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The effectiveness of storage and relocation options in renewable energy systems

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Abstract

Across the world, energy planners and transmission system operators are faced with decisions on how to deal with challenges associated with high penetration levels of intermittent energy resources and combined heat and power (CHP). At the same time, distributed plant operators are eager to reduce uncertainties related to fuel and electricity price fluctuations. These interests meet-up for options in distributed supply that introduces the principle of storage and relocation, typically by integrating heat pumps (HP) or electric boilers (EBs) into the operational strategies of existing CHP plants. This paper introduces the principle of storage and relocation by energy system design, and proposes for the storage and relocation potential of a technology option to be found by comparing options by their storage and relocation coefficient R_c, defined as the statistical correlation between net electricity exchange between plant and grid, and the electricity demand minus intermittent renewable electricity production. Detailed operational analyses made for various CHP options within the West Danish energy system, point to the concepts of CHP-HP and CHP-HP cold storage for effectively increasing energy system flexibility. For CHP-HP cold storage, R_c increases from 0.518 to 0.547, while the plant's fuel efficiency increases from 92.0% to 97.2%. These findings are discussed within frameworks of renewable energy systems, suggesting principles for 1st, 2nd, and 3rd generation system designs.

Keywords: Renewable energy system design; Storage and relocation; High penetration levels of intermittent resources and CHP; Large-scale heat pumps; CHP-HP cold storage

1. Introduction

The bright future of intermittent energy resources rests on successfully increasing energy system flexibility. System flexibility may be increased by introducing storage and relocation options such as electrical energy storage facilities [1], pumped hydro storage [2], hydrogen production and storage [3], compressed air energy storage and biomass gasification [4], vehicle-to-grid systems [5], or as in focus of this paper, by integrating large-scale heat pumps (HP) with combined heat and power (CHP) plants. But how are such options compared with respect to technical and economic effectiveness? On the basis of assessments of various CHP concepts [6,7], this paper introduces a method for assessing a technology option's storage and relocation effectiveness, i.e. its effectiveness in providing greater system flexibility. Furthermore a method for assessing the economic cost-effectiveness of these options is introduced.

In support of high penetration levels of intermittent wind power into the energy system, the Danish Ministry of Finance (MoF) recommended in February 2003 that a cost-effective climate strategy for Denmark should be based not only on the continued build-up of wind power capacity, but also the build-up in parallel of large-scale heat pump projects by which system flexibility is introduced. MoF's initial assessments suggested a potential of 1.5 million tons of CO_2 per year from 2012 at an economic CO_2 shadow cost of €-8 per tons of CO_2 for large-scale HP integrated with existing decentralized CHP plants, and 5.0 million tons of CO_2 per year at an economic CO_2 shadow cost of €34 when integrated with existing centralized CHP

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Nomenclature

1G system	1st generation sustainable energy system
2G system	2nd generation sustainable energy system
3G system	3rd generation sustainable energy system
Bt	economic benefits in year t
CHP	combined heat and power
CHP-HP	CHP plant with heat pump
CHP-HP-CS	CHP plant with heat pump and cold storage
COP	coefficient of performance
Ct	economic costs in year t
d	electricity demand minus intermittent renewable energy production (positive for net demand, negative for excess supply)
d_m	mean of d
e	net electricity production (positive for production, negative for consumption)
EB	electric boiler unit
e_m	mean of e
HP	heat pump unit
P_{R_c}	economic R_c shadow cost
quad-generation	combined generation of heat, power, cooling, and liquid or gaseous fuels
r	economic discount rate
R_c	storage and relocation coefficient
R_{c_t}	relocation coefficient in year t
t	year of operation
T	planning period
tri-generation	combined generation of heat, power, and cooling
TSO	transmission system operator
η	plant-level operational fuel to energy efficiency

plants [8], i.e. a combined CO_2 reduction potential of 6.5 million ton per year or about 13% of total CO_2 emissions from Denmark's energy sector in 2002.

The techno-economic appropriateness of a strategy that combines wind power, CHP, and HP, is established by energy system research [9–15], concluding that the introduction of large-scale HP is a feasible option that may effectively be supporting an energy system with fluctuating electricity supply, in particular supporting high penetration levels of CHP and wind power. In 2006, such conclusion is supported for further action by analyses made by the Danish Board of Technology [16] and the Danish Engineering Society [17], and in December 2006, Energinet.dk, the Danish TSO, announced awarding Aalborg University, EMD International, and the Danish Technology Institute €1.5 million for a full-scale demonstration project that will explore further the techno-economic feasibility of integrating a large-scale HP with an existing decentralized CHP plant. The HP is a compression heat pump that uses CO_2 for working fluid in a transcritical cycle allowing for output temperatures that are suitable for district heating purposes.

