Final report slides, WP1.2.

Energy storage concepts for maximising the potential of bioresources

Samuli Rinne, Aalto University 17.1.2017

Sustainable
Bioenergy
Solutions for
Tomorrow

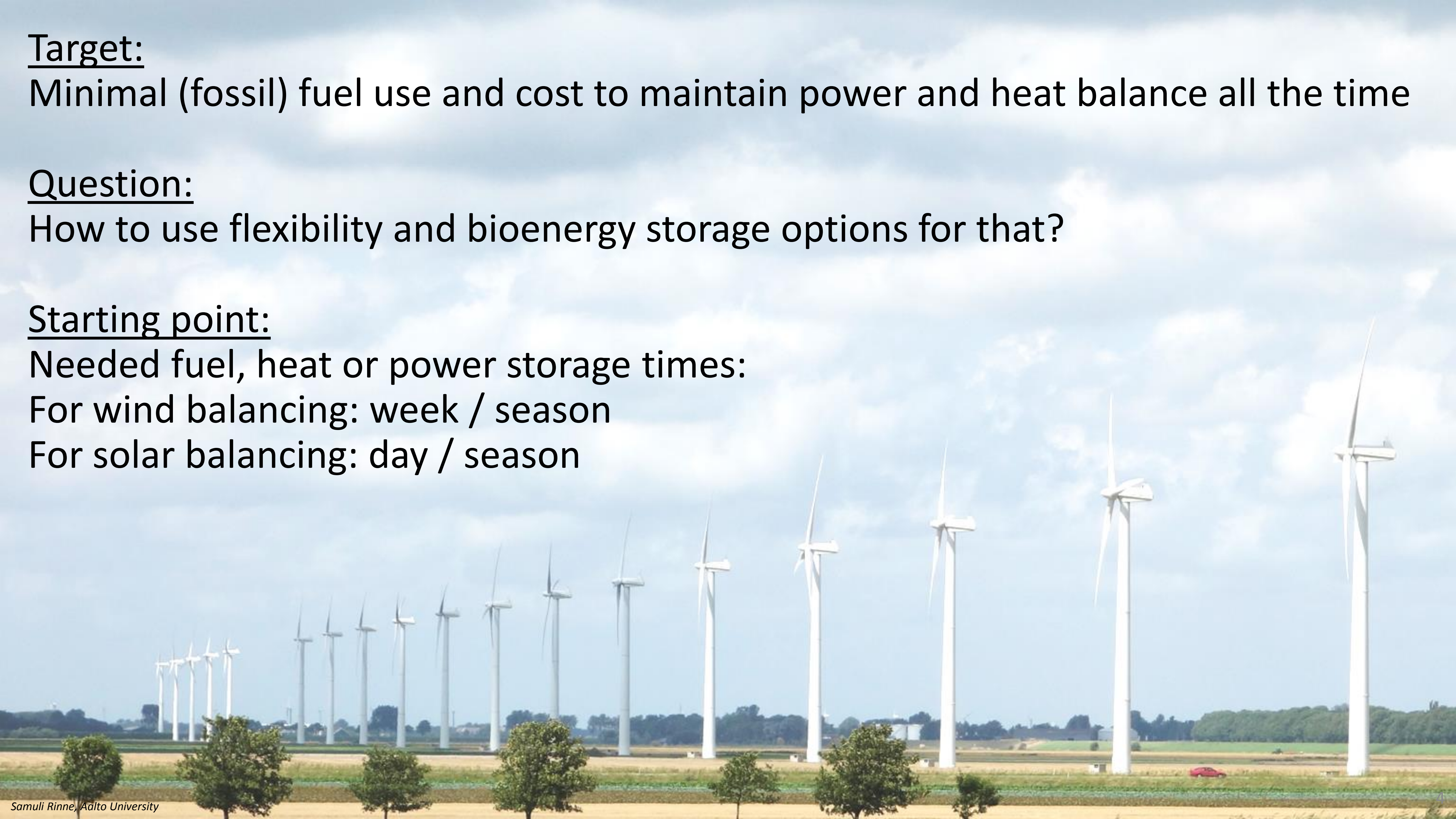
WP1 Energy storage concepts for maximizing the potential of bioresources

- In this WP is studied the integration of bioenergy and other renewables into the energy system.
- Storages and other flexibilities are an essential part of it, due to the variable nature of wind and solar power. And, from other point of view, also due to the storageability of biomass.
- The storage and flexibility possibilities are described in general level in this presentation.
- This presentation is tuned for Finnish context, but can be generalised to some extent also for other countries.
- The issues presented here are hopefully studied and also existing knowledge presented in more detail in the future.
- The insights presented here are authors’ own, not necessarily representing those of Aalto University or other organisations.

Problems and not so big problems concerning the future of biomass use?

May be a problem
Scarce resources. Biomass resources are small compared to the all possible uses, from mid-term and further on.
Carbon balance. The short-term one of biomass is not very good, even though in longer term the situation is much better.
Small particles. Emissions from small-scale combustion have quite strong negative health effects.
Politics. The future of biomass, wind and solar power and, consequently, feasible system solutions, are quite dependent on political decisions. But after some 20-30 years perhaps not?
Weak understanding. Energy issues and especially energy systems are remote and not very understandable for great public.
Greenwash and commercial or political interests. They obscure the reality, what is more sustainable (in all senses) and what is less.
Markets, in short term. Economical recession and not very ambitious climate targets, i.e. low carbon price and lacking mechanisms to compensate that, have caused the biomass markets temporarily to collapse.

Not that big problem?
Excess production of power and heat. Even quite high peaks can be absorbed, when feasible consumer solutions have been well established.
Space heating. Low-exergy energy needs can be satisfied with a variety of solutions and there are also quite new ones to come. Heat storages are very cheap compared to the electricity storages -> excess energy can be flexibly used.
Biomass transports. The energy use for those is moderate. Large trucks, trains and vessels can do the job. However, other externatilities and costs in general may well be more important and a hindrance in practice.
Markets, in longer term. After a certain transition period, there will probably be good markets for all kinds of biomass.



Target:

Minimal (fossil) fuel use and cost to maintain power and heat balance all the time

Question:

How to use flexibility and bioenergy storage options for that?

Starting point:

Needed fuel, heat or power storage times:
For wind balancing: week / season
For solar balancing: day / season

How to handle the power balancing?

- Maintaining seasonal electricity and heat balance needs dispatchable production. According to the studies, the needed amount is 20…40% of the total electricity production (in energy units).
- It is technically possible to use also nuclear plants as regulating power. However, due to the high investment cost, this is not very economical alternative. Also political atmosphere may not favour nuclear power.
- Power-to-gas (P2G) alternatives are not cheap either due to the low peak hours for gas production and weak overall efficiency. However, if e.g. waste heat can be utilised, the system may be in the limits of possibilities.
- From P2G point of view, the possible ideal would be that kind of infrastructure, that allows using biomass as a fuel for near future in balancing electricity and heat production. And in some day perhaps synthetic gas, from P2G production, in the same system.
- DSM can at its best lower the need for dispatchable production by some %-units, but still there is a substantial need for that.
- Storing electricity seasonally (or even weekly) is very expensive and, say, unrealistic. The price of batteries for now is some 150…3000 euros/kWh. In comparison, for heat storages it is 3…30.
- Excess electricity can be converted to heat by heat pumps or electrical resistances. I.e. wind and solar production can be ”overdimemsioned” and excess electricity used for heating. Electrical heating exists anyway, so this is not wasting electricity compared to the current situation.
- Thus, heat storage may well be one part of the solution for system balancing.
- Heat storages have some material input and heat losses, but if storage time is moderate and storages large enough, these are not that important issues from system efficiency point of view.
- Bio-CHPs can contribute to maintain power and heat balance when wind and solar are not enough.
- In every case it makes sense to have DH network to distribute the inevitable excess heat from conversion processes. To blow this heat into the atmosphere and simultaneously use prime energy (concerning also wood!) for heating is wasteful use of resources.

In what case the biomass use should be promoted and in what case it should be limited?

