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Decarbonized Hydrogen Production: Integrating Renewable Energy into Electrified SMR Process with CO_2 Capture

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ABSTRACT

Electrified steam methane reforming has emerged as a promising technology for electrifying the hydrogen production process industries. Unlike conventional fossil fuel-based steam methane reforming, the electrified steam methane reforming process relies exclusively on electrical heating, eliminating the need for fossil fuel combustion. Beyond that, however, significant amounts of electricity required for the electrified process should be imported from the renewable energy-based system rather than fossil fuel-based grid electricity to have an environmental advantage over the conventional process. This study suggests a framework for integrating renewable energy systems into the electrified process for decarbonized hydrogen production. Considering the variability of renewable energy, wind and solar power are supplemented by battery storage, to facilitate a stable electricity supply to the electrified hydrogen production process. A Mixed-Integer Linear Programming (MILP) model is developed to optimally size and operate both the renewable system and potential grid imports. Case studies under various carbon tax scenarios, using historical weather data from a region in Germany, are conducted, followed by a techno-economic assessment to estimate the Cost of Hydrogen (COH). The results show that higher carbon taxes and reduced capital costs for wind, solar, and storage technologies significantly increase the share of renewable-based electricity. These findings highlight the importance of more stringent carbon taxation and improvements in the technology readiness level (TRL) of renewable energy are critical for accelerating large-scale, clean hydrogen production and industrial decarbonization.

Keywords: Hydrogen, Renewable energy, Electrification

1. INTRODUCTION

Interest in sustainable hydrogen production has increased as hydrogen becomes more widely recognized as a clean energy source and a vital chemical feedstock. Among the different strategies for producing hydrogen, furnace heated steam methane reforming (SMR) is widely regarded as an economic solution for large-scale hydrogen production. However, it requires significant heat energy, which results in a large amount of CO_2 emissions. To address these challenges, Wismann et al. [1], in collaboration with Haldor Topsoe, developed an innovative "Electric Heating Steam Methane Reformer", providing a promising eco-friendly alternative to the conventional fossil fuel-based furnace heating technology.

Several studies were investigated, regarding the process design and economic analysis of electrified hydrogen production [2-5]. However, these studies mainly focused on the electrified hydrogen production process itself, with relatively limited consideration of feasibility about introducing renewable energy sources at a commercial scale of the electrified process. Nava et al. [6] considered renewable energy integration for hydrogen production process, but it mainly focused on biogas-based hydrogen production and a relatively small scale of the process [7].

This study provides conceptual guidelines for the clean and sustainable production of hydrogen through renewable-powered electrification, contributing to the decarbonization of the hydrogen industry and the global energy transition.

2. METHODOLOGY

Building upon our previous work on process guidelines and techno-economic analysis for large-scale electrified hydrogen production hydrogen production [5], this study introduces a renewable energy system (RES) model to supply electricity for the process. The integration of renewable energy sources, such as solar and wind, into hydrogen plants requires systematic consideration of their intermittent characteristics due to their dependence on weather conditions.

To ensure a reliable energy supply for the electrified hydrogen plant, battery storage systems and grid are introduced to store any surplus energy or supplement energy in deficit. To effectively manage these fluctuations, a system-wide optimization approach is employed to integrate renewable energy systems, ensuring reliable energy supply and high energy efficiency.

The proposed framework includes process modelling and simulation for the electrified hydrogen plant (**Figure 1**) is developed, with a focus on renewable energy integration. Case studies are conducted to investigate configurational and operational changes of renewable energy systems integrated with electrified hydrogen production process. A techno-economic assessment for these case studies is to estimate the Cost of Hydrogen (COH), which enhances our understanding on the economic feasibility of renewable-based electrification for hydrogen production.

