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A Novel Planning Method for Multi-Scale Integrated Energy System

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Abstract—**The interdependencies of electricity, heat and gas systems have significantly increased in recent years, and their further coupling becomes increasingly important to realize the efficient and secure operation of the future low carbon energy systems. Integration of multi- energy systems at different scales represents an opportunity for overall system improvements using the flexibilities across the distributed local small scale to utility energy network level, bus also poses a new challenge of complexity. Therefore, a 'whole system' planning approach is essential to capture the synergies and reduce the risks associated with securing an integrated system. However, the common use of centralised planning models overlook the different ownerships of sub-energy systems, and can lead to impractical in reality as the subsystems are often independently managed. In this paper, a novel decentralized planning framework is proposed to allow a two-level integration with multiple subsystems, which includes the lower-level of several local communities and the upper-level of an integrated electricity and gas distribution network. The two levels are separately optimised to minimise their own cost while an overall carbon emission budget is achieved for the whole system using a carbon-led bi-level coordinated strategy. A case study is also provided to illustrate the application of the proposed framework.**

Index Terms--**carbon emission; energy hub; integrated energy system; optimisation; planning**

I. INTRODUCTION

Integrated energy systems (IES) represent an important opportunity for grand energy transition [1], [2]. Different energy sectors can be interlinked with each other through energy conversion technologies in IES, so that the system is more flexible and robust to deal with variability from different sectors and improve the overall efficiency [3]. Due to the strong coupling across multiple pathways, system levels and time scales, IES are also able to facilitate the integration of renewable energy and accelerate carbon emission reduction [4]. As efforts towards low-carbon energy supply are made [5], making the most of the ability of IES in decarbonisation is of great importance currently. With concern of economic aspect at the same time, optimal operation and expansion design for IES is the most effective way towards the opinion above.

Current research on optimal planning for IES lies in different levels, from distributed local small scale to utility energy network level. Optimal design for sizing of hybrid renewable energy system with a battery energy storage systems is presented in [6], for a small-scale residential micro-grid. Reference [7] presents a co-optimization planning strategy for distributed energy resource to minimize total annual cost as well as to cut the CO2 emissions from coal-based power plants. The proposed scheme was tested on a community micro-grid. A comprehensive planning model is introduced in [8] for a distribution energy system with different renewable energy based distributed generation, electric vehicle and energy storage systems. An expansion-planning model for large-scale combined gas and electricity network is developed in [9], with gas-fired generation units as linkages between the two systems.

Some research also make efforts to realize overall planning for multiple IESs. Reference [10] presents an optimization framework that combines the optimal operation and planning of multiple building energy systems with consideration of electric network constraints. An optimal expansion planning model for distribution level gas and electricity energy system with multiple energy hubs are proposed in [11]. The multiple IESs are modelled in a single system in above works in order to get the overall optimal planning scheme for the whole energy system.

Although centralised planning models can acquire the global optimal results for decision makers, it is, however, not in line with reality. Existing IESs are planned and operated independently as far as they belong to various stakeholders. Different planning and operation goals are to be achieved during the process, due to various conditions of them, including financial budget, carbon emission budget and customer willingness in the area. Therefore, decentralized planning strategy for multiple IESs is necessary. With a marked growth of technologies and applications of IES around the world, the interaction between small-scale IESs and 'upper level' networks also increases [12]-[14]. An intelligent large-scale IES that coordinates various energy sectors, through a combination of interconnected small-scale IESs, will be an important part of the future energy scenario [15].

These factors above indicate a growing need for accurate and efficiently coordinated operation and planning between multiple small-scale IESs and the upper level networks, which will manage energy supply within lower level systems to meet the requirements of local customers and coordinate with upper level systems at the same time to improve whole system performance. Towards this end in view, the rest of this paper is organised as follows. Section II states the operational planning model for two-level IES. Section III illustrates the coordinated interaction framework between the two system levels subject to an overall carbon emission budget. Section IV tests the effectiveness of the proposed method with a modified illustrative example. Section V makes a conclusion of this work.

