Integrated Bioenergy Hybrids

Flexible renewable energy solutions

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Ilkka Hannula, Elina Hakkarainen

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Cover photo: Picture of a hybrid heating system in Løgumkloster (Denmark) consisting of solar thermal collectors, wood chip boiler and hybrid + absorbition heat pumps.

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For more information about this document, please contact:

Ilkka Hannula
Principal Investigator
VTT Technical Research Centre of Finland
ilkka.hannula@vtt.fi

Elina Hakkarainen
Research Scientist
VTT Technical Research Centre of Finland
elina.hakkarainen@vtt.fi

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Summary

The status and potential of *integrated bioenergy hybrids* have been surveyed for Finland, Germany and Austria. In this work, an integrated bioenergy hybrid is defined as an energy conversion process that has at least two energy inputs, one of which is bioenergy. The term RES (renewable energy source) hybrid can also be used if all energy inputs are from renewable sources. The state-of-the-art survey for Finland, Germany and Austria revealed that elements for the implementation of RES hybrids in various sectors are already in place. In addition, region-specific characteristics in terms of configurations, applications and scales of hybrids were identified.

Currently, most hybrid systems are found in the heating sector, particularly in detached houses outside the district heating network. This is mainly due to simple and robust integration of different heat sources and the natural flexibility offered by the integrated system. In domestic heating systems, bioenergy and ground-source heat are typically considered as alternative options for base load production. Depending on the heating behavior of the household, bioenergy can be used either as a base load producer or to complement other heat source(s) during peak demand.

District heating and cooling networks can be considered as large-scale hybrid applications. Bioenergy offers a quick way to increase the share of RES in heat production through these networks, while utilisation of other renewable heat sources enables increased use of bioenergy for other end uses and sectors. Solar thermal is not yet a widely applied technology for district heat production in the surveyed countries, although a large project is currently underway in the city of Graz, Austria. In general, solar thermal could make a significant contribution to the production of district heat during summer periods. Waste heat recovery is a growing trend, which reduces the need for investments in new energy generation capacity.

At farm-scale the availability of and experience with bioenergy offers good preconditions for hybrid systems. Besides increasing the level of self-sufficiency in energy and reducing energy related costs, hybrid systems might also allow additional revenue streams for the farms.

In the power sector, the role of hybrid systems varies depending on the market conditions. In Finland, the role and potential is currently limited due to the rather well established and strong Nordic power grid and the abundance of flexibility options due to access to hydro. In Germany, virtual power plants are an interesting topic, and coupling of biogas and biomethane with hydrogen from wind is currently being demonstrated. In general, bioenergy can have a significant role as a flexible component in a VRE (variable renewable energy) dominated energy system.

Integrated bioenergy hybrid technologies and applications varied between the countries studied, but some general development pathways and trends in market uptake can also be identified. The general status of technologies is summarised in Table 1.

Table 1. Summary on existing and developed bioenergy RES hybrid solutions in case study regions. DH refers to district heating and DC to district cooling.

	Domestic scale	Utility-scale and DH/DC networks	Industry	Farm-scale
On market / Implemented	• Biomass + solar thermal • Biomass + ground-source heat • Biomass + waste heat recovery • Biomass + electric heating • Biomass + DH • Biomass + PV	• Biomass + waste heat recovery • Biomass + passive solar energy	• Biomass + ground-source heat • Biomass + waste heat recovery • Biomass + PV	• Biomass + ground-source heat • Biomass drying • Biomass + PV • Biomass + wind • Biogas production
Ongoing developments	• Two-way DH connection • Optimized control algorithms	• Biomass + solar thermal • Biomass + geothermal • Hydrogen enhanced biofuels • Waste heat utilisation from new sources • Low-temperature grids • Prosumer integration	• Biogas related networks • Hydrogen enhanced biofuels	• Biomass + solar thermal • Liquid biofuel production

In general, the technical potential of integrated bioenergy hybrids can be considered significant as no major limitations have been identified. However, it is difficult to estimate the market potential of RES hybrids as there is no universal way to assess the value of flexibility in isolation from the energy system. So the economic feasibility is always highly case specific. The majority of hybrid concepts currently in the market are focused on domestic heating applications. However, the lack of standardised interfaces between technologies is identified as a disadvantage that leads to additional costs due to the need for extra equipment (e.g. multiple control systems etc.).

An important motivation behind hybrid systems is the possibility to switch between different energy sources in an optimal way. Usually one or more of the following drivers can be expected:

- Increase in self-sufficiency in terms of energy and reliability,
- Reduction in emissions, lower environmental impact,
- Avoided cost of purchase of oil or electricity (especially peak power cost),
- Lower maintenance requirement for biomass or oil boiler,
- Increase in component lifetime and efficiency,
- Optimised dimensioning of system components,
- Avoided investment in storage system (bioenergy is storable) or in new production capacity (waste heat recovery),

- Better waste management and additional incomes in the case of biogas utilization.

Energy storage encompasses a family of diverse technologies, but in the context of bioenergy hybrids two main concepts were identified: 1) biomass drying with VRE and 2) chemical storage of electricity in biofuels via hydrogen. They can be used to complement VRE variability by creating demand during periods of abundance. Chemical storage of electricity in biofuels has also the unique feature among storage technologies that it is not constrained by its system stage, i.e. it never fills up. Due to its comparably high costs, it is likely to be among options that are deployed only after the potential of more cost-effective solutions has been exhausted.

Those hybrid concepts that have already been commercialised in the case study regions would benefit from measures that accelerate technology transfer. An online database for sharing information on best practices and successful case examples could be one measure to facilitate deployment. For emerging and new hybrid technologies further investment in R&D is needed to drive down costs and to increase understanding of the value of hybrids in a VRE dominated energy system.

For additional information, please refer to other related reports and presentations on our project website: http://task41project7.ieabioenergy.com/iea-publications/

Key Findings

- Bioenergy can have a significant role as a flexible component in a low emission energy system dominated by VRE (variable renewable energy) generation.
- The motivation for integrated bioenergy hybrids depends on the application, but usually relates to
    - efficiency improvements (e.g. preheating of process feeds with other RE sources before biomass conversion),
    - lower cost through equipment sharing (e.g. common steam system),
    - improved resource efficiency (e.g. hydrogen enhanced biofuels)
- The technical potential for integrated bioenergy hybrids is considerable as no significant limitations have been identified.
- The market potential for integrated bioenergy hybrids is difficult to estimate as there is no universal way to assess the value of flexibility in isolation from the energy system. So the economic feasibility is always specific to the case in question.
- The majority of hybrid concepts currently in the markets of the case study countries are focussed on domestic heating applications. However, in Germany there has also been notable interest in virtual power plants and power-to-gas concepts.
- Integrated bioenergy hybrids can provide flexible resources for both energy supply and energy storage.
- The role of bioenergy in a hybrid system depends on the application. Other RES can be used to support bioenergy, or bioenergy can support other RES.
- District heating and cooling networks offer great potential for an efficient utilisation of renewable energy and waste heat sources.
- There is a lack of standardised interfaces between technologies, which leads to the need for multiple control systems and thus added costs.
- Using biomass for storing VRE in solid fuels through drying or in gaseous or liquid fuels through electrolysis are potential future hybrid concepts.

Key actions in the next five years

- Creating an online "knowledge library" for sharing information on best practices and successful case examples related to integrated bioenergy hybrids.
- Standardisation of interfaces between RES technologies.
- Control system development for integrated hybrids.
- Improving flexibility of existing bioenergy technologies, including
  - lower minimum load,
  - higher maximum load,
  - faster load changes and ramp rates,
  - low-cost start-up and shutdown.
- Developing novel bioenergy concepts that are capable of creating demand during periods of abundance in a VRE dominated energy system.
- Developing novel bioenergy concepts that can supply energy during periods of high prices in a VRE dominated energy system.
- Developing novel bioenergy concepts that can bridge long-term energy imbalances.

Introduction

In this report, the term *integrated bioenergy hybrid* is introduced to describe an energy conversion process that has at least two energy inputs, of which one is bioenergy. The term RES (renewable energy source) hybrid can also be used, if all energy inputs are from renewable sources.

The significant cost reductions achieved by *variable renewable energy* (VRE) technologies during the last decade, provide a backdrop for our report. According to recent data [1], the generation costs of VRE have already reached or are approaching those of conventional power and heat generation options. This trend is likely to continue, leading eventually to high shares of VRE in the energy sector [2]. As the share of variable energy supply continues to increase, it raises the important question of how to best ensure the stability and reliability of energy supply. Technically and economically viable solutions to the problem, such as fast-response natural gas boilers and combined cycles, already exist in the market place. However, the ambitious long-term carbon mitigation goals agreed by the world governments in Paris, are not likely to be met with a fossil-based backup strategy. So there exists a clear need for technologies that are simultaneously low-GHG, flexible and cost-effective.

Bioenergy is an easily storable source of renewable energy that can be used to bridge temporal imbalances between energy supply and demand. A large number of bioenergy solutions are already available in the market place, and they are widely applied at various size ranges and locations. A particular goal of this report is therefore to understand how bioenergy is already contributing to a more flexible low-emission energy system, and to have a look at its potential in the near future. The countries surveyed in this report include Finland, Germany and Austria.

Integration of energy sources into the same process can cause costs and benefits in several ways: cost may increase through the need for additional equipment, while benefits might be obtained through savings in feedstock, and operating and maintenance costs. In general, the motivation for investing in RES hybrids is most likely connected to 1) efficiency improvements, 2) lower cost through equipment sharing, and/or 3) improved resource efficiency of biomass use. Some of these impacts, such as changes in efficiency and costs, are usually easy to define, while those related to the flexibility and reliability of the process are less easily identifiable.

A common way for analysing and comparing different process configurations against each other is to compare their generation costs using a metric called the levelised cost of energy, LCOE. The LCOE can be calculated by summing up all plant-level costs (investment, feedstock, operating and maintenance, emissions) and dividing them by the amount of energy that the plant will generate. Costs that are incurred at different points in time (e.g. investment vs operating costs) are made comparable by “levelling” them over the economic life of the plant.

However, comparing the costs of different technologies is only meaningful as long as benefits provided by each technology are the same [3]. This is often not the case when comparing technologies connected to variable energy sources, as the LCOE does not capture the temporal profile of energy generation. In order to capture the effects of VRE generation, the standard LCOE method needs to be expanded. In principal, this can be done in two ways: 1) by assessing the costs of integration to the energy system, or 2) by assessing the effect of VRE on the total system costs. It has been found conceptually simpler, and often more useful, to assess VRE in terms of its impact on total system costs [3]. Some of the effects will be positive and some negative and the system value can be determined by calculating the net benefits that VRE brings to the remaining parts of the system.

The definition of flexibility can be ambiguous depending on what dimensions of flexibility are intended. In terms of flexible generation, different bioenergy processes can be assessed in the following areas:

- The ability to select the generation level,
- The ability to select the speed at which output levels are changed, and

- The start-up and shut-down time of the plant.

In general bioenergy technologies allow fairly wide operational windows and steep ramping gradients, which provide good starting points for integration with variable energy sources. However, some additional costs can also be expected as a result of flexible operation. For example, costs associated with part-load operation and cycling of the bioenergy equipment include premature component failures due to thermal stresses and possibly also increased emissions and reduced fuel efficiency when operating outside name plate capacity range.