3. PROBLEM DEFINITION

In this study, among various configurations of the electrified hydrogen production, the most cost-effective CO_2 capture integrated electrified hydrogen production process alternative is selected. Heat integration is applied throughout the electrified hydrogen production process, and an electric boiler is used to provide the additional low-pressure steam required for the CO_2 capture process. Based on simulation results using Aspen HYSYS, the estimated total power consumption for this large-scale electrified hydrogen production process is 424.1 MWe. The techno-economic analysis of the large-scale electrified hydrogen production process was conducted, assuming that an unlimited and consistent supply of renewable energy is available at a given renewable energy-based electricity cost. A break-even point of the renewable electricity cost was identified, at which the electrified hydrogen production option might be more economical than the conventional hydrogen production process.

However, in practical circumstances, it is difficult to continuously provide 424.1 MWe of renewable-based power [8]. Therefore, in this study, the large-scale electrified hydrogen production process is reduced in size to a tenth of its initial size, requiring 42.4 MWe of constant power, which is still a commercial-scale hydrogen plant, as shown in **Table 1**.

The main objective of this study is to develop a model of a renewable energy system (RES) employing an optimized combination of wind turbines (WT), solar photovoltaic (PV) arrays, and electrical energy storage (EES), with grid electricity support, to provide the steady power required for the electrified hydrogen production process.

The 2023 annual weather data for the German region of Freiburg im Breisgau, including wind speed and solar radiation, is adopted for the case study [9]. By using realistic weather data, the time-dependent characteristics of solar and wind power generation are fully considered in the RES model. The capacity of each renewable power generation facility, including WT, PV, and EES, and their hourly operating conditions, are determined using an optimization framework to minimize the COH.

COH breakdown of the electrified hydrogen production hydrogen plant, without electricity and the carbon tax is shown in **Table 1**. The utility cost, including natural gas and grid electricity, has been updated to 2023 German industrial price of 41€/MWh and 95.18 €/MWh, respectively [10-11]. The other economic parameters used are referred to the previous study [5]. The COH for electricity and carbon tax is estimated in the case study section that provides a full breakdown based on the modeling and simulation results of renewable energy system.

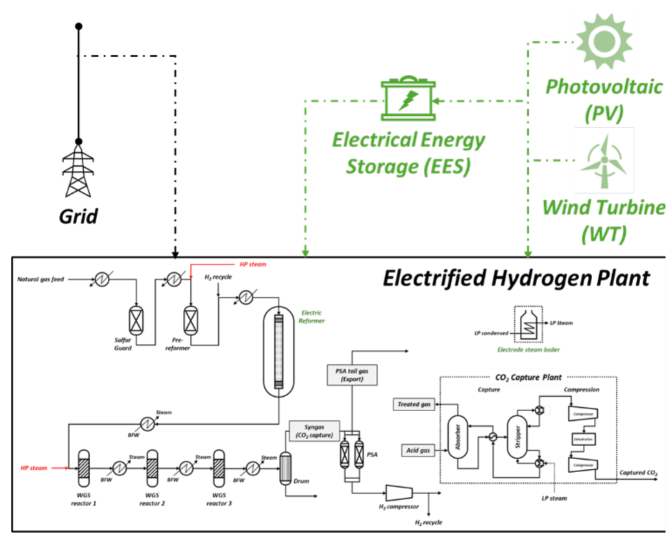

Figure 1. An electrified hydrogen production hydrogen plant integrated with renewable energy and grid

Table 1: Key Process Performance Data & Cost of Hydrogen Breakdown for the Electrified Hydrogen Production Process

	Unit	Ref. [5]	Case study
Performance			
Natural gas	t/h	63.9	6.4
Power consumption	MW_e	424.1	42.4
H_2 Production	t/h	22.8	2.3
Cost of Hydrogen			
Capital	$/kg	0.26	0.82
Fixed O&M	$/kg	0.09	0.31
Variable O&M	$/kg	0.07	0.15
Natural gas	$/kg	1.81	1.81
Electricity (RES)	$/kg	1.91	TBD
Carbon tax	$/kg	-	TBD
Total	$/kg	4.14	TBD

4. OPTIMIZATION MODEL

A mathematical model is developed for a renewable energy system (RES) to provide electricity required for the electrified hydrogen production process. The values of design parameters of the RES model are presented in **Table 2**.

