# Minimization of Variable Renewable Energy Curtailment in an Islanded System using Power-to-Gas Technology: a Reunion Island Case Study

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***Abstract*—This paper shows a case study application of a novel power-to-gas operation simulation optimization model on Reunion Island to demonstrate how variable renewable energy curtailed can be minimized using such technologies. The proposed plant is integrated into a waste management facility to increase the methane production output for electricity generation. Two sizing scenarios are presented for the plant to analyze their operation over the simulated year, investigating the strengths and weaknesses of both. Results show that about 12% of curtailed electricity can be consumed to produce power for roughly 500 residents and increase the biogas plant capacity by 6%, using feedstocks that would have otherwise been discarded.**

***Index Terms*—curtailment, power-to-gas, methanation, optimization**

## I. Introduction

As the world transitions to renewable sources of energy, islands have a specially difficult challenge to incorporate variable renewable energy (VRE) into their energy mix. Without interconnections to other energy grids, all installed capacity must be maximally utilized on the island. Energy network coupling technologies such as power-to-gas (PtG) are one such way [1]. Converting electrical power to hydrogen ($H_2$) and possibly further to methane ($CH_4$), VRE can be used to satisfy the decarbonization targets of other sectors, such as industry or transportation. Reunion Island is one such place which had 87.5% energy dependence rate in 2019 with a heavy reliance on fossil fuels but great ambitions to decarbonize [2].

The purpose of this study is to investigate the minimization of VRE curtailment – energy available but not used – in an islanded system using power-to-gas technology. The analysis is done using a novel operation simulation optimization model using the French territory of Reunion Island as a case study of model application. Specifically, green $H_2$ and by-product carbon dioxide ($CO_2$) are used as feedstock to a biological reactor for $CH_4$ production which will be used to produce electricity in a biogas plant. The benefits from this application are fourfold: an increase of VRE utilization, an increase in $CH_4$ production from the biogas plant, a decrease in carbon emissions from reduced fossil fuel use in electricity generation and a decrease in energy dependency of the island.

## II. Methodology

### A. Evaluation of Variable Renewable Sources

To investigate the utilization of curtailed energy from VRE sources, the amount of curtailed on Reunion Island must first be found. Open Data is available online showing the hourly electrical production by source of the island [3]. The data used, as for all other data used in this study, was for the year 2019. From this table, an hourly electrical production profile of VRE sources – wind and solar photovoltaic (PV) – can be generated over the year. To estimate the amount of curtailed VRE, a comparison of the actual generation profile versus the potential generation can be done. Potential energy production profiles were generated from [4] using the centre of the island as geographical location, the latitude as tilt angle for PV (21°) and the nacelle height of island wind farms (60 metres [5]). The capacities were taken from other open-source data of all electrical generation facilities [6], summing the total PV and wind installed capacities. Finally, the difference between potential VRE and actual generation was done to generate an hourly curtailed power profile. A duration curve can be used to present the curtailment power in descending order over the year, as shown in Fig. 1. From this plot it can be seen that curtailment is available almost 70% of the year with low durations of high power. This plot can also be used to determine the sizing of equipment, which will be described further in the next subsection.

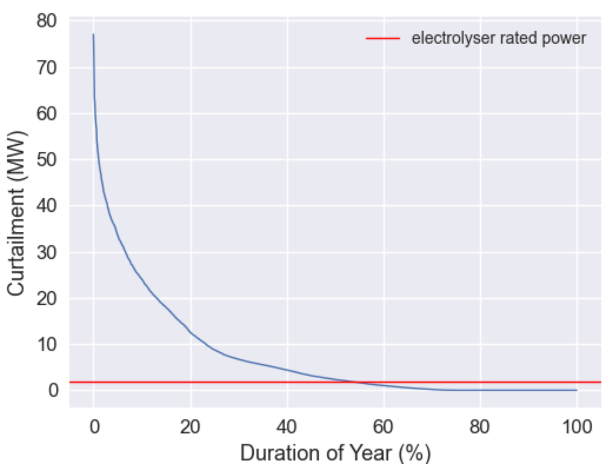


Fig. 1. Duration curve of variable renewable energy curtailment on Reunion Island and resulting electrolyser rated power.

