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Optimal design and operation of a hybrid renewable micro-grid with decoupled LAES

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ABSTRACT

Climate changes and energy crisis have drawn considerable attention across the world, which called upon the urgency for new energy provision and carbon emission reduction globally. Hybrid renewable energy system (HRES) integrated with LAES is a good option to achieve the de-carbonization of energy sector. This study focuses on exploring the value of LAES in a hybrid renewable micro-grid, in which the decoupled off-design LAES energy storage model was developed and inserted into the system MILP framework, which is applicable for discussing the optimal E/P ratio of LAES, digging the value streams out and optimally sizing the different system components and LAES units separately to achieve good economics and environment benefits. The simulation results indicated three important aspects. Firstly, for a specific micro-grid equipped with LAES, there exist the optimal charge/discharge E/P ratio of LAES, corresponding to the optimal sizes of liquefaction unit, power recovery unit and storage tank when providing different services. Secondly, if wind penetration reaches about 50%, LAES annual benefits can reach about 90% of its annual investment cost when six explicit value streams are stacked, including the time shifting, renewable firming, peak shaving, flexibility and reserve value, as well as the waste heat utilization, which is totally 8.2% higher than that of battery storage at the same investment cost. Thirdly, compared with the LAES cost reduction and large electricity price difference, more renewable penetration is the major driving force to increase the value and attractiveness of LAES, the optimal charge/discharge E/P ratio and storage tank size is 27/14 h and 608 t when there is 75% of wind power, resulting in about 60% of carbon emission reduction on 2016 level for a micro-grid.

Keywords: hybrid renewable micro-grid, decoupled LAES, optimal E/P ratio, value streams decomposition, optimal design & operation

NONMENCLATURE

Abbreviations	
HRMG	hybrid renewable micro-grid
LAES	Liquid air energy storage
LFU	Liquefaction unit
PRU	Power recovery unit
Cha E/P	Charge energy/power
Dis E/P	Discharge energy/power
MILP	Mixed-integer linear programming
RTE	Round trip efficiency
Symbols	
P	Electricity power
Q	Heat power
Qf	Fuel power
RP	Ratio of power
RM	Ratio of mass flow rate
a/b/p/q	Regression coefficients
c	compressor
t	turbine
r	rated power
h/rh	Heat/ Recoverable heat
V	volume
η	efficiency

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1. INTRODUCTION

The conventional energy system have been traditionally considered as independent. However, with the HRES development, the interdependency and increased complexity inside the energy system have been recognized, which requires a more effective and efficient sizing and operating methodology to cope with the challenge.

MILP(mixed integer linear programming) has been one of the powerful tools to achieve optimal design and operation of MES(multi-energy system) due to its moderate calculation complexity and ability to find the global optimal point. R. Yokoyama[1]proposed a hierarchical MILP method to achieve optimal design and scheduling of a poly-generation system. F. J. de Sisternes[2, 3] explored the potential value of energy storage in electricity sector de-carbonization by using expanded IMRES(MILP planning model), but the author only considered the power vector. P. Gabrielli[4] proposed a MILP-based model to achieve optimal design of multi-vector energy system with hydrogen storage.

The storage value (including LAES) has been extensively discussed among researchers. Eduardo A[5] conducted the techno-economic analysis of a multi-vector energy system with battery storage and thermal storage to provide energy, reserve and reliability services, but the flexibility value of storage wasn't considered. S. Mazzoni[6] applied LAES into a micro-grid to achieve optimal operation, but the optimal size cannot be determined. C. P. Xie[7] assessed the economic value of decoupled LAES in UK electricity market, but it didn't take the technical details of LAES into account. Andrea Vecchi[8] contributed his efforts in building the off-design power recovery unit model of LAES and conducting the thermo-economic analysis, but only paid attention to arbitrage and reserve service of grid-scale LAES in macro electricity market.

Overall, few work focused on exploring the value of LAES in small-scale or commonly think it is not profitable to deploy LAES in a micro-grid or community. So the research questions this work tried to answer includes: 1) what's the specific value of LAES in micro-grid? 2) is it attractive to invest LAES in a micro-grid? How can it be a good investment? 3) if it is of value, what sizes of the LAES system should be selected to generate the best cost-effectiveness and environment benefits? By answering the above questions and with aims to cover the gap missed by the literatures above, the major contributions of this work lie in the following four aspects:

a. the decoupled off-design LAES energy storage model was developed; b. the optimal charge/discharge E/P ratio of LAES was discussed when serving as different functions; c. the value streams of thermal storage, LAES and battery storage in a HRMG were decomposed; d. a hierarchical MILP framework is capable of achieving the optimal design and operation of system components and decoupled LAES units.