Table 2: Design Parameters of RES

Parameter	Description	Value
η	PV efficiency	0.19 [12]
θ	Static loss of EES	0.05 [13]
χ	Charge rate	0.1 [13]
$\Delta\chi$	Discharge rate	0.15 [13]
$Demand$	Electricity demand (MWh)	42.4 [5]
$Rad(t)$	Solar radiation (kWh/m^2)	Hourly data [9]
$v(t)$	Wind Speed (m/s)	Hourly data [9]
$I_{POA}(Rad)$	Plane of array irradiance (kWh/m^2) [12]	
$uE_{WT}(v)$	Power performance of unit wind turbine [14]	

The resulting MILP model of the RES is shown below. The equations regarding wind turbine and solar power generation are (1)-(3), and equations regarding electrical energy storage are (4)-(10). When the amount of renewable energy produced exceeds the demand for the electrified hydrogen production process, the renewable energy system is designed to use the generated renewable energy directly (E_{DU}) for the electrified hydrogen production process and store the remaining electricity in electrical energy storage (StoreIn) (Equations (4)-(6)). Static loss, charge rate, and discharge rate are all taken into consideration with the State of Charge (SOC) of the electrical energy storage (Equations (8)-(9)). Additionally, it is designed to have the same initial and final SOC, considering multiple-period operation (Equation (10)).

$$E_{WT}(t) = N_{WT} \cdot uE_{WT}(v(t)) \tag{1}$$

$$E_{PV}(t) = A_{PV} \cdot I_{POA}(Rad(t)) \cdot \eta \tag{2}$$

$$E_{Ren}(t) = E_{WT}(t) + E_{PV}(t), \quad \forall t \tag{3}$$

$$StoreIn(t) = E_{Ren}(t) - E_{DU}(t), \quad \forall t \tag{4}$$

$$Demand(t) = StoreOut(t) + Grid(t) + E_{DU}(t), \quad \forall t \tag{5}$$

$$SOC(t+1) = (1-\theta) \cdot SOC(t) + (1-\chi) \cdot StoreIn(t+1) - \frac{StoreOut(t+1)}{1-\Delta\chi}, \quad \forall t \tag{6}$$

$$SOC(t) \leq CAP_{EES}, \quad \forall t \tag{7}$$

$$(1-\theta) \cdot SOC(t) + (1-\chi) \cdot StoreIn(t+1) \leq CAP_{EES}, \quad \forall t \tag{8}$$

$$\frac{StoreOut(t+1)}{1-\Delta\chi} \leq (1-\theta) \cdot SOC(t), \quad \forall t \tag{9}$$

$$SOC(0) = SOC(8760) \tag{10}$$

To determine the optimal design and operating condition of the renewable energy system, the cost of hydrogen (COH) is defined as an objective function of optimization. As shown in equations (11)-(20), the cost of hydrogen (COH), is estimated considering the total annual cost (TAC) and the annual hydrogen production ($Prod_{H2}$). Capital expenditures (CAPEX) considering maximum capacity for WT, PV systems, and electrical energy storage (EES), as well as operating expenditures (OPEX) for these facilities are included in TAC. Grid electricity import and carbon tax considering CO_2 emission factors for each technology are also included in TAC. All the costing parameters for the COH estimation of renewable energy system are shown in **Table 3**. The optimal set of design variables for the renewable energy system is determined by using the MATLAB optimization solver "intlinprog" to minimize COH while considering the set of constraints (Equations (1)-(10)).

