Thermal Storage Power Plants (TSPP) - Operation modes for flexible renewable power supply [1]

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Abstract

The paper at hand presents a simulation model for Thermal Storage Power Plants (TSPP). Such plants can theoretically cover highly variable residual load patterns during the transition from fossil to renewable electricity supply. TSPP can use electricity surplus from the grid, photovoltaic power and biomass or – during transition – natural gas as primary energy sources in order to generate highly flexible power just on demand. The core of a TSPP is a Carnot Battery consistent of an electric heater, a large-scale high-temperature heat storage and a Rankine power cycle. Gas turbines with waste heat recovery can be added for occasional peak loads that exceed the capacity of the steam turbine.

After a brief introduction that explains the challenges of the energy transition that can be tackled by TSPP, the paper describes basic configurations and operation modes and the equations and parameters of the simulation model used for this analysis. After that, the feasibility of TSPP is tested for different configurations by modelling their technical and economical performance in the frame of highly variable residual load patterns derived from a 90% renewable electricity scenario in Germany. Finally, the results of this analysis and an outlook for further work are discussed.

Keywords: flexible solar power, firm capacity, Carnot Battery (CB), renewable electricity, heat storage, Thermal Storage Power Plant (TSPP)

1. Introduction

A key challenge of the transition of the power sector towards renewable energy is to reliably cover the residual load that appears after massively introducing variable renewable energies like solar and wind power [1] [2]. The traditional “horizontal” structure of the load curve (Figure 1, upper graph) is strongly altered and in the long-term substituted by a “vertical” sequence of different agents that alternate in dominating supply (Figure 1, lower graph). As an example, night-time supply might be characterized by low winds that force conventional thermal power plants to come into operation, followed by a sunny day with strong solar power that reduces residual load close to zero. If wind power remains low, next evening peak load will lead to the so called “duck curve”, again forcing conventional power plants into full load operation. On the other hand, if wind power gets stronger

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during the night, daytime solar power might be replaced by nighttime wind power, and most conventional power plants could eventually stay off. While solar energy offers a regular day-night cycle, the availability of wind power is highly variable and irregular.

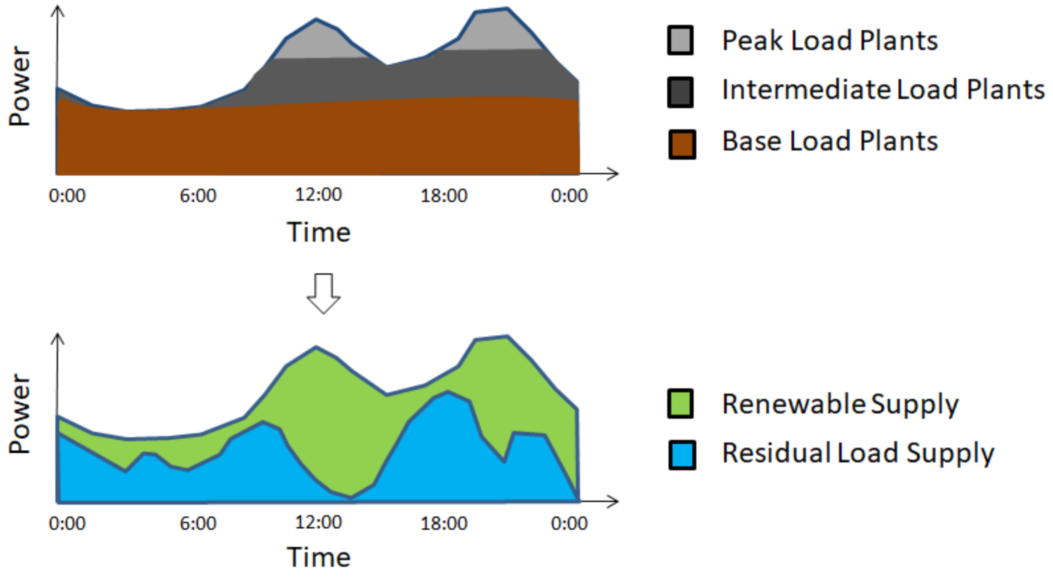

Figure 1: Introducing solar and wind power eliminates the traditional "horizontal" supply structure of the load curve by base, intermediate and peak load plants (upper graph). This structure is subsequently replaced by a "vertical" – that means by a sequential – dominance of different alternating energy sources (lower graph).