Energy storage encompasses a family of diverse technologies, but in the context of bioenergy hybrids two main options can be identified: 1) biomass drying with VRE and 2) chemical storage of electricity into biofuels through hydrogen [4]. These technologies have significant technical potential due to their applicability at large scale and are potential future RES hybrid concepts.

Bioenergy hybrids status today in case study countries

This chapter summarises the status of integrated bioenergy hybrids (also called bioenergy RES hybrids) in Finland, Austria and Germany, based on recent status reports prepared for these countries [5]. The main focus will be on the status of hybrids in Finland, which will be complemented with examples from Austria and Germany. To structure our findings and the following discussion we have created four categories for bioenergy hybrids depending on their application and scale, namely:

- Domestic applications,
- Utility-scale applications and district heating and cooling networks,
- Industrial applications,
- Farm-scale applications.

Domestic applications

RES hybrids in domestic applications are mainly found in the heating sector. Detached houses, especially outside district heating networks, usually have a hybrid heating system based on multiple energy sources, such as oil, biomass, electric resistance heater or heat pump. In Finland, hybrids covered almost 8% of the heating markets in small-scale buildings in 2015 [6], and many companies that provide stand-alone renewable heating solutions have already included flexible heating solutions in their offerings, e.g. solar thermal collectors that can be integrated with a wood pellet burner, a biomass burner or a heat pump. Some companies also offer entire hybrid heating systems that enable the use of multiple heat sources for domestic hot water and/or space heating: systems typically include a heat storage and flexible connection for heat sources, such as bioenergy (stove or wood pellet burner), solar heat, heat pump and waste heat recovery (Figure 1).

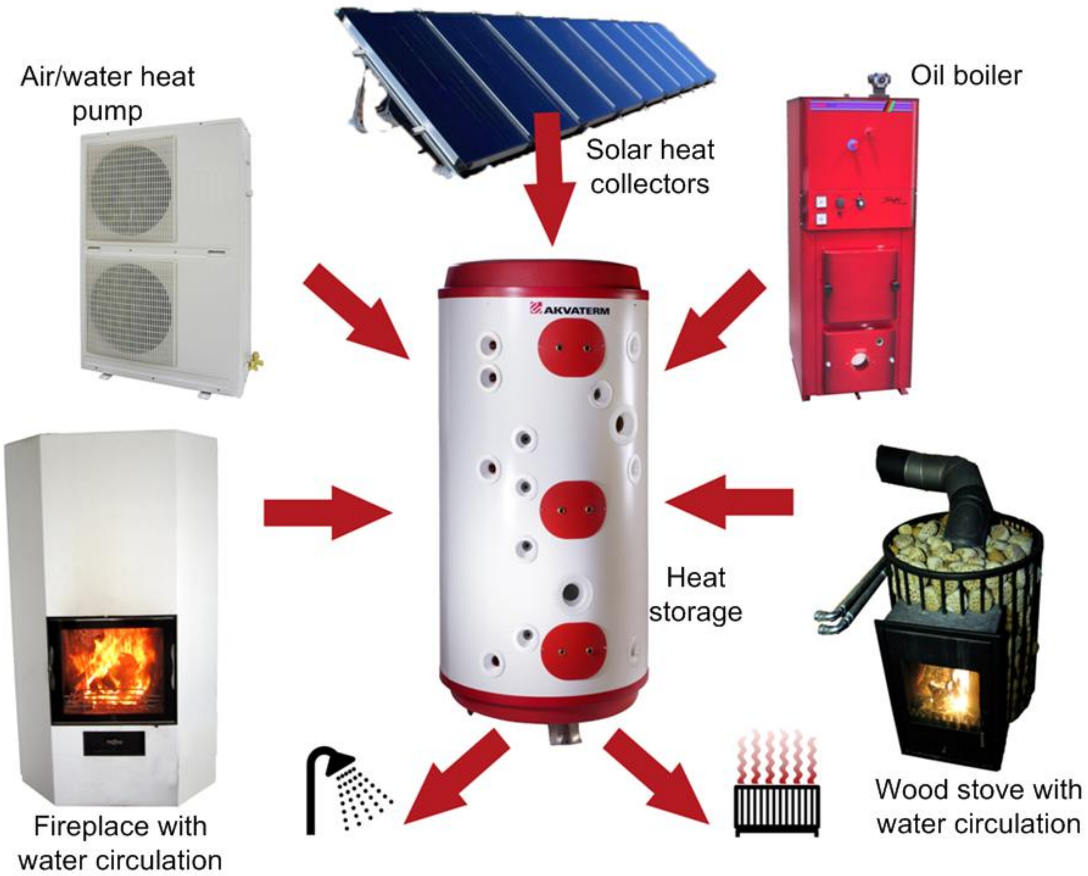

Figure 1. Flexible hybrid solution for domestic hot water and space heating by Finnish company Ekolämmöx; taken from [7].

RES hybrid solutions for domestic heating are already mature systems whose main challenge relates to the selection of technologies and their correct dimensioning. With a properly dimensioned heat storage, oil consumption in detached house heating can be either fully or partly cut using RES. Biomass nowadays is seldom the only heat source in a Finnish detached house due to the increasing share of electric heating, heat pumps and district heating, but its role as an additional heat source is emphasized [8][9]. With relatively high investment cost, ground-source heat pump, air/water heat pump and biomass boiler are usually considered as alternative base load heat sources in domestic applications. The investments in heat pumps and biomass boilers help customers to protect themselves against expected future increases in the purchase prices of oil and electricity. Depending on the household's heating approach, the role of biomass in a RES hybrid system can be roughly divided in two categories:

1) Biomass as the base load producer: the consumption, operation costs and work load can be reduced via integration of other heat sources;
2) Biomass to complement other heat sources (e.g. heat pump as base load producer): peak demand and electricity costs can be reduced and over dimensioning of the heat pump avoided.

Solar heat collectors are able to complement base load heat sources through integration with thermal storage (Figure 2). A hybrid system that integrates bioenergy and solar thermal is not yet a "standard" in Finland, whereas in Germany and Austria the combination of biomass and solar thermal is already well established. Currently, 60% of all pellet boilers in Germany are combined with solar heat [10]. The benefits of integrating solar heat with a biomass based heating system are reduced feedstock costs, especially during the summer period, and increased lifetime of the boiler if properly controlled. With integration with ground-source heat pump, the life time of the pump can be enhanced. Other reasons for solar thermal installations in households include cost savings in fuel or electricity, scalability to customer's needs, effortless use, minor O&M costs, long life and the desire to contribute to CO_2 emission reduction in a simple carefree way [11].

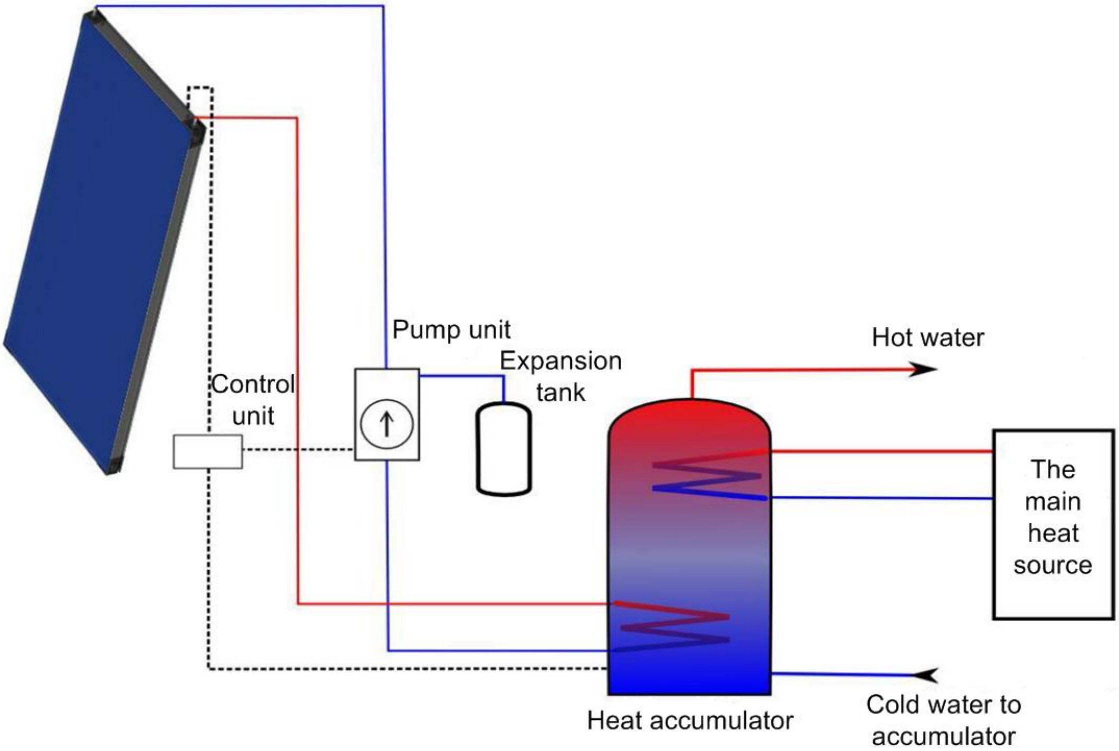

Figure 2. Integration of solar heat collectors with the heating system through thermal storage; taken from [11].

Solar heat can also be utilised to support the heat pump by upgrading the temperature of the ground cycle liquid before input to the heat pump during spring and autumn. Surplus solar heat during summer time can be stored in boreholes for use in autumn and winter through upgraded water temperature from the boreholes [12].

In Germany, the combination of solar thermal heat generation with bioenergy is common. There are several manufacturers offering combined systems, as well as additional research projects. For example, Buderus installed a combined system in a reference house with the area of 380 m² in Hutthurm near Passau, with a wood gasification boiler, solar panels, an oil-fired condensing boiler and a combined water tank [13]. Another example is the system offered by Brunner GmbH, which includes a pellet, woodchips or wood log boiler with a buffer tank combined with solar panels and/or heat pumps.

In Finland the gradually increasing district heat prices have encouraged customers, even in the case of existing buildings, to displace their district heat consumption with other energy sources. Since a solar thermal system always requires another complementary heat source in Finnish climate conditions, solar thermal is a good match for district heat connected buildings. From the DH heat provider point of view, end-user production reduces the heat sales, but on the other hand, new service businesses are expected to arise.

Jyväskylä Energy, an energy company in Central Finland, has for the first time in Finland demonstrated a two-way district heating network connection in a pilot single family house in Jyväskylä (Figure 3). The estimated annual heat production by solar heat collectors (2 kW, 4 m^2) from a Finnish company called Ruukki is 7.2–10.8 GJ (2-3 MWh). Solar heat is primarily utilised in the building and is complemented by a wood stove and district heat. In the case of surplus solar heat production, heat can be fed to the district heating network. Water fed to the network has to be >75 °C and the pressure is raised above that in the feed water line of the network by a pump. The system does not include any thermal storage, since the district heating network provides the required flexibility. The building has energy measurement for both directions, and the same price is paid for the solar thermal energy as the customer pays for the district heat [14][15].

