulos et al. [9]. The problem formulation considers a set of bus trips K , which require charging at specific locations and times during the duration of a single day. These trips $k \in K$ must be allocated

to available candidate charging stations $j \in N$, which are spread out at locations M , and are available at different time slots (sets F_1, F_2, F_3). The main aim of the problem is to minimize both financial investments and operational costs (deadheading and charging costs). Two types of charger types are considered: slow and fast which are represented by sets N_1 and N_2 . The model integrates three planning horizons: charging slots for slow (set F_1) and fast chargers (set F_2), and demand charge time slots defined by the energy grid operator (set F_3).

The decision variables of the problem include the binary assignment variables $x_j, q_{kj}, u_{kjjf_1}^s$ and $u_{kjjf_2}^h$. Variable x_j takes the value of 1 when a charger is installed at $j \in N$, while q_{kj} takes the value of 1 when bus $k \in K$ gets assigned to charger $j \in N$. Variable $u_{kjjf_1}^s$ takes the value of 1, when a bus $k \in K$ gets assigned to a slow charger $j \in N_1$ and time slot $f_1 \in F_1$, or is zero otherwise. Similarly, $u_{kjjf_2}^h$ is used for assignments to fast chargers $j \in N_2$ and their respective time slots $f_2 \in F_2$.

Several dependent variables are introduced to capture the interaction between the charging station network, the energy grid, and the electric buses. The variables $UD_{jff_3}^s$ and $UD_{jff_3}^h$ are binary indicators specifying whether any trip k is assigned to charge at a slow or fast charger j during a demand charge time slot f_3 . To accurately represent energy transfers during charging, the model defines a set of energy flow variables. Variable $EC_{kjjf_1}^s$ denotes the amount of energy transferred from a slow charger j to bus trip k during time slot f_1 , while $EC_{kjjf_2}^h$ captures the energy delivered from a fast charger during time slot f_2 . Similarly, $DC_{kjjf_3}^s$ and $DC_{kjjf_3}^h$ quantify the energy provided from slow and fast chargers, respectively, to a bus trip k in each demand charge time slots f_3 . At the aggregate-level, the variable DEC_{f_3} measures the total energy consumption at all chargers, both slow and fast, within each demand charge time slot. Finally, IP^{max} represents the maximum power drawn across all demand charge time slots $f_3 \in F_3$, reflecting the peak load imposed on the energy grid by the charging activities.

Finally, given that buses K need to charge at specific time points τ_k within the day and we know their State of Charge (parameter SoC_k) at that point, it is assumed that the energy that can be transferred from a charger to the bus only depends on the type and location of charger that they assigned to. This is why the parameters PEC_{kj}^s and PEC_{kj}^h are introduced as precomputed values that specify the amount of energy required to recharge any bus k , if an assignment q_{kj} occurs. Finally, to link between time horizons F_1, F_2, F_3 , precomputed parameters $z_{f_3}^s$ and $z_{f_3}^h$ are used. For example, $z_{f_3}^s \in F_1$ takes the value of F_1 based on the slot f_1 that a time slot f_3 belongs to. Similarly, $z_{f_3}^h$ takes the value of F_2 for each f_3 based on which f_2 that specific f_3 belongs to.

The Mixed-Integer Linear Formulation (MILP)

To evaluate the proposed concept, we utilize two MILP models, one that incorporates a tactical planning set of constraints, and one that does not. These two models can be derived based on the following baseline formulation, which is given below starting with objective function O_1 .

$$\begin{aligned} \text{minimize } O_1 = & \sum_{k \in K} \sum_{j \in N} dc \cdot t_{kj} \cdot q_{kj} + \sum_{j \in N} b_j \cdot x_j \\ & + \sum_{k \in K} \sum_{j \in N} \sum_{f_3 \in F_3} ToU_{f_3} \cdot DEC_{f_3} \\ & + DCR \cdot IP^{max} \end{aligned} \quad (1)$$

Objective function (1) is formulated to minimize the total monetary costs associated with the alternative charging station configurations (feasible solutions). The first component represents the cost incurred from deadheading (with dc being the cost per minute), defined as the travel time between the end of a bus route and the assigned charging station (specified as t_{kj}). The second term captures the fixed capital expenditure related to charging station installation, with b_j being the monetary cost of installing charger b_j . The third component reflects the daily charging costs, determined by the charging schedule and the ToU tariffs (parameter ToU_{f_3}). Finally, the fourth term accounts for costs arising from peak demand charges and multiplies decision variable IP^{max} , which takes the value of maximum power output consumed from the grid with parameter DCR , which is the cost penalty applied by the energy authority for IP^{max} .

Moving on to the constraints of the baseline MILP formulation, Constraint (2) ensures consistency between assignment and installation decisions by allowing a trip to be assigned to a charging station only if that station is installed. Constraint (3) guarantees that every installed station is utilized by at least one trip (assignment of a bus trip k to a charger j through q_{kj}), preventing idle or unnecessary investments. Constraint (4) enforces that each trip is connected to exactly one charging station. Finally, Constraint (5) incorporates the investment limitations of the operator by ensuring that the total cost of installed stations does not exceed the available budget.

$$q_{kj} \leq x_j, \forall k \in K, \forall j \in N \quad (2)$$

$$\sum_{k \in K} q_{kj} \geq x_j, \forall j \in N \quad (3)$$

$$\sum_{j \in N} q_{kj} = 1, \forall k \in K \quad (4)$$

$$\sum_{j \in N} x_j b_j \leq b^{max} \quad (5)$$

Constraint (6) guarantees that if a bus is assigned to a charging station, it can start charging in at most one slot, either slow or fast, at that location. Constraint (7) enforces that each trip is scheduled to exactly one charging slot overall, ensuring consistency in the allocation process. Constraint (8) introduces a capacity restriction for slow chargers by allowing at most one bus to occupy a given slow-charger time slot. Similarly, Constraint (9) applies the same restriction to fast chargers, ensuring that only one bus can be assigned to each fast-charger time slot.

$$\sum_{f_1 \in F_1} u_{kjjf_1}^s + \sum_{f_2 \in F_2} u_{kjjf_2}^h \leq q_{kj} \quad \forall k \in K, \forall j \in N \quad (6)$$

$$\sum_{f_1 \in F_1} \sum_{j \in N_1} u_{kjjf_1}^s + \sum_{f_2 \in F_2} \sum_{j \in N_2} u_{kjjf_2}^h = 1, \forall k \in K \quad (7)$$

$$\sum_{k \in K} u_{kjjf_1}^s \leq 1 \quad \forall j \in N_1, \forall f_1 \in F_1 \quad (8)$$

$$\sum_{k \in K} u_{kjjf_2}^h \leq 1 \quad \forall j \in N_2, \forall f_2 \in F_2 \quad (9)$$

Constraints (10) up to (13) are the charging scheduling constraints, which are central to the results presented in this article. Constraint (10) ensures temporal feasibility at slow chargers by requiring that charging can only begin after the bus has completed its trip and traveled to the station. Similarly, Constraint (11) imposes the same condition for buses assigned to fast chargers. Constraint (12) guarantees that charging at slow chargers must begin before the latest permissible start time defined for each trip. Finally, Constraint (13) applies this latest start-time requirement to fast chargers, ensuring that the charging schedule remains feasible with respect to operational constraints.

$$(1 - u_{k,jf_1}^s)M + u_{k,jf_1}^s c_{f_1}^s \geq (\tau_k + t_{kj}), \quad (10)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_1, \forall f_1 \in \mathcal{F}_1$$

$$(1 - u_{k,jf_2}^h)M + u_{k,jf_2}^h c_{f_2}^h \geq (\tau_k + t_{kj}), \quad (11)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_2, \forall f_2 \in \mathcal{F}_2$$

$$-(1 - u_{k,jf_1}^s)M + u_{k,jf_1}^s c_{f_1}^s \leq (p_k^s + t_{kj}), \quad (12)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_1, \forall f_1 \in \mathcal{F}_1$$

$$-(1 - u_{k,jf_2}^h)M + u_{k,jf_2}^h c_{f_2}^h \leq (p_k^h + t_{kj}), \quad (13)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_2, \forall f_2 \in \mathcal{F}_2$$

Constraint (14) ensures that the energy delivered at a slow-charger slot is conditional on the slot being selected by any bus $k \in \mathcal{K}$; if the slot is not chosen, no energy can be delivered. Similarly, Constraint (15) enforces the same activation rule for fast chargers, guaranteeing that energy delivery is tied to the selection of a valid charging slot.

$$EC_{k,jf_1}^s \leq M \cdot u_{k,jf_1}^s, \quad (14)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_1, \forall f_1 \in \mathcal{F}_1$$

$$EC_{k,jf_2}^h \leq M \cdot u_{k,jf_2}^h, \quad (15)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_2, \forall f_2 \in \mathcal{F}_2$$

Constraints (16) to (19) guarantee that EC_{k,jf_1}^s and EC_{k,jf_2}^h take the proper values when assignments u_{k,jf_1}^s and u_{k,jf_2}^h occur. In more detail, *Big-M* Constraints (16) and (17) specify that if a bus is assigned to a slow-charger slot $f_1 \in \mathcal{F}_1$, the delivered energy must be equal to the precomputed charging energy value of PEC_{kj}^s for that charger and slot, ensuring the vehicle receives the required amount. Similarly, Constraints (18) and (19) guarantee that buses assigned to fast-charger slots receive at least the recomputed amount of energy PEC_{kj}^h .

$$EC_{k,jf_1}^s \geq (-M)(1 - u_{k,jf_1}^s) + PEC_{kj}^s, \quad (16)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_1, \forall f_1 \in \mathcal{F}_1$$

$$EC_{k,jf_1}^s \leq M(1 - u_{k,jf_1}^s) + PEC_{kj}^s, \quad (17)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_1, \forall f_1 \in \mathcal{F}_1$$

$$EC_{k,jf_2}^h \geq (-M)(1 - u_{k,jf_2}^h) + PEC_{kj}^h, \quad (18)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_2, \forall f_2 \in \mathcal{F}_2$$

$$EC_{k,jf_2}^h \leq M(1 - u_{k,jf_2}^h) + PEC_{kj}^h, \quad (19)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_2, \forall f_2 \in \mathcal{F}_2$$

Constraint (20) links the energy delivered at slow-charger slots to the corresponding demand charge time slots, ensuring that DC_{k,jf_3}^s takes a value other than zero if EC_{k,jf_3}^s takes a value other than zero. Constraint (21) performs the same mapping for fast-charger slots, so that their energy use is also reflected in the respective demand periods. Constraints (22) and (23) guarantee that once a slow charging assignment

u_{k,jf_3}^s occurs, then the transfer of energy should be equal to DCP^s (for all slots f_3 , except for the last one).

$$DC_{k,jf_3}^s \leq M \cdot EC_{k,jf_3}^s, \quad (20)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_1, \forall f_3 \in \mathcal{F}_3$$

$$DC_{k,jf_3}^h \leq M \cdot EC_{k,jf_3}^h, \quad (21)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_2, \forall f_3 \in \mathcal{F}_3$$

$$DC_{k,jf_3}^s \geq (-M)u_{k,jf_3}^s + DCP^s, \quad (22)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_1, \forall f_3 \in \mathcal{F}_3: f_3 \leq FCS_{k,jz_{f_3}^s}$$

$$DC_{k,jf_3}^s \leq DCP^s + M \cdot u_{k,jz_{f_3}^s}^s, \quad (23)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_1, \forall f_3 \in \mathcal{F}_3: f_3 \leq FCS_{k,jz_{f_3}^s}$$

Constraints (24) and (25) ensure that when a charging session at a slow charger continues into the next demand charge time slots, the remaining energy requirement is correctly transferred forward (as discussed in [9]). Constraints (26) and (27) work similarly to (22) and (23) but for fast chargers. Constraints (28) and (29) guarantee that if charging at a fast charger extends into the following demand charge time slots, the remaining energy (RE_{kj}^h) requirement is accounted for in the next interval. Finally, Constraint (30) aggregates the total energy delivered across all slow and fast chargers in each demand charge time slots, providing the basis for computing the overall system demand.

$$DC_{k,jf_3}^s \geq (-M)u_{k,jz_{f_3}^s}^s + RE_{kj}^s, \quad (24)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_1, \forall f_3 \in \mathcal{F}_3: f_3 = FCS_{k,jz_{f_3}^s} + 1$$

$$DC_{k,jf_3}^s \leq RE_{kj}^s + M \cdot u_{k,jz_{f_3}^s}^s, \quad (25)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_1, \forall f_3 \in \mathcal{F}_3: f_3 = FCS_{k,jz_{f_3}^s} + 1$$

$$DC_{k,jf_3}^h \geq (-M)u_{k,jz_{f_3}^h}^h + DCP^h, \quad (26)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_2, \forall f_3 \in \mathcal{F}_3: f_3 \leq FCS_{k,jz_{f_3}^h}$$

$$DC_{k,jf_3}^h \leq DCP^h + M \cdot u_{k,jz_{f_3}^h}^h, \quad (27)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_2, \forall f_3 \in \mathcal{F}_3: f_3 \leq FCS_{k,jz_{f_3}^h}$$

$$DC_{k,jf_3}^h \geq (-M)u_{k,jz_{f_3}^h}^h + RE_{kj}^h, \quad (28)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_2, \forall f_3 \in \mathcal{F}_3: f_3 = FCS_{k,jz_{f_3}^h} + 1$$

$$DC_{k,jf_3}^h \leq RE_{kj}^h + M \cdot u_{k,jz_{f_3}^h}^h, \quad (29)$$

$$\forall k \in \mathcal{K}, \forall j \in \mathcal{N}_2, \forall f_3 \in \mathcal{F}_3: f_3 = FCS_{k,jz_{f_3}^h} + 1$$

$$DEC_{f_3} = \sum_{k \in \mathcal{K}} \sum_{j \in \mathcal{N}_1} DC_{k,jf_3}^s + \sum_{k \in \mathcal{K}} \sum_{j \in \mathcal{N}_2} DC_{k,jf_3}^h, \quad (30)$$

$$\forall f_3 \in \mathcal{F}_3$$

In Constraints (31) to (36), the modelling of peak demand charge is presented. Constraint (31) defines the per-period usage indicators for slow chargers by linking them to the assigned charging slots, ensuring that utilization in each demand charge time slots is properly captured. Constraint (32) establishes the same usage indicators for fast chargers, reflecting their activation across periods. Based on these indicators, Constraint (33) calculates the peak demand contribution from slow chargers in each demand charge time slots $f_3 \in \mathcal{F}_3$, while Constraint (34) performs the corresponding calculation for fast chargers. Constraint (35) then aggregates these contributions to obtain the total peak

demand across both charger types for each period. Constraint (36) ensures that variable $IP^{\max}$ takes the actual maximum value of peak energy demand across all time slots f_3 , as it has been recorded in TIP_{f_3} .

$$M \cdot \sum_{k \in \mathcal{K}} u_{k|z_{f_3}^s} \geq UD_{f_3}^s \geq m \cdot \sum_{k \in \mathcal{K}} u_{k|z_{f_3}^s}, \quad \forall j \in \mathcal{N}_1, \forall f_3 \in \mathcal{F}_3 \quad (31)$$

$$M \cdot \sum_{k \in \mathcal{K}} u_{k|z_{f_3}^h} \geq UD_{f_3}^h \geq m \cdot \sum_{k \in \mathcal{K}} u_{k|z_{f_3}^h}, \quad \forall j \in \mathcal{N}_2, \forall f_3 \in \mathcal{F}_3 \quad (32)$$

$$IP_{f_3}^s = \sum_{j \in \mathcal{N}_1} (CP^s \cdot UD_{f_3}^s), \quad \forall f_3 \in \mathcal{F}_3 \quad (33)$$

$$IP_{f_3}^h = \sum_{j \in \mathcal{N}_2} (CP^h \cdot UD_{f_3}^h), \quad \forall f_3 \in \mathcal{F}_3 \quad (34)$$

$$TIP_{f_3} = IP_{f_3}^s + IP_{f_3}^h, \quad \forall f_3 \in \mathcal{F}_3 \quad (35)$$

$$IP^{\max} \geq TIP_{f_3}, \quad \forall f_3 \in \mathcal{F}_3 \quad (36)$$

Constraint (37) enforces the state-of-charge feasibility of buses by requiring that, after completing their assigned trip and traveling to a charging station, the remaining battery level does not fall below the minimum state-of-charge threshold. This guarantees that every vehicle can safely reach a charger without violating operational energy limits.

$$SOC_k - e \cdot q_{kj} \cdot d_{kj} \geq SOC_k^{\min}, \quad k \in \mathcal{K} \quad (37)$$

Constraint (38) imposes capacity limits on charging station locations by ensuring that the number of chargers installed at any site does not exceed its predefined maximum capacity.

$$\sum_{j \in \mathcal{N}: \theta_j = v} x_j \leq Cap_v, \quad \forall v \in \mathcal{V} \quad (38)$$

Two formulations that are compared in this study

Given this MILP formulation in the current article two cases of problems are compared. The first is *Problem (Q)*, which solves the EB-CSLP when considering the charging scheduling constraints and is defined as follows:

Problem (Q):

$$\begin{aligned} & \text{Minimize } O_1 \\ & \text{s.t. Constraints (2) to (38).} \end{aligned}$$

And its solution will be compared to *Problem ($\hat{Q}$)*, which does not include the charging scheduling constraints (10) up to (13), and is defined as follows:

Problem ($\hat{Q}$):

$$\begin{aligned} & \text{Minimize } O_1 \\ & \text{s.t. Constraints (2) to (9), and (14) to (38).} \end{aligned}$$

CASE STUDY

To examine the proposed model and evaluate the distinct cases of planning when considering tactical planning and when not, we apply our proposed model to data from Manhattan, New York, United States.

Due to the limited availability of ToU tariff and demand charge data, this case study employs data from May 2017. A daily ToU tariff profile was constructed by integrating hourly load data obtained from the New York Independent System Operator (NYISO, [Website](#)) with average electricity prices per kWh reported by the U.S. Bureau of Labor Statistics ([Website](#)). The NYISO load data were statistically averaged and subsequently combined with

the corresponding average kWh prices for the same period to derive the ToU tariffs utilized in the analysis. Peak demand charge values were sourced from a report issued by the National Renewable Energy Laboratory ([Website](#)). For the operational context, data on the New York bus network during the study period were obtained from the openly available General Transit Feed Specification (GTFS) provided by TransitFeeds ([Website](#)) and the Metropolitan Transportation Authority (MTA). The case study focuses on bus lines M1 and M2 (Figure 1), and M4 (Figure 2) operating in Manhattan, New York. Since it is hard to know the exact number of buses required to run the services, we estimate this number by solving the Single Depot Vehicle Scheduling Problem (SD-VSP) [10] for the trips schedule available for the time under study. The solution to SD-VSP derives that 73 buses are needed overall to run the services for the three bus lines. So, in this case study we assume that 73 buses will need to charge evenly throughout the day at specific time points (τ_k).

We consider two types of chargers, slow and fast. At each candidate location, up to 6 chargers may be installed, 3 of which can be fast and 3 of which can be slow. The power output of slow chargers is 150kW, while for fast chargers it is considered 300kW. The maximum battery capacity of buses is considered 350kWh, and minimum allowable state of charge is 70kWh (20% of SoC_{max}). The time slots for slow chargers have a duration of 2 hours, and the time slots for fast chargers have a duration of 1 hour. The considered day span starts from 06:00 and ends at 24:00.

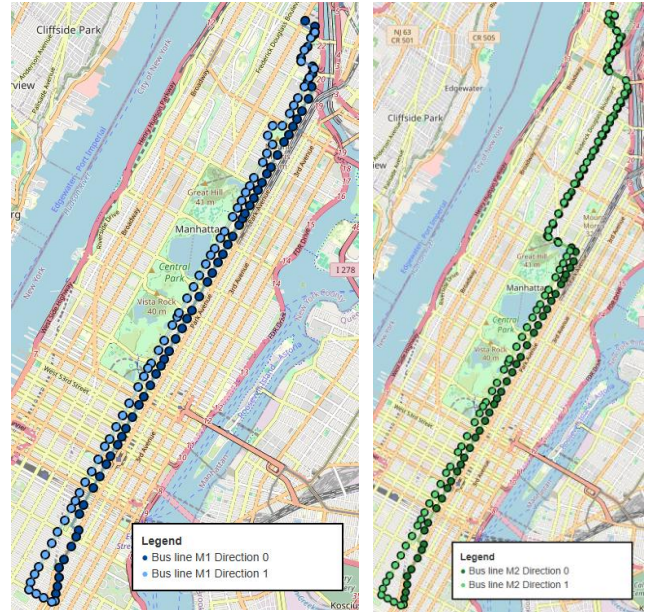


Figure 18: Bus lines M1 and M2 considered in the case study.

Information on bus depot locations was retrieved from publicly accessible sources. In Figures 3a and 3b, the study area is displayed, where candidate charging station locations are displayed with blue markers, and last stops of bus trips examined are displayed with orange markers.

For the solution of the proposed models for problems (Q) and ($\hat{Q}$) the academic version of Gurobi solver has been used, while the models have been implemented in Python. The models can be solved in a conventional consumer-grade laptop in a few minutes (<5).

The solution of problems (Q) and ($\hat{Q}$) provide useful insights on the importance of charging scheduling when applied to a considerably sized bus network of three bus

lines for Manhattan, New York. Both solutions, as they are presented in Tables 1 & 2, calculate the optimal number, location, and type of charger, as well as an assignment of buses to the charger and their respective time slots.



Figure 19: Bus line M4 considered in the case study.

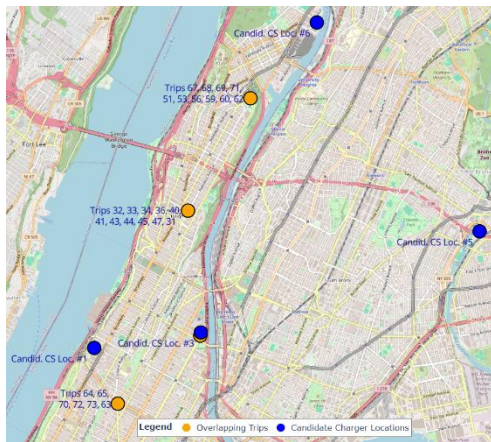


Figure 20a: Upper side of Manhattan, where candidate charging stations are displayed in blue color and bus trips last stops are displayed in orange.

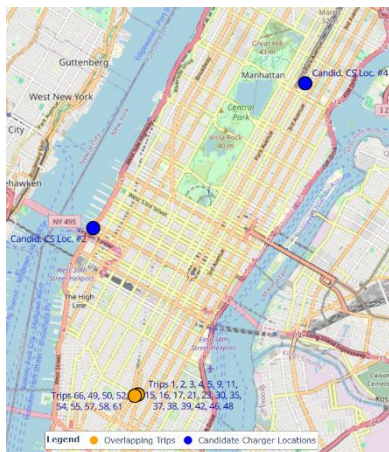


Figure 3b: Lower side of Manhattan, where candidate charging stations are displayed in blue color and bus trips last stops are displayed in orange.

Based on this discussion, in Table 1, it can be observed that the solution to the problem with charging scheduling constraints proposes the installation of 10 chargers in the study area to serve the 73 bus trips that require recharging, for bus lines M1, M2 and M4. In the columns of Table 1, one may notice that the chargers are selected for locations #1, #2, #3 and #6, while in the rows of the table, it can be observed that the time slots that the buses get assigned to. For example, bus 2 gets assigned to a fast charger at location #2 (check Figure 3b), at time slot 13:00 to 14:00. In the same way, bus 55 is selected to charge at a slow charger at location #2, and occupies one 2-hour slot from 16:00 to 18:00 (two consecutive one-hour time slots in Table 1). Finally, for this solution to the problem with charging scheduling constraints the objective function value is 312,171.36 dollars, while the deadhead time is 518.74 minutes.

Table 1: Solution derived for Problem (Q) with charging scheduling constraints.

Time Slots	Chargers Selected for Location #1			Chargers Selected for Location #2			Chargers Selected for Location #3		Loc. #6
	Slow	Slow	Slow	Slow	Fast	Slow	Fast	Fast	
13:00-14:00	-	-	-	-	50	-	2	-	-
14:00-15:00	3	-	-	49	4	1	52	32	31
15:00-16:00	3	-	-	49	30	1	5	6	33
16:00-17:00	34	-	-	54	35	55	9	8	7
17:00-18:00	34	-	-	54	37	55	58	13	10
18:00-19:00	11	59	57	38	15	39	16	12	14
19:00-20:00	11	59	57	38	61	39	17	20	18
20:00-21:00	44	40	41	64	23	63	42	22	24
21:00-22:00	44	40	41	64	66	63	21	26	19
22:00-23:00	69	45	47	65	70	25	46	27	28
23:00-24:00	69	45	47	65	48	25	72	73	29

Moving on to the presentation of Table 2, one may notice that the solution to the Problem ($\hat{Q}$), that does not consider the charging scheduling constraints, includes the installation of a considerably smaller number of chargers. More specifically, in Table 2, a solution of 7 chargers is proposed, 5 of which are slow and 2 of which are fast. As can be seen in Table 2, that follows the same format with Table 1 of the solution of Problem (Q), three slow chargers are proposed to be installed at location #1 (see also Figure 3a). One slow and one fast charger are proposed for location #2, while one fast charger is proposed at location #3 and one slow for location #6. Overall, the solution presented in Table 2, yields an objective function value of 151,227.47 dollars, and a deadhead time of 405.43 minutes.

If one closely inspects Tables 1 and 2, they may find that except for the difference in the number of chargers proposed, the solution to problem ($\hat{Q}$) is able to spread the charging of buses through several time slots inside the day from 06:00 to 24:00, and thus being able to reduce the number of chargers required. On the other hand, this cannot happen for Problem (Q), since the charging scheduling constraints (10) to (13) require the charging of buses to happen based on parameters τ_k , p_k^s and p_k^h . There is also the difference in objective function values, where problem ($\hat{Q}$) that does not include the charging scheduling constraints, considerably underestimates the costs required to set up and operate a charging stations network for our

experiment of 73 buses across three bus lines in Manhattan. To add to that, the solution to model ($\hat{Q}$) not only underestimates the number and cost of chargers required to support the same electric bus fleet of 73 vehicles, but also yields a lower aggregate deadheading time, an outcome that cannot be regarded as plausible, when comparing to the solution of (Q).

Table 2: Solution derived for Problem ($\hat{Q}$) that does not include charging scheduling constraints.

Time Slots	Chargers Selected for Location #1			Chargers Selected for Location #2		Loc. #3	Loc. #6
	Slow	Slow	Slow	Slow	Fast	Fast	Slow
06:00-07:00	33	32	31	50	9	12	51
07:00-08:00	33	32	31	50	11	13	51
08:00-09:00	3	4	59	52	2	14	53
09:00-10:00	3	4	59	52	57	8	53
10:00-11:00	43	36	34	30	35	10	60
11:00-12:00	43	36	34	30	16	6	60
12:00-13:00	64	40	63	1	49	20	56
13:00-14:00	64	40	63	1	55	7	56
14:00-15:00	45	41	65	58	15	24	68
15:00-16:00	45	41	65	58	5	18	68
16:00-17:00	73	47	70	54	42	22	67
17:00-18:00	73	47	70	54	17	19	67
18:00-19:00	72	-	-	38	23	27	62
19:00-20:00	72	-	-	38	66	28	62
20:00-21:00	-	-	-	37	21	44	71
21:00-22:00	-	-	-	37	39	26	71
22:00-23:00	-	-	-	48	46	29	69
23:00-24:00	-	-	-	48	61	25	69

CONCLUSION

The results of this short paper aim to extend the existing body of literature on the EB-CSLP. Recent research has approached the EB-CSLP as an integrated optimization challenge, combining both strategic and tactical planning levels. The findings of this study further support this research direction by demonstrating the importance of explicitly accounting for charging scheduling at the disaggregate-level, where individual bus scheduling to time slots is considered. A key contribution of this paper lies in its use of real-world data from Manhattan, New York, thereby bridging the gap between theoretical models and practical applications. While scientific research increasingly develops advanced models that incorporate charging scheduling, it is common in real-world transport planning and business contexts that such detailed formulations are not adopted due to their perceived complexity. This paper demonstrates that such models are not only feasible in practice but also provide necessary and valuable insights that can inform more cost-effective and operationally efficient decision-making.

Future research could extend this work by formulating the EB-CSLP as a bi-level optimization problem [11], capturing the interaction between the electric bus operator and the energy management authority, particularly with green energy consumption. Furthermore, the inclusion of seasonal variations, such as changes in temperature, as well as fluctuating travel patterns, would enhance the realism and robustness of the planning model.

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The Simple Economics and Engineering of Electricity Markets

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Abstract—This paper proposes a transparent unifying modeling in support of energy transition. The approach introduces scalable zoom-in zoom-out representation of diverse engineering components in terms of a triplet of energy, power and rate of change of reactive power, named interaction variables associated with each system module. These variables are technology agnostic and are commonly understood by the engineers, economists, and policy makers. It is described how they can be used to establish protocols for integration of new technologies at value while ensuring reliable electricity services.

Keywords—protocols/standards, changing electric energy systems, electricity markets, forward markets, complete markets.

INTRODUCTION

This paper suggests that a systematic transition to sustainable energy services requires investing in right technologies and utilizing them the right way in real-time. This need creates new engineering challenges, because, given the intermittency of many renewable resources time-varying uncertain demand and supply imbalance must be managed in ways not currently practiced by the industry. Also, the delivery of power is becoming more difficult since the electric power grid was not built to support the resulting power flows. Nevertheless, as new resources are being added, the electricity service must remain reliable and affordable. At the same time, the climate change is causing more frequent failures of equipment. Hurricanes and fires, in particular, typically result in large loss of power grid equipment. It is hard to enable resilient service during such events because industry standards ensuring reliable service during normal conditions do not cover such extreme events. In Section II we briefly summarize the basic functions needed to provide electricity services. In Section III we describe major growing complexity of data-enabled decision making for supporting these functions. In Section IV we propose a simple unifying modeling of energy dynamics for managing this complexity. In Section V we review problems of aligning engineering innovation and market design, and in Section VI propose a unifying energy-based market design for achieving this. In Section VII concluding remarks are made by claiming that this simple energy dynamics-based unifying approach to engineering and economics supports the overall change of industry operating and planning paradigm.

BASIC FUNCTIONS COMPRISING ELECTRICITY SERVICE

Providing reliable and resilient electricity service can be conceptualized by identifying several key functions which must be performed [1]. The functions complement each other over time as the system conditions vary and their decomposition depends on predictions given and the actual methods used to perform them.

