WASTE HEAT RECOVERY IN REMOTE RENEWABLE ENERGY HUBS

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ABSTRACT

This paper delves into the investigation of the potential valorisation of waste heat generated inside a Remote Renewable Energy Hub (RREH). The RREH concept involves harvesting renewable energy where it is most abundant and producing synthetic fuels for export to energy demand centers. The case study explored in this work is an RREH located in the Sahara Desert, exporting 10 TWh of synthetic methane per year to Belgium. The primary aim of this study is to examine the impacts on costs resulting from the incorporation of waste heat recovery techniques into the system. The results suggest a cost reduction of up to 3.88% by using waste heat recovery techniques, confirming their potential in reducing infrastructure size and optimizing the cost efficiency of the overall power-to-gas supply chain in RREH.

1 INTRODUCTION

The increasing global energy demand and the imperativeness to transition from fossil-fuel-based to decarbonized energy systems have sparked significant interest in renewable energy sources. However, the large-scale deployment of renewable energy systems close to an energy demand centre (EDC), such as Europe, faces many challenges. One of these challenges arises from the uneven distribution of renewable resources worldwide. Hence, many countries, constrained by low renewable energy potential or limited land availability, encounter obstacles in achieving substantial growth in their renewable energy production. In response to this issue, the concept of remote renewable energy hub (RREH) was introduced by Berger et al., 2021. An RREH, as shown in Figure 1, is strategically positioned in a region abundant in renewable energy sources (RES) and relies on technologies such as photovoltaic panels and/or wind turbines for harvesting RES. These technologies are connected via a high voltage direct current (HVDC) line to a power-to-x plant linked to a direct air capture (DAC) unit. The energy carrier "x" derived from this process supplies an offsite EDC. In their study, Berger et al., 2021 consider synthetic methane as the energy carrier and compute a price for CH_4 delivered at the EDC of 149€/MWh - considering the higher heating value (HHV).
However, the cost of synthetic methane derived in remote hubs from renewable energy sources remains higher than the average price of natural gas supplied in the European Union (economics, 2023), highlighting the need for a cost reduction of the energy supplied by the RREH to establish its economic viability.
Hence, in Dachet, Benzerga, et al., 2023, the valorisation of heat in RREH has been identified to reduce the RREH costs. Various studies on power-to-x technologies (Götz et al., 2016; Tiktak, 2019; Cormos, 2023; Toro and Sciubba, 2018; Li et al., 2022) have also identified byproduct valorisation as a potential solution to decrease overall costs. These valuable byproducts encompass waste heat, as well as

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chemical substances that are surplus to the requirements of the sub-processes of the RREH, such as oxygen.

This study seeks to optimize the synthetic methane production chain by internally utilizing the waste heat generated during the process. Specifically, Waste Heat Recovery (WHR) technologies including heat recovery steam generator (HRSG) and organic Rankine cycle (ORC) are considered to assess the impact on the sizing of the RREH and the cost of synthetic methane production.

2 LITERATURE REVIEW

This section aims to present an overview of existing research articles on the valorisation of waste heat generated by various sub-processes within the original energy hub Figure 1.