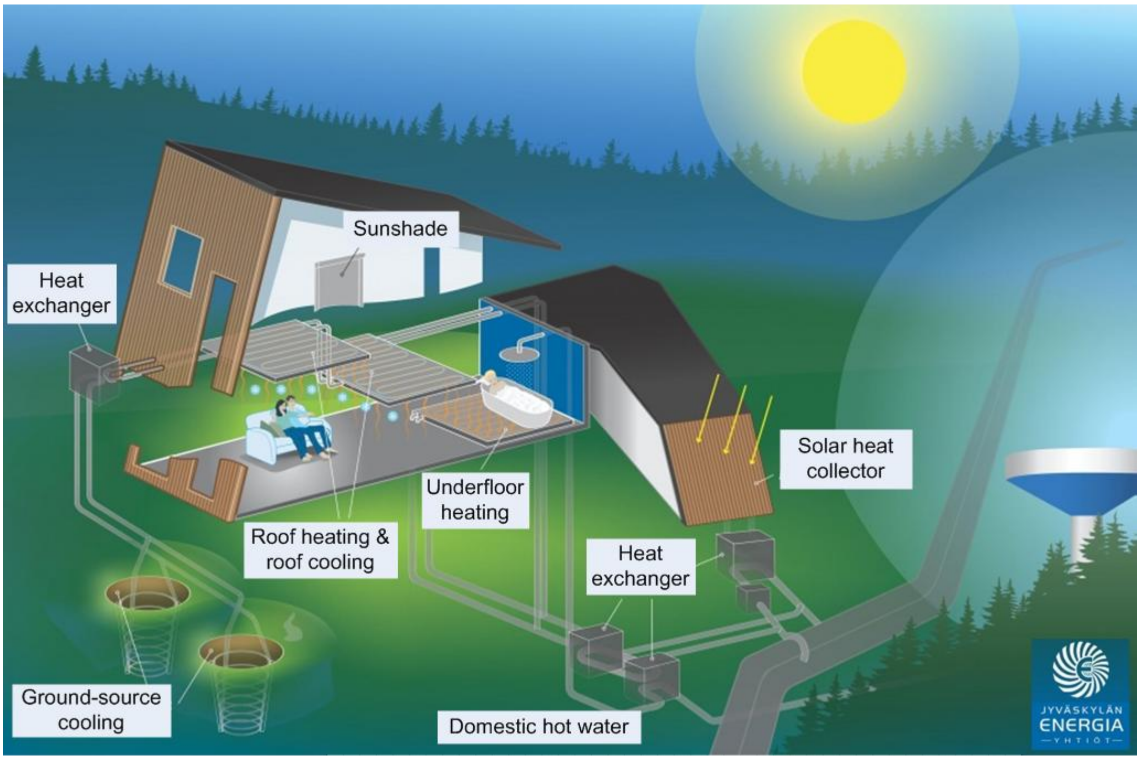

Figure 3. Schematic of pilot building having two-way district heating network connection; taken from [14].

Utility-scale applications and district heating and cooling networks

Utility-scale applications cover the range from single buildings to large district heating and cooling networks. An example of a single building application is the Sakarinmäki school building in Helsinki Finland, which is a pilot implemented by Helen (energy utility in Helsinki). The goal is to cover at least 80% of the building's heat demand by renewable sources. Previously, the heat production was covered by fossil light oil. The new hybrid heating system integrates ground-source heat, solar thermal and heat accumulators with existing oil boilers, which are capable of burning bio-oil. Heat produced by collectors from a Finnish company called Savosolar is used when available, whereas ground-source heat is the main heat source. Two heat accumulators were installed to store the solar heat. The existing oil boiler units are used where the demand cannot be covered with solar and ground-source heat, and the oil used is mainly bio-oil. The nominal capacity of the oil boilers is 1,500 kW and consequently, the whole heating demand of the building, 1,200 kW at maximum, could be covered by oil. The daily production by the different heat sources can be followed on Helen's website, and the data is also used for educational purposes [16][17].

In many countries solar heat integration with district heating networks is of high interest in order to cut emissions in the heating sector, while providing renewable energy at a constant and affordable price. Solar thermal utilisation reduces the consumption of fuels and makes it possible to use more bioenergy for other end-uses. In Denmark, solar thermal integration with the district heating plant, typically also using biomass, is rapidly becoming common. Solar thermal typically represents 20−30% of the annual heat demand. Figure 4 shows a hybrid district heating plant in Løgumkloster in Denmark. The plant produces 108–115.2 TJ (30–32 GWh) energy annually, with wood pellets as the base producer (3 MW). Solar collectors (15,300 m^2) produce approx. one-fourth of the total production (28.8 TJ i.e. 8,000 MWh). The peak solar field power is 13.5 MW, and 7,400 m^3 heat storage is able to dispatch 400-500 MWh. Other heat sources are natural gas, absorption heat pump and electric heat pump [18][19].

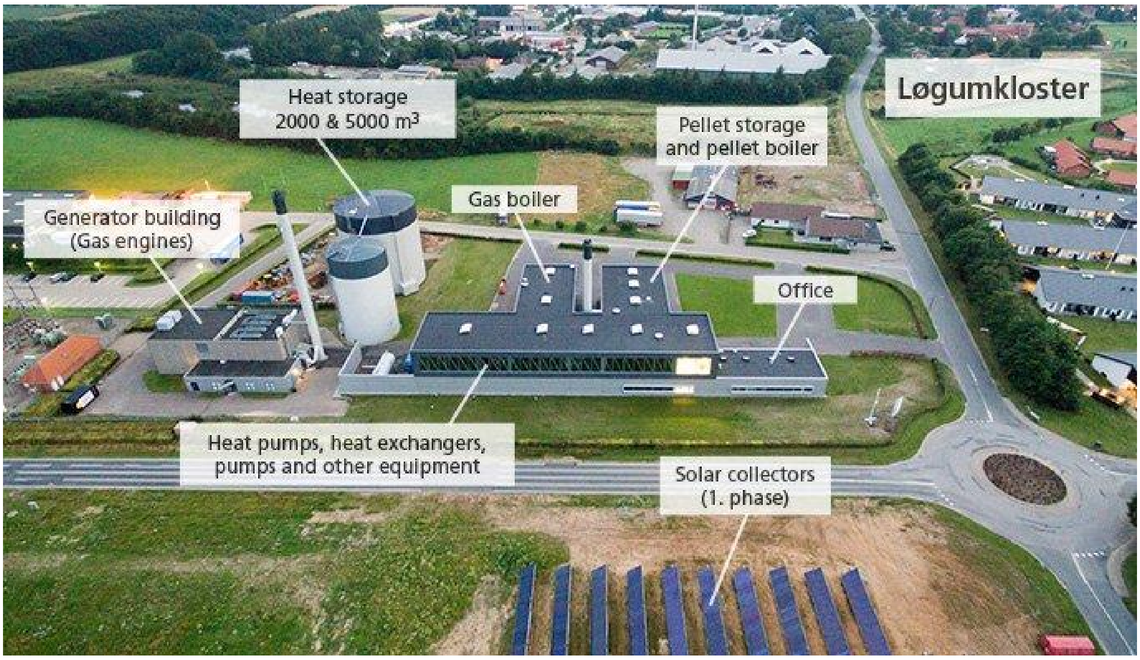

Figure 4. Hybrid district heating plant (CHP) combining wood pellets, solar thermal energy and natural gas in Løgumkloster in Denmark [18].

The first step towards solar thermal utilisation in district heating has been taken in Finland by Savon Voima (energy utility). One of its district heating units using heavy fuel oil to produce heat for a residential area was replaced at the end of 2015 by a pilot system, which consists of a wood pellet burner, electric heater and solar heat collectors. Solar collectors are used to preheat the return district heating water before it is heated to the final temperature in the pellet boiler or electric heater. Solar heat is available from the beginning of February until October, but during the remaining period, other heat sources are needed to cover the heat demand. During the summer period, heat is produced with collectors and electric boiler, since current electricity prices are low. The annual solar share is rather low and during the summer period, approx. 2.5% of the production can be covered by solar thermal. Technical data on the hybrid is shown in Table 2. The installation does not include any storage system, which reduces the investment cost, but limits the achievable solar share. The main goal of the pilot is to investigate the use of solar heat in parallel with other heat sources in district heat production, and the technical and economic feasibility of scaling up the system [20][21].

Table 2. Technical data of Savon Voima's hybrid district heating system.

Component	Capacity	Area	Annual production	Investment
Wood pellet burner	500 kW			
Electric heater	70 kW			
Solar heat system	8 kW	12 m^2	3000 – 4000 kWh	12 000 €
Hybrid system, annual			1000 MWh	350 000 €

In Germany, there are several demonstration projects at a residential scale. For example, Hamburg city district "Jenfelder Au" has been part of a project funded by the research initiative EnEffStadt [22]. Here, innovative city drainage has been combined with several renewable energy sources, including a biogas plant, solar thermal and geothermal systems. For the village of Wüstenrot, a roadmap for energy use and new building settlement "Vordere Viehweide" (according to the "plus energy" standard) is currently been implemented within the project EnVisaGe [23]. In this case, geothermal heat supply in a low temperature local heating grid is combined with biomass heat and solar thermal systems. Vaillant installed a district heating grid for "Quartier Dortmund-Brackel" with six pellet boilers of 90 kW each, six condensing boilers, and 232 solar collectors with 550 m^2 collecting area [24].

In the Styrian city of Gleisdorf in Austria, six low energy houses and one office building have been constructed within the EU project "Large Scale Solar Heating Systems for Housing Developments". Besides building optimizations, the integration of large-scale solar thermal heat was a focus of the project. Solar thermal collectors with an area of 213 m^2 have been integrated into the winter gardens of the buildings. Further installations include a wood pellet boiler and a 14 m^3 buffer tank made of steel. The size is chosen in order to function as a monthly buffer. The whole concept guarantees a 100% renewable heat supply. Both heat sources have a share of about 50%. The supply of single buildings is provided by the buffer tank. Decentralised hot water tanks in the buildings are raised to a high grid temperature of 65 – 70 °C during a 2 hour phase at night. The hydraulic concept is shown in Figure 5. [25].