II. Problem Formulation

A. Problem Statement

The planning method presented here is to allow operational planning for a two-level IES, which includes the lower-level of multiple small-scale energy systems and the upper-level of an integrated distribution-scale network contains both electricity and gas. The two levels are operated by different parties so that they have different planning and operation goals. In the meantime, the overall carbon emission of the whole system for both levels to achieve together is limited by the government. The planning optimization is carried out by a bi-level coordinated strategy based on detailed models of the two levels. The lower-level model (Section II.B) focuses on optimal planning of distributed local generation and energy conversion devices within each local system to achieve individual cost minimization. The upper-level (Section II.C) investigates on expansion planning and investment decision-making for distribution network considering integrated optimal power flow for operational cost deduction. The two levels will interact with each other by carbon emission coordination process, in which the two levels will communicate bilaterally and adjust their planning decisions accordingly until exchange power converge while the overall carbon emission criterion (OCEC) is satisfied. The unit of OCEC is gCO2.

The carbon emission intensity (CEI) is distributed onto every bus in electric network and every node in the gas system to address decentralized planning problem [16]. The unit of CEI is gCO2/MWh. Using the decentralized CEI (DCEI), the planning decision for lower-level systems are established while maintain the constraints of their distributed carbon emission criteria (DCEC) within an acceptable cost range. The new criterion for corresponding systems will be calculated if there is infeasibility during lower-level planning process, and sent to upper-level to generate new upper-level criterion (UCEC), with the OCEC unchanged. The CEI will be reallocated after the planning decision for upper-level is adjusted due to new criterion limitations. The process continues iteratively until the CEC for both levels are no longer changed and the planning scheme for both levels are coordinated under the OCEC limitation. The detailed iterative process is given in Section III.

B. Optimization Problem for Lower-Level

The optimization problem for lower-level small-scale systems is formulated as energy flow model based on energy hub, as shown in Fig. 1. Each small-scale system exchange electricity and natural gas with upper-level, and supplies electricity and heat to local consumer. Energy flows within a small-scale system are linked by a combination of distributed energy generation and energy conversion units, i.e., power-to-heat unit such as heat pump (HP), gas-to-power & heat unit like combined heat and power plant (CHP), gas-to-heat unit such as gas boiler (GB), renewable energy generation (RG) like photovoltaic (PV), etc. Each small-scale operator is in charge of daily scheduling of every device within the system to meet demand-side requirements and sending energy exchange information to upper-level. The aim for small-scale system is to minimize total investment and operation cost in consideration of energy balance, device operation limits, the DCEC and self-limited factor of the local district. Different local requirements and limitations may lead to various combination of units in planning decision and different dispatch strategies in daily operation process. The lower-level model is formulated as following.

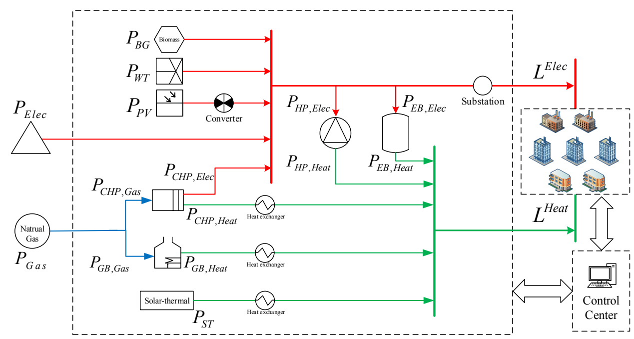

Figure 1. Linearized energy flow model for lower-level system

The optimization objective function (1) minimizes the equivalent annual cost of a lower-level system including device investment and operation cost.