The International Renewable Energy Agency IRENA has published a scenario for a global energy transition to achieve the 1.5 ° C climate protection goal aiming at 90% renewable share on global electricity by 2050 [3]. This means that by that time, most of the residual load world wide will have to be covered by renewable power stations that must be flexible enough to do so. This might be easily achievable in countries with large storable hydropower and biomass resources like Norway or Brazil, but will represent a significant challenge in countries like Germany that depend mainly on variable wind power and solar energy.

A comprehensive analysis of flexibility options in Germany [4] including demand side management, grid expansion and several options for storage and flexible production concludes that "Longer periods with little wind and solar radiation ("dark and windless periods") can be technically bridged, either with long-term energy storage devices or with flexible producers (gas-fired plants, for example)." Limitations of international grid interconnection for the compensation of European residual load transients have been estimated and quantified by the German Ministry for Economic Affairs and Climate Action [5].

Another challenge of the energy transition relates to surplus power (and its curtailment and re-dispatch) that may appear when wind and solar power capacities are strongly increased and produce excessive power, particularly if the remaining thermal power plants are not flexible enough to reduce or increase their capacity properly in order to follow the highly variable residual load patterns. Schill [6] states that it will be particularly important to increase the flexibility of conventional (residual) power production and to reduce must-run capacity, as this will reduce curtailment and the need for storage capacity during energy transition. Analysis by Bundesnetzagentur and Bundeskartellamt [7] [8] [9] [10] reveal that curtailment of excess wind power has been strongly increasing since 2015

(Figure 2). A consequence of this is the reduction of utilization of coal and lignite power plants in the year 2020 to around 2000 and 5000 full load hours per year, respectively [11] [12] (Figure 3).