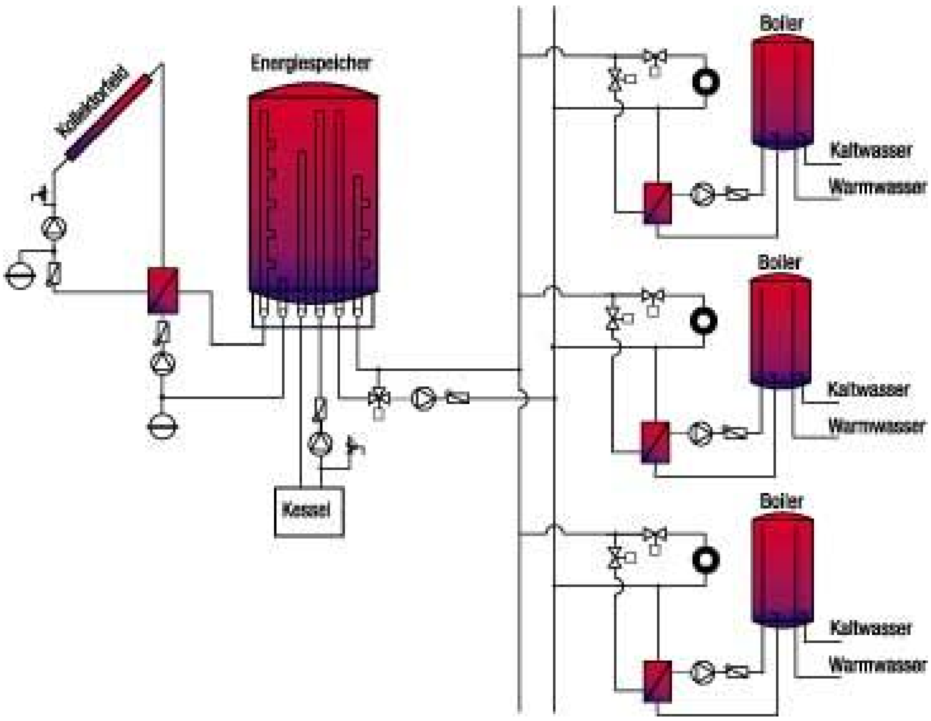

Figure 5. Hydraulic concept of the heating grid in Gleisdorf in Austria [25].

In Austria, integration of heat pumps with biomass based heating grids has become a standard technology in recent years. There are several ways of using this technology. The first option is to integrate the heat pump as a single heat producer using ambient energy (air, water or soil) as a heat source. This concept could also be extended to several sources of waste heat.

The second option is the integration of the heat pump into the recirculating water. This concept was studied at the Tamsweg combined heat and power plant [26]. The left side of Figure 6 illustrates the situation before the installation of the heat pump. Three bundles of heat exchangers (HEX) are streamed in counter-current with the return flow of the heating grid. The return flow is divided into two parts based on heat levels and directed to different bundles. In this way the amount of condensed water is increased. The inclusion of the heat pump (HP) in the system is shown on the right side of Figure 6. The evaporating part of the heat pump is connected to the first heat exchanger bundle to lower the temperature of the return flow. The energy is diverted to the water circuit just before the hottest bundle (HEX3).

The third option is also implemented in an Austrian district heating plant. In Flachau, the heat pump is integrated with an existing cooling circuit, which is situated in the flue gas stream after the flue gas has already passed one or several direct condensing bundles. On the other side the return water also passes the direct condensing bundle in a first step and the condensing part of the heat pump in a second step.

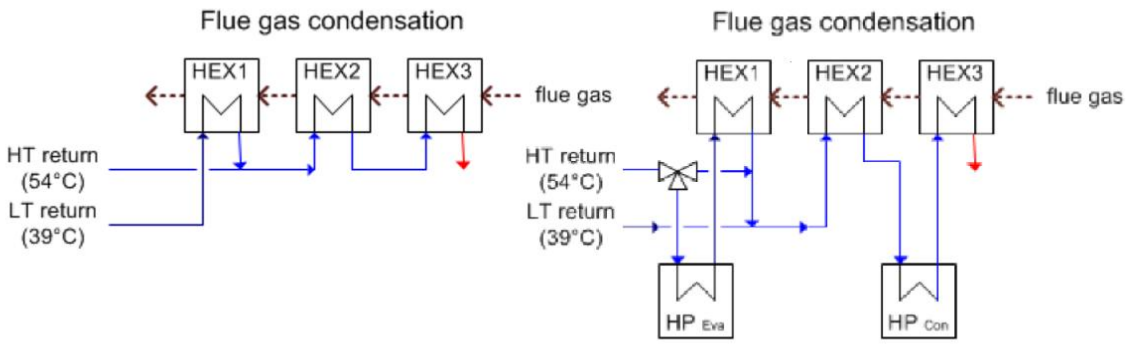

Figure 6. Sketch of the condensation system of the Tamsweg CHP plant before (left) and after (right) the integration of the heat pump [26].

Waste heat recovery to a district heating grid by a heat pump is a growing trend in Finland. In Mäntsälä, heat from the outlet cooling air from Yandex's data centre is recovered to a district heating network owned by Nivos. This new solution has not only reduced the natural gas consumption for district heating production, but also lowered the purchase price of district heat for customers by 5% and decreased district heat production related CO_2 emissions by 40% in the centre of Mäntsälä. The data centre produces heat at 37 °C (inlet air 20 °C) with a power demand of 15 MW. The outlet heat is recovered to a district heating network by a heat pump. The capacity of the heat recovery system is 4 MW, producing annually 72 TJ (20 GWh) of district heat i.e. approx. half of the annual demand of the centre of Mäntsälä [27][28]. Waste heat from several other industrial processes could be recovered to district heating networks as well. This would not only decrease the amount of wasted heat, but also decrease the investments in new biomass-based capacity in DH networks.

Conventional heating grids are characterized by central heat production with consumers along the network (Figure 7, top). In more complex grids there can be several distributed producers, but still, in classical setups there is a clear distinction between heat producers and consumers. Buildings, which are not part of the network, usually have their own heat supply, which has an overcapacity in most cases. Examples of such supply in Austria are solar thermal energy during sunny days in summer time and heat produced by biomass boilers in warmer winter periods and during transition times. Small- and medium-scale industry is often reluctant to participate in heating grids.

A bi-directional heating grid (Figure 7, bottom) could be the solution to integrating such heat sources into the grid. Prosumers (Producer and Consumer) would generate additional heat for the grid. As a result, there is potential to replace peak load boilers and to cover the summer period demand by the production of prosumers instead of using an inefficient main boiler. The technical and economical evaluation of such a system is actually under development in the project BiNe2+, which is funded by the Austrian climate and energy funds (KLIEN) and the Austrian funding agency (FFG). The implementation of new decentralized heat producers into an existing heating grid will be realised in Großschönau, where a heat pump, a biomass boiler for chipped wood and an existing solar collector field will be connected to the grid.

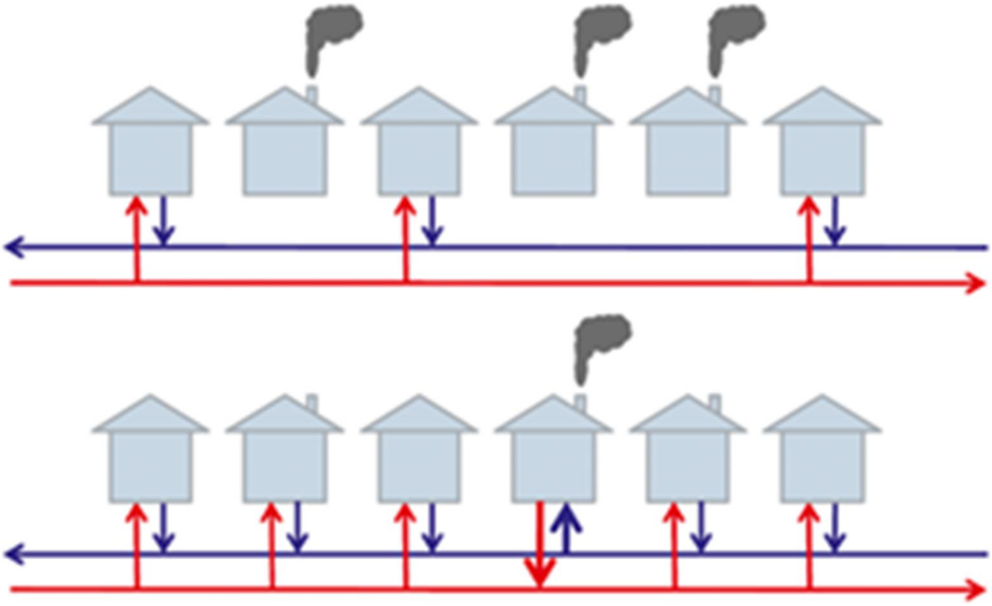

Figure 7. Basic layout of conventional (top) and bidirectional (bottom) heating grids [29].

A good example of the large-scale hybrid platform in Finland is Helen's concept based on trigeneration of heat, power and cooling for a dense urban area [30]. Helen's goal is to be a CO_2 neutral energy utility by 2050, and wider utilisation of biomass plays a key role in the transition. Key actions made or decided in order to increase the share of bioenergy in district heat production are wood pellet co-combustion with coal, distributed heat production with bioenergy and the use of biogas [31]. Helen also seeks new heat sources, such as heat pumps, solar thermal and geothermal. Helen's Katri Vala heat pump co-generating district heating and cooling plant is the largest of its kind in the world. The heating and cooling capacity of the plant, produced by five heat pumps, is 90 MW and 60 MW, respectively. The COP is 3 – 3.5 for DH and 5 for co-produced district heating and cooling. The plant is highly efficient since it takes advantage of waste heat streams by recovering heat from the return water of district cooling and from purified sewage water (Figure 8). In 2015, the heat pump plant covered 7% of Helen's district heating and 60% of district cooling. Helen's district cooling system is the third largest in Europe, and is expanding rapidly. During the summer period, almost all of the heating demand of the centre of Helsinki and about half of the entire city can be met by the Katri Vala plant [32][33][34].

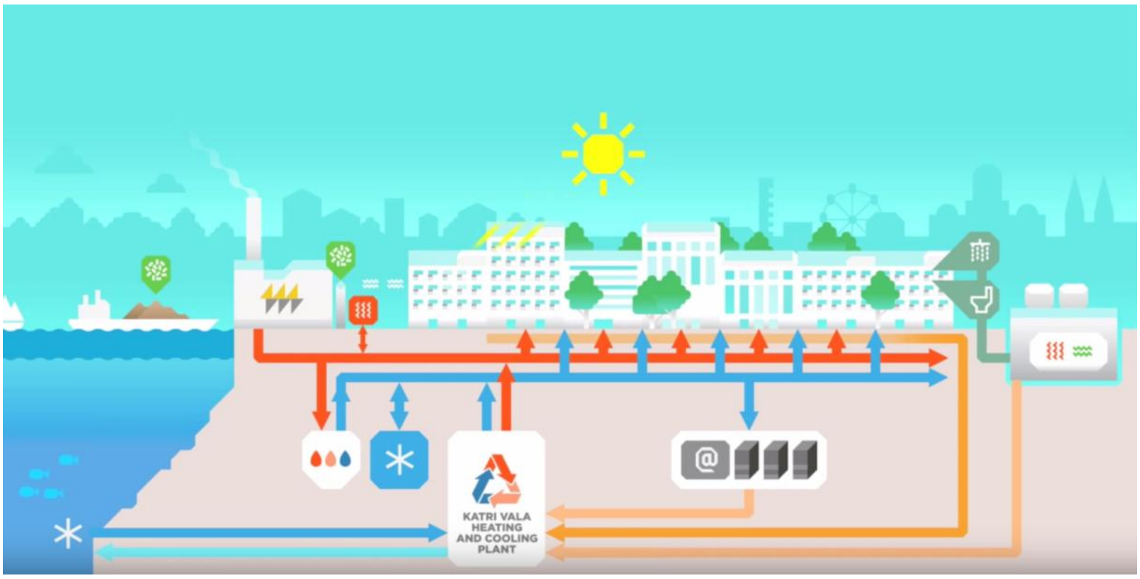

Figure 8. Helen's integrated district heating and cooling system based on multiple heat sources [35].