Basic functions underlying electricity service

Shown in Figure 1 is a typical daily system load profile, and its decomposition into predictable, controllable and/or uncontrolled parts. Today's hierarchical control by the modern energy management systems (EMS) is based on decomposing this load into its predictable components, and hard-to-predict components. The basic Step 1 requires feed-forward scheduling to balance predictable system demand component. The scheduling must be done to produce more energy so that thermal energy losses in the transmission and distribution (T&D) grid are compensated, and the full load is still served, Step 2. Computer applications in EMS are more complicated when performing Steps 1 and 2, because of required grid congestion management, Step 3. This means that scheduled resources for delivering power to predicted system load, must do so only within allowed operating limits (thermal line flows, voltages). Unfortunately, methods for voltage profile scheduling as system conditions vary have not been standardized and continue to be one of the major causes of systemwide blackouts [2]. Next, Step 4 concerns functions for balancing hard-to-predict deviations from the power profile for which schedules were done. Generally, fast-responding equipment, gas power plants and fast storage, are designed to in a feedback way respond to deviations in frequency and voltage caused by these hard-to-predict power imbalances. They are expected to regulate and stabilize frequency and voltage within the limits determined by the industry standard. As an example, automatic generation control (AGC) is required to maintain frequency by ensuring that the Area Control Error (ACE), representing accumulated energy deviations in between schedules, crosses zero at least once. This way frequency will not deviate excessively due to hard to predict power imbalances. Notably, this CPS1 standard is derived assuming that hard-to-predict load portion has almost zero mean value within the scheduling interval, which is no longer the case in systems with intermittent resources. Voltage deviations are result of deviations in reactive power away from its predicted profile, and have long been managed using automated voltage control in France, Spain, Italy, and, more recently in China.

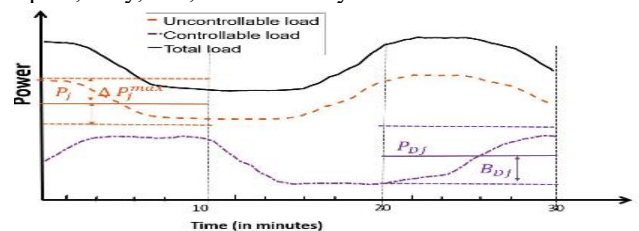


Figure 1 Decomposition of system load

Steps 5 and 6 concern major equipment failures and methods for ensuring uninterrupted service for at least 30 minutes following such events. Ensuring reliable service during such events is difficult, and costly. Today's industry approach is to keep generation and T&D reserves in preventive way for what is perceived to be the worst case equipment failure. Ensuring resilient service during many equipment failures caused by extreme conditions is practically impossible by redundant system hardening. As a result, it becomes necessary to predict system conditions as they evolve and have computer applications to advise operators how to manage in a corrective, not preventive, way what is still left on the system. This is the major reason for flexible management in the changing industry. The new normal will be power balancing under uncertainties.

MAJOR GROWING COMPLEXITY OF DATA-ENABLED ELECTRICITY SERVICES

Time varying power imbalances and the related grid delivery problems brought about by uncertainties of system conditions require much more reliance on situational

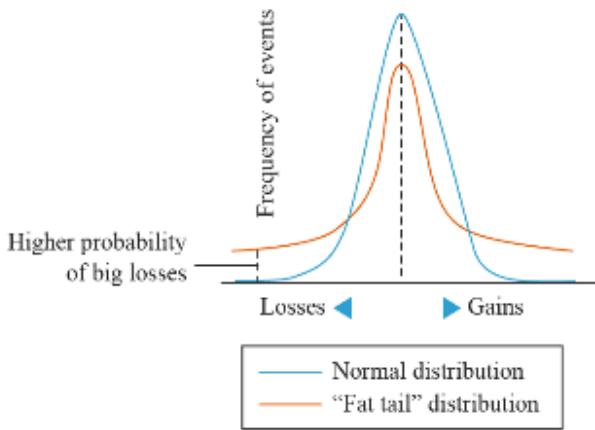


Figure 2: Minimizing blackouts

awareness, timely predictions of changes and decision making tools to adjust as quickly as possible. Given assumptions embedded within today's computer applications for feedforward decision making, and automation for feedback control, it is hard to guarantee service by relying on these. The commonly made assumptions are decoupling of real and reactive power, validity of linearized models, and weak tie-lines between utilities. It is fairly straightforward to create counter-examples to validity of these assumptions, and, as a result not having confidence that today's hierarchical control can manage rapidly changing industry. Consequently, the pressure is increasing on humans in the loop to make decisions during low probability high impact events. The hope is that this challenge would be met by using AI/ML, but these tools are at best work in progress at this point in time. One way forward would be to enhance the existing decision tools and automation. Shown in Figure 2 is how enhancing data-enabled decision tools and automation can significantly help with localizing the effects of system condition changes on the number of electricity users served during such events. The orange plot depicts frequency of events and the number of customers affected. It can be seen and it is documented in many papers that the probability of large number of customers losing service is not negligible. The blue curve shows the same, when appropriate control actions are taken to localize the effects of equipment failures. In short, very important, the data-enabled enhanced scheduling software and automation can reduce

the impact of equipment failures significantly by adjusting all controllable equipment in anticipation of these events.

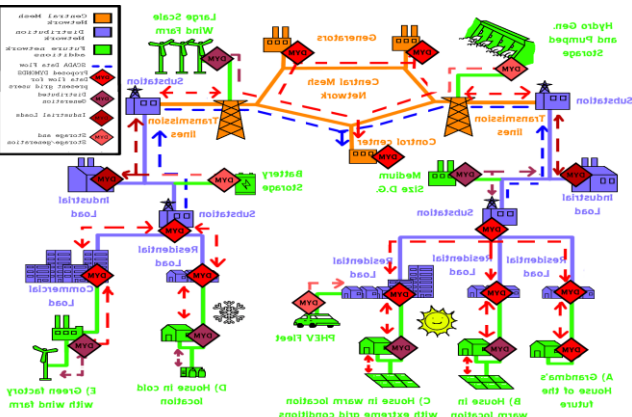


Figure 3: Next generation SCADA: DyMonDS [3]

Consider an end-to-end electric power system, shown in Figure 3. It can be seen that equipment comprising this system is very heterogeneous; it includes very large conventional power plants, hydro, nuclear, fossil, supplying large aggregates of electricity users at the substations, by delivering power in bulk power grid; the substations are connected by distribution grids to lower voltage level electricity users, all the way down to households. More recently clusters of small end users or some larger commercial users, municipalities, energy communities, such as shopping malls, large industrial complexes, airports, and alike, have begun to plan and operate as microgrids. This is leading to an end-to-end electrically interconnected grid, with many distributed energy resources (DERs), such as solar roof tops, responsive electricity users, EV charging stations, combined heat and power (CHP) supplying power to universities, and alike. Some of these resources at times produce more than they locally need, and send power back to utilities.

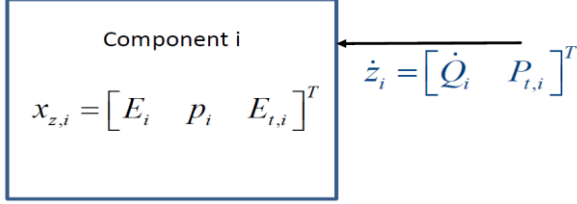
Protection relay logic needs to change to safeguard power grid even when power flows back to utilities. This could be a major under-taking, and, instead, utilities set limits on power which can be sent back. This in turn requires more adaptive automation by solar PVs and other DERs so that they can send limited power from intermittent resources. There have already been instances of DER damages caused by inadequate control. These problems are likely to grow in complexity and numbers as more DERs get deployed, unless carefully designed protocols for integrating them into utility system are established.

FROM COMPLEXITY TO STRUCTURE: ENERGY DYNAMICS

Currently used mathematical models for simulating, analyzing and controlling large-scale electric power grids have evolved over time. At first, conventional power plants have been viewed as the only dynamic controllable components, T&D equipment has been modeled as RLC impedances interconnecting generators and loads, and loads have been represented by estimating their consumed real and reactive power. These models are routinely used for scheduling generation to supply predictable component of system load, Steps 1-3 described in Section II above. These equipment models are subject to real and reactive power constraints, resulting in high-order nonlinear Differential Algebraic Equations (DAEs) [4]. Much effort has gone into simulators based on these models,

particularly for assessing off-line if the worst case equipment outages are transiently stable. More recently, modeling of electromagnetic transients (EMT) in T&D and in power electronically switched inverter based resources (IBRs) has led to another level of complexity since these dynamics can be excited by the fast varying

Table 1 Aggregate energy dynamics model



New unified model in energy space:

$$\begin{aligned}\dot{E}_i &= -\frac{E_i}{\tau_i} + P_i = p_i & E_i(0) &= E_{i,0} \\ \dot{P}_i &= 4E_{ti,i} - \dot{Q}_i & P_i(0) &= P_{i,0} \\ \dot{E}_{ti,i} &= -\frac{E_{ti,i}}{\tau_i} + P_{ti,i} & E_{ti,i}(0) &= E_{ti,i,0}\end{aligned}$$

intermittent resources. Not surprisingly, these additional granularity is leading to effectively non-scalable models and the need for rethinking how to manage the overall complexity. Needless to say, these models derived for simulating dynamic response are not in the form which lends itself to designing system control. Also, the industry standards set for the integration of different equipment do not ensure that the desired performance would be met. This is a largely overlooked issue which represents the key road block to integrating innovative solutions, hardware and software, into the changing systems with some confidence.

As one way forward, we summarize in this paper our approach to managing complexity by taking a step back and recognizing inherent structure of equipment models. We show that, based on this structure, it becomes possible to establish models of different granularity for different purposes. When designing technology-specific equipment and its internal local feedback control, very detailed models are needed to specify the ability of equipment to produce/consume power at certain rates. Given these specifications, it becomes possible to establish zoom-out technology-agnostic models of large-scale interconnected systems and assess their performance and design transparent coordinating control for ensuring the desired system performance. We review this structure next.

A. Unifying structure of models: Use of physical states

A close look into the dynamic models of energy conversion technologies in typical electric power system equipment reveals that their detailed dynamic models are basically a result of writing the First Law of Thermodynamics (FLT). Fundamentally, this conservation of energy law states that the rate of change of stored energy dissipates internally as power is sent to the module, according to

$$\frac{dE_i(t)}{dt} = -\frac{E_i(t)}{\tau_{ui}} + p_i(t) \quad (4)$$

The first term stands for thermal losses due to damping. To derive the commonly used model of generator, kinetic stored energy E in its rotor is expressed in terms of speed and inertia, and when applying FLT given in Equation (1),

one obtains the well-known swing equation of the generator.

A more complicated model of a synchronous generator can similarly be obtained starting from the same fundamental equation. Since the stored energy is a function of its own physical variables only, denote these as $x_i(t)$ for equipment component i , it can be shown that dynamical model of any energy conversion technology takes on the same structural form [5], given initial conditions for the state variables $x_i(t_0) = x_i(0)$.

$$\frac{dx_i(t)}{dt} = f_i(x_i(t), u_i(t), m_i(t), p_i(t)) \quad (2)$$

The DAE models of interconnected power grid are next obtained by stating these dynamical models for all components and writing the power flow constraints. The same structure is obtained for equipment based on multi-energy conversion. At present these models are routinely used for most of the analysis and simulations. While the structure given in Equation (1) helps model many components of different types, the scalability problem becomes a major problem in interpreting the results, and, even harder for designing controllers which guarantee performance of the interconnected system. An unfortunate way out of these problems has been to over-design hardware and not to rely on control in any significant way. Given that control becomes key to flexible operation under uncertainties, Figure 2, it is necessary to begin to rely on control co-design approaches, making the grid smart, instead of on only making the grid strong. The key question then becomes how to proceed. In what follows we propose a unifying multi-layered modeling using aggregate energy dynamics and exploring its structure.

B. Unifying structure of complex multi-layered power systems models: Use of energy dynamics

To start with, any system component, subsystem, referrer to from here on as *module*, can be represented by its energy dynamics given in Equation (1) above. However, existence of physical systems requires to account for entropy increase according to Second Law of Thermodynamics (SLT); not all work produced by the module can be sent to the rest of the system and we must distinguish between rate at which maximum work can be produced, known as the energy in tangent space, and the power which actually enters/exits the module. The rate of change of actual power $p_i(t)$ into the terminals of module i can be shown to be related to the rate of change of energy in tangent space $E_{ti}(t)$ as [6]:

$$\frac{dp_i(t)}{dt} = 4 E_{ti}(t) - \frac{dQ_i(t)}{dt} \quad (3)$$

Equation (2) can be interpreted as one way of expressing SLT for energy systems. Rate of change of reactive power $\frac{dQ_i(t)}{dt}$ accounts for the entropy-like loss of rate of power, or axergy. Given the flow/effort analogies in different types of energy systems, this quantity also has physical meaning not only in electric power grids but in any type of energy conversion.

Shown in Table 2 are defining terms of all the variables used in these models for inductor and capacitor modules whose flow and effort are $f(t)$ and $e(t)$, respectively. Summarized in Table 3 is the 3rd order model of aggregate energy dynamics.

Perhaps the most important for composing scalable models of complex energy systems is the observation that when using energy dynamics the model of energy conversion is linear and the interaction variables is the only part of the model which depends on the rest of the system, Table 4. According to generalized Tellegen theorem, when writing the model of the interconnected system the interaction variables must balance at the points of interconnection.

Perhaps most important for enabling interactive scalability in complex energy systems is the observation that the energy dynamics model of any module i takes on technology-agnostic form shown in Table 3. The expression for aggregate variables are technology specific, and their physical dynamical variables are shown in Equation (2). This zoom-out model of the module is third order, but the order and complexity of different components given in the form of Equation (2) are very complex and much higher order. It can be further shown that the interaction variables have very unique structural properties, since they are constant when the module is disconnected from the rest of the system.

Table 2: Module i characterization of energy dynamics [6]

Definitions	Inductor	Capacitor
Stored energy: $E_i = \int_{b_i(t_0)}^{b_i(t)} a_i(b_i(t)) db_i$	$E_i = \int_{i_i(t_0)}^{i_i(t)} \psi_i di_i = \frac{1}{2} L_i i_i^2$	$E_i = \int_{v_i(t_0)}^{v_i(t)} q_i dv_i = \frac{1}{2} C_i v_i^2$
Stored energy in tangent space: $E_{i,j} = \int_{b_{i,j}(t_0)}^{b_{i,j}(t)} a_{i,j}(b_{i,j}(t)) db_{i,j}$	$E_{i,j} = \int_{i_{i,j}(t_0)}^{i_{i,j}(t)} \psi_{i,j} di_{i,j} = \frac{1}{2} L_i \left(\frac{di_i}{dt} \right)^2$	$E_{i,j} = \int_{v_{i,j}(t_0)}^{v_{i,j}(t)} q_{i,j} dv_{i,j} = \frac{1}{2} C_i \left(\frac{dv_i}{dt} \right)^2$
Time constant: $\tau_i = \frac{E_i}{P_i}$	$\tau_i = \frac{L_i}{2R_i}$	$\tau_i = \frac{R_i C_i}{2}$
Instantaneous real power: $P_i = \langle e_i, f_i \rangle = v_i i_i$	Instantaneous reactive power: $\dot{Q}_i = \langle e_i, \dot{f}_i \rangle - \langle \dot{e}_i, f_i \rangle = v_i \frac{di_i}{dt} - \frac{dv_i}{dt} i_i$	

Linear model in energy space:

$$\dot{x}_{z,i} = A_{z,i} x_{z,i} + B_z \dot{z}_i$$

$$x_{z,i}(0) = x_{z,i,0}$$

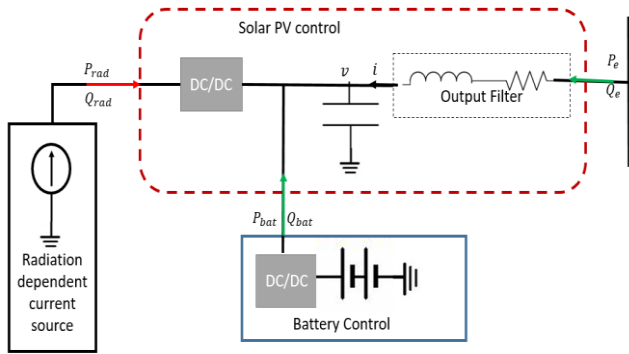
$$A_{z,i} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 4 \\ -\frac{1}{\tau_i} & 0 & 0 \end{bmatrix} \quad B_z = \begin{bmatrix} 0 & 0 \\ -1 & 0 \\ 0 & 1 \end{bmatrix}$$

Table 3: Dynamic model in energy space [7]

It can be further shown that their rate of change depends solely on internal state variables given initial conditions for the state variables $x_i(t)$ and their rate of change $\frac{dx_i(t)}{dt}$. These properties set the basis for specifying modules in terms of their interaction variables only when composing the dynamic model of the interconnected system. These models further lend themselves to distributed control design of local automation $u_i(t)$ in Equation (2) needed to specify the interaction variables. These properties are key to coordinating control co-design for provable performance [7,8]. Instead of starting with very complex physical models, each module provides information about the ranges of its rate of change of interaction variable,

and can be tested for this in a stand alone mode. The vendors/manufacturers do not have to provide information to system operators/planners about the detailed internal physical dynamics given in Equation (2), they can design the technology specific internal control $u_i(t)$ which observes internal constraints, and have a choice regarding the complexity of these controllers so that they can guarantee the specified ranges of their interaction variables and, at the same time stabilize/regulate their internal output variables of interest $y_i(t)$, so that it is stabilized locally and regulated to desired reference.

We observe that this is where major innovations are needed in the changing electric energy systems. For example, in systems with IBR-based wind- or solar- power plants, the technology-specific control design would require controller which for given ranges of interaction variable (power, rate of change of reactive power) also stabilizes/regulates frequency and voltage at the point of interconnection to acceptable operating values. Today this control design is work in progress. Once the specifications/testing of interaction variables are provided by vendors, it is necessary to perform the system level tests regarding reliability (existence of equilibria, stability, no resonance between modules). Viewed from the control point, if interaction variables are controlled/specified, it can be seen from Table 4 that this becomes a coordination problem of linear dynamic systems, subject to Tellegen's type constraints, which are linear in energy dynamics. Inter-operability tests are then obtained using well-known dissipativity and passivity conditions for linear systems. If conditions are not met, system operator may require additional coordination, and fast storage controllers to be added. As an illustration of such physically intuitive condition, consider a small system of generator connected to intermittent DER. An intermittent DER creates load variations whose ranges must be given in terms its interaction variable, instantaneous power and rate of change of reactive power. Generator specifies its interaction variable, and the transmission line also specifies its interaction variable at the sending and receiving ends. Recently derived sufficient condition for existence of equilibria in this system establishes the inequality which states that maximum rate of change of load interaction variable must be bounded by a combination of rates of change of generator's interaction variable and that of the transmission line [8]. This physically intuitive result helps system designer to understand if the rates at which power is provided can balance. Arriving at such provable bounds when using complex DAE models is practically impossible. Notably, careful technology specific local control design of modules is critical for having provable performance. Shown in Figure 4 is a sketch of such control design for solar PV with battery control.



EnergySpace Model:

$$E(t) = P_{rad}(t) + P_{bat}(t) + P_e(t) - \frac{E(t)}{\tau} = p(t)$$

$$\dot{p}(t) = 4E_t(t) - \dot{Q}_{rad}(t) - \dot{Q}_{bat}(t) - \dot{Q}_e(t)$$

$$\text{Here, } E(t) = \frac{1}{2} Li(t)^2 + \frac{1}{2} Cv(t)^2$$

- The power electronics switch control of battery can be so designed that would ensure

$$P_{bat}(t) = -P_e[n] + P[n] - K_F^P(i_F(t) - i_F^{ref}[n]) - K_V^P(V(t) - V^{ref}[n])$$

$$Q_{bat}(t) = -Q_e[n] + Q[n] - K_F^Q(i_F(t) - i_F^{ref}[n]) - K_V^Q(V(t) - V^{ref}[n])$$

$$\text{Coupled Droop: } \alpha \Delta P[n] + \beta \Delta Q[n] = \Delta V[n]$$

Figure 4 Battery controller for solar PV in energy space

C. Some examples of energy dynamics modeling and control; relations to today's droop control

As shown in Figure 4 for the case of solar PV component, each module has fast complex dynamics, in this case filter dynamics and power electronics switching. When posing the local control problem, battery control in this example, it can be seen that fast control of energy dynamics could be made such to stabilize filter dynamics and result in coupled droop characteristic shown. Today's approach often neglects the fast filter dynamics and adds digital control droops. It can be seen from Figure 4 that careful local power electronics switching design could lead to coupled *physical* droop. Many open questions remain concerning the tuning of digital droops currently used so that they are aligned with the physical coupled droop.

PROBLEMS OF ALLIGNING ENGINEERING AND MARKETS

It can be concluded based on the engineering challenges described that in order to ensure provable performance in the changing electric energy systems, the next generation primary control will be needed. For new modules to be integrated in these systems, they need to be characterized and tested for ranges of energy, power and rate of change of reactive power they can provide/consume. At the same time their controllers should stabilize and regulate local outputs of interest.

However, making the modules *smarter* generally costs more and vendors are reluctant to do so, unless there are explicit mandates in regulated systems, and/or market incentives in systems undergoing restructuring. Current interconnection standards are not sufficient to ensure that new systems will perform reliably, as experienced very recently in the European blackout [2].

A. Lack of two sided market incentives

Today's electricity markets are by and large one-sided, and demand does not participate. This requires many make shift market rules for making resources whole, price caps for preventing excessively high prices, etc. Also, there are no market incentives for voltage support at value. As

documented in several worldwide blackouts, not supporting voltage profile as system conditions vary has become one of the major causes on their occurrence. Important for the changing systems with large amounts of renewables, voltage control in IBR-based resources is becoming key as fossil plants retire, requiring market incentives.

B. Lack of market incentives for managing short-term uncertainties: Operating problem

Functions 4-6 concern electricity service under uncertainties. These can be deviations in power from predicted, and/or unexpected equipment failures. They are critical for ensuring reliable service during such hard-to-predict system changes and are provided by requiring stand-by, preventive reserves, just in case the worst case outage occurs. This is very conservative and costly. In addition, there is not much reliance on controlling production by intermittent resources as they are often viewed as uncontrolled uncertain load, requiring even more preventive reserves. Providing preventing reserve is still based on strictly engineering criteria, and there are no market incentives for reliability.

Markets consider functions other than 1-3 under a general notion of *ancillary services*. These are intended to support hard to predict deviations in demand. However, the distinction between function 4 (frequency and voltage regulation), on one hand, and supplying reliable service during large equipment outages, functions 5 and 6, on the other hand, is at best gray. The cost is socialized and no market incentives exist for providing electricity service at value under uncertainties. In particular, there are no mechanisms in place, such as blackout costs, for providing incentives to market participants to manage uncertainties.

C. Lack of markets for managing long-term uncertainties: Planning problem

In today's markets planning for resource adequacy is somewhat disjoint from operations, although it is well known that determining near-optimal investments requires transparent signals for decision making under various physical and financial uncertainties. Capacity markets are not sufficiently liquid to value multi-temporal uncertainties. Shown in Figure 5 are market participants and their inter-dependencies.

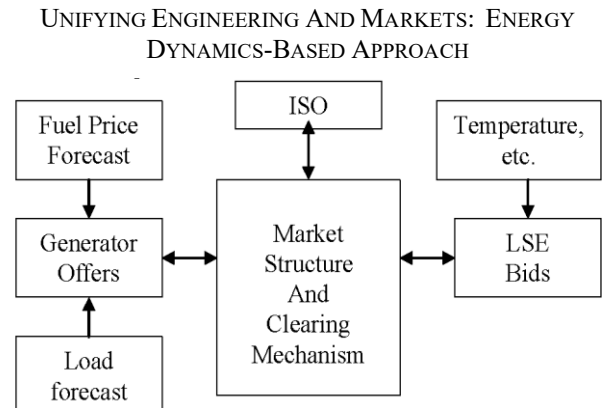


Figure 5: General energy market [9]

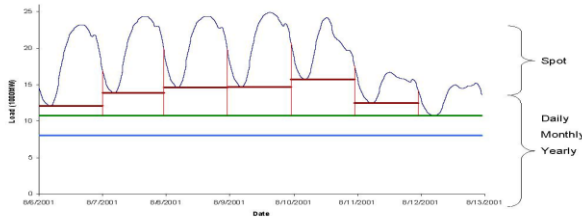


Figure 6: Stratum Energy Market [9]

The above are just some of the examples of current market design issues. One way forward would be to streamline market design by defining market derivatives in terms of interaction variables only, energy, power and rate of change of reactive power. This will uniquely support electricity service using transparent commonly understood engineering specifications. Moreover, these specifications should be part of the bidding process. One possible approach to supporting management of multi-temporal uncertainties is to introduce a set of coordinated forward energy sub-markets each defined for specific time horizon ranging across day-, month-, season-, year-, and five year-horizons, proposed some time ago as a Stratum Energy Market (SEM)[9].

Simple economic signals defining bids which go with stratum of rates of change of interaction variables can form the complete set of multi-temporal market derivatives. This way the engineering and economic characterization align. Seemingly very diverse stakeholders provide transparent unifying bids for selling and/or purchasing the three market derivatives, energy, ranges of power and ranges of rate of change of reactive power. We recall that it is not necessary to reveal internal physical dynamics and local control design, for having systematic control co-design in support of delivering electricity service reliably and at high quality. The same way, it is not relevant for a SEM to know what type of resource provides these market derivatives. Shown in Figure 6 is a market sketch in which stakeholders provide bids for all three market derivatives, energy, power and rate of change of reactive power. In what follows we briefly describe how this approach would overcome most of the problems with today's markets.

Overcoming lack of two sided market incentives

This basic problem is created by the asymmetric characterization of supply and demand. This problem is straightforward to overcome by requiring all stakeholders to characterize their interaction variables in a feedforward manner for all time horizons comprising SEM. Adaptive load management (ALM) was proposed some time ago for demand participation at value in DAM and RTM. The bids are for energy, both supply and demand. Stakeholders create these bids according to their own sub-objectives. Both gaming and risk management are minimized this way, and there is no need for price caps which distort markets. Our MIT Dynamic Monitoring and Decision Systems (DyMonDS) Digital Twin was recently used to simulate and compare outcomes with and without demand participation.

Overcoming lack of incentives for managing short-term uncertainties: Reliable operations

In operations physical power deviations lead to frequency and voltage deviations outside the ranges allowed by protection relays, and can result in wide-spread blackouts. It is necessary to understand how market derivatives characterizing ranges of power deviations can be used to avoid the resulting frequency problems. To explain this, we refer to an early paper which proposed a power exchange market for frequency control (PXFC) by suggesting that bids for frequency control should be in terms of incremental power and its cost [10]. If ranges of hard-to-predict demand power deviations around predictable patterns are specified (market derivative for frequency control) are specified, ranges of fast responding power needed to balance these deviations are offered as frequency-power droops, it is straightforward to determine how many *units* of frequency regulation would be needed to keep the system frequency within a pre-defined small threshold away from nominal frequency [10]. Droop characteristics of resources are units of power for frequency regulation and once these are specified, this information becomes sufficient to estimate how many of these units are needed. Notably, not all types of resources respond at the same rate, and they are paid only for the units they can provide. Shown in Figure 7 are the demand characterization and supply bids, as sufficient for supporting frequency regulation through market incentives.

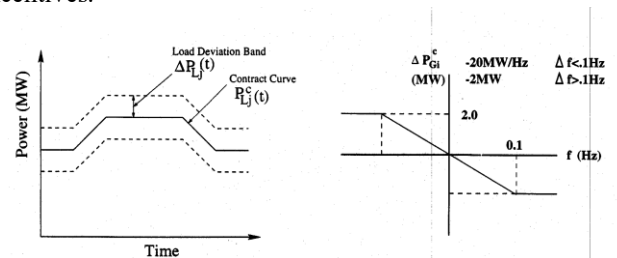


Figure 7: Demand and supply power specifications [10]

This is an important paper supporting the idea that frequency regulation at value only requires specification of power deviations away from energy patterns. The market derivative specifying rates of change of reactive power still needs to be introduced. The basic premise is that determining supply and demand for reactive power balancing at the right rate is necessary to ensure that IBR-based DERs participate in voltage/reactive power system support.

Overcoming lack of incentives for managing long-term uncertainties: Stratum Energy Market

Implementing market incentives in support of longer term resource adequacy is a natural combination of proposed SEM and complete market derivatives proposed for spot markets using energy dynamics. These derivatives need to be specified in a forward manner by all stakeholders. As explained and illustrated in the early SEM paper [9], such design supports seamless multi-temporal risk sharing when planning for future longer term investments. Important, the problem of missing money disappears. The longer forward time horizons in the SEM, more incentives provided for large investments at value.

CONCLUSIONS AND FUTURE WORK

In this paper we propose a unifying approach to streamlining engineering innovations and market design in support of changing societal needs for reliable, affordable and clean electricity services. The basic idea is to model multi-layered complex energy systems using energy dynamics, instead of requiring full knowledge of specific technologies and their internal automated control. All system components are characterized in terms of their interaction variables (energy, power, and rate of change of reactive power) when assessing their ability to participate in physical delivery and in providing their economic value. Technology specific designs are left to vendors/manufacturers and are not needed for achieving system-level performance. We are in the process of designing a DyMonDS Digital Twin to demonstrate potential benefits from this approach. Notably, the approach is a natural outgrowth of today's AGC performed by Balancing Authorities (BAs), where ACE is becoming more granular temporally and spatially to support intelligent Balancing Authorities (iBAs).

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Optimizing Energy Efficiency and Order Admission in Single-Stage Production Systems for Two Customer Classes

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Abstract—Improving energy efficiency in manufacturing is a critical challenge, driven by both environmental concerns and economic pressures. This research explores the benefits of integrating customer admission policies with production control strategies, considering energy costs and consumption.

We focus on a single-stage manufacturing system that produces one type of item for two distinct customer classes. Customer orders are accepted or rejected based on the system's current state. The production facility can be in various operational modes—working, idle, off, or undergoing setup—each with different energy consumption levels. The core production control problem is to decide when to activate the facility and whether it's more cost-effective to turn it off instead of leaving it idle. The goal is to minimize an average profit rate function that incorporates revenue from sales, inventory costs, backlog penalties, and energy-related expenses.

To model this system, we use a Markov decision process and employ the value iteration algorithm to determine the optimal policy that maximizes the average profit rate. Our numerical studies reveal the structural properties of this optimal policy.

Keywords—Energy Efficiency, Production Systems control, Markov decision processes

INTRODUCTION

In an era where environmental consciousness and energy security are pivotal societal priorities, industrial enterprises must embrace energy-efficient manufacturing practices to maintain a sustainable competitive edge. Given the energy-intensive nature of manufacturing processes, it is essential to adopt strategies that not only address traditional performance metrics—such as inventory levels and backorders—but also emphasize the efficient use of energy in production. The integration of inventory and backorder management with energy-efficient operations presents a valuable opportunity for cost optimization, enhanced operational performance, and environmental sustainability.