2. SYSTEM MODEL DESCRIPTION

2.1 Hybrid renewable micro-grid

In order to achieve independent demand supply, economic savings and CO2 reductions, a future HRMG for a campus in Birmingham is proposed.

The HRMG is connected to the national electricity and gas grid, and is composed of traditional technologies, like CHP, boilers and heat pumps, and renewable-based generators(wind turbines and solar panels), as well as energy storage devices. Its development compromises two stages, namely at least 50% and 100% of carbon emissions by 2030 and 2050 respectively on 2016 level. The system optimal design and operation was formulated as a two-level MILP model.

2.2 Decouple LAES

LAES is compromised by three major sub-systems, air liquefaction units (LFU), air storage tank and air power recovery unit(PRU), of which capital expenditures have large differences, shown as in fig.1.

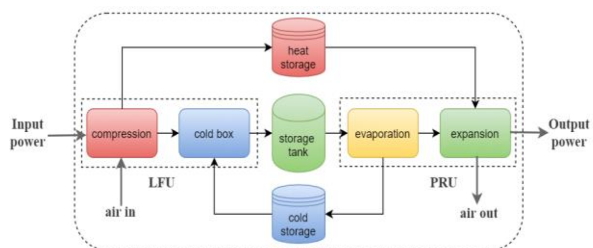

Fig 1 decoupled LAES units

2.2.1 air turbine/compressor model

The variable-speed three-stage air compressors are adopted to produce liquid air and absorb intermittent renewable energy. The stored cryogenic liquid air will be drawn from tanks to expand in multi-stage turbines. As the variation in renewables and loads, liquefaction units and generator sets are normally working at part load conditions. Based on the reasonable technical and economic assumptions the linear regression of the performance curve was obtained as in eq.(2.1-2.3), the coefficients vary with the specified nominal conditions[9, 10].

$$RP_{c/t}(t) = a \cdot RM_{c/t}(t) + b \quad (2.1)$$

$$RM_{c/t}(t) = \frac{\dot{m}_{c/t}(t)}{\dot{m}_{c/tr}} \quad (2.2)$$

$$RP_{c/t}(t) = \frac{P_{c/t}(t)}{P_{c/tr}} \quad (2.3)$$

<u>2.2.2 air tank</u>

For air storage tank, it receives liquid air from liquefaction unit and supplies the air for expansion, at any time t, the storage volume V_{LAES} is expressed in eq.(2.5), which is bounded by the allowed minimum and maximum volume in eq.(2.4 -2.5)[11].

$$V_{LAES}(t) = V_{LAES}(t-1) + \int_t^{t+\Delta t} m\_LA\_in(t) - \int_t^{t+\Delta t} m\_LA\_out(t) \quad (2.4)$$

$$V_{min} \le V_{LAES}(t+1) \le V_{max} \quad (2.5)$$

2.3 Other components

Other key system components performance parameters will be shown in Tab.1.

Tab.1 other key components parameters

components	**Captial cost(£)[]**	**O&M cost (% of capital cost)[6]**
gas engine	$6962.5 * Pr^{-0.164}$ /kW[2]	0.05
gas boiler	80/kW	0.02
electric chiller	$1164.2 \cdot P_r^{-0.284}$ /kW	0.015
heat pumps	$1319.4 \cdot P_r^{-0.268}$ /kW	0.015
air compressor	$Cost_{c0}(\frac{P_c}{P_{c0}})^{-0.4}$ [4]	0.01
air turbine	$Cost_{t0}(\frac{P_t}{P_{t0}})^{-0.4}$ [4]	0.01
liquid air tank	44/kWh	0.01
solar PV	900/kW[12]	3 /year/kW
wind turbines	1300/kW	7.5 /year/kW
battery	420/kWh	0.02
heat storage	10/kWh	0.02

3. DEMAND PROFILES

A campus in Birmingham was chosen as the case study. Four representative weeks in a year were chosen to represent four seasons. The electricity, heat demands and ambient temperature adopted the average demand profiles in four seasons. The solar & wind capacity factor and electricity price were selected and scaled by the methods proposed in the work[13, 14].

