State-of-The-Art of Modeling Methodologies and Optimization Operations in Integrated Energy System

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Abstract. Rapid advances in low carbon technologies and smart energy communities are reshaping future patterns. Uncertainty in energy productions and demand sides are paving the way towards decentralization management. Current energy infrastructures could not meet with supply and consumption challenges, along with emerging environment and economic requirements. Integrated Energy System (IES) whereby electric power, natural gas, heating couples with each other demonstrates that such a significant technique would gradually become one of main comprehensive and optimal energy solutions with high flexibility, friendly renewables absorption and improving efficiency. In these global energy trends, we summarize this literature review. Firstly the accurate definition and characteristics of IES have been presented. Energy subsystem and coupling elements modeling issues are analyzed. It is pointed out that decomposed and integrated analysis methods are the key algorithms for IES optimization operations problems, followed by exploring the IES market mechanisms. Finally several future research tendencies of IES, such as dynamic modeling, peer-to-peer trading, couple market design, are under discussion.

1. Introduction
Nowadays the energy industry is facing fierce transformation from generations to generations. Wide distribution of utility networks offers the convenience of energy consumption and variable resources integration. Web smart grid has brought the concept of ICT infrastructure construction and fast-response communication into the development of flexibility and real-time energy management[1]. With arising of distributed energy resources and regional integrated energy networks, the traditional electric energy system is witnessing the lessening impact of unified interconnected networks and the emerging influence of decentralized energy generations tendency. The double operations mode of ‘Interconnection’ and ‘decentralization’ will govern the vision of energy generation, transmission and consumption. Integrated energy system (IES) has aroused under such macro energy transients stages. It represents frontier demands for modern energy system of high efficiency, complementary medias for redundancy and variable resources consumption with systemic stability. Consequently this novel issue will contribute to academic and industrial focuses continuously.

This paper aims to provide the readers with amplyate and miniature overview in integrated energy system (IES) with the emphasis on the energy systems modeling methodologies and optimization operations. We retrospect and summarize the basic IES concepts with comparisons of former theories. Following by introductions of subsystem analysis and coupling components modeling, up-to-date optimization algorithms and energy market mechanisms are presented. Future research tendencies are also externalized.

2. IES concepts and definition
Integrated Energy System as a concept has been approached by peers from different aspects. Three different summarizing perspectives are proposed as Smart Grid 2.0, Interconnected Energy Network, and Internet + Energy Network, in which the merge modes are different in physical and informative merge characteristics. Key technical constraining conditions development in time-scale and application scenarios in different regions contributes to the typical forms of Internet + Energy Net development [2]. Variable perspectives reflect the up-to-date technology sharpening the energy and power systems. In a strict definition, ‘integration’ is related to parallel energy medias coupling and restructured while ‘system’ is focusing on the physical main infrastructure body with deriving other minor application issues.

In 2007, energy hub [3] was proposed by G. Anderson in ETH as the linear energy transfer relationship between multi-energy flow while later the system concept has appeared. G. Strbac proposed Multi-Vector Energy System [4] enabling storage and transport, which is based on the UK situation of highly co-operation of natural gas and electricity with large wind farms integration. The Multi-Energy System [5] raised by P. Mancarella, divides the internal and external regional networks and could be under the interpretation of microgrids and virtual power plants. Besides, Wu Jianzhong is focusing on the combination scheming with coupling elements in Integrated Energy System operations[6].

![Diagram of overall Integrated Energy System concept with multi-energy flow](image)

**Fig. 1** A typical diagram of overall Integrated Energy System concept with multi-energy flow

As it is shown in Figure 1, an typical overall concept depiction of integrated energy system is presented: electric power flow, natural gas flow and heating flow are the majority energy carriers, which are consists of interconnection networks and terminal energy units. From the integrated perspective, system maximum benefits could be realized as follows:
- High penetration harvest of renewable and intermittent energy.
- Complementarity of mutual storage for load shifting and curtailments.
- Reliability for energy supply, changing the scenarios of single energy supply or non-switchable energy supplies.
- Efficiency improvements by providing much more available conversion sections