The industrial sector is the largest consumer of energy and the highest emitter of CO₂ among end-use sectors. Globally, manufacturing and industrial systems account for over one-third of total energy consumption and are directly responsible for more than 45% of global CO₂ emissions [1].

Therefore, reducing energy usage in energy-intensive production processes is both necessary and urgent. Historically, manufacturing research has focused on productivity, quality, and cost, often overlooking energy consumption. However, productivity and energy use are closely linked. Achieving sustainable manufacturing requires a holistic approach that integrates energy efficiency with productivity—especially critical during periods of energy scarcity.

A key contributor to elevated energy consumption, as identified in the literature, is energy loss during non-productive periods, such as idle times and setup phases [2]. In this context, production control policies that minimize idle time can significantly enhance energy conservation. From an economic perspective, manufacturers can reduce energy costs by implementing energy-saving practices. It has been noted that in many manufacturing environments, energy consumption during idle periods can be nearly as high as during active production [3]. Thus, avoiding unnecessary downtimes is a practical and effective strategy for improving energy efficiency.

This paper investigates the structure of the optimal policy for single-stage production systems serving two customer classes. The objective is to integrate production, inventory, and order admission control in a manner that minimizes total costs arising from inventory holding, backorders, order rejections, and energy consumption.

The paper is organized as follows. Section 2 reviews relevant literature on optimal production, inventory, and order admission control, with a focus on energy efficiency. Section 3 outlines the problem formulation and the methodological approach adopted. Section 4 presents the numerical analysis of the optimal policy structure and the insights derived. Finally, Section 5 concludes the paper and discusses directions for future research.

BACKGROUND AND LITERATURE

A substantial body of literature addresses production control, inventory rationing, order admission control problems and energy consumption management. However, most existing studies treat these areas in isolation, often overlooking the interdependencies among these operations.

One relevant category of research focuses on integrated order admission and production control (see e.g., [4], [5]).

Another related stream of literature examines joint production and inventory rationing problems (see e.g. [6]). Inventory rationing refers to the allocation of limited inventory to satisfy demands from different customer classes (see also [7] and [8]).

As noted, studies that simultaneously address production control, order admission, and inventory rationing are relatively scarce. A notable exception is the work of Benjaafar, Elhafsi, and Hung in [9], which demonstrates that incorporating order admission control can significantly enhance system performance in inventory rationing contexts.

Energy consumption management—defined as the monitoring and reduction of energy use in manufacturing facilities—has also gained attention. A comprehensive review of energy efficiency and sustainability in manufacturing systems is provided in [10].

Improving energy efficiency in manufacturing is critical for several reasons: reducing operational costs, enhancing competitiveness, minimizing environmental impact, ensuring regulatory compliance, optimizing resource utilization, and increasing resilience to energy price volatility. One effective approach involves implementing control strategies that reduce energy consumption during non-productive periods. For instance, machines can be powered down when not in use and restarted just before production resumes. This practice conserves both energy and resources. Several studies have explored production control strategies that involve switching machines on and off to minimize total energy consumption [11], [12], [13].

Clearly, by coordinating production, inventory management, order admission, and energy consumption control, manufacturers can achieve more efficient and sustainable operations. This work focuses on an optimal control strategy that integrates these elements to minimize total system costs—including those associated with inventory, backorders, order rejections, and energy consumption—during the operation of a production system.

PROBLEM DESCRIPTION

We examine a single stage production system that produces a single item to satisfy demand from two different customer classes. Customers arrive at random times and each customer requests one unit of product. Customers of each class arrive according to Poisson processes with rates λ_i , $i = 1, 2$. Processing times are also independent random variables, exponentially distributed, with mean $1/\mu$. The production facility may be in one of the following four states:

Operating: the facility is producing items ($s = 1$).

Off: the facility is switched off and requires a setup procedure to start producing ($s = 0$).

Idle: The facility is currently not producing, but it is ready to resume production immediately ($s = 2$).

Setup: the system is preparing to return to its operational state and resume production ($s = 3$).

Setup times are also random and exponentially distributed random variables with rate σ .

The overall performance measure of the system is the mean cost rate. This quantity reflects costs associated with order rejections, inventory holding, backorders, and energy consumption. We consider four types of cost:

- r_i unit profit loss due to order rejection of class i customer (selling price less cost of purchasing raw parts and processing per item plus cost due to customer loss of goodwill, contractual penalties etc.),
- h unit holding cost rate (cost per unit time per finished item in the storage facility),
- b_i unit backlog cost rate for customers of class i (cost per unit time of delay of a pending order),
- c_s energy cost per time unit at state s , $s = 0, 1, 2, 3$.

We have made the assumption that 1st class customers are generally preferred over the 2nd class customers. This implies that $r_1 \geq r_2$ and $b_1 \geq b_2$. It is also reasonable to assume that energy consumption is greater when the system is operating, than when it is idle and of course energy consumption is minimal when the system is switched off, therefore $c_1 > c_2 > c_0$.

Dynamic Programming Modeling

The state of the system is described by the variables s , n , and k , where s is an integer which corresponds to the system's state ($s = 0$, when the system is switched off, $s = 1$, if it is operating, $s = 2$ when it is in idle state, and $s = 3$ if it is under setup), n is the inventory of finished items, when it is positive or the number of class 1 pending orders, when it is negative, and k equals the number of class 2 pending orders. The state space of the system is $X = \{(s, n, k) | s = 0, 1, 2, 3, n \in \mathbb{Z}, k \in \mathbb{Z}^+\}$.

The evolution of the system is driven by four types of events that may occur:

- Production completion: it is possible only when the production facility is in operating state.
- Setup completion: it may occur only when the production facility is under setup.
- Class 1 order arrival: it is always feasible.
- Class 2 order arrival: it is always feasible.

The decisions that can be made depend on the events occurring and the current state of the system. Table 1 presents a list of decisions associated with these events and system states.

Table 14: List of events and related decisions

Event	State	Decision
Production completion	1	Increase n , set $s = 0$
		Increase n , set $s = 2$
		Increase n , keep $s = 1$
		Reduce k , set $s = 0$
		Reduce k , keep $s = 1$
Setup completion	3	Set $s = 1$
		Set $s = 2$
Class 1 order arrival	0	Reject order
		Accept order, keep $s = 0$
		Accept order, set $s = 3$
	1	Reject order
		Accept order
	2	Reject order
		Accept order, set $s = 0$
		Accept order, set $s = 1$
	3	Reject order
		Accept order
Class 2 order arrival	0	Reject order
		Accept from inventory

		Accept, increase k
		Accept from inventory, $s = 3$
		Accept, increase k , $s = 3$
	1	Reject order
		Accept from inventory
		Accept, increase k
	2	Reject
		Accept from inventory
		Accept, increase k
		Accept from inventory, $s = 0$
		Accept, increase k , $s = 0$
		Accept from inventory, $s = 1$
	3	Accept, increase k , $s = 1$
		Reject order
		Accept from inventory
		Accept, increase k

The system's state may change only if one of the above events occurs. In such systems, an optimal policy is always a stationary state-feedback control policy. In this work we seek the optimal stationary policy.

Using the uniformization technique (see e.g. [14], [15]) the problem can be formulated as a Markov decision process. Let $v = \lambda_1 + \lambda_2 + \mu + \sigma$ be the uniform rate of event occurrence. Following the standard stochastic dynamic programming approach, we define $V_m(s, n, k)$ as the total expected cost over the first m events (decision stages) when the initial state is (s, n, k) . Then the Bellman equations for the optimal total expected cost over the first $m + 1$ events are

$$\begin{aligned}
V_{m+1}(s, n, k) = & \frac{1}{v} \{ h n^+ + b_1 n^- + b_2 k + u_1 [c_1 + \\
& \mu [I_k \min[V_m(s, n+1, k), V_m(s, n, k-1), V_m(s-1, n+1, k), V_m(s-1, n, k-1), V_m(s+1, n+1, k), V_m(s+1, n, k-1)] + (1-I_k) \min[V_m(s, n+1, k), V_m(s-1, n+1, k), V_m(s+1, n+1, k)]] + \\
& \lambda_1 \min[V_m(s, n, k) + r_1, V_m(s, n-1, k)] + \\
& \lambda_2 [I_n \min[V_m(s, n, k) + r_2, V_m(s, n-1, k), V_m(s, n, k+1)] + (1-I_n) \min[V_m(s, n, k) + r_2, V_m(s, n, k+1)]] + \sigma V_m(s, n, k) \} + \\
& + u_0 [c_0 + \lambda_1 \min[V_m(s, n, k) + r_1, V_m(s, n-1, k), V_m(s+3, n-1, k)] + \\
& \lambda_2 [I_n \min[V_m(s, n, k) + r_2, V_m(s, n-1, k), V_m(s, n, k+1), V_m(s+3, n-1, k), V_m(s+3, n, k+1)] + (1-I_n) \min[V_m(s, n, k) + r_2, V_m(s, n, k+1), V_m(s+3, n, k+1)]] + (\sigma + \mu) V_m(s, n, k) \} + \\
& + u_2 [c_2 + \lambda_1 \min[V_m(s, n, k) + r_1, V_m(s, n-1, k), V_m(s-1, n-1, k), V_m(s-2, n-1, k)] + \\
& \lambda_2 [I_n \min[V_m(s, n, k) + r_2, V_m(s, n-1, k), V_m(s, n, k+1), V_m(s-1, n-1, k), V_m(s-1, n, k+1), V_m(s-2, n-1, k), V_m(s-2, n, k+1)] + (1-I_n) \min[V_m(s, n, k) + r_2, V_m(s, n, k+1), V_m(s-1, n, k+1), V_m(s-2, n, k+1)]] + (\sigma + \mu) V_m(s, n, k) \} + \\
& + u_3 [c_3 + \lambda_1 \min[V_m(s, n, k) + r_1, V_m(s, n-1, k)] + \lambda_2 I_n \min[V_m(s, n, k) + r_2, V_m(s, n-1, k), V_m(s, n, k+1)] + (1-I_n) \min[V_m(s, n, k) + r_2, V_m(s, n, k+1)]] +
\end{aligned} \tag{5}$$

$$\sigma \min[V_m(s-2, n, k), V_m(s-1, n, k)] + \mu V_m(s, n, k) \}$$

for $m > 0$ and $(s, n, k) \in X$, where $V_0(s, n, k) \equiv 0$ for any $(s, n, k) \in X$. Furthermore we have that $u_j = 1$ if system's state $s = j$ otherwise is 0. In a similar manner $I_k = 1$ if $k > 0$ and 0 otherwise. The optimal long-run average cost J^* function can be approximated numerically by the value iteration algorithm (see e.g. [14], [15]).

NUMERICAL EXPERIMENTS

To investigate the structure of the optimal policy, we conducted a series of numerical experiments using the value iteration algorithm described in equation (1). These experiments revealed two distinct scenarios:

- In the first scenario, it is optimal to shut down the production facility and initiate a setup phase to restart production—without ever placing the system in an idle state.
- In the second scenario, it is preferable to avoid shutting down the facility and instead maintain it in standby mode.

We present results from two test cases that illustrate the differences between these scenarios.

Test case 1

The first scenario is illustrated in Test Case 1, with its parameter values provided in table 2. The structure of the optimal policy is depicted in figures 1–10. More specifically figures 9–10 highlight the recurrent region of the optimal policy specific to this case (enclosed in the red dashed line).

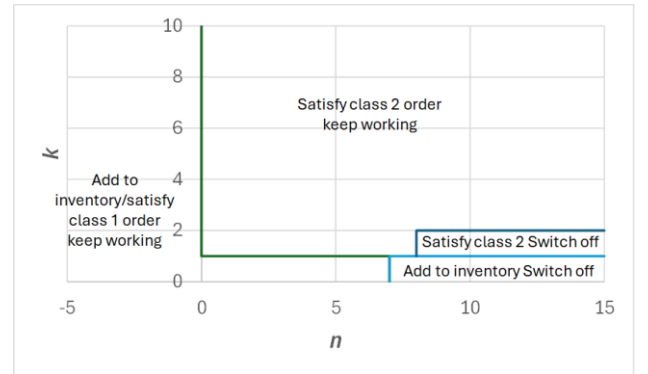


Figure 21: Optimal production control policy (Case 1)

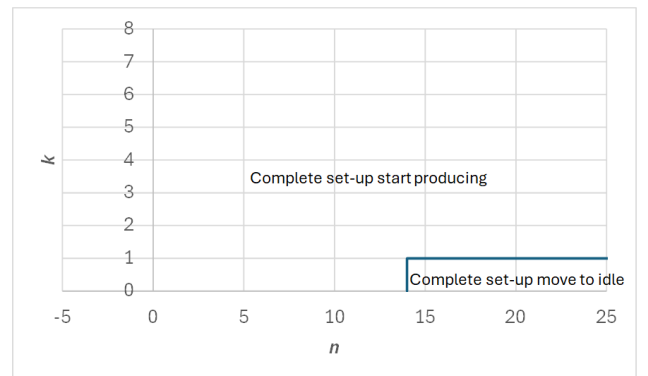


Figure 22: Optimal set-up control policy (Case 1)



Figure 23: Optimal class 1 order admission control policy when $s = 0$ (Case 1)

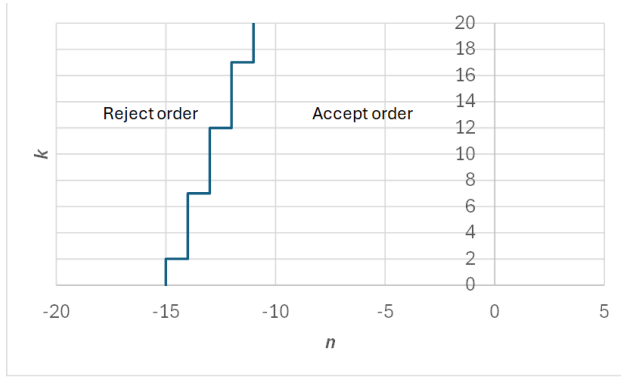


Figure 24: Optimal class 1 order admission control policy when $s = 1$ (Case 1)

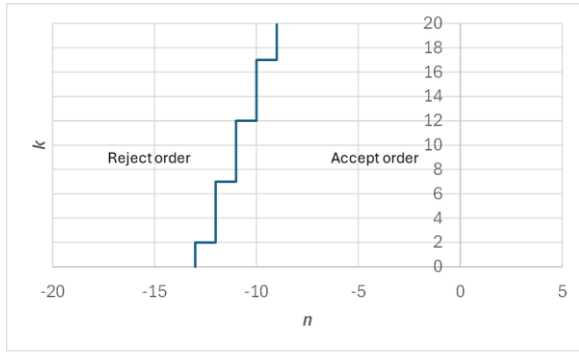


Figure 25: Optimal class 1 order admission control policy when $s = 3$ (Case 1)

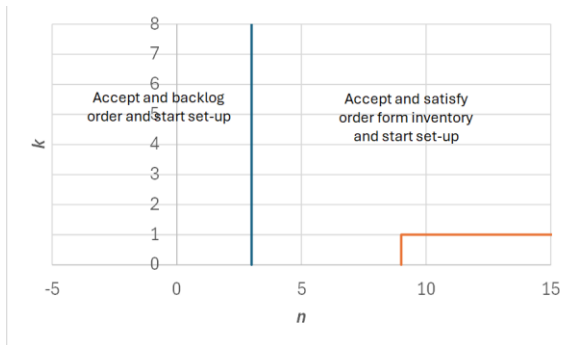


Figure 26: Optimal class 2 order admission control policy when $s = 0$ (Case 1)

Table 15: Parameter values in test case 1

λ_1	λ_2	μ	σ	h	b_1	b_2	r_1	r_2	c_0	c_1	c_2	c_3
4	5	10	4	1	5	1	25	15	0	10	7	1

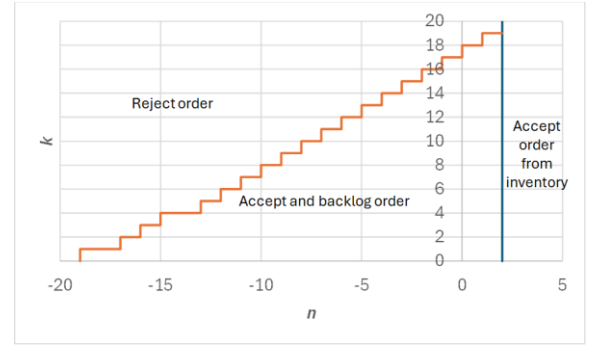


Figure 27: Optimal class 2 order admission control policy when $s = 1$ (Case 1)

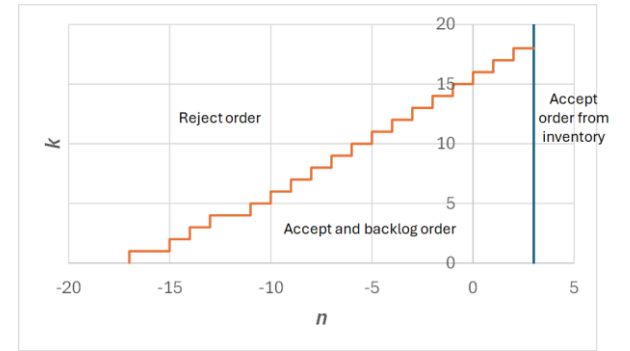


Figure 28: Optimal class 2 order admission control policy when $s = 3$ (Case 1)

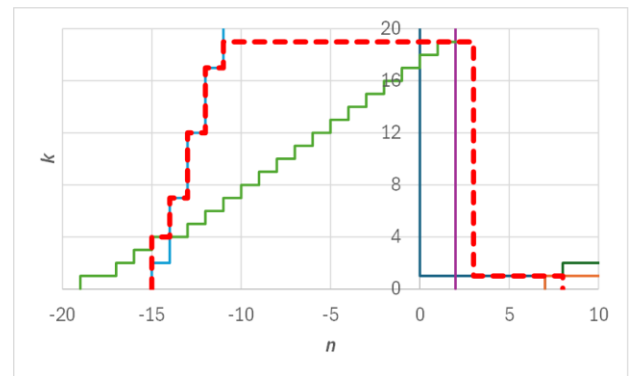


Figure 29: Recurrent region under the optimal policy, $s = 1$ (Case 1)

Based on the results, we can draw several conclusions regarding the structure of the optimal policy in this case:

- The optimal production policy follows a threshold-based approach. Production continues until the inventory reaches an upper limit, at which point the system is shut down. It remains inactive until the inventory falls to the setup threshold, triggering a setup phase.
- Class 1 orders are given a priority over the class 2 orders. When the inventory level exceeds the priority threshold, orders from both classes are fulfilled. Otherwise, any newly produced item is either used to replenish inventory or to fulfill a pending Class 1 order, regardless of the number of pending Class 2 orders.

- Class 1 orders are accepted based on a switching curve, which appears to be a non-increasing function of the total number of Class 2 backorders.
- Class 2 orders are also accepted according to a nearly linear, non-increasing function of Class 1 backorders. Overall, the admission criteria for Class 2 orders are stricter than those for Class 1.
- Order admission for both classes tends to be more restrictive when the production system is undergoing a setup phase.

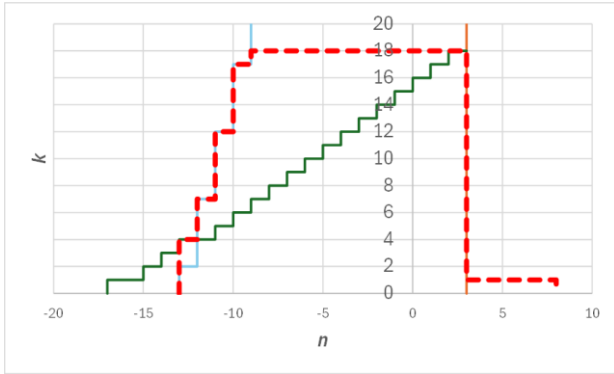


Figure 30: Recurrent region under the optimal policy, $s = 3$ (Case 1)

Test case 2

Test Case 2 illustrates the second scenario, with its parameter values listed in Table 3. The optimal policy structure is shown in Figures 11–15, with Figure 15 specifically highlighting the recurrent region relevant to this case. The recurrent area is enclosed by the red dotted line.

Table 16: Parameter values in test case 2

λ_1	λ_2	μ	σ	h	b_1	b_2	r_1	r_2	c_0	c_1	c_2	c_3
4	7	10	1	1	5	1	25	15	0	5	3	1

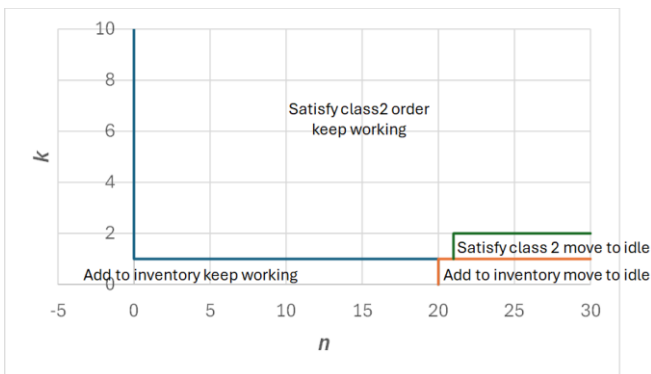


Figure 31: Optimal production control policy (Case 2)

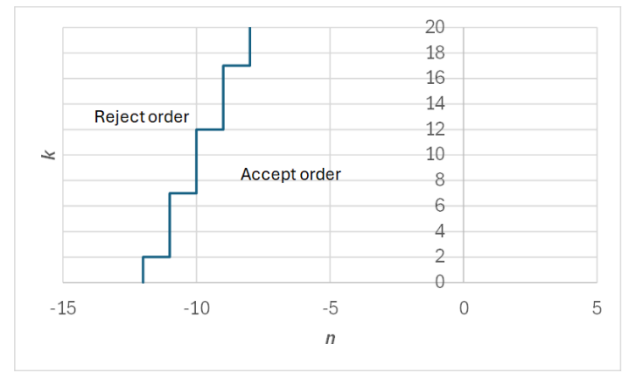


Figure 32: Optimal class 1 order admission control policy when $s = 1$ (Case 2)

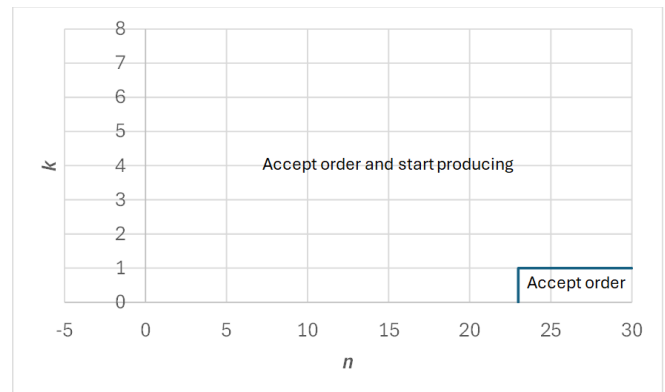


Figure 33: Optimal class 2 order admission control policy when $s = 2$ (Case 2)



Figure 34: Optimal class 2 order admission control policy when $s = 2$ (Case 2)



Figure 35: Optimal class 2 order admission control policy when $s = 1$ (Case 2)

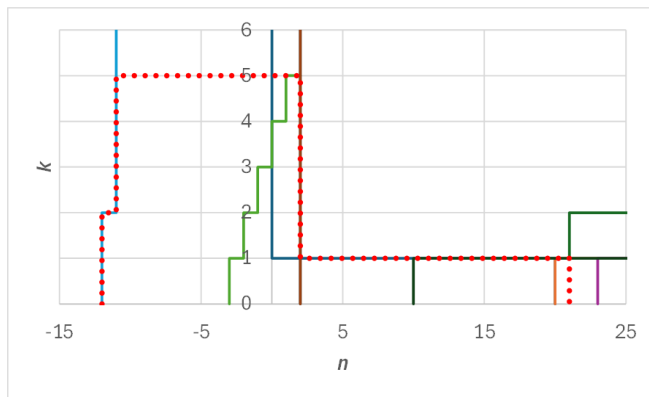


Figure 36: Recurrent region under the optimal policy (Case 2)

As one may observe there are three major differences from the first case: demand is higher, the average setup rate is lower, and finally the unit energy costs when the system is operating or idle is lower. As a result the structure of the optimal policy is quite different now:

The optimal production policy still follows a threshold-based approach. Production continues until the inventory reaches an upper limit, at which point the system halts production and remains idle. It stays inactive until the inventory drops to the restart threshold, triggering a new production phase. Thus, the production facility is never shut down, and no setup is required.

The order admission and priority control structure remains consistent with that of the previous case.

CONCLUSIONS

This study explores the advantages of combining customer admission policies with production control strategies, taking into account energy costs and consumption. We examine a single-stage manufacturing system that produces a single type of item for two distinct customer classes. The objective is to minimize the average profit rate function, which accounts for costs related to order rejection, inventory holding, backlog penalties, and energy usage.

To model the system, we adopt a Markov decision process framework and apply the value iteration algorithm to identify the optimal policy that maximizes the average profit rate. Our numerical experiments uncover key structural characteristics of this optimal policy.

Future research may build on this work by proposing and analyzing simple yet effective heuristic policies. Additional investigations could also consider multi-stage manufacturing systems serving multiple customer classes or systems that do not exhibit Markovian properties.

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Multi-Stage Stochastic Microgrid Design Model

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Abstract— Microgrids play a critical role in integrating renewable energy resources, enhancing grid reliability, and accelerating the transition toward more sustainable power systems. Optimal design of hybrid renewable energy systems in microgrids contributes to decarbonization, reduces energy costs and strengthens grid resilience in areas that face frequent supply disruptions. Despite their economic and environmental advantages, renewable energy resources, especially solar and wind - are inherently uncertain and highly dependent on weather conditions. Accurate forecasting of uncertain parameters such as solar radiation, wind speed, temperature and precipitation is essential to ensure energy supply security and to support integrated resource planning across the energy, food and water sources. Therefore, renewable energy generation and its interdependencies with food and water sources must be considered in the framework of the water-energy-food nexus, especially in the case of climate change and resource scarcity. However, previous studies usually focus on the optimal sizing of different combinations of solar-wind-battery-hydrogen hybrid systems. In contrast, this study introduces a stochastic optimization model effectively determines optimal capacities of solar-wind-biogas-battery-hydrogen hybrid system, primarily considering renewable energy uncertainties and demand variation. In this study, the multi-stage stochastic optimization model is developed to design a main grid-connected microgrid comprising solar PV panels, wind turbines, biogas power plant, a diesel generator, a battery energy storage system, a PEM electrolyzer and hydrogen storage. Solar radiation, wind speed, ambient temperature and energy demand are stochastic parameters and meteorological data of Dortmund, Germany were used in the study to generate scenarios. Monte Carlo simulation is employed for scenario generation and number of scenarios is decreased by using K-means algorithm to reduce computational burden. The model results indicate that when the capacity of each renewable energy source is capped at 10 MW, the microgrid has the highest renewable penetration, meeting most of the energy requirement from clean energy and producing large amounts of green hydrogen, thus restricting electricity imports from the main grid. When the capacity of each source is limited to 4 MW, green hydrogen production decreases, leading to greater reliance on grid electricity and increased operational costs. Further reducing each source's capacity to 2 MW results in even higher grid dependency and lower hydrogen output, highlighting the trade-offs between renewable energy constraints and microgrid performance. In conclusion, the developed model offers crucial opportunities supporting long-term decarbonization strategies and energy

autonomy in order to build a sustainable and resilient energy future.

Keywords— *Microgrid, Green Hydrogen, Multi-Stage Stochastic Optimization*

INTRODUCTION

Energy has served as the cornerstone of industrialization, technological development, and social progress. Global energy demand continues to increase due to population growth, urbanization, and rising living standards. Historically, this demand has been fulfilled mainly by fossil fuels such as coal, oil, and natural gas. However, the heavy reliance on carbon-rich fossil fuels has resulted in severe environmental consequences such as greenhouse gas emissions, climate change, and air pollution. Additionally, the reduction of fossil fuel reserves raises concerns about long-term energy security and the stability of supply chains. These challenges call for a fundamental shift toward more sustainable, cleaner, and decentralized alternatives to ensure both environmental protection and reliable energy access in the future [1].

Renewable energy sources such as solar, wind, hydropower, and biomass have emerged as promising solutions to reduce dependence on fossil fuels and mitigate their environmental impacts. Especially solar and wind energy have experienced rapid global utilization owing to declining technology costs and supportive policies. However, the integration of renewable energy into power systems is accompanied by significant challenges because of their stochastic and intermittent nature. Fluctuations in solar radiation, wind speed, and other weather-dependent parameters create imbalances between supply and demand, complicating grid management and threatening energy security. Overcoming these challenges requires advanced operational strategies and energy storage systems that can balance fluctuations and ensure a secure and stable supply [2, 3]. In this context, microgrids have become increasingly important as flexible, localized energy systems capable of integrating multiple renewable energy resources and storage technologies. Microgrids enhance energy resilience by allowing operation in both grid-connected and islanded modes, reducing dependence on centralized generation, and providing backup power during outages [4]. Beyond economic and technical benefits, microgrids contribute to

decarbonization goals by promoting higher renewable energy penetration and reducing greenhouse gas emissions. Furthermore, microgrids support the water-energy-food (WEF) nexus, which is particularly important in the face of climate change.

To address the intermittency of renewables and improve the reliability of microgrids, hybrid energy systems that combine multiple renewable sources with storage technologies have arisen. By integrating complementary resources such as solar, wind, and biogas, along with batteries and hydrogen-based storage, hybrid systems can smooth variability, increase efficiency, and reduce dependence on a single energy source. Batteries are well-suited for short-term balancing, while hydrogen energy storage—through electrolyzers, storage tanks, and fuel cells—offers high energy density and long-duration flexibility [5, 6]. Biogas ensures stable supply during periods of low solar and wind availability. Such hybrid systems not only improve continuous energy reliability and reduce grid dependency but also enable the production of green hydrogen, which serves as both an energy vector and a decarbonization pathway [7].

Given the complexity of hybrid microgrid systems, optimization plays a central role in their design and operation. Decisions related to the sizing of generation and storage units, scheduling of resources, and energy trading with the main grid must be optimized to balance economic, environmental, and technical objectives [8]. Over the past decades, various advanced optimization approaches have been applied, ranging from stochastic programming [9-11] to robust optimization [12, 13] and metaheuristic algorithms [14, 15]. However, because decisions in energy systems are made under conditions of uncertainty arising from fluctuating renewable output, variable demand, and volatile market prices, stochastic optimization has become a particularly effective method, explicitly modelling uncertainties through probability distributions, scenario generation, and multi-stage formulations. Two-stage stochastic programming is commonly used for investment and operational planning under uncertainty, while multi-stage stochastic optimization extends this framework to dynamic decision-making across sequential time periods.

