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**You, Shi; Jin, Lin; Hu, Junjie; Zong, Yi; Bindner, Henrik W.**

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# 从基于服务的灵活性交易到跨行业能源系统的集成设计、规划和运行: 丹麦的能源互联网理念

尤石<sup>1</sup>, 林今<sup>2</sup>, 胡俊杰<sup>1</sup>, 宗毅<sup>1</sup>, Henrik W. BINDNER<sup>1</sup>

- (1. 电力与能源研究中心(丹麦科技大学), Elektrovej 325, DK 2800;
2. 清华大学电机工程与应用电子技术系, 北京市海淀区 100084)

## The Danish Perspective of Energy Internet: From Service-oriented Flexibility Trading to Integrated Design, Planning and Operation of Multiple Cross-sectoral Energy Systems

YOU Shi<sup>1</sup>, LIN Jin<sup>2</sup>, HU Junjie<sup>1</sup>, ZONG Yi<sup>1</sup>, Henrik W. BINDNER<sup>1</sup>

- (1. Center for Electric Power and Energy (Technical University of Denmark), Elektrovej 325, DK 2800, Denmark;
2. Dept. of Electrical Engineering Tsinghua University, Haidian District, Beijing 100084, China)

**ABSTRACT:** Motivated by the success of internet technologies, energy internet, also referred as web-based smart grid (SG) or SG 2.0, is expected to offer innovative applications based on advanced connectivity and intelligent management of distributed energy resources (DER), systems and services with a strong focus on enabling a paradigm shift in the energy industry. Being the European leader in the development of SG technologies, Denmark has developed its unique understanding of the energy internet. Based on the learning from a number of research and development activities in Denmark, this paper introduced two important subjects of the energy internet from the Danish perspective, i.e., service-oriented flexibility trading and integrated design, planning and operation of multiple cross-sectoral energy systems. Both elements are anticipated to bring in new business opportunities and challenges for different stakeholders in the energy industry; meanwhile these emerging solutions would both require and foster the transform of energy markets to facilitate the development of energy internet.

**KEY WORDS:** energy internet; cross-sectoral energy systems; energy markets; service-oriented flexibility; smart grid (SG)

**摘要:** 受到信息互联网的成功激励, 世界范围内的能源行业都期望通过能源互联网技术(也被称为基于 Web 的智能电网或智能电网 2.0), 为全行业提供基于先进互联及分布式能源智能管理的全新应用。作为欧洲智能电网领域的领先国家, 丹麦对于能源互联网的发展有着较为独特的视角。文中在调研了丹麦大量研究与研发活动的基础上, 重点介绍丹麦所秉持的两类重要的能源互联网技术理念, 即基于服务的灵活性交易, 以及跨行业能源系统的集成设计、规划和运行。丹麦希望基于上述理念, 为能源工业的不同利益相关方带来全新

的商业机会和挑战, 并进一步使用新型的技术解决方案促进能源市场的转型和能源互联网的发展。

**关键词:** 能源互联网; 跨行业能源系统; 能源市场; 基于服务的灵活交易; 智能电网

## 0 INTRODUCTION

When the rapid development of information and communication technologies (ICT) has proven its significance in boosting the digital economy and reshaping the daily life of general public[1], another noticeable trend is the growing importance of distributed energy resources (DER) in the energy industry. By 2013 the total installed capacity of residential PV systems (less than 10kW) in Germany has reached 4 094 MW[2]. Meanwhile, a total number of 37824 plug-in electric vehicles (EV) are commuting on the roads in Norway (more than 1% of the total registered passenger cars)[3]. Due to these two paradigm shifts: the present energy system has shown a much higher degree of digitized decentralization in comparison to a conventional energy system. On the one hand, the evolution brings a series of challenges to the energy sector in providing economically efficient energy supply meanwhile maintaining high levels of quality and system security. On the other hand, it also stimulates a wide range of innovative technological applications, business practices and market reforms that cover the whole

value chain of the energy industry[4-8].