4. MILP MODEL FORMULATION

The optimal design and operation problem is formulated as a hierarchical MILP model, which includes two levels, namely the upper design level and the lower operation level, introducing binary variables, integer variables and continuous variables to represent selection value, the selected number and operational parameters. It can be described as in the general form in eq.(4.1)[4].

$$\min(\boldsymbol{c}^T\boldsymbol{x} + \boldsymbol{d}^T\boldsymbol{y}) \quad (4.1)$$

$$\boldsymbol{Ax} + \boldsymbol{By} = \boldsymbol{b}$$

$$\boldsymbol{x} \ge \boldsymbol{0} \in \boldsymbol{R}^{N_x}, \boldsymbol{y} \in \{0,1\}^{N_y}$$

Where, ***x*** represents continuous variables, ***y*** represents binary variables, ***A*** and ***B*** are corresponding constraints matrices, and ***b*** is the constraint known-term; N_x and N_y represent the dimension of ***x*** and ***y***.

The commercial software MATLAB, YALMIP and Gurobi are combined to conduct the simulation.

In the system MILP framework, the decision variables are divided into three categories, design variables, operation variables and auxiliary variables.

The constraints are described as four categories, technical constraints, operation constraints, economic constraints and power balance constraints, which are applied for each components in the system.

The aim of the study is to minimize the total annual cost and environment impact of the system, which is expressed as in eq. (4.2).

$$min\{C_{anu,tot} = C_{inv} + C_M + C_{CO2} + C_{op} + C_{cur} + C_{LOP} - C_{inc}\} \quad (4.2)$$

5. RESULTS AND DISCUSSION

5.1 Optimal E/P ratio of LAES

E/P ratio is defined as the ratio of stored energy and rated charge/discharge power, called charge/ discharge E/P ratio. Return on investment (ROI), defined as the ratio of net profit and investment cost was used to qualify the economic effects, higher ROI means good cost-effectiveness. To be noted, the capacity and cost of LAES and other storage will be added into the system exogenously before their values are fully understood.

In a highly-independent micro-grid with high renewable penetration(50% wind power), when a LAES with 6 MWh rated storage capacity applied into the simple micro-grid, it can achieve arbitrage saving, wind firming and operating reserve simultaneously.

The arbitrage saving is defined as the avoided electricity cost accumulated in a year, meaning that it is capable of storing electricity at bottom prices and releasing the energy at peak prices. The wind firming benefits refers to the avoided curtailment pelnaty and boosted wind TIF. The reserve value was assessed by comparing the avoided penalty of loss of power with the system without LAES as the operating reserve, see fig.2.

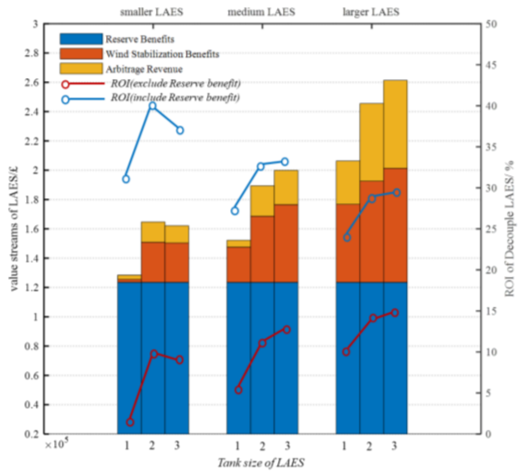

Fig 2 optimal E/P ratio of LAES

The samller, medium and larger LAES represent the systems are equiped with different sizes of decoupled units, or say different Cha/Discha E/P ratios.

If just considering the economics, it is better to prepare a small LFU, which is able to charge the tank to full and then almost stands still to serve as operating reserve(the largest revenue source), but the wind firming and arbitrage saving will be contained significantly(left bar group & bule curve).

