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A collection of SWOT factors (strength, weaknesses, opportunities and threats) for hybrid energy networks

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Abstract

District heating and cooling (DHC) systems traditionally have strong links to electricity and gas networks via combined heat and power (CHP) processes. However, the role of CHP plants will significantly change due to a growing competition for renewable fuels and an increasing share of renewable electricity production. Consequently, other heat sources will be needed for DHC networks in the future. Here, especially heat pumps will play a major role, but also power-to-gas processes can contribute via recovering its waste heat, thus creating different coupling points between the DHC, electricity and gas system. By an optimized planning and operation of locally available coupling points a "hybrid energy network" (HEN) can be created.

To analyze the strengths, weaknesses, opportunities, and threats (SWOT analysis) of hybrid energy systems, a three-stage process is being conducted based on a literature search, qualitative input from experts during a dedicated workshop and a comprehensive feedback and discussion phase with experts. Currently, the first two stages of the method have been completed, collecting a wide range of inputs, comments and feedback from the different experts of the IEA ISGAN Annex 6 "Power Transmission and Distribution Systems" and the IEA DHC Annex TS3 "Hybrid Energy Networks".

Results: besides a novel classification approach for Hybrid Energy Networks, different SWOT factors were collected, e.g. strengths include the potential to cost-efficiently support the integration of Wind and PV electricity as well as to decarbonize heating and cooling demands. Weaknesses include their complexity, the required investments into coupling points and (current) regulatory restrictions. Opportunities include by trend increasing incentives for flexibility and efficiency services, upcoming (green) financing options and regulations. Threats include possible disruptions of existing business models and uncertainties of the future development including the regulatory framework as well as competing flexibility services.

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1. Introduction

1.1. Sector integration and the role of DHC networks

Coupling the electricity and gas sector together with a closer integration with other sectors, i.e., transport, heating & cooling and industry, is considered one of the key measures for decarbonizing the energy system. It is referred to as "sector coupling", "sector integration", "smart energy system" or "hybrid energy system".

District heating and cooling (DHC) networks are traditionally linking the heating & cooling sector to the electricity and often also to the gas sector through widespread combined heat and power (CHP) plants. However, the role of CHP plants will significantly change in the future since decarbonization will make the use of fossil fuels impossible, and for renewable fuels, there will be a growing competition with hard-to-decarbonize sectors such as air transport and certain industrial processes. Further on, an increasing share of renewable electricity production from hydro, wind and photovoltaics (PV) will drastically reduce the amount of electricity produced from CHP plants. Consequently, other heat (and cold) sources will be needed for covering the heat (and cold) demand in DHC networks in the future; as well as other coupling points will be needed in order to provide flexibility between the different sectors.

1.2. Relevant sector coupling technologies

Alternative heat sources for DHC networks such as waste heat from industrial processes, the service sector (e.g. cooling of data centers or tertiary buildings) and urban infrastructures (e.g. sewage channels), ambient heat (e.g. ground water), solar thermal and geothermal energy usually have a lower temperature level than traditional DHC networks. Their utilization in existing DHC networks can only be done either by a reduction of the network temperature levels [e.g. 1,2] or by the installation of heat pumps (HP). The later is "upgrading" thermal energy from the alternative heat source to the temperature level of the DHC network by using a high exergetic driving energy. On one hand, this can be done by high temperature fluids (via ad- or absorption processes) or combustion processes [3].

However, the most common HPs are electricity driven **compression HPs** that at the same time create an important coupling point to the electricity network: a so-called power-to-heat (PtH) unit. They have a very high conversion efficiency (typically about 300%, considering the heat source "added" to the driving electricity), with a high dependency of the efficiency on the temperature lift between heat sink and source (the lower, the better).

Another power-to-heat unit are **electric boilers** (eBs) directly transform electricity into heat with an efficiency of close to 100%. They have very low specific investment costs compared to HPs and enable generation of heat at very high temperatures and very fast heating gradients. EBs typically are used for applications with limited operating hours (e.g. short-term electricity market participation, see [4]).