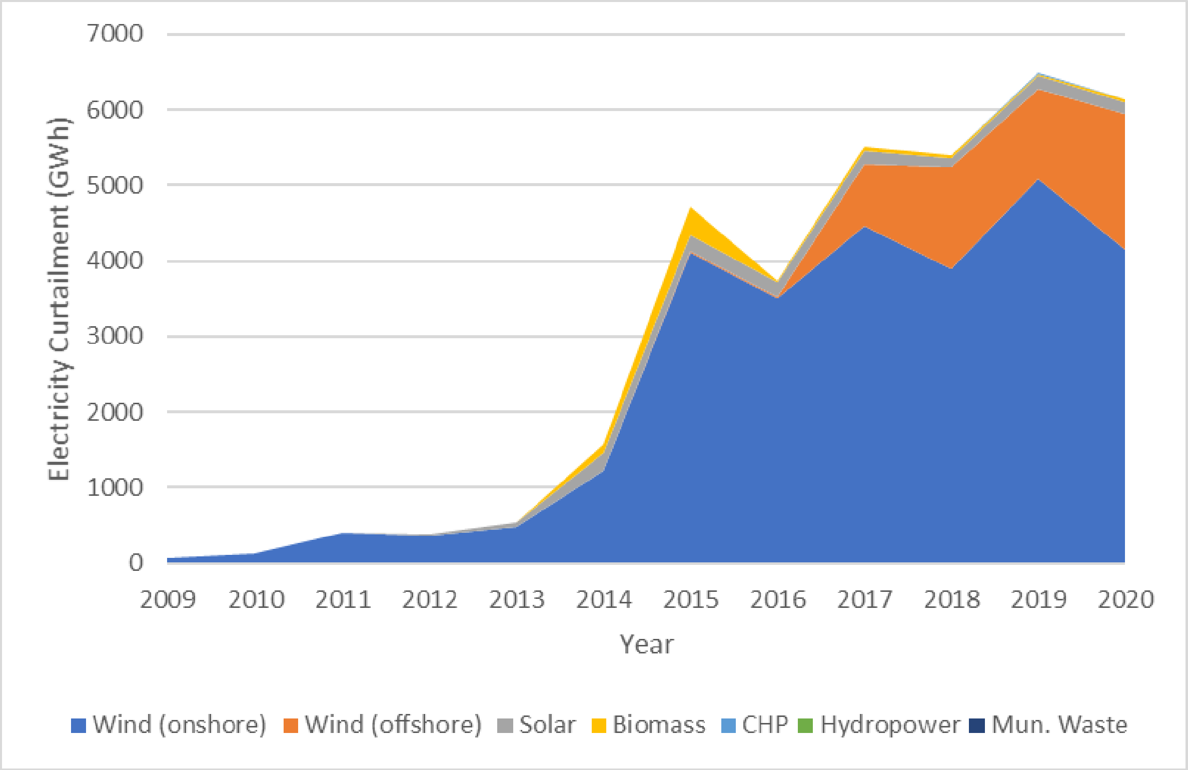

Figure 2: Development of electricity curtailment from renewable production in Germany since 2009 [7] [8] [9] [10].

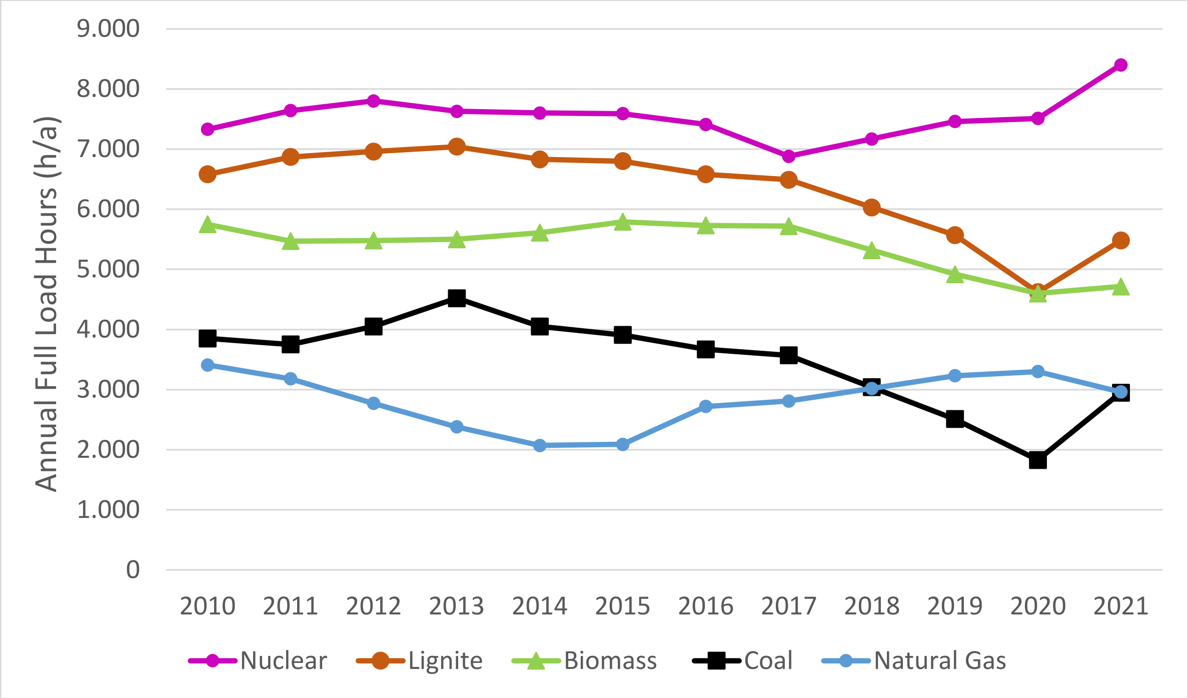

Figure 3: Development of annual thermal power plant utilization in Germany in the past decade [11], [12], [13].

