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Design of a renewable energy system with battery and power-to-methanol unit

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Abstract−An energy storage system consisting of a battery and a power-to-methanol (PtM) unit was investigated to develop an energy storage system for renewable energy systems. A nonlinear programming model was established to optimize the energy storage system. The optimal installation capacities of the battery and power-to-methanol units were determined to minimize the cost of the energy system. The cost from a renewable energy system was assessed for four configurations, with or without energy storage units, of the battery and the power-to-methanol unit. The proposed model was applied to the modified electricity supply and demand based on published data. The results show that value-adding units, such as PtM, need be included to build a stable renewable energy system. This work will significantly contribute to the advancement of electricity supply and demand management and to the establishment of a nationwide policy for renewable energy storage.

Keywords: Battery Energy Storage, Electricity Supply and Demand, Nonlinear Programming, Power to Methanol, Renewable Energy

INTRODUCTION

Uncertainty and fluctuation in electricity supply and demand have been a key issue that has attracted the attention of academics and practitioners. The fluctuation in demand becomes large during the time of peak demand, and the uncertainty in supply is exacerbated with a higher proportion of renewable energy sources, such as solar and wind power, in energy systems [1-4]. In practice, the power production in each generator is determined every few minutes based on the expected demand minutes ahead [5]. Additional solutions include the spatial integration of the electricity network and the curtailment of renewable energy sources [4,6]. Finally, energy storage is employed to resolve the instability that arises from the mismatch. In modern grids, however, the greater penetration of renewable energy resources, such as solar and wind power generation units, is inevitable. The uncertainties in supply from renewable resources require a higher amount of reserve to ensure system security and reliability [7,8]. To lower the reserve cost, the size of the electricity reserve should be optimized.

On May 8, 2016, the electricity supply in Germany far exceeded the demand due to fair weather and strong wind. At that time, the price of electricity plummeted, and went negative for 10 hours [9]. If a similar situation occurred in a 100%-renewable system, only an enormous energy storage system could handle it. The excess electricity could be distributed to outside the grid or consumed by a technology known as power-to-x, to produce hydrogen or methanol [10]. In this work, a power-to-methanol system is considered as an energy storage unit for its advantages over other such systems, such as the ability to store methanol relatively safely for a long time and to capture carbon dioxide [11].

Our objective was to investigate the benefits of the application of the battery and power-to-methanol (PtM) unit to an isolated 100%-renewable energy system. This work can be considered a preliminary assessment of employing the emerging technology for a large-grid system. To the authors' knowledge, this is the first work to address such a problem. A nonlinear programming (NLP) model has been developed for managing the renewable electricity grid with the battery and PtM. The proposed model was applied to a large-scale energy system in Ontario, Canada with published data.

PROBLEM STATEMENT

An optimization model was developed for an imaginary power producer in Ontario, Canada, that supplies the electricity generated only from wind and solar power plants. The installed capacities are 3871 MW for the wind farm and 233 MW for the solar photovoltaics (PV) plant. When the supply is higher than the demand, the excess is charged to the battery (also noted as BESS - battery energy storage system) or the PtM. When the supply is not enough to meet the demand, the deficit is discharged from the battery. Four configurations of the energy system are generated according to variations in the energy storage policy (Figs. 1-4):

• Configuration 1: An energy system without energy storage. The excess electricity is assumed to be lost.

• Configuration 2: An energy system with a battery only. The electricity is charged to or discharged from the battery when needed.

• Configuration 3: An energy system with a battery and PtM. The electricity charged to the battery can be discharged only to the

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Fig. 1. Electricity grid configuration 1.

PtM. The battery acts as a power regulator to the PtM.

• Configuration 4: An energy system with a battery and PtM. The electricity charged to the battery can be discharged to both the customer and the PtM.

The selected battery type in this work is lithium-ion (nickel manganese cobalt oxide/manganese oxide, NMC/LMO), which costs about 420 US$/kWh [12]. When storing the electricity in a battery, there are two types of associated loss: loss during conversion and

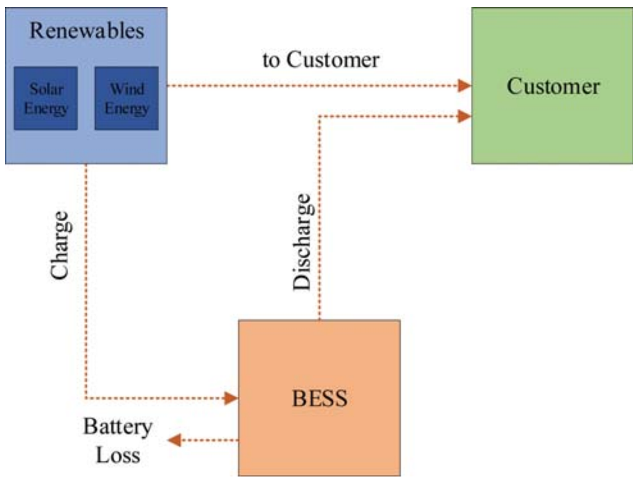

Fig. 2. Electricity grid configuration 2.