Another important coupling point are **power-to-gas** (PtG) processes, i.e. electrolysis creating hydrogen (and subsequent processing if required); that can be used in **CHP plants** and subsequent use of the waste heat in DHC networks (e.g. [5]). However, such fuels should be preferably used in hard-to-decarbonize sectors such as industry and aviation (e.g. [6]). On the other hand, the PtG process itself generate significant amounts of **waste heat**, that can be recovered in DHC networks (e.g. [7,8]). As a consequence, a more accurate term would be power-to-gas&heat (PtG&H).

1.3. Aim of the Study: a SWOT analysis of hybrid energy networks

In the framework of this study, a "hybrid energy network" is a highly integrated DHC and electrical network, considering also but not focusing on linkages to the gas network using the above-named coupling points. In order to capture the multitude of coupling points and integration options, a SWOT analyses was performed. A SWOT analysis is a strategic method to identify internal factors (strengths and weaknesses) and external factors (opportunities and threats) favorable and unfavorable to achieve a specific objective or to assess any kind of business case. SWOT assessments in combination with empirical surveys are frequently used to summarize and classify heterogeneous views of experts. They are especially valuable for topics with insufficient knowledge, lack of historical data, or lack of consensus found within the studied field. In this context, the following aspects are analyzed:

- Strengths: characteristics of Hybrid Energy Networks that give an advantage over individual networks.
- Weaknesses: characteristics of Hybrid Energy Networks that give a disadvantage relative to individual networks.
- Opportunities: elements in the environment that Hybrid Energy Networks could exploit to their advantage.
- Threats: elements in the environment that could cause trouble for Hybrid Energy Networks.

The SWOT analysis aims at supporting the general understanding of the properties and characteristics of a Hybrid Energy Network, considering different viewpoints, e.g., the overall energy system, electricity and DHC network, etc., and thus making an attempt to be an intermediate and facilitator between the different stakeholders.

1.4. Previous SWOT assessments on individual technologies and aspects of HEN

Multiple such assessments related to developments in the field of energy were recently published:

Schweiger et al. [9] analyzed SWOT factors of 4th generation district heating. To this end, they paired a SWOT analysis with the multicriteria decision-making technique called Analytic Hierarchy Process (AHP). A two-stage expert survey was conducted to first establish a list of main SWOT factors that were then in a second stage weighted according to their relative importance as perceived by the involved experts. Results of the qualitative assessment show that SWOT factors with the highest relative importance include the ability of 4GDH to serve as a label bundling and the increased value creation within the national economy through the inclusion of local, renewable energy sources.

Skov et al. [10] assessed SWOT factors for power-to-X technologies in the Danish context. They also applied a SWOT-AHP analysis method. Results show that academic experts indicate strengths as the most important category while practitioners' opportunities. All experts consider Denmark as being a power-to-X knowledge hub as one of the most important factors and a substantial opportunity for power-to-X success.

A comprehensive analysis of SWOT factors for hybrid energy networks is still missing but could act as intermediary between the different views of stakeholders.

2. Method

2.1. Expert involvement methodology

To analyze the strengths, weaknesses, opportunities, and threats of hybrid energy systems, a three-stage process to structure and guide expert involvement is being conducted.

- **First**, a preliminary list of SWOT factors was collected employing a literature search, including qualitative input from experts during a dedicated workshop meeting.
- In the **second** stage, a comprehensive discussion phase with experts took place to add, discuss, clarify and classify SWOT factors. During this process experts were able to comment on existing factors, add additional ones and exchange ideas and concerns to help in clarification and classification of SWOT factors. This stage also involved direct stakeholder interviews.
- The **third** and last stage (not yet carried out) will consist of a qualitative survey using the Analytic Hierarchy Process method to assess the relative importance of SWOT factors.