The integration of large-scale HP with existing CHP plants introduces the principle of relocation into the energy system and provides a means for better balancing distributed generation and wind power. The term "relocation" is used to represent the bridging of energy carriers in 2nd generation renewable energy systems, allowing for advanced optimization of energy system carrier locuses under given constraints. The integration of a large-scale HP with an existing CHP-plant provides a key example of a relocation technology. The availability of a HP enables system operators to opt for a distributed generator to use electricity for heat production, rather than producing electricity due to heat production. The option for producing heat to thermal storage results in de-facto relocation of energy resources without interfering with energy services. The principle of relocation is illustrated in Fig. 6. The paper introduces new metrics for comparing options with respect to their ability to support intermittency.

2. The evolving renewable energy system

While a pre-sustainability energy system is characterized by separating the conventional fuel-based production of heat and power (Fig. 1), a 1st generation renewable energy system (1G) is characterized by the introduction of intermittent resources and co-generation (Fig. 2). For both designs, primary system components may be grouped within four categories: resources, conversion, exchange, and demand.

For a 1G system, intermittent resources and CHP are initially identified by low-capacity factors, i.e. the dispatchable capacity available to the system operator for balancing services is low, if not zero. Grid authorities are well prepared to handle such balancing challenges as these fluctuations show similarities to fluctuations in electricity demand, and for small-scale penetration of wind power and CHP, few practical problems arise and fundamental energy system design modifications are not required. However, for high penetration levels of intermittent producers, it is necessary to increase the operational flexibility of the energy system.

The fundamental problem is that the combination of wind power production and distributed CHP production is basically out-of-sync with electricity demand, or vice versa, and that distributed CHP producers are not able readily to provide the required balancing services due to heat supply constraints.

Fig. 3 illustrates the extent to which wind power production deviates from electricity demand. For 2006, a negative deviation occurs for 6753 h, no deviation occurs for 90 h, while a positive deviation occurs for 1917 h. The

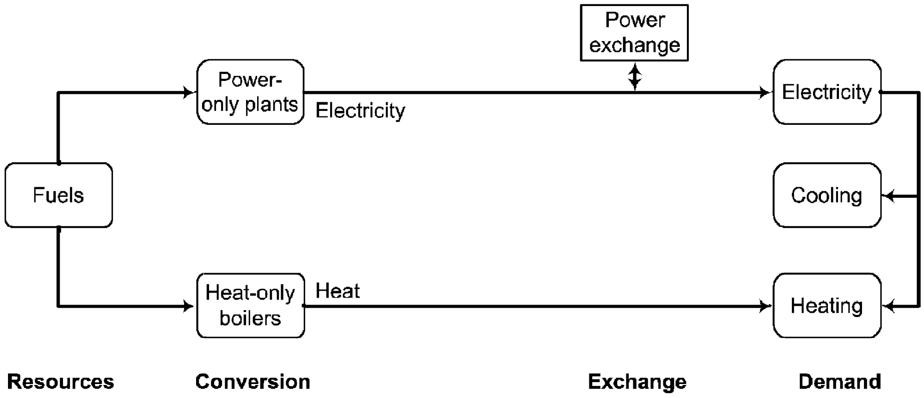

Fig. 1. Pre-sustainability energy system.