### B. Site Evaluation and Sizing of Power-to-Gas Plant

The PtG plant critical component is the electrolyser, producing green $H_2$ via electrolysis from VRE sources. As such, the size of the electrolyser and equipment downstream are determined by the available curtailed power. Based upon Fig. 1, a proton exchange membrane (PEM) electrolyser of 2 MW rated power was chosen, allowing for operation of the plant approximately 54% of the year at rated power. It has been shown that the levelized cost of energy is close to minimized around 50% [7], so this was seen as sufficient operational time.

The end-use application of produced $H_2$ depends upon demands from sectors on the island as well as future ambitions of the government. A study has already been done showing the potential of converting 15 12-metre intercity buses to fuel cell vehicles [8]. Instead, this study will investigate further converting $H_2$ to $CH_4$ in a biological reactor. Currently, there is a large multi-channel waste treatment and recovery plant being constructed in the Pierrefonds locality [9]. Among the many activities, 30,000 tons per year of organic household waste will be fed into two anaerbic digesters to produce biogas for electrical energy [10]. As the biogas is roughly 60% $CH_4$ and 40% $CO_2$ [11], it must first be purified to almost 100% $CH_4$ for use in the gas turbine. The effluent from this process provides a high-quality source of $CO_2$, the second feedstock needed in the methanation reactor, at low to zero cost.

Based upon a levelized cost minimization study in [12] for a PtG plant using VRE sources as the electricity supply, it was found that reactor and $H_2$ tank capacity varied greatly depending if wind or PV were utilized. When wind was used, the reactor energy output capacity was 36% of electrolyser capacity and $H_2$ storage was just over 3 hours of rated electrolyser production whereas using PV for electricity was found to size the reactor at 17% electrolyser capacity with 6.5 hours of $H_2$ storage. However, the wind-based scenario achieved better levelized cost due to more $CH_4$ production. As the energy used in this study is a combination of these sources, two reactor and storage capacities will be investigated: wind-based and the average size between PV and wind (known as avg-based scenario going forward). The reactor and $H_2$ storage size of each scenario is shown in Table I.

TABLE I
REACTOR AND $H_2$ STORAGE CAPACITIES FOR EACH SCENARIO.

| | Unit | Wind-based | Avg-based |
|---|---|---|---|
| Reactor capacity | $MW_{th,CH_4}$ | 0.72 | 0.53 |
| $H_2$ storage capacity | kg | 134 | 198 |

The PtG plant is assumed to be located near one of the digesters to directly consume the $CO_2$ by-product. As the $CO_2$ source is relatively constant and much higher than needed (over 300% more when reactor is the largest size investigated), it was found that the equivalent of 4 hours of reactor production at rated capacity was sufficient for $CO_2$ that it did not affect production optimization.

Equipment sizing was done based upon these values and can be seen in Table II. Sizing of the plant was verified that it does not surpass available hourly $CO_2$ or local high-voltage allowable power (roughly 40 MW) [13]. A $H_2$ compressor is neglected due to sufficient output pressure from the electrolyser and low storage pressure. $CO_2$ is assumed to be purified and stored prior to reactor injection. A buffer $CH_4$ tank sized for 4 hours of reactor rated capacity is included. The biogas facility and proposed PtG plant is shown in Fig. 2.

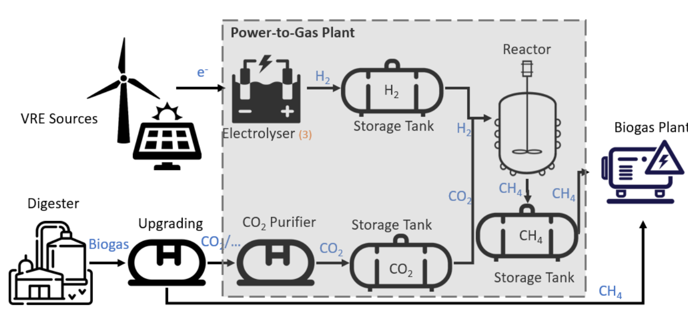


Fig. 2. Proposed system with power-to-gas plant boundary shown.