loss by self-discharge. The conversion loss arises during the charging or discharging of the battery when the current converts from AC

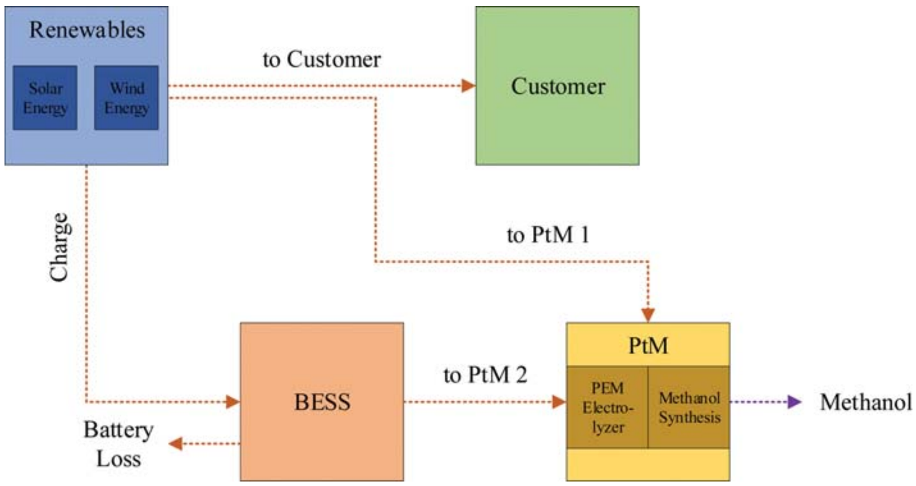

Fig. 3. Electricity grid configuration 3.

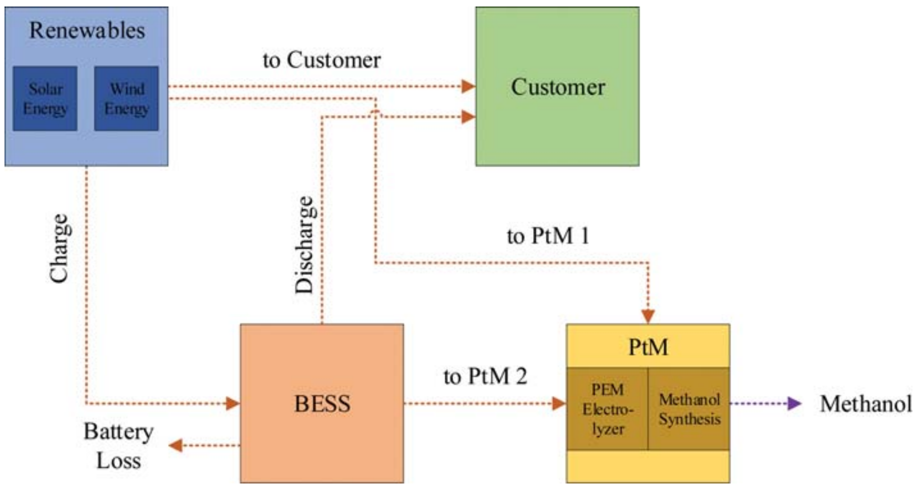

Fig. 4. Electricity grid configuration 4.

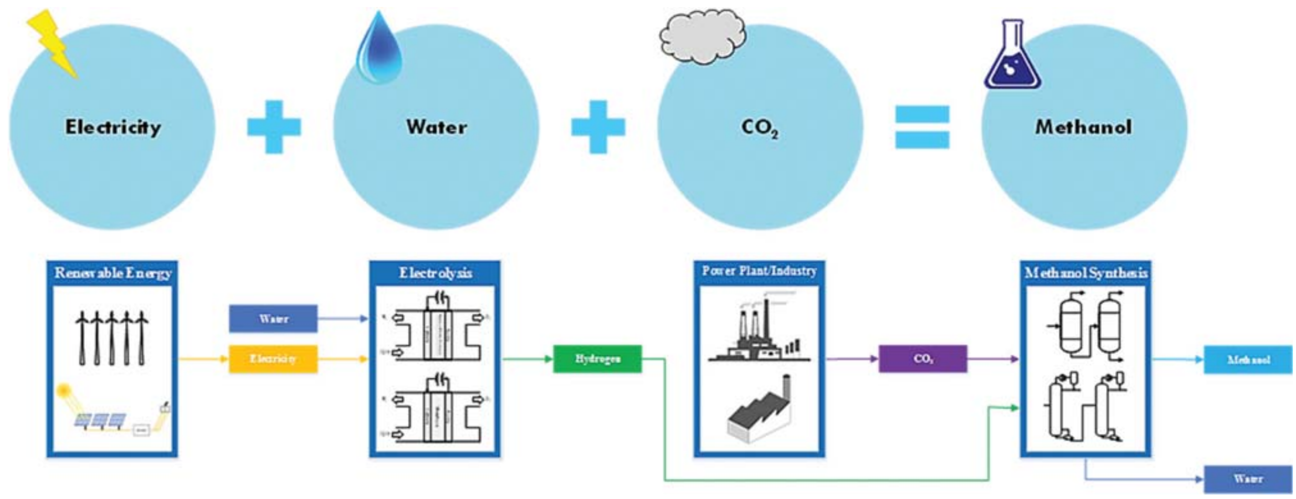

Fig. 5. Power-to-methanol concept.