Table 3: Costing parameters of RES

Parameters	Unit	Values [15]
Natural gas price	€$_{2023}$/MWh	41 [10]
Grid power unit price (GP)	€$_{2023}$/MWh	95.18 [11]
CO_2 emission factor (EF)	gCO_{2e}/kWh	13 (WT) [16] 43 (PV) [16] 744 (Grid) [16]
WT capital cost (CC_{WT})	$$_{2023}$/kW	1010.2 (Advanced) 1809.6 (Current)
WT O&M cost (AOC_{WT})	$$_{2023}$/kWyr	16.394 (Advanced) 32.252 (Current)
PV capital cost (CC_{PV})	$$_{2023}$/kW	562.6 (Advanced) 1610.9 (Current)
PV O&M cost (AOC_{PV})	$$_{2023}$/kWyr	11.381 (Advanced) 22.219 (Current)
EES capital cost (CC_{EES})	$$_{2023}$/kW	190.5 (Advanced) 520.1 (Current)
EES O&M cost (AOC_{EES})	$$_{2023}$/kWyr	15.879 (Advanced) 47.674 (Current)
Plant lifetime	yr	30 [7]
Fixed charge rate (FCR)	1/yr	0.0586 [7]
Capacity factor	%	90 [7]
Unit carbon tax ($CTAX_{unit}$)	$$_{2023}$/t$CO_2$	0 - 180

$$TAC = FCR \cdot (\sum CAPEX) + \sum(OPEX + CTAX) \quad (11)$$

$$CAPEX_{PV} = CC_{PV} \cdot \max_t E_{PV}(t) \quad (12)$$

$$CAPEX_{WT} = CC_{WT} \cdot \max_t E_{WT}(t) \quad (13)$$

$$CAPEX_{EES} = CC_{EES} \cdot CAP_{EES} + SOC(0) \cdot (GP + EF_{Grid} \cdot CTAX_{unit}) \quad (14)$$

$$OPEX_{PV} = AOC_{PV} \cdot \sum_t E_{PV}(t) \,/\, 8760 \quad (15)$$

$$OPEX_{WT} = AOC_{WT} \cdot \sum_t E_{WT}(t) \,/\, 8760 \quad (16)$$

$$OPEX_{EES} = AOC_{EES} \cdot \sum_t StoreOut(t) \,/\, 8760 \quad (17)$$

$$OPEX_{Grid} = EC_{Grid} \cdot \sum_t Grid(t) \quad (18)$$

$$CTAX_{total} = CTAX_{unit} \cdot (\sum_t E_{PV}(t) \cdot EF_{PV} + \sum_t E_{WT}(t) \cdot EF_{WT} + \sum_t Grid(t) \cdot EF_{Grid}) \quad (19)$$

$$COH_{total} = TAC / Prod_{H2} \quad (20)$$

5. CASE STUDY RESULTS

In this contribution, a total of eight case studies are conducted by varying the carbon tax (0 - 180 \$/tCO_2) under two different scenarios: one reflects the comparatively high capital and operating costs corresponding to the current state of renewable energy (WT, PV, and EES) technical maturity, while the other reflects the potential expenses in 2050, when renewables will be expected to be advanced and more economical. For each case study, the mathematical model of the RES determines the optimal solution for combination of WTs, PV system, EES, and grid electricity imports. The optimized annual operating conditions of RES & Grid for each case study are shown in **Figure 2**.

The optimization results for each case study are presented in **Tables 4** and **Table 5**, with a breakdown of the grid's and the renewable energy facility's performance and cost of hydrogen. In the current technology scenario without carbon tax, the most economical option to supply the electrified hydrogen production power demands is to rely mainly on grid electricity while 27% of the total demand is supplied by the renewable energy systems. However, as the carbon tax increases, the renewable energy system introduction is encouraged by increasing tax on indirect CO_2 emissions from grid electricity. When the carbon tax is increased to \$180/tCO_2, the renewable energy ratio increases from 27% to 51%. As technological maturity increases and the unit cost related to renewable energy system decreases, the ratio of renewable energy increases from 27% to 56%, even without the carbon tax. Furthermore, if the carbon tax is increased to \$180/tCO_2, the renewable energy ratio increases to 72%.

As shown in **Table 5**, the overall cost of hydrogen varies from 1.78-3.27 \$/kgH_2 depending on the carbon tax when the technical maturity is at its current level. However, the overall cost of hydrogen is expected to vary from 1.38-2.28 \$/kgH_2, when the technical maturity reaches the advanced level in the future, indicating a cost reduction of 22.5-30.3% can be achieved depending on the carbon tax.