Building upon these foundations, this study introduces a stochastic optimization model for the optimal design and operational management of a grid-connected hybrid microgrid. The system under investigation integrates solar photovoltaic panels, wind turbines, a biogas power plant, a diesel generator, a battery energy storage system, a PEM electrolyzer, and hydrogen storage. The model explicitly considers uncertainties in renewable generation and demand, using meteorological data from Dortmund, Germany to generate stochastic scenarios via Monte Carlo simulation, followed by scenario reduction using K-means clustering. The proposed model determines the optimal sizing, design and scheduling of system components under different capacity constraints, aiming to minimize total cost.

The rest of the paper is structured as follows: Section 2 presents the model formulation and methodology in detail. Section 3 provides the results of the case studies, and Section 4 is devoted to the conclusions.

MODEL FORMULATION AND METHODOLOGY

This study proposes a novel stochastic optimization framework that is structured as a sequence of four interconnected two-stage stochastic models, each representing

a quarter of the year. In the first stage, investment decisions for distributed energy resources are made; in the second stage, quarter-specific operating schedules are optimized conditionally on scenario realizations. Linking four two-stage programs in sequence yields a novel multi-stage model, where investment strategies can be adapted periodically. Given the stochastic nature of electricity demand and renewable generation, an energy management program in the form of a stochastic optimization model that considers possible scenarios is particularly apt for managing uncertainties associated with electricity demand and stochastic renewable energy. In this study, Monte Carlo simulation is employed for scenario generation for stochastic parameters based on the related probability density functions. The number of scenarios is decreased by using K-means algorithm to reduce computational burden.

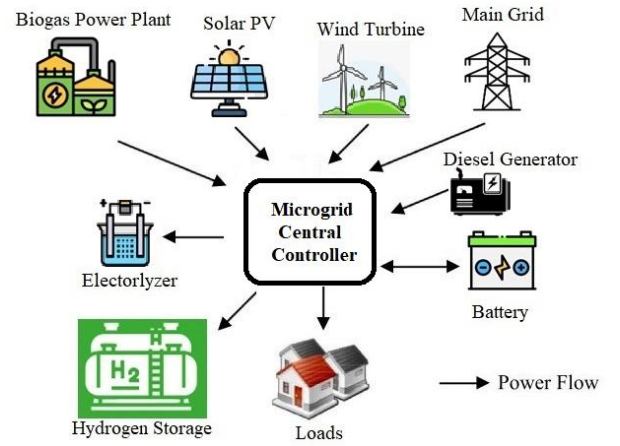


Figure 37: The Microgrid Structure

Mathematical Model

The objective function of the model is to minimize the total investment and operational costs of the microgrid over all stages.

$$\text{Min } Z = \text{Min} \sum_{f=1}^F C_{TAIC} + \sum_{s=1}^S (C_{TOC} - R_{GH}) \quad (6)$$

where C_{TAIC} is the total annualized investment cost of first stage investments, C_{TOC} refers to the total operation and maintenance cost and R_{GH} denotes the green hydrogen revenue in the second stages. The calculation of each of them is shown below:

$$C_{TAIC} = \sum_{a=1}^A CRF(i, l) \cdot (C_a \cdot (IC_a + FOC_a)) \quad (2)$$

where a is the index of energy resources. The project lifetimes (l), investment costs (IC), and fixed operational costs (FOC) for the energy resources were obtained from literature reviews [16, 17]. The interest rate (i) was assumed to be 5% for the CRF calculation.

$$C_{TOC} = \sum_{n=1}^N p^n \sum_{t=1}^T \sum_{a=1}^A (VOC_a \cdot E_a) \quad (3)$$

where VOC_a and E_a are the variable operational cost and energy generation of the a -th energy resource. p^n denotes the probability of n th scenario and the sum of all scenarios equals to 1.

$$R_{GH} = \sum_{n=1}^N p^n \sum_{t=1}^T [(P_H - VOC_H) \cdot H_{elt}] \quad (4)$$

where P_H is the price of green hydrogen (4 €/kg), VOC_H is the variable operational cost of the hydrogen systems, and H_{elt} is the green hydrogen production.

Model Constraints

In this section, the constraints of the model are introduced. Equation 5 shows the total hourly supply-demand balance constraint.

$$D_t^n = E_{pdt}^n + E_{bdt}^n + E_{bgdt}^n + E_{wdt}^n + E_{sdt}^n + E_{dgt}^n \quad \forall t \quad \forall n \quad (5)$$

where D_t^n is the electricity demand at hour t in the n -th scenario. All decision variables and parameters in this study are defined for hour t in the n -th scenario in this short article. E_{pdt}^n , E_{bdt}^n , E_{bgdt}^n , E_{wdt}^n , E_{sdt}^n and E_{dgt}^n represent the purchased electricity from main grid and energy generation from battery, biogas power plant, wind turbine, solar PV and diesel generator in order to meet demand.

Electricity supplied from the main grid can be utilized to meet energy demand, to charge the battery, and to produce green hydrogen.

$$E_{purt}^n = E_{pdt}^n + E_{pbt}^n + E_{pht}^n \quad \forall t \quad \forall n \quad (6)$$

When the state of charge exceeds the minimum level (20%), the battery can be discharged to meet demand and to supply electricity for hydrogen production.

$$E_{bt}^n \geq E_{bdt}^n + E_{bht}^n + SOC_{min} \quad \forall t \quad \forall n \quad (7)$$

$$E_{bt}^n = SOC_t^n \cdot C_{bat} \quad \forall t \quad \forall n \quad (8)$$

$$SOC_{min} \leq SOC_t^n \leq SOC_{max} \quad \forall t \quad \forall n \quad (9)$$

Renewable energy from the biogas plant, wind turbine, and PV system is allocated to meet energy demand, to charge the battery, and to produce green hydrogen.

$$E_{bgt}^n = E_{bgdt}^n + E_{bgbt}^n + E_{bght}^n \quad \forall t \quad \forall n \quad (70)$$

$$0 \leq E_{bgt}^n \leq E_{bgmax} \quad \forall t \quad \forall n \quad (18)$$

$$E_{wt}^n = E_{wdt}^n + E_{wbt}^n + E_{wht}^n \quad \forall t \quad \forall n \quad (92)$$

$$0 \leq E_{wt}^n \leq E_{wmax} \quad \forall t \quad \forall n \quad (103)$$

$$E_{st}^n = E_{sdt}^n + E_{sbt}^n + E_{sht}^n \quad \forall t \quad \forall n \quad (114)$$

$$0 \leq E_{st}^n \leq E_{smax} \quad \forall t \quad \forall n \quad (125)$$

The diesel generator is used to meet energy demand, and Equation (16) shows its lower and upper limits.

$$0 \leq E_{dgt}^n \leq E_{dgmax} \quad \forall t \quad \forall n \quad (136)$$

Equations (17)–(19) describe, respectively, hydrogen production, the electricity consumption for hydrogen generation, and the bounds on electricity consumption. Equation (20) defines the amount of hydrogen in the storage tank, while Equation (21) imposes the tank capacity limits.

$$H_{elt}^n = E_{elt}^n \cdot e_{p2h} \cdot \eta_{el} \quad \forall t \quad \forall n \quad (17)$$

$$E_{elt}^n = E_{pht}^n + E_{bht}^n + E_{wht}^n + E_{sht}^n \quad \forall t \quad \forall n \quad (148)$$

$$E_{elmin} \leq E_{elt}^n \leq E_{elmax} \quad \forall t \quad \forall n \quad (159)$$

$$HS_t^n = HS_{(t-1)}^n + H_{elt}^n \quad \forall t \quad \forall n \quad (20)$$

$$0 \leq HS_t^n \leq HS_{max} \quad \forall t \quad \forall n \quad (216)$$

where e_{p2h} and η_{el} are the electricity-to-hydrogen conversion factor and the electrolyzer efficiency, respectively.

RESULTS

This section analyses the results of the stochastic optimization model for three microgrid configurations. To investigate the impact of scaling renewable infrastructure,

three distinct case studies were analyzed, each renewable energy resource constrained by a maximum installed capacity: 2 MW, 4 MW, and 10 MW in order. The analysis focuses on techno-economic performance, grid interaction, and the emergence of green hydrogen production as an essential mechanism as renewable capacity increases.

In the first case study under 2 MW renewable installed capacity constraint, the microgrid operates with significant reliance on the main grid. The limited renewable generation is insufficient to meet demand, resulting in no surplus energy available for green hydrogen production. The microgrid purchases approximately 9 GWh annually from the main grid, which constitutes 33% of its total energy demand. Although no solar PV investment is selected in the first-stage; however, thanks to the model's multi-stage decision structure, in the second first-stage the model adopts PV investment, enabling PV generation over the remaining nine months of the year and producing a substantial reduction in grid purchases relative to the first quarter. Given the grid purchase price of €0.30/kWh, electricity supplied from the grid is only used to meet demand, and investing in a diesel generator is not economically feasible. Analysis of daily operation, such as on January 15th (Figure 2-1), confirms this pattern, showing frequent periods where demand exceeds renewable generation, necessitating continuous grid support. This high grid dependency is the main reason for the system's total cost, which is the highest among the three case studies at approximately €3.44 million. This case highlights the challenges of operating a microgrid with insufficient inherent generation capacity.

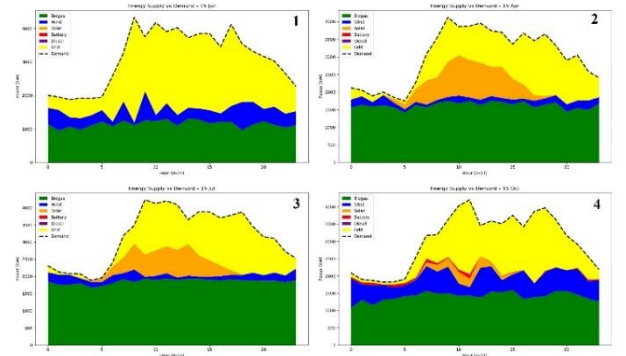


Figure 2: Seasonal Comparison of Hourly Energy Supply and Demand – Case Study 1

Doubling the renewable capacity to 4 MW in the second case study brings major benefits. The increased renewable energy generation creates significant energy surpluses and the model incorporates an 839 kW electrolyzer, enabling the production of 63,597 kg of green hydrogen annually. This hydrogen generation creates a substantial revenue stream of €254,388. The system's reliance on the grid gets drastically reduced. Grid purchases fall to 1.5 GWh, meeting only 6% of the annual demand. Although the total installed cost is higher than in the 2 MW case, the net system cost is reduced by 64% to approximately €1.25 million compared to the 2 MW case. The operational profile, as seen on representative days across seasons (Figure 3), shows a more balanced supply-demand dynamic.

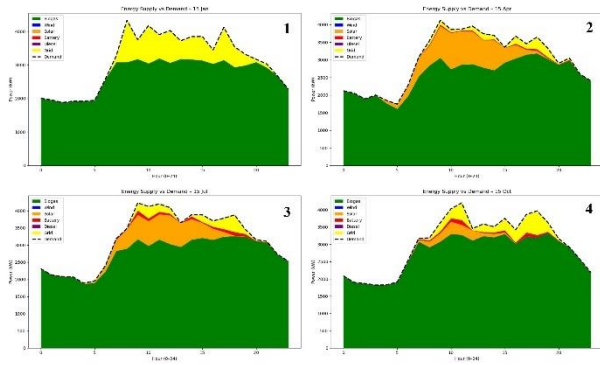


Figure 3: Seasonal Comparison of Hourly Energy Supply and Demand – Case Study 2

The 10 MW case represents the most advanced design among the three case studies for maximum autonomy and profitability. The optimal design maximizes the biogas capacity and includes a larger electrolyser (1,133 kW), while solar PV is optimized at a lower level than the 4 MW case and wind power is excluded. This configuration achieves the highest level of energy autonomy, with grid purchases falling to just 593 MWh per year, meeting just 2% of the annual demand. The substantial renewable capacity leads to a significant increase in green hydrogen production, reaching 108,298 kg per year. This surge drives hydrogen revenue to €433,192. The combination of high hydrogen revenue and minimal grid expense results in the lowest net cost at €896,907—a 28% reduction from the 4 MW case and a 74% reduction from the 2 MW case. This key finding indicates that the economies of scale from increased renewable capacity, coupled with the value of hydrogen as an energy vector, can lead to a more cost-effective system than a smaller, grid-reliant one. The system operates with a high degree of self-sufficiency, as visualized on sample days in Figure 4.

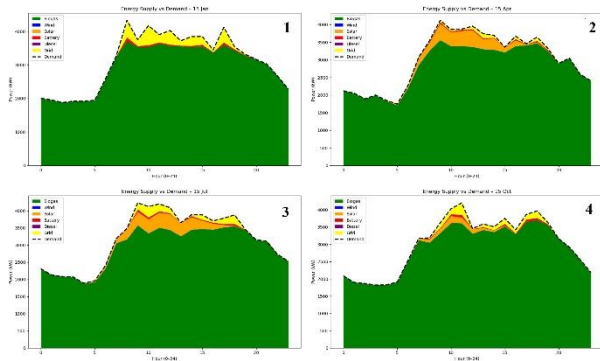


Figure 4: Seasonal Comparison of Hourly Energy Supply and Demand – Case Study 3

The key results for each case study are summarized in Table 1.

Table 17: Key Results for Case Studies

Energy Source	2 MW Case	4 MW Case	10 MW Case
Biogas Power Plant	1936	3340	3725
Wind Turbine	2000	36	0
Solar PV	2000	2405	1473
Battery Storage	395	230	133
Diesel Generator	0	0	0
Electrolyzer	0	839	1133

Grid Electricity Purchase (kWh)	8.924.099,39	1.519.368,87	593.366,76
Share of Grid Electricity (%)	33%	6%	2%
Green Hydrogen Production (kg)	0	63597	108298
Green Hydrogen Revenue (€)	0	254.388,00	433.192,00
Net Cost (€)	3.203.943,69	1.254.336,55	896.906,61

In the 2 MW case, the first stage selects high-capacity investments in the biogas power plant and wind turbines. In the second first-stage, 2 MW solar PV installation is added; by the fourth first-stage, wind capacity is increased up to 2 MW cap and battery investment is undertaken. Under the 4 MW capacity limit, the first stage commits to sizable biogas and electrolyzer capacities. In the second first-stage, the model introduces the full planned capacity of solar PV, expands the electrolyzer, and installs a battery system. The third and fourth first-stages continue increasing the biogas plant and battery capacity. In the 10 MW case, the first-stage executes the full biogas and battery investments and commits to a substantial electrolyzer capacity. The second stage adds a large solar PV capacity and further electrolyzer capacity, followed by an additional PV investment in the third first-stage. Across case studies, the multi-stage decision structure defers solar PV investment in the first-stage and adopts it in the second first-stage, enabling nine months of PV generation over the remainder of the year and markedly reducing grid purchases relative to the first quarter. The model selects no diesel generator investment and grid electricity is only used to cover demand. The model utilizes surplus renewable energy for green hydrogen production, as electricity sales are not considered an option. In addition, Figure 5 shows hourly green hydrogen production on representative days for the case study 3.

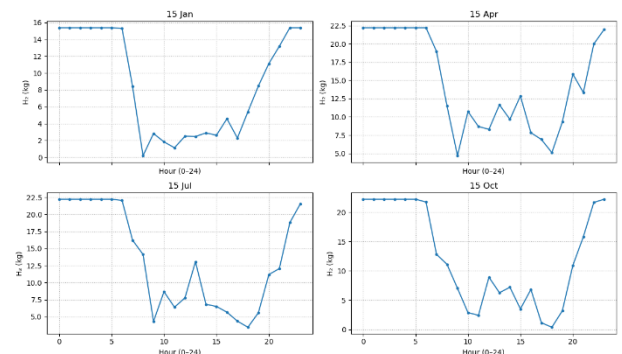


Figure 5: Seasonal Comparison of Hourly Hydrogen Production – Case Study 3

CONCLUSION

This paper introduces a novel multi-stage optimization framework for the optimal design and operation of a grid-connected hybrid microgrid. The main innovation lies in a sequential design, where the annual planning horizon is divided into four quarters, each modeled as a two-stage stochastic program. This approach allows investment decisions to be adapted periodically, providing a more dynamic and realistic framework than conventional single-stage models for planning under uncertainty.

The analysis of three distinct renewable capacity scenarios (2 MW, 4 MW, and 10 MW) yields clear and significant insights. The 2 MW case results in high grid dependency and the highest system cost, proving that limited renewable capacity is economically challenging. A major shift occurs at 4 MW: renewable surpluses become sufficient to support economically viable green hydrogen production, which serves as a flexibility resource. Relative to the 2 MW case, grid purchases fall by 83% and total net cost declines by 64%. The 10 MW case demonstrates the most advanced design among the three case studies for maximum autonomy and profitability. With high renewable capacity and hydrogen storage integration, the system achieves near-total autonomy. Remarkably, this most self-sufficient configuration also proves to be the most cost-effective, with a net cost of 74% lower than the 2 MW case.

Overall, this study conclusively shows that green hydrogen is an asset for the economic viability of renewable microgrids. The proposed multi-stage framework provides a beneficial decision-support tool for achieving cost-effective and low-carbon energy systems. Future studies will focus on the influence of variable energy markets and the addition of new energy sources.

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The Future of Sport Facilities: "The Bee-Sportive" Sustainable Concept

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Abstract—This article presents a concept for the sports complex of the future, aiming to offer a solution to the need for energy-efficient and sustainable sports facilities. The concept, prepared for the Erasmus+ program Next Gen Sport Facilities, is backed by extensive literature research and brainstorming. The name of the concept is The Bee-Sportive. It is designed according to outcomes of identification of existing wicked problems to develop future sport complex.

The Bee-Sportive Complex is a futuristic and sustainable sports facility concept that integrates smart technologies, energy efficient applications setting a new perspective for urban sports infrastructure. Inspired by the efficiency and collaborative nature of bees—symbolized by the honeycomb structure and emblematic of Istanbul Technical University—the complex embodies a holistic design philosophy that combines environmental responsibility with community engagement and technological advancement.

This paper presents the conceptualization, design strategies, and projected outcomes of the Bee-Sportive Complex. At the architectural level, the complex utilizes modular, beehive-inspired forms that promote spatial efficiency and adaptability. Sustainability is achieved through a multi-layered approach, incorporating photovoltaic solar panels, wind turbines, kinetic energy harvesting gym equipment, greywater recycling, and permeable pavements for rainwater infiltration. These strategies collectively aim to reduce the complex's energy consumption by 40% and water use by 30%.

While planning an energy-efficient and environmentally friendly campus, an analysis was conducted on the existing sports complex. The energy consumption data of the current campus sports complex was measured using the eQUEST tool, and the planned efficiency improvements were based on this data. The design focused on the high energy usage for space heating and cooling according to eQUEST data, and especially on the excessive electricity consumption during summer months. Renewable energy solutions were proposed to reduce carbon emissions and create an eco-friendlier campus. The concept of bees and honeycombs was incorporated into the environmentally conscious design to reinforce this theme visually.

Artificial intelligence applications were integrated into the model both to manage the sports complex in terms of energy and other aspects, and to offer an innovative sports experience.

Green infrastructure, including vegetated roofs and biodiversity-supportive landscaping, further integrates the

complex into its natural surroundings, promoting ecological sustainability. Social inclusion, energy efficiency, and community-based use are central pillars of the design, making the Bee-Sportive Complex a replicable model for urban development.

The Bee-Sportive Complex is an innovative sports facility design created to offer people technology-integrated, cutting-edge experiences without disrupting the balance of nature, while also aiming to be an energy-efficient and sustainable complex. This article outlines the key considerations behind the design, as well as the sustainable and technological features integrated into it, presenting the project as a proposal for the sports complexes of the future.

Keywords—Sustainability, Energy efficiency, Sustainable design, eQUEST, Sport facilities, Multiscale strategies

INTRODUCTION

Sports complexes and university campuses are high-energy facilities that operate for long hours, host large crowds, and require significant heating, cooling, lighting, and water resources [1]. Compared to traditional academic buildings, sports buildings typically consume two to three times more energy per unit area due to their size, occupancy rates, and intensive ventilation requirements [2]. This high demand not only increases operating costs but also contributes significantly to carbon emissions, making them critical focal points for sustainable urban development. Therefore, designing such facilities to be innovative, smart, and environmentally friendly is no longer optional, but essential. Sustainable sports complexes integrate energy efficiency measures, renewable energy systems, and ecological design strategies to reduce resource consumption, ensure long-term durability, and create healthier environments for their occupants [3]. Recent studies highlight that applying a multi-scale approach, from building-level improvements to campus-wide digital twins, maximizes both environmental and social benefits [4]. In this context, digital tools and simulation platforms are particularly valuable. eQUEST enables the identification of high-consumption components and the evaluation of efficiency improvements by providing detailed building energy modeling. ArcGIS also supports campus-scale planning by linking buildings to mobility, infrastructure, security, and green spaces, thereby placing building-level gains within a holistic campus framework [5]. The Bee-Sportive concept aims to create a replicable model that

combines these approaches, bringing together technology, sustainability, and community participation.

DESIGN, VISION AND CONCEPT

ArcGIS for Smart Campus Planning

In large and heavily used areas such as the ITU Ayazağa Campus, spatial planning tools are central to sustainability goals. ArcGIS integrates different data such as buildings, roads, green spaces, and water infrastructure into a single digital platform, providing decision-makers with powerful analysis capabilities. The literature shows that GIS-based analyses are an effective tool for energy efficiency, security, and green infrastructure management on campuses [6]. Within the scope of Bee-Sportive, ArcGIS enabled the modeling of the sports complex not only at the building scale but also as a “hub” within the overall spatial network of the campus. This allows pedestrian flows, rainwater flow directions, and green space distributions to be evaluated at the campus scale.

As shown in Figure 1, the ArcGIS layers of the ITU Ayazağa Campus provide a comprehensive spatial planning framework by digitally integrating buildings, roads, parking areas, vegetation, and forested areas.

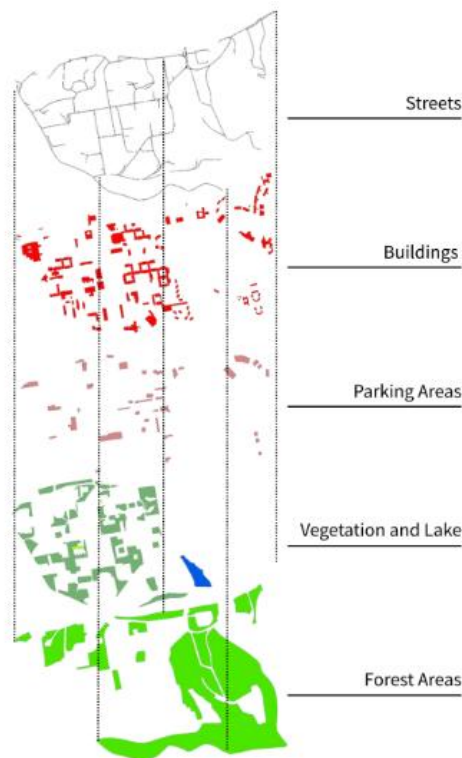


Figure 1. Digital Twin Layers of ITU Ayazağa Campus

Smart Mobility & Digital Hive Connectivity

The Ayazağa Campus hosts tens of thousands of students, staff, and visitors daily. This high level of activity necessitates the sports complex also serving as a mobility hub. The Bee-Sportive model therefore envisions the complex as a “hive mobility hub.” Metro connections, bicycle lanes, and pedestrian paths converge at this hub, while it is recommended that campus ring routes be supported by autonomous and low-carbon vehicles. Similar applications have been tested at other university campuses, and a significant increase in the transition to public transportation has been reported [7]. In addition, digital twin technologies and real-time crowd density maps (such as the Pulse system

used at Dublin City University) enable more effective management of campus security and accessibility [8].

Green Infrastructure & Smart Management

Campus-scale green infrastructure integration plays a critical role in climate adaptation and resource efficiency. It is recommended that the microclimate advantage provided by the ITU Forest be supported by permeable surfaces, rain gardens, and green roofs around the sports complex. Such solutions can reduce surface runoff by up to 70% [9] and reduce the cooling load of buildings by 40% during the summer months [10]. In addition, the sports complex can be integrated into the campus microgrid with AI-supported HVAC and lighting management systems, allowing real-time monitoring of energy consumption. Thus, building-scale efficiency is integrated with campus-scale smart management systems.

Community & Biophilic Engagement

Campus sustainability is not limited to technical solutions; community participation and user experience are also key to success. The Bee-Sportive concept therefore embraces biophilic design principles: spaces with natural light, green roof gardens, and social areas integrated with the forest strengthen students' connection with nature. Academic studies show that biophilic design increases the sense of belonging on campuses and contributes to user well-being [11]. Furthermore, gamified energy and water conservation competitions, as exemplified by UC Davis and the University of Cape Town, increase student participation and reduce consumption rates [12]. This approach can be disseminated at ITU through student clubs and sports teams. Thus, the sports complex will become not just a physical facility but a social and ecological “hive” for the entire community.

BUILDING ENVELOPE RETROFITS

High-Performance Insulation

The building envelope is the primary regulator of heat transfer between the interior and exterior environments. Enhancing thermal insulation in walls and roofs is a foundational strategy for reducing heating and cooling loads. Research indicates that upgrading insulation in existing buildings can lead to whole-building energy savings of 5–20%, with the magnitude highly dependent on the baseline building stock, local climate, and operational schedules [13]. For sports complexes, which feature extensive façade and roof areas, the implementation of continuous insulation systems to mitigate thermal bridging is particularly critical to realizing these savings.

Advanced Glazing System

Fenestration represents a significant weak point in the building envelope. The transition from single-pane to double- or triple-pane glazing with low-emissivity (low-E) coatings dramatically reduces U-values and controls solar heat gain. Studies show that such upgrades can reduce specific space conditioning energy use by 10–25% [14]. In large sports halls with substantial glazing, the application of high-performance windows, coupled with strategic daylighting design, offers a dual benefit of energy reduction and enhanced visual comfort for occupants, mitigating issues like glare which can impair athletic performance.

Solar Shading Devices

In cooling-dominated climates, solar radiation through glazing is a major driver of energy demand. Fixed and dynamic external shading devices—including overhangs, louvers, and blinds—are effective passive measures. A comprehensive review by Kirimtat et al. (2020) concludes that such devices can reduce cooling energy demand by 5–25%, with performance dictated by orientation, geometry, and climate. Horizontal louvers are optimal for south-facing facades, while vertical fins are more effective on east and west orientations. For sports facilities, these strategies directly target peak cooling loads and improve occupant comfort [15].

Green Roof Systems

Green roofs provide a multi-functional solution that combines thermal mass, evapotranspirative cooling, and added insulation. Their energy-saving performance is variable, with meta-reviews reporting reductions in annual building energy demand ranging from 2% to 15% [16]. The effectiveness is contingent upon climate, substrate depth, and irrigation. In the context of sports complexes, extensive green roofs can significantly lower roof surface temperatures, thereby reducing the urban heat island effect and decreasing cooling loads for buildings beneath them, in addition to managing stormwater runoff.

HIGH-EFFICIENCY BUILDING SYSTEMS

Advanced HVAC Systems

Heating, Ventilation, and Air-Conditioning (HVAC) typically constitute the largest energy end-use in sports complexes. The adoption of high-efficiency systems, such as Variable Refrigerant Flow (VRF) and air-to-water heat pumps, offers substantial savings. Kim et al. (2017) demonstrated that VRF systems can achieve 20–40% energy savings compared to traditional packaged units or central chilled-water systems, due to superior part-load performance and zoning capabilities[17]. Furthermore, the integration of Demand-Controlled Ventilation (DCV), which modulates outdoor air intake based on real-time CO₂ sensors, is particularly suited to spaces with fluctuating occupancy like gyms and arenas, preventing energy waste from over-ventilation [18].

Smart Lighting Systems

Lighting retrofits represent one of the most cost-effective efficiency measures. The transition from traditional metal halide or fluorescent lighting to Light Emitting Diodes (LEDs) alone can reduce lighting energy consumption by 40–60% (DOE, 2022). When paired with smart controls—including occupancy sensors for auxiliary spaces and daylight harvesting systems for perimeter areas and zones with skylights—total lighting energy savings can exceed 70% [19]. For sports complexes, this not only cuts energy costs but also reduces internal heat gains, thereby lowering concomitant cooling loads.

SMART MANAGEMENT AND EMERGING TECHNOLOGIES

AI-Supported Building Management

The integration of Artificial Intelligence (AI) and Machine Learning (ML) with Building Energy Management Systems (BEMS) moves control strategies from reactive to predictive.

These systems use historical data, weather forecasts, and occupancy predictions to optimize HVAC setpoints and start/stop times. Reviews of this technology suggest it can yield whole-building energy savings of 10–20% by eliminating wasted energy in unoccupied periods and fine-tuning system operation beyond the capabilities of static schedules [20]. For facilities with highly predictable event schedules, such as stadiums, the potential for pre-conditioning and load-shifting is significant.

CASE STUDY APPLICATION AND QUANTIFICATION OF EFFICIENCY STRATEGIES AT İTÜ SPORTS COMPLEX

Case Study Description and Baseline Modeling

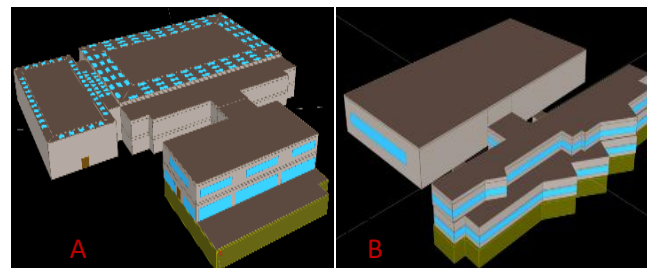


Figure 2. a) Fitness center Energy Model b) Olympic Swimming Pool Energy Model

This study focuses on two distinct facilities within the Istanbul Technical University (İTÜ) sports complex: the Fitness Center (housing a gymnasium, indoor basketball court, and fitness areas) and the Olympic Swimming Pool (including multipurpose classrooms and studios). To establish a performance benchmark, detailed energy models of both facilities were developed and calibrated using the eQUEST simulation software, reflecting Istanbul's temperate-humid climate and the specific operational schedules of a university sports complex.

The combined total annual energy consumption for the baseline scenario was calculated to be 11,249,011 kWh/yr. Figure 3, shows the result conversions and annual energy consumption and it serves as the reference point against which all proposed energy conservation measures (ECMs) were evaluated.