to DC, or from DC to AC. The self-discharge loss comes from the internal electrochemical reactions. The round-trip conversion efficiency is 95%, and the self-discharge loss is 0.1% per day [12]. The variable and fixed O&M costs of the battery are given as 59 US$/MWh and 25.2 US$/kW-year, respectively [13]. The battery degradation rate is assumed 1.5% per year. The power conditioning system (PCS) cost is given as 105 US$/kWh [12].

The power-to-methanol production consists of two main steps as shown in Fig. 5: the production of hydrogen from renewable electricity using water electrolysis and the methanol synthesis utilizing CO_2 from industry or conventional power plants fueled by fossil fuels. The stoichiometric number (SN) of the mixture of hydrogen and CO_2 (syngas) is controlled to be around two for optimal production of methanol [14].

Among different technological options for the water electrolysis, a proton exchange membrane (PEM) electrolyzer is selected in this work for its ability to react to the intermittent renewable energy supply with a fast reaction of proton transport on the polymeric membrane [15]. The efficiency of the PEM electrolyzer is $65\%_{LHV}$ or 4.7 kWh/Nm^3 [16]. This means that to produce 1 kg of H_2, 52.29 kWh of electricity is required by the PEM electrolyzer.

It is assumed that the oxygen generated in the electrolysis is not sold for additional revenue. An unlimited and free supply of CO_2 is assumed for the methanol synthesis. As the supply and demand data are available on an hourly basis, the ramping time of the equipment, which takes a few minutes for PEM electrolysis, is not taken into account in this study.

PROPOSED MODEL

A nonlinear model was developed to find the optimal management plan for each configuration given in Section 2 that minimizes the annualized total cost. Based on the general cost function structure that can be also found elsewhere [17-19], the formulations and assumptions were developed to describe the current configurations and their applications. The optimal capacities of the battery and PtM were determined along with the other decision variables for every hour of the management horizon, as follows:

- P^C, the amount of electricity supply to the customer from power plant directly,
- P^{CH}, the amount of electricity to the battery (charging),
- P^{DC}, the amount of electricity from the battery to the customer (discharging),
- P^{TP1}, the amount of electricity supplied to the PtM directly,
- P^{TP2}, the amount of electricity from the battery to the PtM (discharging),
- P^{TP}, the amount of utilized electricity in the PtM,
- E, the amount of electricity remaining in the battery,
- M, the amount of methanol produced.

We used a discrete-time framework. Time period t is an element of a set of time periods T that defines the management horizon. As depicted in Fig. 4, the renewable energy supply (P_t^{SP}) from the wind power plant (P_t^{WI}) and solar PV plant (P_t^{PV}) is sent to the customer (P_t^C), to the battery (P_t^{CH}), or to the PtM (P_t^{TP1}) at time t. On the other hand, the customer demand (P_t^{DM}) is satisfied by the electricity from the plant (P_t^C) or by discharge from the battery (P_t^{DC}). Assuming an isolated energy system, the shortage in the electricity supply at time t is expressed as P_t^0. Note that the penalty due to the shortage is not considered in this study.

The balance equations for the supply and demand are expressed as

$$P_t^{SP} = P_t^{WI} + P_t^{PV} \qquad \forall t \in T \qquad (1)$$

$$P_t^{SP} = P_t^{C} + P_t^{CH} + P_t^{TP1} \qquad \forall t \in T \qquad (2)$$

$$P_t^{DM} = P_t^{C} + P_t^{DC} + P_t^{0} \qquad \forall t \in T \qquad (3)$$

In configurations 3 and 4, the total electricity supplied to PtM (P_t^{TP}) is the summation of the supply from the power plants (P_t^{TP1}) and from the battery (P_t^{TP2}). The production of methanol (M_t) is expressed as P_t^{TP} multiplied by the conversion factor (θ).

$$P_t^{TP} = P_t^{TP1} + P_t^{TP2} \qquad \forall t \in T \qquad (4)$$

$$M_t = P_t^{TP} \cdot \theta \qquad \forall t \in T \qquad (5)$$

The conversion loss in the battery (L_t^C) is typically assumed to be proportional to the charging amount (P_t^{CH}), whereas the self-discharge loss (L_t^{SD}) is proportional to the amount of electricity in the battery at time t−1 (E_{t-1}). E_t is determined by adding the electricity remaining at time t−1 (E_{t-1}) to the amount charged at time t (P_t^{CH}), then subtracting the amounts discharged to customer (P_t^{DC}) or to PtM (P_t^{TP2}), and also considering the losses, L_t^C and L_t^{SD}.

$$L_t^C = P_t^{CH} \cdot r^{cl} \qquad \forall t \in T \qquad (6)$$

$$L_t^{SD} = E_{t-1} \cdot r^{sd} \qquad \forall t \in T \qquad (7)$$

$$E_t = E_{t-1} + P_t^{CH} - P_t^{DC} - P_t^{TP2} - (L_t^{SD} + L_t^C) \qquad \forall t \in T \qquad (8)$$

where r^{cl} and r^{sd} are the loss rates by conversion and self-discharge.