Table 4: Optimal Solution for Renewable Energy Supply

Carbon tax		0	60	120	180
Current state					
Capacity	WT [MW]	23	39	47	51
	PV [MW]	37	50	63	71
	EES [MWh]	5	74	135	178
Annual power gen. [GWh]	WT	34	60	71	78
	PV	54	73	92	103
	EES	0	2	7	12
	Grid	246	203	176	163
Renewable ratio		0.27	0.39	0.47	0.51
Advanced state					
Capacity	WT [MW]	53	62	69	74
	PV [MW]	85	126	132	137
	EES [MWh]	246	467	518	572
Annual power gen. [GWh]	WT	80	94	106	113
	PV	124	184	192	199
	EES	20	46	53	58
	Grid	147	108	100	94
Renewable ratio		0.56	0.68	0.70	0.72

Table 5: Economic Results of Cost of Hydrogen (COH)

Carbon tax [\$/tCO_2]		0	60	120	180
Current state cost of hydrogen (COH) [\$/kgH_2]					
CAPEX	WT	0.14	0.25	0.29	0.32
	PV	0.21	0.28	0.35	0.40
	EES	0.01	0.13	0.24	0.32
OPEX	WT	0.01	0.01	0.01	0.02
	PV	0.01	0.01	0.01	0.01
	EES	0.00	0.00	0.00	0.00
	Grid	1.41	1.16	1.01	0.93
CTAX		0.00	0.52	0.91	1.26
Total COH		1.78	2.36	2..84	3.27
Advanced state cost of hydrogen (COH) [\$/kgH_2]					
CAPEX	WT	0.19	0.22	0.24	0.26
	PV	0.17	0.25	0.26	0.27
	EES	0.16	0.31	0.34	0.38
OPEX	WT	0.01	0.01	0.01	0.01
	PV	0.01	0.01	0.01	0.01
	EES	0.00	0.00	0.01	0.01
	Grid	0.84	0.62	0.57	0.54
CTAX		0.00	0.30	0.56	0.80
Total COH		1.38	1.72	2.01	2.28

These case studies suggest that either an aggressive carbon tax to reduce grid-based electricity use or a significant reduction in capital costs accompanied by the technological innovation of RES is required to increase the use of renewable energy for the commercial-scale, low-carbon hydrogen production process.