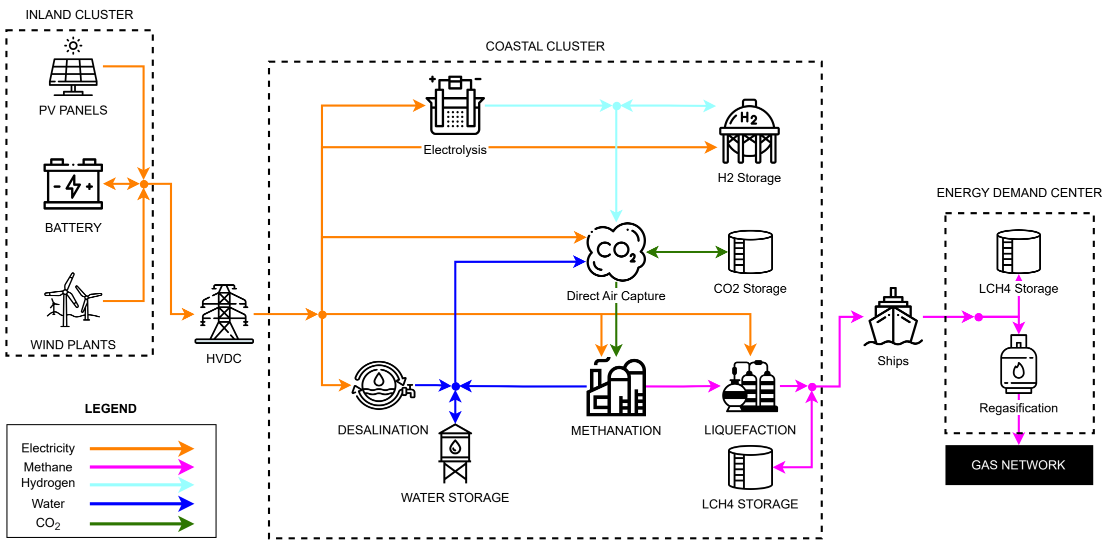

Figure 1: Reference RREH configuration. Icons represent conversion or storage nodes. Bullets and arrows schematically represent conservation hyperedges. Berger et al., 2021

2.1 Energy Hub Modeling and Cost Analysis

The concept of RREH was introduced by Berger et al., 2021. They modelled the structural and energy costs of an energy hub producing synthetic methane from renewable energy sources to supply a 10 TWh (HHV) annual demand of gas in Belgium. Their hub was located in Algeria where wind and solar were considered as RES. Various technologies, including desalination, DAC, and electrolysis, were employed to synthesize the required chemicals locally. The authors reported a methane price of 149€/MWh (HHV) using PV/Wind and a 7% weighted average cost of capital (WACC) configuration. In this paper, this will be referred to as the reference configuration. However, Berger et al. showed that depending on the chosen RES and WACC the price ranged from 88€ to 200€/MWh (HHV).
Dachet, Benzerga, et al., 2023 further extended Berger's work by considering the importation of CO_2 from industrial hubs with installed Post Combustion Carbon Capture (PCCC) technologies. This importation led to a lower price of 136€/MWh (HHV) in reference configuration. Furthermore, Dachet, Dubois, et al., 2023 developed a taxonomy, for improving the RREH cost-effectiveness, where they identified heat as a potential avenue for further decreasing the total cost of an RREH. An example of this taxonomy applied to (Berger et al., 2021) is available in 6 Exploring this new avenue is the goal of this paper.

2.2 Heat Recovery

Technology	Operating temperature	Applicability	Mode	Waste heat recovery
AEC	"Low" : 20-80°C	Mature	Exothermic Endothermic	50-70°C -
PEM	"Low" : 20-200°C	Commercialization	Exothermic Endothermic	50-70° -
SOEC	"High" : 300-1000°C	Lab-scale	Exothermic	-

Table 1: Summary of water electrolysis for heat valorisation (ENS.dk, n.d.[b]; Li et al., 2022)

Several studies have explored the heat recovery potential in the sub-processes of the studied energy hub. Cormos, 2023 used the pinch methodology to investigate a 500MW methanation unit (MU) integrating WHR, obtaining a CH_4 production cost of 65.40€/MWh (HHV). In their paper, the heat released by the MU was collected by a heat recovery steam generator (HRSG), which yielded 32.82MW of electrical power. The pinch methodology, introduced by Linnhoff and Hindmarsh, 1983, optimizes the energy consumption of chemical processes by applying thermodynamic principles. This is achieved through the optimization of heat exchanger networks (HEN) and heat recovery systems. This methodology has been widely applied for studying heat recovery in power-to-x plants (Toro and Sciubba, 2018; Cormos, 2023). Although the performance of the methanation process is optimal during constant production mode (ENS.dk, n.d.[b]; Götz et al., 2016) it requires large hydrogen storage. To overcome this issue, methanation can operate in dynamic production mode, reducing hydrogen storage needs but requiring heat during the standby periods. Part of the excess heat generated during the methanation can be stored and later supplied to meet the internal heat demand of the MU (Candelaresi et al., 2021). As the amount of thermal energy released during the methanation process is higher than the internal heat demand of the MU, the excess heat can still be used for electricity generation.

The methanation process, which is a crucial component of the energy hub, requires hydrogen which is synthesized by electrolysis.

A summary of the electrolysis process in the context of waste heat is provided in Table 1. The latter might be classified in two categories: low or high temperature.

