VTT Technical Research Centre of Finland

Value-Optimised use of Biomass in a Flexible Energy Infrastructure

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RESEARCH REPORT

VTT-R-00807-21

Value-Optimised use of Biomass in a Flexible Energy Infrastructure – Summary report of ERA-Net VaBiSys -project

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beyond the obvious

Report's title

Value-Optimised use of Biomass in a Flexible Energy Infrastructure

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Summary

The overall objective of the VaBiSys project was to develop new technologies and concepts that improve the value of bioenergy resources in an energy system that is dominated by variable renewable energy (VRE) such as wind and solar.

When an energy system becomes dominated by VRE generation, completely new types of flexible resources are needed to maintain a stable and reliable supply of energy. Our project aimed to understand the role that bioenergy can play in this transition as a source of sustainable flexibility. As bioenergy is a finite resource, it will be important to identify those applications and concepts that bring most value for the future energy system.

These issues were addressed by 1) Development of new bioenergy solutions to serve energy markets with a high need for flexibility; 2) Significantly extending the flexibility of known bioenergy technologies; 3) Identification of costs, benefits and development needs for potential bioenergy concepts in a VRE dominated energy system; 4) Improved understanding about the economic, social and environmental sustainability of biomass used in a flexible energy system; and 5) Accelerating the deployment of flexible bioenergy technologies via market assessments and development of potential business plans.

The project consortium included three research organizations and partners from industries and SME's. In the research work packages led by the research organizations and Valmet Oy, the main objectives were addressed using energy systems modelling, computations fluid dynamic modelling, socio-techno-economic studies and by experimental research in pilot and commercial facilities. During the project, new solutions to expand the flexibility limits of existing boiler technologies were found, and new bioenergy technologies were validated. Based on the system level studies and techno-economic assessment, flexible bio-CHP plants can balance future energy systems, while further decoupling the energy system from the use of fossil resources.

Confidentiality	VTT Public

Helsinki 24.9.2021

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Preface

This is a public summary report on the main results and conclusions of the ERA-Net VaBiSys-project (2018-2021).

The VaBiSys project was funded under the ERA-Net Bioenergy network and BESTF3 ERA-Net co-fund mechanism. VTT would like to acknowledge Business Finland for providing the national funding for the project.

The project consortium included VTT Technical Research Centre of Finland Ltd (VTT), DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH (DBFZ), RISE Research Institutes of Sweden AB (RISE), Valmet Technologies Oy, Enertech AB, Falbygdens Energi AB, SFTec, Helen Oy and E.On Gas Sverige AB. VTT acted as the coordinator of the consortium.

Helsinki 24.9.2021

Authors

Contents

1. Introduction

The global energy system is currently in transition, driven by reductions in the generation costs of variable renewable energy (VRE), such as solar and wind power. Furthermore, the looming climate crisis causes political efforts to shift to a low-carbon society by cutting GHG emissions. Today the cost of VRE has already reached, or is approaching, the cost of conventional power and heat generation options. Because the trend is likely to continue, it will lead to high shares of VRE in the energy system.

For energy systems that are characterised by stagnating electricity demand and well developed supply infrastructure (as in most developed countries), a rapid addition of new VRE generation puts extreme technical and financial pressure on existing generators that were originally designed to operate as baseload units. This happens because high penetration of VRE quickly erodes the capacity factors of baseload units and renders these capital-intensive plants unprofitable and/or unusable. In addition, oversupply from both pre-existing capacity and VRE additions tends to depress wholesale market prices, as can be currently observed in several European markets. Low prices can trigger the retirement of pre-existing generation capacity and thus raise the important question of how to best maintain the stability and reliability of the future energy system.

From the technical aspect, a reliable supply of energy can be maintained in the future by using conventional and mature fossil technologies, but the mitigation targets agreed by the world’s governments in the Paris agreement are incompatible even with fossil fuel power plants in a supportive role. As a result, there exists a clear need for new integrated low-GHG technologies that can balance energy demand with energy supply. This situation is creating a new operational environment for bioenergy. Essentially the flexibility, such as the ability to quickly respond and adapt to higher fluctuations in the electricity demand in the grid, of bioenergy production will gain importance. As sustainable bioenergy is a finite resource, it will be important to identify those applications and concepts that bring most value for the future energy system.

2. The main objectives of the VaBiSys project

The VaBiSys (2018-2021) was a collaborative research project, where responsibilities of work packages were given to three research organizations (VTT, DBFZ and RISE) and an industrial partner Valmet Oy. The project had five specific main objectives:

1. Identify costs, benefits and development needs for potential bioenergy concepts in a VRE dominated energy system
2. Understand sustainability and acceptability issues related to biomass use in a flexible energy system
3. Significantly extend the flexibility of known bioenergy technologies
4. Develop new bioenergy technologies to serve energy markets with a high need for flexibility
5. Accelerate the deployment of flexible bioenergy technologies via market assessments and business plans.

The first and second objectives are addressed in the section 3 “Costs, benefits and impacts of bioenergy concepts”. The costs, benefits and development needs for flexible bioenergy concepts in VRE dominated energy systems were investigated using system modelling, in a work package led by VTT Furthermore, the work package strived to increase the understanding of the sustainability of flexible bioenergy from economic, environmental and social standpoints.

The third objective was pursued in a work package led by Valmet Oy, an industrial partner in the consortium. The technologies considered were solid fuel fired circulating fluidized bed (CFB) boilers, bio-oil boilers and Organic Rankine Cycle (ORC). The main results and conclusion on the specific objective are presented in section 4 “Flexibility limits of biomass power plants”.

Work under the fourth objective is reported in section 5 “Efficient and flexible CHP technologies for local self-supply” and section 6 “Design of new solar drying systems and optimized biomass logistics”. Regarding section 5, flexible operation of a small scale biomass-fired CHP units was assessed using simulation, in a work package led by DBFZ. In section 6, the results from the work led by VTT on the proof-of-concept and experimental evaluation of a solar drying system for food chips is reported.

Finally, the research efforts towards the fifth objective are reported in section 7 “Business perspective on flexible bio-based power production”. The associated work package led by RISE generated future scenarios, production portfolios and a system model for assessing investment profitability of new biomass CHP.

3. Costs, benefits and impacts of bioenergy concepts

3.1 Description of goal, scope and context of the work

The work focused on analysis of costs, benefits, and impacts of bioenergy concepts while improving the state-of-art modelling and analysing capabilities on several fronts. These included integrating a regional forest biomass supply chain to an energy system model, representing new biomass technology concepts as a part of the future energy systems, studying their impacts on local and system level, and assessing the social impact and public acceptance.

3.1.1 Integrating regional biomass supply chains with an energy system model

Separate energy system models and biomass supply chain models do exist and have been used together, but here we did a full integration of the modelling of regional biomass supply chains and energy systems (Figure 1). Typically, energy system models describe whole countries or only few regions within a country, e.g. electricity bidding zones, but the modelling of local demands is crucial with local biomass supply chains. Biomass is much cheaper to use near the place of supply and transportation results to additional costs and emissions.

Our model describes the forest biomass supply in Finland, including domestic forest biomass, industry waste wood, and imported biomass. For modelling purposes, Finland is divided into 19 regions providing biomass either directly or through terminals to the power and heat plants. Considered biomass feedstocks include industry waste wood (e.g. bark and sawdust), forest logging residues, small diameter stem wood, and imported pellets.

The model needs also finer division of power and heat sector's biomass demand in Finland. For modelling purposes, Finland is divided into 10 heating regions, one of which is the Helsinki's district heating and cooling (DHC) system. This part of the model enables to study the availability of biomass for Helsinki, considering demand in other heating regions, and the impact of the biomass-based heating solutions in future energy system in light of the information obtained from power sector and the biomass supply side of the model.

These more detailed regional models are integrated to a model of Northern European power system.

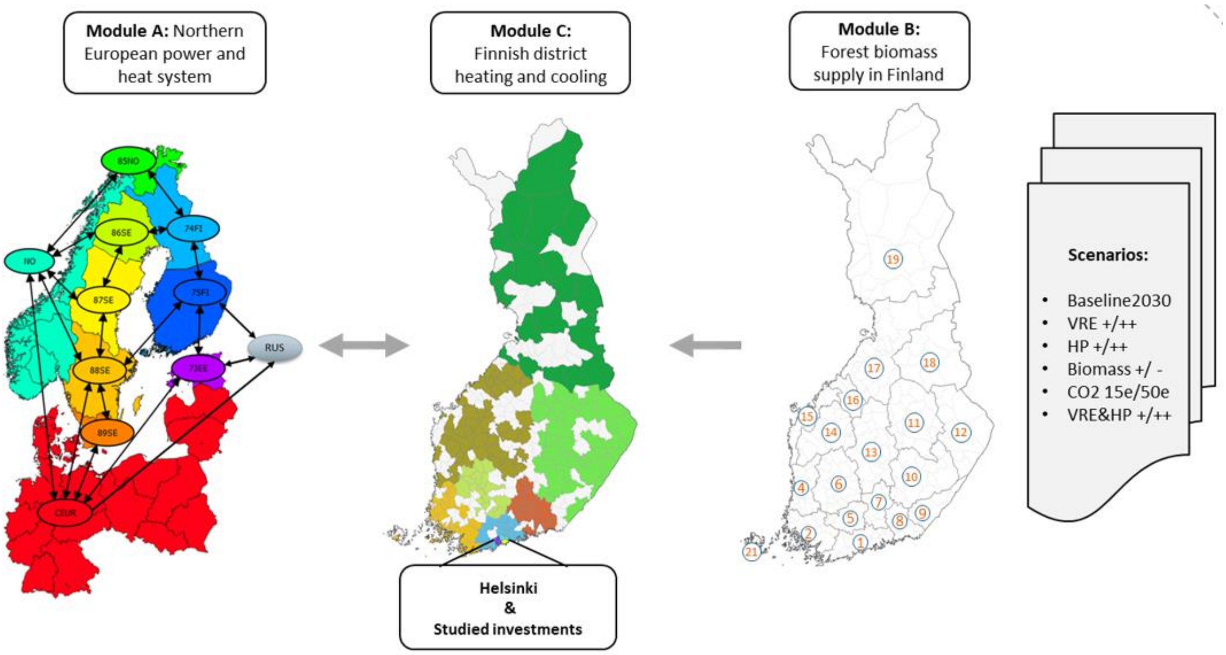

Figure 1. The modelled system includes Northern European energy system (Module A), more detailed power and district heating model for Finland (Module C), and forest biomass supply for Finland (Module B). Each module fully interacts with each other and are optimized simultaneously.

3.1.2 Representing biomass technology concepts in future energy systems and evaluating their impacts on multiple criteria

The impacts of bioenergy concepts were studied in two case studies. One case study was from a small district heating system with 20 MW peak power and the other one from a much larger system with 3000 MW peak power. The scale of the systems and existing units in these two systems are very different and require solutions in whole different scales.

In a smaller system, we were able to simulate the operation of the whole system with a CityGML model (Figure 2). The coloured buildings are connected to the district heating network. The colour indicates annual peak heat demand (W/m2/year).