Bundesverband der Elektrizitäts- und Wasserwirtschaft BDEW [13] has shown lately that the expansion of renewable electricity in Germany has been stagnating, with a significant reduction of renewable power generation and an according increase of fossil and nuclear electricity share between the years 2020 and 2021. Besides of year-to-year weather fluctuations, this stagnation is certainly linked to the fact that both the commitment of covering the difficult residual load with increasing renewable share and the concurrent curtailment of renewable excess power imply economic risks that limit interest in further renewable energy investment, particularly wind power.

The abovementioned reveals some fundamental changes of paradigm within the power sector that can be expected in the near to mid term future in Germany and other countries where renewable energy sources are implemented and fossil fuel and conventional thermal power plants are phased out:

- During transition, traditional base load and intermediate load plants like nuclear, coal and combined cycle power plants will face highly variable loads and frequently interrupted operation times, strongly reducing their technical and economic performance in terms of efficiency and financial turnover. In principle, only highly flexible peaking plants like gas turbines will be able to fully cover residual load patterns properly and with reasonable cost.
- A fundamental difference between solar power and wind power will gain more and more importance: solar power obeys a regular day-night cycle that is imposed by the speed of rotation of the earth, while wind power depends on stochastically varying weather patterns. When its installed capacity becomes large enough, solar power will be regularly available during daytime, will regularly reduce the residual load to zero, will regularly produce surplus power and will regularly force conventional thermal power plants into off- or standby mode.
- On the other hand, irregular weather patterns will not only lead to irregular availability of wind power, but will also interrupt, alter or reduce the regular availability of solar power during daytime, and will thus intensify the variability of renewable energy on the grid.
- While regular variations of energy availability can be easily buffered by short-term storage technologies like electrochemical or thermal batteries, irregular patterns of demand and supply cannot, but will require thermal power plants and renewable or fossil fuel in order to be bridged. Unfortunately, renewable fuel is usually scarce and expensive.
- Situations with stochastic renewable power surplus destabilize the grid and thus will be avoided as far as possible. Producing surplus bears the risk of curtailment and economic loss. On the other hand, the availability of frequent and regular surplus power is a precondition for the economic operation of any storage technology. As investors are not likely to invest in power plants that would primarily produce surplus in order to be stored by others at low or zero cost, the only visible remedy is that regularly available “surplus” power (e.g. from large PV plants) and storage devices (e.g. Carnot Batteries) are developed together as units.

Taking into consideration the above said, requirements and characteristics of future “residual load power plants” can be narrowed down as follows:

- They should include a regularly varying primary renewable energy source (preferably solar power) and a buffer storage (e.g. electrochemical battery or Carnot Battery) adapted to the regular cycle of the selected primary renewable energy source in order to convert variable renewable energy into dispatchable renewable power.
- They should include renewable fuel as backup in order to guarantee full power capacity at any time during long lasting residual load events and peak load situations (preferably biomass, biomethane, hydrogen or other synthetic renewable fuels).

- They must be highly flexible in order to be able to bridge irregular and variable residual load events and surplus periods that will not only vary from year to year because of varying weather patterns, but will also change with time due to increasing variable renewable energy shares.

Recognizing this, Hermann et al. [14] and Geyer [15) propose to transform conventional thermal power plants by adding an electric heater and heat storage in order to be able to absorb surplus power from the grid and thus reduce fuel consumption. Gordon et al. [16] and Trieb and Thess [17] propose to feed the thermal storage additionally with power from large scale PV plants in order to enhance its utilization. In all cases, firm capacity is guaranteed by some kind of fuel, while fuel consumption is reduced by variable solar power that can be stored for later use on demand. Thermal Storage Power Plants (TSPP) as defined in Section 2 of this paper seem to be well-suited to cover the residual load with renewable energy and to reduce curtailment of excess power. They must be understood as highly flexible thermal power plants rather than as simple storage devices.