The required battery capacity (E^{max}) is decided to be the same or larger than any E_t during the time horizon. The installed capacity of the battery (B) is then designed after additionally taking the battery degradation rate (r^{dg}) into account during the plant life (l).

$$E^{max} \geq E_t \qquad \forall t \in T \qquad (9)$$

$$B = E^{max} \cdot (1 + r^{dg})^l \qquad \forall t \in T \qquad (10)$$

The installed capacity of PtM (E^{PtM}) is decided in a similar way, assuming no degradation.

$$E^{PtM} \geq P_t^{TP} \qquad \forall t \in T \qquad (11)$$

The battery flow at time t (P_t^B), is for either charging (P_t^{CH}) or discharging exclusively to the customer (P_t^{DC}) and PtM (P_t^{TP2}).

$$P_t^B \geq P_t^{DC} + P_t^{TP2} \qquad \forall t \in T \qquad (12)$$

$$P_t^B \geq P_t^{CH} \qquad \forall t \in T \qquad (13)$$

$$P_t^B = P_t^{DC} + P_t^{TP2} + P_t^{CH} \qquad \forall t \in T \qquad (14)$$

$$P_t^{CH} \cdot P_t^{DC} = 0 \qquad \forall t \in T \qquad (15)$$

$$P_t^{CH} \cdot P_t^{TP2} = 0 \qquad \forall t \in T \qquad (16)$$

The objective is to minimize the annualized total cost (C^{AT}). The capital costs (C^C), and operation and management (O&M) costs (C^{OM}) are calculated for the solar PV plant, wind power plant, battery, power converter system, PEM electrolyzer, and components in the methanol synthesis process, i.e., compressors, the methanol synthesis reactor, and the distillation unit. The aforementioned cost is deducted by revenue from electricity and methanol sales to obtain C^{AT}.

$$C^{AT} = \Sigma_{t \in T}\left[\left(\frac{C^C}{l} + C^{OM}\right) - \frac{\alpha \cdot (P_t^C + P_t^{DC}) + \beta \cdot M_t}{h}\right] \qquad (17)$$

Because there are four configurations in this study, the equations used are slightly different. For clear understanding, the equations used for each configuration are listed in Table 1.

CASE STUDY

C^{AT} from each configuration in Section 2 is calculated using GAMS/CONOPT solver [20] based on the published data and a list of assumptions to develop the cost functions. All the costs in this work are based on year 2017.

For the methanol synthesis reaction, the ratio of H_2 and CO_2 is assumed to be controlled as 3 : 1, which is desirable for methanol production [21-23]. The methanol synthesis efficiency is assumed as a constant of 75.5% $MWh_{HHV\text{-}Methanol\ out}/MWh_{HHV\text{-}H2\ in}$ [24], or equal