Olympic swimming pool	Fitness Center
Area	Area
7862 m ²	5250 m ²
Gas conversion	Gas conversion
1 Btu=0.000293071 kWh	1 Btu=0.000293071 kWh
328.15x106 Btux0.000293071 kWh/Btu	27,440,000,000x0.000293071=8,041,700 kWh
=96,171 kWh	
Electricity	Electricity
800.84x103=800,840800.84x103=800,840 kWh	2,310.2x103=2,310,200 kWh
Total annual energy	Total annual energy
800,840 + 96,171	2,310,200+8,041,700
897,011897,011 kWh	10,351,900 kWh
Total annual energy per m2	Total annual energy per m2
897,011897,011 / 7862	10,351,900 / 5250
114.1 kWh/m ² -year	1,973 kWh/m ² -year
Total annual energy for all facilities	Total annual energy Per m2 for all facilities
11,249,011 kWh	2,087 kWh/m ² -year

Figure 3. Annual Gas and Electricity consumption with the combined overall annual energy consumption of both facilities.

Implementation of BEESportive Strategies and Cumulative Results

Aligned with the BEESportive concept, a sequential package of ECMs was modeled to simulate a comprehensive deep-energy retrofit. The strategies were applied in a logical

progression, where savings from one measure reduced the load for subsequent systems. The results of this cumulative implementation are presented in figure 4. The calculations demonstrate that the integrated BEESportive design can potentially achieve a final energy consumption of 5,770,300 kWh/yr, corresponding to a 48.7% reduction from the baseline.

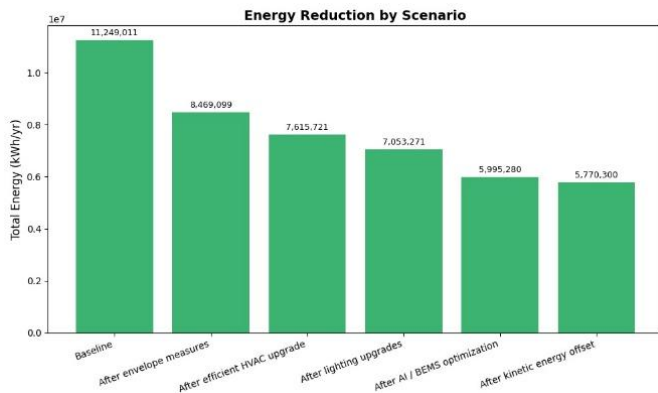


Figure 4. Cumulative Energy Savings from Sequential Implementation of BEESportive Strategies

Analysis of Individual Strategy Impact

The sequential application of measures allows for a clear analysis of each strategy's contribution to the overall goal.

Envelope Upgrades (24.71% savings): The implementation of high-performance insulation, windows, shading, and green roofs provided the most significant single reduction in energy use. By drastically reducing the thermal loads on the buildings, these passive measures achieved savings of over 2.7 million kWh annually, establishing a more efficient baseline for the active systems to serve.

Efficient HVAC Upgrade (Cumulative: 32.30% savings): Applying a high-efficiency HVAC system (e.g., VRF with demand-controlled ventilation) to the already reduced load from the envelope upgrades yielded a further 7.6% in savings (653,378 kWh). This demonstrates the critical synergy between passive design and mechanical system selection, where downsized, right-sized systems operate more efficiently.

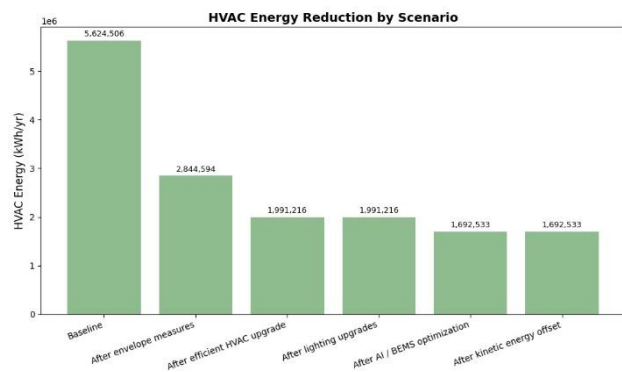


Figure 5. Cumulative Energy consumption from HVAC and the savings

Lighting Upgrades (Cumulative: 37.30% savings): The retrofit to LED lighting with daylight and occupancy controls, achieving a 50% reduction in lighting energy, provided an additional 5.0% saving (562,450 kWh). This also contributes to a secondary saving by reducing internal heat gains, thereby slightly lowering cooling loads.

AI / BEMS Optimization (Cumulative: 46.70% savings): The introduction of an AI-driven Building Energy Management System, applying predictive control to the optimized envelope and systems, resulted in a further 9.4% saving (1,057,991 kWh). This highlights the substantial value of smart, dynamic management in fine-tuning performance beyond what is possible with static, high-efficiency components alone.

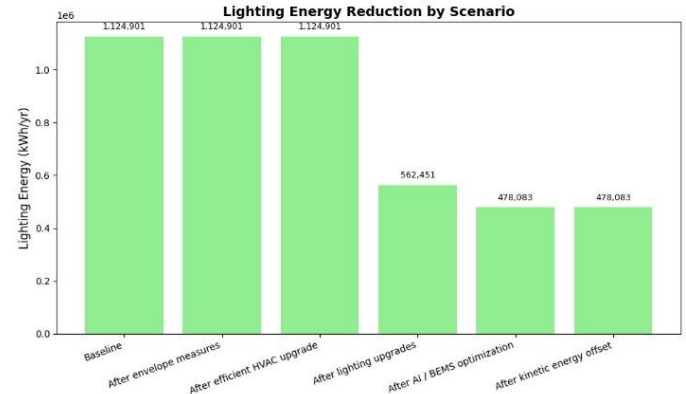


Figure 6. Lighting energy consumption and the saving

Synthesis of Results for the BEESportive Concept

The results validate the hierarchical effectiveness of the strategies discussed in the literature review. The most significant savings originate from passive envelope improvements and high-efficiency system retrofits (HVAC and lighting). The AI/BEMS optimization then captures a further, substantial layer of savings by optimizing the operation of these improved assets. The final outcome of 48.7% reduction in total energy consumption confirms that a deeply integrated, holistic design approach is technically feasible and highly effective for achieving transformative energy performance in a university sports complex. The proposed next-generation BEESportive facility, embodying these principles, would operate at an annual energy consumption of just 5,770,300 kWh.

ENERGY PERFORMANCE ASSESMENT OF THE BEE-SPORTIVE COMPLEX

Sports complexes are among the most energy-intensive building types due to their extended operating hours, high occupancy levels, and large interior volumes. As such, a detailed assessment of energy performance, coupled with renewable energy integration, forms one of the most critical components of sustainable design [21].

In this study, the existing campus energy profile was modeled using eQUEST, and multiple scenarios were evaluated. Electricity consumption of the facility calculated via eQUEST and reported as CSV file to investigate the self sufficiency rate of the system after calculating solar and kinetic energy production. Renewable generation from photovoltaic panels and kinetic flooring contributed 177,546 kWh, lowering grid dependency to 1,437,878 kWh.

Within the Bee-Sportive concept, renewable integration was not limited to conventional sources such as photovoltaic systems, but also extended to kinetic energy recovery from sports equipment and active surfaces. This approach reflects a dual objective: promoting sustainable energy generation while simultaneously enhancing user engagement in sustainability practices.

In our modeling, kinetic flooring and fitness equipment were considered as supplementary renewable sources, contributing approximately 40,005 kWh annually, as illustrated in Figure 7. Although this value is modest compared to solar PV generation, it plays a symbolic and functional role in linking physical activity with environmental responsibility. Comparable studies in fitness facilities have reported similar ranges, showing that kinetic recovery technologies can cover 1–3% of a building's electricity demand under typical occupancy conditions [22].

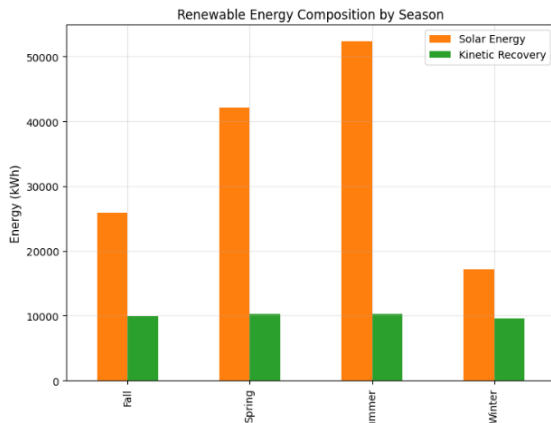


Figure 7. The Facility's Kinetic Energy and Solar Energy Production Potential

For the solar energy application PV_LIB Python used as a tool to calculate the solar energy production potential of the building. For kinetic energy, values from the literature used as a base for Python coding of energy production from sport equipments.

With using kinetic energy, our results demonstrate consistency with the broader literature while highlighting the unique context of large-scale sports complexes. Importantly, the inclusion of kinetic recovery offers educational and behavioral benefits: users can directly perceive the relationship between their activity and the energy generated, reinforcing a culture of sustainability within the facility [23].

Thus, while kinetic energy alone cannot provide substantial self-sufficiency, its integration alongside PV systems strengthens the conceptual framework of participatory sustainability, where every user becomes an active contributor to the energy ecosystem. This feature also opens pathways for future research and design innovations, including piezoelectric flooring in spectator stands or kinetic harvesting from high-traffic circulation areas, further expanding the role of sports facilities as living laboratories of sustainable energy.

Seasonal analyses revealed that self-sufficiency rates varied significantly, reaching 11% in spring and summer but dropping to 7.9% in winter (Figure 8). These findings highlight the importance of storage systems and additional efficiency strategies to mitigate the intermittency of renewable sources [24].

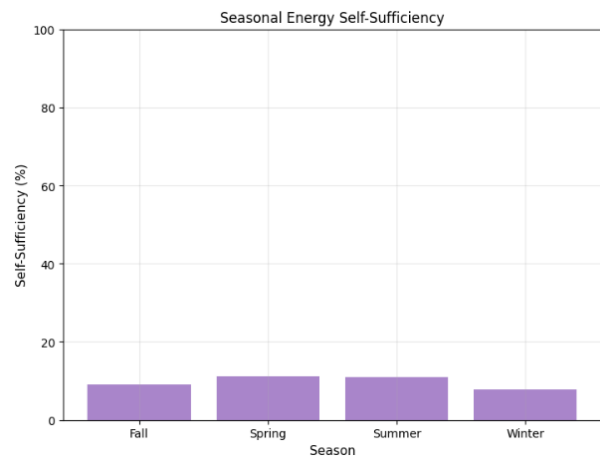


Figure 8: Seasonal Energy Self-Sufficiency Rates of the Complex

CONCLUSION

The Bee Sportive framework demonstrates that deep energy retrofits, when coupled with advanced management systems and renewable integration, can transform sports complexes from highly consumptive facilities into models of sustainable design. The findings confirm that passive envelope strategies provide the foundation for significant energy reductions, which are then amplified by efficient HVAC and lighting systems, and fine-tuned through AI enabled management. The case study application at Istanbul Technical University validates this approach, revealing that the sequential implementation of these measures achieves a remarkable 46.7% reduction in annual energy consumption, surpassing our initial target.

Moreover, the integration of renewable technologies, including both conventional solar PV and participatory kinetic harvesting, strengthens the facility's resilience while embedding sustainability into the daily experience of its users. The combined implementation of solar and kinetic energy ensures 9.8% self-sufficiency for the complex's electricity consumption, demonstrating a meaningful step toward energy independence. With the addition of energy storage systems, expanded passive design measures, and enhanced digital twin applications, future iterations of the Bee Sportive complex can further enhance this self-sufficiency and move decisively toward net zero operation.

Beyond its technical outcomes, the concept offers a cultural shift: by linking physical activity with energy generation, it positions sports facilities as living laboratories where the campus community actively participates in sustainability. In summary, the Bee Sportive vision provides a replicable and forward-looking model for universities worldwide, demonstrating how sports complexes can evolve into ecological and social hubs that advance institutional climate goals while enriching the student experience.

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Assessing the Role of Climate Change in Shaping Farm-Level Decision-Making

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Abstract— This study aims to evaluate the specific impacts of climate change on agricultural production by examining how selected meteorological variables influence the yields of key crops - including wheat, maize, and sunflower in the Slovak Republic, while also exploring how these climatic factors affect farm-level decision-making and producers' adaptive strategies. The analysis reveals that average climatic conditions exhibit a stronger correlation with yield anomalies than extreme weather events, highlighting the predominant role of mean climate factors in shaping crop productivity. The relationship between crop yields and meteorological variables is economically heterogeneous, as each crop responds differently to climatic conditions due to its unique production characteristics. Consequently, the economic impact of individual meteorological indicators on yield outcomes varies across crops, influencing farm revenue, input use efficiency, and risk management decisions. The results of our analysis confirm that climatic and soil conditions play a critical role in determining the yields of selected agricultural crops.

Keywords— crop production; climate conditions; farm-level decision-making

INTRODUCTION

The region of Slovakia is diverse in terms of air temperature. In the lowlands, the air temperature is on average about 4 °C higher than in the mountains in the north. These temperature differences cause a number of negative consequences. Shifts in regional thermal gradients have led to altitudinal and latitudinal migration of native plant species toward cooler northern and higher elevation zones in Slovakia, while thermophilic and non-native cultivars are increasingly introduced in southern lowland areas. There are also new types of pests and diseases that we have not known before. The constantly increasing air temperature also brings with it potentially higher evaporation, which ultimately causes the landscape to dry out and therefore irrigation is needed to a greater extent. Due to the effects of climate change, there is an increase in the average annual air temperature every year. As we have already mentioned, rising air temperatures cannot be considered the only factor affecting the agricultural sector.

The risk to agricultural crop productivity is posed by the combination of ever-increasing global temperature with changes in precipitation, longer duration of heatwaves and

intense drought. Overall, we consider agriculture to be a sector that is significantly affected by climate change. Between 1980 and 2019, climate-related extremes in European Environment Agency (EEA) Member States caused economic losses totalling an estimated €446 billion. Weather- and climate-related extremes caused economic losses of assets estimated at EUR 738 billion during 1980 - 2023 in the European Union [1]. The average annual temperature in Slovakia increased by almost 2°C between 1881 and 2016, at a rate that has been accelerating in recent decades. In fact, during the years 2000-2020, the average temperature increase in the country of 0.065 °C per year significantly exceeded the world average (0.031 °C per year) [2].

Climate change presents an escalating challenge to agricultural sustainability, primarily through increased drought frequency and temperature variability. Drought is widely recognized as one of the most critical stressors limiting crop productivity, as it severely restricts water availability and triggers complex physiological and biochemical responses in plants [3]. Authors [4] identify droughts as among the most economically damaging natural disasters, with long-term impacts on ecosystems and rural livelihoods. In the Slovak context, [5] and [6] document regional climate shifts, noting that rising temperatures and uneven precipitation patterns are influencing crop viability, particularly in lowland areas. [7] further confirms the intensification of drought trends across Slovakia. These climatic pressures compel farmers to adapt their practices - modifying crop selection, sowing dates, and irrigation strategies - to mitigate risks and maintain yields. In response to climate change, Slovak farmers are increasingly adopting regenerative practices like no-till sowing and rotational grazing to improve soil health and reduce input costs. Despite limited uptake due to higher expenses and weak subsidies, field data show that regenerative wheat farming can be more profitable than conventional methods, supporting its role in climate adaptation [8]. Moreover, access to climate-resilient technologies and institutional support plays a crucial role in shaping adaptive behavior, especially in vulnerable regions like southern Slovakia where water scarcity is intensifying [9] [10], [11]. Our findings, consistent with those of [12], indicate that the extended vegetation period due to rising temperatures may offer opportunities for growing more crops. However, the benefits depend on how well farmers and

crop systems adapt to shifting precipitation, increased drought, and the risk of ground frosts during the growing season.

Higher temperatures and more frequent extreme weather events due to climate change are expected to lead to yield losses of current crop varieties in large parts of Europe [13]. The negative impact of warmer temperatures has already been observed in many European countries, with average crop production leading to a continent-wide decrease in yield of 2.5% for wheat and 3.8% for barley, over a 20-year period since 1989 [14]. However, it can be expected that increased CO₂ concentrations in the atmosphere will compensate for some yield losses and even lead to yield increases for cereals such as wheat in temperate regions such as Europe [15].

MATERIALS AND METHODS

This study investigates the influence of selected meteorological variables on the yields of three economically significant crops—wheat, maize, and sunflower—cultivated in the Slovak Republic. These crops represent a significant share of national agricultural output and are sensitive to meteorological fluctuations that directly affect production volumes, market stability, and farm-level profitability. To assess the impact of environmental stressors on yield performance, we employed multiple linear regression models using agroclimatic predictors with high economic relevance using key agroclimatic predictors: total atmospheric precipitation during the growing season, average air temperature across the national territory, soil temperature at a depth of 0–7 cm, and soil moisture at a depth of 7–28 cm. These variables were selected based on their agronomic relevance and the availability of consistent long-term datasets.

$$\begin{aligned} \text{crop yield in } t^{*ha-l} = & \beta_0 + \beta_1 \cdot \text{precipitation} + \beta_2 \\ & \cdot \text{air temperature} + \beta_3 \cdot \text{extreme drought} + \\ & \beta_4 \cdot \text{soil temperature (0–7 cm)} + \beta_5 \\ & \cdot \text{soil moisture (7–28 cm)} + \varepsilon \end{aligned} \quad (17)$$

Each predictor was processed as a quarterly time series spanning the period 2008–2023, allowing for the capture of seasonal dynamics and intra-annual variability. To account for the impact of extreme climatic events, a binary (dummy) variable representing the occurrence of extreme drought was incorporated into the models. Drought data were sourced from annual assessments published by the Slovak Hydrometeorological Institute (SHMI), which provide standardized evaluations of drought severity and spatial distribution.

Meteorological and environmental data used in this analysis were obtained from reputable sources, including the Slovak Hydrometeorological Institute (SHMI), the International Energy Agency (IEA), the Climate Change Knowledge Portal (World Bank), and Meteoblue. These platforms offer high-resolution datasets and validated climate indicators essential for robust modeling of crop-climate interactions.

RESULTS AND DISCUSSION

Recent climatological assessments indicate a statistically significant warming trend across Slovakia, with notable seasonal asymmetry. Observable shifts in temperature patterns over recent decades confirm that the country is already experiencing tangible effects of climate change. Rising average temperatures, altered seasonal dynamics, and an increased frequency of extreme heat events are particularly

evident in agricultural regions. These evolving climatic conditions are not only reshaping ecological systems but also presenting substantial challenges to long-term food security, land management, and agricultural resilience. According to Figure 1, the rate of warming was slightly higher in the warmer half of the year (April to September) than in the colder half (October to March). Between 2011 and 2016, the number of days with an average temperature above 27°C was five times higher than in the period 1951–1960, while days with an average temperature below -5°C fell by half.

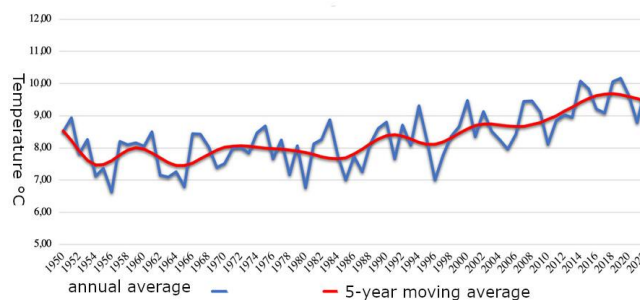


Figure 1 Average annual surface air temperature in Slovakia for the period 1950 – 2022

Source: Author's own processing based on data from Climate Change Knowledge Portal

Monitoring long-term temperature trends is essential for understanding the progression of climate change and its regional impacts. Figure 2 shows the average annual air temperature in Slovakia in °C during the monitored period and also its deviation from the normal, which is determined as the period from 1961 to 1990. The initial period is determined on the basis of the lowest impacts of climate change, so we will start from comparing the values with this period. The most significant average annual air temperature was recorded in 2022, when it was measured at up to 9 °C with a deviation of 2.6 °C. The year 2016 can be described as very to extremely warm compared to the normal of 1961 - 1990. The average territorial deviation from the normal is almost incomparable to 2018, as the average annual deviation of air temperature from normal increased by almost 1 °C over the course of two years. We consider 2010 to be the most optimal year during the monitored period, as the average annual air temperature deviates only minimally from normal.

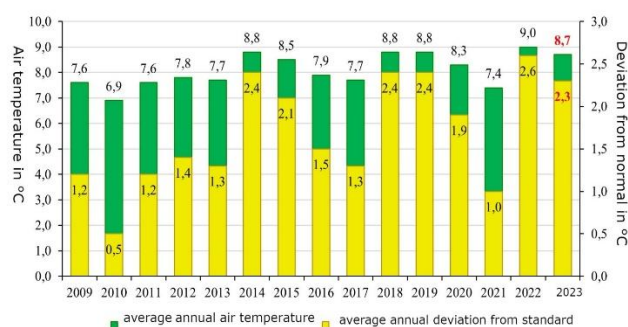


Figure 2 Average annual air temperature in Slovakia in °C

Source: Author's own processing based on data from the Slovak Hydrometeorological Institute (SHMI)

Precipitation variability is a critical component of regional climate dynamics and plays a decisive role in shaping hydrological regimes, agricultural productivity, and ecosystem resilience. In the context of Slovakia, long-term monitoring of annual precipitation totals provides valuable insight into the evolving nature of water availability under

chang Figure 3 presents the annual precipitation levels recorded across the territory of the Slovak Republic during the observed period, alongside calculated surpluses and deficits relative to the climatological norm. According to the Slovak Hydrometeorological Institute (SHMI), the average annual precipitation is approximately 762 mm, serving as a benchmark for evaluating deviations. The data reveal pronounced interannual fluctuations, with a subtle declining trend that may signal a transition toward drier conditions. Although annual totals remain within a range considered climatologically favorable, the increasing irregularity and seasonal imbalance of precipitation patterns pose significant challenges for water resource management, soil moisture retention, and long-term agricultural planning climatic conditions.

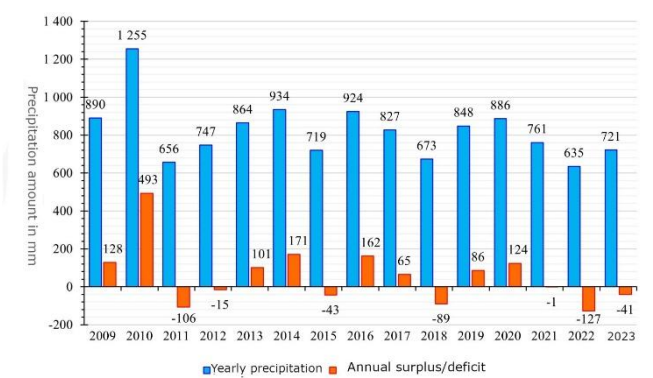


Figure 3 Total atmospheric precipitation in Slovakia in mm
Source: Author’s own processing based on data from the Slovak Hydrometeorological Institute (SHMI)

The results of the regression analysis provide empirical evidence on the sensitivity of crop yields to selected agroclimatic variables under the prevailing conditions of the Slovak Republic. Using a multivariate linear modeling framework, yield responses for wheat, maize, and sunflower were estimated as a function of quarterly meteorological and soil parameters over the period 2008–2023.

Table 18: Estimated Coefficients for Wheat, Maize, and Sunflower Yields in Slovakia (2008–2023)

Variable	Wheat	Maize	Sunflower
Intercept	-6.6914***	4.5169***	2.5586***
Precipitation	-0.3435**	-0.0148***	-0.0080***
Air Temperature	-0.0223	-0.2093	0.0389**
Drought	-2.0707**	-1.3484**	-0.7454**
Soil temperature at a depth of 0-7 cm	-0.583***	-1.9190**	-0.8188*
Soil moisture at a depth of 7-28 cm	0.0035**	-2.1160***	22.4001**

Notes: * for p < 0.1; ** for p < 0.05; *** for p < 0.01

The model incorporated total atmospheric precipitation, average air temperature, soil temperature (0–7 cm), soil moisture (7–28 cm), and a binary indicator for extreme drought events. The estimated coefficients reflect the marginal effects of each predictor on crop yield (t·ha⁻¹), allowing for

the identification of statistically significant relationships and the quantification of climate-induced production risks. These findings contribute to a deeper understanding of the biophysical and economic drivers of yield variability and offer a foundation for adaptive decision-making in agricultural planning and climate resilience strategies. When examining the relationships between hectare yields of selected crops and key environmental impacts we can conclude that each of the studied crops is relatively highly dependent on climatic conditions.

The regression analysis revealed distinct crop-specific sensitivities to key agroclimatic variables, underscoring the complex interactions between environmental stressors and agricultural productivity in the Slovak Republic. The estimated coefficients for wheat, maize, and sunflower yields (expressed in t·ha⁻¹) highlight both statistically significant and economically relevant relationships.

Precipitation

Precipitation exhibited a statistically significant negative effect on wheat yields (−0.3435**), suggesting that excessive rainfall during the growing season may lead to waterlogging, increased disease pressure, and delayed harvests. These conditions can result in substantial economic losses, emphasizing the need for improved drainage infrastructure and weather-indexed insurance mechanisms. For maize, the effect was smaller but still significant (−0.0148***), indicating that rainfall excess particularly during sensitive phenological stages can reduce profitability. In contrast, sunflower yields responded positively to precipitation, with a significant coefficient (+0.0389**), implying that this crop may benefit from increased moisture availability under warming conditions, potentially enhancing its economic attractiveness in future climate scenarios.

Extreme Drought

Drought was consistently detrimental across all crops, with the strongest negative impact observed for wheat (−2.0707**). This reinforces the vulnerability of wheat to water stress and highlights the economic imperative of investing in drought-resistant cultivars and supplemental irrigation systems. Maize also showed a significant negative response (−1.3484**), confirming its sensitivity to drought and the value of climate-resilient hybrids and timely irrigation. Sunflower, while less affected, still exhibited a significant yield reduction (−0.7454**), indicating that drought resilience remains a relevant consideration for sunflower producers.

Soil Temperature (0–7 cm)

Soil temperature varied markedly across crops. Wheat showed a strong positive response (−0.583***), suggesting that warmer soil conditions during early growth stages enhance yield potential. This finding supports agronomic strategies such as early sowing and soil warming techniques (e.g., mulching) to improve profitability. Conversely, maize exhibited a significant negative effect (−1.9190**), potentially due to oversaturation or poor drainage in warmer soils, which may impair root development. Sunflower also showed a smaller but significant negative response (−0.8188*), indicating that elevated soil temperatures may not be optimal for its growth, and adaptive management practices should be considered.

Subsoil moisture emerged as a critical yield determinant, particularly for wheat and sunflower. Wheat responded positively and significantly (+0.0035**), suggesting that maintaining adequate moisture at depth supports stable yields. This underscores the economic value of conservation tillage, organic amendments, and other soil water retention practices. Sunflower demonstrated a remarkably strong positive effect (+22.4001**), indicating that deep soil moisture is a key driver of yield and profitability. This finding supports investment in soil moisture monitoring technologies and crop rotations that promote deep rooting systems. In contrast, maize showed a significant negative response (−2.1160***), which may reflect its sensitivity to waterlogging or differences in root architecture.

Economic Implications

The regression findings reveal that yield sensitivity to agroclimatic variables has direct consequences for crop profitability in the Slovak Republic. Wheat demonstrates high vulnerability to drought conditions but benefits significantly from warmer soil temperatures during early growth stages. These sensitivities suggest that profitability in wheat production is closely tied to timely sowing and effective soil management practices. Maize, on the other hand, is particularly susceptible to excess moisture and elevated temperatures, indicating that its economic performance depends on precision irrigation and temperature regulation strategies. Sunflower yields show strong positive responses to deep subsoil moisture, highlighting its potential for high returns in regions with stable water reserves and well-structured soils.

The cost-benefit analysis of adaptation strategies underscores the economic viability of targeted interventions. Investments in irrigation infrastructure such as drip or subsurface systems can substantially mitigate drought-induced yield losses, especially for wheat and maize. In areas prone to waterlogging, drainage systems are economically justified to protect maize yields. Soil temperature regulation techniques, including mulching and no-till farming, offer cost-effective solutions for both sunflower and maize, enhancing root zone stability and thermal conditions. Furthermore, the adoption of moisture monitoring technologies, such as soil sensors and remote sensing platforms, can improve input efficiency, reduce production risk, and support data-driven decision-making at the farm level.

Strategic crop selection and rotation planning also play a critical role in optimizing profitability under variable climate conditions. Aligning crop choice with local soil profiles and climatic characteristics enhances yield stability and economic returns. Sunflower is particularly well-suited to zones with deep moisture availability, while maize performs best in well-drained soils with controlled water inputs. Wheat thrives in environments with moderate moisture and warmth, benefiting from early-season thermal accumulation. Incorporating rotational systems that improve soil structure and water retention - such as alternating deep-rooting and shallow-rooting crops can reduce input costs over time and enhance long-term farm resilience.

These insights provide a foundation for climate-smart agricultural planning, emphasizing the need for regionally tailored adaptation strategies that balance agronomic performance with economic sustainability.

CONCLUSIONS

Our research confirms that agroclimatic variability has a direct and measurable impact on crop profitability in the Slovak Republic. The regression analysis highlights distinct sensitivities among major crops as wheat, maize, and sunflower, each requiring tailored management strategies to maintain economic viability under changing climate conditions. Wheat's vulnerability to drought and its responsiveness to warmer soil temperatures emphasize the importance of timely sowing and soil care. Maize's susceptibility to excess moisture and heat calls for precision irrigation and thermal regulation, while sunflower's strong yield response to deep subsoil moisture positions it as a promising crop in regions with stable water reserves.

The economic analysis of adaptation strategies demonstrates that investments in irrigation, drainage, and soil temperature regulation are not only agronomically effective but also financially justified. Technologies such as moisture sensors and remote sensing enhance decision-making and reduce risk, supporting more resilient farm operations. Moreover, strategic crop selection and rotation planning aligned with local soil and climate profiles can optimize yields, lower input costs, and reinforce long-term sustainability.

In conclusion, climate-smart agriculture in Slovakia must be grounded in crop-specific responses, economic reasoning, and adaptive management. By integrating targeted interventions and informed decision-making, farmers can mitigate climate risks and harness emerging opportunities for profitable and resilient production systems.

Ultimately, the findings of this study reinforce the need for proactive and informed managerial decision-making in Slovak agriculture. As climate variability intensifies, farmers must not only respond to short-term weather fluctuations but also plan strategically for long-term resilience. This includes evaluating investment options, adjusting crop portfolios, and integrating climate data into operational planning. Supporting these decisions through targeted policy incentives, extension services, and access to climate information will be essential for safeguarding agricultural productivity and economic viability in the years ahead.