$$\begin{aligned} \min \sum_{i\in\Omega_{Tech}^{new}} C_{Tech,i}^{Invest} \times N_{Tech,i} \times R_{Tech,i}^{EAC} + \sum_{i,j\in\Omega_{Tech}^{old\&new}} C_{i,j}^{Maint en} \\ + \sum_{t} \Delta t \times (C_{Elec,t}^{Oprt} \times P_{Elec,t} + C_{Gas,t}^{Oprt} \times P_{Gas,t}), \end{aligned} \tag{1}$$

where Ω_{Tech}^{new} and $\Omega_{Tech}^{old\&new}$ is the set of equipment to be installed or already existing, $C_{Tech,i}^{Invest}$, $C_{i,j}^{Mainten}$, $C_{Elec,t}^{Oprt}$, $C_{Gas,t}^{Oprt}$ are the corresponding investment, maintenance or operation cost (£,million/MWh), $N_{Tech,i}$ is the number of device i to be installed, $R_{Tech,i}^{EAC}$ is the equivalent annual costs (EAC) conversion rate for each device, $P_{Elec,t}$ and $P_{Gas,t}$ are electricity and gas power exchange (MW) with upper-level, based on which the first term denotes the investment cost of newly installed technologies, the second term is the annual maintenance cost of all the devices within the system, and the third term represents the operation cost for purchasing electricity and gas from upper-level. Investment costs of different kinds of technologies are all converted into EAC value according to their specific lifetime periods and discount rates to budget decision-making fairly.

The constraints (2) – (8) are to ensure that the operation constraints and local requirements of lower-level systems are satisfied.

Constraints (2) – (4) set the limitation of energy balance between load and supply in terms of electricity, heat and gas flow.

$$P_{Elec,t} - \sum_{\Omega^{old\&new}_{Tech,E,In}} P^{In}_{Tech,t} + \sum_{\Omega^{old\&new}_{Tech,E,Out}} P^{Out}_{Tech,t} = L^{Elec}_{t}, \forall t \quad (2)$$

$$\sum_{\Omega^{old\&new}_{Tech,H,Out}} P^{Out}_{Tech,t} = L^{Heat}_{t}, \forall t \quad (3)$$

$$P_{Gas,t} = \sum_{\Omega^{old\&new}_{Tech,G,In}} P^{In}_{Tech,t}, \forall t \quad (4)$$

where $P^{In}_{Tech,t}$ and $P^{Out}_{Tech,t}$ are power input and output of each technology respectively (MW), L^{Elec}_{t} and L^{Heat}_{t} are local electricity and heat demand from the district (MW).

Constraints (5) enforces that every device in the system is working within their operation restrictions, to secure that the power inputs do not exceed the working capacity.

$$\underline{P_{Tech}} \le P_{Tech,t} \le \overline{P_{Tech}}, \forall \text{Technology} \quad (5)$$

where $\underline{P_{Tech}}$ and $\overline{P_{Tech}}$ represent the lower- and upper-limit of power (MW) for each technology.

Constraints (6) imposes the DCEC for a lower-level system to meet.

$$\sum_{t} \Delta t \cdot (\rho^{Emiss}_{Elec,t} \cdot P_{Elec,t} + \rho^{Emiss}_{Gas,t} \cdot P_{Gas,t}) \le DCEC + \varepsilon, \forall t \quad (6)$$

where $\rho^{Emiss}_{Elec,t}$ and $\rho^{Emiss}_{Gas,t}$ are the decentralized CEI (gCO_2/MWh) at each time slot for each lower-level system, ε is the adjustment amount of DCEC should there be any infeasibility during the planning process. If the DCEC is feasible for the system to meet, the adjustment amount should be zero; otherwise, the non-zero adjustment amount will be used as communication information for the upper level to change the UCEC and execute upper-level optimal planning.

Constraint (7) and (8) denotes budget limitations of the local district other than carbon budget that must be met.

$$F^{Total}_{eb} \le \overline{F^{Budget}_{eb}}, \forall eb \in \Omega_{EnergyHub} \quad (7)$$

$$\underline{W^{Budget}_{eb}} \le W_{eb} \le \overline{W^{Budget}_{eb}}, \forall eb \in \Omega_{EnergyHub} \quad (8)$$

where F represents the financial cost for the entire low-level system, and W represents the local social willingness of corresponding planning and operation scheme.