- If there is a surplus of sustainable biomass (especially industrial by-products and forest residues), then fossil fuel use should be changed to biomass use as much as possible. From the climate point of view, coal is first to be replaced, remembering also the indirect emissions (and coal use) behind the borders.
- If biomass is used more than the sustainable supply is, the use should be limited by focusing on energy efficiency. The same applies, if it seems probable that this is the case in the near future.
- The biomass surplus-case is acute in many cases just now, but in the future there will be most probably a deficit of sustainable biomass, remembering the huge amount of fossil fuels used and also the current and potential raw material uses for biomass.
- Investments in energy sector are made for long term.
- Thus, already now, it makes sense to always think the system efficiency and emissions from system point of view.
- In practice this means that the energy production based on combustion should be minimised. I.e. biomasses should be allocated so that they replace condensing power and heat-only boilers. Both of them are inefficient in the system level, when also the exergy efficiency is considered. Exergy efficiency here means the value which is gained from fuel compared to the value what could have been gained in the best case.

Is there enough biomass?

- As stated in an earlier slide, the needed amount is 20…40% of the total electricity production (in energy units).
- Fuel need for that in EU 27 is 1500-3000 TWh/a. Even if additional hydropower can handle a part of that, 1000-2000 TWh fuel is needed.
- Forest fuel potential in the same area is 400 TWh/a, i.e. small compared to the needs of power (and heat) production, not to talk about the other uses. Agriobiomasses from unused or degraded land adds some to that, but the balance issue in general remains the same.
- World primary energy consumption now is 160 000 TWh/a and it is projected to be e.g. 250 000 TWh/a in 2050.
- In global level the estimated biomass potential from harvest residues (incl. agrobiomasses) and cultivation on unused or degraded land varies a lot in different studies, but rough average may be 50 000 TWh/a.
- Pressure for other uses (raw materials, liquid biofuels…) must be also remembered.
- So, in the future world, biomass is a scarce resource (again to remember, compared to the all potential uses). Thus, biomass can well contribute to the sustainable energy system, but it must be used wisely, not wasting it.
- As a result from these, all the feasible methods, which
  - increase the amount of sustainably harvested biomass or
  - increase the system efficiency

…should be promoted. Some possibilities are presented in the next slides.

Sustainable Bioenergy Solutions for Tomorrow

A summary of the proposed system: Some parts of the power and heat production chain in sustainable system.

How to use the parts to maximise the value of biomass as a flexible component in the sustainable energy system? In other words, how to use biomass to minimise system level emissions and costs?

Wood terminal
- Enables matching of wood fuel production and consumption
- Comminution place
- Transfer from trucks to larger trucks, trains and vessels
- Wood drying, natural, or artificial with excess heat
- Wood chip screening

Heat pump
- Utilises cheap electricity, when there is more production than consumption
- Most feasible when upgrading e.g. heat from waste waters
- Reduces the need for heat-only boilers
- Reduces up-down ramps of CHP plants
- Quick regulation possible

Wind and solar power
- Can produce a significant share of total electricity production, if…
- …flexible CHP plants and HPs, heat storages and DSM are used, wisely.

Hydropower
- Regulating power
- Limited, especially when Norwegian hydro power will be exported more

Heat storage tank
- Enables matching of heat production and consumption
- For CHP, HPs, electrical resistances, geothermal energy…
- The larger, the smaller the relative losses
- For large units, investment cost is round 3 euros/kWh (vs. 150-3000 euros/kWh for electricity storage)

Borehole heat storage
- Seasonal
- The larger, the smaller the relative losses

Forest fertilisation
- The more the forest grows, the more fossil fuels can be sustainably replaced by biomass
- Wood ash is suitable for peatlands, nitrogen for mineral soils

Combined heat and power plant
- Produces power when wind and solar is not enough, and heat as an easily storable by-product
- Quick ramping is needed in future
- High power-to-heat is needed, since there may well be a surplus of heat in system level


Drawing: Sanni Salo, muodo.fi

Snow melting from walking and cycling lanes
- Makes walking and cycling more popular, which…
- …decreases energy needs in traffic and has significant positive health effects.
- Utilises excess heat and/or electricity

Demand side management
- A part of system balancing
- The consumer must have some advantage (e.g. in price) when participating in the flexibility measures
- Participation must be voluntary, not dictated

Electricity&district heating networks
- Enablers of balancing: the one who has surplus, sells to one who has deficit
- The wider the network, the better the balancing possibilities
- Openness in management and use possibilities are crucial

Wood chip dryer
- Water in biomass can be evaporised prior to boiler, by excess heat or even electricity…
- …instead of using prime energy from combustion itself, in boiler
- Low-temp heat for drying can also be recovered from flue gas scrubber

Biomass gasifier /liquidification
- Produces fuel mainly for diesel buses, trucks, trains, vessels and aviation
- Better alternative for cars may be electricity with flexible charging, or preferably walking, cycling and public transport, due to the limitations in biomass amount

Gas engine
- Regulating power
- Some models can utilise biomass-derived oil or gas
- Conversion process from biomass to oil or gas has a energy loss of roughly 20-50%
- Loss, i.e. excess heat, can be used for district heating, if network and storages exist
- Advantage compared to steam power plant, in addition to fast ramping, is better electricity production efficiency, which counteracts the conversion loss issue

Wood fuel supply, Fast Track
- Moist biomass should be used or dried quickly, to avoid biomass degradation
- The fellings are now made more in wintertime than in summertime, good from energy point of view
- With high wind share even better match of biomass production and fuel needs seems probable
- Moist fuel can be dried efficiently, see ”Wood chip dryer”

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The previous slide presents one possibility to arrange a flexible energy system to integrate a very high share of renewables. It is a bit refined in the rest of the slides.

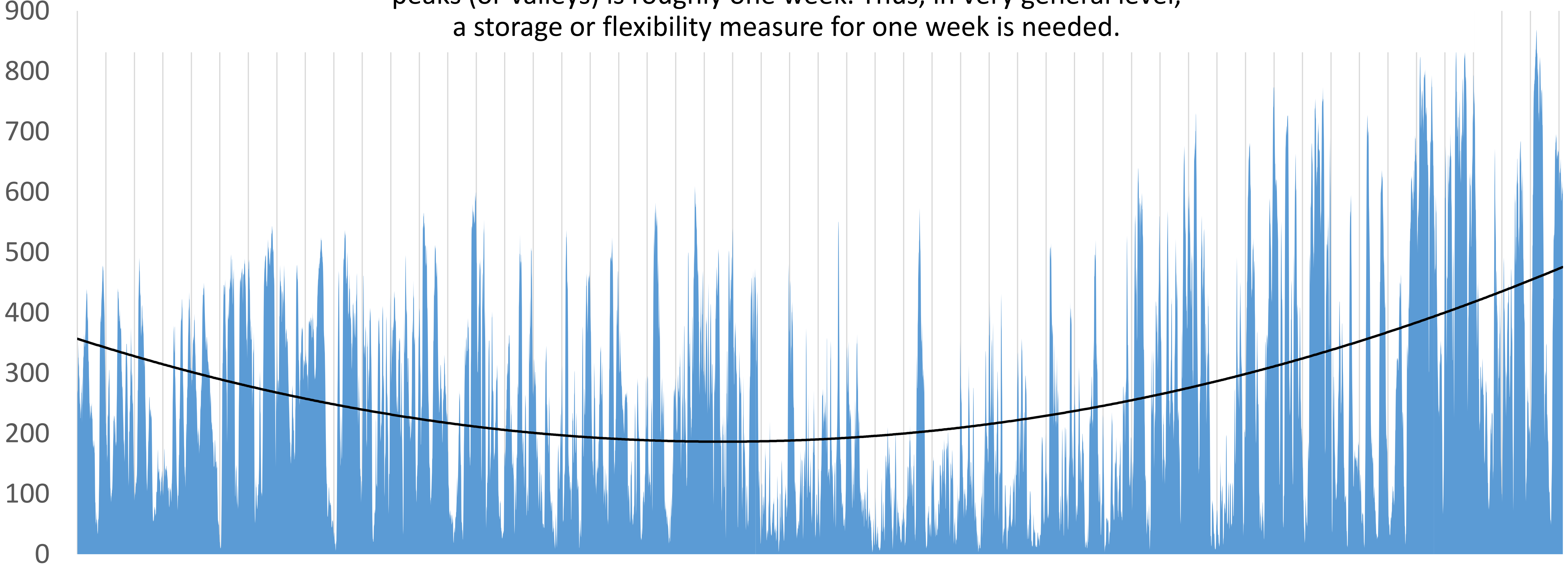
The remembering aspects considering the suitable level of system flexibility can be kept in mind:

- By building a flexible system with a variety of production methods, operation in different market and political situations has a moderate cost.
- But the flexible system is also expensive to invest, so what is the most profitable level of investments?
- From environmental point of view, perhaps quite high investments, i.e. acceptance of low internal return rate level is preferable. Also, to foster technical development, new technology and/or new combinations of old technologies should be demonstrated and the results made public as much as possible.
- However, ”old” technologies must not be rejected, only because if they possibly are ”old-fashioned”. Judging some solution just by its age is often a wrong generalisation. This applies for both directions: ”too old” or ”too new” are not fruitful approaches.
- If there are possibilities to have several advantages by just one solution, that could be resource-efficient and also economically viable. Probably e.g. the optimal heat pump capacity in DH networks is that which is achieved by using the kind of heat sources which would be useful on their own also, like heat extraction from district cooled buildings.
- ”Multiple stakeholder”-problem can here be a bit challenging, but still, the idea of multiple advantages at the same time should be strongly considered.