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Federated Data Spaces and Cloud-Edge Intelligence for Secure, Flexible, and Decentralized Energy Systems

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Abstract— Electrical power and energy systems are undergoing an unprecedented transformation, demanding urgent upgrades to make them more reliable, resilient and secure. In order to develop holistic risk management systems for the energy systems, there is a need for improving collection and homogeneous representation of data coming from legacy equipment and modern communication devices, i.e. IoT and DERs. The scope of this paper is to establish a framework for data collection mechanisms that should be developed in the frame of an energy data platform towards establishing a secure and trustful data sharing framework for all energy data value chain stakeholders. The proposed framework is under demonstration and evaluation in 3 demo sites around Europe and the preliminary evaluation actions are reported in this paper.

Keywords—*data sharing, privacy, security, IoT/DER, SCADA, federated environments*

INTRODUCTION

The European energy sector is undergoing a profound and multifaceted transformation, driven by two primary forces: decarbonization and digitalization. This dual shift is at the heart of the EU's Green Deal [1] and the REPowerEU [2] Plan, which set ambitious goals, including a 45% renewable energy target by 2030. This transition is necessary not only for mitigating climate change but also for enhancing energy independence and security in a volatile geopolitical landscape. Historically, the energy system was centralized and unidirectional, with large power plants delivering electricity to consumers. Today, this model is being replaced by a decentralized network where millions of Distributed Energy Resources (DERs), such as solar panels, wind turbines, electric vehicles (EVs), and battery storage systems, are integrated at the grid's edge. This new paradigm introduces significant challenges for traditional grid management. The intermittent nature of renewables and the dynamic, bi-directional energy flows from DERs can lead to grid instability, voltage fluctuations, and congestion, particularly at the distribution level.

The key to navigating this complexity is effective data and intelligence sharing among a diverse set of stakeholders, including Distribution System Operators (DSOs), aggregators, Local Energy Communities (LECs), and individual prosumers. However, the current data landscape is highly fragmented. Data is often trapped in proprietary systems and organizational silos, hindering the development of innovative, data-driven services that are essential for a resilient and efficient energy system. The lack of a unified data exchange mechanism prevents DSOs from gaining real-time visibility into their networks, makes it difficult for aggregators

to optimize flexibility services, and limits consumer participation in the energy market. To address these critical issues, a new, comprehensive framework is needed to create a trusted and interoperable data ecosystem. This paper proposes a Federated Energy Data Space framework, coupled with a Cloud-Edge Data and Intelligence Service Platform, designed to overcome existing barriers and unlock the full potential of a digitalized, decentralized energy sector.

THE FEDERATED ENERGY DATA SPACE: A PARADIGM FOR DATA SOVEREIGNTY AND INTEROPERABILITY

The Federated Energy Data Space is a conceptual and architectural framework designed to enable secure and sovereign data sharing without a single, centralized authority. Unlike traditional models that require pooling all data into a monolithic repository, this framework allows data providers to retain full control over their data while making it available for specific, predefined purposes. This model is built on two core principles: data sovereignty and interoperability. Data sovereignty ensures that the data owner always controls who can access their data and for what purpose, fostering trust and legal compliance. Interoperability guarantees that different systems and data formats can seamlessly communicate with each other, eliminating technical silos.

The core components of this framework are essential for building a robust and collaborative data ecosystem:

- **Trust and Governance:** This element establishes the foundational "rulebook" of the data ecosystem, comprising a comprehensive set of legal, business, and technical policies and standards for data exchange. It's the bedrock upon which trust is built. By adopting principles from pioneering initiatives like the International Data Spaces Association (IDSA[3]) and Gaia-X[4], the framework embeds data sovereignty as a core tenet. This means data owners retain full control over their data, defining precisely who can access it and for what purpose.

The governance model ensures compliance with relevant legal frameworks, such as the GDPR, and establishes clear guidelines for data licensing, usage policies, and liability. This clarity builds confidence among all participants, from large corporations to small startups, encouraging broader participation. It creates a secure and trusted environment where stakeholders can share sensitive or valuable data with the cryptographic assurance that it will be used exactly as agreed upon. The governance structure itself is often managed by a neutral entity or a

consortium of participants, ensuring fair and transparent enforcement of the rules for everyone.

- **Secure Data Connectors [5]:** Secure Data Connectors are the technological enforcers of the governance rules, acting as standardized, secure gateways for data exchange. These components facilitate direct, peer-to-peer (P2P) data sharing between participants without routing the data through a central platform or intermediary. Each participant deploys a connector within their own IT infrastructure, giving them a sovereign endpoint to the data space.

Functionally, a connector acts as a policy enforcement point. When a request for data is made, the connector first verifies the identity and authorization of the requesting party. It then consults the data usage policies defined by the data owner and only permits the exchange if all conditions are met. This direct-connect, policy-enforced approach dramatically enhances security and data sovereignty. Furthermore, it eliminates single points of failure and performance bottlenecks that are common in centralized data architectures, leading to a more resilient and scalable ecosystem.

- **Semantic Interoperability [6]:** For data to be truly valuable, it must be understood. Semantic interoperability ensures that data from diverse sources is not just accessible but also meaningful and usable across the ecosystem. This is achieved by implementing a common ontology and shared data models. The ontology defines a common vocabulary and the relationships between key concepts within the domain (e.g., defining what a "smart meter" is and how it relates to a "grid connection point"). The data models then provide a standardized structure for the data itself (e.g., specifying that a smart meter reading must include a timestamp, a consumption value, and a unit of measurement).

This semantic layer acts as a universal translator. It harmonizes data from various sources—such as smart meters using different protocols, EV charging stations from multiple vendors, and proprietary weather sensors—into a consistent format. Without this, the ecosystem would be a "Tower of Babel," where data is technically available but practically useless. By ensuring all participants speak the same "data language," semantic interoperability enables the seamless integration of services and the development of complex, cross-domain applications.

- **Federated Identity Management:** A decentralized, or federated, system for authenticating and authorizing participants and their digital assets is vital for security and scalability. Instead of a single, central authority that manages all identities, a federated model allows participants to "bring their own identity" from a trusted identity provider. This ensures that only verified and trusted entities can participate in the data space. This system manages the identities of not just organizations and users, but also their data-providing assets like IoT devices, APIs, and even the connectors themselves. Using technologies like **verifiable credentials** and digital certificates, each entity can cryptographically prove its identity and its right to access specific data. This approach prevents unauthorized access, creates a reliable audit trail for

all transactions, and maintains the overall integrity of the ecosystem. It simplifies onboarding for new participants, as they can leverage their existing identity management systems, thereby reducing friction and encouraging the network to grow.

This framework moves beyond the conventional, centralized data platform model to a distributed, collaborative ecosystem. It fosters a more dynamic and democratic energy sector where data is viewed not as a commodity to be hoarded but as a shared resource for the common good.

THE CLOUD-EDGE DATA AND INTELLIGENCE SERVICE PLATFORM

To operationalize the principles of the Federated Energy Data Space, a multi-layered Cloud-Edge Data and Intelligence Service Platform is proposed. This platform is specifically designed to handle the complexity and sheer volume of data generated by DERs. It leverages the strengths of both cloud and edge computing to process data efficiently and securely where it is most needed.

- **Edge Layer:** This layer is located at the physical source of the data—at substations, within local energy communities, or at individual households. Its primary function is to perform real-time data processing and analytics. This proximity to the data sources significantly reduces latency, which is critical for real-time grid management. A key feature of the edge layer is federated learning, a privacy-preserving technique that allows AI models to be trained on local data without the data ever leaving the device. This is crucial for applications that involve sensitive data, such as energy consumption forecasting and predictive maintenance, as it balances the need for powerful analytics with stringent privacy requirements.
- **Cloud Layer:** The cloud layer provides the centralized intelligence and coordination necessary for grid-wide services. It aggregates high-level insights from the edge layer, runs advanced analytics, and hosts AI-enabled orchestration mechanisms. These mechanisms function as the central nervous system of the platform, coordinating actions across diverse stakeholders. For example, they can coordinate DSOs to manage grid stability, aggregators to dispatch flexibility services, and market platforms for price signals. The cloud layer also supports long-term planning, market integration, and the development of new, innovative energy applications.

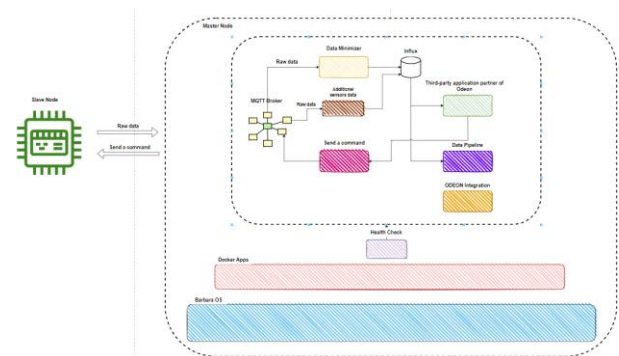


Figure 38 Edge layer architecture snapshot

The seamless integration of these two layers creates a powerful, end-to-end architecture.

The edge layer provides the local, real-time intelligence for dynamic and localized grid management, while the cloud layer provides the holistic view and coordination required for a resilient and stable energy system.

DATA INTEROPERABILITY AND GOVERNANCE FRAMEWORK

Effective data handling within the Federated Energy Data Space is underpinned by a robust data interoperability and governance framework. This framework relies on configurable data pipelines that manage the end-to-end flow of data, from provider preprocessing to final storage and cataloguing. The process ensures that data is standardized, secure, and ready for use.

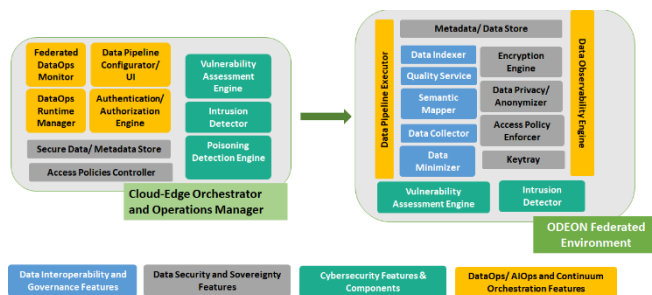


Figure 39 End to end framework architecture

The data flow begins with preprocessing at the data provider's end. This involves extracting and transforming data into a compatible format and, if needed, developing APIs for exposure. A key element, as seen in projects like the proposed, is the use of an IoT gateway. This gateway handles multiple protocols, such as MQTT and CoAP, and implements data minimization techniques, ensuring that only valuable data enters the data space. It also provides the necessary connectors to ensure compatibility with standardized protocols.

Once preprocessed, data is ingested into the environment via the data pipelines, which are configured and executed in distinct phases:

- **Data Collection:** This initial phase focuses on acquiring data from its source. Recognizing that data providers operate with diverse technologies and protocols, the framework offers maximum flexibility. Providers define their preferred ingestion method, choosing from a comprehensive suite of options:
 - **Manual Uploads:** Ideal for static or historical datasets, allowing users to upload files (e.g., CSV, JSON, Parquet) directly through a secure portal.
 - **Automated API Calls:** For systems that expose data via REST or GraphQL APIs, the pipeline can be configured to pull data on a schedule (e.g., hourly, daily) or triggered by specific events.
 - **Pub/Sub Mechanisms:** For real-time data streams, the pipeline can subscribe to messaging brokers like MQTT or Apache Kafka. This event-driven approach is perfect for IoT sensor readings and other time-sensitive information.

- **Preconfigured Connectors:** To simplify integration with common industry systems, the platform includes specialized connectors. These connectors handle the protocol-specific complexities for standards like OCPP (for EV charging stations), MODBUS and OPC-UA (for industrial equipment and SCADA systems), abstracting the technical details away from the data provider.

This adaptable approach ensures a low barrier to entry and allows the ecosystem to easily accommodate new data sources as it grows.

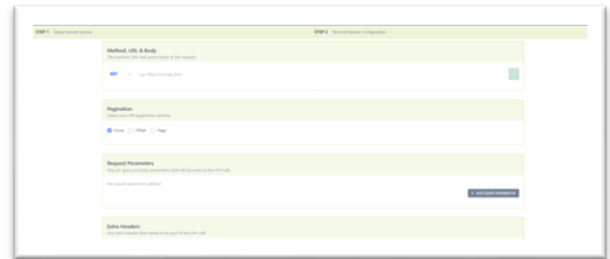


Figure 40 Configuration of data collection process

- **Semantic Mapping:** The system maps dataset fields to a common information model. This is a critical step for achieving semantic interoperability. Providers can manually correct and enrich these mappings, ensuring that data from different sources is consistently interpreted. The process is a human-in-the-loop workflow:
 - **Automated Suggestion:** The system first analyzes the source data's schema and suggests initial mappings based on field names and data types (e.g., mapping a source field named `temp_celsius` to the CIM field temperature).
 - **Manual Refinement:** Data providers then use an intuitive graphical interface to review, correct, and enrich these mappings. They can apply simple transformations, such as converting units (e.g., pounds to kilograms) or standardizing formats (e.g., date strings to ISO 8601).

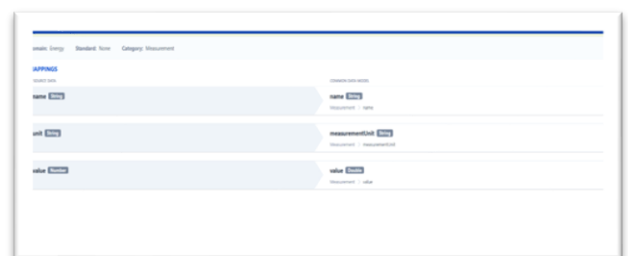


Figure 41 Configuration of semantic mapping process

- **Data Quality Enhancement:** This phase involves defining rules and using machine learning (ML) techniques to address common data quality issues, such as missing values, duplicates, and outliers. This ensures that the data used for analysis and decision-

making is reliable and accurate. Key processes in this phase include:

- **Validation Rules:** Providers can define custom rules to enforce data integrity (e.g., energy_consumption must be a positive number, location_coordinates must be within a valid range).
- **Missing Value Imputation:** The system can automatically handle missing data points using various strategies, from simple statistical methods (e.g., filling with the mean/median) to advanced ML models that predict the missing value based on related data.
- **Outlier and Anomaly Detection:** ML algorithms trained on historical data identify and flag values that deviate significantly from the norm, such as a faulty sensor reading or a data entry error.
- **Deduplication:** Sophisticated algorithms find and merge duplicate records, even when they are not exact matches.

By the end of this phase, the data is clean, reliable, and accurate—transformed from raw information into a trustworthy asset ready for sophisticated analysis and decision-making.

DATA SECURITY AND SOVEREIGNTY

The Data Security & Sovereignty Block is a dedicated set of configurable services executed within the data pipelines to safeguard all data assets. This block is integral to the framework's design, ensuring robust access control, data privacy, and end-to-end security. These security steps are complementary to the interoperability processes and are seamlessly integrated into the same configurable pipeline structure. Key security measures include:

- **Data Anonymization:** This is an optional but powerful service that allows data providers to surgically remove or obscure Personally Identifiable Information (PII), striking a crucial balance between data utility and individual privacy. Before sharing a dataset, a provider can apply a range of sophisticated techniques to minimize the risk of re-identification. The platform supports various anonymization methods, including:
 - **k-Anonymity:** This technique ensures that any individual in the dataset cannot be distinguished from at least k-1 other individuals. It achieves this by generalizing quasi-identifiers.
 - **Differential Privacy:** Considered the gold standard, this method adds mathematically calibrated statistical noise to the data. This makes it virtually impossible for an attacker to determine if any single individual's information is present in the dataset, providing a provable privacy guarantee while preserving the dataset's aggregate statistical properties.

By offering these tools, the framework empowers data providers to confidently share sensitive data for

research and analysis while adhering to strict privacy regulations like GDPR.

- **Data Encryption:** Data protection is enforced both when data is moving between participants and when it is stored. The framework implements robust encryption as a fundamental security pillar.
 - **Encryption in Transit:** All data exchanged in peer-to-peer (P2P) transactions is protected using industry-standard transport protocols like Transport Layer Security (TLS) 1.3. This creates a secure, encrypted tunnel between the data consumer's and provider's connectors, preventing eavesdropping, tampering, or man-in-the-middle attacks as data traverses the internet.
 - **Encryption at Rest:** Beyond securing data in transit, the framework provides options for encrypting data while it is stored in databases or file systems. Using strong algorithms like AES-256, this measure ensures that even if physical storage is compromised, the data remains unreadable without the correct cryptographic keys.

Secure management of these cryptographic keys is paramount and handled through integrated key management services, ensuring that protection is never compromised.

- **Access Policies Management:** This is the central nervous system for data governance, providing the means to define, control, and enforce who can access data and what they can do with it. Going far beyond simple allow/deny rules, the system enables highly granular, dynamic policies based on the principle of Attribute-Based Access Control (ABAC). A data provider can create policies that evaluate a richset of attributes before granting access, such as:
 - **Identity Attributes:** The role, organization, or specific identity of the requester.
 - **Resource Attributes:** The sensitivity level or type of the requested dataset.
 - **Environmental Attributes:** The time of day, geographic location, or security status of the device making the request.

Crucially, this extends to **Data Usage Control**, where policies remain attached to the data even after it has been accessed.

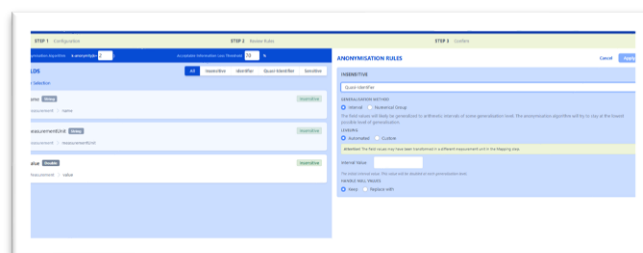


Figure 42 Configuration of data anonymization process

Following the execution of these services, additional processes handle data and metadata information. Data storage

involves selecting the appropriate location, either a centralized cloud data space or federated data spaces, which affects the pipeline's execution and data storage repository. Data indexing is also crucial for handling metadata, which enables dataset profiling and searchability. This includes defining both static and dynamic metadata and access policies for the metadata itself.

DATA CYBERSECURITY BLOCK

The Cybersecurity Block is a critical component designed to secure the federated environments against the unique cyber threats of a decentralized energy system. It operates in two phases: Design-time for initial configuration and Runtime for continuous, proactive protection.

The Intrusion Detection and Vulnerability Assessment process is initiated during the design-time phase, where security administrators establish the foundational security posture. This involves deploying monitoring agents across the stack and configuring the Intrusion Detector based on the system's specific topology and domain knowledge. During the runtime phase, a continuous cycle of protection begins. Behavioral monitoring is constantly performed by the deployed agents, feeding data to a centralized intrusion detection system designed to identify anomalies. A subsequent vulnerability assessment is triggered by any detected event, mapping it to known threats, calculating the overall risk, and storing the output on the ledger for an immutable audit trail. This dynamic process can automatically trigger system reconfiguration or the application of mitigation measures to neutralize threats.

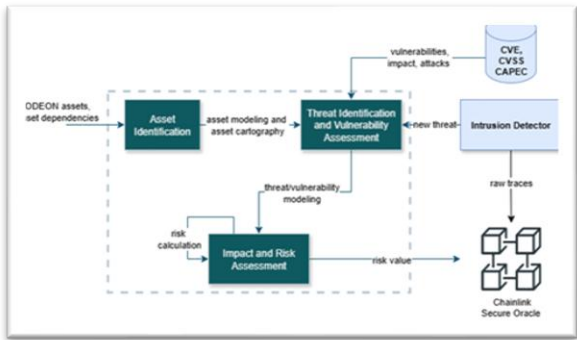


Figure 43 Intrusion Detection and Vulnerability Assessment

Similarly, the Poisoning Detection process begins with a critical design-time phase where machine learning models are trained using both normal behavioral data and a pool of known poisoning attacks to recognize adversarial manipulations. During runtime, the system leverages these trained models to continuously monitor data, detecting deviations that indicate a potential ML poisoning attack. This ensures the proper and ethical execution of the platform's ML and AIOps processes by guarding against malicious data manipulation.

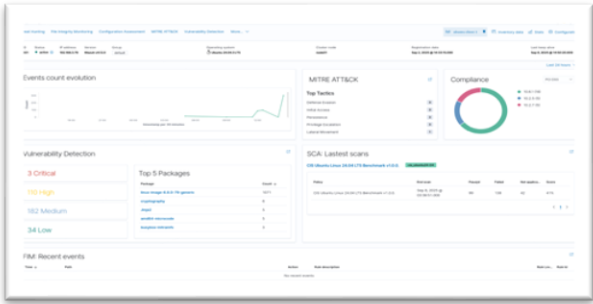


Figure 44 Intrusion Detection Dashboard Overview

DATA ORCHESTRATION AND OPERATIONS MANAGEMENT

At the heart of the orchestration subsystem is the DataOps Runtime Manager (DRM). The DRM is responsible for the optimized and reliable execution of data workflows across the various data spaces. It embodies a DataOps approach, ensuring that data pipelines are not just static workflows but are dynamically managed and optimized for performance and resource efficiency.

- When a data processing request is triggered, the DRM first consults a catalogue to assess the required resources and expected performance metrics. It then cross-references this with a catalogue of available IT infrastructure. If resources are insufficient, an error is returned. Otherwise, the DRM performs an optimal resource allocation and deploys the workflow via the Data Pipeline Executor.

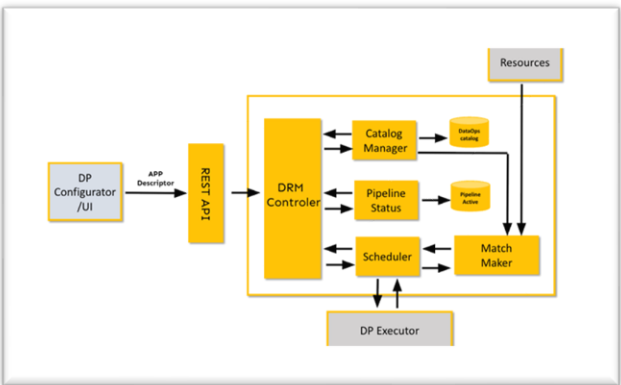


Figure 45 DataOps Runtime Manager architecture overview

- A DataOps Runtime Monitoring module is also made available for low-level monitoring of the resources used for executing data pipelines. This module is complemented by the Data Observability Engine (DOE), which monitors the execution's telemetry data in real-time. Should the DOE detect a remediable anomaly, such as a performance degradation, it notifies the DRM. The DRM can then dynamically reschedule the workflow or migrate it to another node with more resources to maintain performance and data integrity.

This robust orchestration system ensures continuous management, traceability, and observability through data tracking, process monitoring, and proactive alerting. It guarantees that the entire data ecosystem operates efficiently and reliably, which is critical for real-time grid management.

USE CASES AND ENVISIONED VALIDATION

The proposed framework has the potential to unlock a wide range of transformative use cases across the entire energy value chain, from grid management to consumer empowerment.

- **Real-time Flexibility Activation:** DSOs can use the platform to identify and activate flexibility services from DERs to alleviate grid congestion. For example, during a period of high demand, the system can send a signal to a fleet of EVs to pause charging for a specified time. This is a critical tool for managing the intermittency of renewable energy sources and maintaining grid stability. The framework provides the necessary real-time data exchange and orchestration capabilities for this to happen at scale.
- **Predictive Grid Management:** By analyzing data from smart meters, DERs, and weather forecasts, the platform can predict potential grid issues, such as voltage sags or overloads, before they occur. The AI-enabled orchestration mechanisms can then proactively take corrective action, such as adjusting voltage regulators or dispatching a demand-response signal, thereby improving grid resilience and reliability.
- **Human-Centric Energy Services:** The framework empowers prosumers and Local Energy Communities by providing them with the tools and data to optimize their energy consumption, participate in local flexibility markets, and even sell excess energy to their neighbors. This fosters a more inclusive and democratic energy system where citizens are active participants rather than passive consumers. For example, a community can pool its DERs and use the platform to collectively manage its energy profile and optimize local energy exchange.

The effectiveness of this framework will be validated through large-scale pilot projects across multiple European countries. These pilots will demonstrate the technical feasibility and commercial viability of the proposed solution in diverse regulatory and market environments. The validation process will involve a wide range of stakeholders—DSOs, aggregators, communities, and prosumers—to ensure the framework meets the needs of the entire energy ecosystem. The results of these pilots will be instrumental in identifying and addressing any remaining barriers to widespread adoption.

CONCLUSION

The decarbonization and digitalization of the European energy sector are essential for achieving the EU's ambitious climate and energy goals. The current fragmented and siloed data landscape poses a significant barrier to this transition. This paper has proposed a Federated Energy Data Space framework, coupled with a Cloud-Edge Data and Intelligence Service Platform, to create a secure, interoperable, and sovereign data ecosystem. By enabling trusted data exchange, leveraging advanced AI and federated learning, and implementing a robust DataOps approach, this framework can accelerate the deployment of data-driven energy services. It empowers citizens to become active participants in the energy transition, reinforces the resilience and security of future energy systems, and provides the foundation for a more sustainable and decentralized energy model. The envisioned

large-scale validation will be a crucial step in proving the framework's potential to usher in a new era of decentralized, digital, and sustainable energy for Europe.

ABBREVIATIONS

ABAC: Attribute-Based Access Control
AI: Artificial Intelligence
AIOps: Artificial Intelligence for IT Operations
CIM: Common Information Model
DER: Distributed Energy Resource
DSO: Distribution System Operator
GDPR: General Data Protection Regulation
IDSA: International Data Spaces Association
IT: Information Technology
LEC: Local Energy Community
PII: Personally Identifiable Information
SCADA: Supervisory Control and Data Acquisition

ACKNOWLEDGMENT

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Visualization Tool for Hydro Power Plant Operators: Interactive Data Monitoring & Surveillance on Large Screen with Voice Warning

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Abstract - The Visualization Tool is an application, designed to provide hydro power plant operators with real-time monitoring capabilities. The tool integrates clear graphical representations, automated alerts, voice warnings, and interactive parameter management to ensure efficient supervision of operational parameters. The application was developed for The Di-Hydro Project using Python and its graphical libraries: Tkinter for the interface [4] and enhanced with matplotlib [9] and pandas [7], it runs as lightweight executable application connected to the control room database. Displayed on large TV screens, the solution ensures operators can visualize current values, pre-alerts, alerts, and tendencies from up to ten meters away, offering an accessible and cost-effective alternative to SCADA systems.

Keywords - visualization, monitoring, surveillance, hydro, operators

Table 5: Abbreviations

Acronym	Description
AP2K	ACCENT PRO 2000 S.R.L.
AM	Air-Mouse
CORS	Cross-Origin Resource Sharing
CSV	Comma-Separated Values
DT	Digital Twin
GUI	Graphical User Interface
HDMI	High-Definition Multimedia Interface
HP	Hydro Power
HPP	Hydro Power Plant
HTTP	Hypertext Transfer Protocol
ms	Milliseconds
Numpy	Numerical Python
O&M	Operations & Maintenance
PC	Personal Computer
PPC	Public Power Corporation
PyPI	Python Package Index
RESTful API	Representational State Transfer Application Programming Interface
RF	Radio Frequency
SCADA	Supervisory Control and Data Acquisition.
TV	Television
UI	User Interface
UPS	Uninterruptible Power Supply
USB	Universal Serial Bus
VT	Visualization Tool
WSGI	Web Server Gateway Interface

INTRODUCTION

Modern HPP operators require advanced monitoring and visualization systems to ensure stability, efficiency, and safety. The presented Visualization Tool provides operators with an interactive and intuitive interface for real-time data surveillance.

Developed entirely in Python programming language, the application offers robustness and low implementation costs while maintaining adaptability. It features clear graphical displays of turbine, well, gate, and main status parameters, alongside real-time alerts and warnings. The integration of computer-generated voice messages further enhances operator's awareness, reducing the risk of overlooked anomalies. [5]

The Visualization Tool is developed for The Di-Hydro Project and the parameters are received from the partners involved. So, we get the data from PPC's Ilarionas HPP, from sensor data or just other measurements.

This project has received funding from the European Union's **Horizon Europe research and innovation programme** (under the topic HORIZON-CL5-2022-D3-03-08/Development of digital solutions for existing hydropower operation and maintenance and responds to the Call HORIZON-CL5-2022-D3-03/Sustainable, secure and competitive energy supply) under grant agreement No 101122167.

I. EASE OF USE

The system prioritizes user-friendly interaction by offering a simple and clear graphical user interface. Operators can quickly identify current parameter values, trend tendencies, and alert states thanks to visual cues such as color-coded warnings and blinking indicators.

An Air-Mouse and TV remote control provide wireless interaction, eliminating the need for a keyboard or traditional mouse. The tool is displayed on a large-format TV screen, visible up to ten meters away, ensuring that multiple operators can simultaneously monitor data in the control room. Pop-up windows allow quick adjustment of pre-alert and alert thresholds, making the tool both adaptable and responsive to operational needs.

II. VISUALIZATION TOOL'S FUNCTIONALITIES & ELEMENTS

The Visualization Tool addresses three practical needs:

- Continuous, synchronized display of live and historical parameter relevant to turbine operation and ecological impacts.
- Tight coupling between sensor data and predictive outputs (nowcasts/forecasts and anomaly detection) to support proactive operator decisions.
- A minimal hardware footprint and modular software stack suited for pilot deployments and control rooms.

The VT is a client-side application that runs local visualization executable and communicates with a lightweight Flask test/data gateway [1] (CORS enabled where needed [2]). The reference hardware consists of a PC, large TV display, UPS, an Air-Mouse for motion control, and a lockable on-wheels frame for easy deployment.

Local plant telemetry (SCADA/PLC): On-site PLC tags (temperature, voltage, current, RPM, exciter values) are polled/streamed into the local gateway and exposed to the VT for the Turbine and Main Status panels. The VT supports site-specific tag mappings so no deep recoding is required when deploying at new plants.

Hydro-meteorological forecasts: Inflow and reservoir forecasts (e.g., Waterjade) are ingested to inform gate/turbine scheduling and risk anticipation.

Water quality & environmental sensors: Streams from partners (e.g., INO/AIMEN) carry turbidity, dissolved oxygen, sediment load and biodiversity indices. These feed a dedicated Water Quality view and can be combined with Digital Twin outputs for simulation.

All inputs are normalized and annotated with provenance before rendering; this ensures traceability and confidence estimation for operator decisions.

The VT UI is organized into three primary tabs: Turbine, Water Quality, and Maintenance. The interface prioritizes clarity, rapid situational awareness, and lightweight interactions suitable for control-room contexts.