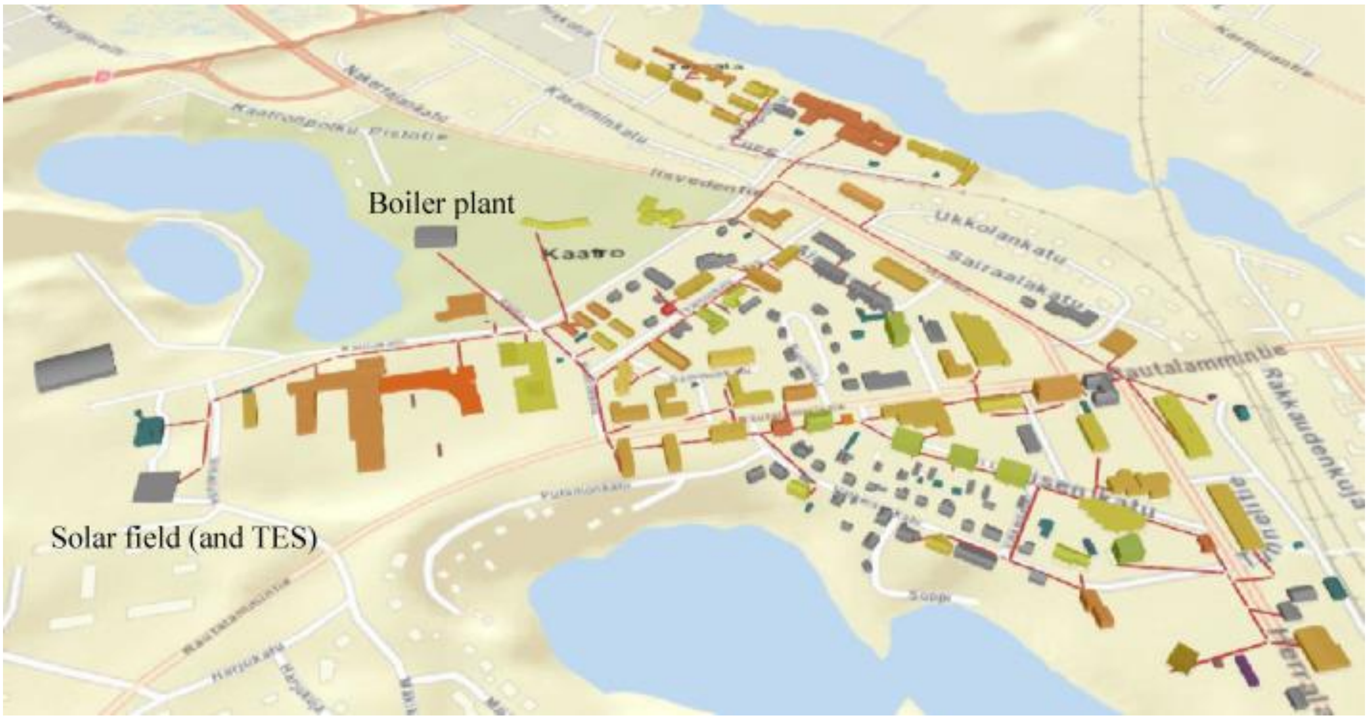

Figure 2. Schematic illustration of the smaller case study and the simulated system.

The focus of the study was the role of solar heat in decarbonization of a Nordic district heating (DH) network, where most of the annual heat demand is satisfied with bioenergy. We used actual data from a Finnish municipality to create a dynamic model of the heating system with Apros® simulation software. With the help of modelling, we examined various decarbonization scenarios for the existing heating system, using different combinations solar thermal collectors, thermal energy storage (TES) and limitations on how and when solar heat can access the system.

The other case study took a deep dive on local and system level impacts of bioenergy technologies in phasing out fossil fuels from a DHC system of the Finnish capital. The modelled system is more complex than previous one and it was modelled on a more general level (Figure 3). We modelled multiple future scenarios and assessed the impacts on energy security, flexibility provision, economic performance, and emissions.

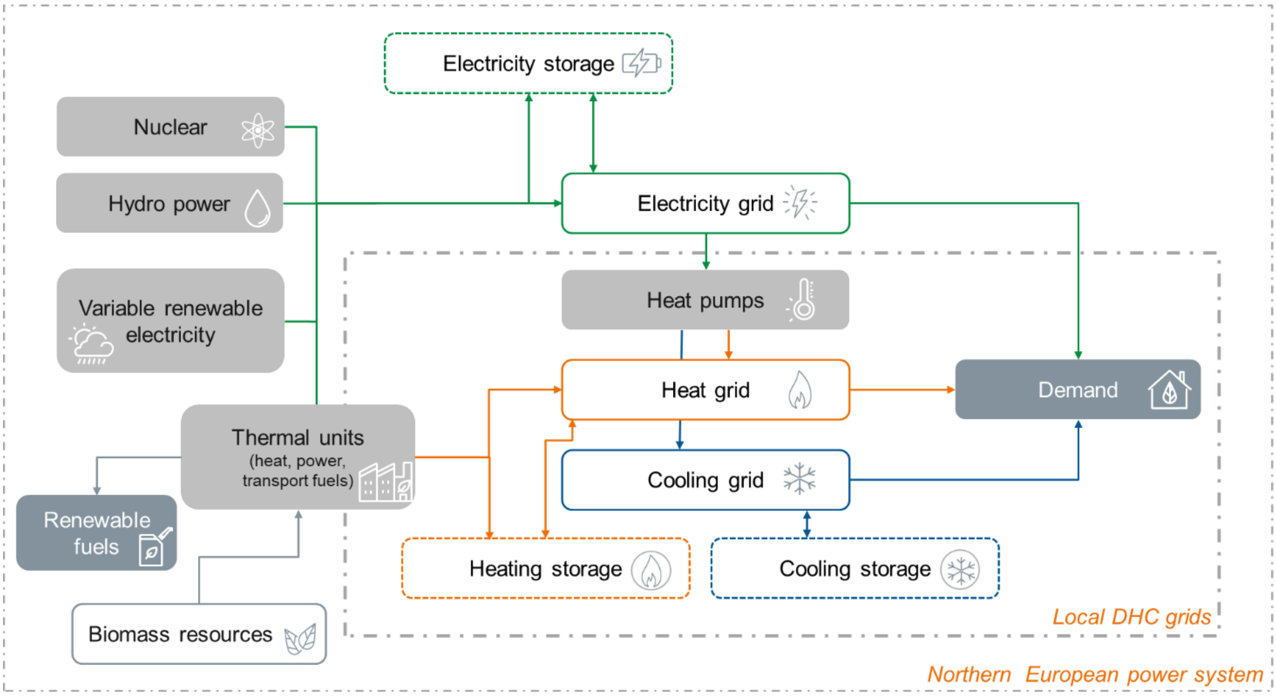

Figure 3. Schematic illustration of the modelled energy system in the larger case study.

3.1.3 Social impact and public acceptance assessment for the bioenergy concepts

The work in this task was focused around the concept of social acceptance, and how it could be applied in the context of flexible bioenergy. Social acceptance of renewable energy technologies is often described to consist of three interlinked dimensions of public acceptance, socio-political acceptance and market acceptance. As many of the flexible bioenergy concepts studied in the project were still in development phase, the main focus of the task was on factors that could be important especially from market acceptance point of view. Within research literature, market acceptance has been defined as a process of market adoption of an innovation (Wüstenhagen et al. 2007). In addition to acceptance by consumers and end-users, intra-firm relations and acceptance by investors and market players are essential elements of market acceptance.

The work was based on a literature study and expert interviews and discussions among the consortium members. Five expert interviews were held during 2020. Some of the interviews were conducted as pair-interviews and thus altogether eight experts from five different organizations participated to the discussions. Interviewed experts consisted of researchers and company representatives from Finland, Sweden and Germany. Participating experts represented research institutes working with bioenergy, public and private energy companies and technology manufacturers. During the theme interviews, the three dimensions of social acceptance were discussed, focusing especially on potentially relevant criteria for market acceptance. The findings from the interviews were analysed using a conceptual framework developed by Sovacool & Lakshmi Ratan (2012).

3.2 Main results

According to results of the smaller case study, zero emissions during the summer can be achieved with annual solar share of 13.2% and at 44 €/MWh levelized cost of heat (LCoH), if the integration is supported by TES and a careful planning of solar heat integration. Our results show that a simple approach of pursuing for a maximal solar share does not necessarily lead to a reduction in carbon emission or in LCoH. In fact, aiming at higher solar shares of 15–25% in our case system, actually increase greenhouse gas emissions compared to the base case. This highlights the importance of focusing on emissions reductions instead of simple addition of renewable energy when DH utilities plan for solar heat investments. The results are published in a journal article (Mäki et al. 2021).

In the case of Helsinki, heat only boiler was found to be a robust solution from economic and climate perspective, but it reduced local electricity self-sufficiency. Combined heat and power solution was more valuable investment for the system than for the city indicating a conflict of interest and biased results in system level models. Bringing a biorefinery near the city to utilize excess heat would reduce emissions and increase investment's profitability, but biomass availability might be a bigger limiting factor.

Our results show that the availability of domestic biomass resources constrains bio-based technologies in Southern Finland and further highlights the importance of considering both local and system level impacts. Novel option to boost biorefinery's production with hydrogen from excess electricity is beneficial with increasing shares of wind power. The method and results are documented in a journal article (Lindroos et al. 2021).

The socio-political and community level acceptance of bioenergy is a topical question. While the importance of renewable energy has been largely recognised, local bioenergy projects have also faced resistance, and the role of biomass in the energy system has been under debate. In addition, the political framework is changing at the national and European levels, creating uncertainty to the markets.

Acceptance of flexible use of bioenergy is tightly connected to acceptance of bioenergy. Especially, the task results suggest that the key factors of socio-political and community acceptance of flexible bioenergy are closely intertwined with those of bioenergy in general. On the contrary, aspects specific to flexible use of biomass seem relevant for its market acceptance. Under current conditions, the results suggest economic aspects as the major barriers for acceptance of flexible bioenergy. Thus, successful cases and examples of profitable business cases would be needed in order to enhance acceptance of the emerging concepts for flexible use in future. Market acceptance may be further hindered by lack of knowledge and relevant tools, and lack of sufficient cooperation between the different market players.

In addition to market acceptance, it is important to address public and local concerns related to environmental sustainability of biomass. If flexible concepts enable smart and more targeted use of biomass, it may have a positive effect on their acceptance. According to the results, flexibility is seen as a complicated concept that might be difficult to explain to non-professionals and to the public. This finding is important to consider in any future work related to the concept of acceptance.

3.3 Main conclusions

Bioenergy currently represents a “drop-in option” that enables significant decarbonization without major changes at system level. New biomass-based technology options include integrated processes, for example the production of transport fuels and utilizing the excess heat in district heating. However, expanding the use of bioenergy has its own constrains, most important ones being its availability, logistics of raw material, and social acceptance. Each of these vary from location to another and understanding local conditions is a crucial part of the bioenergy development projects.

Studied biomass options reduced the emissions within the energy system, but sometimes had mixed impacts on local level and system level. For an example when fossil fuel CHP units are replaced with biomass heat only boilers, the lost electricity production needs to be replaced with other units in the system, and that, at least temporarily, means a rebound effect when the use of fossil fuels increases in the other parts of the system. Similarly, production of bioliquids from wood might increase emissions in the power and heat sectors but reduce more emissions in transport sector. These results highlight the need to study wider scopes and across the sectors to capture the full range of impacts.