Table 1. Summary of equations used of each configuration

Parameter	Config. 1	Config. 2	Config. 3	Config. 4
P_t^{SP}	$P_t^{WI}+P_t^{PV}$	$P_t^{WI}+P_t^{PV}$	$P_t^{WI}+P_t^{PV}$	$P_t^{WI}+P_t^{PV}$
$P_{t\ t}^{SP}$	P_t^C+Loss	$P_t^C+P_t^{CH}$	$P_t^C+P_t^{CH}+P_t^{TP1}$	$P_t^C+P_t^{CH}+P_t^{TP1}$
P_t^{DM}	$P_t^C+P_t^0$	$P_t^C+P_t^{DC}+P_t^0$	$P_t^C+P_t^0$	$P_t^C+P_t^{DC}+P_t^0$
P_t^{TP}	-	-	P_t^{TP1}	$P_t^{TP1}+P_t^{TP2}$
M_t	-	-	$P_t^{TP}\cdot\theta$	$P_t^{TP}\cdot\theta$
L_t^C	-	$P_t^{CH}\cdot r^{cl}$	$P_t^{CH}\cdot r^{cl}$	$P_t^{CH}\cdot r^{cl}$
L_t^{SD}	-	$E_{t-1}\cdot r^{sd}$	$E_{t-1}\cdot r^{sd}$	$E_{t-1}\cdot r^{sd}$
E_t	-	$E_{t-1}+P_t^{CH}-P_t^{DC}-(L_t^{SD}+L_t^C)$	$E_{t-1}+P_t^{CH}-P_t^{TP2}-(L_t^{SD}+L_t^C)$	$E_{t-1}+P_t^{CH}-P_t^{DC}-P_t^{TP2}-(L_t^{SD}+L_t^C)$
	-	$E^{max}\geq E_t$	$E^{max}\geq E_t$	$E^{max}\geq E_t$
B	-	$E^{max}\cdot(1+r^{dg})^l$	$E^{max}\cdot(1+r^{dg})^l$	$E^{max}\cdot(1+r^{dg})^l$
	-	-	$E^{PtM}\geq P_t^{TP}$	$E^{PtM}\geq P_t^{TP}$
	-	$P_t^B\geq P_t^{DC}$	$P_t^B\geq P_t^{TP2}$	$P_t^B\geq P_t^{DC}+P_t^{TP2}$
	-	$P_t^B\geq P_t^{CH}$	$P_t^B\geq P_t^{CH}$	$P_t^B\geq P_t^{CH}$
P_t^B	-	$P_t^{DC}+P_t^{CH}$	$P_t^{TP2}+P_t^{CH}$	$P_t^{DC}+P_t^{TP2}+P_t^{CH}$
	-	$P_t^{CH}\cdot P_t^{DC}=0$	-	$P_t^{CH}\cdot P_t^{DC}=0$
	-	-	$P_t^{CH}\cdot P_t^{TP2}=0$	$P_t^{CH}\cdot P_t^{TP2}=0$
C^{AT}	$\sum_{t\in T}\left[\left(\frac{C^C}{l}+C^{OM}\right)-\frac{\alpha\cdot P_t^C}{h}\right]$	$\sum_{t\in T}\left[\left(\frac{C^C}{l}+C^{OM}\right)-\frac{\alpha\cdot(P_t^C+P_t^{DC})}{h}\right]$	$\sum_{t\in T}\left[\left(\frac{C^C}{l}+C^{OM}\right)-\frac{\alpha\cdot P_t^C+\beta\cdot M_t}{h}\right]$	$\sum_{t\in T}\left[\left(\frac{C^C}{l}+C^{OM}\right)-\frac{\alpha\cdot(P_t^C+P_t^{DC})+\beta\cdot M_t}{h}\right]$

*Loss: electricity assumed to be loss

to 78.4% $MWh_{LHV\text{-}Methanol\ out}/MWh_{LHV\text{-}H2\ in}$. Including the PEM electrolyzer, the whole power-to-methanol unit can produce methanol with conversion θ 9.13×10^{-2} kg/kWh. The capital cost and O&M cost for the PtM (PEM electrolyzer and methanol synthesis units) are taken from publications by the Thermochemical Power Group [25-27]. The capital cost function of the PEM electrolyzer is

$$C^{C,PEM}=1.5\cdot10^{6}\cdot(E^{PtM})^{0.85}, \tag{18}$$

where $C^{C,PEM}$ is the cost in Euro and E^{PtM} presents the installed capacity in MW.

The capital costs for the methanol synthesis unit (including the compressors, methanol synthesis reactor, and distillation unit) are estimated referring to those of commercial large-scale plants [25-27].

$$C^{C,\,PtM}=14.2\cdot10^{6}\cdot\left(\frac{M^{in}}{5400}\right)^{0.65} \tag{19}$$

where $C^{C,PtM}$ is in Euro, and M^{in} represents the mass flow of syngas entering the reactor, in kg/h. In practice, the operation and main-

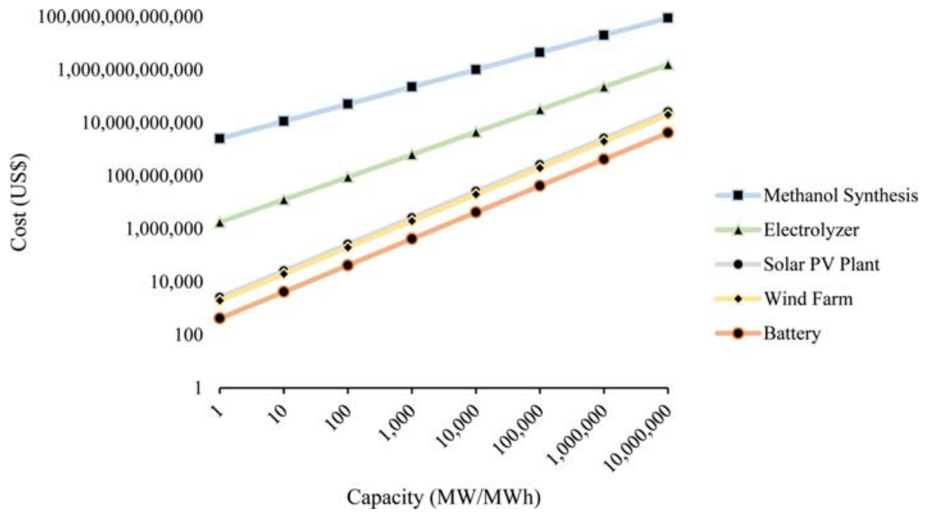

Fig. 6. Capital costs by the capacities of the components.