The TSPP concept is similar to that of concentrating solar power plants (CSP) that have been known and operated for many decades. The CSP concept is also based on a thermal power station and a high temperature heat storage that is fed by a concentrating solar thermal collector field. Hybrid operation with gaseous fuel allows to bridge solar gaps and to provide firm power capacity on demand. Unfortunately, CSP plants require beam solar radiation and cannot be operated satisfyingly under German weather conditions with prevailing diffuse sunlight.

A drawback of using PV power in order to heat up a thermal energy storage is its much lower average annual efficiency of about 15-20 % compared to concentrating solar thermal collectors that can achieve 45-55% annual efficiency [18]. On the other hand, using photovoltaic arrays instead of concentrating solar collectors for the collection of solar energy also offers some advantages:

1. The solar collector field and the power plant can be placed at several kilometers distance, because energy is transferred in form of electricity and not by heat transfer fluid like in a parabolic trough CSP plant, or by concentrated solar radiation like in a central receiver CSP plant. A possible transformation of conventional power plants to TSPP is thus easier than an equivalent transformation to CSP plants.
2. PV absorbs direct and diffuse sunlight and thus suits better in regions with scarce direct solar irradiation like Germany.
3. Direct and diffuse sunlight used by PV represents a larger and less volatile primary energy resource than the direct sunlight used by CSP.
4. The parasitic losses of a PV collector field are lower than those of an equivalent CSP collector field, and collection of energy as well as operation and maintenance are comparably simple.
5. Contrary to solar heat, part of the generated PV power can be delivered directly to the grid. Depending on the share delivered directly, this avoids significant losses related to heat storage and the conversion from heat to electricity within the thermal power cycle.
6. The use of greenfield PV and biomass suggests the introduction of integrated Agri-PV installations especially in countries with intensive agriculture.
7. In addition to PV power, any grid surplus can be absorbed and stored for later use.

At the end of the day, it will be a decision based on local conditions regarding availability of space nearby the power plants and annual solar radiation intensity, whether PV or concentrating solar thermal collectors would be used as primary energy source in a TSPP. Here, in view of an application in Germany, the focus clearly lies on the globally applicable PV alternative.

The scope of the work at hand is to present a TSPP simulation model that is tested in the frame of an electricity scenario for Germany for the year 2040 with 90% to 100% renewable electricity share and highly variable residual load patterns [17].

The model includes optional sector coupling with any kind of base load device like a low temperature heat pump or an electrolysis unit that can increase the load factor and economic performance of the TSPP. Operation modes of TSPP range from standby while charging the Carnot Battery with excess power, to peak load supply by the included gas- and steam turbines.

The paper is organized as follows: Section 2 (Method) describes the basic configuration of a TSPP including primary energy sources, heat storage and power equipment and explains the corresponding operation modes and the related model equations. Section 3 (Data and assumptions) presents the technical and economic parameters used by the simulation model and Section 4 (Results) discusses the results of a systematic variation of the Carnot Battery size and its impact on technical and economic performance. Section 5 briefly discusses possible variants of TSPP configuration and sector coupling that could be assessed in the future. Section 6 finally shows conclusions and outlook for further work.