Over the last decade, smart grid (SG) as a generic term has been utilized to streamline the design, development and roll-out of different innovative solutions that cover the entire spectrum of the electrical energy system from power generation to the end points of consumption. Although there exists regional differences in view of what SG is, the following key characteristics of SG are generally agreed upon[9-11]:

1) Automated self-healing electrical systems and electrical components with high resilience to disturbances, attacks and natural disasters;

2) Customer participation in electrical system operation and market operation;

3) ICT-enabled interconnectivity applied in multiple system levels such as transmission, distribution and residential premises etc., in the electricity sector;

4) Data-driven approaches enabled intelligence and optimization applied to multiple system levels in the electricity sector;

5) Flexibly accommodated DER and SG technologies into multiple system levels at varying scales;

6) Value-added new products, services and markets.

Energy internet, also referred as web-based SG or SG 2.0, is the visionary future energy system [12-16]. In Fig. 1, a schematic overview of different technological layers of Energy internet is presented. Within its technological setup, the Energy internet infrastructure consists of both ICT and energy infrastructures, which enables advanced connectivity among different energy components, energy systems and multiple stakeholders. It also stimulates intelligent applications in different energy-related activities. In addition, both advanced connectivity and intelligent applications must be achieved at a large-scale level to facilitate the high degree decentralization, comparable to the internet industry. Therefore, Energy internet imposes critical requirements on its infrastructure design in heterogeneity, scalability and openness[17-18]. Moreover, the development of

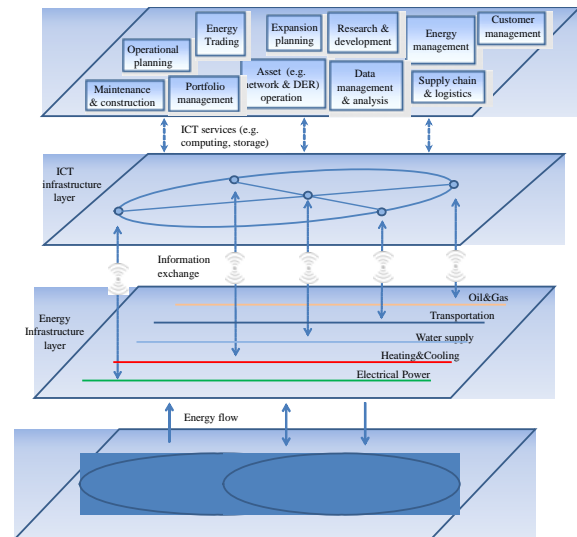


Fig. 1 Schematic overview of technological layers of energy internet

Energy internet could draw on extensive knowledge and experience from the internet industry. This exchange would cover both technology and business aspects such as adopting the service-oriented solutions to the energy sector[19], meanwhile considering the practical features of energy sector that involves system of systems (SOSs) with multi-level complexities and multi-physics. In comparison to SG, energy internet emphasizes using an integrated perspective on design, planning and operation of multiple cross-sectoral energy systems, which shall maintain the key characteristics of SG and extend their applications.

Although energy internet is relatively fresh, approaches, technologies and supporting tools are already under fast development. Approaches such as energy hub[20] and information-centric[21] are progressively developed to facilitate the architectural development of energy internet. Meanwhile, technologies like virtual power plant (VPP)[22] and Microgrid[23-24] are already deployed for optimal operation and management of multi-energy sources in liberalized energy market places. In terms of supporting tools, multi-energy planning tools like EnergyPlan[25] and cyber-physical simulation platforms[26] demonstrate significant value in meeting the needs of energy internet development from diversified perspectives.

Being the European leader in the development of SG technologies, Denmark has its unique understanding of energy internet solutions based on its

long-term supporting scheme of developing clean and effective energy solutions. This paper hereby introduces two important subjects of the energy internet from the Danish perspective, i.e., service-oriented flexibility trading and integrated design, planning and operation of multiple cross-sectoral energy systems in order to share the knowledge and experience gained from a series of research and development activities performed in Denmark. A brief review of the energy development in Denmark is presented in the next section before highlighting the two energy internet elements. The last section discusses potential challenges for further development and application of energy internet solutions as well as open research questions.