Low-temperature electrolysis processes like alkaline electrolysis (AEL) and proton exchange membrane (PEM) operate under 200°C. The low-temperature electrolysis process itself can be separated into two production modes: endothermic and exothermic. In industrial applications, the low-temperature electrolysis process usually works under exothermic mode as it produces hydrogen at a faster rate than the endothermic mode Li et al., 2022. Under the exothermic mode, current electrolysis processes release waste heat at a temperature of 50°C, the latter is expected to rise to 70°C for future technologies (ENS.dk, n.d.[b]). This waste thermal energy amounts to approximately 20% of the input electrical energy fed into the methanation. It offers potential usage for district heating (external usage) or electricity generation through an ORC (Tiktak, 2019).

High-temperature process like solid-oxide electrolysis cell (SOEC) substitutes part of the required input electricity with heat and can achieve theoretical electrical efficiency above 100% (Götz et al., 2016; Brisse et al., 2008; Laguna-Bercero, 2012). SOEC is suited for heat integration, as 20.5% of the input energy of the process is required thermally (ENS.dk, n.d.[b]). However, large-scale plants with an installed capacity of H_2 (HHV) production over 100MW are still in the research and development phase (ENS.dk, n.d.[b]).

Direct Air Capture, supplies CO_2 in the energy hub, further utilised in the methanation process. The DAC is a heat prosumer that requires and releases heat during its internal chemical reactions (Keith et al., 2018). In their paper presenting a process for capturing CO_2 from the atmosphere, Keith et al., 2018 introduced an optimized DAC process that already implemented a heat recovery steam generator. Some researchers have also underlined the possibility of utilizing the waste heat released by the methanation to improve the CO_2 provider system (Götz et al., 2016; Schaaf et al., 2014).

The liquefaction unit, responsible for cooling down the methanation gas, which exits the methanation process at a temperature ranging between 300 and 700°C depending on the technology, and is reduced to a liquefied form at -162°C for transportation, offers additional potential for heat recovery (Götz et al., 2016). Other researchers have adopted a system-based approach to waste heat recovery. Das and Hasan, 2021 investigated a PV/Wind/Micro Gas Turbine/Battery system using waste heat recovery techniques and obtained significant size reduction of hardware components.

3 METHODOLOGY

The studied system is schematized in Figure 1. It can be viewed as a set of nodes representing technologies $\mathcal{T}_g$, and a set of hyperedges $\mathcal{H}_g$ representing flow (mass, energy) balances between nodes. Each node $\tau \in \mathcal{T}_g$ is characterized by a set of parameters (CAPEX, OPEX, efficiency, lifetime...), a set of variables, and a set of objectives. Variables can be internal (capacities) or external (input/output flows). Objectives represent one or several cost functions. It is implemented as a linear programming problem using the graph-based optimisation modelling language (GBOML) developed by Berger et al., 2021.

The main assumptions underlying the model are as follows:

- Centralised planning and operation: A single entity is responsible for making all investment and operational decisions.
- Perfect forecast and knowledge: It is assumed that the demand curves, as well as weather time series, are available and known *in advance* for the entire optimisation horizon.
- Permanence of investment decisions: Investment decisions result in the sizing of installation capacities at the beginning of the time horizon. Capacities remain fixed throughout the entire optimisation period.
- Linear modelling of technologies: All technologies and their interactions are modelled using linear equations.
- Spatial aggregation: The energy demands and generation at each node are represented by single points.

The detailed optimization framework used in this paper can be found in Berger et al., 2021. The system of this paper, represented in Figure 2, was implemented in Python using the GBOML library developed by Miftari et al., 2022.

The data of the original system (Figure 1) originates from Berger et al., 2021. Most of the data in the original model and this paper was retrieved from the Danish Energy Agency website ENS.dk, n.d.(a), which provides a comprehensive catalogue of energy-related technologies. Data of technologies non-present in the ENS.dk, n.d.(a) catalogue is retrieved from the most up-to-date and available scientific papers found to the best of the author's abilities. A cost correlation method was applied to obtain the capital cost of technologies with sizing differing from the available data. All data, parameters, code and results can be found as indicated in section 6.

The impacts of implementing waste heat valorisation on the original RREH will be analysed into two angles: changes in installed capacities and changes in production costs. Changes in the installed capacities will be compared to the capacities in the reference configuration without waste heat recovery. Changes in production costs will be expressed in €/MWh$_{CH_4}$ (HHV) and broken down between the different technologies.