While larger liquefiers with bigger storage tank is capable of achieving high level of reserve margin, more renewable penetration and arbitrage saving, but the system investment increased as well (right bar group & bule curve), leading to worse economics. Thus the decision makers should weigh the importance of economics and environment benefits when introducing a LAES into the system. In this simulated case, medium LAES with charge/discharge E/P ratio 12/6(middle bar group) is chose to balance the cost and envinronment impact, which will be applied into the section 5.2 to conduct analysis in the complete micro-grid.

5.2 *LAES and other Storage value*

In this section, the value of LAES, BES(battery storage) and TES(thermal storage) in a micro-grid with various generators will be discussed.

5.2.1 energy storage value in system without reserve

When wind power percentage increases with time, the value of heat storage, LAES and battery storage was discussed, thier effects on the system with 50% of wind penetration was shown as in fig.3, in which keeps the storage capacity of heat storage and LAES the same(6 MWh), and the investment cost of LAES and battery

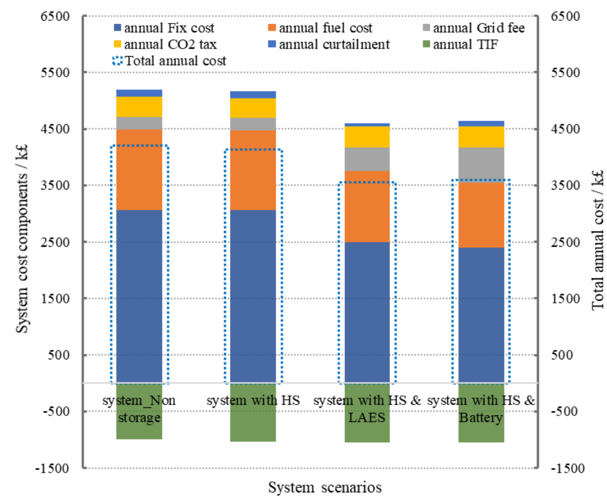

Fig 3 system costs with storage

storage nearly the same.

When applied LAES into the micro-grid with 50.6% of wind power percentage as the example, the annual revenue of LAES totally reached up to k£ 593(74.7% of its annual investment cost) when not taking operating reserve value into account, there are five major revenue streams and their corresponding contributions, namely arbitrage saving(19.85%), wind firming benefits(13.82%), peak-shaving gain (33.74%), flexibility value(25.33%) and waste heat benefits(7.27%).

Battery storage differentiates with LAES due to its high efficiency and storage loss, as well as non-storage tank and quick response, but it can also achieve the same functions with those of LAES in micro-grids except for no waste heat, the value contribution of battery are decomposed as arbitrage saving (26.1%), wind firming benefits(8.8%), peak-shifting gain(48.5%) and flexibility value(16.6%). Overall, the total value of LAES is higher than that of battery storage by 8.2% when the same investment was made.

5.2.2 LAES value in system with operating reserve

When LAES is applied into the micro-grid considering the operating reserve, part of capacities of LAES and gas engine will serve as the reserve margins, which is the scheduled output to ensure the robust operation of the system when emergencies occur.

If LAES serves as part of reserve capacity, the arbitrage saving of LAES will be sacrificed by 19.6% in order to provide enough operating margin, but in return, the capital cost of gas engine and fuel cost will be lowered down by 17% and 45.8% respectively, transferring into the reserve value of LAES up to 20.4% of

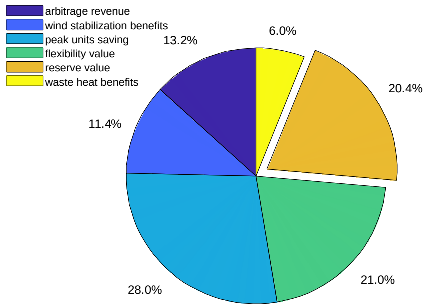

Fig 4 LAES value when serving as reserve

total value, shown as in fig.7. By now, the total revenue of LAES is equivalent to 90.2% of its investment cost. While considering its implicit potential values, it is believed that the proper investment of LAES in micro-grids will be increasingly attractive when more renewables and less CO2 emissions are required.