## 1 ENERGY INTERNET IN DENMARK: AN ENERGY SOLUTION THAT EMERGES AS THE TIMES REQUIRE

Due to the concerns on energy independency and climate change, the energy sector in Denmark experienced a dramatic change after the energy crisis in late 1970 s[27-28]. As illustrated in Fig. 2[29], compared to a highly centralized electrical energy solution in 1985, the electrical power infrastructure in 2009 comprises with a large-scale integration of decentralized wind power and combined heat and power (CHP) plants that not only differ in sizes and ownerships but also are operated under different technical and economic regimes. In addition, joining the liberalized Nordic power exchange in 2000, also facilitated the process of energy decentralization in Denmark, leading to a quick increase in the number of distributed generation (DG) and independent power producers, energy retailers and trading agents[30].

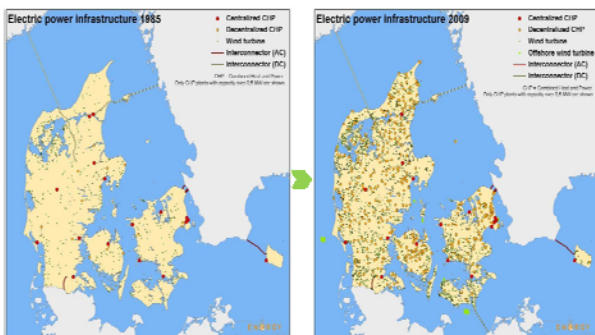


Fig. 2 Evolution of the Danish power system

Although the highly decentralized energy system made a new world record in 2014, i.e., 39% of the electricity consumption of Denmark from wind power[31] with efficient CHP-based district heating solutions covering 50% of heating needs[32], it is still an ambitious and challenging mission to meet the political targets of Danish government, i.e., 35% of its total energy from renewables (with 50% wind powered electricity) by 2020 and 100% by 2050. On the one hand, having a robust and resilient infrastructure solution becomes a must in order to handle the rapid and extensive integration of intermittent renewables like wind as well as the associated challenging conditions such as little wind over a long period leading to huge demand on power reserves; on the other hand, reaching 100% renewable requires an integrated perspective on the development of technology and business that could optimally coordinate a broad variety of measures across different energy sectors[33-35].

In the last decade, Denmark has been among the leading positions in Europe in working on SG. According to the SG projects outlook 2014 published by EU, Denmark not only has the highest investment in SG per capita and per national electricity consumption but also leads the research and innovation activities particularly in the initial stages[36]. Among many of these Danish initiatives, energy internet has already been implicitly reflected by a number of work related to “aggregation”, “flexibility”, “data communication”, “market access”, “transport and heating” and “integrated systems” amongst others, which constitute the Danish blueprint of a future energy system. In the following two sections, these loosely connected elements of energy internet are elaborated through an integrated approach. The elaborated two subjects i.e., service-oriented flexibility trading and integrated design, planning and operation of multiple cross-sectoral energy systems shall reflect the unique understanding and experience in energy internet from the Danish perspective.

## 2 SERVICE-ORIENTED FLEXIBILITY TRADING

### 2.1 Flexibility identification

Flexibility is understood as the ability of a

system to respond to potential changes in a timely and cost-effective manner. For a future energy system with high degree of uncertainties that have to be addressed second by second, such as for wind power fluctuation, flexibility is the key for achieving the same level of system redundancy as in today’s energy system with little investment. Such flexibility can be found in generation, transmission and distribution systems, customers, and energy market etc. In Denmark, the study on flexibility covers the entire value chain, as illustrated in Fig. 3, which presents a vivid application of energy internet.



Fig. 3 Flexibility value chain

DERs such as EVs[37], heat pumps (HPs)[38], household appliances[39], and industrial loads[40-41] constitute the majority of the resources of flexibility in the Danish context. Compared to mobilizing the flexibility from generation side (e.g., using wind farm to provide spinning reserve with delta control[42]) and grid side (e.g., FACTS[43] and utility-side storage[44]), flexibility acquired from demand-side resources are more attractive to system operators who could use the flexibility either for ancillary services or to defer the process of grid extension[34-35].