Industrial application

A wide variety of applications of bioenergy RES hybrids can be found in industry. In Finland, wood fuels already cover close to 35% of industrial energy consumption. Biomass plants are potential opportunities for bioenergy RES hybrids, since biomass could be saved from the summer period for the winter period with the help of solar thermal integration as an example. One potential sector for hybrid systems can be found within the food and beverage industry.

An example is a "GeoBio" hybrid solution providing heating and cooling in a logistic center in Sipoo in Finland. The hybrid system produces almost fully CO_2-free energy by utilising ground-source heat and wood pellets as the main energy sources. RE sources cover 95% of the final energy consumption. The use of heat pumps, used as the base load producer, is prioritised in order to maximise capacity factor. Pellets are used during the winter period with increased heat demand, whereas heavy fuel oil serves as backup fuel. In the end, approximately half of the annual heat demand is covered by ground-source heat and the other half by wood pellets. In addition to ground-source heat, heat is recovered from the cooling system, and the total heat production capacity is 6.0 MW. Ground-source heat is collected from 150 bore holes, each 300 m in length, and the system is one of the largest heat pump plants in Finland [36][37]. Modular design probably brings benefits to the system in terms of optimizing the efficiency. Technical details of the plant are shown in Table 3.

Snellman in Finland is a good example of replacing oil by renewable in the food industry. The company has replaced all of its more than 1,000 tonnes of oil consumption by biogas, which is partly produced from its sludge and sewage, to produce heat and steam. The production and utilisation of biogas creates new local networks; Snellman's biogas is produced in a nearby production unit in Jepua, and biogas is also used in other local industries. Ventilation heat recovery is combined with biogas utilisation to produce heat, and the payback period of two years was achieved for the investment. Interest in PV installation exists, but for the time being, the investment has not been considered beneficial enough. In the future, electricity demand of the facility could also be covered by biogas [38][39][40].

Table 3. Technical data of the Adven's "GeoBio" hybrid system.

Component	Capacity	Share of the total production	Temperature
Wood pellet burner	4 (2 x 2 MW)	close to 50 %	max 120 °C
Ground-source heat	2 (2 x 1 MW)	close to 50 %	max 50 °C
Heavy oil boiler	6 (2 x 3 MW)	under 5 %	-
RES hybrid	-	95 %	-

At the slaughterhouse of the company Großfurtner in Austria, animal byproducts are used to generate biogas. This biogas is burned in a CHP-system that can cover 80% of the heat demand. Additional heat is generated by geothermal power. The concept is illustrated in Figure 9 [41].

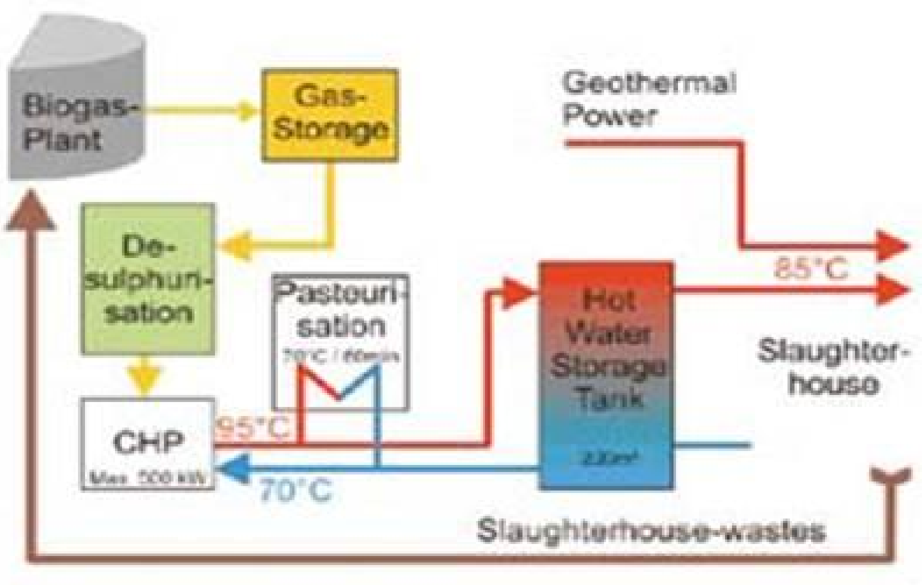

Figure 9. Energy-Flow chart, connection of the biogas plant to the slaughtering facility [41].

While in Finland the industrial hybrids mainly focus on heat production, thus replacing oil consumption, in Germany great focus has recently been on virtual power plants and Power-to-Gas concepts. An overview of Power-to-Gas projects in combination with bioenergy is shown in Table 4. There are also other examples of industrial applications in Germany. In the regenerative power plant "RegenerativKraftwerk Bremen", an industrial location is supplied with power, heating and cooling from wind power, photovoltaics and biomethane [42]. By combining these energy resources with accumulators and charging infrastructure for electric vehicles, the plant is used as a virtual power plant to provide ancillary services.

In Germany, a typical industrial application combines wind power with bioenergy for heat and power generation and for mobility. As an example, the Enertrag hybrid power plant in Prenzlau uses mainly wind power from several wind turbines. Here, a conversion of surplus wind power into hydrogen takes place and the hydrogen is used as a fuel (hydrogen powered cars with fuel cells) or for heat and power generation with the combined combustion of electrolysis hydrogen and biogas [43].

Table 4. Power-to-Gas projects in combination with bioenergy[1].

Project name	Audi e-gas project	BioPower2Gas	Methanisierung am Eichhof	PtG Eucolino Schwandorf [44]	PtG Biogasbooster (MicroPyros)	Stromlückenfüller (GP Joule)
Category	Industry	Demonstration plant	Demonstration plant	Research	Pilot plant	Pilot plant
Status	Operating	Operating	Operating	Operating	Operating	Operating, first stage of expansion (4/40)
Start-up	25.06.2013	March 2015	January 2012	15.11.2012	June 2014	18.05.2015
Power consumption	6300 kW_{el} [45]	Up to 1200 kW_{el}	25 kW_{el}	108 kW_{el}	unclear	20 kW_{el}, first stage; up to 200 kW_{el}
H_2-Production	1300 m^3/h	60 – 220 m^3/h	6 m^3/h	21.3 m^3/h	Unclear	40 m^3/h (final stage)
SNG-Production	300 m^3/h	15 – 55 m^3/h	4 m^3/h	5.3 m^3/h	0.4 m^3/h	n.a.
CO_2 source	Biogas plant (EWE AG)	Biogas plant/Natural gas distribution network	Biogas plant	(Within) Biogas plant	Biogas plant of purification plant Straubing	Biogas
Heat usage	Hygienisation, plant periphery	District heat [45]	No	Yes	Unclear	Local heating grid [45]
Location	Werlte, Lower Saxony (Germany)	Allendorf (Eder) and Philippsthal, Hessen, Germany; Jühnde, Lower Saxony, Germany	Bad Hersfeld, Hesse, Germany	Schwandorf, Bavaria (Germany)	Straubing, Bavaria (Germany)	Reußenköge, Schleswig-Holstein (Germany)
Websites	[46]	[47]	[48]	[49]		[50]
Further notes				Methanation within the process of producing biogas; increasing of methane content of biogas	Uses microbial methanation of hydrogen at 80°C	Combined combustion of hydrogen and biogas for power production; follow-up project: combination of PEM-electrolyzer (MW-size) and biogas-CHP

Farm-scale applications

Integrated bioenergy hybrids constitute an attractive proposition for farms due to a farm's high energy demand that is distributed rather evenly over the year, its wide utilisation of biomass potential, and its large rooftop areas available for solar energy harvesting. For farms the availability of biomass, desire to increase energy self-sufficiency and the expected increase in purchase price of oil and electricity can be identified as the main motivators behind renewable energy investments.

In Finland, bioenergy is mainly used for heating in wood chip and wood pellet boilers. Small-scale CHP installations have been seen as a good choice for farms, if an investment subsidy is received and all the produced heat can be utilised, as profitability is highly dependent on the level of heat utilisation [51].

There is a growing trend towards installing PV systems on farms, seen for example from the increasing number of joint purchases of PV panels. The PV production allows reduction in the amount of power that needs to be purchased from the grid. Farms that combine small-scale biomass CHP, PV, wind, heat pump and waste heat utilisation for wood chip drying can already be found in Finland. Figure 10 gives an example of a farm-scale hybrid system that achieves 100% self-sufficiency both in terms of heat and power on an annual basis. This is achieved by combining wood chip boiler, wind mill and ground-source heat pump. The heat pump also flexibly connects the heat and power sectors.

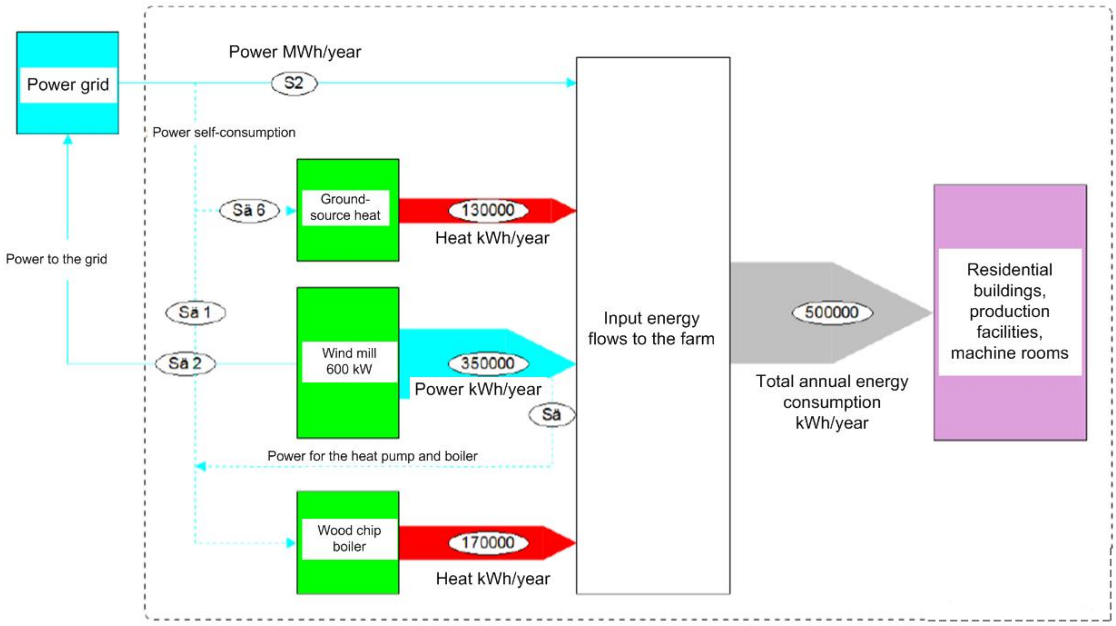

Figure 10. Hybrid power and heating system at a farm in Tuuri in Finland; retrieved from [52].