Hourly wind power production in Finland and trendline

Since there is more wind in the wintertime, the increasing wind power share decreases the dispatchable power need difference between seasons. However, electrical heating should be strongly reduced if the seasonal shapes of the production and consumption would match. This seems not probable.

The more short-term fluctuation in the dispatcable power need obviously increases. The interval between peaks (or valleys) is roughly one week. Thus, in very general level, a storage or flexibility measure for one week is needed.



Year 2015. Interval between vertical lines is one week.

Storage and flexibility possibilities in power and heat supply and the sources of their costs

Flexible use of CHP, heat pumps and electrical heating

Standing trees
Heaps in logging site
Roadside storages
Bioenergy terminals

Power and heat consumption profiles + flexibilities

Storage silo

Reducing power to heat ratio or using condensing tail temporarily

Heat storage tank

DH network

Plant site storage

Receiving station

Trucks and trains

Capacity cost
- Construction of separate storage
- Larger structures than for constant load
- Land area
- ”Emotional cost”, resistance for too new/old ideas

Operation cost
- O&M of storage structures
- Extra handling of material
- Net storage losses
- Changed system efficiency

External cost
- Impacts on air quality
- Dust and noise
- Barrier effect
- Impact to the society (income distribution, tech. development etc.)

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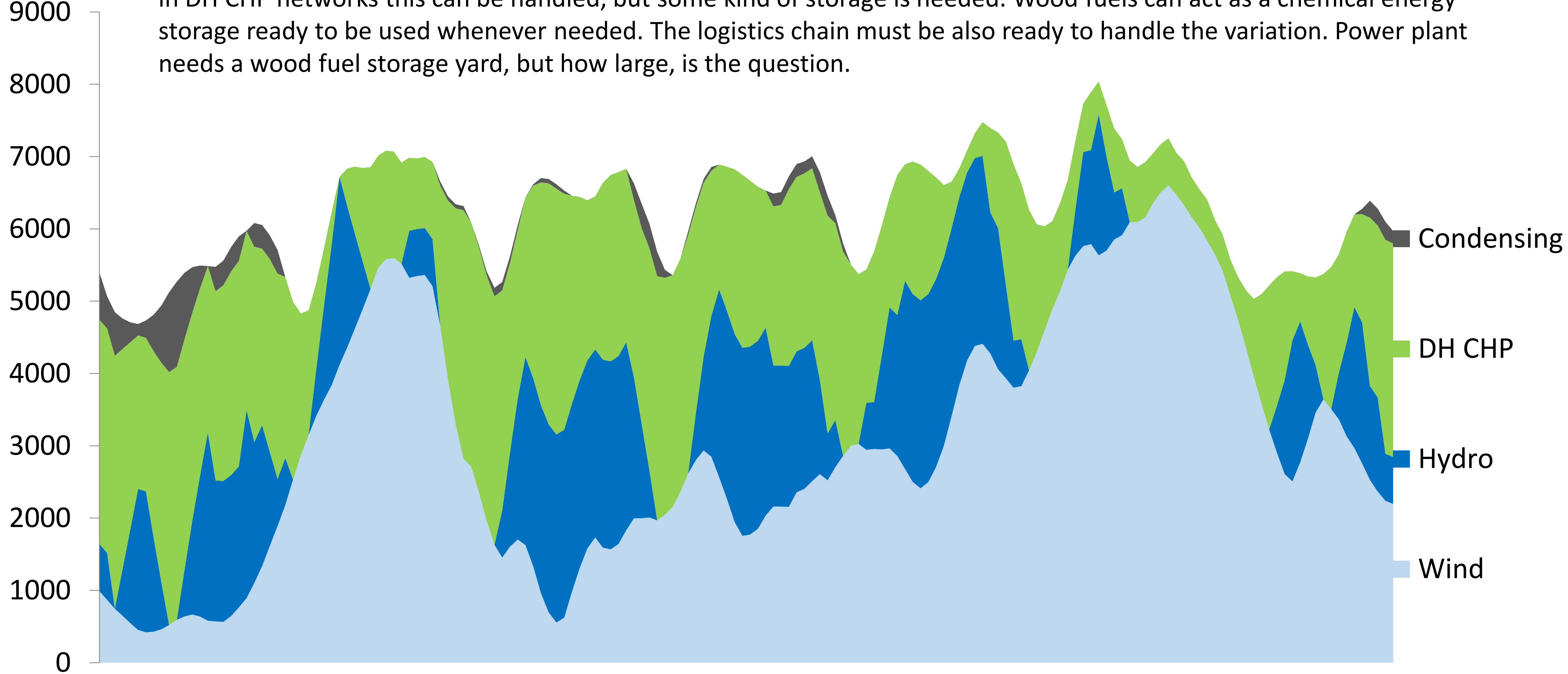
Simulated scenario of power production in Finland in a week on March, MW. Excluding nuclear and industrial CHP, which run at constant output. 8700 MW installed wind power, about 25% of the power production as measured in energy.

Also thermal power production must stongly take part in balancing, despite the use of hydropower. With heat storages in DH CHP networks this can be handled, but some kind of storage is needed. Wood fuels can act as a chemical energy storage ready to be used whenever needed. The logistics chain must be also ready to handle the variation. Power plant needs a wood fuel storage yard, but how large, is the question.



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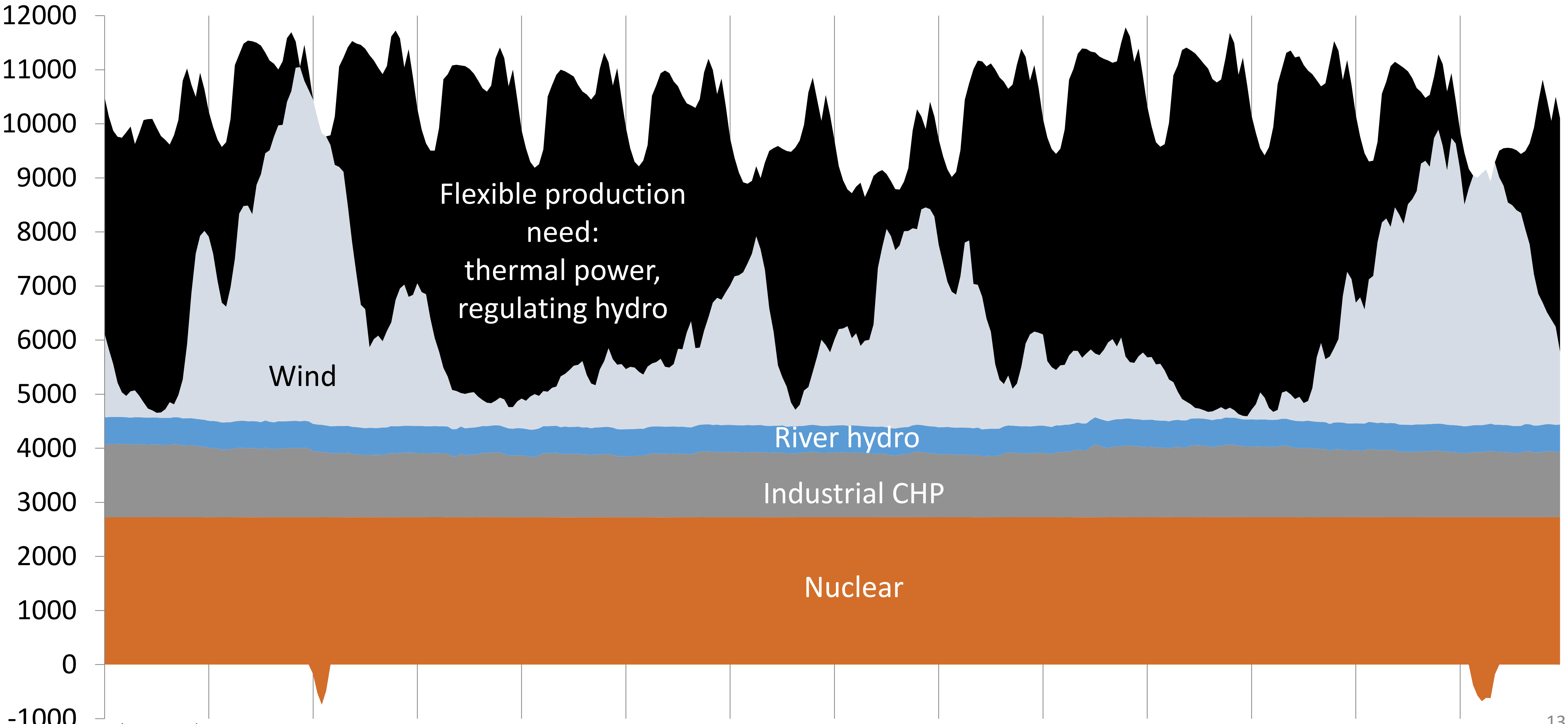
Electricity production in Finland during two weeks, MW, if there were 8000 MW installed wind power capacity