2.2 Flexibility characterization

The process of flexibility characterization intends to ensure the flexibility of either an individual DER or an aggregated DER portfolio can be understood: modelled and utilized at the same level as a conventional flexibility resource like a generator in order to support relevant analysis and applications. In Danish R&D activities such as iPower[45-47], flexibility is characterized by a number of time-dependent parameters and constraints in relation to power capacity, energy capacity, minimum on/down time etc.

To better characterize intrinsic features of

different DER systems, the iPower consortium has developed three flexibility models (i.e., buckets: batteries and bakeries), as illustrated in Fig. 4. The “bucket” is a power and energy constrained integrator that is suitable for modelling supermarket refrigeration and households with HPs etc., allowing electrical energy stored in form of thermal energy while respecting the constraints on the energy level and the power consumption. The “battery” is also a power and energy constrained integrator, but with the added restriction that the unit must be fully charged at a specific deadline. An example of the battery model could be an electric vehicle that must be ready for using at a specific time. The ‘bakery’ model extends the battery model with an additional constraint that the process must run in one continuous stretch at constant power consumption. An example of the bakery model could be a washing machine that must run for a certain time continuously.

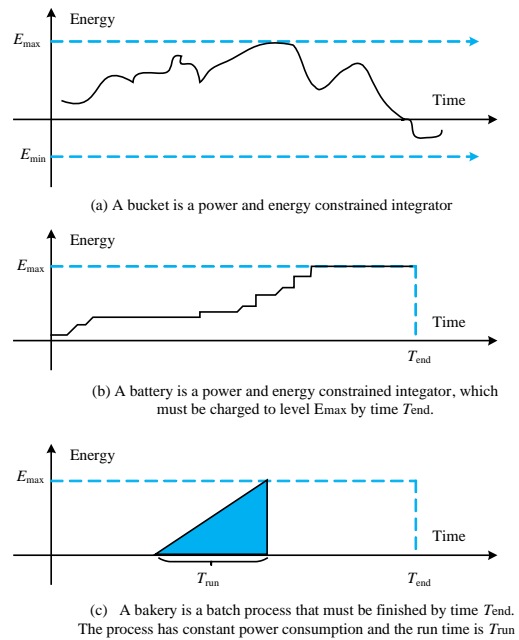


Fig. 4 Illustration of three flexibility models, bucket, battery and bakery

The suggested models present a proper taxonomy for modelling flexibility, which also contributes to developing appropriate control algorithms for aggregated flexibility operation and management. A hierarchical relationship exists between the three models, meaning a bucket provides a better quality of flexibility than a battery, which is again superior to a bakery. It is discussed that better quality means less

restricted, not necessarily more flexible[45]. In addition, polytope-based representations of flexibility are developed as in Fig. 5, to visualize the change of flexibility over time[48-49] and to enable flexibility representation in SCADA applications.

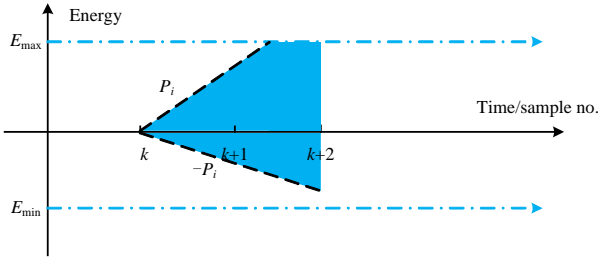


Fig. 5 Polytope representation of flexibility

### 2.3 Flexibility operation and management through direct and indirect control solutions

The flexibility of individual DER is usually scaled up through aggregation in order to meet the minimum volume requirement for service provision (e.g., ancillary services in power system) and market entry (e.g., Nordpool spot market). However, achieving an optimal operation and management for thousands of geographically distributed units is a challenge to the conventional control solutions. Generally, the more economic benefits a service can offer to the service providers, the more critical requirements it may impose, such as primary frequency reserve having critical requirements on accuracy and time of response. In Denmark, two categories of control strategies are developed to perform aggregation-based control over the DERs, namely direct control and indirect control[50] as illustrated in Fig. 6.