Table 2. Summary of the constants used in the model

Constant	Description	Value
h	Management horizon data	2 years
l	Plant life	15 years
r^{cl}	Battery roundtrip (AC-DC-AC) conversion loss rate (%)	5%
r^{dg}	Battery degradation rate	1.5%/year
r^{sd}	Battery self-discharge rate (0.1%/day)	0.0042%/h
REC	Renewable energy certificate	100 US$/MWh
SMP	System marginal price	80 US$/MWh
α	Electricity price per MWh	100 US$/MWh
β	Methanol price per ton	470 US$/ton
θ	Methanol production (PEM electrolyzer and methanol synthesis unit) conversion factor	9.13×10^{-2} ton/MWh
	Solar power plant capital cost	2,620,000 US$/MW
	Solar power plant O&M cost	48,000 US$/MW/year
	Wind power plant capital cost	1,980,000 US$/MW
	Wind power plant O&M cost	60,000 US$/MW/year
	Battery (NMC/LMO) capital cost	420,000 US$/MWh
	Battery variable O&M cost	59 US$/MWh
	Battery fixed O&M cost	25,200 US$/MW/year
	PCS capital cost	105,000 US$/MWh
	PtM O&M cost factor	1.04%
	REC weighting factor for battery	5
	REC weighting factor for PV solar power	1
	REC weighting factor for wind power	1
	Currency exchange rate from Euro to US Dollar	1.19 US$/Euro

tenance (O&M) cost is often estimated by multiplying a cost factor to the capital cost. The cost factor for PtM is set to be 1.04% [25-27].

The capital costs for the solar PV and wind power plants are given as 2,620 US$/kW and 1,980 US$/kW, whereas the annual O&M costs are 48 US$/kW and 60 US$/kW, respectively [13]. The change in the capital cost with respect to the capacity of each component is shown in Fig. 6. Note that the methanol synthesis reactor takes the highest portion, followed by the electrolyzer, the solar and wind power plants, and the battery. The plant life (renewable energy generation plant, battery, and PtM) is assumed to be 15 years with a constant electricity price α of 10 cents/kWh (0.1 US$/kWh). The methanol price β is assumed to be 470 US$/t. All the constants used in the model are summarized in Table 2.

1. Case Study 1: Base case

The electricity supply and demand data used for this case study are taken from the supply and demand data in Ontario in 2015-2016 [28]. The capacity factors of wind farm and PV plant are 26.47% and 13.15%, respectively. The total supply is assumed to match the total demand with a ratio of 1 : 1 during the hourly time horizon of the two years. The profile of the supply and demand is depicted in Fig. 7. The magnitude of supply and demand is high, with the excess supply reaching ~2,000 MW at one time, while the unmet demand reached ~1,000 MW at another time.

The results are provided in Table 3. Note that the cost is positive in all configurations with no subsidy for the renewable energy

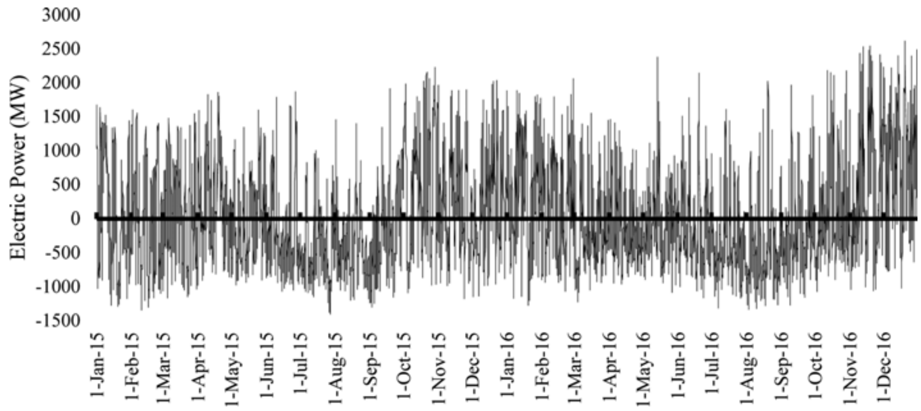

Fig. 7. Difference between electricity supply and demand at ratio 1 : 1.

Table 3. Simulation results of case study 1 (supply : demand=1 : 1)

	Installed battery capacity (TWh)	Installed PtM capacity (MWh)	Annualized total cost (Million $/year)	Shortage occurrence (%)	Shortage capacity (%)
Config. 1	0	0	7,290	57.73	29.37
Config. 2	1.19	0	63,500	12.62	7.85
Config. 3	0	2,614	0.127	57.81	29.43
Config. 4	0	2,614	0.127	57.81	29.43