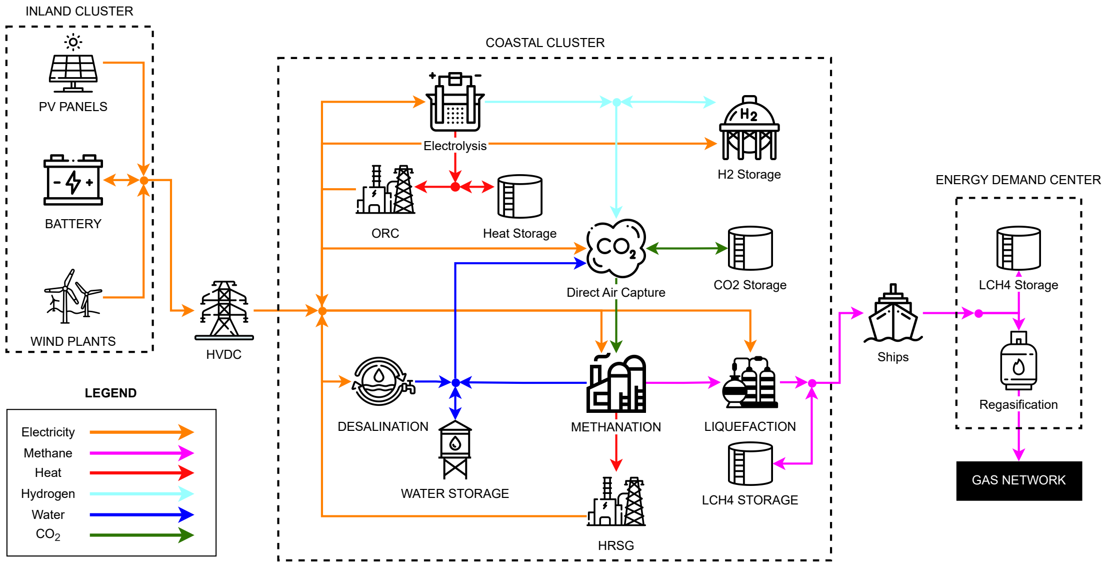

Figure 2: Waste heat recovery technologies are added to the system of Figure 1 : Organic Rankine Cycle (ORC) and heat storage at the top left and a Heat Recovery Steam Generator at the bottom.

4 CASE STUDY

In this section, we delve into our case study by examining the waste heat generated in each of the sub-processes of the RREH and how it can be valorized. The various input and output commodities associated with each technology involved in the process have been identified and gathered in Table 2. The new system including heat recovery is shown in Figure 2.

4.1 Technologies

The DAC plant considered in this paper is based on the model developed by Keith et al., 2018 and includes an HRSG system. It is supposed to be independently optimized and will not be investigated for further heat recovery

The methanation is an exothermic chemical process providing recoverable heat :

$$CO_2(g) + 4H_2(g) \rightarrow CH_4(g) + H_2O(g) + 165.1[kJ] \quad (1)$$

In this paper, heat is recovered at 300°C by a steam generator used for electricity generation. The methanation unit is assumed to operate in steady state operations yielding a constant output of CH_4 and heat.

The electrolysis considered in this paper is a PEM electrolysis working under an exothermic and unsteady production mode. During this mode, heat is supposed to be released and available at 70°.
The Danish Energy Agency estimated that 22.6% of the electrical input was converted to heat losses of which 19.6 % and 3% are assessed to be recoverable and unrecoverable respectively (ENS.dk, n.d.(b) p.128). Low-temperature waste heat will be recovered and sent for thermal energy storage (TES) for later use in an Organic Rankine Cycle (ORC) for power generation as suggested by (Tiktak, 2019).
It has been suggested to use the excess heat from PEM/AEC electrolysis in combination with SOEC but as substantial plant data for SOEC is lacking, this solution will not be investigated in this paper (ENS.dk, n.d.[b]).

Process	Type	Input	Output
PEMEL	Chemicals	Desalinated seawater (I)	High-grade hydrogen (O)
			High-grade oxygen (B, O)
	Energy	Electrical power (O)	Heat at 70° (B,O)
Methanation	Chemicals	Hydrogen (O)	H_2O (g) (O)
		Carbon dioxide (O)	CH_4 (g) (O)
	Energy	Electrical power (O)	Heat (B)
DAC	Chemicals	Water (O)	CO_2 (g) (O)
	Energy	Electrical power (O)	
		Heat (I)	Heat (B)
Liquefaction	Chemicals	CH_4 (g) at 300°(O)	CH_4 at -162° (O)
	Energy	Electrical power (O)	Heat (O)
Regasification	Chemicals	CH_4 at -162° (O)	CH_4 at 25° (E)
	Energy	Electrical power (O)	Cold (O)

Table 2: Input and output commodities associated with each technology involved in the reference RREH, following Dachet, Dubois, et al., 2023 taxonomy. E = exports, I = imports, B = byproducts, O = local opportunities.