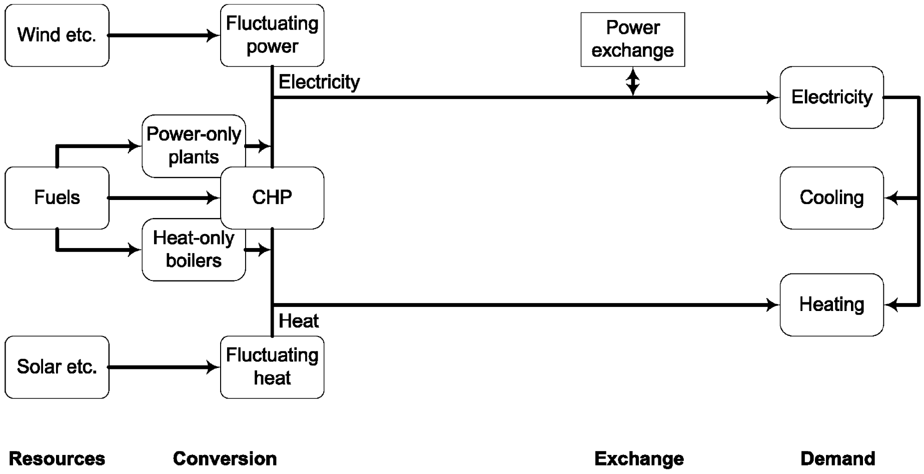

Fig. 2. First generation renewable energy system (1G) introducing intermittent resources and CHP.

overall statistical correlation between electricity demand and wind power production is low at 0.19. The low correlation is not compensated by the typical distributed CHP producer; in fact, the overall statistical correlation between a typical CHP plant's electricity production and electricity demand minus wind power production is 0.518, to be elaborated upon below.

The unreadiness of fluctuating suppliers to provide balancing services contributes to understanding the nature of the serious problem that arose on the night between 31 December 2006 and 1 January 2007 in the Danish electricity system. For the first time, Energinet.dk effectuated an emergency plan to avoid excess electricity production as heavy winds resulted in power production 400 MW above demand and export markets, if unregulated. Initially, Energinet.dk reduced production on large-scale CHP plants according to bids in the down-regulating markets. Subsequently, export capacities to Norway, Germany, and Sweden were fully utilized, and while this was still not sufficient, Energinet.dk requested small-scale CHP plants to stop production. These requests were distributed using personal SMS-messages to plant operators. This latter action reduced power production further by 100 MW, which was still not sufficient and it became necessary for Energinet.dk to force 200 MW of land-based wind turbines to a stand-still for about 10 h. While such emergency plan for critical excess has been in existence for years, this was the very first time that it was executed, indicating that system flexibility is urgently required [18].

Critical techno-economic events and low statistical correlation between fluctuating suppliers and electricity demand are key challenges in a 1G system and something that is deeply embodied in electricity markets. Fig. 4 illustrates that periods of decreasing wind production drives up spot market prices. For example, on Wednesday morning, 10 January 2007, between 6 a.m. and 8 a.m., wind production came close to a weekly minimum, which drove spot market prices to a weekly maximum. Such relationship is also clearly indicated for Monday afternoon, Saturday afternoon, and for mid-day Sunday. Similarly, periods of increasing wind production drive down spot market prices. For example, on Tuesday midday till late evening, high wind production kept spot market prices low during peak demand. This relationship is also clearly indicated for Monday morning, Friday morning, for the