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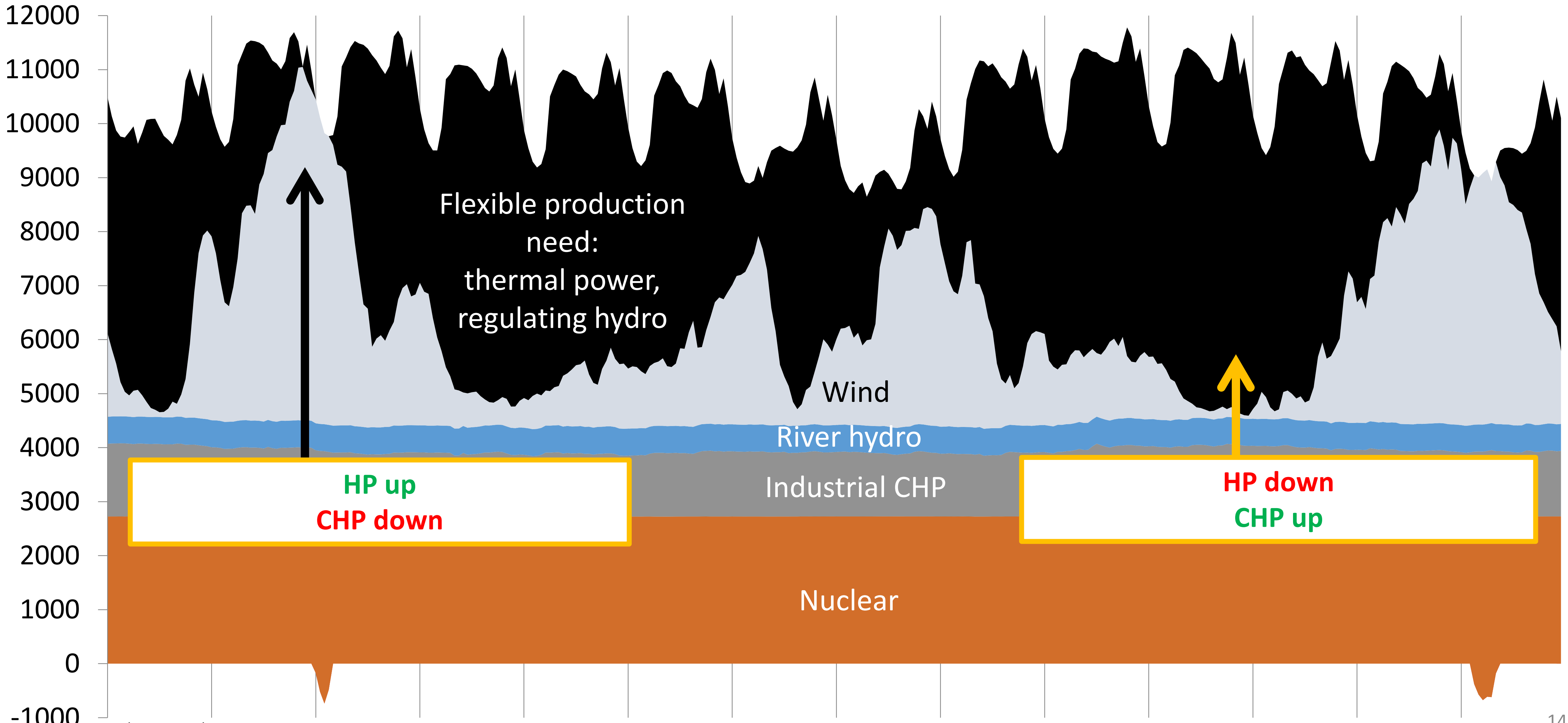
District heating CHP, heat pumps and electrical heating can balance the mismatch between electricity production and consumption (at least partly)



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Some drawbacks of energy storage and flexible production and consumption, in general. These must be evaluated case by case:

- Decreased level of utilisation for existing devices,
  more equipment than would be needed for constant load

- Need for additional equipment

- Decreased total system efficiency (however, not necessarily that important,
  if fossil fuel use is still decreased and solar/wind energy use increased)

Further, these have impact on the issues expressed in next slides.

In principle the evaluated storage or other solution should be compared to the basic situation from all of these viewpoints, in system level. I.e. the consequences for all the energy production should be addressed.

Storage and flexibility possibilities in CHP or other conversion plant area

Storage or flexibility type	What is stored or the use of what is timely shifted?	Feasible max. (?) storage or flexibility time	Direct losses, mainly energy losses
Fresh chip pile	Comminuted biomass	Days to weeks	Microbiological activity (biomass decomposition, loss of dry mass)
Dried chip pile	Comminuted and slightly upgraded biomass	Months	Microbiological activity, but a minor one compared to fresh chips
Pellet storage	More upgraded biomass		Practically no losses during storage. However, manufacturing takes electricity about 3% of fuel energy content.
Torrefied biomass storage			Practically no losses during storage. However, the energy content of the final product is only 50-80% of the raw materials energy input.
Bio oil storage			
Biogas or synthetic gas storage			In principle no losses during storage, but leakages can change the situation.
Liquefied gas storage			Very small loss in the form of evaporating liquid due to the thermal losses.
Intermediate storage chip bin	Comminuted biomass	Days	Microbiological activity (biomass decomposition, loss of dry mass)
Feed-in chip bin		Hours	
Snow and ice melting from fuel and slight preheating of fuel	Impacts on melting energy consumption timing	Hours… days	Melting energy
Snow and ice melting from plant yard, storage pile bottoms and roads			
Stationary or semi-mobile, electrically driven crusher at the plant	Uncomminuted biomass in plant yard or in the feeding table of the automatic slow-speed crusher. Impacts on electricity consumption timing.	Hours	Since there is a direct connection to other operations, this is feasible only when there is free capacity (no trucks coming to unloading, no urgent need for crushed fuel). The question is only about changing the timing of the crushing. Thus, no direct losses.