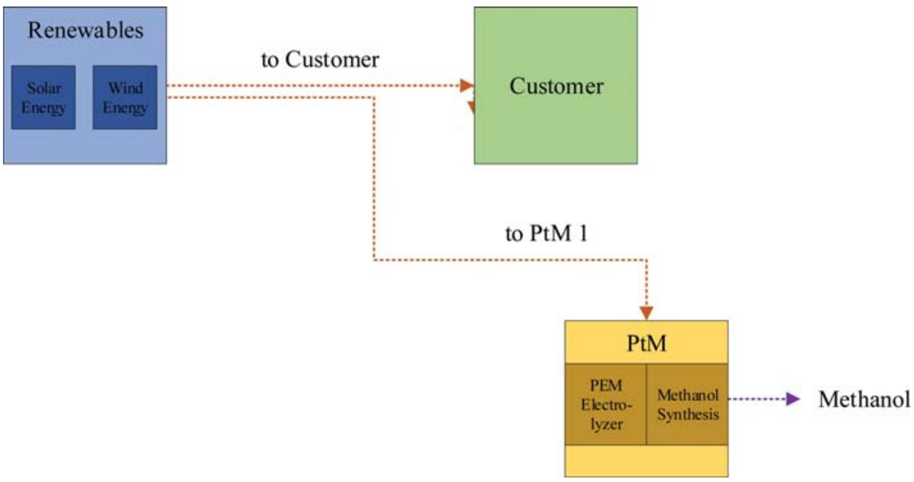

Fig. 8. Configurations 3 and 4 without the battery.

Table 4. Simulation results of case study 2 (supply : demand=1.5 : 1)

	Installed battery capacity (TWh)	Installed PtM capacity (MWh)	Annualized total cost (Million $/year)	Shortage occurrence (%)	Shortage capacity (%)
Config. 1	0	0	11,200	40.55	19.01
Config. 2	7.99	0	426,000	0	0
Config. 3	0	4,527	330	40.60	19.05
Config. 4	0	4,527	330	40.60	19.05

Table 5. Simulation results of case study 3 (supply : demand=1 : 1)

	Installed battery capacity (TWh)	Installed PtM capacity (MWh)	Annualized total cost (Million $/year)	Shortage occurrence (%)	Shortage capacity (%)
Config. 1	0	0	6,770	57.73	29.37
Config. 2	1.19	0	61,900	7.69	8.11
Config. 3	0	2,614	−396*	57.81	29.43
Config. 4	0.003	2,331	−412*	74.12	67.72

*(-) minus sign means profitable

system. According to this result, the battery is not required in configurations 3 and 4 to have minimum annualized total cost, as shown in Fig. 8, when the shortage capacity is around 30%. This new configuration will be called configuration 5. The resulting shortage occurrences and shortage capacities in the configurations are different because the optimization is limited by the same renewable energy supply capacity for a fair comparison. The required supply capacity for the zero shortage is varied to a great extent for the configurations. The shortage capacity, in other words, also presents the self-consumption ratio of each configuration. In this case, configuration 2 has the highest self-consumption ratio.

2. Case Study 2

In this case study, the supply is increased to 1.5-times of the demand to reduce the occurrence and capacity of the shortage. As seen in Table 4, although the shortage rate can be reduced by expanding the supply capacity, the annualized total cost became bigger than that in case study 1. In configuration 2, the shortage rate could be completely removed while the installed capacity of the battery was increased by 6.7-times without discharging the excess electricity. Note that the capacity of the battery that should be installed for configuration 2 and that of the PtM for configuration 3 are also raised with the expanded supply.

3. Case Study 3

The previous case studies show a positive cost. Taking the example of Korea, a subsidy is given to the renewable energy [29].

$$\alpha = \text{SMP} + (\text{REC} * \text{REC Weigting Factor}) \tag{20}$$

where SMP and REC stand for system marginal price and renewable energy certificate, respectively. The values are assumed to be a constant 0.08 US$/kWh for SMP and 0.1 US$/kWh for REC [30]. In 2018, the REC Weighting Factors are 5 for battery discharge, 1 for wind power supply, and 1 for solar PV power supply [29]. In this case study, electricity price α value is a part of the optimization because REC weighting factor is different from the source of electricity, depending on whether it is from battery or from the renewable power sources. Simulation results for the supply-to-demand ratio of 1 : 1 are shown in Table 5. The annualized total cost from configuration 3 is shown to be negative, but the results also show a high occurrence of shortages in this system.

4. Case Study 4

Simulation is repeated for configuration 4 with an additional constraint, $P_t^0=0$, to remove by changing Eq. (3) to Eq. (21).

$$P_t^{DM} = P_t^C = P_t^{DC} \qquad \forall t \in T \tag{21}$$

The change in the annualized total cost is studied by varying the supply capacity. As additional revenue can be made with the excess electricity by producing methanol, more revenue can be acquired with a larger supply. With no subsidy assumed for this case, the result shows a positive annualized total cost (Table 6); however, the loss is reduced while increasing the supply.