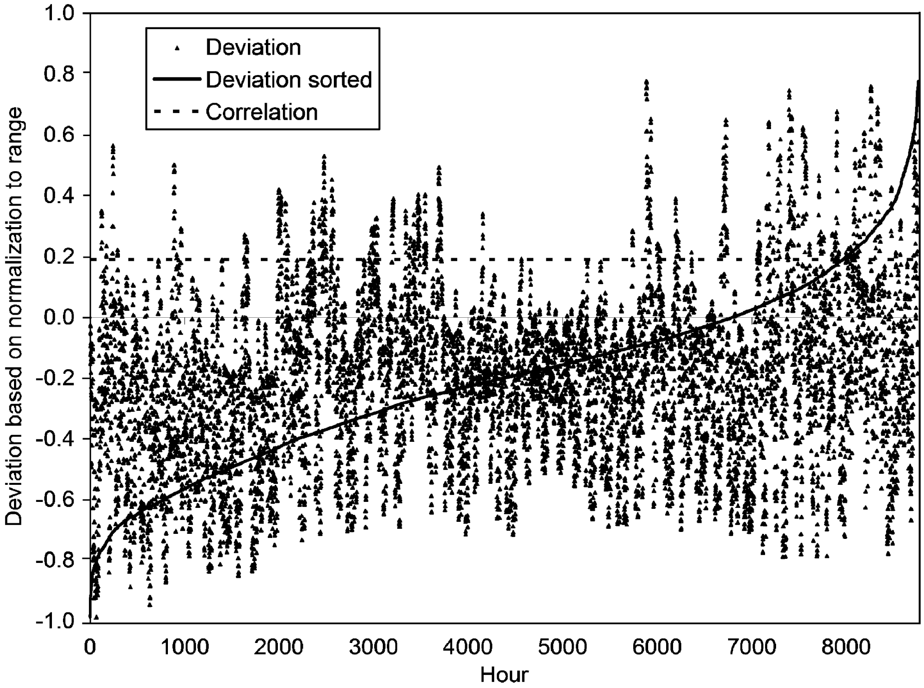

Fig. 3. Hourly deviation between wind power production and electricity demand normalized to maximum values for 2006 in the West Danish electricity system. A negative deviation of −1 says that wind production is at its annual minimum, while electricity demand is at its annual peak. A positive deviation of 1 says that wind production is at its annual maximum, while electricity demand is at its annual minimum.

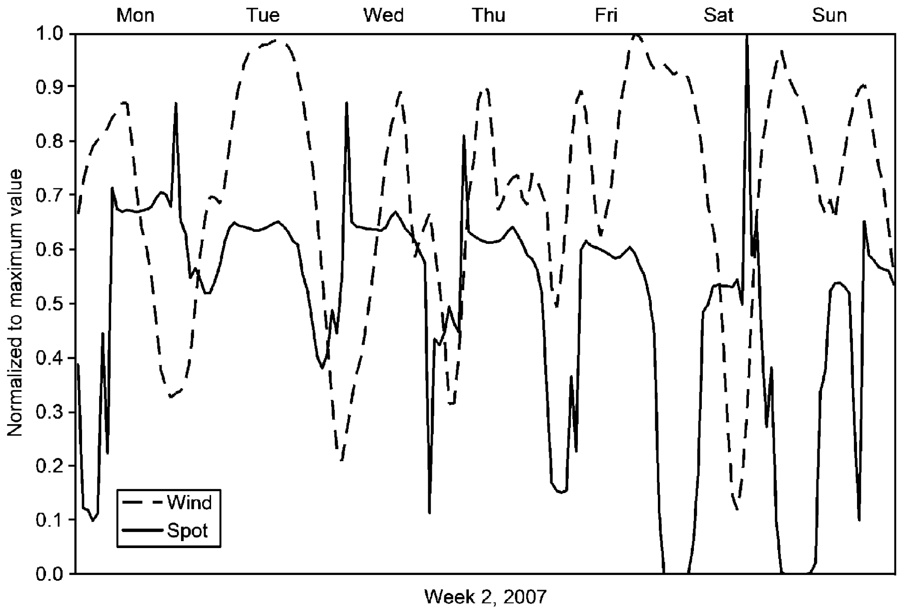

Fig. 4. Normalized spot market prices and wind production for Week 2, 2007.

night between Friday and Saturday, and for the night between Saturday and Sunday. In 2006, the correlation between spot market prices and wind power production was medium at −0.30, indicating that as wind production goes up or down, spot market prices are rather likely to take the opposite direction. Fig. 5 illustrates that spot markets react to wind production as a negative demand. While the correlation coefficient for electricity demand and spot market prices is high at 0.55, indicating that as demand goes up or down, spot market prices are very likely to take a similar direction; the correlation coefficient for electricity demand minus wind production and spot market prices is significantly higher, 0.67 for week 2 in 2007, 0.68 for all of 2006. It appears that electricity demand minus wind production correlates strongly with spot market prices.