In the liquefaction plant, the synthetic methane exiting the methanation unit at 300° is cooled down to reach the liquefaction temperature of -162° used for LNG tanker transportation. Heat recovery from this process is not investigated.
The regasification plant located at the energy demand centre, in this case Belgium, oversees the temperature increase of the natural gas from -162° to 25° providing a local opportunity of cooling flow. This opportunity is not investigated

4.2 Scenarios

1. The first scenario investigates the recovery of methanation heat with an HRSG for power generation.
2. The second scenario investigates the recovery of the low-temperature heat from electrolysis for power generation using an ORC and thermal energy storage (TES).
3. The third scenario studies the integration of both the HRSG and ORC/TES configurations.

The full supply chain is modelled and optimized using the GBOML language over a five-year period (2015-2019), with an hourly resolution. The purpose of the RREH is to supply 10 TWh (HHV) of methane per year to Belgium.

5 RESULTS

This section presents the results of the case study. Table 3 shows the final production cost for methane (HHV) in €/MWh across the reference and studied scenarios.

Reference	Scenario 1	Scenario 2	Scenario 3
149.76	145.40	147.87	143.95

Table 3: Price for synthetic CH_4 (HHV) in €/MWh, delivered at the energy demand center (Belgium), considering different heat recovery scenarios

Although costs are lower in each scenario compared to the reference case, these reductions did not come from the same technologies. A breakdown by technology for changes in costs and capacities for each scenario is available in Table 4 and Table 5. A visual representation of the cost for each scenario is displayed in Figure 4.

The first scenario highlights the results of waste heat recovery for power generation.
Scenario 2 highlights the results of using thermal energy storage acting as a buffer in the heat recovery process for power generation. Scenario 3 identifies the optimal balance between a TES/ORC and an HRSG configuration.

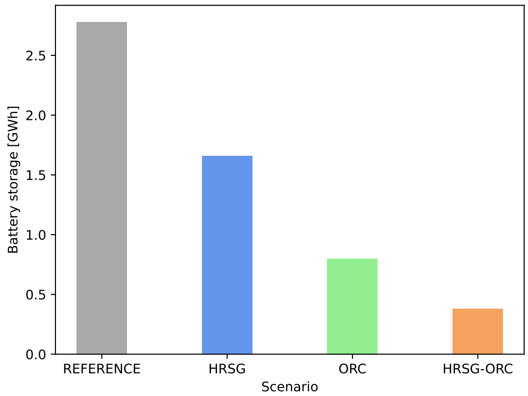

Figure 3: The installed capacity of batteries storage decreases as more waste heat is recovered.

The main observation when looking at the results is the reduction in lithium-ion battery storage capacities, as shown in Figure 3. The cause of this reduction is detailed below. The battery is the primary technology inducing cost reduction across scenarios 1 to 3 due to its size reduction of -40.30%, -71,13% and -86.38% respectively.
Across each scenario, the size reduction occurred primarily in technologies upstream of the electrolysis, while the downstream technologies responsible for CH_4 synthesis remained unchanged.

5.1 Scenario 1 : heat recovery from methanation

Waste heat recovery using an HRSG coupled to the methanation unit was analysed. The electrical power generated by the HRSG was directly injected into the coastal cluster's electricity network. Under steady production assumed for methanation, the HRSG yielded a constant power output of 76 MW, equivalent to 23.5% of the methanation power consumption and 2.9% of the renewable power production in the reference scenario.

The integration of this additional electricity source into the coastal cluster resulted in a decrease in the installed capacity of certain technologies primarily observed in the inland cluster and the power harvesting, storage, and distribution chain. Notably, the battery storage and output flow capacities were reduced by 40.30% and 34.98% respectively, followed by the PV panels (5.22%) and wind plants (2.45%). Although the electrolysis capacity increased by 0.83% and taking into account the cost of the HRSG system, this scenario achieved a 2.91% global cost reduction.