The Turbine tab contains up to three identical sub-tabs (one per turbine). Each sub-tab presents six key parameters: Temperature, Voltage, Current, RPM, Exciter Voltage and Exciter Current.

For each parameter the UI exposes:

- Real-time value and timestamp; [12][13]
- Pre-alert, alert and limit thresholds (editable by the operator);
- Tendency graph showing recent history (last 20 values) with threshold lines and hover tooltips; [9][10]
- A clear/acknowledge button and a blinking visual indicator when thresholds are exceeded;
- Voice alerts (text-to-speech) that announce parameter, turbine number and severity level. [5]

Table 1: Turbine Tab Parameters

Type of Display	Parameters Displayed	Responsible Partner	Use Case Application Partners

Turbine Parameters & Status	a) Temperature b) Voltage c) Current d) RPM e) Exciter Voltage f) Exciter Current	AP2K	PPC - Greece
Well & Gate Valve	a) Water Level b) Compressor Pressure	AP2K	PPC - Greece
Main Status	a) Diesel Engine (ON/OFF) b) Exciter (ON/OFF) c) Turbine (ON/OFF) d) Disconnectors (ON/OFF) e) p10 (ON/OFF) f) p20 (ON/OFF)	AP2K	PPC - Greece

Graphs are rendered with embedded matplotlib canvases [9] and include interactive cursors for precise time/value inspection with mpcursors. [10] Thresholds are adjustable via pop-ups and immediately update the trend overlays so operators can tune sensitivity on-the-fly.

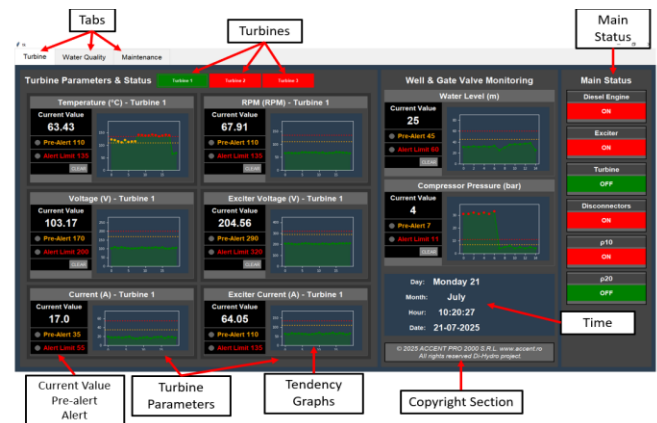


Figure 1: Turbine Tab

The Water Quality tab uses structured tables and graphs to display Current Data, Input Data (operator entries), Current Output and Digital Twin Output, all for a consistent set of hydrological parameters: head, power, reservoir level, river flow, sediment load, turbine efficiency, water temperature and volume. A weekly rainfall forecast graph provides environmental context influencing inflow and sediment dynamics.

Operator inputs are instrumented with visual status indicators (green = default/unmodified, red = modified) and stored with provenance for subsequent processing.

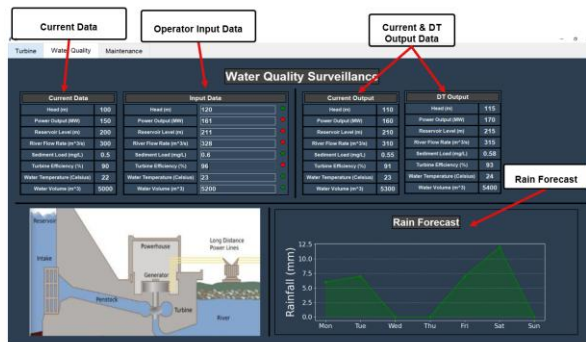


Figure 2: Water Quality Tab

The Maintenance tab provides a left-hand real-time monitoring panel (gauges with thresholds) and a right-hand interactive maintenance timeline. The timeline displays predictive (green), periodic (orange) and programmed (red) maintenance windows; operators can modify dates/durations and inspect tooltip details (start/end).

Table 2: Water Quality Parameters

Type of Display	Parameters Displayed	Responsible Partner	Use Case Application Partners
Water Quality Surveillance	a) Head b) Power Output c) Reservoir Level d) River Flow Rate e) Sediment Load f) Turbine Efficiency g) Water Temperature h) Water Volume	AP2K	PPC - Greece

A vertical navigator lists equipment sets (Turbine/Generator/Intake groups) for quick selection.

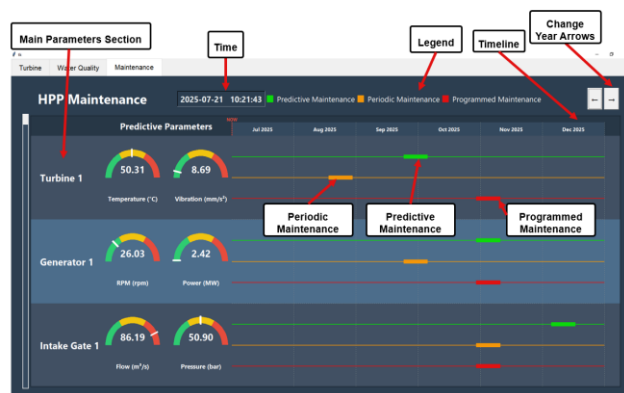


Figure 3: Maintenance Tab

Interaction innovations:

- Air-Mouse control: Motion-based input enables hygienic, one-hand control of the interface where physical keyboards/mice are impractical;

- Voice alerts: Offline text-to-speech provides immediate audible notifications, improving operator reaction times; [5]
- Hover tooltips & pop-ups: Allow detailed inspection without cluttering the main view.

Table 3: Maintenance Parameters

Type of Display	Parameters Displayed	Responsible Partner	Use Case Application Partners
Maintenance	a) Turbine b) Generator c) Intake Gate	AP2K	PPC - Greece

The VT is implemented in Python using a modular, class-based architecture that separates display, data processing and server concerns. The principal classes and responsibilities are:

- *HPPMonitoringApp*: Main application orchestrator initializes UI, tabs, periodic updates and threading; [11]
- *GraphDisplay*: Manages embedded matplotlib graphs, threshold lines, and interactive cursors; [9][10]
- *ValueDisplay*: Encapsulates parameter logic, validation, threshold comparison and current value rendering;
- *RectangleIndicator*: Renders ON/OFF binary status elements for main subsystem indicators;
- *TimeDisplay*: Provides the live clock and timestamp formatting; [12][13]
- *CustomPopup*: Handles alert dialogs, audio callbacks and acknowledgment flows. [5]

Concurrency is handled using threading, queue and *root.after()* loops so the GUI remains responsive while polling or processing background inputs. [11][14][4] *CSV*, *pandas* and *numpy* are used for data persistence and manipulation; *Flask* (with *CORS*) forms the local gateway used during testing and demonstration. [6][7][8][1][2]

HARDWARE, DEPLOYMENT & PILOT CONSIDERATIONS

The VT was designed to run on commodity hardware: a standard Windows 11 PC and a large TV for the operator display, protected by a small UPS. For pilot deployments (e.g., PPC/Iarionas) the software is packaged as a standalone executable; site-specific tag mappings and small customizations are applied without full re-engineering. The relocatable on-wheels frame facilitates temporary installations and demonstrations.

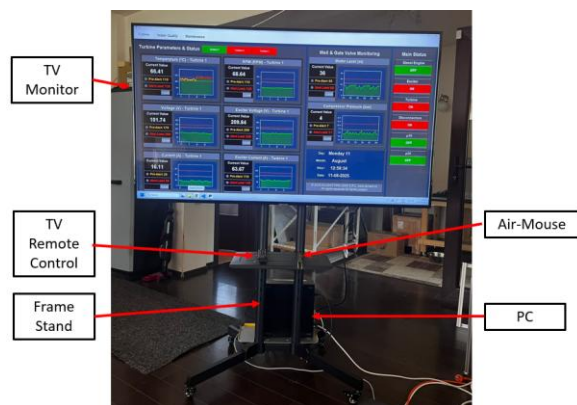


Figure 4: Hardware Setup

Security considerations for production deployments include: hardened network boundaries, authentication for configuration panels, and integration to plant historians for read-only access where required.

In the PPC/Illarionas pilot context, VT customization involved mapping local SCADA tags, integrating a subset of INO/AIMEN water quality streams, and rendering short-term inflow forecasts. During testing the VT proved effective at surfacing leading indicators (e.g., rising sediment load correlating with decreased turbine efficiency) enabling operators to test gate strategies in the simulation environment before acting on the plant.

Quantitative evaluation metrics to be collected during extended pilots include: [6][7][12][13]

- Time-to-detect (alerts) vs. baseline SCADA alarms;
- Operator response time to voice/screen alerts;
- Accuracy of predictive inputs vs. observed outcomes;
- Usability metrics from operator feedback sessions.

Table 4: Hardware Specifications

Component	Specifications
PC	Intel Core I5
TV Monitor	Samsung, Resolution:1920x1080, Diagonal: 65"/165cm Width: 145 cm, Height: 84cm
Stand	Frame stand with lockable wheels and tray
Air-Mouse	Size: 14x4.5cm
TV Remote Control	Samsung Remote Control

CONCLUSIONS

The Di-Hydro Visualization Tool provides a practical, extensible and operator-focused HMI for small and medium HPPs. By unifying telemetry, environmental monitoring and predictive analytics, the VT helps bridge the gap between raw sensor data and actionable operational decisions. Its low hardware cost, modular architecture and emphasis on provenance and usability make it a strong candidate for pilots and scaled deployments in the Di-Hydro ecosystem.

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Global Carbon Intensity and Decoupling Trends: A Data-Driven Analysis for Climate Policy

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Abstract— This study uses a multidimensional analytical framework on a global scale to deeply examine the complex relationship between economic growth and carbon emissions. The dataset used is obtained from the Our World in Data (OWID) platform, which includes indicators such as annual country-level carbon dioxide (CO₂) emissions, gross domestic product (GDP), and primary energy consumption from 1990 to 2022. This comprehensive database provides a solid basis for examining long-term trends and cross-country differences. In the first stage of the study, a cluster analysis was conducted using 2022 data to examine the carbon efficiency of countries. In this analysis, CO₂ emissions per GDP and CO₂ emissions per unit of energy consumption were standardized, and an optimal three-cluster solution was obtained using the k-means algorithm, reflecting the carbon intensity performance of countries. The resulting groups were labeled as "Low Intensity," "Medium Intensity," and "High Intensity" clusters, respectively. These clusters were visualized on a global map by combining them with the country's ISO-3 codes, and important inferences were provided about regional/national carbon efficiency profiles. This clustering revealed that countries with different levels of economic development may exhibit similar emission profiles, highlighting the need for a customized rather than a general approach in policy design. Secondly, a multiple linear regression model was developed to identify the main drivers of CO₂ emissions. This modeling confirmed that GDP and primary energy consumption have statistically significant roles in explaining emission levels. These findings support that economic growth and energy demand management should be at the core of emission reduction strategies. Finally, the study examined in depth the dynamics of the decoupling between economic growth and carbon emissions. A decoupling index was calculated for each country based on year-to-year changes in CO₂ and GDP. The global trend was visualized by calculating annual averages. This analysis provided important insights into the extent to which sustainable low-carbon economic growth has been achieved over time. By combining clustering, regression, and decomposition methods, this study provides a comprehensive assessment of carbon intensity trends. It offers a scientific contribution for designing more targeted and country-specific climate mitigation policies. Our findings underscore the necessity for tailored strategies that account for the distinct economic and environmental conditions of individual countries in combating global climate change.

Keywords— carbon intensity; economic growth; energy consumption; k-means clustering; decoupling analysis

I. INTRODUCTION

The escalating threat of climate change, primarily driven by anthropogenic carbon emissions, has placed the concept of sustainable economic development at the forefront of

global policy discourse. The traditional growth model, heavily reliant on fossil fuels, has long been associated with a corresponding increase in carbon dioxide (CO₂) emissions. However, as nations commit to international climate agreements such as the Paris Agreement, there is a growing urgency to achieve a decoupling of economic growth from carbon emissions—a state where GDP can grow without a proportional increase in CO₂ output.

The existing literature on this relationship often focuses on aggregate global or regional trends, which can obscure the significant diversity in national economic structures and environmental policies. A one-size-fits-all approach to climate policy, while administratively convenient, risks being ineffective and inequitable. A more nuanced, data-driven understanding of how different countries perform in terms of carbon efficiency is essential for designing targeted and effective climate mitigation strategies. This study addresses this research gap by proposing a multidimensional analytical framework that combines statistical clustering, regression analysis, and decoupling trend assessment to provide a comprehensive, country-specific perspective on the nexus between economic activity and carbon emissions. The objective is to move beyond generalities and provide a scientific basis for designing tailored policies that account for the distinct economic and environmental conditions of individual nations.

II. LITERATURE REVIEW

The relationship between economic growth and environmental degradation, often explored through the Environmental Kuznets Curve (EKC) hypothesis, suggests that environmental pressure increases with economic development up to a certain point, after which it begins to decline [1]. While the EKC has been a foundational concept, its applicability to carbon emissions is debated, as some studies find little evidence of a global turning point [2]. This highlights the complex and non-linear nature of the GDP-CO₂ relationship.

A key concept in this field is carbon intensity, defined as the amount of carbon emissions per unit of economic output (CO₂/GDP) or energy consumption (CO₂/Energy) [3, 4]. These metrics are crucial for evaluating a country's carbon efficiency [5]. Studies on carbon intensity often reveal a wide range of performance across countries, influenced by factors such as the energy mix, the economic structure (e.g., industrial vs. service-based), and technological

advancements [6]. The heterogeneity of these profiles necessitates a disaggregated analytical approach.

The concept of decoupling has emerged as a central pillar of low-carbon development strategies. Decoupling can be absolute, where emissions decrease as the economy grows, or relative, where emissions grow at a slower rate than the economy [7]. Analyzing decoupling trends provides a dynamic perspective on a country's progress toward sustainability [8, 9]. The Our World in Data (OWID) platform has become a critical resource for such analyses, providing a publicly accessible, comprehensive database of environmental and economic indicators that allows for robust, long-term assessments [10].

Despite the rich literature on these topics, a unified framework that systematically combines static performance metrics (carbon intensity clustering), causal drivers (regression), and dynamic trends (decoupling) is less common. This study aims to fill this gap by integrating these analytical methods to provide a holistic and actionable assessment of global carbon performance.

III. METHODOLOGY

This study employs a three-stage methodological approach using a comprehensive dataset from the Our World in Data (OWID) platform. The dataset spans from 1990 to 2022 and includes key indicators for a wide range of countries: annual country-level CO₂ emissions, Gross Domestic Product (GDP), and primary energy consumption.

Stage 1: Cluster Analysis of Carbon Intensity

In the initial stage, we performed a cluster analysis to group countries based on their carbon efficiency profiles for the year 2022. The two key metrics used were CO₂ emissions per unit of GDP and CO₂ emissions per unit of primary energy consumption. Both variables were standardized to ensure they contribute equally to the clustering process. The k-means clustering algorithm [11] was chosen for its efficiency in grouping large datasets. The optimal number of clusters was determined to be three, based on an elbow method analysis. These clusters were subsequently labeled as:

- Low-Intensity Cluster: Countries with high carbon efficiency.
- Medium-Intensity Cluster: Countries with moderate carbon efficiency.
- High-Intensity Cluster: Countries with low carbon efficiency.

The results of this clustering were then mapped globally using country ISO-3 codes to provide a clear visual representation of regional and national carbon efficiency patterns.

In line with the existing literature, cluster analysis has proven to be an appropriate method for examining cross-country differences in carbon emissions and efficiency profiles [12, 13]. Previous studies have successfully applied k-means clustering to group countries based on carbon intensity indicators, confirming its suitability for large, heterogeneous datasets. Consistent with this methodological foundation, our study also employed the k-means algorithm.

Stage 2: Multiple Linear Regression

To understand the key drivers of CO₂ emissions, we developed a multiple linear regression model, as shown in Equation (1). Similar modeling approaches have been widely applied in the literature to investigate the relationship between emissions, GDP, and energy consumption [14, 15, 16, 17].

$$CO_{2,t} = \beta_0 + \beta_1 GDP_t + \beta_2 EnergyConsumption_t + \varepsilon_t \quad (1)$$

Where:

- $CO_{2,t}$ is the annual CO₂ emissions in year t .
- GDP_t is the Gross Domestic Product in year t .
- $EnergyConsumption_t$ is the primary energy consumption in year t .
- β_0 is the intercept term.
- β_1, β_2 are the regression coefficients.
- ε_t is the error term.

The model was tested for statistical significance, multicollinearity, and heteroscedasticity to ensure the robustness of the findings. The primary goal was to confirm the statistical significance of GDP and primary energy consumption in explaining the variation in CO₂ emission levels.

Stage 3: Decoupling Trend Analysis

In the final stage of this study, the dynamics of the relationship between economic growth and carbon emissions were examined by calculating a year-to-year decoupling index for each country. Following Tapio [18] and subsequent panel studies [16], the index was defined as in Equation (2):

$$Decoupling Index_t = \frac{\% \Delta GDP_t}{\% \Delta CO_{2,t}} \quad (2)$$

A value of the Decoupling Index less than 1 suggests that emissions are growing more slowly than the economy (i.e. decoupling – weak or strong), whereas a value greater than 1 indicates “re-coupling,” where emissions increase faster than GDP.

To capture global trends, annual averages of this index across all countries were computed for the years 1990 to 2022, allowing us to visualize the extent to which sustainable, low-carbon economic growth has been achieved over time.

IV. RESULTS AND DISCUSSION

4.1 Cluster Analysis Findings

The cluster analysis yielded three distinct groups, providing a granular view of global carbon efficiency. The “Low Intensity” cluster generally comprises highly developed economies with robust service sectors and a significant share of renewable or nuclear energy in their power grids. Countries like Sweden and Switzerland, for instance, fall into this category, demonstrating a high degree of carbon efficiency despite their advanced economies.

The “Medium Intensity” cluster is a diverse group, including both developed and rapidly industrializing nations.

These countries show moderate carbon efficiency, often due to a mix of established industrial sectors and a growing focus on clean energy technologies. This cluster highlights the ongoing transition and the challenges of balancing economic growth with environmental responsibility.

The "High Intensity" cluster consists of economies that are still heavily reliant on carbon-intensive industries and fossil fuels for energy. Many developing nations with large manufacturing bases and economies in transition fall into this group. The presence of countries at different stages of economic development within these clusters underscores the study's core finding: a country's development status does not unilaterally determine its carbon intensity. This finding supports the need for policies that are not generalized but are instead specifically designed to address the unique challenges of each cluster.

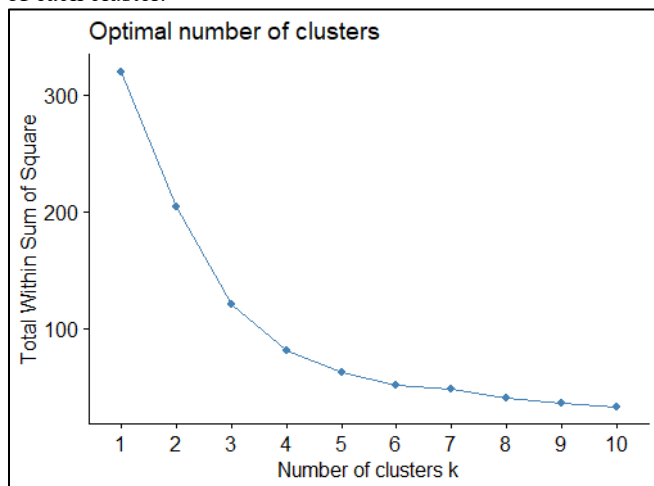


Figure 1. Determination of the Optimal Number of Clusters using the Elbow Method

Figure 1 illustrates the determination of the optimal number of clusters using the Elbow Method. As shown in the graph, the within-cluster sum of squares (WCSS) declines sharply up to 3, after which the rate of decrease becomes marginal. This inflection point, commonly referred to as the "elbow," indicates that three clusters provide the most appropriate balance between explanatory power and parsimony. Accordingly, the analysis proceeded with a three-cluster solution, enabling a meaningful classification of countries based on their carbon efficiency profiles.

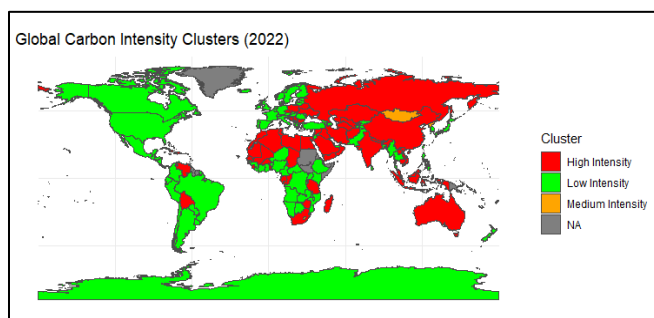


Figure 2. Global Distribution of Carbon Intensity clusters

Figure 2 presents the global distribution of the three carbon intensity clusters for the year 2022. Countries in the

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Low-Intensity Cluster (green) demonstrate higher carbon efficiency, largely attributed to advanced economies with diversified energy mixes and substantial shares of renewables or nuclear energy. The Medium-Intensity Cluster (orange) comprises nations with moderate efficiency, often undergoing industrial transitions or scaling up clean energy adoption. The High-Intensity Cluster (red) includes economies heavily dependent on carbon-intensive industries and fossil fuels. The presence of both developed and developing countries across different clusters underscores that carbon intensity is not solely determined by economic development levels but also by structural and policy-specific factors.

4.2 Regression Analysis Insights

The multiple linear regression model [19] provides robust evidence that GDP and primary energy consumption are statistically significant determinants of CO₂ emissions. Both variables exhibit a strong positive correlation with emissions, and the explanatory power of the model is remarkably high ($R^2 = 0.9641$), indicating that over 96% of the variation in $\log(\text{CO}_2)$ is explained by the independent variables. The overall significance of the model is further confirmed by the extremely large F -statistic (70,730) and the highly significant p -value ($< 2.2e^{-16}$), underscoring the joint explanatory strength of $\log(\text{GDP})$ and $\log(\text{Energy Consumption})$.

Table 1. Regression Results Model Explanations

Statistic	Value	Interpretation
R^2	0.9641	The model explains 96.41% of the variation in the dependent variable ($\log(\text{CO}_2)$). This indicates the model has a very high level of explanatory power.
F -statistic	70,730	The model as a whole is statistically significant.
p -value	$< 2.2e^{-16}$	This confirms that the independent variables ($\log(\text{GDP})$ and $\log(\text{Energy Consumption})$) collectively have a significant effect on the dependent variable.

The regression coefficients presented in Table 2 provide further insights into the relative contributions of GDP and primary energy consumption to CO₂ emissions. The results indicate that a 1% increase in GDP leads to an average 0.17% rise in CO₂ emissions, whereas a 1% increase in primary energy consumption results in an average 0.85% rise in CO₂ emissions. This disparity underscores the dominant role of energy consumption in driving emission growth. In other words, while economic expansion contributes to higher emissions, the environmental impact is primarily governed by the scale and structure of energy use.

Table 2. Regression Results for the Determinants of CO₂ Emissions

Variables	Coefficient (β)	Std. Error	t-value	p-value	Economic Interpretation
$\log(\text{GDP})$	0.172	0.0093	18.46	***	A 1% increase in GDP increases CO ₂ emissions by 0.17% on average.
$\log(\text{Energy Consumption})$	0.85	0.0084	100.87	***	A 1% increase in energy consumption increases CO ₂ emissions by 0.85% on average.

These findings are consistent with the broader empirical literature, which emphasizes that energy intensity and fuel mix are the most critical determinants of carbon emissions [20]. From a policy standpoint, the results reinforce the need to prioritize energy sector transformation—through efficiency improvements and decarbonization—over purely economic measures, as reducing the carbon intensity of energy appears far more effective than moderating GDP growth.

4.3 Decoupling Trend Analysis

Figure 3 illustrates the annual fluctuations in the global decoupling index from 1990 to 2022. The graph clearly shows that decoupling is not a linear process but rather characterized by volatility, with alternating phases of decoupling and re-coupling. Positive index values (>1) indicate periods where GDP growth outpaced CO₂ emissions, suggesting a decoupling effect, while negative values (<1) reflect re-coupling episodes in which emissions increased faster than economic growth. Result highlights that despite a long-term improvement trend, sharp downturns occurred during specific years, particularly around global economic shocks or recovery periods. Conversely, peaks in the index coincide with times when technological improvements and low-carbon policies were more effective.

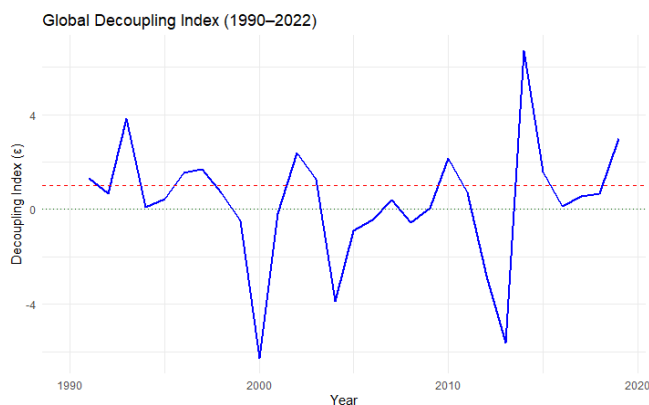


Figure 3. Global Decoupling Index Trends (1990–2022)

The analysis of the decoupling index revealed a nuanced global trend. While the overall trend shows a gradual improvement in decoupling over the past three decades, it is not a linear or consistent progression. Periods of strong decoupling were often followed by periods of weak decoupling or even re-coupling, particularly during phases of global economic recovery. This volatility is a reminder that decoupling is a fragile process, susceptible to economic shocks and policy shifts. The analysis showed that countries with advanced low-carbon technologies and diversified economies were more resilient in maintaining a decoupling trend, while fossil-fuel-dependent economies struggled. This highlights the importance of sustained, long-term policy commitments to low-carbon development.

Figure 4 presents the decoupling index trajectories for four representative countries (China, Greece, Türkiye, and the United States) over the period 1990–2019. The patterns reveal significant heterogeneity across nations, reflecting differences in economic structure, energy mix, and climate policy. China exhibits periods of strong decoupling, particularly in the mid-2000s, coinciding with major technological transitions and efficiency gains. However, volatility remains evident, with sharp re-coupling episodes in the late 1990s. Greece shows a highly irregular pattern, with pronounced decoupling during the economic crisis of the late 2000s, but also steep re-coupling phases, highlighting the fragility of progress in smaller economies with structural vulnerabilities. Türkiye demonstrates relatively consistent but weak decoupling until the late 2010s, after which a sharp re-coupling trend emerges. This indicates that energy demand growth remains tightly linked to emissions in the Turkish economy. The United States illustrates notable peaks in decoupling during the 2008 global financial crisis and subsequent recovery, largely due to shifts in energy markets. Nonetheless, re-coupling episodes suggest that structural dependence on fossil fuels continues to hinder sustained decoupling.

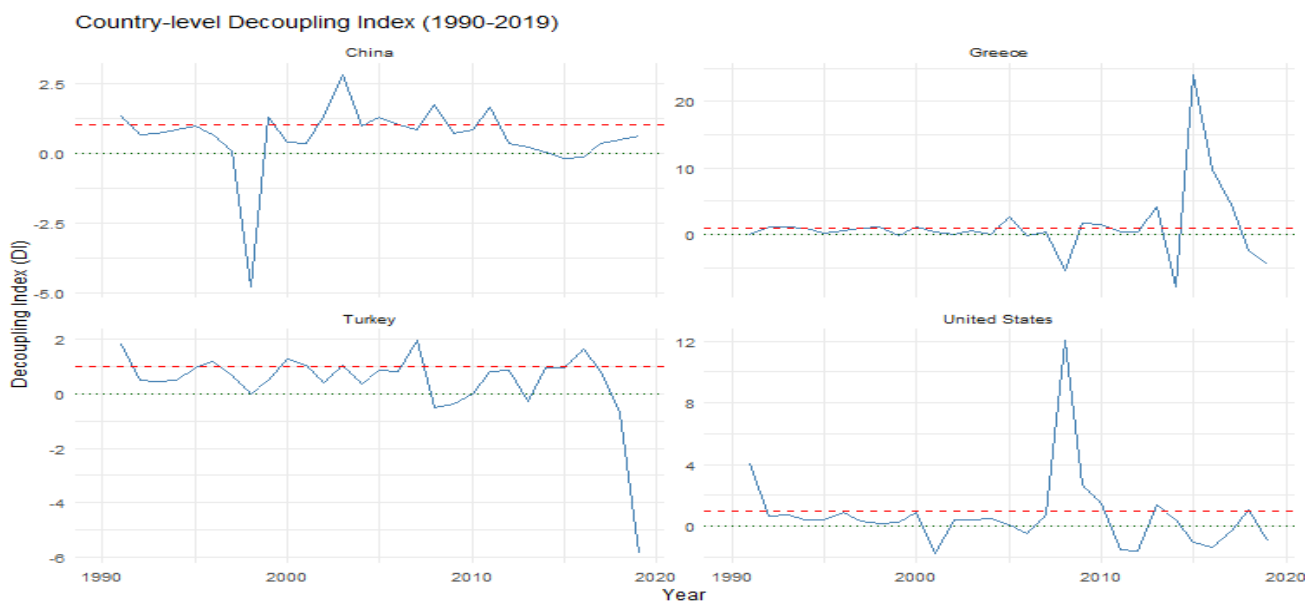


Figure 4. Country-level (China, Greece, Türkiye, and the United States) Decoupling Index for Selected Economies (1990–2019)

V.CONCLUSION

By integrating cluster analysis, regression modeling, and decoupling trend assessment, this study has provided a comprehensive, data-driven framework for understanding the complex dynamics of global carbon intensity. Our findings demonstrate that a one-size-fits-all approach to climate policy is insufficient and that effective strategies must be tailored to the distinct economic and environmental profiles of individual countries [21, 22]. The clustering analysis revealed that countries with similar carbon efficiency profiles do not always share the same level of economic development, a crucial insight for targeted policy design. Furthermore, the regression analysis reinforced the critical role of economic growth and energy consumption as primary drivers of emissions, emphasizing that emission reduction strategies must be centered on improving energy efficiency and transitioning to cleaner energy sources [23].

The analysis of decoupling trends revealed that while progress is being made on a global scale, it is neither guaranteed nor linear. The path to a low-carbon, sustainable economy is fraught with challenges, and maintaining decoupling requires continuous innovation and policy support. This study's contribution lies in providing a robust, multidimensional assessment that can serve as a scientific guide for policymakers. By understanding a country's specific position within the global carbon intensity landscape, governments can design more effective, equitable, and impactful climate mitigation policies, ultimately accelerating the global transition to a sustainable future.