TABLE II
PRIMARY EQUIPMENT PARAMETERS USED IN SIMULATION.

| Parameter | Unit | Value | Ref. |
|---|---|---|---|
| ***PEM Electrolyser*** | | | |
| Capacity | $MW_{el}$ | 2 | NA |
| Efficiency | kWh/kg $H_2$ | 50 | [14] |
| Load | % | 5-100 | [14] |
| Pressure | bar | 30 | [14] |
| ***Biological reactor*** | | | |
| $CO_2$ conversion rate | % | 100 | [12] |
| Load | % | 40-100 | [15] |
| Pressure | bar | 10 | [16] |
| ***$H_2$ storage tank*** | | | |
| Pressure | bar | 10-30 | NA |

### C. Optimization of Plant Operation

To simulate operation of a PtG plant over the project lifespan, the system can be converted into an optimization problem, using mathematical formulation to represent all the equipment, feedstock parameters, external system limitations, end-use applications and operational objectives. A unit commitment (UC) style model is used to form a mixed-integer linear optimization problem. There are several possible objective functions which can be maximized/minimized based upon simulation objectives. The formulated UC problem of the system is defined in Equations (1)-(3) and based upon [17]:

$$max \sum_{t \in T} n_{rea}(t) \tag{1}$$

s.t.

$$\sum_{g \in G} A_g(P_g, \overline{P}_g, \delta_g) + N(s) = L \tag{2}$$

$$(P_g, \overline{P}_g, n_g) \in \Pi_g \qquad \forall g \in G \tag{3}$$

where the objective function (1) is the maximization of the summation of the molar production of the reactor $n_{rea}$ at each time step $t$ in the simulation period $T$. Equation (2) matrix $A_g(P_g, \overline{P}_g, \delta_g)$ determines how the generators interact with system requirements $L$ while $N(s)$ refers to other potential decision variables involving operation of the system. $P_g$, $\overline{P}_g$ and $\delta_g$ represent the feasible power, maximum power and status of the generator, respectively. Finally, (3) defines the feasible region for each generator and the cost associated to it, with the set $\Pi_g$ representing the description of this feasible operational region for each generator. For reference, generators are defined as equipment which produce either final products or internal system feedstock i.e. the electrolyser, reactor, and $CO_2$ purification system.

Based upon the above formulation, operation of the proposed PtG plant was simulated and optimized over one year at hourly time steps. All production of $CH_4$ from the reactor is assumed to be consumed by the biogas plant for electrical power generation for the island. Constraints were added to the generators to reduce the cycling affect from the variable nature of the electrical sources. Specifically, minimum off times and, for the reactor, a minimum on time was included. To ensure the equipment does not stay in idle for an indefinite period while waiting to run again, maximum idle times were also included. The values of these additional constraints are shown in Table III.

TABLE III
OPERATIONAL CONSTRAINTS OF THE ELECTROLYSER AND REACTOR USED IN OPTIMIZATION.

| | Min on time (hours) | Min off time (hours) | Max idle time (hours) |
|---|---|---|---|
| **Electrolyser** | - | 3 | 6 |
| **Reactor** | 6 | 6 | 6 |

## III. RESULTS AND DISCUSSION

The optimized simulation profiles of the primary equipment – electrolyser, reactor and $H_2$ tank – will first be analysed to understand why they operated the way they did. Then, $CH_4$ production will be analysed before the impact on curtailment and electricity generation is finally discussed.

### A. Operational Profile Analysis

The first week of operation for the wind-based is shown in Fig. 3. Even with constraints to limit cycling of the equipment, it can be seen that both the reactor and electrolyser run continuously at rated capacity for only very short periods. As the electrolyser produces $H_2$ at a rate much greater than the input requirements for the reactor (1.48 times and 1.97 times greater for the wind-based and avg-based scenario, respectively), its operation will only stay at rated capacity for short periods until the $H_2$ tank is full. The tank caused 171 and 428 stoppages in the avg-based and wind-based scenarios, respectively. A larger tank size allowed for more continued operation of the electrolyser, despite the reactor being smaller in the avg-based scenario. Another limitation to electrolyser operation is the VRE curtailment profile: $H_2$ cannot be produced if electricity is not available. Indeed, it was found that the curtailment profile limited electrolyser production for 2806 hours in the wind-based scenario and 2701 hours for the avg-based scenario; slightly less but not a significant amount.