4. Flexibility limits of biomass power plants

4.1 Solid fuel fired circulating fluidized bed (CFB) boiler for flexible generation

4.1.1 Description of goal, scope and context of the work

The initial objective was to assess and find ways of stretching the operational flexibility, namely minimizing the acceptable low load, decreasing the boiler start-up time and increasing the load change rate, of bubbling fluidized bed boilers and circulating fluidized bed boilers. Quite early, during the assessment phase, the highest technological and economic improvement potential was identified in the CFB boilers start-up time and low load development, hence the scope was narrowed from the initial plan. The greatest improvement potential was seen in

- faster start-up time (e.g. warm start 6 h → 3 h) and
- lower minimum load (40 → 20 % MCR).

The results will improve the possibilities of manufacturers to offer technologically and economically attractive solutions for flexible energy system. Further, the results were used in energy system evaluations made by other consortium partners.

4.1.2 Main results

Given targets were reached by removing the identified bottlenecks with improving the operation range of current solutions and creating novel solutions.

Start-up rate can be improved with utilizing high automation degree and advanced process control in plant operation, changing the refractory and pressure vessel, mainly drum design to meet the new temperature change rate requirements, designing the lower furnace and start-up boiler in a manner that the furnace heat up rate is adequate. It is a solution combining several factors, consisting of mechanical and operational items, focusing on various areas of the CFB boiler. The fast start up solution meets the requirements of industrial standards and can be commercially utilized.

Low load improvement comes with a combination of mechanical and operational items also. Typically, decreasing furnace temperature is limiting the low load operation, hence one cannot go below given process conditions. With novel mechanical design, combined with advanced process control, it is possible to reach lower minimum than previously, approximately 40 → 20 % of full design load.

Development of above mention solutions contained various methods from empirical full-scale boiler measurements and process analysis to multiphase CFD modelling and dynamic boiler simulation, not to forget FEM and other mechanical modelling.

CFD modelling was used to investigate operation of existing and alternative CFB boiler designs at full and low loads. The goal was to determine how the low load operation could be improved without compromising the full load performance. As an example, Figure 4 shows temperature and particle volume fraction fields for simulations of an existing CFB that served as the starting points for the development. The simulations were carried out with models developed at VTT for full scale CFB simulations. During the project these tools were developed further to better capture the mixing behavior in the bottom bed at ultralow loads.

CFD modelling was also used to investigate the distribution and evolution of thermal loads on the boiler refractories during start-up. Figure 4 also shows a snapshot from a cold start simulation. Relatively short multiphase combustion simulations were carried out iteratively with longer refractory thermal conduction simulations to capture the evolution of the thermal during the start-up ramp. The results served as input for start-up burner placement and design, more detailed FEM modelling of refractories and evaluation of limiting factors of refractory materials.

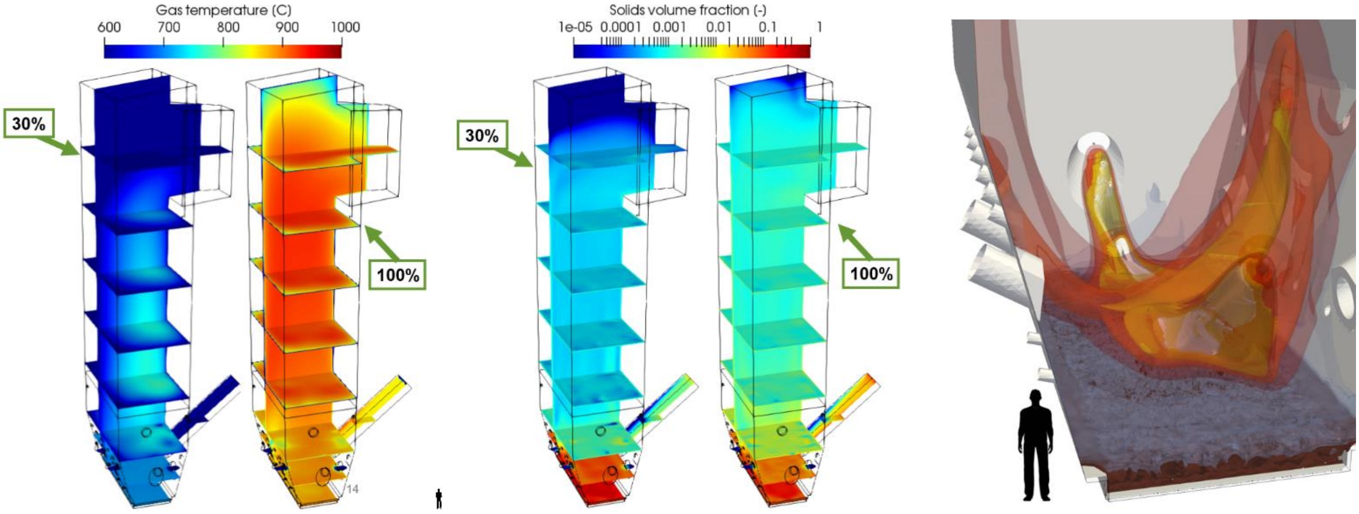

Figure 4. Examples of CFD simulations: a CFB boiler in steady operation at 30% and 100% loads (left and centre) and a CFB start up simulation (right).

Additional capital and operational cost of fast start-up rate and low load solutions were calculated and compared against benefits. Depending on the assumptions on heat and power price fluctuations, it was seen the payback time of given solutions were between 1-3 years, which is considered reasonable in this industry.

4.1.3 Main conclusions

The objectives to increase operational flexibility of CFB was reached by creating solutions to enable low minimum load and faster start-up time. Based on indicative techno economic analysis, the solutions are feasible, having payback times 1 – 3 years. Results are indicative and subject to input assumptions, such as future wholesale power price. New, flexible CFB boiler is profitable in a fluctuating energy market and thus CFB technology can have a role in balancing the wind and solar dominated varying energy system.

4.2 Operation limits of a bio-oil boiler and ORC

4.2.1 Description of goal, scope and context of the work

A biopower plant that uses solid biomass such as wood chips needs to produce large volumes of electrical energy during the year to get economy. A biopower plant also needs to have a stored resource that can produce electricity when it is needed and to be a flexible resource in the energy system. These usually consist of back-up and top-load facilities that have few operating hours, perhaps none in certain years, but they are important because they have high starting availability and fuel in storage. A fuel that can be used for these purposes is bio-oils. Bio-oils are currently used as top-load plants in several CHP plants, e.g. of Stockholm Energi but could be used to a greater extent.

The most common customers of bio-oil in Sweden today are district heating producers, industrial companies, greenhouses, grain dryers and heating of properties. Today, there is good knowledge of how bio-oil should be handled and what technology is required for efficient and stable combustion. Bio-oils mainly consist of vegetable residues and waste products from food and technical production.

For most smaller district heating plants around Sweden, the plants are built with hot water boilers that deliver >120 °C and work with relatively low pressure. To produce electricity, mainly ORC technology is used. Turboden ORC is a specific technology where the boiler is oil-filled and works with temperatures up to 300 °C and a relatively low pressure in comparison with steam. The high temperature means that the efficiency of the ORC unit is significantly better, up to of 25%, but the challenge is that it requires a new boiler and equipment to handle hot oil. The advantage is that hot oil is not pressurized in the same way as steam and that the system thereby becomes somewhat simpler and cheaper. Through heat exchangers, hot water can then be produced, which means that the district heating system can function normally. The requirement for a new boiler means that an installation of a Turboden ORC only becomes relevant in the event of a complete boiler replacement.

The aim of this task was to investigate the performance of the energy system at Falbygdens Energi, Sweden with respect to emissions, ramp rates and flexibility limits. Specific aims were to find the operation limits of the bio-oil boiler and the ORC. This was investigated by performing a measurement campaign in November 2019. The tests were performed in a collaboration between Falbygdens Energi, Enertech and RISE.

4.2.2 Main results

Falbygdens Energi supplies the small city of Falköping with district heat and also some electricity to the grid. The plant consists of two grate fired solid fuel boilers (Marjarp I and II) and one bio-oil boiler. The grate fired boilers are fired with wood chips and are used as base load in the district heating net. The bio-oil boiler is only used for peak load or as back-up. The Marjarp II boiler and the bio oil boiler were used in this study. The Marjarp II boiler is a hot oil boiler, i.e. uses oil instead of water in the heat exchangers, which is connected to an ORC (Organic Rankine Cycle) that produce 2,4 MW electricity and 10 MW heat at full load. The ORC system is provided by Turboden S.p.A[1].

Bio-oil boiler

The bio-oil is stored in a heated tank with a maximum capacity of 200 m^3, the temperature of the oil is maintained at 42 °C. A common concern when storing bio-oil is that it is degraded over time. The potential biogenic processes that may occur in the oil is depending on the origin of the oil, storage conditions and the production process. Bio-oil can be produced from a large variety of sources *e.g.* forest, agricultural or food residues. The origin of the oil used at the Marjarp plant is from vegetable raw materials and it is called Bio 25. Two fuel samples were taken during operation of the boiler, the samples were taken at full load and at low load at two different days, each sample was 5l. The fuel analysis of the oil is shown in Table 1. A part of the aim with this present study was to assess the use of bio-oil in terms of storage and handling over time. This is done by interviewing the plant staff and present their experience in this report. In general, the staff experience is positive regarding the bio-oil, no significant issues have been reported during the years the plant has been using bio-oil. The oil that is used can be stored at their facility for several years without any noticeable degradation.

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[1] Company website: https://www.turboden.com/

Table 1. Fuel analysis of bio-oil.

	Sample 1 Full load	**Sample 2 Low load**
Density 15˚C, g/cm^3	0,9144	0,9143
Density 40˚C, g/cm^3	0,8958	0,8957
Viscosity, 40˚C, mm^2/s	31,2	31,3
Viscosity, 80˚C, mm^2/s	9,77	9,73
Moisture, mass-%	0,3	0,4
Ash, mass-%	0,054	0,024
Sulphur, S, mass-%	<0,01	<0,01
Carbon, C, mass-%	76,3	76,0
Hydrogen, H, mass-%	11,9	11,9
Nitrogen, N, mass-%	<0,05	<0,05
HHV, MJ/kg	39,24	39,24
LHV, MJ/kg	36,71	36,71

Load flexibility and response time

The bio-oil boiler is constantly being held at stand-by to enable fast start-up if any of the solid fuel boilers goes down. This mean that some water is circulated through the boiler and it is typically being held at 68 °C. The normal start-up sequence begins with 3 minutes long pre-ventilation of the combustion chamber. After that, the burner is started, and the load is increased in incremental steps until full (or the desired) load is reached. The typical start-up sequence is shown in Figure 5, where both the control signal to the burner and the oil flow is shown. The time to reach full load is approximately 13 minutes (+3 min pre-ventilation). When running the boiler in manual operation it is possible to obtain a faster start by manually setting a faster ramp up of the control signal to the burner. In this mode, the time to reach full load is 80 s (+3 min pre-ventilation). The burner can be operated at any load between minimum load (approximately 15%) and full load. The time to increase load from stable conditions at 1,8 MW (minimum load) to full load is approximately 1 min. The reverse process is slightly faster and to decrease from 12 MW to 1,8 MW takes 40 s in manual operation.