### 3. IES modeling techniques, approaches and analysis methods

#### 3.1. Unique energy network mode issues

With Kirchhoff voltage law and Kirchhoff current law, similar analogy can be concluded from these three energy carriers. For node energy balance, the Kirchhoff current law, gas flow rate balance equation and heating mass flow continuity equation could be all included in same principle. The node variables loss can be formed into Kirchhoff voltage law, gas pressure drop equation and loop pressure equation. In some ways, IES modeling could be made into unified formulation considering node variables and branch variables.
Table 1. Comparison with three energy system modeling’s variables

| Energy Carrier | Node Variable | Branch Variable | Constraints |
|----------------|---------------|-----------------|-------------|
| Electric Power | Voltage       | Current         | Kirchhoff voltage law; Kirchhoff current law |
| Natural Gas    | Pressure      | Gas flow rate   | Pressure drop equation; Flowrate balance equation |
| Heating        | Pressure, Temperature | Mass flow rate, Heat power | Flow continuity equation; Loop pressure equation; Head loss equation |

3.2. Coupling components modeling in IES

The coupling components between the two energy carriers could be taken account into linear relation expression describing the numeral single input-output situation, which could be formulated as follows:

\[ E_1 = \varphi E_2 \]  

(1)

Where \( E_1 \) and \( E_2 \) represent different energy flow and is \( \varphi \) the energy transfer efficiency.

3.2.1. Combined Heating and Power. With the efficiency of up to 80\%, the combined heating and power (CHP) could realize the multiple outputs in power and heating as cogeneration unit. It is also called combined heat and power district heating and sometimes works as decentralized energy. Some lower power CHP is defined as micro-CHP for inhouse usage. Commonly the ratio between heating generation and power generation is constant. Thus, the operations problem could turn into single optimal energy flow problem based another other fixed energy flow. CHP will be strongly supported when local combined network is under interconnection with outer power grid; otherwise in islanded mode, the CHP should be adjusted more accurately to fulfill demands.

3.2.2. Power to Gas. Power to Gas (P2G) facilities could promote antiparallel flow, through water electrolysis generating hydrogen or methane (synthesized by carbon dioxide and oxygen). P2G could realize long-term and wide-area storage, which is beneficial to co-planning and co-operation of power system and gas network. Seasonal storage flexibility with renewables harvest could be also improved by P2G. However, the overall process of P2G owns probably transfer efficiency of only 20\%-40\%. The less development of P2G commercialization and the unexpected market demands for hydrogen will be the major obstacles of its further popularization.

3.2.3. Heat Pump. Driven by electricity, the heat pump is another high potential tool to increase system’s flexibility, which could be sourced from electric networks or fluctuant renewable energy. Serving as the negative load, it could support the CHP operations when CHP reaches its heating output limitation. Further more, the curtailment of renewable peaking generation is also achieved in IES or isolated microgrid equipped with heat pumps.

3.2.4. Gas turbine. The gas turbine is the linkage between natural gas network and electric power network. It could be considered as the gas load or power generation from two perspectives. In small IES
communities such as microgrids, gas turbine is taken into account in operating as main resources with high dynamic response. In long-term’s energy substitution, gas turbine plays a necessary role in system flexibility adjustment.

3.2.5. Comprehensive Energy Hub. Energy hub issues could be expressed in conversion matrix connecting the multiple inputs and outputs, describing the linear relationship. Such kind of model could be extended and characterized by self-defined components such as battery energy storage systems and solar heat exchanger [7]. The energy management system containing non-dispatchable resources and dispatchable energy resources or storage could be considered as electrical hub, optimized by different levels’ dispatch strategies [8]. Such methodology can be used for non-linear hub problems.

4. System modeling and optimization operations

4.1. Decomposed analysis method

The decomposition problem could be described as: under hypothesis of given value in master problem, subproblem could be calculated to convergence through iterations. The decomposition techniques have been widely applied in solving possible decomposable structures such as complicating variables or complicating constraints. Different kinds of energy flows could be defined as the elements under the decomposable framework. Dual decomposition mathematical structure includes individual and coupling constraints, which is forcing the Lagrangian multipliers to relax the coupling constraints [9]. The decomposition-coordination algorithm with inner, boundary and coordinated variables, has been proposed in [10], in which sub-problems are firstly solved and then part of boundary variables are selected as coordinated variables to solve interfaced constraints. The decomposed techniques could reduce the calculation scale when the energy system is increasingly complex but it is hard to guarantee the convergence due to much more iterations.