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MultiFuture: A Modular and Sustainable Sports Complex Integrating Renewable Energy and Inclusive Urban Life on ITU Maslak Campus

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Abstract— Modern sports facilities serve as dynamic and high-energy environments that provide diverse user groups access across various times and functions. These facilities cause large physical footprints to support movement-intensive activities, accommodate large audiences, and host multiple programs in the meantime. As a result of these, they consume high heat and electricity loads and it makes them critical targets for sustainable design interventions. Rethinking these facilities is the key for the aim of this work while not only to reduce environmental impact by architectural and structural but also to create inclusive, multifunctional spaces for urban life.

This project presents a next-generation sports complex that integrates sustainable design, modular adaptability, and social inclusivity. To integrate design and energy solutions and evaluate their results Istanbul Technical University's Maslak Campus has been selected as the project site due to its urban character and diverse user population. The proposed facility utilizes modular and multifunctional systems both for sports fields and closed usage areas, mobile amenities such as dressing rooms to create areas for every sport and needs. From a social perspective, thanks to the inclusive and flexible use of space it offers, it is designed to be a multi-faceted center that encourages social interaction, healthy living and cultural sharing rather than just a sports area. Bringing together users from different age groups, physical ability levels and social backgrounds, this complex aims to contribute to social integration by making sports accessible to all segments of society. On an environmental and technical level, the proposed prefabricated steel grandstands allow for spatial reconfiguration based on the type of sport, audience size, or environmental conditions like solar orientation. This design maximizes space efficiency and usability, while localized maintenance reduces the need for full-scale overhauls. Building-Integrated Photovoltaics (BiPVs) placed along the proposed structure provide daylight, shading, and produce electricity which supports along glazed facades house solar panels that offer both shading and load-bearing functionality.

Simulations using E-Quest software indicate a 9.2% reduction in electricity use and an annual renewable output of 9 kWh/m² based on proposed structural additions to the one building of the case facility. Based on energy results and usage scenarios this approach aims not only to reduce energy but also adapt infrastructure for the life cycle of the facility and increase social connectivity—redefining what a sports complex can be: a sustainable, multifunctional and community-driven space for the future. This study was conducted within the scope of the

NextGenSportsFacilities Project, funded by the Erasmus+ Programme.

Keywords— *sustainability, modularity, multifunctionality, inclusivity, sports*

INTRODUCTION

Sport facilities are among the most dynamic and resource-intensive public spaces with their large footprints across different sports with diverse program requirements and population groups. These facilities operate nearly 24/7 from early morning practices to late night tournaments following with the maintenance operations. Therefore, they require large, movement-intensive areas to accommodate both athletes and audiences and high quality ventilation and heating systems to support environmental needs [1]. As a result of these, sport facilities will play a critical role in the public spaces of the future due to their significant energy consumption, spatial footprint and crucial role of social solidarity. Sport facilities have also been discussed in the literature as central elements of urban planning and public health. They not only host professional competitions but also create daily meeting points for local communities.

Moreover, advancements in technology provides integration of digital tools such as energy simulation in design phases of any building to simulate and optimize. These tools facilitate to compute the energy consumption or renewable energy potential of the building in design phases to optimize design, maintenance and life cycle of it. Therefore integrating these tools for sport facilities future design improve social and environmental impacts. eQuest is one of the energy simulation softwares that provides energy consumption parameters with building components properties and facilitate design phase of the building [2]. Furthermore [3] is also another study that shows the high impact of the technological assessment in a multifunctional educational building that could be combined with the sport facilities while in [4] the study demonstrated that utilizing measured 15-minute interval data for calibration and applying zone-based scheduling and comfort conditions, energy efficiency improvements also could be achieved for existed buildings.

In this study, the aim is to rethink the future sport facilities not only in terms of reducing environmental impact through

architectural and structural design, but also in terms of creating inclusive, multifunctional spaces that contribute to urban life based on existing wicked problems of current sport facilities. The ITU Maslak Campus was chosen as the case study because of its central location in Istanbul and its diverse user population, including students, staff and visitors from outside the university. This diversity provides a realistic environment to test how inclusive and flexible design strategies can work in practice. To address this aim, a design framework that integrates sustainable design interventions and administrative strategies was developed and applied to the Istanbul Technical University (ITU) Sport Complex located in Istanbul, Maslak. The complex includes an Olympic pool, stadium, indoor and outdoor football and basketball courts, tennis facilities, and a gymnasium. Like many existing sports complexes, the ITU facilities face structural and operational difficulties that limit their efficiency and community impact. These challenges provide a useful basis to explore future-oriented solutions.

Furthermore, based on the case study the future complex design approach was structured based on three main wicked problems: (1) Flexibility and maintenance issues, (2) Lack of renewable energy systems and water management and (3) Lack of data and deficiency in planning and communication also limited connection to the community.

DESIGN FRAMEWORK

The design framework focuses on architectural and structural strategies that respond to the current limitations of sports facilities. It highlights multifunctional use of space and modular systems as key approaches to create adaptable, efficient and long-lasting complexes. The following subsections explain these strategies in detail.

Multifunctionality

The first approach was developed through architectural and structural revisions. Since the sport complexes have many sport areas, fields or spaces, multifunctional spaces was proposed to create those wide range footprints into one multifunctional space while ensuring that different sports and user groups could be accommodated within a single structure. It is proposed as calculations and adjustments of six sports; Athleticism, Football, American football, Tennis, Volleyball and Basketball. Those sports could be designed as one athleticism and American football sport field sizes and then with the proposed convertible field grid it is possible to convert this one field into 4 volleyball, two basketball and 4 tennis courts at the same time as shown in Figure 1. Therefore the complex becomes optimizable based on needs and demands without being inactive during any off season of any sport.

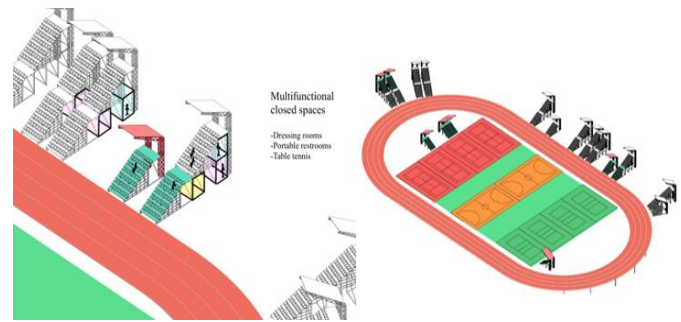


Figure 46: Multifunctional and Modular Space Arrangements

Modularity

The other structural design proposed was shaped around modular design systems which allows flexibility in spatial configuration, adaptation to changing needs or even environmental factors like solar orientation and shading and efficient maintenance across the life cycle of the building. Since maintenance is another target problem of existing buildings and it requires high amounts of financial support to maintain the complex as a whole, modular systems provide maintenance step by step with local interventions while using financial savings in a controlled manner and extending the life cycle period of the complex.

SUSTAINABILITY STRATEGIES

Sustainability strategies are essential in sports facilities due to their intensive energy demand and continuous operation. This study focuses on architectural and technical measures that reduce environmental impact while improving user comfort. Three main strategies are examined: energy efficiency and passive design, the integration of building-integrated photovoltaics (BIPVs) and simulation-based evaluation of energy performance.

Energy Efficiency and Passive Design

This approach is shaped around the structural and architectural design system of sustainable framework. Energy efficiency was pursued through natural ventilation, daylight use, and careful passive design strategies. To create natural ventilation and daylight usage efficiency, an extended glass-ceiling sun corridors are proposed on closed sport complex spaces as shown in Figure 2.

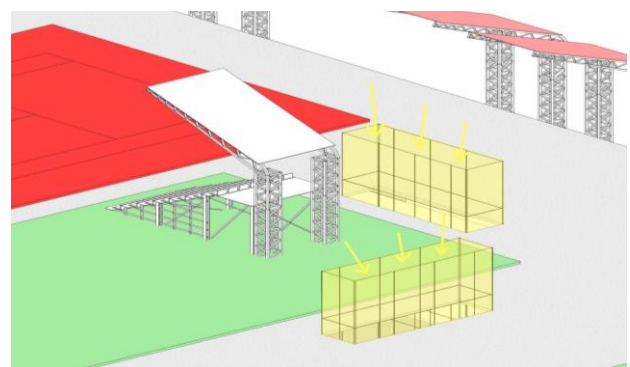


Figure 2: Sun Corridors

Building-Integrated Photovoltaics (BIPVs)

It is proposed for renewable energy that the integration of structural elements that double as building-integrated photovoltaic systems. These triangle vertical steel structure elements as shown in Figure 3 already existed in the current ITU pool building and work as structural elements of the building. It is proposed to be adapted to serve dual purposes: as shading devices and as renewable energy generators with integrating PVs into these structures.

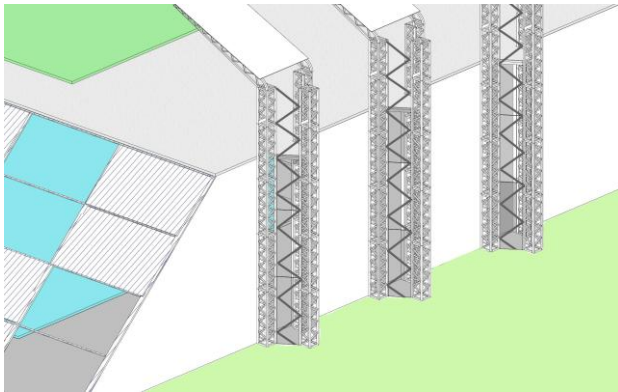


Figure 3: Triangle Vertical Steel Structure Elements of the ITU Pool Building

Energy Simulation Results

To assess the energy implications of these interventions, an energy model was developed and conducted simulations using eQuest software as shown in Figure 4. eQuest is a building energy simulation software that provides users to evaluate building performance based on load profiles, building properties and operational scenarios. Furthermore, the software integrates the robust calculation engine of DOE-2 with a user-friendly graphical interface as a widely accessible tool.

Firstly, ITU Pool Building plan was created as .dwg file and exported to eQuest software to be able to create building geometry. Other inputs such as; weather file (in .bin format), space type and schedules, mechanical system and HVAC information by types and usage were created for the simulation. Building properties for each building component were defined as shown in the Table 1. Furthermore, fins and overhangs are modelled as building element in the software to simulate BIPV scenarios for 25m² area that works both as shading devices and renewable energy generators. Energy simulations were calculated for both existed scenario and designed scenario to compare the results and its effect on the energy consumption.

Table 19: Building component properties

Building Components	Material Name	U Values (W/m ² K)
Interior Doors	Wood Door Panel	-
Exterior Doors	Glass	1.8
	Aluminium	

Windows	Glass	1.8
	Aluminium	
Ground Floor	Structure, Steel Bar Joist Layer	0.57
	Oak Flooring	
	EIFS, Exterior Insulation	
	Concrete Masonry Unit	
Interior Floor	Structure, Steel Bar Joist Layer	-
	Oak Flooring	
	Concrete Masonry Unit	
Wall	Paint	0.57
	Plaster	
	EPS	
	Concrete Masonry Unit	
Roof	EIFS, Exterior Insulation	0.38
	Damp-proofing	
	Concrete, Precast	

The results were promising: it is observed that a 9.2% reduction in electricity consumption compared to the baseline condition and an annual renewable energy output of 9 kWh/m² generated by the proposed BIPV system. These results demonstrate that meaningful energy savings can be achieved through a combination of architectural design and renewable integration.

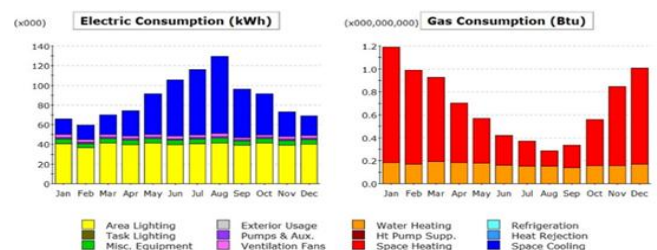
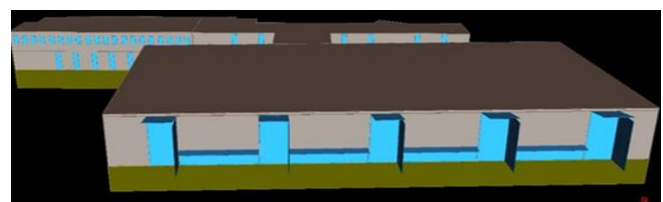


Figure 4: Equest Model of the ITU Building with simulation results

ADMINISTRATIVE FRAMEWORK

Administrative measures play a crucial role in ensuring design innovations translate into long-term usability, inclusivity and resilience. Therefore, the proposed framework emphasizes three dimensions of administration: sports engagement, social connectivity and collective management. Therefore, the third approach was formed based on administration around community and engagement.

Sports Engagement

The solutions proposed as design strategies also helped to shape community engagement as modular systems and multifunctional spaces require careful planning and active involvement of users and the community to function effectively.

Social Connectivity

Since today's lifestyles often emphasize individual space usage, collective and adaptable solutions are increasingly necessary in a rapidly changing world. As part of this approach, modular and multifunctional systems were proposed as user-friendly components, allowing the community and users to efficiently adapt the structures according to their needs. To further enhance social interaction, different types of food courts inside the complex were also proposed to bring people together from both inside and outside the facility.

Collective Management

To bring all these functions together, an application with its interfaces was proposed. This application aims to support planning and arranging field usage, creating teams, organizing tournaments or matches, finding friends across the complex with shared interests, and facilitating communication within the community. In this way, collective management of the facility is supported by digital tools, more effective participation and coordination.

CONCLUSION

In conclusion, this research shows that for future sport complexes it is important to think that the integration of modular architectural systems, multifunctional programming, and renewable energy technologies can substantially reduce the environmental footprint of university-based sports complexes while accordingly enhancing social connectivity. The findings highlight that sustainability in sports architecture extends beyond technological efficiency, requiring a holistic approach that combines design, administration, and social engagement. The ITU Sports Complex case study provides how these strategies can be implemented in practice, with measurable energy savings and qualitative improvements in user experience. Based on sustainability solutions for the future sport complex, integration of renewable energy sources such as photovoltaic panels in ITU Pool building structure shows the

important amount of energy savings while energy producing based on the Equest energy analysis tool. More broadly, this framework offers a replicable model for universities and municipalities seeking to develop next-generation sports facilities that are sustainable, adaptable, and socially inclusive.

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Multi-Criteria Decision Making Approach to Increase the Sustainability Impact of Artificial Intelligence Use in Industry 4.0 Applications in Turkish Industry

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Abstract—With Industry 4.0, artificial intelligence technologies have assumed strategic roles in many areas, from manufacturing to data analysis. This study aims to evaluate the impact of artificial intelligence applications on sustainability criteria using multi-criteria decision-making methods. The weights of the alternatives determined based on environmental, economic, and social criteria were calculated using the SWARA method, and an AHP transformation was applied for consistency. The ranking of the alternatives was performed using the CoCoSo method. Sensitivity analyses were conducted to test the robustness of the model by creating scenarios using the λ parameter and criterion weights. The absence of significant changes in the rankings demonstrates the model's stability. The results are expected to support the strategic use of AI with a focus on sustainability and contribute to the digital transformation planning of industrial enterprises.

Keywords—industry 4.0, artificial intelligence, sustainability, SWARA, CoCoSo

I. INTRODUCTION

Today, the rapid depletion of natural resources, the deepening of environmental problems, and the rising expectations of societies have made sustainability a holistic development approach that must be addressed in its environmental, economic, and social dimensions. High energy and resource consumption, carbon emissions, and waste production, particularly in the industrial sector, necessitate the development of more environmentally friendly production systems. In this context, the concept of Industry 4.0, at the heart of this digitalization-based transformation, aims to restructure production processes through technologies such as cyber-physical systems, the Internet of Things, artificial intelligence, and big data [1][2].

Artificial intelligence solutions not only increase operational efficiency with functions such as fault prediction, quality control, production planning and customer demand forecasting, but also provide

environmental benefits such as reducing energy consumption, managing waste more efficiently and reducing carbon footprint [3]. From an economic perspective, it offers increased productivity, cost-effectiveness and improvements in decision-making speed; on a social level, effects such as freeing employees from repetitive tasks and directing them to creative areas, improving digital skills and increasing customer satisfaction are prominent [4][5][6]. However, research conducted specifically for Turkey shows that these technologies have not been systematically analyzed from a sustainability perspective [7][8][9].

The number of studies in the literature that apply the SWARA and CoCoSo methods together to AI technologies in the context of sustainability is quite limited. Therefore, this study aims to evaluate the impacts of AI solutions implemented in Turkish industry on sustainability criteria by using the SWARA and CoCoSo methods in an integrated manner. In addition, the consistency test performed with AHP and the sensitivity analysis based on criterion variations with the λ parameter performed for the CoCoSo method reveal the stability of the model in a multidimensional way and provide method-based contribution.

II. IMPLEMENTATION

A. Application Criteria

- K1 (Recycling): Recycling performance is increased by providing automatic classification of waste, predictive maintenance of equipment and optimization of material recovery processes with artificial intelligence and Industry 4.0 technologies [1].
- K2 (Energy efficiency): Thanks to AI and smart production systems, energy consumption patterns are analyzed, thus ensuring more efficient energy use in manufacturing processes [1].

- K3 (Waste reduction): With AI-supported analysis, waste of materials, water and energy is reduced at the source, thus enabling cleaner and more efficient production [6].
- K4 (Resource use efficiency): Effective use of production resources such as raw materials and energy is possible thanks to real-time monitoring, predictive analysis and decision support systems [2].
- K5 (Carbon emissions): AI applications contribute to the reduction of carbon emissions by optimizing production processes and integrating them with energy-efficient equipment [1].
- K6 (Resource efficiency): AI technologies help use resources (materials, energy, time) with minimum loss by enabling better planning of production processes [10].
- K7 (Cost effectiveness): Artificial intelligence-supported predictive maintenance and process improvement studies reduce production costs and increase operating efficiency [10].
- K8 (Productivity increase): AI tools such as automation, machine learning and data analytics increase productivity by accelerating production processes [4].
- K9 (Data management): Artificial intelligence systems provide effective data management by supporting decision-making processes through data collection, analysis, and visualization [5].
- K10 (Decision support): AI supports fast and accurate decision-making processes by providing decision-makers with real-time analysis and predictive insights [11].
- K11 (Creating Innovation): AI enables the development of new product ideas and creative solutions by analyzing patterns in data [6].
- K12 (Employee Skill Development): With digitalization, employees are encouraged to acquire new skills through AI-supported training programs and technology-based task distribution [5].
- K13 (Customer satisfaction): AI systems increase customer satisfaction by providing personalized service, on-time delivery, and quality control capabilities [11].
- K14 (Employee happiness): By reducing routine and monotonous tasks, AI supports employees in engaging in more creative and fulfilling work, increasing job satisfaction [1].
- K15 (Contribution to society): Artificial intelligence-supported sustainable applications support social equality and social benefit as well as reducing environmental impact [12].

B. Alternatives

- A1 – Big Data Analytics: Big data analytics, which includes the analysis of multi-dimensional digital traces obtained from web statistics, social media content and online systems, enables meaningful results to be obtained from high-volume and diverse data sets [3].
 - A2 – Cloud Computing: This technology enables data sharing regardless of physical location and provides a
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computing infrastructure that offers flexible, multiple access through online virtual servers [3].

- A3 – Cyber-Physical Systems: These systems, where physical processes are integrated with digital components, enable real-time monitoring and management of production environments with the help of sensors and control algorithms [3].
- A4 – Internet of Things (IoT): The structure that enables devices to exchange data by connecting with each other or with central systems; allows the synchronized operation of production tools [3].
- A5 – Digital Twin / Simulation: This technology allows simulation of a real system through its reflection in the digital environment and allows testing of various scenarios [12].
- A6 – Blockchain: A digital ledger system that records transactions in a decentralized, transparent, and secure manner. It increases traceability and data volume [12].
- A7 – Autonomous / Industrial Robots: Robot systems that perform processes such as material handling, assembly, and quality control without requiring human intervention, provide efficiency [3].
- A8 – Additive Manufacturing: This technology, which performs layered manufacturing based on digital modeling, is preferred especially for prototyping and low-cost production of complex parts [12].

III. SWARA APPLICATION

The SWARA (Stepwise Weight Assessment Ratio Analysis) method was chosen to determine the relative importance of the criteria in this study. SWARA's ability to produce reliable and meaningful results even with a small number of expert opinions, its simple and transparent calculation process, and its ability to directly reflect the decision-makers' prioritization logic made it suitable for this study.

In this context, weight values for 15 criteria were obtained from each of four experts. To determine the final weight of the relevant criterion, the geometric mean of the values obtained from the experts was taken, and these average weights were used in the analysis process. The relevant values are presented in Table 1.

IV. CONSISTENCY TEST APPLICATIONS

As seen in Table 2, W values below 0.3 indicate a lack of strong agreement among experts. Therefore, to focus not only on ranking but also on numerical consistency, the SWARA results were converted to a n AHP pairwise comparison matrix, extending the analysis process as presented in Table 3. In the literature, it is stated that SWARA results can be converted into AHP pairwise comparison matrix with the statement “Any system consisting of (n-1) independent w_i/w_j ratios and a normalization condition is equivalent to SWARA” [13].

Table 1: Combined Criterion Weights

NO	Class	Criteria	Mean w_i
1	Environmental	K5	0,124519639
2		K3	0,090110178
3		K1	0,095279913
4		K4	0,05307668
5		K2	0,087614878
6	Economical	K10	0,038091436
7		K7	0,086421324
8		K9	0,077103877
9		K8	0,084064977
10		K6	0,068436786
11	Social	K15	0,021125298
12		K14	0,026300511
13		K13	0,022706283
14		K11	0,023555795
15		K12	0,011804675

The criterion weights obtained with SWARA were directly converted to the AHP pairwise comparison matrix and no additional normalization was performed in this process; because in the SWARA method, "Normalization of weights completes the linear equation system" and the weights are normalized by the method of "dividing the Q_i value by the sum of all Q_j " [13], [14]. The consistency rates of all matrices were found to be at an acceptable level, and only one expert's evaluation of one class was presented as an example to avoid repetition.

Table 2: Kendall's W Consistency Outcomes

Class	No of Experts	Mean Correlations	Kendall's W
Environmental	4	-0,0333	0,225
Economical	4	-0,1500	0,1375
Social	4	-0,2167	0,0875

Table 3: SWARA-AHP Pairwise Comparison Matrix for Environmental Criteria

	K1	K2	K3	K4	K5	w_i	$(A \cdot w)_i$	λ_i
K1	1	1	1,79 6	1,25	1,56 2	1,32 1	6,609	5
K2	1	1	1,79 6	1,25	1,56 2	1,32 1	6,609	5
K3	0,55 6	0,55 6	1	0,69 5	0,86 9	0,73 5	3,678	5
K4	0,8	0,8	1,43 7	1	1,25	1,05 7	5,287	5
K5	0,64	0,64	1,15	0,8	1	0,84 6	4,23	5
Total	3,99 6	3,99 6	7,18 1	4,99 5	6,24 4	λ_{max}	CI	CR
						5	0	0

Table 4: SWARA-AHP Normalized Pairwise Comparison Matrix for Environmental Criteria

Normalized	K1	K2	K3	K4	K5	w_i	$(A \cdot w)_i$	λ_i
K1	0,2502	0,2502	0,2502	0,2502	0,2502	0,2502	1,2511	5
K2	0,2502	0,2502	0,2502	0,2502	0,2502	0,2502	1,2511	5
K3	0,1393	0,1393	0,1393	0,1393	0,1393	0,1393	0,6963	5
K4	0,2002	0,2002	0,2002	0,2002	0,2002	0,2002	1,0009	5
K5	0,1601	0,1601	0,1601	0,1601	0,1601	0,1601	0,8007	5
Total	1	1	1	1	1	1	λ_{max}	5
			CI	0	RI	1,12	CR	0

V. CoCoSo APPLICATION

The criteria and alternative implementations identified in the study were scored by the same experts on a scale of 1 to 100. These scores numerically represent the level of contribution each alternative makes to the relevant criteria and are categorized on a five-point scale ranging from "very low" to "very high." The arithmetic average of the expert assessments for each alternative was used to obtain a composite score representing the group's opinion. These values were analyzed using the CoCoSo (Combined Compromise Solution) method to compare the holistic performance of the alternatives and determine the most suitable option. Based on the values in Table 4, the most suitable option was determined as Alternative 8, "Additive Manufacturing." The most suitable option to be selected

after the additive manufacturing alternative was determined as Alternative 7, Autonomous/Industrial Robots.

VI. λ -BASED SCENARIO ANALYSIS

In this study, a sensitivity analysis was conducted by varying the value of λ between 0.1 and 0.9, and alternative rankings were recalculated for each scenario. The results showed that the rankings remained constant across all scenarios and that the method was highly stable with respect to the λ parameter. This finding confirms that the default value of $\lambda = 0.5$ can be safely used in this study.

Table 6: λ Changes and Rankings

	$\lambda = 0.1$	$\lambda = 0.2$	$\lambda = 0.3$	$\lambda = 0.4$	$\lambda = 0.5$	$\lambda = 0.6$	$\lambda = 0.7$	$\lambda = 0.8$	$\lambda = 0.9$
A ₁	7	7	7	7	7	7	7	7	7
A ₂	6	6	6	6	6	6	6	6	6
A ₃	3	3	3	3	3	3	3	3	3
A ₄	4	4	4	4	4	4	4	4	4
A ₅	5	5	5	5	5	5	5	5	5
A ₆	8	8	8	8	8	8	8	8	8
A ₇	2	2	2	2	2	2	2	2	2
A ₈	1	1	1	1	1	1	1	1	1

VII. SENSITIVITY ANALYSIS BASED ON CRITERIA WEIGHTS

To examine the impact of criteria weights on the ranking of alternatives, a sensitivity analysis method similar to that employed by Ersoy in the literature was employed [15]. In this study, the financial performance of Fortune 500 companies was evaluated using the CoCoSo method across 15 different weighting scenarios, with the highest-scoring alternative remaining constant across all scenarios. In this study, criteria weights were systematically varied across different scenarios, and rankings were recalculated using the CoCoSo method. The analysis demonstrated that the method can produce stable and reliable results despite weighting changes. As can be seen from the table, the rankings of the alternatives remained largely constant across the 105 different scenarios.

For example, A₃ ranked 3rd in 101 scenarios (96.2%), while A₆ remained constant at 8th place in all scenarios (100%).

Similarly, A₈'s 98.1% success rate of ranking first indicates that weight changes do not significantly impact the ranking structure.

This result demonstrates that the CoCoSo method is highly stable despite changes in weight sets, supporting the model's reliability.

VIII. CONCLUSION

Additive Manufacturing technology, which emerged as the most suitable option based on the analyses, significantly aligns with both the current industrial transformation process and the sustainability approach. Similarly, Özkan and Turan's study also noted that additive manufacturing systems generate less waste compared to traditional production methods and that resources used in production can be utilized more effectively [16]. Furthermore, thanks to the flexible design capabilities it offers, this technology not only improves production processes but also contributes to designing products with longer lifespans and lower environmental impact. Furthermore, its ability to work in harmony with artificial intelligence, the Internet of Things, and digital manufacturing infrastructures places additive manufacturing in a strategic position in future production systems [17]. In conclusion, the findings of this study align with similar assessments in the literature and demonstrate that the additive manufacturing alternative has strong potential as a sustainable production approach. Therefore, transitioning to additive manufacturing technologies in businesses can be a significant step toward more efficient, flexible, and sustainable production processes. This technology also contributes to overall sustainability. To expand the application, it is recommended that employees be trained and pilot projects be developed through university-industry collaborations. The "Autonomous/Industrial Robots" alternative, which ranked second according to the analysis results, is identified in the literature as a fundamental component of Industry 4.0 and is gaining importance, particularly with the digital transformation of production processes. As stated in the study of Özmen, Takva, Aslan and İlerisoy, autonomous robots provide speed, accuracy and security to the production process by taking part in repetitive, risky and physically demanding jobs in the construction industry [18].

Table 5: CoCoSo results for all alternatives

Alternative	S_i	P_i	k_{ia}	k_{ib}	k_{ic}	k_i	Ranking
A ₁	0,339	12,185	0,118	2,223	0,852	1,671	7
A ₂	0,377	12,346	0,120	2,375	0,866	1,747	6
A ₃	0,418	12,551	0,122	2,538	0,882	1,830	3
A ₄	0,352	13,210	0,128	2,355	0,923	1,788	4
A ₅	0,347	13,160	0,127	2,335	0,919	1,776	5
A ₆	0,280	12,027	0,116	2,000	0,837	1,564	8
A ₇	0,415	13,327	0,130	2,591	0,935	1,898	2
A ₈	0,458	14,242	0,139	2,822	1	2,052	1

The use of these systems in areas such as prefabrication, transportation, and assembly both increases efficiency and reduces human-related errors. Furthermore, automation allows for more planned production with less energy and

resource consumption, making these technologies meaningful for sustainable production goals. These assessments presented in the literature are consistent with the results obtained in the study [10].

Table 7: Ranking Distribution of Alternatives in 105 Scenarios Based on Criteria Weights

<i>Alternative</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>	<i>6</i>	<i>7</i>	<i>8</i>
<i>A1</i>	0 (0 %)	0 (0%)	0 (0 %)	0 (0%)	0 (0 %)	1 (1,0 %)	104 (99,0 %)	0 (0 %)
<i>A2</i>	0 (0 %)	0 (0%)	0 (0 %)	2 (1,9 %)	8 (7,6 %)	94 (89,5 %)	1 (1,0 %)	0 (0 %)
<i>A3</i>	0 (0 %)	0 (0 %)	101 (96,2 %)	3 (2,9 %)	1 (1,0 %)	0 (0 %)	0 (0 %)	0 (0 %)
<i>A4</i>	0 (0 %)	0 (0%)	3 (2,9 %)	86 (81,9 %)	14 (13,3 %)	2 (1,9 %)	0 (0 %)	0 (0 %)
<i>A5</i>	0 (0 %)	0 (0%)	1 (1,0 %)	14 (13,3 %)	82 (78,1 %)	8 (7,6 %)	0 (0 %)	0 (0 %)
<i>A6</i>	0 (0%)	0 (0%)	0 (0 %)	0 (0%)	0 (0 %)	0 (0 %)	0 (0 %)	105 (100,0 %)
<i>A7</i>	2 (1,9 %)	103 (98,1 %)	0 (0 %)	0 (0,%)	0 (0 %)	0 (0 %)	0 (0%)	0 (0 %)
<i>A8</i>	103 (98,1 %)	2 (1,9 %)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0%)	0 (0 %)

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