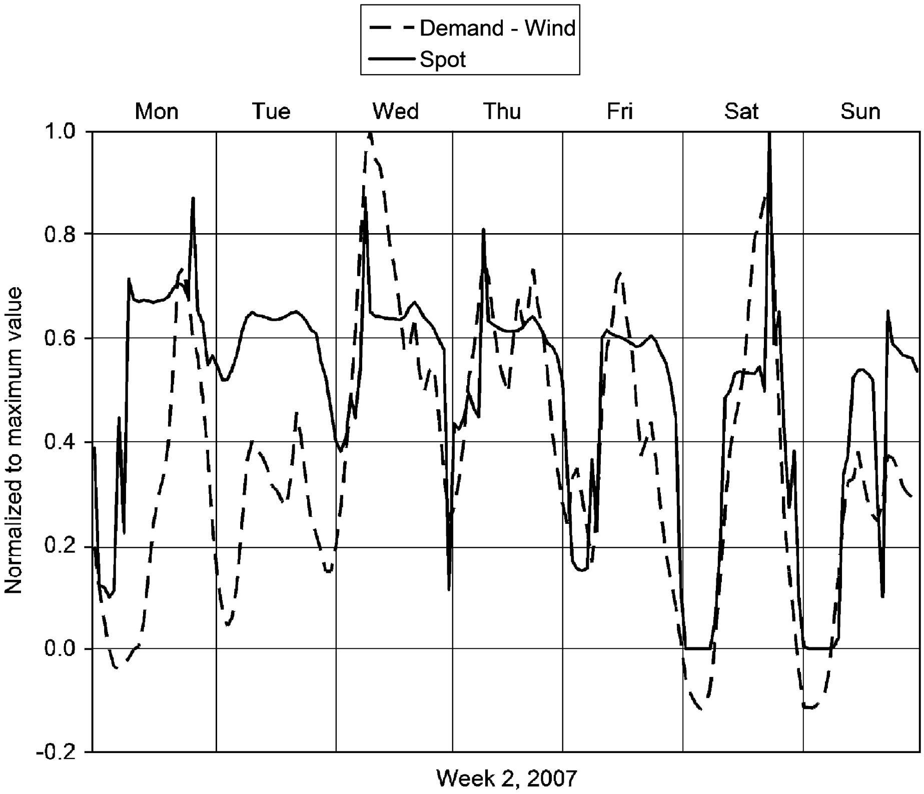

Fig. 5. Normalized spot market prices and electricity demand minus wind production for Week 2, 2007.

The missing flexibility is costly to existing wind turbines owners and is keeping new investors away. When aggregating spot market impacts on an hourly basis for 2006, it appears that Danish wind turbine owners received 8% less for electricity compared to an average producer's income, potentially loosing out on €17 million in annual income from spot market trading. This is partially the reason for the erection of new wind turbines is at a standstill, adding only nine wind turbines (or 12 MW) in 2006, down from 642 MW in 2000 [19].

While off-shore wind farms and new distributed CHP plants are still favoured long-term Danish policy options [20], projections show significant increases in excess electricity supply towards 2015 [21]. This situation is a key policy challenge in the continued move towards renewable energy. What are the options for increasing system flexibility in order to solve balancing problems, while further stimulating the introduction of wind power and CHP?

In 2001, considering various flexible demand options, storage options, infrastructural and interconnection options, the Danish Energy Authority emphasized the cost-effectiveness of introducing thermal storages and large-scale HP to allow for more flexible and system-responsive CHP production modes [22]. This recommendation pointed towards an innovation in renewable energy system design, the principle of relocation, and the 2nd generation renewable energy system (2G).

3. The principle of relocation

A relocation technology introduces flexibility by bridging energy carriers. Fig. 6 illustrates the inclusion of relocation as a fifth system category, introducing the 2G system. An electric boiler (EB) provides simple relocation of electricity to heat. An electric-drive compression HP provides efficient relocation of electricity to both heat and cooling [23].

The conceptual operational modes of relocation for a CHP-HP plant are as follows. In a situation with high wind production, or similar intermittent power generation, spot market prices on electricity drop, stimulating CHP plants to replace co-production of heat and power with purchase of electricity for heat and/or cooling production, possibly producing for thermal storage. The challenge in this situation is maintaining a high coefficient of performance (COP) for the HP. In situations with medium wind production, co-generators and HP may possibly run concurrently, obtaining state-of-the-art plant-level fuel efficiencies in energy conversion for electricity, heat, and cooling. In situations with no wind production, spot market prices on electricity rise, co-generators are stimulated to increase electricity production without HP, minimizing heat production, possibly utilizing stored heat from thermal storage. The challenge in this situation is maintaining high fuel conversion efficiencies.