2.2. Background and involved experts

The first two stages of the SWOT analyses were initiated by an international cooperation between the IEA ISGAN Annex 6 "Power Transmission and Distribution Systems" and the IEA DHC Annex TS3 "Hybrid Energy Networks".

- The IEA International Smart Grid Action Network (ISGAN) supports the accelerated development and deployment of smarter, cleaner electricity grids around the world. **IEA ISGAN Annex 6 "Power Transmission and Distribution Systems"** [11] focuses on the potential system-related challenges in the development of future smarter grids, including technologies, market aspects, and policies. The Annex's main goal is to facilitate the application of advanced technologies that enable power grids to maintain and improve the security, reliability and quality of electric power supply.

- The IEA Technology Cooperation Programme on District Heating and Cooling (DHC) including Combined Heat and Power (CHP), is dedicated to make DHC and CHP powerful tools for energy conservation and the reduction of environmental impacts of supplying heat. The aim of the **IEA DHC Annex TS3 "hybrid energy networks"** [12] is to promote opportunities and to overcome challenges for DHC networks in an integrated energy system context from a technical and strategical point of view, focusing on the coupling to electricity networks.

The heterogeneous backgrounds of the IEA DHC Annex TS3 and ISGAN Annex 6, i.e., from academia as well as industry, is an ideal setting for this study.

3. Preliminary results

Currently, the first two stages of the method have been completed, collecting a wide range of inputs, comments and feedback from the different experts.

3.1. A classification approach for Hybrid Energy Networks

One of the first fundamental discussion points was the actual definition of a hybrid energy network, since the above-mentioned coupling points can exhibit different integration levels, i.e. starting from traditional DHC networks, that already integrate the electricity and the gas network via CHP plants, up to the concept of the 4th generation networks from Lund et al. [13] and even 5th generation networks, described e.g. in Buffa et al. [14].

In order to allocate the different technology options such as coupling points, as well as the connected business models and strategies in the framework of a highly integrate energy system and to differentiate the levels of energy system integration, a classification approach of a Hybrid Energy Network was developed as a basis for the SWOT analyses, see Fig. 1. This classification differs from the concept of the 4th generation of DHC networks from Lund et al. [13], since the main characteristic of a Hybrid Energy Network is the integration between the different networks, and not the supply temperature or the time period where the different generations were dominating. I.e. a newly setup 4th generation DHC network can be realized with minimum system integration and a constantly adapted 2nd or 3rd generation DHC network can be a highly integrated solution in the overall energy system.