C. Optimization Problem for Upper-Level

The upper-level optimization seeks the minimum annualized investment and operation cost of the distribution-scale energy system, considering network constraints from both electricity and gas system. The upper-level expansion includes transmission line, gas pipeline and large centralised renewable generation for the goal of carbon emission reduction in the entire region.

The upper-level model is formulated as following.

$$\begin{aligned} \min & \sum_{x\in\Omega^{new}_{Line}} C^{Invest}_{Line,x} \cdot N_{Line,x} \cdot R^{EAC}_{Line,x} + \sum_{y\in\Omega^{new}_{PipeL}} C^{Invest}_{PipeL,y} \cdot N_{PipeL,y} \cdot R^{EAC}_{PipeL,y} \\ & + \sum_{z\in\Omega^{new}_{CRG}} C^{Invest}_{CRG,z} \cdot N_{CRG,z} \cdot R^{EAC}_{CRG,z} + \sum_{x,y,z,w\in\Omega^{old\&new}_{Tech}} C^{Maintenance}_{x,y,z,w} \\ & + \sum_{t} \Delta t \cdot (\sum_{s\in\Omega_{GenUnit}} C^{Oprt}_{s,t} \cdot P_{s,t} + \sum_{u\in\Omega_{GasWell}} C^{Oprt}_{u,t} \cdot P_{u,t}), \end{aligned} \quad (9)$$

where the first three terms denote the investment cost for newly constructed transmission lines, pipelines and centralized renewable generation, the fourth term represents the total annual maintenance cost for upper-level, and the fifth term indicates the operation cost of generation units in electric network and gas source wells in gas network. $\Omega_{GenUnit}$ and $\Omega_{GasWell}$ are the set of generation units and gas wells in electric system and gas system respectively; $C^{Oprt}_{s,t}$ and $C^{Oprt}_{u,t}$ are the operation cost of each generation unit and gas well per unit of energy; $P_{s,t}$ and $P_{u,t}$ are the power output of generation units and gas sources.

The energy network constraints include AC electricity power flow (10) [17], gas flow (11) [18] and feasibility domain for control variables (12)-(14).

$$f_{Elec}(P,Q,V,\theta) = 0 \quad (10)$$

$$f_{Gas}(M,p,k_{cp}) = 0 \quad (11)$$

$$\underline{V} \le V \le \overline{V} \quad (12)$$

$$\underline{p} \le p \le \overline{p} \quad (13)$$

$$\underline{k_{cp}} \le k_{cp} \le \overline{k_{cp}} \quad (14)$$

where P, Q represent active and reactive power at the electric node; V, θ represent electric node voltage and phase angle; $\underline{V}$ and $\overline{V}$ represent lower and upper bounds of bus voltage; M represents gas flow; p is gas node pressure; $\underline{p}$ and $\overline{p}$ represent lower and upper bounds of gas pressure; k_{cp} is compressor ratio; $\underline{k_{cp}}$ and $\overline{k_{cp}}$ are the lower and upper bounds of the compressor ratio.

III. ITERATION FRAMEWORK

As mentioned in Section II, the lower-level and upper-level problem are coupled with each other through carbon emission coordination. The OCEC is given by government for the entire distribution network to meet. Initial DCECs and UCEC and the DCEI will be calculated according to load proportion and operation results of the original system before expanding. Then lower- and upper-level then carry out optimization and adjust their CECs iteratively until the adjustments satisfy the convergence conditions. The iteration procedure is described in Fig. 2. The main interaction process is implemented as follows.

Step 1: Run lower-level optimization according to local forecasting load and set the result of electric and gas utilization as initial parameters.

Step 2: Use the initialization from step one to conduct upper-level optimization, and calculate the initial DCECs for lower-level systems and UCEC for upper-level system according to their load proportion.

Step 3: Calculate the DCEI on every bus and node in upper level using upper-level optimization results.

Step 4: Run lower-level optimization again using DCEI in local carbon emission constraints; check convergence, if yes go to step 6, otherwise adjust DCECs and UCEC according to the results with OCEC unchanged and go to step 5.