In the context of aggregation-based flexibility operation, direct control is developed as an aggregator sends control signal to each local controller which takes this as the local reference input. In this centralized structure, decision making is performed by the aggregator, where local outputs and state information is collected from local controllers and fed back to the aggregator controller. Today, most commercial applications for flexibility aggregation are based on direct control, such as Power Hub developed by the Danish utility DONG Energy[51]. These VPP-alike aggregators typically aggregate DERs with size above 100 kW in order to enter the existing power

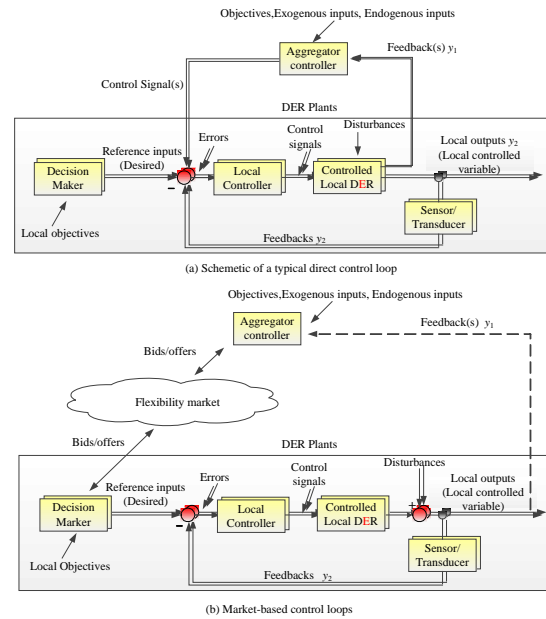


Fig. 6 Schematic overview of direct vs. indirect control market for trading spot energy or regulating reserves.

Contrary to direct control, indirect control exploits an aggregation effect (i.e., a smoothing by summation of diversity in combination with strong correlations of observable exogenous variables and control signals that can be captured in an aggregated model.) reducing the need for dedicated bi-directional communication links. This type of control is typically achieved through a market-alike setup where either double-side auction or single-side auction schemes could be implemented in. In a double-sided auction bids and offers are submitted by all parties, and the market prices are derived from certain clearing mechanisms and become the control reference signals for the DERs to follow obligatorily[52]. For single-side auction scheme, uni-directional price signals are distributed by the aggregator and market clearing is performed by the voluntary response of the DERs[53]. In case the aggregator has the information of the operational status of an electrical network, a control loop with optimal pricing can be formulated to address critical problems e.g. real-time power balancing and network congestion[54-55]. In Denmark, both auction schemes have been demonstrated in Ecogrid EU[56] and iPower at different scales. Indirect control has proven its advantages of easy to understand by the customers: transparency and little requirement on communication overhead amongst

others. However, forecasting the aggregated response of a large group of different DERs at different time scales remains a challenging task. This is due to the fact that the flexibility at the DER side is heavily dependent on the behaviour and willingness of DER owners (i.e., the decision maker as in Fig. 6) as well as the intrinsic physical constraints bounded to each DER application as explained in section 3.2.

### 2.4 Service-oriented flexibility trading platform

In a typical application of flexibility, system operators like transmission system operators (TSOs) and distribution system operators (DSOs) always play the role as service requesters due to their obligations on securing the system operation. However, when the two bodies with conflicting interests (i.e., global perspectives at the transmission level vs. local perspectives at the distribution level) desire to utilize the same flexibility assets, an activation of a given service can impose negative influence on system parameters governed by other services[57]. One example could be perceived as a moment when a TSO requires down-regulation service from a flexibility aggregator (i.e., to increase the power consumption), and meanwhile a DSO requests on using the same flexibility for peak load reduction. To handle these potential conflicts between multiple services requested by multiple stakeholders: a flexibility clearing house (FLECH) has been proposed: developed and demonstrated by the Danish iPower consortium[58-59]. Fig. 7 illustrates the conceptual design of FLECH with a list of new functions required by different stakeholders in order to fulfill the needs of flexibility trading. This service-oriented flexibility trading platform, as a neutral body, is able to facilitate the business process of specifying, contracting,