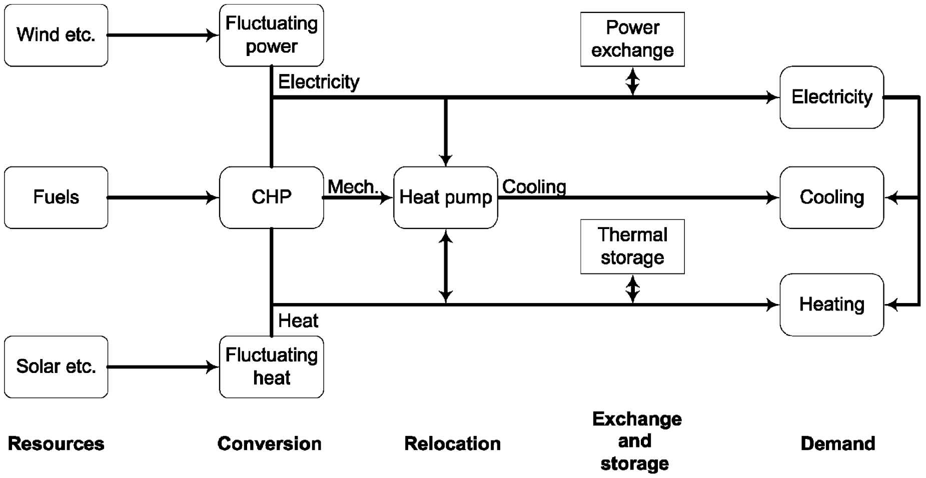

Fig. 6. Second generation renewable energy system (2G) introducing relocation and thermal storage for added operational flexibility.

Integrating an EB or a HP with a distributed CHP plant increases the operational flexibility of the plant, better enabling the delivery of balancing services reflected by electricity markets, including spot markets, upwards and downwards regulating markets, and reserve capacity markets.

4. The relocation coefficient and relocation cost-effectiveness

For the purpose of comparing the potential of storage and relocation options for introducing system flexibility, we will define the storage and relocation coefficient R_c as the statistical correlation between net electricity exchange between plant and system (e), and the electricity demand minus intermittent electricity production (d):

$$R_c = \frac{\sum(e - e_m)(d - d_m)}{\sqrt{\sum(e - e_m)^2 \sum(d - d_m)^2}} \tag{1}$$

The higher the coefficient, the better a plant operates according to system requirements, thereby providing evidence of whether an option supports the introduction of greater system flexibility. As it was previously found that a high statistical correlation exists between spot market prices and minus intermittent electricity production, here wind power, it is indicated that by navigating in spot markets for electricity, coefficients as high as 0.68 for distributed CHP plants may be achieved when operating on market conditions in the West Danish energy system.

For the purpose of assessing the cost-effectiveness of storage and relocation options, we will define the storage and relocation shadow cost P_{R_c} as the economic costs associated with increasing R_c by 1%-point, as given by the economic net present value of a given option compared to the reference divided by the net present value of the change in R_c:

$$P_{R_c} = \frac{\sum_{t=1}^{T}(B_t - C_t)/(1+r)^t}{\sum_{t=1}^{T}(\Delta R_{c_t})/(1+r)^t} \tag{2}$$

The unit of P_{R_c} is € per %-point. P_{R_c} is a useful measure for assessing how a policy objective on increasing system flexibility may be cost-effectively met. A relatively lower P_{R_c} provides evidence of cost-effective options for increasing system flexibility.

5. Coefficients and cost-effectiveness for selected relocation options

We have compared R_c and P_{R_c} for three CHP options for which operational strategies have been optimized according to economic costs and benefits operating within the context of the 2006 current West Danish energy system and market.

The Reference Option (CHP) is an existing 3.5 MW_e decentralized natural gas fired CHP plant with thermal storage, typical to 25% of the CHP capacity in Denmark, operating on market conditions. Option A (CHP-HP) adds a large-scale electric-drive compression heat pump for utilization of condensed flue gas allowing for the fuel-efficient concurrent operation of CHP unit and HP unit. Option B (CHP-HP-CS) furthermore adds a “cold storage” to allow for the storage of low-temperature heat recovered from condensed flue gasses, thereby allowing for independent operation of CHP unit and HP unit. These innovative CHP-HP concepts are introduced and assessed further by Blarke and co-workers in Refs. [6,7].

The low-temperature heat source for both CHP-HP options is recovered heat from cooling and condensation of flue gasses from 60 to 30 °C. This relatively high-temperature level heat source allows for the HP unit to reach a COP of 3.7 [24]. The HP unit applies a transcritical cycle process using CO_2 as working fluid allowing for delivery temperatures up to 90 °C, which is suitable for district heating delivery or production to thermal storage. For Option A, the HP unit may only be operated concurrently with the CHP unit, but may be disengaged whenever feasible according to operational short-term marginal costs. For Option B, the HP unit may be operated both concurrently and independently of the CHP unit under constraint of a 250 m^3 cold storage.