Biogas production and consumption at farm-scale in Finland is modest, but has recently seen gradual growth. In 2014, the total heat and power production from biogas at farm-scale was 14.96 TJ (4,155 MWh_{th}) and 3.98 TJ (1,106 MWh_e), produced in 13 farm-scale biogas reactors [53]. One of the

[1] If not stated otherwise, all data from www.powertogas.info (Deutsche Energie-Agentur – dena), [accesses 9.12.2015].

existing farms producing biogas (Kalmari farm) upgrades biogas for transport use in addition to its use for heat and power production. The farm is fully energy self-sufficient, and the main income of the farm comes from the vehicle biogas [54]. The main parameters of the farm are shown in Table 5.

Table 5. The main parameters of the Kalmari biogas farm [54].

Biogas reactor	Reactor volume	1,000 m^3
	Cow manure	2,000 m^3/year
	Confectionary by-products	200 m^3/year
	Fat	600 m^3/year
	Post-storage tank	1,500 m^3
Biogas (raw)	CH4 content	62–64%
CHP		25 kWel
		50 kWth
Gas boiler		80 kWth
Upgrading to traffic fuel	Capacity	50 Nm^3/h of raw biogas
	Electricity consumption	1.2–1.4 kWh/kg
	Water consumption	10 liter/kg
	CH4 content	95% ± 2%
End-products	Electricity	270 GJ/year (75 MWh/year)
	Heat	540 GJ/year (150 MWh/year)
	Biomethane for traffic fuel	3,600 GJ/year (1,000 MWh/year)

Large rooftop areas for solar harvesting have great potential for biomass drying at farm-scale. Solar thermal wood chip drying is technically scalable to large-scale power plants as well, but the space required by the solar collectors sets a restriction. However, distributed wood chip drying on farms would allow advantage to be taken of the technology in large-scale and also enhance energy efficiency in transportation by reducing the amount of transported water (moisture). Distributed wood chip drying would create new business opportunities for farmers.

A pilot-scale test facility connecting a solar heat collector installation to an existing biomass dryer has been set up at VTT Technical Research Centre of Finland Ltd. The installation allows the study of the efficiency, controllability and economics of the system among other things. The solar heat will also be usable for the recently installed direct air capture (DAC) system.

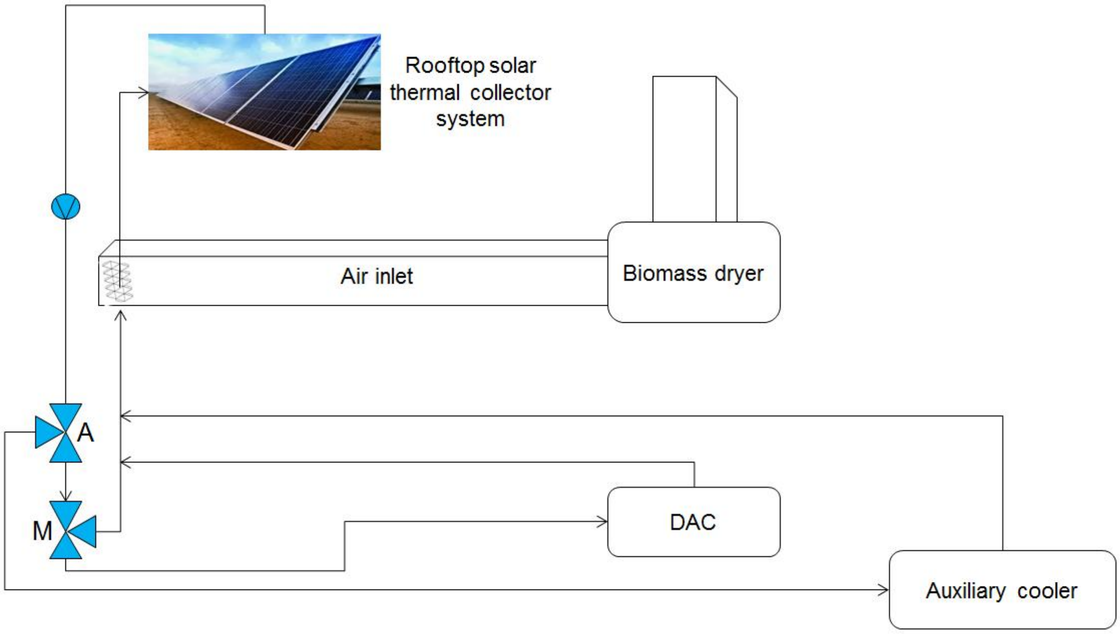

Figure 11. Solar thermal wood chip dryer for pilot-scale testing at VTT.

Technical potential of bioenergy hybrids deployment in case study countries

Based on the current status of bioenergy RES hybrids in case study regions, the areas and applications with the most potential for different hybrid systems can be evaluated and preliminary estimates for the anticipated market sizes given. This Chapter focuses on the future perspectives and potential of bioenergy RES hybrids in Finland. However, estimates on the potential in Germany and Austria are also presented.

Domestic applications

The largest potential for domestic hybrid applications lies in the heating sector, the main motivators being reduction in energy costs, increased self-sufficiency and user friendliness. Especially in the buildings outside the DH network it is challenging to economically cover the whole heat demand with a single heat source. A hybrid system combining for example a heat pump or wood stove as a base producer and an oil boiler or electric resistance heater for topping up is already common in detached houses. In the power sector, hybrid solutions remain rare due to the fact that the majority of buildings are connected to the power grid. However, market growth in PV installations to reduce grid sourced power consumption has been detected.

The potential for renewable energy and hybrid technologies is significant in Finland. It covers 200,000 oil boilers, 100,000 other water circulation based systems, 500,000 directly electric heated systems, 500,000 summer cottages and 100,000 premises outside the district heating network [56]. Altogether, 1.4 million buildings could either use RE technologies or be integrated with a district heating network. Currently, approx. 5,000 oil boilers are replaced annually by non-fossil heat sources. By replacing 20,000-30,000 boilers annually, the oil consumption of 500 million liters/year (18 PJ/year i.e. 5 TWh/year) for heating could be cut well before 2030 [57].

The current amount of pellet burners in buildings is 27,000 [58] and it is estimated that at least 100,000 more wood pellet burners could be installed in Finland, mainly to replace direct electric heating and oil boilers [59]. The current wood pellet production capacity is about 650,000 tonnes [60], representing approx. 11.7 PJ (3.25 TWh) of energy. Of this, approx. 273,000 tonnes i.e. 4.896 PJ (1.36 TWh) could be utilised in buildings and on farms in the future.[2] Approx. 1.55 million fireplaces are already located in detached houses out of 2.9 million in all buildings, and the potential annual growth is 70,000 fireplaces [9]. In Germany, the total number of pellet boilers was evaluated to be 428,500 in 2016. Of these, 12,500 have capacity of over 50 kW, 265,000 capacity less than 50 kW (excl. fireplaces), and 151,000 are used as fireplaces. The wood pellet production and consumption were estimated to be 2.2 Mt and 2.025 Mt in 2016, whereas the production capacity was 3.2 Mt. [61]The potential increase in heat pump installations is from 730,000 in 2015 (over 18 PJ i.e. 5 TWh) to 1.7 million by 2030 [62]. By 2020 there could be over one million heat pump installations with a total capacity of over 6,000 MW (production over 36 PJ i.e. 10 TWh) [63]. The number of heat pumps installed in Germany is of the same level with respect to Finland; as of 2015, around 792,000 heat pumps were installed in Germany, generating about 38.16 PJ (10.6 TWh) of renewable heat.

[2] Calculated assuming 27,000 wood pellet boilers in buildings and consumption of 58,000 tonnes, and future investments in 100,000 wood pellet boilers.

Solar thermal market development has been rather slow in Finland (31 MW_{th} in 2014) compared to Germany (12,388 MW_{th} in 2014) and Austria (3,261 MW_{th} in 2014) [64] despite the high potential due to large heating markets. Solar thermal integration can reduce fuel consumption and the need for maintenance of the biomass or oil boiler. This is significant especially during low heat demand in spring, summer and autumn. Both in the case of heat pump and biomass boiler, solar thermal integration improves the life time of a pump or a boiler, since running hours and the number of start-ups are reduced. By storing solar heat in boreholes, the efficiency of a heat pump can be increased. Both solar thermal and PV reduce the need to purchase electricity for running the heat pump. Solar thermal always requires a complementary heat source, since the production during the winter months is minimal.

The advantage of a hybrid system is based on using each heat source to its full potential. Ground-source heat is typically the most feasible heat source in large-scale residential buildings (>200 m^2). In smaller ones, a hybrid system might be more beneficial, especially if a fireplace or stove is installed [65]. A report by the Bioenergy Association shows that wood pellet based heating is economically competitive with oil and electric heating both in existing and new residential buildings (Figure 12).[3] The customer price of pellets is approx. 5.8 c/kWh as of 2015 [59].

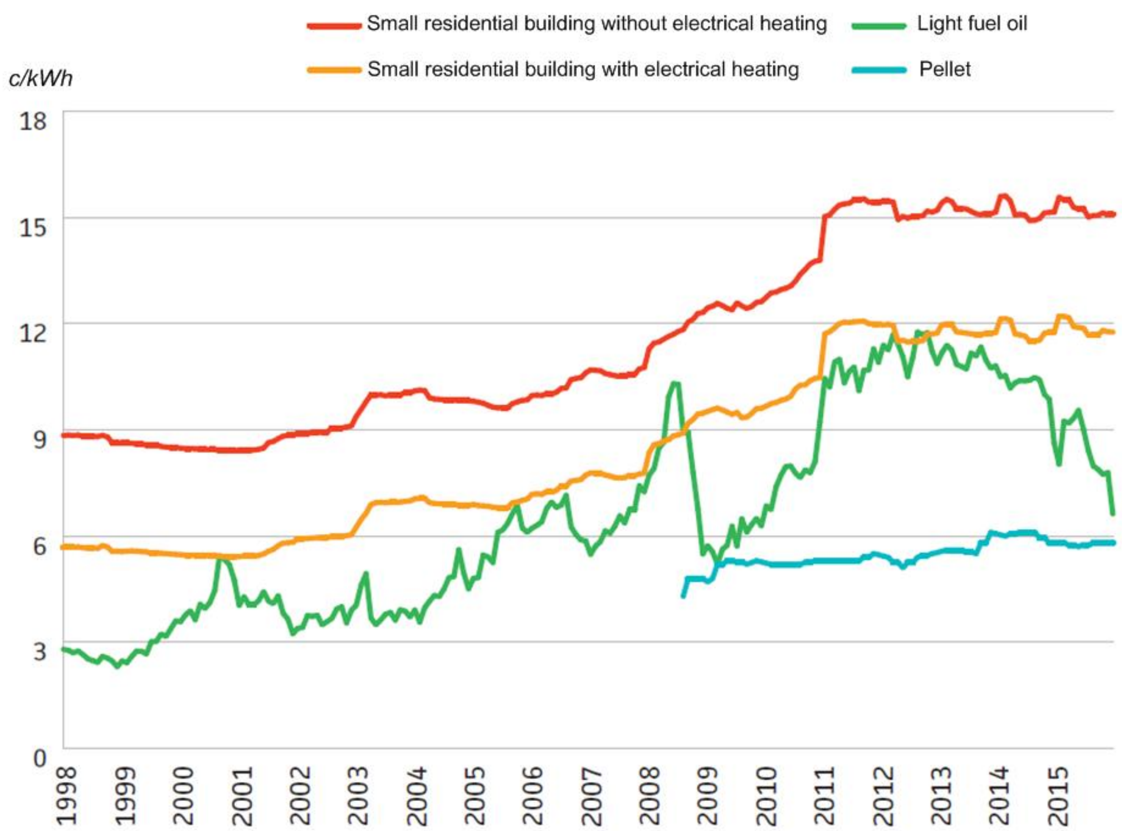

Figure 12. Purchase price of electricity, wood pellets and oil from 1998 to 2015 in Finland; retrieved from [59]

[3] Carbon tax for light fuel oil in Finland: 8 c/L.