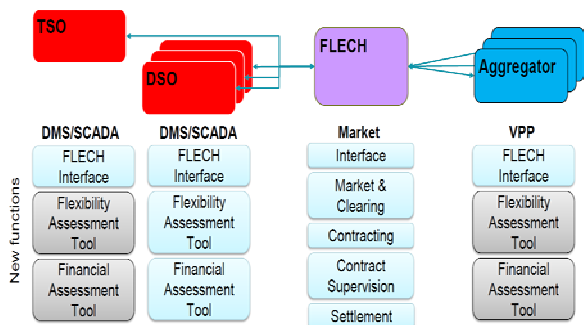


Fig. 7 Conceptual design of FLECH with new functions

delivery and settlement of DER flexibility services.

At present, since there are no market-oriented services at the distribution system level, the FLECH-related R&D activities have more focuses on the distribution level, such as developing DSO services for improved distribution system operation and DER integration, as in Fig. 8. Services such as PowerCut planned and PowerMax, which are developed to support congestion management at scheduling phase and operation phase, were lively demonstrated in November 2014 at SYSLAB of the Technical University of Denmark. In addition to demonstrating the technical feasibility of FLECH through which a DSO can purchase services from several aggregators simultaneously, the applicability of different control strategies was also demonstrated.

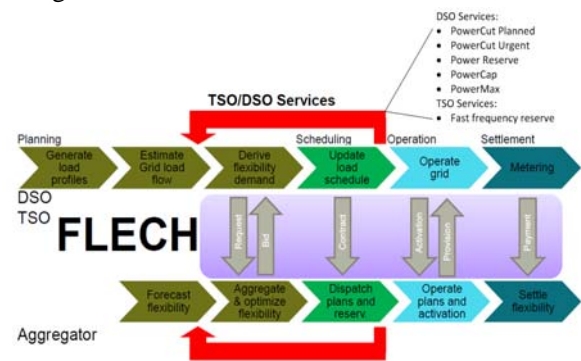


Fig. 8 FLECH-enabled interactions between system operators and aggregators for flexibility trading

However, the innovation of FLECH still requires further in-depth investigations at least on several important aspects, such as 1) baseline formulation at the distribution level for service delivery verification: 2) efficient coordination or prioritization algorithms for addressing conflicting service requests, and 3) acquiring a regulatory supporting framework[60].

## 3 INTEGRATED DESIGN, PLANNING AND OPERATION OF MULTIPLE CROSS-SECTORAL ENERGY SYSTEMS

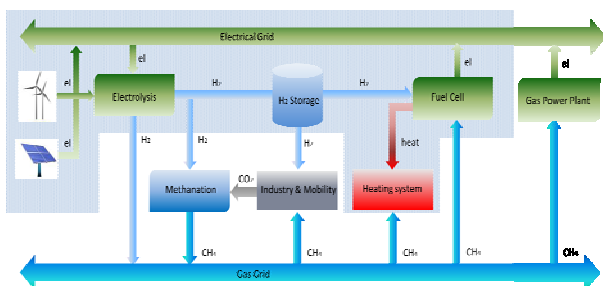
### 3.1 Hydrogen as an alternative energy carrier

Historically, the extensive use of CHPs already offers the Danes extensive experience on how to optimally coordinate the simultaneous production of heat and electricity in a dynamic market environment and how to develop the corresponding infrastructure from an integrated perspective. Today, such way of

thinking from an integrated perspective has been extended to design, planning and operation of the future Danish fossil-free energy system. This very complex SOSs intend to integrate multiple cross-sectoral energy systems from an individual household level to interconnected energy infrastructures[61]. Through integration, not only can flexibility be mobilized from the DER side in the electrical sector, but also other energy sectors can offer the flexibility at a much larger scale.

As depicted in Fig. 9, hydrogen as a viable and advantageous energy carrier option can deliver clean and efficient energy services in a wide range of applications and also stimulates the synthetic operation of multi-energy systems[62].