Step 5: Run upper-level optimization again using new UCEC in upper-level constraints, then go to step 3.

Step 6: Output expansion planning decision for lower- and upper-level.

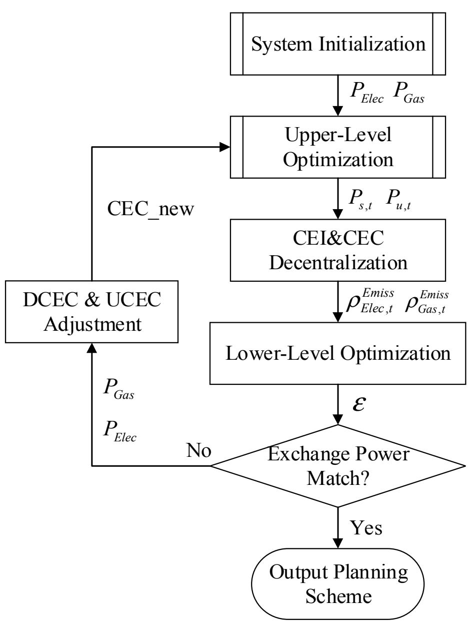

Figure 2. Carbon emission iteration procedure between two levels

IV. CASE STUDY

The proposed planning method is employed on a modified 4-bus/4-node energy system with three lower-level systems at bus/node 1, 2, and 3, as shown in Fig. 3. The upper-level system includes two gas-fired generation units at bus 1 and 4, two gas sources at node 2 and 4, electric loads at bus 2 and 4, and gas loads at node 3 and 4. There are five existing electric transmission lines and four existing gas pipeline in the original system, and a set of six candidate transmission lines and six gas pipelines is considered in the expansion-planning problem. A candidate wind farm as centralized renewable generation is also considered in upper-level planning decision-making. Three lower-level systems representing different local energy systems are interacting with upper-level using the coordination method described in Section III. The choice among new CHP, GB, HP and PV or their potential combinations is optimised in the lower-level system expansion-planning problem.

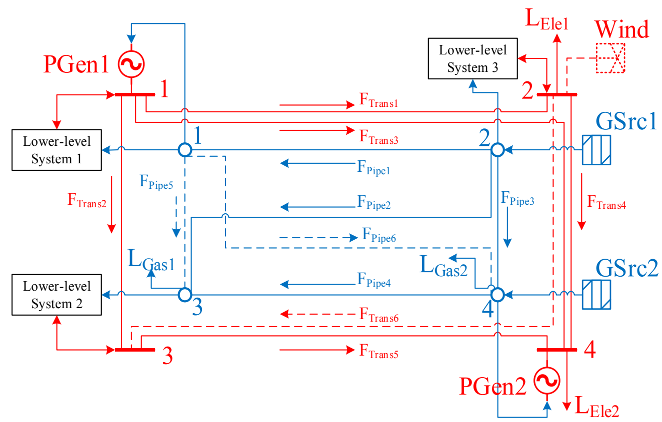

Figure 3. Modified 4-bus/4-node two-level IES

Wind profile is obtained from Scottish Renewables [19]. Two typical daily load profiles representing summer and winter scenarios are based on [20] for each upper-level load and lower-level system. The capacity of the generation units and gas sources are listed below in Table I. The peak power and gas load in upper-level is shown in Table II. The expansion or building costs of different candidate considered in upper- and lower-level are listed in Table III.

TABLE I. GENERATION UNITS AND GAS SOURCES CONFIGURATION IN UPPER-LEVEL

Energy Supply	**Power Generation 1**	**Power Generation 2**	**Gas Source 1**	**Gas Source 2**
Capacity (MW)	70	80	200	200

TABLE II. ORDINARY POWER AND GAS LOAD IN UPPER-LEVEL

Load	**Electric Load 1**	**Electric Load 2**	**Gas Load 1**	**Gas Load 2**
Capacity (MW)	22	25	10	15

TABLE III. COST OF NEWLY BUILT CANDIDATES

Candidate	**CHP**	**HP**	**PV**	**Line**	**Pipeline**	**Wind Farm**
Cost (£/MW)	20000	3000	100000	200000	200000	500000

The case studies are carried out in different carbon limitation scenarios, namely a series of OCEC is implemented to verify efficiency of the proposed method. From the original carbon emission amount, three lower OCEC are set, according to which the corresponding planning results are obtained as shown in table IV.