Storage and flexibility possibilities in CHP plant and their direct and indirect impacts (1)

Storage or flexibility type	Description in more detail	Direct impacts	Indirect impacts
Steam circuit of boiler	By allowing the fluctuation in pressure and temperature, heat can be stored to water and steam	Lower power-to-heat ratio, i.e. lower electrical efficiency if pressure and temperature are lowered. Less potential to replace condensing power for the same heat load.	Quick ramps can shorten the lifetime of the boiler. However, if this is important or not, depends on what is the first limiting factor for the lifetime of the plant: “normal” hours of use (max. e.g. 300 000), shortened lifetime for ramps or ageing due to the technically better options some day? This question applies also to the other methods, that may shorten the lifetime of the components.
Spinning mass	Rotating mass of turbogenerator smoothes the quick load changes and maintains the grid frequency	No direct impacts, but the timeframe can be only tens of seconds or so.	Building and maintaining plants to have spinning reserve.
Bypass of high-pressure preheaters	Usually a part of steam is extracted from several points of turbine to preheat the boiler infeed water. This improves the electrical efficiency of the plant. By not extracting the steam from first stages of turbine, more steam can be led through the rest of the turbine. However, boiler steam production must be high enough and turbine and generator must be able to handle the overload.	Lower electrical efficiency. Less potential to replace condensing power for the same heat load.	Overloading boiler can shorten its lifetime.
Partial bypass of turbine	Part of the steam can be led directly to heat production via bypass valve. By keeping bypass valve constantly slightly open, electricity production can be quickly increased by closing the valve and consequently letting all the steam flow through turbine.		If bypass is done too quickly, turbine lifetime can be shortened.
Downregulation of HP, driven by electricity from CHP	A part of the CHP electricity production can go to heat pump. When quick increase in electricity production is needed, HP is shut down and the required heat taken fron CHP or heat storage. HP can be also only administratively connected to CHP, i.e. it can be physically elsewhere than in the power plant area.	If HP is connected to the CHP DH network and running most of the time to be ready for doing the mentioned regulation, HP limits the possibilities of CHP to replace condensing power.	HP lifetime can be shortened due to the quick and frequent load changes. However, the effect may not be large.
Power plant overloading	The whole power/CHP plant is temporarily overloaded.	Possiby lower overall efiiciency.	Overloading can shorten the lifetime.
Starts and stops according to the heat and power needs, more frequently than now	CHP plants are currently stopped and started only a couple of times a year. Much more frequent starts and stops are however technically possible.	Starts and stops spend extra fuel.	Starts and stops can shorten the lifetime of the plant.
Ramping up and down faster than now	The minimum ramp-up time for solid fuel CHP plats from min to max output is 4-6 hours. Quicker ramps are however technically possible.	Electrical and possibly also total efficiency may be a bit lower than in more stable running mode.	Quick ramps can shorten the lifetime of the plant due to increase thermal stresses.

Storage and flexibility possibilities in CHP plant and their direct and indirect impacts (2)

Storage or flexibility type	Description in more detail	Direct	Indirect
Heat recovery from excess heat flows in the plant	During low electricity prices, CHP output can be reduced and heat produced by HP. Heat source can be boiler room, turbine cooling, flue gases (in most usual case), even bottoms of chip stacks etc.	Additional heat exchangers in the flowing fluids or gases cause additional pressure loss that requires more fan power, also when HP is not in use. HP electricity use in general.	Requires extra equipment, HP and heat collection devices.
Changeovers between CHP/condensing power production	Condesing turbine or turbine tail is used when the price of electricity is high enough, i.e. the cheaper production is already running at full power. If a condensing tail of CHP turbine is used, heat can be supplied from e.g. storage.	Using condensing power instead of CHP increases the electrical efficiency by e.g. 10%-units, from 33 to 43%, but the heat output is totally lost. The system loss due to this depends on the alternative heat production method, replacing CHP, its system effects, and the difference between those of CHP and alternative method. If CHP turbine has a condensing tail, it requires a small but constant steam flow, the energy of which is lost in condensing water.	Requires extra equipment, condensing power plant or condensing tail in CHP plant. However, condensing power cannot be avoided, if there is annual or shorter-time power deficit and imports, DSM measures etc. are not enough.
Changeovers between CHP/HP/el. resistances in heat production	CHP is used, when electricity is expensive , HP when it is relatively cheap and electrical resistances when it is very cheap.	In principle no direct negative impacts. Positive side-impact can be a better efficiency for CHP when HP is used wisely to smoothen the CHP load. However, also vice versa. If changeovers are too quick, especially CHP efficiency can drop.	Requires extra equipment, parallel capacity of CHP/HP/el.resistances. Positive side-impact can be longer lifetime for CHP when HP is used wisely to smoothen the CHP load.
Heat storages	Heat is stored for later use to steel tanks (shorter-term), borehole storages (longer term) etc.	The electrical efficiency of CHP or COP of HP is reduced, if hotter water or steam in higher pressure is supplied for storaging, than would have otherwise been be fed directly to use.	Requires extra equipment, storages and heat exchangers.
Steam accumulators	Low- or mid-pressure steam is stored for industrial or DH use.		
DH network	DH supply temperature can be raised by about 5 degrees compared to the normal situation and thus increase the heat content of the DH netowrk (if return temp maintains at the same level than in normal case).		Quick changes in supply temperature can shorten the lifetime of DH network or increase the risk for leakages.
Larger than normal DH pipes	Larger pipes increase the water volume of DH network, thus enabling more heat to be stored by varying the DH supply temperature.	See above, what comes to heat storage in general. Also, larger pipes have larger heat loss. However, dynamic pressure loss in network and thus also pumping energy is reduced.	Larger pipes need more pipe material and insulation. Also the installation work can require more time and heavier equipment.
Fuel drying	Wood fuels can be dried in power plant area or in terminal by using excess heat or electricity. Drying can be timed to the moments of cheap heat or electricity, using wet and dry chip storages as buffers. If drying is done in DH area, energy source can be flexibly chosen. In principle drying steam can be extracted from different extraction points of the turbine. The higher the temperature, the more drying capacity, but the less power production compared to heat production.	A part of the drying energy is lost, because heat transfer from air to material to be dried is not 100%. E.g. a certain belt dryer has an efficiency of 60%.	Requires extra equipment: dryer, heat exchangers, conveyors. Also may increase land area need.

For storage and flexibility options, also the following issues should be considered. However, one problem is that these should always be judged in some known context. I.e. the impact of unit technologies should be estimated in system level.

Storage or flexibility technology or method	Energy losses			Material input for storage or flexibility measure and the following energy input					Other impacts, + and -	Possibilities to recover energy losses?	Possibilities to decrease - -sides and increase + -sides	Material input for storage or flexibility measure and the following energy input after ”optimising round”				
	Reason	%	e/MWh	Reason	% of energy output/stored etc.	$e/kWh_{capacity}$	$e/MWh_{product}$	e/kWcapacity	(listed and, if possible, somehow evaluated by numbers)			Reason	% of energy gain in system level	$e/kWh_{capacity}$	$e/MWh_{product}$	e/kWcapacity
Example: Heat storage tank, large (30 000 m^3)	Loss through tank envelope	3/ mo	0,5/ mo	Tank material (steel), base (concrete) and insulation (mineral wool)	For steel tank (wall thickness in avg e.g. 10 mm) 150% of the single storage cycle	3 (without land area cost)	Depends on the amount of cycles	Depends if heat exchanger is needed or not	- Land area need, roughly 1 m^2/MWh capacity (cost depends on land value) - Barrier effect (visual, trans-portational) + Possibilities for artwork, solar panel installations…	Small. In principle double skin-structure and heat recovery from intermediate space with HP could be possible, but hardly feasible.	Increased insulation, high-strength materials, alternative storage forms (ground pit etc.), high structure in relation to basal area, utilisation of facade and roof					

What is the optimal plant size (1)

- Plant sizing (one bigger or several smaller) is also a kind of multicriteria optimisation task.

  The targets can be e.g.

  - Short fuel transportation distances and/or possibility to use large transport units
  - As little as possible fuel transports through populated and on the other hand otherwise silent, natural areas
  - Economics of scale in plant size
  - Economical power or heat transmission network. As much MWhs per line length as possible.
  - Reliability. One unit is easier to administrate and can possibly use more reliable techniques than the small(est) ones, but on the other hand the downtime of small unit is not that significant than that of larger one.