District heating and cooling networks

District heating networks can be found in 166 of slightly over 300 municipalities in Finland [66]. The total length of the network was approx. 14,300 kilometers at the end of the 2014, and the annual expansion is 250–500 km [67]. The market share of district heating is expected to increase from 122.4 PJ (34 TWh) in 2015 to 144–151 PJ (40–42 TWh) by 2025 through urbanization, mainly in the areas with existing networks [68]. On the other hand, energy efficient construction and high district heat prices are expected to diminish the demand. In 2015, the market share of district heating in space heating of residential, commercial and public buildings in Finland was 46% [68], whereas in Germany and Austria it was 12% [69] and 10% [70], respectively.

The district cooling network in Finland is one of the most rapidly expanding in Europe. In 2012, district cooling was provided by eight energy utilities in Finland [66]. The demand in urban areas is expected to increase further from the 684 TJ (190 GWh) in 2014 to 1,530 TJ (425 GWh) by 2030 [68]. Due to a lack of customer awareness and projects lacking economic viability, the district cooling market is developing slowly in Germany. The total installed cooling capacity was 153 MWth in 2013 [69].

District heating and cooling networks offer great potential for an efficient utilisation of renewable energy and waste heat sources [71]. In 2013, biomass (mainly wood chips) became the largest source of district heat (29%), overtaking natural gas (26%), coal (26%) and peat (13%) in Finland [66]. There is a transition towards wider utilisation of biomass and waste streams. Thanks to typically large storage volumes in district heating and cooling networks, there is potential to integrate variable RE sources (wind and PV) with district heating networks, which simultaneously increases flexibility in the power system (Figure 13).

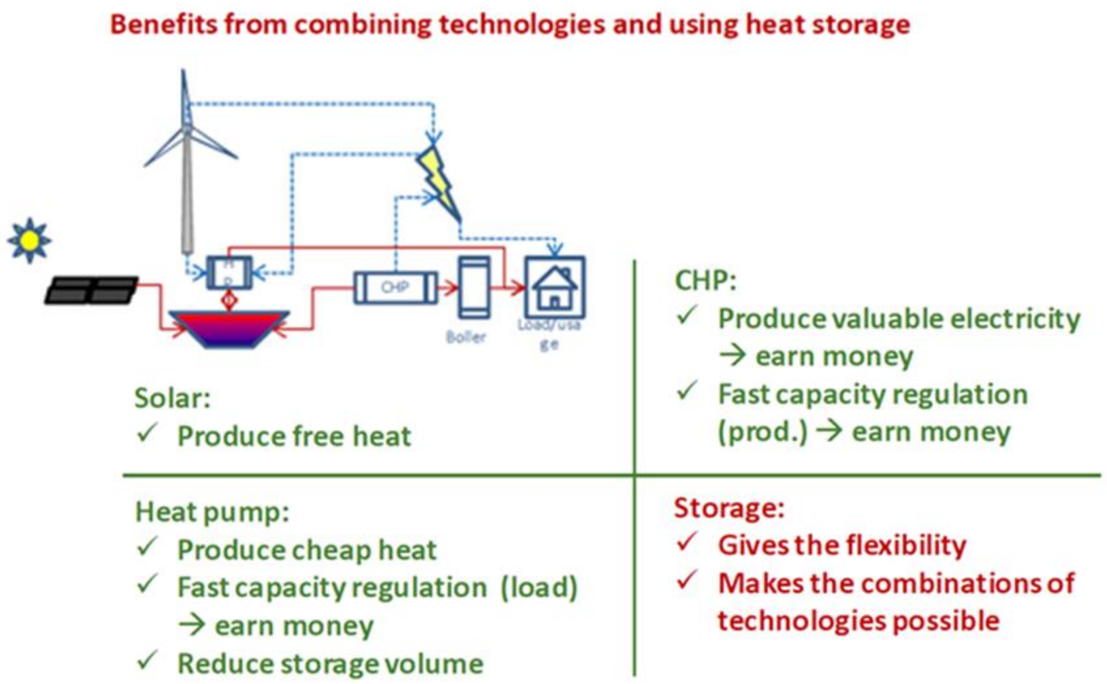

Figure 13. Integration of district heating network and CHP (bioenergy) with power sector [72].

Bioenergy plays a key role in the fast transition towards CO_2 neutral district heating production. Bioenergy is available around the year, but in order to guarantee its availability and sufficiency to all end-uses with a cost-competitive price, it is beneficial to release the pressure on biomass utilisation in energy production with other heat resources. In the future, bioenergy is foreseen to enable renewable balancing services in the energy system with an increasing amount of variable renewable generation and to provide for the peak loads. An example of recent bioenergy investments in flexible capacity is Fortum Värme's new biomass CHP plant (wood chips and wood residues) in Stockholm, Sweden [73]. In Finland, there have already been some investments in pulverized wood pellet burners, which can cover the peak heat demand periods with a rather fast response time, thus replacing oil and natural gas in peak production.

Solar thermal with low operation costs is an attractive way to cut CO_2 emissions in district heat production. Bioenergy is expected to be a good complement to variable solar thermal production due to its easy storability and balancing ability. Reference cases of solar thermal integration with district heating biomass boilers can be found for example in Denmark. So far, solar fractions of 5-25% (i.e. ~10,000 m^2, ~7 MWth) are most common, but even larger systems are foreseen to be cost-effective [72]. Large-scale heat storage, usually found in the district heating system, improves the usability of the solar heat. In the district heating area, centralised solar heat production is identified to be more beneficial than building-scale production due to economies of scale [64].

The economic feasibility of solar thermal and biomass integration depends on the price of the fuel replaced.[4] The solar heat price in Denmark has fallen to 30 €/MWh, with the average price being around 45 €/MWh [72]. The cost-competitiveness is expected to further improve due to reduction in collector prices. In existing large solar thermal installations in other applications, investment decisions have mostly been made based on economic benefits. Solar thermal can also bring operational benefits: the minimum heat load covered by a biomass boiler with rather poor part load efficiency or by fossil oil can be avoided during the summer period. However, the reduced operating hours of the boiler, CHP based power production and faster achievement of minimum load of the boiler are potential barriers for large-scale solar thermal investments.

Industrial applications

Large energy consumption, a high share of fossil fuels (excluding the pulp and paper sector) and availability of different waste heat resources create potential for hybrid systems in industry. Grid sourced power can be replaced by auto power production, but the largest potential exists in the heating and cooling sector. However, industrial heat demand is typically associated with higher temperature levels than district heating and cooling networks, and can therefore be considered as a separate market. The potential heating and cooling sources in addition to bioenergy are solar thermal energy, heat pumps and different waste heat sources, which are typically found in industry.

In Finland, the energy consumption in industry was 521 PJ (144.7 TWh) in 2014, representing 47% of the final energy consumption [74]. The largest energy source is wood fuels with a share of close to 35% i.e. 182 PJ (51 TWh). Oil, natural gas and coal still represent 12%, 8% and 7.5%, respectively, equating to a potential of 143 PJ (40 TWh) for renewables. The largest energy consumers were the forest industry, chemical industry and metal industry. One example of a bioenergy RES hybrid system in the food industry is the combination of biogas combustion and ventilation heat recovery for heat production. The total energy use in the food product manufacturing industry is 16 PJ (4.5 TWh) and in the beverage manufacturing industry is 2 PJ (0.57 TWh), or a total of 18 PJ (5 TWh) [75].

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[4] For example in Denmark, the household gas price (2012, 2nd half) was close to 110 €/MWh [72].

In many countries, solar energy is already utilised in industrial heating and cooling applications. For example, PepsiCo's Tolleson facility in Arizona uses solar thermal collectors to produce hot water, thus reducing the natural gas consumption of the facility (7% annually), and Heineken Breweries is installing solar thermal collectors in all of its facilities to produce process heat. Example of solar thermal utilisation in a brewery is shown in Figure 14. In Europe, the food industry has begun using solar energy for process heat production [76][77]. In Finland, the challenge for industrial solar thermal utilisation is the mismatch between production and demand. However, the already widespread utilisation of bioenergy offers a potential complement to solar thermal due to its storable nature.

Figure 14. Savosolar's collectors for process heat production in a brewery in Austria, ©Savosolar.

Waste heat recovery plays an important role in industry in increasing the overall energy efficiency. This, combined with bioenergy, offers a good basis for renewable heating and cooling solutions. For example, Saarioinen, a food industry company, has invested in solutions which recover waste heat from the cooling system to the heating system. While bioenergy and ground-source heat are typically alternative heat sources at household scale, at industrial scale the integration can achieve economic feasibility.

Farm-scale applications and biogas

The direct energy consumption in agriculture in Finland was 36 PJ (10 TWh) in 2013, thus representing approx. 3% of the final energy consumption. Bioenergy made up 45% i.e. 16 PJ (4.5 TWh) of the total consumption, while light and heavy fuel oil represented 34%, with electricity 15% and peat 6%, respectively [78]. The numbers roughly indicate a 20 PJ (5.5 TWh) potential for renewable energy in agriculture. High oil consumption as a vehicle fuel opens up potential for liquid biofuels and also for biogas. Approximately one-third of the oil i.e. 4.2 PJ (1.2 TWh) is consumed for heating and drying, and could be replaced with renewable sources. In addition to the 36 PJ (10 TWh) consumption in agriculture, 6.5 PJ (1.8 TWh) of energy is consumed annually in greenhouses (size >1,000 m^2) [79][80].

The main drivers for renewable energy implementation at energy-intensive farms are reliable energy delivery, energy self-sufficiency and minimized energy related costs. The number of farms in Finland was around 51 000 in 2015 [81], resulting in an average annual energy consumption of 709 GJ (197 MWh) per farm. The continuously decreasing number of farms and the increasing unit size create greater potential for hybrid systems. Since the energy consumption is high, it is challenging to economically cover all the demand with a single energy source. Different process integration options become interesting in order to reduce waste energy, resulting from the mismatch between demand and production over the year. Currently, the utilisation of RE on farms aims to reduce the consumption of oil and grid power. When bioenergy utilisation becomes wider, variable RE sources can either decrease the biomass consumption and use it rather for balancing, or increase the amount of further refined biomass based products.