In Denmark, the interest of using hydrogen as an alternative energy carrier keeps growing. The first full-scale hydrogen-powered community of EU was demonstrated in Lolland, Denmark, which presents a showcase example of hydrogen-based solutions[63]. In this application, excess wind power is converted to hydrogen via centralized production and stored in low pressure tanks. Through a number of installations of domestic fuel cell micro-CHPs, the need for heat and electricity from each household is met individually, resulting 100% carbon neutral. This type of applications focuses on the bidirectional energy exchange feature between electricity and hydrogen, as depicted in the shared area of Fig. 9.



**Fig. 9 Schematic overview of the role of hydrogen systems in a multi-carrier energy system**

Another hydrogen-based potential application, so called power-to-gas (PtG) as illustrated in the unshaded area of Fig. 9, intends to enable a much larger scale application for hydrogen-based energy storage. The hydrogen produced by electrolysis can be converted into methane, utilized in the industrial and

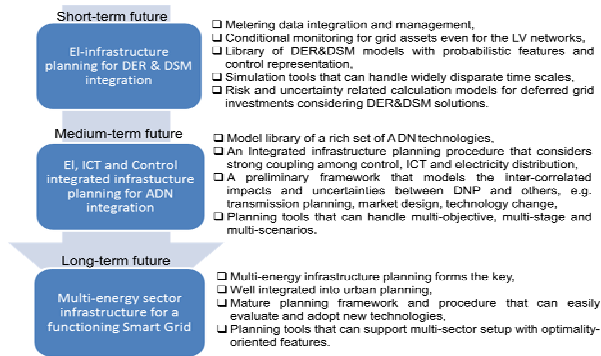
mobility sectors or accommodated directly in the gas grid. Although the amount of hydrogen that can be added to natural gas in the gas grid strongly depends on the composition of the natural gas at the point of injection, a total storage potential is huge. According to the feasibility analysis presented by the Danish project CopeHydrogen, the storage potential of the Danish gas infrastructure is estimated as 11 TW·h which is able to buffer in “light wind years”[64].

### 3.2 Integrated design, planning and operation of urban energy infrastructure

The latest Danish initiative of developing an urban coherent flexibility energy system in the Copenhagen city district Nordhavn with 40 000 new residents (i.e., EnergyLab Nordhavn) to the greatest extent represents the strong Danish interest and expertise in integrated energy solutions[65]. In addition to fertilizing and demonstrating a number of technical achievements inherited from a large number of prior activities related to SG and smart city, a special focus of this four-year project (i.e., 2015~2019) is on re-thinking the infrastructure design principle wherein electricity, thermal and transport infrastructure are designed as a whole to maximize the value of every individual technology. For instance, the heating infrastructure in Nordhavn will use low temperature district heating combined with distributed electrical heat boosters (such as immersion heaters or heat pumps integrated with local heat storage) installed at the customers’ premises. Such solution not only advances the heating infrastructure with higher efficiency of heat distribution but also fosters the deployment of electrical heating solutions which can be flexibly used to balance wind production. However, this initiative will affect the planning and operation of electrical distribution.

From the design and planning perspective, a number of new features will be added onto the existing design and planning principles as depicted by Fig. 10, following the development of energy internet technologies from short-term to long-term. In near future this will primarily focus on integration and utilization of smart meter data to support a better understanding of the load pattern with active demand





**Fig. 10** New features of distribution network planning following the development of energy internet

and the impacts of DER. In the medium term, technologies like active distribution network (ADN) will be benchmarked to enable the application of a variety of SG technologies. Both technical dynamics and economic values of ADN applications considering the strong coupling between ICT, electricity and various control solutions will be identified and included in a formalized planning framework. In the long run, integrated multi-disciplinary design and planning procedures for smart regions/cities will be developed based on comprehensive knowledge of both individual energy systems and the interactions between them in order to realize the complete value of energy internet.

Regarding the operational aspect, EnergyLab Nordhavn aims at developing and demonstrating the coordinated operation of different energy sectors through a new multi-energy marketplace. A series of market-design related subjects will be investigated, such as 1) Dynamic prices and tariffs designs at end user level, 2) Market coupling of electricity and district heating markets through integrated optimization, 3) Optimal electricity, thermal, transport and gas system operation through SCADA and control and 4) Customer models and business cases. The flexibility from different energy sectors, such as shifting the charging period for EVs and utilizing the fuel-shift possibilities between electricity and heat, would therefore be managed as a whole in real-time through economic signals.