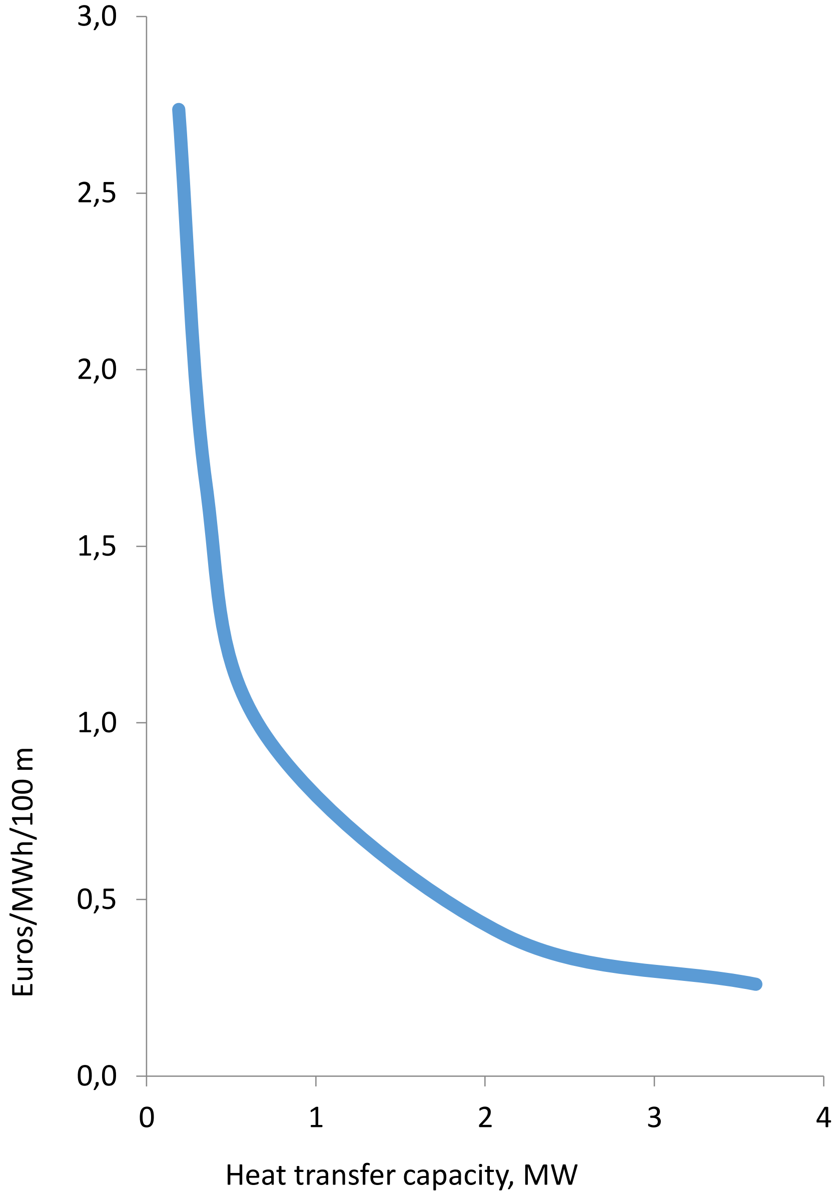
- As an educated guess, the optimum may lie somewhere near current practice (in Finland), which is one CHP plant for smallish city or 2…4 for larger one. This applies, if fuel is solid. If fuel is liquid or gaseous, then also smaller plants can be competitive.
- Terminologically, the above mentioned is still strongly distributed energy production according to e.g. EU definitions. So, the question may be formulated like ”distributed” or ”very distributed”?

What is the optimal plant size (2)

- The fact behind the size statement in the previous slide is that (forest) fuel collection area, to meet the demand, is relatively large and goes well outside city borders.
- Let’s take an example. In principle the following alternatives to arrange heating with biofuels are possible:
  - A town- or city-wide DH network and 1-4 CHP or (in less effective case) heat only-plants. An example of needed forest residue harvest area is given below:
    - The Finnish forest fuel potential is about 40 TWh/a. Land area (excl. Lapland) is 200 000 km^2. Followingly, the average forest fuel gain is 200 MWh/km^2/a.
    - In a city of 100 000 inhabitants, the heating need is roughly 1 TWh/a, including residential, commercial, public etc. buildings
    - Excess electricity to run HPs and electrical resitances could in future handle e.g. 30% of heat supply, municipal solid waste 10% and energy efficiency 10%.
    - Thus, 500 GWh remains to be covered by bio-CHP. In a plant with good specs power-to-heat ratio is e.g. 2/3. The produced electricity is needed in system level (or in local as well) and must be taken into account. So, about 800 GWh fuel is needed in our example case, assuming there is a flue gas scrubber etc.
    - To get 800 GWh from forest fuels, an area of 4000 km^2 is needed. Average transport distance is consequently about 35 km, in practice usually more because of the competiting use of fuel and land area near the town. This well exceeds the borders of the city with that population.
  - Smaller units. The same urban structure than in the previous example.
    - The collection area does not change.
    - The external costs of transports probably even increase, since more fuel must be transported through densely habitated areas. Some DH pipes can be avoided, but one may ask, which one is more harmful to environment, an underground pipe or a frequent traffic?
    - The smaller the units are, the worse the above mentioned issue gets.
    - In principle the best alternative is to have some plants around the city, otuside the densely habitated area.
    - Small unit size mean that CHP units are expensive. If heat-only boilers are built, the question of where to get dispatchable electricity production must be addressed.
  - Very small, i.e. building-wise units. Buildings situated ”in the middle of forest” so that the fuel can be harvested from very surroundings of the each building.
    - For one household, the collection area could in the same logic e.g. 15 MWh /2/3 = 23 MWh This means an area of 0,12 km^2. i.e. 12 hectares.
    - This sparse habitation would mean a very extensive urban sprawl, if widely adopted. The massive use of private car would easily detoriate the good effects of possible short distances for wood transports.
    - That said, for existing buildings in rural areas heating with very local wood fuels could well be and traditionally also has been one viable option.
    - Also, it is not meant here that no new buildings could be built in ”remote” areas. It’s a question of balance, i.e. from energy point of view there should be enough CHP (or more generally, areas with very flexible and dispatchable electricity production) compared to the far less flexible production possibilities in separate houses. On the other hand, there are e.g. good possibilities to produce solar power in the roofs of detached houses. So, in the best case these different kinds of housing complete each other, with different roles in the energy system. The basis in all this is the freedom of choice in housing alternatives, due to the different preferences of people. This difference in preferences can be very advantageous also from energy point of view.
    - This also probably applies to the traffic issues. Private car use may be well acceptable from energy point of view, if the amount of that is moderate, i.e. most journeys are done by more sustainable methods. And, most of the cars (and also heavier vehicles) should probably be electrically driven, equipped with smart charging, taking part in the electricity production-consumption-balancing.

What is the optimal plant size (3)

- Worth of considering is also the issue that the electrical efficiency of engine plants is roughly 10 %-units better than that of steam power plants. In system level this probably means that the system efficiency of the following options is quite equal:
  - Forest fuel chips used directly in CHP plant. Steam turbine process.
  - Forest fuel chips first gasified or liquified and then used in CHP plant, based on internal combustion engine. Excess heat from gasification or liquidification used as DH.
- For efficient system, the use of excess heat as DH (or for other purposes) from all conversion processes is essential.
- The possible use of liquid or gaseous fuel may mean that the ”best alternative” is a bit shifted towards smaller units. The higher is the energy density of fuel, the less important are the transportations. Also, the unit cost and electrical efficiency of engine plants is not that dependent on unit size than steam plants.
- Thus, the liquidification or gasification plant could be a larger one (for economics of scale) and the CHP units using the products of those smaller.
- In addition, one possibility to reduce the harmful externatilities of transports is to have a transfer loading (and possibly drying before that) in terminal. Thus the load size of near-city-transports can be increased.
- On the other hand, avoiding the building of large DH pipes is not really an important issue. The marginal cost of ”extra”capacity in pipe is small, see the figure on the right.
- The same concerns also electrical transmission, i.e. the largest relative cost comes from the small-voltage lines. In Finland it is approximately 20 euros/MWh while the high-voltage transmission cost is round 5 euros/MWh.
- Thus, the overall system efficiency (remembering that ”good” fuels are a scarce resource) and local effects of transports are far more important than attempts to avoid energy transmission networks.



What is the optimal plant size (4)

- The logic about plant size presented in previous slides concerns physical environment. Organisational arrangements may be a bit different story, though.
- Instead of partial optimisation, system optimisation is to be the aim. This may be closer, if acting for system optimum is advantageous also from single producer or consumer point of view.
- In principle the way to this is could be transparent pricing in all the phases of the production chain.
- Also taxes and subsidies should reflect the impacts in the real world, i.e. social and environmental costs and benefits. Externatilities, in other words.
- After these have been implemented, searching for partial optimum leads also to the system optimum. That is, when each stakeholder makes carefully a decision to maximise his own profit, the system benefit is also automatically taken into account. Like in classical ”invisible hand”-idea. Or does it really work like this…
- … since it is difficult or even impossible to define the value of many impacts. Also, even from the single stakeholders’ perspective, the decision-making may be extremely challenging.
- The task is even more difficult, when it is remembered that many of the impacts depend very much on the context and the base level. For example, a small amount of some substance may not be harmful at all in practice, while in larger amount it is lethal. A marginal impact may be very different in different cases.
- To figure out the challenges of optimisation see the next two slides.