Investing in HRSG technologies represents less than 0.25% of the total scenario cost (Table 4). Taking into account the low cost of the HRSG system (0.36€/MWh) compared to the cost of the other technologies of the RREH amounting to 145.4€/MWh, this opens an interesting avenue for reducing the costs of the

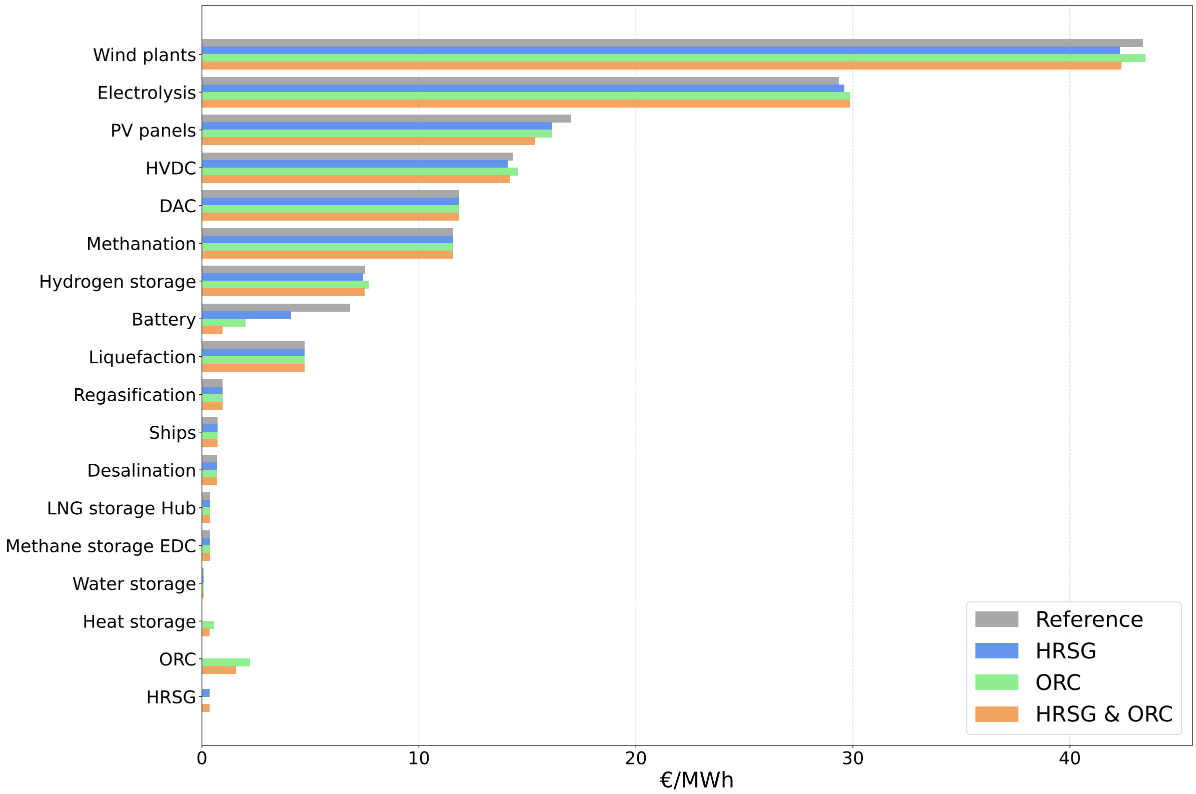

Figure 4: Breakdown of costs per scenario and technology

system.

The main takeaway of this scenario is the role played by the HRSG system in the RREH. Recovering waste heat from the methanation process allowed for constant power production, in the coastal cluster, where the internal energy demand of the RREH is located. This source reduced the need for maximal power production from the RES and maximal storage capacity of the batteries.

5.2 Scenario 2: heat recovery from electrolysis

In this scenario, the heat was recovered from the electrolysis and injected into a network including a TES and an ORC for power generation. The heat was either utilised by the ORC or stored for later power generation. The TES allowed for decoupled power generation between the ORC and the electrolysis, which is susceptible to unsteady production modes. In this scenario, the battery storage capacity was reduced by 71% as an effect of the presence of the ORC in addition to the TES. The electrolysis capacity experienced a slight increase likely due to the incentive to recover waste heat from the latter for power production. This scenario yielded a power output of up to 170MW while a preliminary configuration without TES produced only 50MW.

The investments in WHR technologies for this scenario were higher compared to Scenario 1 and amounted to 1.87% of the total cost. This cost difference may be explained by a higher power output for the WHR technologies and a higher CAPEX for the ORC/TES compared to the HRSG's.
The main observation in this scenario is the increase in capacity for some technologies supplying the electrolysis. Although having a low conversion efficiency, this configuration incentivises the RREH to increase the electrolysis capacity, inducing more waste heat available for power generation.