### 3.3 Development of computer toolkits

Presently, the approaches related to integrated design, planning and operation usually elaborate on the importance of multi-disciplinary criteria, multi-level information exchange and coordination among

different stakeholders, system models with different granularities, and multi-period and multi-objective optimizations. A major research focus in Denmark is therefore on developing different computer toolkits to support the corresponding studies for integrated energy systems. In Tab. 1, several well developed software packages by the Danish researchers are listed. Most of the tools use hourly-based time series analysis to support the studies related to design and planning of integrated energy systems.

**Tab. 1** Tools for integrated energy systems analysis

Tools	Explanation
BALMOREL[66]	Energy model based on partial-equilibrium with emphasis on the electricity sector and CHP.
WILMAR[67]	For analyzing the optimal operation of power systems and can take forecasts of load and wind production as stochastic input parameters.
EnergyPLAN[25]	Deterministic input/output model to assist the design of energy planning strategies on the basis of technical and economic analyses for implementing different energy systems and investments.
STREAM[68]	A scenario building tool that presents an overview of a complete energy system based on the models of energy flow, energy savings model and the duration curve.

However, in an integrated energy system, one major challenge is the fast changing operational dynamics in different physical systems which are incurred by interactions between different stakeholders, different services and different control schemes as explained in Section 3. In Denmark, tools like IPSYS[69-70] have been developed to facilitate the design of intelligent control solutions and to evaluate the control performance from the operational perspective. Advanced functions such as hardware-in-loop, agent-based design for simulating distributed decision making, and co-simulation between different disciplinary software tools to serve the studies in cyber-physical systems, are all included as part of the tool.

## 4 CONCLUSIONS

The energy internet paradigm, stimulated by the advancement of ICT and large-scale rollout of DER, represents a convergence of ideas and technologies in a new energy era. During this paradigm shift, it has to

be clearly understood that all the new technologies depicted in the blueprint of energy internet, such as advanced connectivity and intelligent control, are alternative means to the conventional energy solutions, and they have to serve the goal of delivering a secure and effective integrated energy system solution to the society which is the most important core value of energy internet. In other words, fundamental criteria like energy security and cost-effectiveness must be prioritized over all other factors.

This paper describes two important subjects of energy internet from the Danish perspective, i.e., service-oriented flexibility trading and integrated design, planning and operation of multiple cross-sectoral energy systems. Within the Danish perspectives, using market-based solutions to enable the wide application of flexibility from both the customer side and different energy sectors is considered one of the key solutions to achieve the Danish renewable target. The conventional design philosophy applied in power systems to activate resource sharing, such as establishing cross-border interconnections between different power systems<sup>[70]</sup> is therefore highly enriched by these emerging initiatives. Further, both subjects to a great degree reflect how different technological solutions and business initiatives can be synergized to generate add-on values, which is another core value of energy internet.

However, to have a clear multidisciplinary approach that mirrors the envisaged integration of a wide range of solutions across different energy sectors taking all constraints and interactions remains a very challenging task. In addition, open questions related to standardization and interoperability, ICT security, uncertainties of new technologies, lack of regulatory support, risk for customer acceptance and developing new business models for different stakeholders etc., require persistent effort globally.

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尤石

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作者简介：

尤石(1981)，博士，研究员，主要从事分布式能源接入与控制，基于市场的主动配电网及多能源系统的规划和运行等领域的研究工作；

林今(1985)，博士，主要从事新能源接入与控制、分布式能源接入与控制以及电力系统优化与控制领域的研究工作；

胡俊杰(1986)，博士后，主要研究领域包括电动汽车和光伏在主动配电网中的优化调度与控制等；

宗毅(1971)，高级研究员，主要从事分布式能源系统的智能控制以及灵活性等领域的研究；

Henrik W. BINDNER(1964)，高级研究员，主要从事风电并网，智能电网中通信，控制，控制系统架构设计和运行，以及以高可再生能源渗透率为前提的独立电网等领域的研究。

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