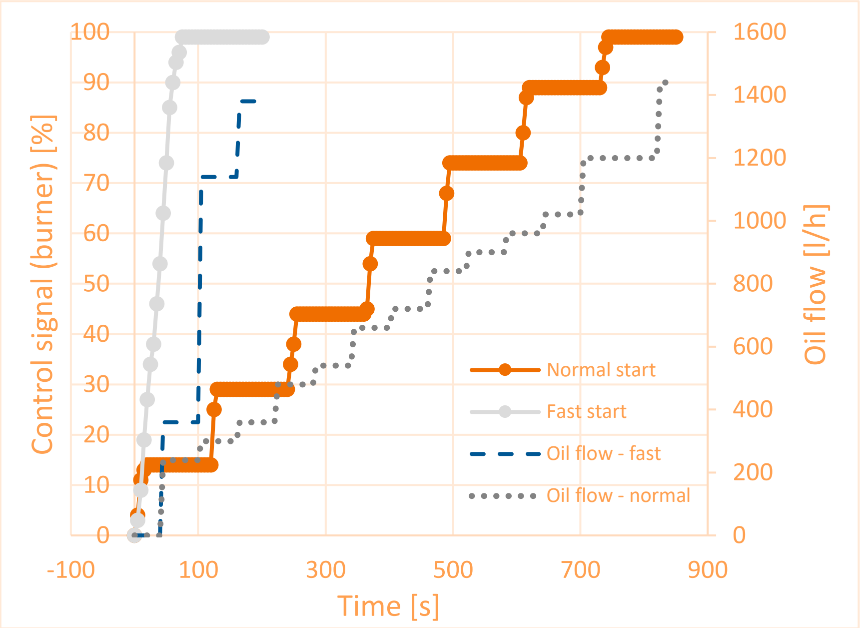

Figure 5. Test of start-up from cold conditions. Normal start and a forced fast start.

However, the presented ramp rates relate to the burner load. The actual load increase in the district heating system is slower than the burner load increases due to the thermal inertia in the water contained in the tube walls of the boiler, approximately 30 m^3. The response time in the district heating system is to a large extent affected by other parameters that the start-up of the burner. Typically, the circulation through the boiler is kept low during start-up since the water temperature is too low to be directly fed into the district heating system. The temperature needs to be increased from the stand-by temperature (68 °C) to the district heating temperature which is approximately 85 °C. Figure 6 show the temperature and flow delivered to the district heating system during normal start-up of the boiler. The water flow is gradually ramped up from the pre-ventilation of the boiler until full load is achieved. As the figure show it is difficult to quantify the response time for a heat only boiler as it is so tightly connected to other circumstances, *e.g.* outlet temperature of the water.

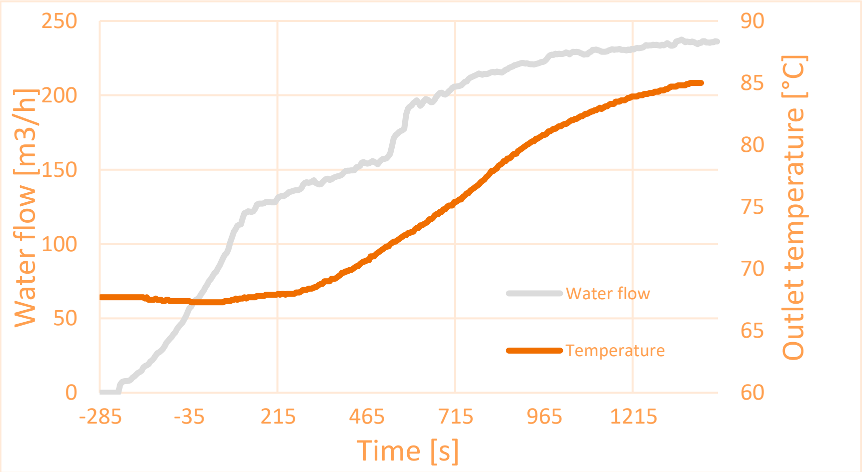

Figure 6. Test of start up from cold conditions. Normal start and a forced fast start. Time 0 min is when the burner is started.

Emissions of bio-oil boiler

The emissions from the bio-oil boiler was measured five different test cases to show how the emissions of gases and particles are affected during start-up and shutdown of the boiler and when changing load. The operating conditions and corresponding emissions are shown in Table 2.

Table 2. Emissions during high- and low load.

Operating mode	**NO mg/nm^3, 6 % O_2**	**SO2 mg/nm^3, 6 % O_2**	**CO mg/nm^3, 6 % O_2**	**O_2 %**	**CO_2 %**	**Particles (dust) mg/nm^3 6 % O_2**
From cold to full load (Normal cold start sequence)	104	0,5	1	5,1	11,7	18
Full load. Normal operation.	116	2,8	<1	4,4	12,2	19
Full load to low load. Stop in the meantime.	117	4,7	5	6,9	10.3	23
Low load	104	4,6	<1	5,7	11.3	17
Low load to full load, fast	114	4,4	<1	4,6	12.1	19

As Table 2 show, the emissions are generally low and the differences between the cases is minor. The particle sampling takes 30 min and the results are thus a result of a 30 minutes average. To illustrate this, a plot of CO and NO emissions during normal and fast start-up is shown in Figure 7. During start-up there is a small CO-peak but after approximately 30s the emissions reach steady state conditions and the differences between the test cases are not shown since the sampling is done for 30 minutes. In conclusion, the emissions from the bio-oil boiler is not significantly affected during start-up or when changing load.

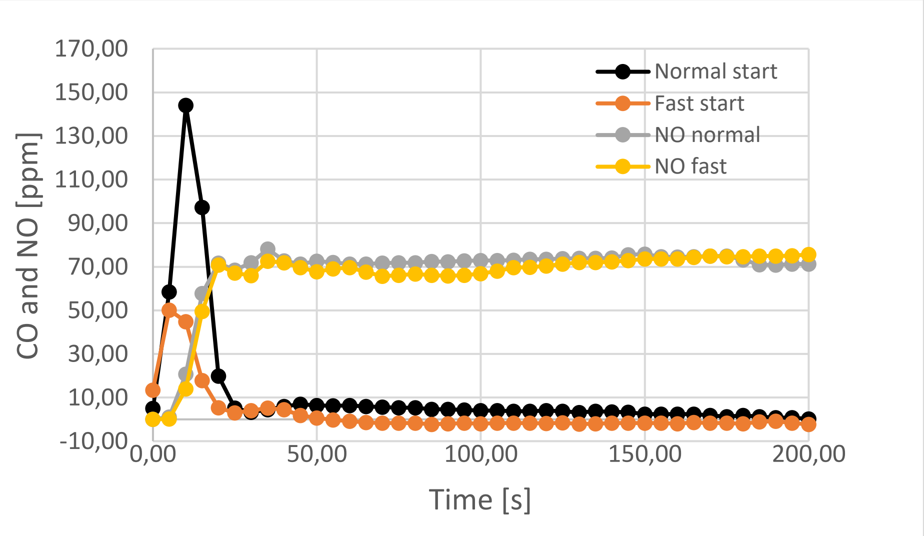

Figure 7. Test of start-up from cold conditions. Normal start and a forced fast start. Time 0 min is when the burner is started.

Load flexibility and ramp rate ORC

The electricity production in the ORC is in this case decreased by bypassing oil in the three-way valve at a maximum rate according to the operators’ experience (see Figure 8). If the ramp rate is decreased further loud “bangs” are heard from the ORC system. The sound is likely a result of uncontrolled gas formation or thermal stress somewhere in the system. The maximum decrease in electricity production is approximately 85 kW/min (based on the decrease from time 200 s to 600 s). The sound-problem is likely not a generic problem with the OCR technology, but something that can be solved in cooperation with the ORC manufacturer.

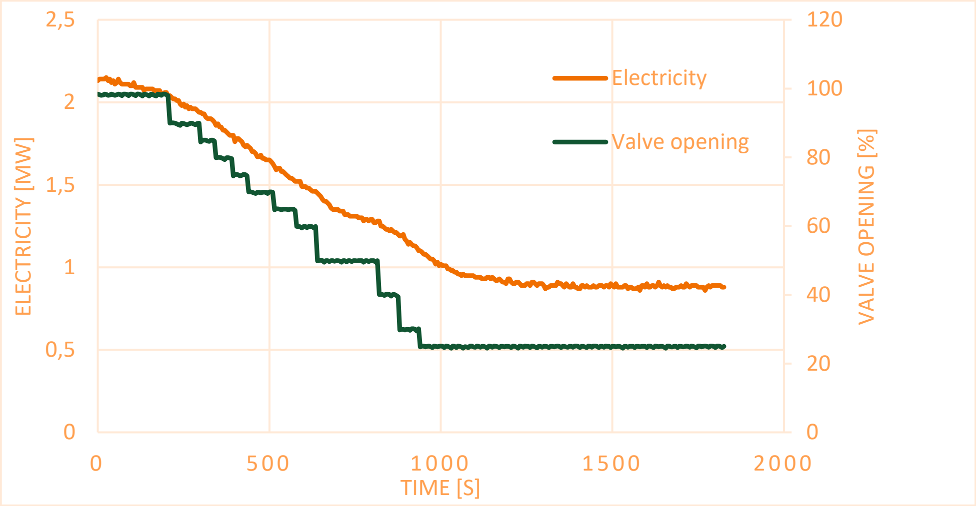

Figure 8. Decrease of electricity production in the ORC when bypassing the oil in the three-way valve.

The ramp rate when increasing the electricity production by opening the three-way valve is shown in Figure 9. As the figure show the set point of the valve can be increased faster, since no problems with “bangs” occur when increasing the load in the ORC. The ramp rate is approximately 172 kW/min in this case.

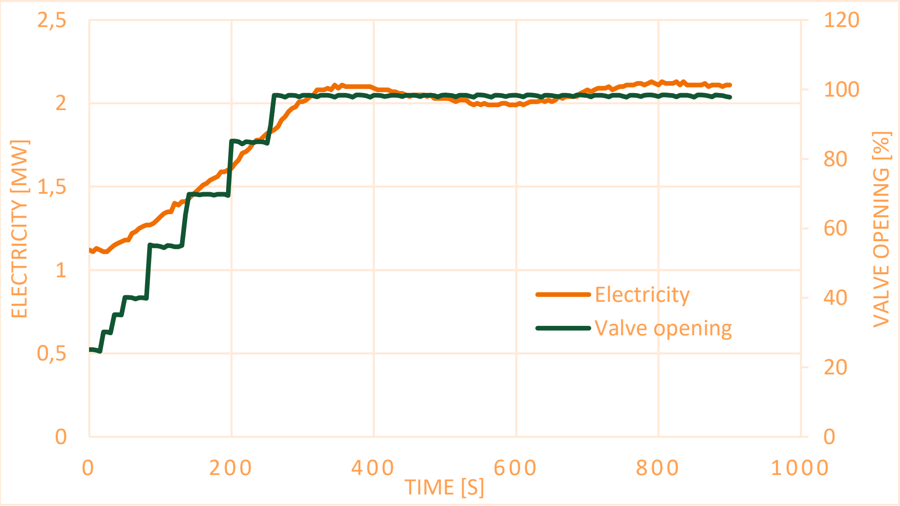

Figure 9. Increase of electricity production in the ORC when opening the three-way valve.

The solid fuel boiler can be operated down to 25 % load. The maximum electricity production was 2,14 MW during the tests and when decreasing the setpoint for the valve to minimum the electricity production was 0,89 MW. However, this is when running the solid fuel boiler at full load. At summertime the ORC is typically operated at 2-300 kW electricity production and reduced heat load in the solid fuel boiler.