General issues to be considered in evaluating the quality of some solution. What is to be expected in these senses, compared to the own or others’ requirements? Also, what is needed in general but probably not realised enough?

Environmental	Societal	Financial	Personal (concerning all the stakeholders)
Primary energy use	Technological diversity	Investment cost and lifetime	Ease of use, understandability
Biodiversity	Diversity of organisations and thoughts	Operation and maintenance cost	Perceived job/other task quality
Sustainability of using renewable energy sources	Demonstrating new solutions, pioneer work	Incomes from sales	Suitable level of challenge
Non-renewable energy use	Possibilities to be common solutions and/or to be standardised	Predictability of costs and incomes	Self-efficacy in work
Emissions from energy production: - CO_2 - Methane - Small particles and black carbon - Hydrocarbons - SO_2 - NO_x - Ozone - Heavy metals - Toxic compounds - Radioactive compounds	Job creation, tax impacts	Risk level and its impact on profitability	Possibilities for personal development
	Quality and safety of job environment and external safety	Internal return rate needed for investors	Possibilities to affect the work or decisions around it
	Locality or globality (depending on the point of view)	Required skills (and price) of personnel	Health effects
			Social appreciation (from the others)
	Impact on housing environment, e.g. urban sprawl		Sense of community
	Predictability of supply		Suitability for certain lifestyle
Emissions from equipment manufacturing	Impact on landscape, space needed, noise, dust		Freedom of choice
Emissions from fuel production, transportation and upgrading	Risk (or possibility…) for greenwash		Suitability for personal values
	Competitiveness (against what and why?)		Salary

Samuli Rinne, Aalto University

Background information needed for energy system optimisation. Classified according to the estimated difficulty in getting the information.

Difficult: Policy and scenario dependent

- Fuel prices, incl. emission trade prices
- Electricity exchange prices
- Economical renewable energy potentials, considering also taxes, subsidies and carbon price
- The amount of nuclear and CCS power (and heat)

Difficult: Not very well known

- The value of biomass in other purposes than energy, especially in those which are able to use low-quality biomass with heterogenous size and structure
- Preferred technologies from some other than purely techno-economical point of view
- Noise, dust and barrier effect from operations, converted to euros

Moderate: Can be calculated, but some uncertainties

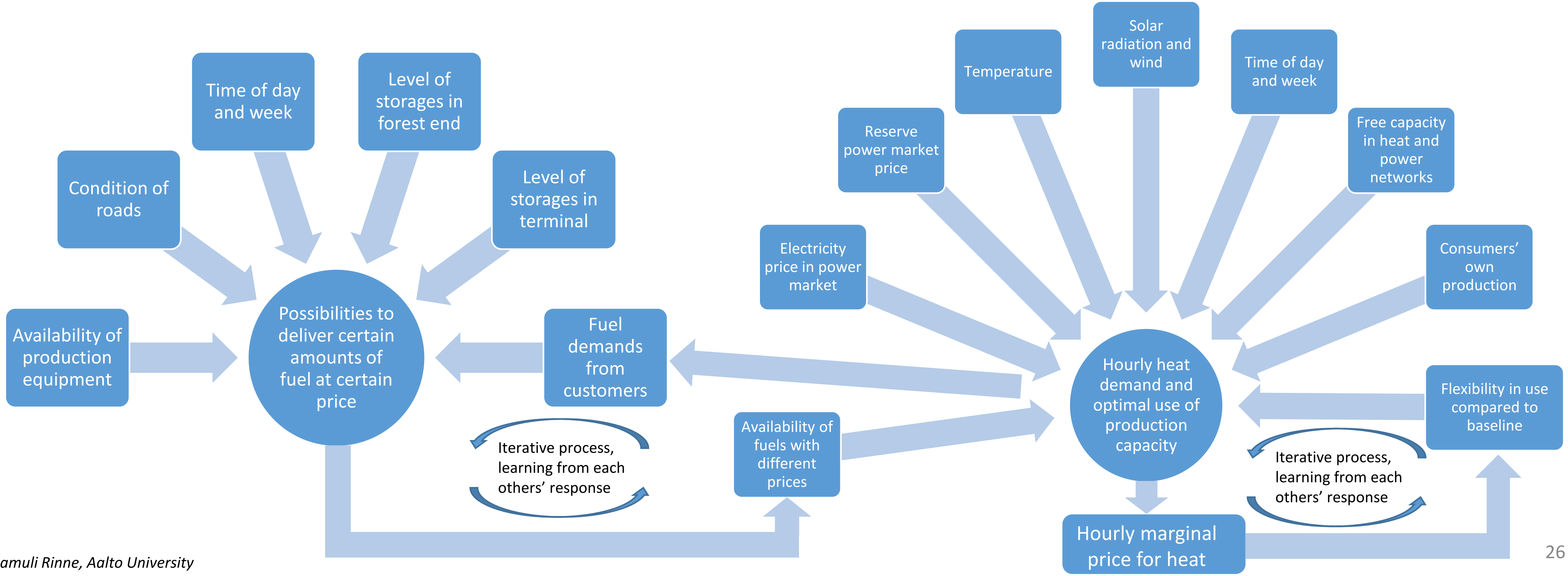
- Potential of flexible consumption, including households, fuel drying etc.
- Investment costs of technologies in different size classes
- Predicted investment behaviour of different stakeholders, i.e. maximum pay-back time
- Operation & maintenance costs of technologies in different size classes
- O&M costs due to the quality of the fuel (moisture content, particle size, impurities)
- Operation and maintenance (O&M) cost changes and shortened lifetime of the power plants due to the increased ramping up and down
- Tolerated level of income uncertainty among different stakeholders
- Conversion and handling resource use:
  briquetting, pelletising, drying, combustion and heat transfer in boiler, liquidification, gasification, transports in forest/road/rail/water (for different forms of biomass)
- Space need of transports and storages, land value in alternative use scenarios in different locations
- Dry matter losses on the logging site and on the roadside or terminal storage

Easy: ”Nature laws” or known behaviour

- Hourly electricity and heat demands, extrapolated from current data (however, demand side management can cause quite large uncertainity in predicitions)
- Solar power/heat and wind power production profiles
- Storage losses from heat or electricity storage in most cases

What is the ”right” way to organise the production-consumption chain?

- As seen in the previous two slides, for optimal solution there seems to be nearly depressingly large amount of issues to be considered
- Setting taxes, subsidies and legislation (which all affect on the optimisation round presented here) is a challenging task and an endless source of political debate. However, when these are in place (or they are just taken as they are), the optimisation in operational level can be done.
- Adapted to the problem of this task, the basic idea could be to use (hourly) marginal cost for fuel, power and heat added with the value of capacity. From smallest to largest, all the stakeholders in the chain could have an automatical devices to do the most of the daily optimisation.
- The following simplified figure shows the idea. The predicted values of named paramaters make it possible to optimise the use of e.g. power plant.
- Currently, some parts of this idea are in use.



Condition of roads

Time of day and week

Level of storages in forest end

Level of storages in terminal

Availability of production equipment

Possibilities to deliver certain amounts of fuel at certain price

Fuel demands from customers

Iterative process, learning from each others’ response

Availability of fuels with different prices

Electricity price in power market

Reserve power market price

Temperature

Solar radiation and wind

Time of day and week

Free capacity in heat and power networks

Consumers’ own production

Hourly heat demand and optimal use of production capacity

Flexibility in use compared to baseline

Iterative process, learning from each others’ response

Hourly marginal price for heat

Samuli Rinne, Aalto University

Targets for biomass storage and use

- To minimise the handling cost and dry matter losses in biomass production chain.

  -> Long-term storages only with dry biomass
  -> As little processing and conversions as possible
  -> Storages mainly outside city areas

- To maximise biomass value. I.e. primarily use as raw material. Or, as the second best alternative, use as fuel for producing as much as possible mechanical energy exactly when needed.