2. Method

2.1 Basic Thermal Storage Power Plant (TSPP) configuration

A TSPP as defined here is a thermal power station that converts different forms of primary energy into power on demand. In this context, it does not differ from any other conventional thermal power plant. It is also very similar to conventional plants in terms of using renewable or fossil fuel for power generation. Another common issue is the optional combined production of combined heat and power for communal or industrial purposes. Nevertheless, there are significant differences between conventional thermal power plants and TSPP as defined here (Figure 4):

- Not only fuel is used as primary energy. Significant share of primary energy is provided by a large photovoltaic power plant used as primary energy source that will have an installed capacity several times larger than that of the steam cycle. For instance, the installation of 20 GW steam turbines in form of TSPP in Germany [17] would allow for the additional installation of 100 GW PV plants without creating grid fluctuations, but on the contrary covering most of the residual load with solar power (please refer to Section 3 for details). As far as possible, PV power will be delivered directly to consumers, while excess power will be stored for later use. Fuel consumption of the steam cycle covering the residual load can thus be reduced by up to 50%.
- A Carnot Battery [19] [20] that consists of an electric heater, a molten-salt or solid-state thermal energy storage [21] and a steam cycle is used to store excess power from the PV plant and, if available, also surplus power from the electricity grid [16] [21] [22]. In this case the steam turbine will be off or in standby, keeping system components warm with the help of heat from the storage. No fuel will be spent during standby, because at that moment the Carnot Battery will be charged with excess power from the grid or from the PV plant.

- A backup heater fed with biomass prevents the heat storage from running empty. It can either directly satisfy the steam turbine's total heat demand, or run at lower capacity and leave the adaptation of heat supply and heat demand to the heat storage.
- Finally, one or several gas turbines can take over peak loads that exceed the capacity of the steam turbine. In this case, their waste heat can be fed into the storage or directly into the steam cycle making use of a Heat Recovery Steam Generator (HRSG).
- The plant can either only cover the highly dynamic residual load on the grid, or additionally provide power to any kind of base load device (heat pump, electrolysis unit or other). This helps to prevent curtailment of excess PV power and increases the utilization (load factor) of the system, which leads to better technical and economic performance.

In order to improve system efficiency in the future, the electrical heater could be replaced by a high temperature heat pump, as will be explained in Section 5 of this paper.