On the basis of optimized economic operational strategies for each option under given constraints, Fig. 7 illustrates the deviations between selected options' net electricity exchange (selling and buying) and the system's electricity demand minus wind production. We found that R_c increases from 0.518 for the Reference Option to 0.547 for Option B, thereby sustaining that the CHP-HP-CS concept increases system flexibility by allowing the distributed CHP plant to operate in better accordance with fluctuating electricity supply and demand.

As summarized in Table 1, we find that R_c as well as plant-level fuel efficiency η significantly increases by adding a HP, and that the introduction of a cold storage allowing for independent operation of the CHP unit and the HP unit leads to further increases. As levelized economic heat production costs increases by about 5% for both Options A and B compared to the Reference Option, P_{R_c} amounts to €11.4–13.3 million per %-point, lowest for Option B.

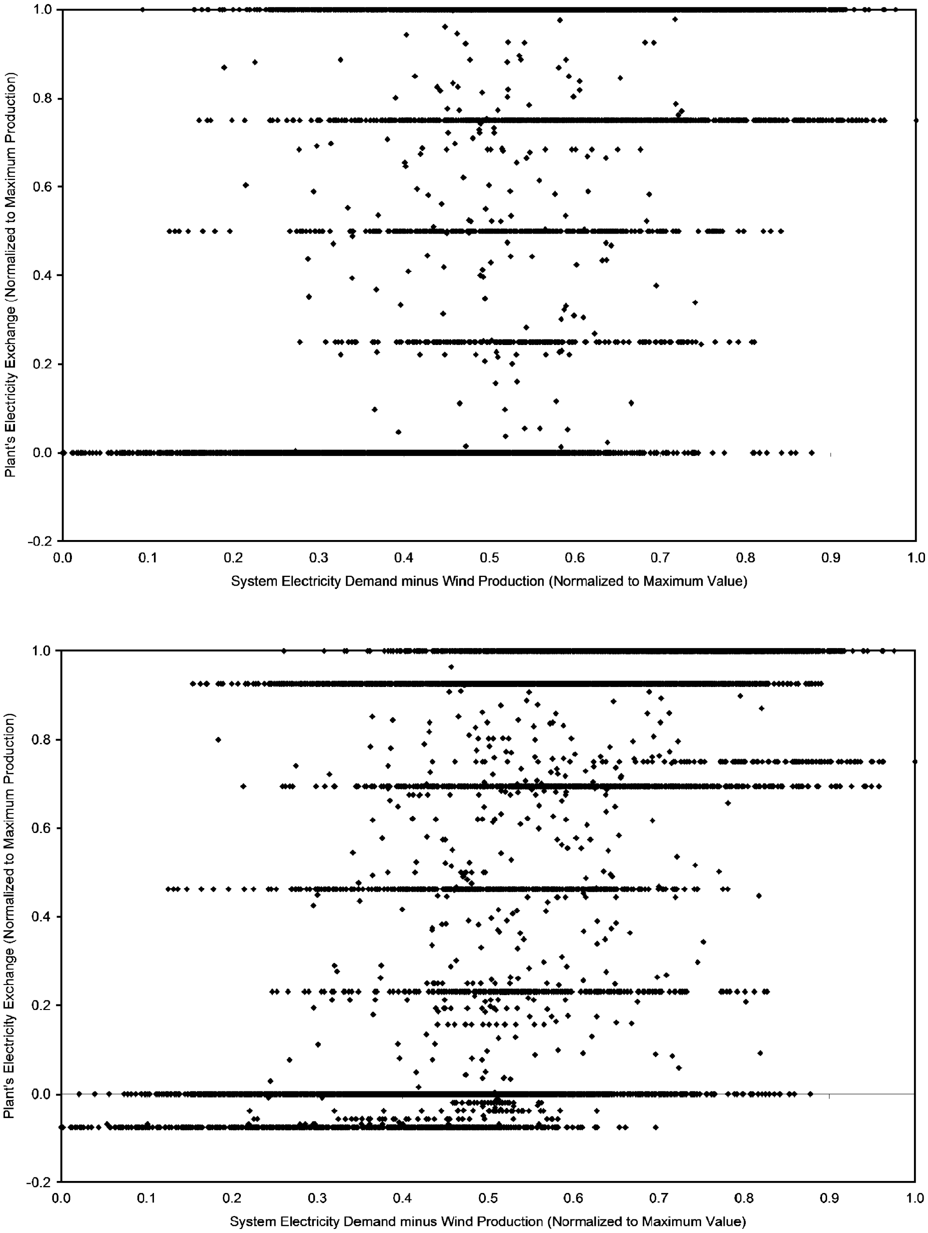

Fig. 7. Hourly deviation between plant's net electricity exchange with system and electricity demand minus wind production. *Top*: Reference Option (CHP). *Bottom*: Option B (CHP-HP-CS).