  -> From system efficiency point of view CHP is the best alternative, in certain conditions also gasification/liquidifying
  -> CHP plants should be able to ramp up and down quickly
  -> No heat-only production with biomass to large extent
  -> Heat storages should be in place to match the heat and power production and demands

Biomass storage or flexibility possibilities before the plant

Storage type	Feasible (?) max. storage time	Direct losses, mainly energy losses		Indirect losses, due to the additional investments or externatilities for storaging	How to decrease losses?
		Reason	%		
Standing trees or other biomass	years	If cuttings are dealyed, decreased growth of wood, i.e. less carbon mitigating from atmosphere. In thinnings also a decreased value of wood due to the decreased share of high-quality logs for mechanical wood industries.	Strongly case dependent	Possibly decreased annual hours for machines -> rent cost increases. Also, machines may be withdrawn from service before the end of the technical lifetime, due to the better enough new models.	Use of machines also for other purposes, if possible. Updating machinery just by essential parts.
Piles in the stand (stumps, small whole trees, logging residues, straw)	days to months	Moisture content increase (decrease of lower heating value). Microbiological activity (biomass decomposition, loss of dry mass). Falloff of needles and small twigs due to the drying.	In May-Jul 5% gain for drying, but 20-40% loss for loss of needles etc. In wintertime no drying but some decomposition, round 1%/month.	Lost biomass may very probably be substituted by fossil fuels.	Forwarding to roadside max. 3 weeks after felling.
Roadside storage (uncomminuted biomass)			1% / month	Landing area is not immediately usable for growing the new tree generation after felling.	Fast Track-production chain, i.e. biomass directly to the plant. Covering of piles. Use of natural (transpiration) drying when applicable.
Terminal (uncomminuted biomass)		Moisture content increase (decrease of lower heating value). Microbiological activity (biomass decomposition, loss of dry mass).		Ground works for terminals, asphalt, lights, electrification, roads, land value. Barrier effect of roads and terminals -> longer distances for other traffic.	
Terminal (comminuted biomass)	days to weeks		1-3% / month		
Terminal (dried biomass)	months		<1% / month, even near zero	Artificial drying	Drying can be done by using excess energies
Transport equipment	hours	Energy loss 0 for this time frame. However, total cost may be high since the wage of the driver is running during waiting for unloading (or in the earlier phase, waiting for chipper).		Possibly decreased annual hours for equipment-> rent cost increases. Also, equipment may be withdrawn from service before the end of the technical lifetime, due to the better enough new models.	Use of machines also for other purposes, if possible. Updating machinery just by essential parts.

One issue in maximising biomass value is simply to maximise the amount of it

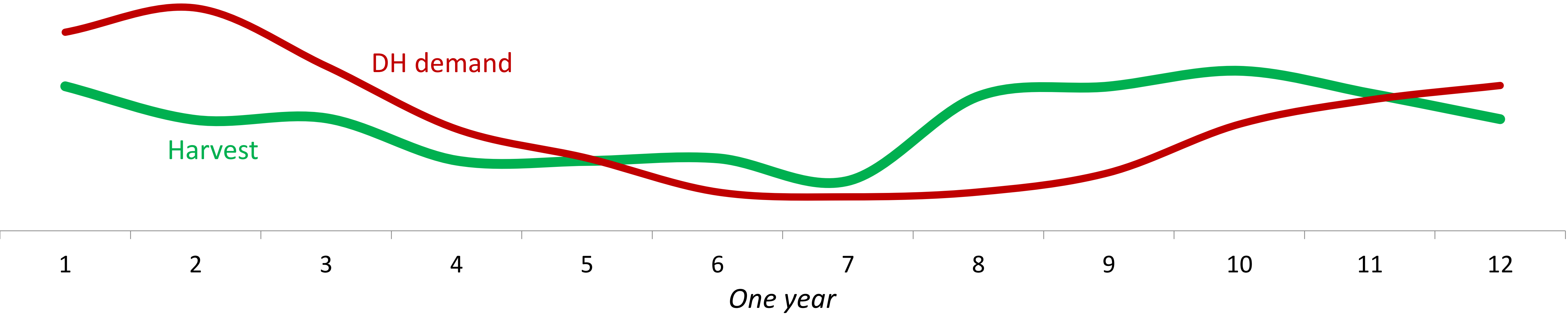
- From this point of view, biomass should be collected fresh, with needles intact, to maximise the yield
- This can be however cause some problems, but there are also solutions for those. See table below.

Possible problem or question	Solution
Nutrient loss	Fertilisation. Nitrogen (+others when needed) for mineral soils, wood ash for peatlands. Energy use in the artificial fertiliser production phase must however remembered.
Decreased carbon storage in the soil	Needles are the fastest decomposing part of the residues, so their contribution to the carbon storage is neglible in every case.
More water to be transported	At least in Finland the load space volume limits usually the load first, rather than weight.
More water to be evaporated in combustion	Fuel can be dried before combustion by using excess heat or even electricity. The source for excess can be e.g. - Recovered low-temperature heat from flue gas scrubber - CHP heat in the hours when there is need for electricity but not that much for heat, i.e. wind, solar and hydro (+nuclear) production is not enough - Vice versa, electricity in the hours when there is surplus production. HP or direct electricity.
Corrosion of superheater	Good materials, co-combustion with fuels containing sulphur or sulphur injection. Sulphur reacts with wood ash, no major sulphur emissions to air are emitted.

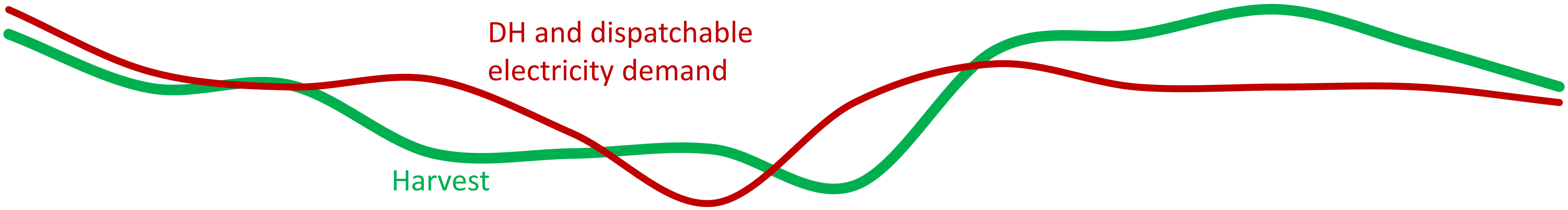
- All of these have some cost, but this cost should be compared to the cost (or environmental penalty) of using fossil fuels instead of biomass, that would be left in the forest. That is to say, in practice biomass which is not collected, is substituted by fossil fuels in system level. Of course with some preconditions, but more or less so.

Minimising the storage time is one way to maximise the biomass value, due to the avoidance of dry matter losses.

Here are shown the potential forest residue harvest from current fellings and district heat use.
The match of fuel production and demand is not that good.



…and here below the possible future, when there are large DH storages and CHP electricity is produced to fill the temporarily gaps of the renewal electricity production. The gap between fuel production and use is now much smaller, i.e. the possibility to have short storage times better. The Fast Track-production chain can be cover a larger share of the demand.



Some requirements for biomass plants in the future, derived from the quality of potentially available biomass

- The lowest quality materials, which are left from other processes, can be used for energy production. The heat value per volume unit may be low and there may be mechanical and chemical impurities.
- These material properties lead to the following requirements:
- Large and not-disturbing enough storage and processing yards for fuel. In practice these may be arranged as terminals, from which there are good transport opportunities with high-volume trucks, trains or vessels to the destination.
- Fuel drying possibility by transpiration (solar energy) or artificially by excess heat or even electricity.
- Rugged equipment in the plant:
  - conveyors designed for high volumes relative to the heat value
  - silos designed for weak flow properties of fuel, tendency to bridge etc.
  - screen and hog for oversizes generously dimensioned for high share of large pieces in fuel
  - furnace and especially superheater materials resistant to corrosive compounds, even if the superheat pressures and temperatures are high to achieve a good power-to-heat ratio
  - possibility to inject sulphur into the furnace in the form of e.g. certain sludges, to reduce the chemical aggressiveness of chlorine and other compounds of flue gases
  - efficient sooting equipment
  - efficient removal of stone and metals from the bottom of the furnace

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