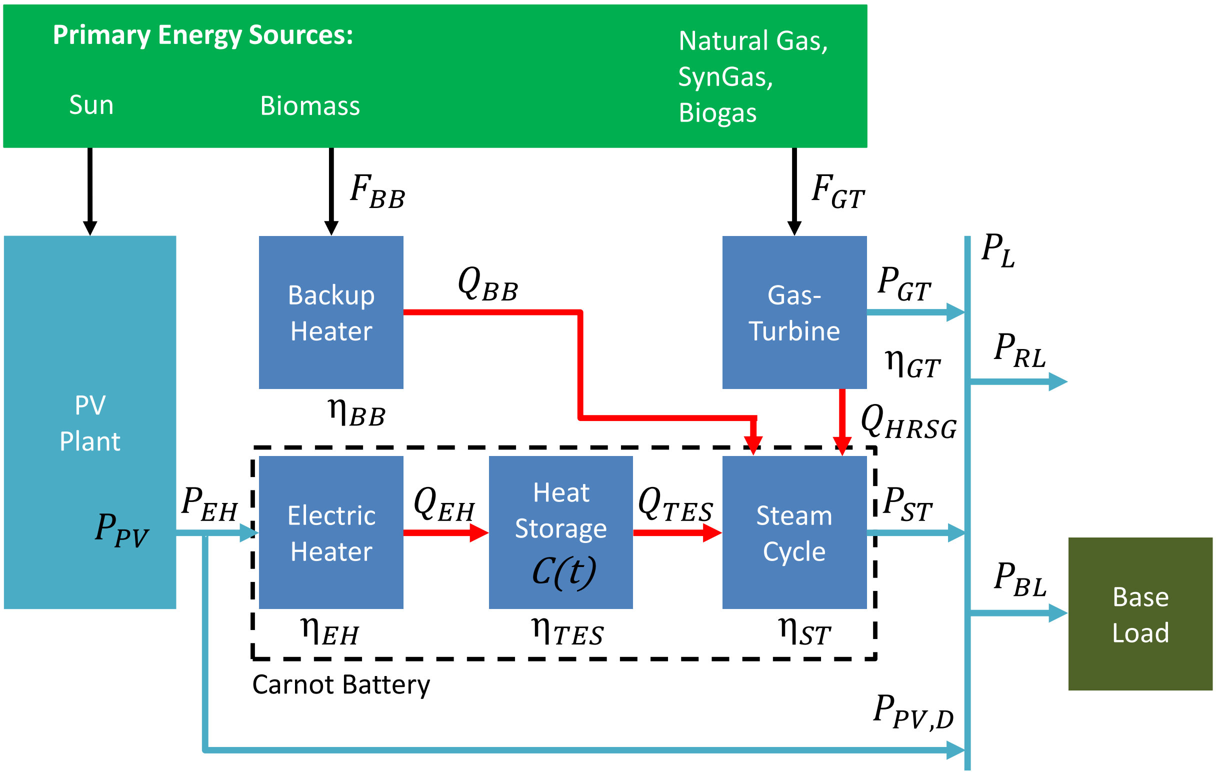

Figure 4: Schematic of a TSPP: primary renewable energy sources, Carnot Battery consisting of electric heater, thermal energy storage and steam cycle. Additional components for firm capacity: biomass backup heater and peaking gas turbine with waste heat recovery. The residual load to be covered can be complemented by connecting a base load device in order to increase utilization. A more detailed illustration of the TSPP configuration can be found in Figure 23. Abbreviations are explained in Table 1.

Thanks to the integrated Carnot Battery, a TSPP is an extremely flexible thermal power station able to respond to any operation mode from base load to peak load or even standby. At the same time, the system makes optimal use of the available primary renewable energy sources, keeping system efficiency as high as possible at any time, as will be discussed in Section 4 in more detail.

For instance, during peak load events the gas turbines' exhaust heat can be partially recovered into the steam cycle, where it is used to drive the steam turbine. Therefore, in spite of only occasional peak load operation, the system will achieve a gas-to-power-efficiency close to that of a classical combined cycle power station. Under residual load patterns, peaking gas turbines would have only about 1500 full load operating hours per year, while the steam turbine may have up to 5000 full load hours, which is possible because of the intermediate Carnot Battery. In case the gas turbine’s waste heat would be recovered by the heat storage instead of a HRSG, the steam turbine would only be driven by the molten-salt steam generator and operated independently from the gas turbine.

In terms of flexibility, the biomass backup heater also profits from the Carnot Battery, because it can also be operated independently from the steam turbine`s highly variable demand. Disconnecting the rather complex biomass combustion process from the dynamic load of the steam turbine is a considerable advantage compared to direct steam generation with biomass. However, for next stage TSPP, we have assumed a conventional system with HRSG and backup steam generator (Figure 4).

TSPP have different operation modes in order to cope with dynamic residual load transients that will be described in the following.

2.2. TSPP operation modes

The operation of TSPP can be affected by several conditions, such as power income from the PV panels, the state of charge of the Carnot Battery (storage tank), the real-time load from the consumers, etc. Figure 5 shows the logic flow chart of a basic TSPP model. Operation of a TSPP consists of six main operation modes (OP) and transients in between:

OP1: The PV plant delivers enough power to cover the load plus extra power to charge the Carnot Battery. Steam turbine and gas turbines remain idle or in standby.

OP2: PV power is not sufficient to cover the load. The steam turbine is activated and fills the gap, using in a first place heat from the storage (**OP2.1**) and, if necessary, additional heat from the biomass backup heater (**OP2.2**).

OP3: PV and steam turbine capacity are not sufficient to cover the load. The gas turbines are activated and fill the gap, providing waste heat that is fed into the HRSG to run the steam turbine. If waste heat is not sufficient to provide maximum power of the steam turbine, the gap is filled with heat from the storage (**OP3.1**) and, if necessary, from the biomass backup heater (**OP3.2**). In **OP3.3** the waste heat from the gas turbine suffices to operate the steam turbine at full capacity.