4.2. Integrated analysis method

Fig. 2 IES problem analysis methods comparison
Unlike the decomposed analysis methods, the integrated analysis methods are directly forging the subproblems into unique equation. Total general expression (2) is investigated as the combination of electrical network, natural gas network and heat network, covering all variables in unique vector \( x \), with Jacobian matrix \( J \) and energy imbalances vector \( f(x^{(n)}) \).

\[
X^{(n+1)} = X^{(n)} - J^{-1} f(x^{(n)})
\] (2)

The integrated electrical-hydraulic-thermal method [11] is explored with grid-connected and islanded modes, determining value of Jacobian submatrix elements and final optimal results. An expansive Newton-Raphson algorithm has been described in [12] to construct the coupling matrix and achieve optimal energy flow, following initially satisfying the calculation of CHP energy dispatch and other coupling equipments constraints. In summary, the integrated analysis method is to implement the non-linear optimization in unique general equation by forming the state variables vectors and coupling Jacobian matrix. Compared to decomposed analysis method, integrated analysis method takes less calculation steps but increases calculation scales and time.

5. Market mechanism for IES

New market structures with integrated approach optimization of electricity-natural gas system should be adapted by implementation of co-optimizing the day-ahead and real-time dispatch, where stochastic models are used to describe the uncertainty renewable energy integration while real-time energy balancing cost is solved by the specific realization of power production. [13] defines the market majority bodies of three different energy (gas-heat-power) participants in multi-lateral trading (MLT). In such a case, gas system is an absolute provider and heat system is an absolute consumer, making power system a prosumer to buy gas and sell electricity to heat networks, which could be turned into a bi-level problem solved by two phase methods: Rough Estimation and Elaborate Adjustment. The common solution to IES market problem is to establish the double stages or multi-stages stochastic programming with assumption of one energy market clearing being fixed.

6. Future research tendencies towards IES

Upon the complex coupling issues and various demanding energy challenges, utilities are facing more obstacles in system planning and operations. It is meaningful to continue concentrating efforts on IES. New research will be needed for the further development to guarantee the IES optimization operations.

6.1. Dynamic models modeling issue

For dynamic models issue, independent systems research are conducted. As for multi-vector energy, no current paper is covering. Drawing on the experiences of RTDS applied in power system, natural gas and heating dynamic models could be established in physical ways connected with electrical part when parts of them are under high interactions with electricity. The other models of natural gas and heating, which own slow dynamic characteristics and are not highly coupled with electricity, could be constructed in digital simulation tools[14]. Further search work on such issues is worthy.

6.2. Peer-to-peer trading technology application in IES

Along with blockchain technology spread, P2P technology unlocks the decentralized decision making in regional energy market, ensuring customers freely handling energy trading. However, the current research progress is only focusing on electricity. The coupling of other energy carriers and P2P makes IES market mechanism more complex, especially in multi-energy flows P2P’s multidirection trading.

6.3. Couple energy market design for IES

The different timing scales with large differences facilitate possibilities of coherent coupling energy markets. Incentive demand response cases under IES will be the most potential technology for such
energy market[15,16]. Coupling elements contributes to flexibility increase, which is meaningful to the pricing schemes in couple markets with high complementarity. Based on above, the coupling market should be designed under diverse markets regulations, integrated externality network limitations and optimal multi-energy flows convexity solutions.

7. Conclusions
The calls of Cleantech, whether from green energy consumption or environment protections, is existing as a hotspot. The Integrated Energy System has boosted the booming of next generations of smart infrastructures. This paper provides concepts and characteristics for IES. Through concerning systems modeling with solutions and markets mechanisms, this paper also offer insights into potential technologies in IES.

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9. References
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