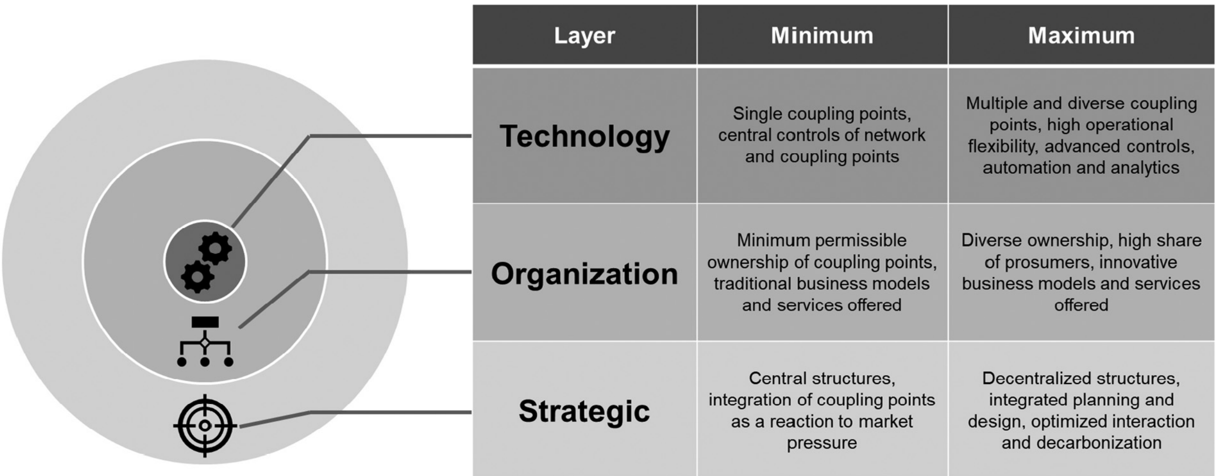

Fig. 1. Classification of hybrid energy networks based on different levels of systems integration.

Considering the setup of Fig. 1, the requirements for a "minimum" integrated Hybrid Energy Network are quite low and many cases fall under this category. In contrast, a "maximum" integrated Hybrid Energy Network is more difficult to reach and far beyond the state-of-the-art. In practice, different intermediate variants of Hybrid Energy Networks can be identified and the individual gaps in each category indicate potentials for improvement. However, the level of system integration does not necessarily correlate with system and/or cost efficiency due to the increasing complexity.

3.2. Identified SWOT factors

Based on the classification in 3.1, a comprehensive number of SWOT-factors for Hybrid Energy Networks with increasing levels of systems integration have been collected.

3.2.1. Strengths

(a) A **higher degree of freedom for planning and operation** of the energy system, including multiple options for energy transformation and storage, i.e.

- PtH plants can make low temperature heat sources such as ambient heat and waste heat as well as cost-efficient thermal storage capacities available;
- PtG can be used if high quality energy is required and the waste heat can be utilized and CHPs to make best use of available renewable fuels for heating and electricity compared to using them for generating either heat or electricity alone. If cost-efficient gas storages are available (e.g. geological cavities) they allow very cost-efficient long-term (i.e. seasonal) storage and could make renewable fuel available in times with limited availability of renewable electricity from hydro, PV or wind
- CHP plants generate both high temperature heat for DHC networks and electricity for grid supply or ancillary services, thus can use renewable fuels with a very high system efficiency

(b) A high level of **security of supply and system stability** due to multiple and distributed options for covering energy demand between the networks in combination with storages on different time scales

(c) A higher level of **system flexibility** enables one to

- manage and mitigate temporal imbalances of intermittent electricity production and demand
- support the containment and restoration of the system frequency
- the maintenance of the voltage levels
- reduce internal portfolio imbalances and thereby minimize imbalance costs
- levelized electricity market prices

(d) Options for innovative and adapted **business models and new revenue streams** including new services (e.g. ancillary services), increasing the self-sufficiency by maximizing own consumption; optimize the revenues from participation in different energy markets

(e) An increased **economic added value** i.e. by creating jobs due to the investment in coupling points

(f) The options to **counteract limitations of the electricity network transfer capacity** and thus to avoid investments into grid reinforcement by

- local utilization of excess electricity (e.g. by PtH or PtG units) from additional deployment of local intermittent renewable electricity production capacities (e.g. repowering of existing wind farms) exceeding the network transfer capacity
- local supply in case of electricity shortage (e.g. by CHP plants) in the case of significantly increasing number of consumers (e.g. large-scale roll-out of electric vehicles) exceeding the network transfer capacity

(g) A **reduction of electricity grid losses** by maximizing local consumption of (renewable) electricity sources instead of transporting the electricity to remote demand locations

(h) A **decarbonization and diversification of the DHC networks**, if using renewable electricity and thus to increase the stability in operation of the heating (and cooling) plants, the fuel supply security, system resilience and to reduce back-up requirements

(i) The option to efficiently **manage various levels of temperatures,** i.e. low temperature heat sources by using (booster) HPs and/or eBs for (locally) adapting the temperature level

3.2.2. Weaknesses

(a) An increasing level of system integration results in an **increasing level of complexity** for planning, designing and operating, due to a higher number of optimization parameters and stakeholders involved. This is including the risk of a high interdependency of the different sub-systems, thus a disturbance in one domain might affect the other negatively