Investigation of how the equipment operated, when permitted by system constraints, also provides some interesting insights. The yearly operational hours of the reactor and electrolyser in each scenario are shown in Table IV, as well as the number of startup cycles. The results show little difference in the operation of the electrolyser, with slightly more operation in the wind-based scenario due to higher reactor capacity. The mean operation at rated capacity – the average number of hours the equipment ran continuously at rated capacity – is the same for each scenario, again highlighting the little difference in electrolyser operation. One noted difference is the amount of power consumption from the electrolyser, as shown in the duration curve in Fig. 4. Although the operational time and startup cycles were similar, the average capacity


Fig. 3. Electrolyser and reactor production results for the first week of the year in the wind-based scenario. $H_2$ storage pressure is also shown on the right vertical axis.

during production was higher for the wind-based scenario. An interesting finding from this duration curve is that the wind-based scenario operated at rated capacity for 6% more of the year or 525 hours, however, it was rarely in continuous operation at rated due to insufficient tank and reactor capacity.

TABLE IV
OPERATIONAL RESULTS OF THE ELECTROLYSER AND REACTOR FOR EACH SCENARIO.

| | Operational hours | Num. startup cycles | Mean operation at rated capacity |
|---|---|---|---|
| | ***Electrolyser*** | | |
| **Avg-based** | 5481 | 450 | 7 |
| **Wind-based** | 5517 | 444 | 7 |
| | ***Reactor*** | | |
| **Avg-based** | 7854 | 81 | 30 |
| **Wind-based** | 6806 | 165 | 16 |

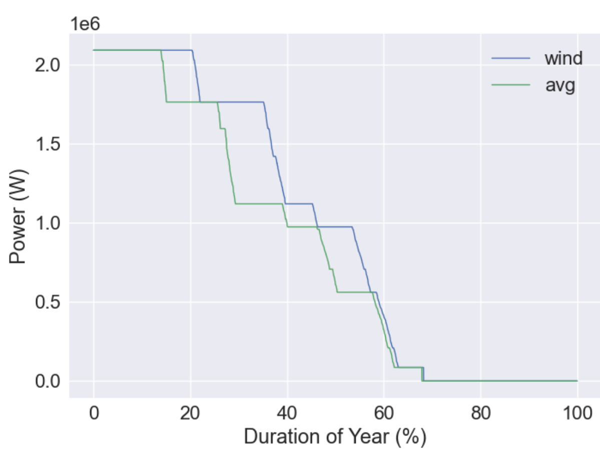


Fig. 4. Electrolyser power consumption duration curve for each scenario.

Reactor operation was quite different in each scenario, with a 15% increase in operational time and an almost doubled mean operation at rated capacity for the avg-based scenario. These points together with the almost 50% less startup cycles shows the improved performance of this scenario in terms of maximizing operation at rated capacity. How these operational profiles converted to actual $CH_4$ production will be investigated next.

## B. Production Analysis

A duration curve of $CH_4$ production for each scenario is shown in Fig. 5. Wind-based maximum production is obviously higher due to the larger reactor capacity, and is able to run at the rated value for over 50% of the year. However, this operation is rarely continuous as already discussed and shown in Table IV. Further, production is limited to 78% of the year, which may pose problems if the $CH_4$ demand is a yearly fixed one i.e. an industrial application. Production from the avg-based scenario is, in total, less than the wind-based scenario, but has some favorable characteristics. First, operation at rated capacity occurs for almost 11% or almost one month more and more continuously (as shown in Table IV). Second, the reactor operates 12% or over six weeks more in the year, giving a more constant source of $CH_4$ production. Total $CH_4$ production over the year and the mean production