6. Conclusion and renewable energy system design perspectives

The current 1G energy system with increasing shares of electricity supplied by wind power and CHP poses challenges to TSOs, policy makers, and investors alike, as existing system designs do not sufficiently provide the necessary operational flexibility. In a 2G system, the principle of storage and relocation is introduced by which flexible operational strategies of distributed generators become better synchronized with system requirements. The effectiveness of a particular storage and relocation technology to increase system flexibility is usefully expressed by its storage and relocation coefficient R_c, defined as the statistical correlation between net electricity exchange between relocation technology and system, and the electricity demand minus intermittent renewable energy production. The storage and relocation shadow cost P_{R_c} is useful for identifying the economic cost-effectiveness of thus increasing system flexibility, by relating comparative net costs and benefits to storage and relocation coefficient increases. It is suggested that the proposed methods may assist researchers and policy makers in comparing the effectiveness of storage and relocation options, such as electrical energy storage facilities, pumped hydro storage, hydrogen production and storage, compressed air energy storage and biomass gasification, and vehicle-to-grid systems.

The application of the methods identifies through detailed operational analyses made for selected CHP-HP options the comparative effectiveness of the CHP-HP-CS concept for which a significantly higher relocation coefficient is reached, and more cost-effectively than for the CHP-HP concept.

With respect to renewable energy system design, the 2G system and the principle of storage and relocation is an important step for further renewable energy system developments. In the future, integrated energy systems and increasing levels of flexibility will be reached by incorporating the demand for mobility, as well as the expansion of co-generation or tri-generation into quad-generation, i.e. adding the facility to produce and store secondary fuels, such as hydrogen or ethanol, from primarily fuels, mainly electricity or waste. Fig. 8 illustrates these principles with the framework of the 3rd generation renewable energy system (3G).

Table 1
Plant fuel efficiencies, relocation coefficients and shadow costs for selected CHP options analyzed within the current West Danish energy system

Case	η (%)	R_c	P_{R_c} (million, € per %-point)
Reference option (CHP)	92.0	0.518	–
Option A (CHP-HP)	96.3	0.540	13.3
Option B (CHP-HP-CS)	97.2	0.547	11.4

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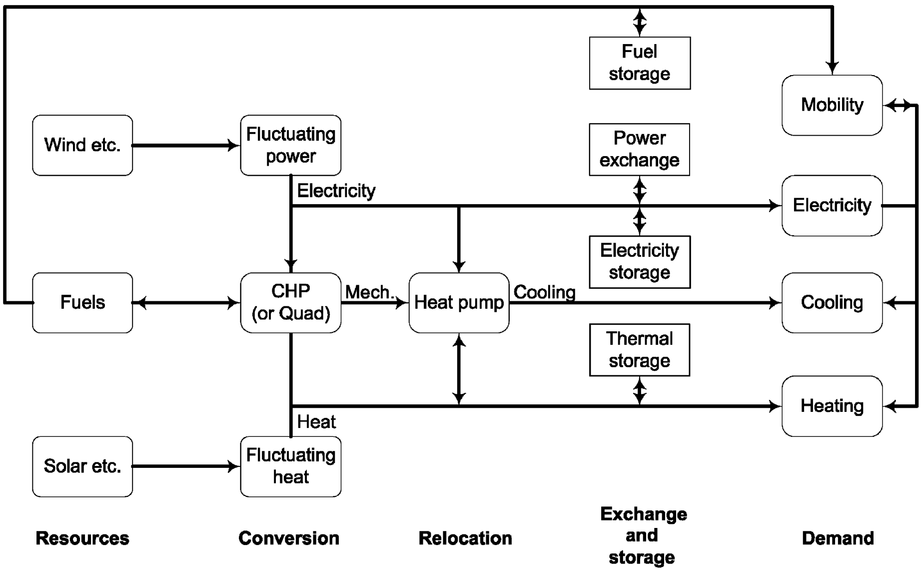

Fig. 8. Third generation renewable energy system (3G) incorporating mobility demand, and introducing electricity storage, and quad-generation for added operational flexibility.

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