Wood and wood chip drying can reduce the required amount of raw material for energy production and lead to annual savings of thousands of euros [82]. Potential heat sources for drying are waste heat from CHP production and solar thermal, both of which are focused on the summer period, when the drying is also most efficient. Based on average wood chip utilisation of 120 loose m^3 on a farm in Finland [83], the total theoretical potential wood chip consumption would be 15.4–22 PJ (4.3–6.1 TWh) and the energy required for the drying would be 2–3.5 PJ (0.6–1 TWh), depending on the time of the year (consumption 93 kWh/i-m^3 in the summer and 158 kWh/i-m^3 in the winter [55]). The annual use of wood in small residential buildings (incl. buildings on farms) is in the range of 5 million solidm^3. Of this, 1 million solidm^3 is sold on the markets (6.1–9.4 PJ i.e 1.7–2.6 TWh), and could be theoretically dried [84].

The highest biogas production potential in Finland is estimated to be in agriculture [85]. Biogas technology has the potential to efficiently combine energy production, waste treatment and nutrient recycling on farms, while simultaneously improving self-sufficiency and the economics of the farm. The annual manure production from domestic animals is over 17 million m^3, leading to a techno-economic potential of 3.2–6.5 PJ/year (0.9–1.8 TWh/year). The biogas potential from the fields is estimated to be approx. 16.9 PJ (4.7 TWh) [86]. However, the market uptake of the technology has been slow, and the share of farm-scale biogas production as a proportion of all production is small (<1%). Bottlenecks include high initial investment, case-specific subsidy policy and the expected work load for the farmers. However, in recent years, market growth has been seen.

With the current policy framework in Finland (investment subsidy and FiT) not all individual farms are able to invest in their own biogas reactor and biogas production is not shown to be feasible at small-scale [85][87]. It might be challenging to find a use for the heat especially during the summer period; one solution is to use it for wood chip or grain drying. Profitability can also be increased by refining biogas for transport, which approximately doubles the benefit with respect to power and heat production [88]. Transport gas production on farms (possibly by forming cooperatives) and in larger reactors improves the gas availability in locations outside the natural gas grid.

In Finland, natural gas is used to connect biogas sources with demand [88] and to reduce the need for local biogas storage. Waste streams from the forest industry offer great potential for biogas production [89]. According to Gasum, the annual wood based biogas production potential could be 54 PJ (15 TWh) [89], corresponding to almost half of the current (2014) natural gas demand [74] and significantly contributing to CO2 reductions (Figure 15). Sitra's estimate for the annual techno-economic biogas potential based on biomass waste (excl. synthetic biomethane) is 18.4–50 PJ (5.1–

13.9 TWh) [90]. By replacing natural gas, which represented 7% of the total energy consumption in 2014 [74], a higher degree of self-sufficiency could be achieved.

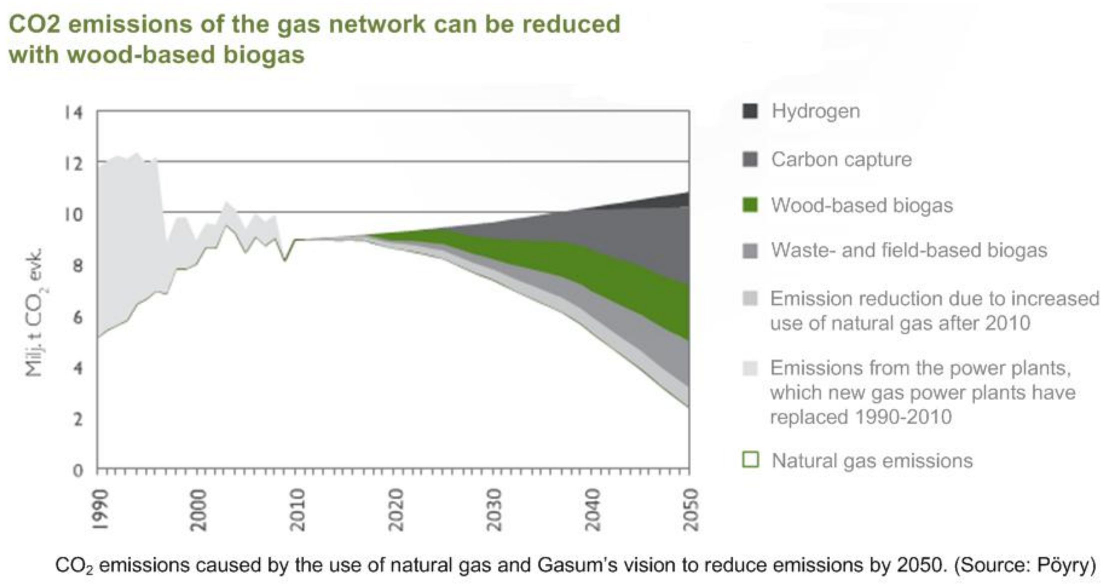

Figure 15. Gasum's vision to reduce CO2 emissions with biogas [89].

Biomass-based energy storage applications

Biomass-based flexibility options are not only confined to energy generation but also include solutions for flexible energy storage. In the following text, drying of biomass and chemical storage of electric energy through hydrogen into biofuels are discussed as examples of biomass based energy storage concepts.

Using VRE to dry solid biomass is a potential long-term and low-cost form of energy storage. During drying both the heating value and the quality of solid fuels are increased. Other benefits include better fuel management, particularly during winter time when large fuel storage and better quality fuel are needed to meet demand peaks. Lower moisture content of biomass also prevents dry matter losses, and improves the efficiency of the thermal conversion processes [91]. If biomass is dried close to the production site, significant cost reductions in road transportation can also be attained.

Recent improvements in the efficiency and cost of solar thermal systems also reduces the cost of solar drying of biomass in tandem with the increasing need for seasonal energy storage. The storage of solid biomass fuel already plays an important role in all bioenergy supply chains. In practice the most feasible way to apply solar drying, and to store dried biomass, is to carry it out in small units, for example on farms, where biomass sources are closer and all logistical solutions are easier to execute compared to urban areas.

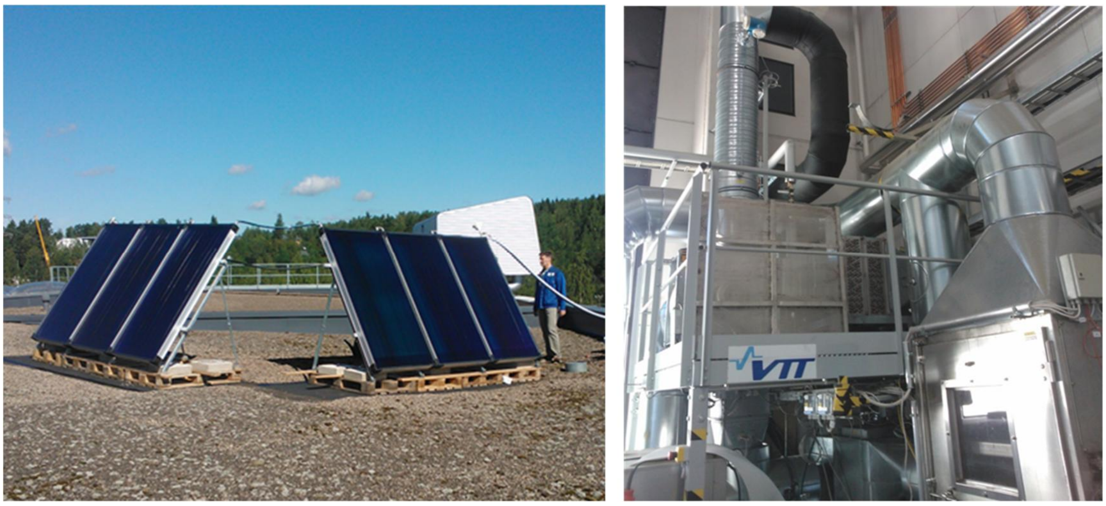

Figure 16. Solar thermal collectors and biomass dryer used by VTT to investigate the possibilities for using solar energy to dry biomass.

The suitability and economics of solar drying of biomass have been studied e.g. by VTT, and initial tests have already been conducted to understand how solar drying differs from traditional warm air drying (see Figure 16). Regarding benefits, new applications for dried fractions and the improved profitability of transport chains are some of the key factors that are expected to provide benefits along with the increased energy density of the solid biomass.

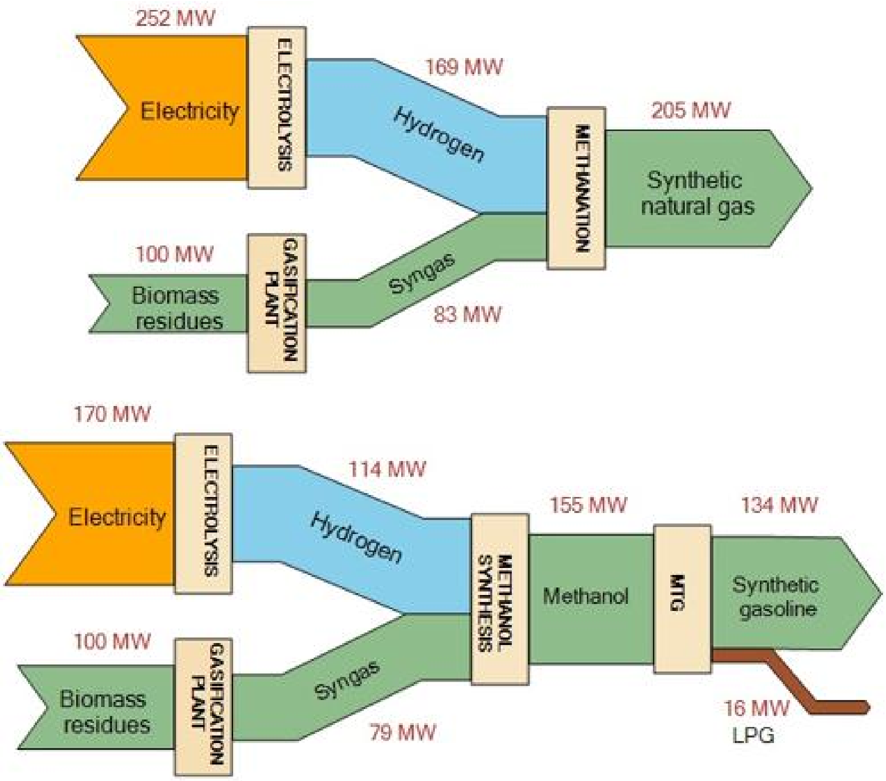

Figure 17. Exemplified energy balances for the production of synthetic fuels from electricity and solid biomass via gasification.

RES integrated biorefineries have recently been advanced as a possible energy storage solution. Most commonly the proposed concepts involve the integration of low-carbon electricity with either biogas or syngas by using electrolytic hydrogen as an intermediate. Such integration allows either intermittent or continuous operation, depending on the ultimate goal. Intermittent operation strategies aim to create demand for VRE during times of excess and thus effectively reduce the need for curtailment. Such operational strategies seek to benefit from the low wholesale price of energy during times of high supply and low demand, but suffer from the low capacity utilisation rates that lead to a high share of capital expenses in the levelised production cost [92].

Concepts that allow continuous operation of RES integrated biofuels production are not driven by flexibility issues, but aim to increase biomass resource efficiency by maximising carbon conversion during biofuels production. Possibilities for equipment sharing also exist and the resulting increase in biofuel output can be very significant, reaching even up to a 2.6 or 3.1-fold improvement depending on the process configuration [93]. However, a continuous low-cost, low-carbon source of electricity is needed to ensure both feasible economics and adequate emissions savings.

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