The ramp rate when increasing the electricity production and running the solid fuel boiler at part load is limited by the oil temperature in the solid fuel boiler, which can be increased by 0,8 °C per minute. When running the solid fuel boiler at low load the temperature of the oil is approximately 265 °C and is increased to 313 °C at full load. This yields a time of 1 h from low to full electricity production, which gives a ramp rate of approximately 30 kW/min.

The biomass boiler and ORC

The emissions from the solid fuel boiler was measured when changing electricity production in the ORC (Table 3). Note that the dust emissions were measured before the ESP since no difference is expected after the electrostatic precipitator (ESP) regardless of the change of ingoing dust concentration. Also, the gas concentration was measured before the flue gas condensation which results in differences in SO_2 which is likely not the case if measurements were performed in the stack instead. In general, the emissions from the solid fuel boiler is very low. No significant CO emissions were measured at any of the tests and the average concentration was below the detection limit of the instrument. The presented test results were performed with the boiler at full load, but tests with reduced load were also done but no gas analysis results were performed at that time (since it was used for the tests in the bio-oil boiler). However, the gas analysis system mounted in the stack used for emission surveillance showed no significant difference when decreasing the load in the solid fuel boiler. In conclusion, the emissions from the ORC-solid fuel boiler system is not affected by changes in electricity production or load.

Table 3. Emissions during high- and low load.

Operating mode	**NO mg/nm^3, 6 % O_2**	**SO_2 mg/nm^3, 6 % O_2**	**CO mg/nm^3, 6 % O_2**	**O_2 %**	**CO_2 %**	**Particles (dust) mg/nm^3 6 % O_2**
High electricity, full load	55,6	10,9	>1	3,6	16,5	171,4
Decrease electricity, full load	45,5	13,9	>1	3,7	16,5	92,9
Increased electricity, full load	27,2	2,8	>1	3,7	16,5	130,9

4.2.3 Main conclusions

A biopower plant needs to have a stored resource that can produce electricity when it is needed and to be a flexible resource in the energy system. Bio-oils can be used for these purposes since they have high starting availability and is a fuel that can be stored for several years. Flexibility and storage solutions will be important to meet the needs, and despite rapid development in terms of such solutions, in the longer term, a powerful expansion of electricity production and the electricity grid will also be needed.

For smaller district heating plants, the ORC technology can be a good option. In this project, the operation limits of a bio-oil burner and an Organic Rankine Cycle (ORC) was studied. The results will improve the possibilities of manufacturers to offer technologically and economically attractive bioenergy solutions to a completely new market based on strengthening the robustness of VRE dominated energy systems. The conclusions of the operational limitation tests are:

- The time to reach full load for the bio-oil boiler is approximately 13 minutes (+3 min pre-ventilation). When running the boiler in manual operation it is possible to obtain a faster start by manually setting a faster ramp up of the control signal to the burner. In this mode, the time to reach full load is 80 s (+3 min pre-ventilation)
- The emissions from the bio-oil boiler are not significantly affected during start-up or when changing load. The emissions are generally low and the differences between the cases is minor.

- The maximum decrease in electricity production for the ORC when running the wood chip boiler at constant load and when bypassing oil in the three-way valve is approximately 85 kW/min (based on the decrease from time 200 s to 600 s). If the ramp rate is decreased further loud “bangs” are heard from the ORC system. The sound is likely a result of uncontrolled gas formation or thermal stress somewhere in the system.
- The sound-problem is likely not a generic problem with the OCR technology, but something that can be solved in cooperation with the ORC manufacturer.
- When increasing the load in the ORC. The ramp rate is approximately 172 kW/min since no problems with “bangs” occur.
- The solid biomass fuel boiler can be operated down to 25 % load. The maximum electricity production was 2,14 MW during the tests and when decreasing the setpoint for the valve to minimum the electricity production was 0,89 MW while running the solid fuel boiler at full load. When decreasing the load of the solid fuel boiler it is possible to run the ORC at 2-300 kW electricity production.
- The ramp rate when increasing the electricity production and running the solid fuel boiler at part load yields a time of 1 h from low to full electricity production, which gives a ramp rate of approximately 30 kW/min.
- The emissions from the ORC-solid fuel boiler system was overall low and was not affected by changes in electricity production or load.

5. Efficient and flexible CHP technologies for local self-supply

5.1 Description of goal, scope and context of the work

For efficient operation with a high value for the overall energy system, it will become increasingly important that decentralized generation will (a) become grid-serving (i.e., it considers the supply of wind and solar energy and the state of the grid) and (b) focuses on the use of locally generated residual materials.

The increase in the required grid supportiveness of decentralized and controllable generation plants, such as biomass cogeneration units, also increases the control requirements for such plants. While high full load hours and high efficiency at the design point of the plants have been preferred in the past, operational flexibility will become increasingly important in the future whereby overall efficiencies remaining high under all circumstances.

For biomass-based small-scale cogeneration units in the power range below 50 kW_{el}, only a minimum modulation range has been explored so far for reasons of process efficiency and stability. A value-optimized flexibilization of such units can therefore only be achieved by varying the feedstocks, shortening the start and stop phases and optimally shifting the operating times.

The objectives regarding the determination of the optimal operating times of small biomass-based cogeneration units included the development of an appropriate control algorithm and the subsequent validation of its operation based on different use cases. The investigations showed how grid supportiveness and self-supply can be increased by optimal control strategies. Furthermore, varying the size of the thermal storage and the ratio between electrical base load and peak load on-site provided indications of suitable plant configurations and local demand profiles.

The objectives of the work also included the experimental validation of the enlargement of the feedstock portfolio of small-scale wood gasifier. Forest residues with suitable particle size distribution, water content and typical ash content were used as reference fuel. This fuel represents the usual feedstock for small-scale wood gasifier. Shredded waste wood (A1 quality) served as a substitute for the standard fuel. The focus here was on appropriate pre-treatment measures to achieve an alternative fuel with the key properties of the standard fuel. The results of these experimental investigations are not the subject of the following sections.

5.2 Main results

As controllable energy generators connected at the low-voltage level, small cogeneration units are principally suitable for ensuring grid-serving behaviour to some extent. Using biomass-fired units, this grid-serving behaviour can additionally be achieved by a renewable energy carrier. However, at present these units are predominantly operated on a heat-led basis, i.e. power generation is affected by the heat demand determined by the season, weather conditions and user behaviour.

For the analysis of value-optimised plant operation, various control approaches were defined that can be considered for small-scale cogeneration units. Within the scope of the project, the following operating modes were implemented:

A) Heat-led operation (HLO). The heat-led operation is still the common operation strategy for small-scale cogeneration today. The operating times of the cogeneration unit depend purely on the respective storage temperatures and the heat demand.
B) Electricity-led operation (ELO). In order to maximize the economic efficiency of small cogeneration units, it is currently advisable to consume on-site as much as possible of the electricity generated instead of feeding it into the public power grid. The feasibility of this mode of operation depends to a large extent on the size of the heat storage and the resulting flexibility for the operating times of the cogeneration unit. In addition to an appropriately sized thermal storage, a high amount of self-consumed electricity requires precise knowledge of the thermal and electrical demand profiles.
C) Grid-serving operation (GSO). Small biomass-fired cogeneration units are capable of being operated grid-serving. For this purpose, the operation must be adapted to the requirements of the electrical grid. Along with the residual load, the electricity exchange price, the peak load phases and the respective share of renewable energies in the electricity mix, various parameters are currently being discussed for the grid supportiveness. From the grid operators' point of view, it is desired that as much as possible electricity is generated decentrally or as little as possible electricity is drawn from the grid during periods with either high residual load or with a low share of renewable energies in the electricity mix. During times opposite of these, decentralised electricity generation offers significantly fewer positive effects.

In order to increase system supportiveness, the optimal operating window for the evaluated cogeneration unit was determined, considering the current operating state and the state of the heat storage predicted for the next 12 hours together with the respectively predicted heat and electricity demand. For the evaluation of the controller's functionality, the residual load was used as a criterion for the state of the power grid. In the future, information on local voltage bands, dynamic power exchange prices or any other signal provided by the grid operator can also be used. The algorithm is also capable of optimizing the self-consumption of the generated electricity. For this purpose, the local power demand was defined as an additional criterion for determining the optimum operating window.

In order to estimate the impact of the electrical load profile on the optimized operation of the investigated cogeneration unit, the ratio of base load to peak load of the selected standard load profile was additionally varied. This has been done under the premise that the amount of energy required in the course of one year remains constant. Both parts of the electrical load profile were stretched or compressed using mathematical methods. Figure 10 shows the modified load profile for different ratios between base load and peak load (Phi) exemplarily for 24 hours.

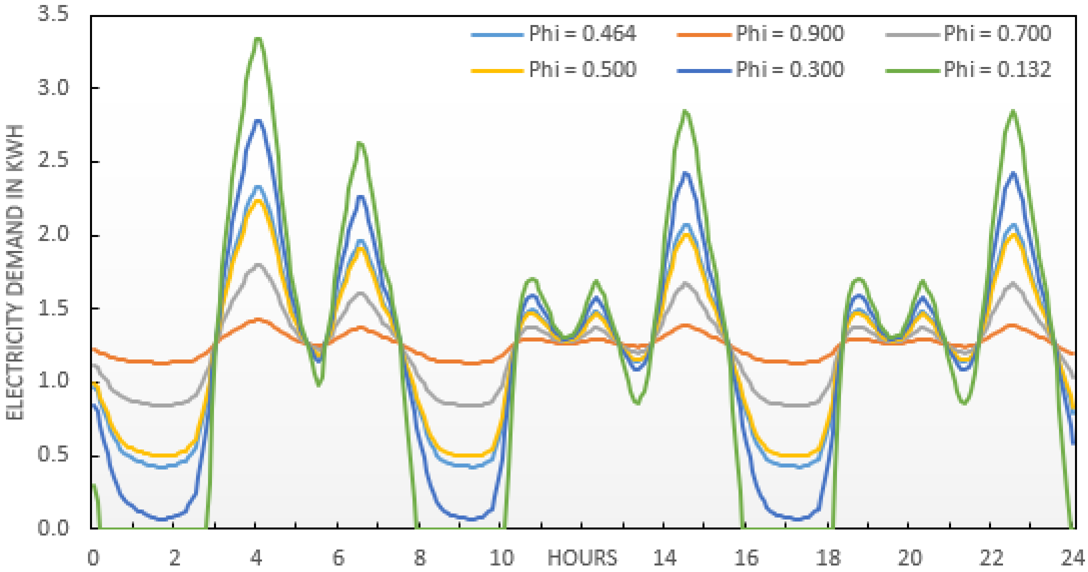

Figure 10. Pattern of the electrical load profile for different ratios between base load and peak load (Phi) exemplarily shown for one day.

The investigations presented below were carried out for a small-scale wood gasifier with a thermal capacity of 79.5 kW and an electrical capacity of 35 kW in a monovalent installation. A multi-family housing estate with an annual consumption of 213,430 kWh was selected for the heat load profile and a standard load profile for household customers with a consumption of 132,811 kWh/a was selected for the electricity demand. The impact of different buffer sizes was analysed using sizes of 3.5 m³, 5.3 m³, 7.0 m³ and 8.8 m³. The GSC_{rel}[2] (relative grid support coefficient) (Klein et al. 2016) and SCF[3] (supply cover factor) (Clauß et al. 2017) were used for the evaluation of the operating modes.