5.3 *Optimal sizing & operation of HRMG with LAES*

5.3.1 system design with cost reduction of LAES

In the scenario with 50% of renewable penetration and current demand level and 'environment' parameters, it is expected LAES cost will be reduced by 15% and 25%, the cost reduction effects is shown in tab.2. As can be seen, the optimal sizes of LFU and PRU is 3 and 3.75 MW respectively, the optimal charge/discharge E/P ratio is 10.4~14/5~6.7 h, which is consistent with the quantitative analysis in section 5.1 & 5.2. It indicated LAES cost reduction will not affect the size selection of LFU and PRU much considering economics. While the tank size increases, as it can help absorb more wind energy, reducing wind curtailment and the grid fee.

Tab2.optimal design & operation of micro-grid with LAES cost reduction

cost reduction case	Engines/MW	WT/MW	Grid/%	HP/MW	Boiler/MW	HS/MWh	LFU/MW	PRU/MW	Tank/t	annual cost(k£)	annual investment/ k£/ LAES	CO2 emissions tons
15%	4	14.63	13.82	5	9	6	3	3.75	145	4277	706.87	20509
25%	4	14.65	13.45	5	9	6	3	3.75	197	4190	641.49	20474

5.3.2 system design with wind penetration increasing

In this part, two scenarios of wind penetration are studied respectively, namely 64% and 76%, when assumed 25% of cost reduction will be achieved. After optimization, the size of gas engine decreased, while the sizes of LFU, PRU and tank all increased in order to absorb and store more wind energy. LAES performed mainly as wind stabilization, peaking shaving and operating reserve, the optimal charge/discharge E/P ratios and storage tank size are 27/14 h and 605t. Meanwhile, in heat sector, the energy shift function of heat pumps combined with heat storage become more significant. The total CO2 emission reduction reached about 55% and 62% in the two scenarios on 2016 level.

Tab. 3 optimal design & operation of micro-grid with higher renewable penetration

Wind power %	Engines/MW	WT/MW	Grid/%	HP/MW	Boiler/MW	HS/MWh	LFU/MW	PRU/MW	Tank/t	annual cost(k£)	annual investment/ k£/ LAES	CO2 emissions tons
64%	2	19.84	20.03	8	9	10	3	5.2	355	3873.3	729.24	15823
76%	1	23.56	20.15	8	11	10	4.8	5.4	605	4058.7	958.57	13250

5.3.3 grid carbon intensity and electricity price changing

In this part, the future grid scenarios are considered, the carbon intensity will drop by 50%, and the electricity prices will go up by 20% and 40%(including larger price differences) respectively on 2016 level[15].

After simulation, if grid carbon intensity goes down and electricity prices increase, the LFU sizes of LAES kept unchanged, the PRU and storage tank sizes are smaller than those in section 5.3.2 but larger than those in section 5.3.1, which is due to less wind power percentage but larger electricity prices. The configurations will allow LAES to capture more arbitrage saving and can thus serving as peak shaving and operating reserve. In heat sector, motivated by larger electricity price differences, the energy shift of heat pumps combined with heat storage become even more active, in order to help save high electricity purchasing cost.

Tab3.optimal design & operation of micro-grid with larger electricity price differences

ele_price case/times	Engines/MW	WT/MW	Grid/%	HP/MW	Boiler/MW	HS/MWh

1	3	13.76	24.67	8	11	10
1.2	3	15.35	20.67	8	10	10
1.4	3	16.38	18.73	8	9	10

LFU/MW	PRU/MW	Tank/ t	annual cost(k£)	annual investment / k£/ LAES	CO_2 emissions/ tons
3	4	213	3679.3	638.5	15689
3	4.2	255	3828.4	673.6	14726
3	4.5	279	3928.9	686.9	14156

6. CONCLUSION

In this work, a decoupled LAES(De-LAES) energy storage model under off-design conditions was developed to adapt to variable renewables and user demands. Then the model was inserted into an optimal design & operation MILP framework of a micro-grid, to discuss the optimal E/P ratio of LAES, dig the value streams out and optimally size the different system components and LAES units separately to achieve good economics and environment benefits.

Overall, the major contribution of this work lies in it is the first time ever to clarify the value of LAES in micro-grids and decomposing the value into six major streams, meanwhile the developed MILP framework is capable of achieving the optimal design and operation of multi-energy system components and decoupled LAES units separately, which will promote the optimal deployment of LAES in different systems. However, there are also limitations, like wind is the only renewable in the system, the network expansion was not fully considered, and the complementary function of electric storage was not discussed, which will be focuses in the next stage.

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