(b) Once electricity is transformed into heat, **the re-conversion into electricity** (Heat-to-Power, HtP) has a very low round trip efficiency and can only be cost-efficient at high temperatures.
(c) The requirement of **additional investments** into coupling points
(d) A highly integrated and interdependent system offers multiple gateways for attacks thus resulting in a **threat to cybersecurity**
(e) Present **electricity tariffs and taxes** are a barriers to exploiting the potential of hybrid energy networks
(f) electricity grid operators currently have **regulatory restrictions** (mainly due to unbundling) for

- the co-optimizing the distribution and generation of energy
- investment and ownership into coupling points
- accessing the flexibility in the DHC network

(g) **price signals** provided by the wholesale markets for electricity in Europe **do not yet take the grid situation** into account, such as localized grid constrains and the location of generation with respect to demand
(h) the **seasonality of the heat (or cold) demand** may lead to price surges on the electricity market
(i) Additional heat (and cold) supply units in the DHC network result in an **increasing supply competition** among each other and to other renewables (e.g. solar- and geothermal energy) especially in summer times
(j) The CO_2 emissions will only decrease if **fossil-free electricity** is used in the PtH processes, however, currently, the electricity mix in many countries is still dominated by fossil fuels and the highest heating peak demand in the coldest periods tend to coincide with low availability of electricity supply from solar
(k) **suitable DHC infrastructures** for efficient sector coupling might not be available or be in a bad condition

3.2.3. Opportunities
(a) An **increased focus on sector integration in research and industry** as well as an increasing number of trainings and education programs
(b) **Digitalization** together with a higher penetration of sensors and other data collectors could open many opportunities in network design and operation
(c) More research and development can lead to **improved performance of coupling points, smart controls and integrated planning and implementation processes**
(d) **Green financing options** and many investors favoring investments into renewable energy projects as well as accepting higher CAPEX and long-term amortization periods.
(e) Current and future **decarbonization incentives and measures** can directly or indirectly support the sector integration
(f) A general **tendency for the transformation of the DHC networks** towards lower temperatures, higher thermal storage capacities as well as decentralized structures support the integration of (decentralized) sector coupling points
(g) **higher shares of (fluctuating) renewable electricity sources** such as wind and PV lead to more incentives for flexibility services and thus support the sector integration
(h) The **European Commission** is acknowledging the role of an integrated energy system and upcoming regulations for energy communities/self-consumption can support sector integration measures

3.2.4. Threats
(a) Silo thinking of many actors and stakeholders and a **possible disruptions of existing business models**;
(b) PtH and PtG units can lead to an **overall higher electricity demand**
(c) Risk of stranded investments in coupling points due to **uncertainties of the future development** of key enabling factors such as

- Political situation, regulatory framework and market design: e.g. subsidies/CO2 pricing; allowed ownership of coupling points; the options to participate in the different electricity markets/the availability of suitable network tariffs;
- The market development in terms of electricity prices as well as the number of alternative flexibility providers (e.g. electric vehicles)/degree of diffusion of coupling points and resulting competition
- medium- and long-term availability of waste heat as a source for HPs from industries or from the service sector that suddenly cease their activity

4. Conclusions and outlook

This study provides first insights into possible strengths, weaknesses, opportunities, and threats for Hybrid Energy Networks. While the first two stages of the methodology include a literature search, qualitative input from experts during a dedicated workshop meeting and a comprehensive discussion phase.

One of the first results was the actual definition of a hybrid energy network, featuring different integration layers (technology, organization and strategic) as well as different levels of integration. Further on, a preliminary list of SWOT factors was collected and presented.

For the qualitative survey of the SWOT factors planned in stage three a broader target group is being considered to possibly include a wide range of policy makers, energy suppliers, network operators, transmission and distribution system operators from IEA DHC members states.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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