As discussed by Dachet, Benzerga, et al., 2023, one of the challenges inside an RREH is to tackle curtailment. The TES might act as a buffer to store this excess power production.

5.3 Scenario 3 : Heat recovery from both electrolysis and methanation

In this scenario, the first two scenarios (HRSG and ORC/TES) were combined for electrical power generation. The integration of these two additional electricity sources decreased the ORC's maximum power production to 100MW, while the output of the HRSG remained constant at 76MW. One possible explanation for this difference is that the power generation costs of the HRSG are lower compared to those of the ORC.
Battery storage capacity was further reduced, reaching 13.62% of the installed capacity in the reference scenario. On the other hand, electrolysis was the only process with an increased capacity (+1.73%). Wind plants witnessed a lower reduction in capacity compared to the HRSG scenario, with a decrease of 2.26%. As a result of these capacity adjustments, the final price for this scenario, employing both HRSG and ORC/TES, was 143.95 €/MWh, representing a 3.88% cost reduction compared to the reference scenario. The investment cost for the WHR technologies amounted to 2.28€/MWh finding a trade-off between the first two scenarios.This scenario combined all the advantages of the first two scenarios, reducing the installed capacities of the power harvesting, storage, and distribution technologies and further decreasing the total cost of the RREH.

Technology	Reference	HRSG	ORC	ORC+HRSG
BATTERY_STORAGE	6.82	4.11	2.00	0.96
CARBON_DIOXIDE_STORAGE	0.00	0.00	0.00	0.00
DESALINATION_PLANTS	0.70	0.70	0.70	0.70
DIRECT_AIR_CAPTURE_PLANTS	11.86	11.86	11.86	11.86
ELECTROLYSIS_PLANTS	29.36	29.60	29.88	29.86
HRSG	0.00	0.36	0.00	0.36
HVDC	14.31	14.08	14.57	14.21
HYDROGEN_STORAGE	7.52	7.43	7.69	7.50
LIQUEFIED_METHANE_CARRIERS	0.71	0.71	0.71	0.71
LIQUEFIED_METHANE_REGASIFICATION	0.95	0.95	0.95	0.95
LIQUEFIED_METHANE_STORAGE_EDC	0.38	0.38	0.38	0.38
LIQUEFIED_METHANE_STORAGE_HUB	0.39	0.39	0.39	0.39
METHANATION_PLANTS	11.58	11.58	11.58	11.58
METHANE_LIQUEFACTION_PLANTS	4.74	4.74	4.74	4.74
ORC	0.00	0.00	2.21	1.57
SOLAR_PV_PLANTS	17.01	16.12	16.11	15.37
THERMAL_ENERGY_STORAGE	0.00	0.00	0.55	0.35
WATER_STORAGE	0.08	0.08	0.08	0.08
WIND_PLANTS	43.36	42.30	43.47	42.37
Cost [€/MWh]	149.76	145.40	147.87	143.95

Table 4: Results of system cost in each scenario. Time horizon for optimization = 5 years

5.4 Comparison of results

The first scenario (HRSG) resulted in the generation of 76 MW of additional power, the second scenario (ORC and TES) yielded an additional power source producing up to 170 MW of electrical power and the third scenario using both an HRSG and an ORC/TES provided between 76 and 176 MW of additional electrical power. Those new power sources located closer to the coastal technologies led to size reductions in the upstream technologies within the inland cluster, primarily in the lithium-ion batteries with reductions of 34.98%, 66.84%, 82.98% in flow capacity, and 40.3%, 71.13%, 86.38% in storage capacity for each of the three scenarios respectively. The electricity generated from the waste heat reduced the energy requirements of the plant. Therefore reducing the RES sizing and providing a constant source of electricity which reduced the need for batteries Waste heat recovery induced a promising reduction in production costs, varying from 1.26% to 3.88% compared to the reference scenario, leading to a new price of synthetic methane reaching 143.95€/MWh in the third scenario.