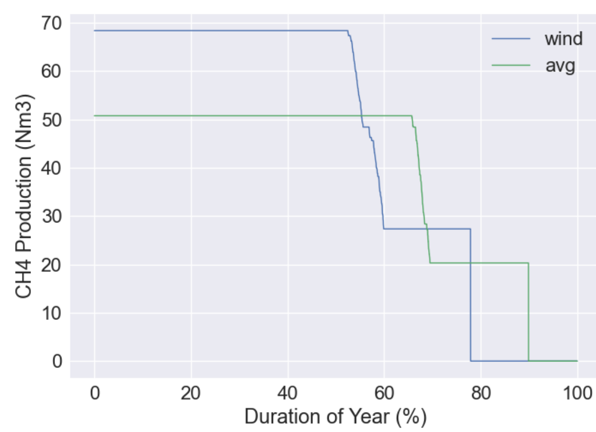


Fig. 5. Reactor $CH_4$ production duration curve for reach scenario.

per hour of operation is shown in Table V. Wind-based sizing allows for higher overall production of $CH_4$ (14% more), albeit at non-constant rate over the year. The average production is also higher, owing to the larger reactor capacity. If the demand requires a continuous flow but it could be slightly smaller, than a system sized like the avg-based scenario is more suitable. If larger, flexible demands are what is needed than a wind-based system can be justified. In either system, degradation from the highly dynamic nature of equipment operation must also be considered in more detailed operational analyses.

## C. Curtailment Consumption and Electrical Potential

As the purpose of this study is to consume curtailed VRE and increase $CH_4$ production from the biogas facility for

TABLE V

$CH_4$ TOTAL AND MEAN PRODUCTION FOR EACH SCENARIO OVER THE SIMULATED YEAR.

| | Total $CH_4$ production ($Nm^3$) | Mean $CH_4$ production ($Nm^3/h$) |
|---|---|---|
| **Avg-based** | 339,652 | 43.2 |
| **Wind-based** | 388,592 | 57.1 |

electricity production, it is beneficial to analyse how much of the curtailed energy is consumed in the PtG plant; it is shown in Table VI. Only 11-13% of the available curtailment can be consumed with the PtG plant scenarios. This can be explained by the high power ratings for low periods of the year of the VRE curtailment profile, as shown in Fig. 1. A trade-off occurs to either invest in large capacity equipment with low yearly rated operational hours or purchase smaller capacities that will give lower production at higher production hours. Using a 40% electrical efficiency of a biogas plant, the produced $CH_4$ can produce between 1,480-1,700 MWh for the year, providing enough electricity for 466-535 residents annually (assuming an electricity consumption of 3.177 MWh/capita [2]) and increase the new 3 MW biogas plant capacity by around 6%.

TABLE VI

VARIABLE RENEWABLE ENERGY CURTAILMENT CONSUMED, POTENTIAL ELECTRICAL PRODUCTION, BIOGAS FACILITY CAPACITY INCREASE AND AVOIDED GREENHOUSE GAS EMISSIONS FROM THE POWER-TO-GAS PLANT ADDITION.

| | Curtailment consumed (%) | Electricity production[a] (MWh) | Capacity increase (%) | Avoided emissions[b] (t $CO_2$eq) |
|---|---|---|---|---|
| **Avg-based** | 11.08 | 1,481 | 5.66 | 1,460 |
| **Wind-based** | 12.78 | 1,694 | 6.48 | 1,671 |

[a]Assuming 40% electrical efficiency of biogas plant.

[b]Assuming 0.986 t CO2eq/MWh for coal-fired plants.

## IV. CONCLUSIONS

A potential power-to-gas plant was investigated in this paper for Reunion Island for the purposes of reducing variable renewable energy (VRE) curtailment in an islanded system. $CH_4$ produced from a biological reactor is applied which will increase the $CH_4$ production of a specified biogas plant. Two sizing scenarios were investigated which weighed production capacity to $H_2$ feedstock storage capacity. In general, the reactor is shown to able to operate up to 90% of the year compared to roughly 63% for the electrolyser, exhibiting a decoupling of the dynamic nature of VRE consumption by the electrolyser to a relatively continuous yearly production of $CH_4$ from the reactor. Optimization of equipment sizing and an economical analysis would further improve case study results. While it is understood by the authors that the current low penetration of VRE on Reunion Island (8.9%) would assume very low curtailment currently occuring, there are objectives for doubling wind capacity and increasing PV by 50% by the end of 2023 [18]. These massive increases in VRE in the coming years will demand energy storage or multi-energy coupling network technologies such as those presented in this paper.

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