Figure 11 shows on the left side the ratio between the on-site consumed electricity in electricity-led mode (SCF_{ELO}) compared to heat-led mode (SCF_{HLO}). Beside the influence of the operating mode, the influence of the storage size and the ratio between base load and peak load is also shown. In the reference configuration (V_{Bu} = 3.5 m³, Phi = 0.49), the electricity-led operation leads to a slight deterioration of the supply cover factor. Even a variation of Phi does not result in a significant change of the obtained result. However, it can be seen that even a small increase of the storage volume leads to significantly improved results. In this case, power demand profiles with distinct low and high load phases lead to an additional increase of the on-site power consumption. The optimised electricity-led operation mode increased the on-site power consumption by a maximum factor of 1.7. A further extend of the storage volume beyond the first volume expanding by 50 % did not lead to a significant increase of the on-site power consumption.

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[2] Klein K; Langner R, et al.: Grid support coefficients for electricity-based heating and cooling and field data analysis of present-day installations in Germany. In: Applied Energy 162 (2016), S. 853–867

[3] Clauß J; Finck C, et al.: Control strategies for building energy systems to unlock demand side flexibility – A review, Bd. 2017. In: IBPSA (Ed.): Building Simulation 2017, 2017

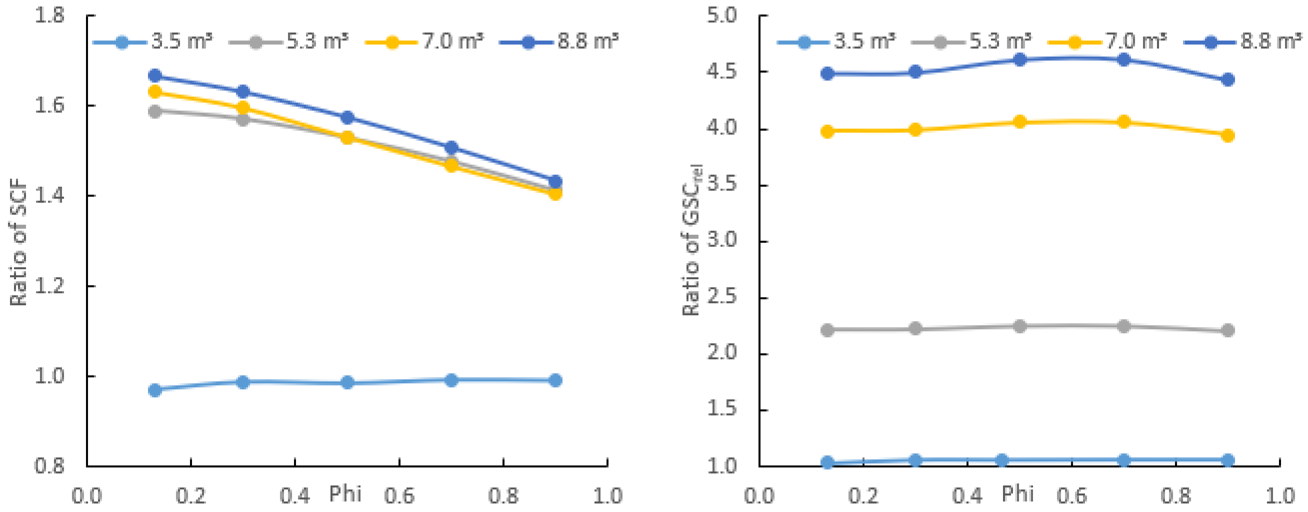


Figure 11. Supply cover factor (SCF) achieved using electricity-led operation mode (left side) and relative grid support coefficient (GSCrel) achieved using grid-serving mode

The results obtained using the grid-serving operation mode are shown on the right side of Figure 11. The reference configuration leads to slightly improved grid supporting coefficients ($GSC_{rel,GSO}$ / $GSC_{rel,HLO} > 1$). Increasing the storage volume by 50% also leads to significantly better results. In contrast to the supply cover factor, a further increase in the storage volume leads to a further improvement of the results. On the other hand, the influence of the base and peak load phases is significantly lower. With an increase in the grid efficiency up to a factor of 4.6, the grid supportiveness of the studied cogeneration unit could be significantly increased.

5.3 Main conclusions

Small biomass-fired cogeneration units can already be operated in a grid-serving manner. This can be achieved by the demonstrated shift of the power consumption to periods of low residual load and power generation to periods of high residual load in the manner demonstrated. The universal development of the algorithm allows the use of almost any signal or parameters (like the local power consumption). The only prerequisite is a certain level of predictability, which is necessary for an optimal determination of the operating times.

The DBFZ studies have shown that a buffer size that is capable of storing the heat generated during 1.5 hours of full load operation already has a large positive impact on the local supply factor. This requires a specific buffer volume of approximately 65 l/kW_{th}. A further increase does not lead to higher supply cover factors. The limit for the storage size seems to be reached when every demand peak can be exploited. A bigger buffer will only exploit low load phases. This also helps to explain the influence of Phi. The higher Phi is, i.e. the smaller the difference between base load and peak load becomes, the more improbable becomes the operation of the cogeneration units during low load phases.

Furthermore, by capping the demand peaks, the electricity-led operation is also able to reduce the required grid connection capacity.

Grid-serving operation can be implemented progressively better with increasing storage size. The influence of load variability seems to be negligible here. The analyses of the DBFZ have shown that larger storage volumes significantly improve the grid-serving determination of power generation and power consumption times.

Although the two investigated modes of operation showed clear advantages over the heat-led mode of operation used as standard nowadays, they are still very rarely used for small biomass-fired cogeneration units. Especially the lack of financial incentive of this additional benefit currently still reduces the economic advantage that can be achieved by the utilization of such optimized algorithms.

6. Design of new solar drying systems and optimized biomass logistics

6.1 Description of goal, scope and context of the work

Sustainable biomass resources are limited, and their utilization therefore needs to be more efficient. In addition, there is an urgent need for low-cost energy storage, particularly for solar energy. Drying considerably increases the calorific value of woody biomass and the resulting dried biomass provides easy seasonal energy storage. The drying both improves the quality of the biomass and extends its storage life.

Objectives with regard to our solar drying studies included building a dryer proof-of-concept prototype, configuring different drying modes for profitable operation of the test facility, and evaluating the efficiency and profitability of solar-enhanced drying in scaled-up solutions. Objectives also included experimenting drying in a solar enhanced dryer and evaluating its suitability for wood fuel drying.

The integration of solar drying and other biomass upgrade systems into flexible energy systems was configured by VTT. The system analysis is described in previous sections. After configuring different options at the system level, practical solutions to integrate solar collectors and movable drying modules such as SFTec’s module, were studied. These modules can be placed near biomass resources and they can be easily transferred to another location and attached to solar and traditional energy sources if desired.

The studied configurations and system solutions were validated by practical tests and trials with the proof-of-concept dryer. Validation showed how these solutions work in practice. In parallel, further optimization of configurations and operational strategies were performed and cross-checked with simulation studies.

An effective deployment of biomass storages within the feedstock procurement area were studied. This included biomass terminals due to their special characteristics in terms of large supply volumes and a high biomass quality. It also included control and tactical planning of biomass procurement based on weather prediction and electricity price. This tactical planning helps mobilise biomass resources in the time of maximum demand and maximum price due to fluctuations in the output of other renewable sources of electricity.

Supply costs for different potential supply chains of supplying both traditional and upgraded wood fuel were determined. Logistics costs can especially be decreased during high demand seasons. The best ways to store dried biomass near the source and how to deliver different, dried and seasoned, wood fuel fractions in a more optimal way according to the needs of the end user were surveyed. Optimisation of wood procurement according to the plant economics was also studied. Based on this study, an enhanced woody biomass supply model with an ability to differentiate between various wood fuel fractions was created. This model and results are included in the system studies described in section 3 “Costs, benefits and impacts of bioenergy concepts”.

6.2 Main results

The cumulative solar irradiation on horizontal surface fluctuated from 0.3 to 6.2 kWh/m^2 during the experiments while the average measured irradiation was 193 to 776 W/m^2 during the experiments. This fluctuation naturally depended on the weather conditions and the duration of each experiment. The applied average drying airflow rates, controlled by the algorithms, were from 420 to 975 Nm^3/h. On sunny days, drying air temperatures in excess of 50 °C were reached, while on cloudy days, only about 20 °C, i.e., only a few degrees warmer than ambient air, was achieved.

The profitability of all conducted drying experiments is presented in Figure 12 as a function of measured irradiation on horizontal surface during the tests. The correlation between profitability and cumulated irradiation is almost linear even when the conditions during the experiments varied. The differences between the tested biomass types and batch sizes are more important than the variation in weather conditions during the experiments.

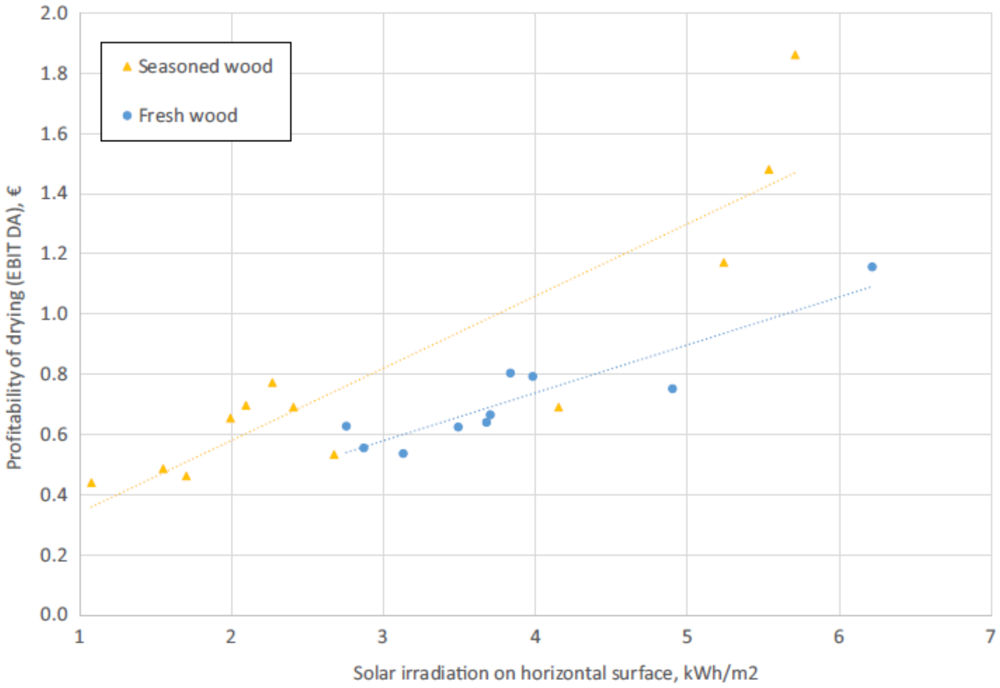


Figure 12. Profitability of drying as a function of measured irradiation on horizontal surface during the experiments.

The drying system calculations were scaled up to a larger drying system equipped with either 90 m^2 (farm dryer) or 5,000 m^2 (biomass terminal) solar collectors. This was done by estimating the constant dryer capacity per solar system surface area. The annual gross margin was consequently also multiplied by the ratio of solar collector surface areas, 90 m^2/12 m^2 and 5,000 m^2/12 m^2 respectively.