All configurations are compared at the same supply and demand ratio in Fig. 9. The occurrence of the power shortage is over 40% in configurations 1 and 3, which is due to the feature of their configuration. In configuration 1, there is no battery; therefore, there is no back-up supply when the customer demand is higher than the electricity supply. While in configuration 3, the power in the

Table 6. Simulation results of case study 4

Supply : Demand	Installed battery capacity (TWh)	Installed PtM capacity (MWh)	Annualized total cost (Million $/year)	Shortage occurrence (%)	Shortage capacity (%)
1.3 : 1	0.866	2,883	44,200	0	0
1.4 : 1	0.692	3,100	35,000	0	0
1.5 : 1	0.538	3,490	26,700	0	0

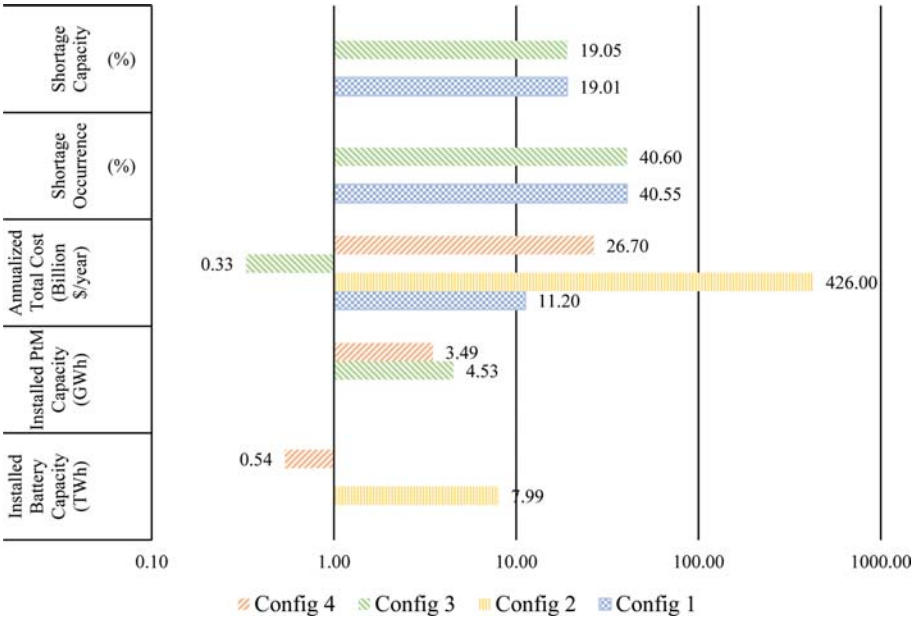

Fig. 9. Comparison of configurations at ratio 1.5 : 1.

battery system is not discharged to the customer (demand). In configuration 2, 7.99 TWh of battery needs to be installed to avoid the power shortage. Although battery shows decent buffering role in this configuration as suggested by Ryu [31], but the size is enormous. Configuration 4 could satisfy the demand with zero shortage while maintaining a reasonable size of battery and the economic value. This result shows that bringing value-adding units such as PtM to power grid is recommended to provide resilience of 100%-renewable energy system.

CONCLUSIONS

This work assesses the feasibility of coupling a battery with PtM by modeling four energy system configurations. The results lead to several findings for designing renewable energy systems and their energy storage. In the current electricity and methanol market, it is difficult to obtain a negative annualized total cost (profit) from renewable energy systems without subsidy. A shortage in electricity supply could be avoided by installing a battery; however, the required capacity is too large, and the cost increases compared to the case with no energy storage. Yet, the installation of the battery is still mandatory to satisfy the demand without shortage. In addition, the supply capacity should be larger than the demand for a stable supply of electricity, and the additional revenue should be obtained from the excess electricity. Therefore, value-adding units such as PtM should be included in the energy system to build a stable and feasible renewable energy system.

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NOMENCLATURE

Sets

P_t^{DM} : electricity demand at time t [MWh]
P_t^{PV} : electricity generated from solar power at time t [MWh]
P_t^{SP} : electricity supply at time t, $P_t^{WI}+P_t^{PV}$ [MWh]
P_t^{WI} : electricity generated from wind power at time t [MWh]
T : time periods that defines the management horizon

Variables

B : installation capacity of battery [MWh]
C^{AT} : annualized total cost [US$/year]
C^{C} : capital cost [US$]
C^{OM} : operation and maintenance cost [US$/year]
E_t : level of electricity charged at battery at time t [MWh]
E^{max} : required capacity of battery [MWh]
E^{PtM} : installation capacity of power-to-methanol unit [MW]
L_t^{C} : battery conversion loss at time t [MWh]
L_t^{SD} : battery self-discharge loss at time t [MWh]
M_t : methanol production at time t [ton]
P_t^{B} : battery flow at time t [MWh]
P_t^{C} : electricity to customer directly from renewables at time t [MWh]
P_t^{CH} : electricity charged to battery at time t [MWh]
P_t^{DC} : electricity discharge from battery to customer at time t

[MWh]

P_t^{TP} : total electricity flow to PTM at time t, $TP1_t+TP2_t$ [MWh]

P_t^{TP1} : electricity to power-to-methanol unit from renewables at time t [MWh]

P_t^{TP2} : electricity to power-to-methanol unit from battery at time t [MWh]

P_t^0 : electricity shortage at time t [MWh]

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