TABLE IV. INVESTMENT COST UNDER DIFFERENT OCEC

OCEC (gCO2)	Investment Cost (£, million)				Iteration Times
	Upper-level	*Lower-level System1*	*Lower-level System2*	*Lower-level System3*	
779370	30.63	12.13	7.93	2.59	5
729370	55.25	13.48	8.69	3.34	7
679370	59.46	13.95	8.99	3.75	22

The expansion costs of independent and coupled planning under the same OCEC of 729370 gCO2 are compared. Table V shows that although upper-level investment cost of independent planning is slightly lower than that of coupled planning, the expansion costs are much higher in lower-level systems so as to meet the DCEC.

TABLE V. EXPANSION COSTS OF INDEPENDENT AND COUPLED PLANNING

Planning Mode	Investment Cost (£, million)				
	Upper-level	*Lower-level System1*	*Lower-level System2*	*Lower-level System3*	*Whole-area*
Independent	52.94	17.37	13.74	8.62	92.67
Coupled	55.25	13.48	8.69	3.34	80.76

Fig. 4 shows the coupled planning decision for upper- and lower-level under different OCEC.

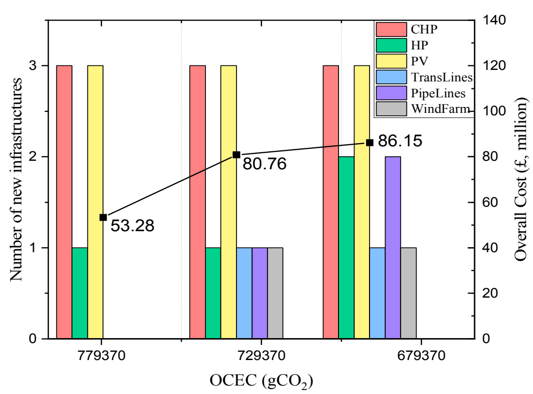

Figure 4. Planning decision under different OCEC

The newly installed CHP and PV will appear even if OCEC is set as the original value, because these two technologies will lead to more operation cost reduction comparing to its investment. The capacity of newly installed CHP and HP will get larger when OCEC decreases, which will result in building more transmission lines and pipelines to transfer the energy. In the meantime, a wind farm will be built when OCEC decreases to 729370 gCO2, due to its ability to reduce carbon emission intensity effectively in the whole system. However, the minimal overall cost will increase fiercely when the wind farm is built.

The model is implemented in MATLAB with YALMIP and solved by CPLEX 12.6 on a PC with an Intel Core i7-6700/3.40 GHz CPU and 16 GB of RAM. The computation time is less than 2 minutes.

V. CONCLUSION

This paper proposes a planning framework for integrating energy systems at different scales using a novel decentralized approach. To represent the different ownerships of sub-energy systems, the local communities at the lower level are modelled as separated energy hubs while the upper level is modelled as the gas and electricity transmission network with bulky generation. By adopting a carbon-led emission-coordinating strategy, the optimal plan of whole system is achieved when the expansion cost of each sub energy system is minimised under their optimally allocated carbon budget from the overall limit.

A test case study demonstrates the effective design of integrated energy system using the proposed method. CHPs are chosen to replace gas boiler as heat supply in local to support system coupling. Small embed renewable, such as PV is built next to demand under high carbon budget scenario. Large and costly renewable generation, such as wind farms are only built in lower emission allowance case. As the results shown, the coordination approach is efficient while tightening emission budget requires more iteration steps. Further work on large-scale real energy system application has already been planned.

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