Investment costs were based on the assumption that the smaller dryer is built inside an existing building, such as a barn, with retrofit costs including, for example, investment in fans, timberwork, and new floor casting to ensure effective drying air distribution. The investment costs of the bigger dryer included, however, a new building as well as a storage facility for the dried biomass, as it cannot be assumed that buildings of this size are available without significant cost. All costs were estimated based on ProAgria's general construction plans. It should be noted that the most important cost is the solar collector system, for which price estimates were received from Savosolar Ltd., a Finnish supplier of solar collector systems. In total, the used default investments were €63,000 and roughly €2.4 million for the 90 m^2 and 5,000 m^2 solar systems, respectively. In this study, interest rates/inflation were not included in the payback time calculation.

Initial calculated payback times for the test dryer were not very appealing to a biomass entrepreneur without subsidies, payback times varying from 17 to 78 years. Therefore, several factor affecting the profitability were considered.

In rural areas, investment subsidies are often available for renewable energy solutions. It is also clear that the drying efficiency can be improved from the test runs. Moreover, in the best experiment, the calorific value of the wood chips increased by 70% of the cumulative solar irradiation, while in most experiments, it was only 40%. Furthermore, significantly lower electricity prices are probable in the near future, especially during sunny days when increasing amount of solar power is available in the grid.

Based on the above assumptions, a sensitivity analysis was performed on different dryers and drying materials (see Table 4). It was assumed all options would receive 30% investment subsidies and that 70% of the solar irradiation energy received on horizontal surface transfers to wood chips as increased calorific value. Other variables in the analysis were electricity and wood chip prices.

Table 4. Payback times of the solar dryer according to the sensitivity analysis.

	30% investment subsidy		**30% investment subsidy and power 50 €/MWh**		**Farm dryer with new building and 30% investment subsidy**
Collector surface area of the solar system	$90 m^2$	$5,000 m^2$	$90 m^2$	$5,000 m^2$	$90 m^2$
Seasoned wood, based on efficiency of lab scale dryer	18	12	Cannot be calculated because the electricity price affects the experiments		36
Fresh wood, based on efficiency of lab scale dryer	50	34			71
Seasoned wood, assuming higher efficiency and chip price 25 €/MWh	10	7	9	6	13
Fresh wood, assuming higher efficiency and chip price 25 €/MWh	20	14	17	12	25
Seasoned wood, assuming higher efficiency and chip price 23 €/MWh	18	12	16	11	23*
Fresh wood, assuming higher efficiency and chip price 23 €/MWh	33	22	26	18	38*
Both wood types, assuming higher efficiency and chip price 21 €/MWh	99	67	56	38	80*

6.3 Main conclusions

In Northern Europe, the feasible season for utilizing solar energy for drying lasts about 7 months from March to September. Annual solar irradiation on collectors placed optimally in Central Finland is about 1050 kWh/m^2, of which about 90% is received during those months. With a drying system similar to that used in our drying experiments, it would be possible to dry almost 14 MT of seasoned wood chips to an average moisture of 20% annually. If the system were scaled up to 90 m^2 of collectors, which is feasible for example for farms, it would be possible to dry 104 MT of wood chips, which is usually more than sufficient for annual heating of the farm.

VTT’s experiments proved that solar collectors could be effectively applied to biomass drying. The moderate drying temperatures achieved are also ideal for ensuring homogenous drying of wood particles and preventing changes to the physical structure of the biomass or loss of volatiles. The use of low-temperature drying also extends the efficient drying time daily and seasonally. Heat losses are also smaller when low temperatures are applied.

The sensitivity analysis, based on the experiment results, indicates that scaled-up dryers could be utilized in biomass drying with realistic payback times, such as 10–20 years. This seems to require a number of prerequisites. Firstly, natural drying outdoors should be utilized as much as possible before solar-enhanced drying. Secondly, the solar system investment costs are still high, calling for investment subsidies. Thirdly, the system should be run at least as effectively as in our best experiments. Fourthly, it is crucial to add monetary value to dried wood chips compared to wet biomass: our experiments suggest wood chip price should increase by at least €2/MWh after drying.

In the future, it would be beneficial to study how the energy balance of drying could be improved. One important improvement would be to scale the whole system more carefully. Another interesting approach is to combine a heat pump and solar collectors to enhance convective air drying. This kind of drying setup will be installed at VTT in 2021. With a heat pump, the drying potential of such a dryer could be increased remarkably.

7. Business perspective on flexible bio-based power production

7.1 Description of goal, scope and context of the work

Below, the objectives of the work package, as outlined in the work plan are presented, as well as the way they were fulfilled in the project:

- To create scenarios for the design of future energy markets
    - Two sets of market scenarios were developed. The first one was 2030 scenarios for Nordic power market with emphasis on Finnish district heating and local biomass supply chains. We used these in WP2 to modelled biomass role in 2030s district heating grids. The second set of scenarios studied more idealistic reference systems where we varied climate conditions from Northern to equatorial and modelled the role of biomass when reducing the amount of burned fuels aiming for carbon neutrality.
    - Scenarios from external sources for future electricity prices were also used in the regions that were not modelled extensively in the above scenarios.
- To generate adequate production portfolios for bio-based flexible electricity production addressing future system needs and demands
    - Data sources for technical and economical parameters of bio-based combined heat-and-power (CHP) plants have been identified.
    - These data sources were used to investigate the profitability of the investment in different types of CHP plants.
    - Industrial partners in the project were consulted to give inputs as regards to the technical and economical parameters of future technologies.
- To estimate potential revenues for electricity production from bio-based production
    - Two models have been developed. The first one evaluates the hourly income that can be made on the electricity markets. The second one evaluates investment profitability indicators based on the outcome of the first model.

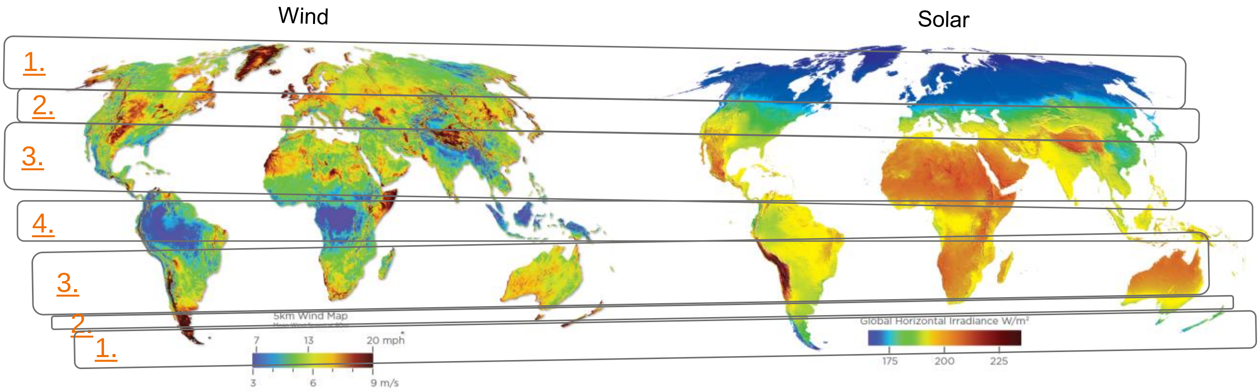
- To analyse the replication potential for flexible bio-based electricity production in a European context and from a market design and policy perspective.
    - The developed models have been applied to case studies in Sweden. However, they are flexible enough to be used in other contexts. What's more, the day-ahead electricity market has a common design in most European country, which makes the model valid without any changes in countries included in the same coupling region as Sweden.

7.2 Main results

In this section, we elaborate on how the objectives mentioned in the previous section were fulfilled.

7.2.1 Creation of scenarios for the design of future energy markets

This task focused on defining plausible characteristics for future energy markets dominated by VRE considering market designs and regulatory characteristics. Simplification and characterization are a great challenge with over 200 countries, many more existing systems, and even wider range of possible future systems. As our focus was the VRE dominant systems, we divided global regions to four different categories according to their solar and wind conditions and described typical demand profiles and access to reservoir hydro power in those regions, see Figure 13.



Reference system	Electricity demand	Hydro	Wind	Solar
1. North	Peak at winter (February demand = 2.0x July demand)	Yes	40 % cf	11 % cf
2. Temperate	Peak at winter (February demand = 1.9x June demand)	No	40 % cf	17 % cf
3. Solar belt	Some heating, but peak at hot season (August = 1.5x April)	No	40 % cf	25 % cf
4. Tropic	Relatively flat demand (January demand = 1.3x June demand)	No	30 % cf	17 % cf

Figure 13. Simplified reference systems and their main characteristics. Original maps from www.vaisala.com/en/lp/free-wind-and-solar-resource-maps.

Within these systems, we modelled carbon neutral energy systems, and the role of optional flexibility options from electrification of transportation, heating, and industrial processes. The main conclusion from the decarbonization part was that wind and solar were the cheapest sources of new generation, but thermal power units provided cheap flexibility options for peak demand hours and are expensive to phase out completely. In future energy systems, electrification of end use sectors both increase the demand and offer flexibility through load shifting providing lower cost decarbonization than in inflexible systems.

The results were presented in two IEA workshops; Flexibility options overview, Webinar: Inter-TCP meeting on Integrated Energy Systems, and Reference Energy Systems; A Joint Workshop by IEA Wind Tasks 25, 26, and 37; Nov. 9th-10th, 2020

7.2.2 Generation of adequate production portfolios for bio-based flexible electricity production addressing future system needs and demands

The framework for a portfolio of relevant CHP units was set by the district heating network chosen for the modelling. Thus, the criteria for limiting the selection of technologies for the portfolio was then chosen for size, technology and fuels especially relevant for Swedish conditions as the modelling performed in later section was based on a Swedish district heating network and Swedish data.

It has also to be noted that although certain combustion technologies have general differences in their flexibility possibilities, it is the combination of the combustion part (boiler technology, fuel feeding system) and the power producing part (steam turbine, with or without bypass) that sets the real limits for the site's flexibility. Thus, each CHP plant often has unique solutions combining these two parts for the specific site which thereby influence both flexibility performance as well as investment costs (CAPEX) and operational costs (OPEX). The complete collection of all these combinations of technology and related costs connected to flexibility would be outside the limits of this project.

Realising this the portfolio of relevant technologies was constructed from two basic data sources with extensive work of collecting data from specific plants and bio-CHP installed in Sweden (Elforsk, 2014) and Denmark (Danish Energy Agency and Energinet, 2020). In cases where data such as low load level, cold and warm start-up was missing, estimations based on a combination of the two sources was made. Data for cases with future improved technologies was based on the new development of Valmet in the VaBiSys project. The improved flexibility is revealed by lower load levels, shorter warm and cold start-up time.

7.2.3 Estimation of the potential revenues for electricity production from bio-based production

In order to estimate the potential revenues for electricity production from bio-based production, an optimization-based model of the sector coupling between individual district systems and the electricity markets was developed. This model is an hourly scheduling model that provides, for a given district heating system, the hourly schedules of all units in that system in order to maximize revenues from selling electricity to the day-ahead electricity markets.

Using an existing district heating system in Sweden, as well as the portfolio of units developed in the previous section, six case studies were designed. Each case study investigates replacing one existing unit with a new unit. Six different new units with different technical parameters, corresponding to different levels of flexibility, were chosen.