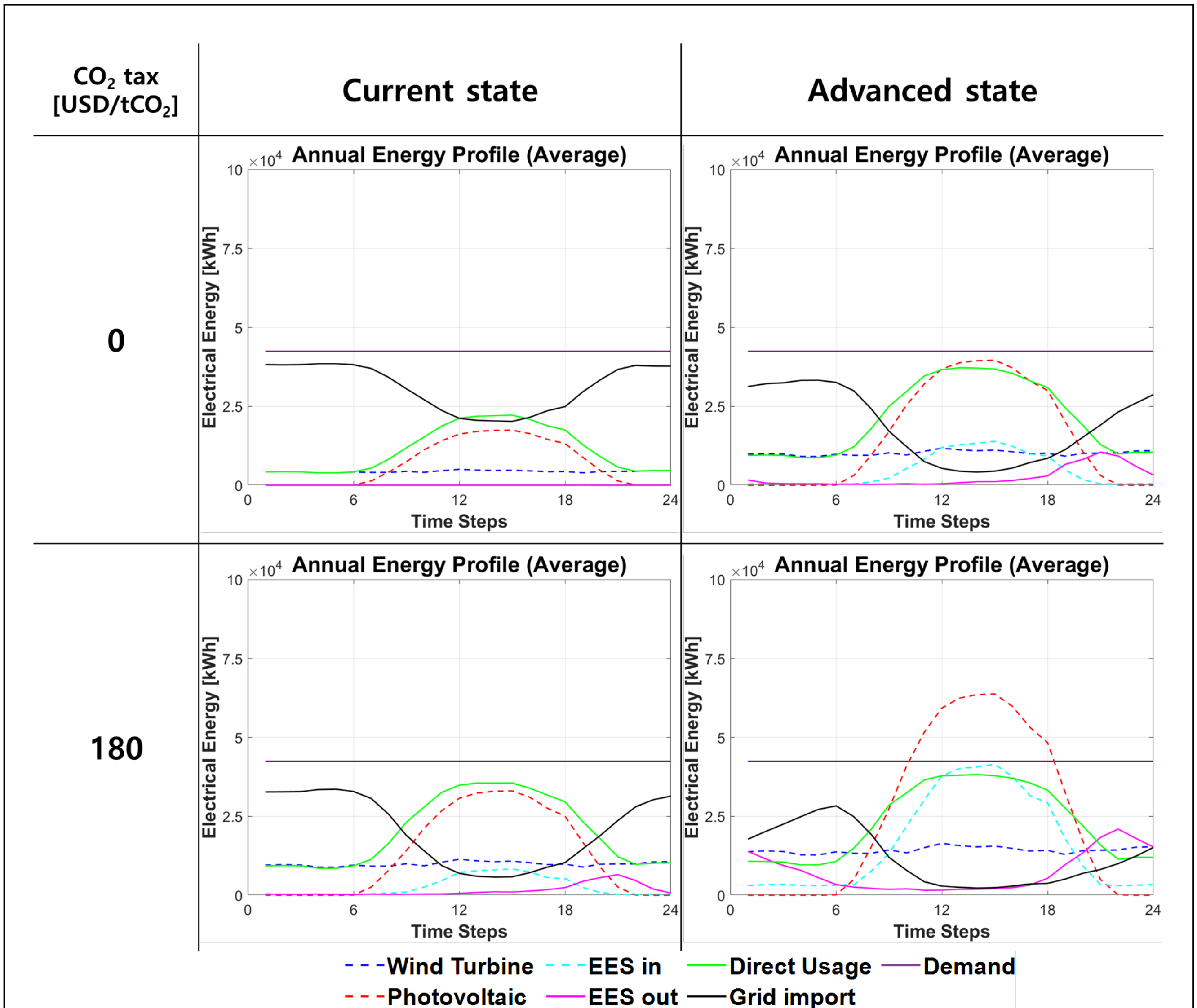

Figure 2: Annual Everage Electricity Supply Profiles of Renewable Energy System & Grid

6. CONCLUSION

This study proposes a comprehensive framework to determine the optimal design and operation of a combined renewable energy system & grid electricity supply for the electrified hydrogen production process. The MILP model is designed to optimize the operating conditions of the electricity supply system and to minimize the total cost including capital and operating costs of the renewable energy system, grid electricity costs, and carbon tax. The case studies investigated show that the optimized combination of the electricity mix is significantly influenced by the carbon tax levels and that the reducing capital costs with advanced technological maturity is crucial for the economic feasibility of the renewable energy system integration.

Future work will extend this framework to scenarios where the electrified hydrogen production process requires additional thermal energy, thereby exploring integrated renewable heat and power supply systems. Time-varying operational strategies that optimize both electricity and heat requirements under different policy conditions would further enhance understanding of the potential pathways toward large-scale, low-carbon hydrogen production.

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NOMENCLATURE

Abbreviation	Description	
AOC	Unit annual operating cost	
$CAPEX$	Capital expenditure	
CC	Unit capital cost	
COH	Cost of hydrogen	
$CTAX$	Carbon tax	
EES	Electrical energy storage	
EF	Emission factor	
FCR	Fixed charge ratio	
GP	Grid power unit price	
$MILP$	Mixed-Integer linear programming	
$OPEX$	Operating expenditure	
PV	Photovoltaic	
RES	Renewable energy system	
WT	Wind turbine	
$Variable$	**Description**	**Unit**
$Independent$		
A_{PV}	Area of solar PV panels	m^2
CAP_{EES}	Capacity of electrical energy storage	kWh
E_{DU}	Direct usage of renewable electricity	kWh
$Grid$	Grid import	kWh
N_{WT}	Number of wind turbine	-
SOC	State of charge	kWh
$StoreIn$	Electricity from renewables to EES	kWh
$StoreOut$	Electricity discharged from the EES	kWh
$Dependent$		
E_{PV}	Total PV power generation	kWh
E_{Ren}	Renewable power generation	kWh
E_{WT}	Total WT power generation	kWh

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