Technology	Unit	Reference	HRSG	ORC	HRSG-ORC
BATTERY_STORAGE_capacity	GWh	2.78	1.66	0.80	0.38
BATTERY_flow_capacity	GW	0.46	0.30	0.15	0.08
SOLAR_PV_PLANTS_capacity	GW	4.27	4.05	4.04	3.86
WIND_PLANTS_capacity	GW	4.30	4.20	4.32	4.21
HVDC_capacity	GW	3.32	3.27	3.38	3.30
WATER_STORAGE_capacity	kt	109.37	108.17	111.94	109.10
HYDROGEN_STORAGE_capacity	kt	12.79	12.65	13.09	12.76
HYDROGEN_STORAGE_flow_capacity	kt/h	0.04	0.04	0.04	0.04
WATER_STORAGE_flow_capacity	kt/h	0.40	0.40	0.40	0.40
HRSG_capacity	GW	0.00	0.08	0.00	0.08
ORC	GW	0.00	0.00	0.14	0.10
THERMAL_ENERGY_STORAGE_capacity	GWh	0.00	0.00	23.69	15.14
THERMAL_ENERGY_STORAGE_flow_capacity	GWh	0.00	0.00	1.79	1.26
ELECTROLYSIS_PLANTS_capacity	GW	3.06	3.09	3.12	3.11

Table 5: Results of system capacities in each scenario. Time horizon for optimization = 5 years

6 CONCLUSION

In this paper, we conducted an investigation of the valorisation of waste heat within an RREH. The study explored the potential valorisation of the waste heat generated during the sub-processes of the RREH for improving its efficiency.

The supply chain was modelled and optimized in an integrated fashion over five years. Two waste heat sources were investigated for power generation: electrolysis was linked to an ORC/TES and methanation to an HRSG. In this paper, the two recovery processes differ in their production mode: the HRSG operates under steady conditions by receiving a constant flow of heat while the ORC operates under non-steady conditions as it receives heat from the unsteady electrolysis.

Future investigations could explore the optimization of the direct air capture process by utilising the heat generated from the methanation unit to meet the DAC heat demand. In the continuity of scenario 2, thermal energy storage for the methanation heat could be investigated. Further research could delve into heat recovery from the liquefaction process and investigate the valorisation of cold flow in the regasification process at the destination cluster. Additionally, conducting a thermoeconomic analysis of the system could unveil further avenues for internal enhancement. Furthermore, exploring the potential revenue streams and local opportunities arising from the utilisation of oxygen and heat from electrolysis could prove fruitful, especially for providing local population with valuable resources.

As evidenced by the literature and the results obtained in this study, the valorisation of waste heat holds great promise in enhancing the overall efficiency and viability of renewable power-to-gas technologies in remote renewable energy hubs.

NOMENCLATURE

Abbreviations

AEC	Alkaline Electrolyser Cell
CAPEX	Capital Expenditure
DAC	Direct Air Capture
DH	District Heating
DHC	District Heating and Cooling
GBOML	Graph Based Optimization Modeling Language
HEN	Heat Exchange Network
HHV	Higher Heating Value
HRSG	Heat Recovery Steam Generator
LNG	Liquified Natural Gas (100% methane)
MU	Methanation Unit
ORC	Organic Rankine Cycle
OPEX	Operation Expenditure
PCCC	Post Combustion Carbon Capture
PEM	Proton Exchange Membrane
RES	Renewable Energy Sources
RREH	Renewable Remote Energy Hub
SOEC	Solid Oxide Electrolysis Cell
TES	Thermal Energy Storage
WHR	Waste Heat Recovery

TAXONOMY OF THE RREH

Following the taxonomy introduced in Dachet, Dubois, et al., 2023, the RREH studied in this paper can be characterized as

$\mathcal{L}_r$	$\{$*Sahara desert*$\}$
$\mathcal{G}_{\mathcal{L}_r}$	the set of technologies and hyperedges $(\mathcal{T}_g, \mathcal{H}_g)$ is represented in Figure 1
$\mathcal{C}_g$	$\{electricity, CH_4, H_2, H_2O, CO_2, O_2, heat\}$
$\mathcal{I}$	$\{$*sea water, air*$\}$
$\mathcal{E}$	$\{CH_4\}$
$\mathcal{B}$	$\{O_2, heat\}$
$\mathcal{O}$	$\{\}$

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ACKNOWLEDGEMENT

Victor Dachet gratefully acknowledges the financial support of the Wallonia-Brussels Federation for his FRIA grant.

DATA AVAILABILITY

The data and models used in this paper are publicly available on the GitHub repository of the GBOML Miftari et al., 2022 avalaible here https://gitlab.uliege.be/smart_grids/public/gboml/-/tree/master/examples/ .