The scheduling model was then run on a number of representative years that represent the lifetime of the new units. In this way, the optimal schedule of all units during these years were obtained. In addition, the revenues and costs corresponding to these optimal schedules were also obtained. Three different scenarios were investigated corresponding to three different electricity price scenarios for Sweden up to 2045. These price scenarios were obtained from studies performed by Svenska kraftnät, the Swedish transmission system operator. These scenarios are named low, ref, and high reflecting different assumptions on future electricity demand up to 2045.

Figure 14 presents the resulting net present values, which can be used to compare the profitability of the different case studies.

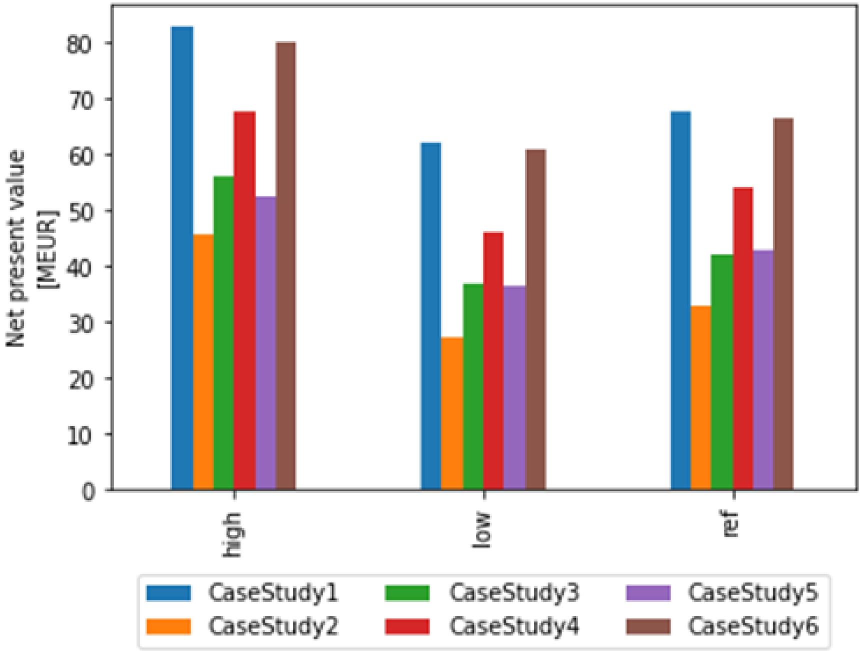


Figure 14: Net present values of the case studies in the 3 scenarios.

Case studies 1 and 6 are very similar. They are both wood chip units. The only difference is that in case study 6, the unit can have a lower load level (10 % instead of 20%) and is slightly more expensive. In the studied district heating system, this technical improvement does not lead to an increase in profitability.

Case study 2 uses two smaller units of 45 MW instead of one big of 90 MW. The units have similar characteristics as the single unit of case study 1. The CAPEX is much higher though. These two new units produce the same amount of heat and about the same amount of electricity as case study 1. In the studied district heating system, the flexibility of having two units (for example by being able to shut down one of them) does not bring any added value to the overall profitability.

Case study 3 is a wood pellet unit with better alpha value than case study 1 (up to 61 % instead of up to 53 %). CAPEX and variable OPEX is much lower than case study 1. However, fuel costs and fixed OPEX are more expensive. In the results, the savings in CAPEX are not as big as the extra fuel costs. Also, since it is more expensive, it is used less often than case study 1. Therefore, although the alpha value is better, it does not lead to larger incomes from electricity markets.

Case study 4 is a waste wood unit with low fuel cost. It has a rather high low load level (40%). It also has the highest alpha value of all case studies (up to 67%). It has a relatively high CAPEX (third largest) and fixed OPEX. It captures a larger share of the total heat demand (second only to case study 5). It gets the most revenues of all case studies from electricity markets.

Case study 5 is an RDF unit. It has the lowest fuel cost of all case studies, but also the highest low load level. It has the largest CAPEX of all units. It produces the most heat of all case studies and is second only to case study 4 in electricity production.

When looking at the absolute results from case studies 4 and 5, they seem to be the most profitable. However, they do so by capturing a larger part of the total heat production from other existing levels. Hence, on the system level, these two investment options are not as profitable as case studies 1 and 6.

7.3 Main conclusions

A model has been developed to simulate operational planning decisions taken by district system heating owners in order to maximize their revenues on the day-ahead electricity markets. This model is used in investment studies to investigate the profitability of investments in new plants with different economical and technical characteristics in a Swedish setting. Doing so allows to capture the impact of different technical choices on the profitability of a new unit over its whole lifetime. Three different future scenarios with different levels of electricity demand up to 2045 are investigated. It is shown in the case studies that scenarios with higher level of electricity demand lead to higher profits for new combined heat-and-power plants. The reason for this is that higher demand of electricity is covered by larger amounts of variable renewable energy (VRE) sources, which has a strong impact on electricity prices and, consequently, on the profitability of the investments. It is shown that higher electricity demand leads to both higher average electricity prices and larger variance in the electricity prices, the latter being due to the largest variation in available capacity from VRE from hour to hour. This in turn leads to larger potential revenues from electricity markets, which increases the profitability of investment in CHP units.

8. Summary

8.1 Modelling of VRE dominated energy systems

The role of biomass in the future energy system was studied both by using general energy system models and models adapted regionally in Finland and Sweden. Numerous different circumstances and facility combinations were included in the heat and electricity production system models. Also, the electrification of energy consumption, including the transport fleet, heating and industries, was taken into consideration. The modelling work was focused on examining how different low emission technologies, including solar, wind, biomass and energy storages can respond to the demand of flexibility caused by these trends in energy consumption.

Within Finland, two regional cases were studied. The first one considered a small district heating network where different combinations of solar thermal collectors, thermal energy storage (TES) and limitations on how and when solar heat can access the system where examined. The second case study considered the decarbonizing options the capital region. While pointing out effective technological combinations for both case systems, the results highlight the importance of systemic view on addressing emission reductions. In other words, focusing on and pushing a single facility investment may cause rebound effect in the regional system or in a wider context.

Overall, the results imply that the cost of fossil-free energy system, with added variable energy production, can be significantly reduced if a certain minimum amount of climate neutral fuel, such as sustainably sourced biomass, is available. The integration of biomass logistics model with the energy system model made it possible to assess the bioenergy concepts in Finland with an enhanced detail.

8.2 Acceptability of flexible bioenergy technologies and their use

An assessment of social impact and public acceptance for the bioenergy concepts was carried out to understand better the potential related impacts and critical aspects of the technologies. The assessment was based on both literary review and expert interviews. Other aspects of acceptability, including socio-politic acceptability and market acceptance were assessed as well. Although the use of renewable energy and renewable energy technologies has been widely covered in the recent literature on social acceptance, the studies generally focus on wind power production, the attitudes of local communities affected and the acceptance in the face of wind power investments. The acceptance of energy use of forest biomass has received far less attention. The least is known about its market acceptance, which is nevertheless recognized as central for implementation of the technology. The findings from VaBiSys project increase the understanding of factors that have an impact on the acceptability of flexible use of bioenergy. These factors may be critical for the development or implementation of new bioenergy concepts in the near future. Therefore, more attention should be given to the views of technology developers and market actors and how they interlink with other aspects of acceptability.

8.3 Flexible bioenergy technologies

The VaBiSys project assessed the operating limits of solid fuel fired circulating fluidized bed (CFB) boilers and bio-oil fired boilers. Computational fluid dynamics (CFD) modelling was deployed to explore the conditions inside the boiler and to support developing new options to improve flexible operation. Furthermore, an integration of Organic Rankine Cycle (ORC) to produce electricity was considered together with the bio-oil boiler.

The major limitations to the flexibility of fluidised bed boilers are the minimum load and start-up time. The CFD models were used to study new boiler designs and operation modes. Combining both technical and operation-related items, solutions to improve the flexibility of CFB boilers were developed. Based on the techno-economic assessment, the expected payback time was 1-3 years, indicating the flexible CFB technology can be used for balancing VRE dominating future energy systems.

A biopower plant needs to have a stored resource that can produce electricity when it is needed and to be a flexible resource in the energy system. Bio-oils can be used for these purposes since they have high starting availability and are fuels that can be stored for several years. During the project, a new combustion model was developed for bio-oil. The model proved to predict well the combustion behaviour during validation experiments.

The operation limits of a bio-oil burner and an Organic Rankine Cycle (ORC) were studied for small scale district heating plants. The results were based on measurements at a case plant. The results improve the possibilities of manufacturers to offer technologically and economically attractive bioenergy solutions to a completely new market based on strengthening the robustness of VRE dominated energy systems.

Micro CHP units using gasification of solid biomass were also studied during the project. Based on the research, operational and fuel flexibility of the small-scale systems were established. For efficient plant operation with a high benefit for the energy system, it will become increasingly important in the future that decentralised electricity generation is grid-serving (i.e. dependent on the supply of wind and solar energy and the state of the grid) and focuses on the use of locally produced residual materials. The increase in the required grid-serving possibilities of decentralised and controllable generation plants, such as biomass CHP plants, increases the control requirements for such plants. While high full load hours and high efficiency at the design point of the plants have been in the foreground up to now, operational flexibility will become increasingly important in the future with continued high overall efficiencies (electricity, heat) in all load ranges.

Operation based on the heat demand is still the common strategy for these small-scale cogeneration units. Based on simulation of a micro CHP unit in regional setting, a buffer size that is capable of storing the heat generated during 1.5 hours of full load operation already has a large positive impact on the local supply factor. Larger storage volumes significantly improve how power generation and consumption times are determined based on demand in the grid.

Finally, using solar energy for solid biomass drying was studied with a container-sized pilot equipment built at the premises of VTT. Drying increases the calorific value of woody biomass and improves the storability of the fuel over seasons. The solar drier pilot was based on earlier laboratory and pilot experiments. The functioning of the dryer was validated by several test runs, and the biomass logistics were incorporated into the system modelling. Based on the results, the technology is promising for improving the quality of solid biomass. As the next steps, the capacity of the experimental equipment will be increased with the help of heat pump integration.

8.4 Business perspective on flexible bioenergy

Business potential of flexible bioenergy concepts were investigated with the help of two sets of market scenarios developed for the purpose. The first one consisted of scenarios for Nordic power market in 2030 with emphasis on Finnish district heating and local biomass supply chains. We used these to model the role of biomass in 2030s district heating grids. The second set of scenarios studied more idealistic reference systems where we varied climate conditions from Northern to equatorial and modelled the role of biomass when reducing the amount of burned fuels aiming for carbon neutrality.

Based on techno-economic data on bio-based combined heat-and-power (CHP) plants, the profitability of the investment in different types of CHP plants was studied. The potential revenues were estimated for electricity production from bio-based production by two models. The first one evaluates the hourly income that can be made on the electricity markets. The second one evaluates investment profitability indicators based on the outcome of the first model. The results in scenarios with higher level of electricity demand show higher profits for new flexible combined heat-and-power plants. This is due to higher electricity demand leading to higher average electricity prices while increased VRE capacity is leading to larger variance in the electricity prices. This in turn offers larger potential revenues from electricity markets, which increases the profitability of investment in flexible CHP units.

The developed models have been applied to case studies in Sweden. However, they are flexible enough to be used in other contexts. What’s more, the day-ahead electricity market has a common design in most European country, which makes the model valid without any changes in countries included in the same coupling region as Sweden.

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