The different operation modes, as well as the equations related to the TSPP model are given in the following. Time steps are given in hours t. Modelling starts in the first hour of the year, with a preset state of charge of the storage, e.g., $C(t=0)=\frac{C_{max}}{2}$ in units of $\mathrm{MWh_{th}}$. Abbreviations used for the model are explained in Table 1.

Table 1: List of model parameters

$C(t)$	Variable thermal energy content of the molten salt heat storage ($\mathrm{MWh_{th}}$)
C_{max}	Nominal storage capacity of the molten salt heat storage ($\mathrm{MWh_{th}}$)
$F_{BB}(t)$	Fuel consumption of the biomass backup heater ($\mathrm{MW_{th}}$)
$F_{GT}(t)$	Fuel consumption of the gas turbines ($\mathrm{MW_{th}}$)
$P_L(t)$	Total electric load (MW)
$P_{L,max}$	Maximum electric load to be covered by the TSPP (MW)
P_{RL}(t)	Residual load on the grid (MW)
P_{HP}(t)	Power demand of the heat pump (MW), assumed to be constant
$P_{ST,max}$	Nominal power of the steam turbine (MW)
$P_{ST}(t)$	Variable power of the steam turbine (MW)
$P_{GT,max}$	Nominal power of the gas turbines (MW)
$P_{GT}(t)$	Variable power of the gas turbines (MW)
$P_{PV,peak}$	Nominal installed power capacity of the photovoltaic power plant (MWp)
$P_{PV,max}$	Maximum power output of the photovoltaic power plant (MW)
$P_{PV,D}(t)$	Photovoltaic power directly delivered to the grid (MW)
$P_{PV}(t)$	Variable power of the photovoltaic power plant (MW)
$P_{EH,max}$	Nominal power of the electric heater (MW)
$P_{EH}(t)$	Variable power of the electric heater (MW)
$Q_{BB,max}$	Nominal thermal power of the biomass backup heater ($\mathrm{MW_{th}}$)
$Q_{BB}(t)$	Variable thermal power of the biomass backup heater ($\mathrm{MW_{th}}$)
$Q_{EH}(t)$	Variable thermal output of the electric heater ($\mathrm{MW_{th}}$)
$Q_{HRSG,max}$	Nominal thermal power of the heat recovery steam generator ($\mathrm{MW_{th}}$)
$Q_{HRSG}(t)$	Variable thermal power of the heat recovery steam generator ($\mathrm{MW_{th}}$)
$Q_{ST,min}$	Minimum heat supplied to steam turbine in standby ($\mathrm{MW_{th}}$)
$Q_{TES,max}$	Nominal thermal output capacity of the thermal energy storage ($\mathrm{MW_{th}}$)
$Q_{TES}(t)$	Variable thermal output capacity of the thermal energy storage ($\mathrm{MW_{th}}$)
SPR	Solar Plant Power Ratio: PV plant capacity / steam turbine capacity
EPR	Electric Heater Power Ratio: electric heater capacity / steam turbine capacity
h_{max}	Nominal storage capacity of the molten salt heat storage in full load hours (h)
$h_{PV,d}$	Daily average full load hours of PV plants (h)
η_{ST}(t)	Variable efficiency of the steam cycle (%)
$\eta_{ST,max}$	Nominal efficiency of the steam cycle (%)
η_{GT}(t)	Variable efficiency of the gas turbines (%)
$\eta_{GT,max}$	Nominal efficiency of the gas turbines (%)
η_{HRSG}	Average efficiency of the heat recovery steam generator (%)
η_{BB}	Average efficiency of the backup heater (%)
η_{TES}	Average efficiency of the thermal energy storage
γ_{TES}	Hourly self discharge of the thermal energy storage (%/h)

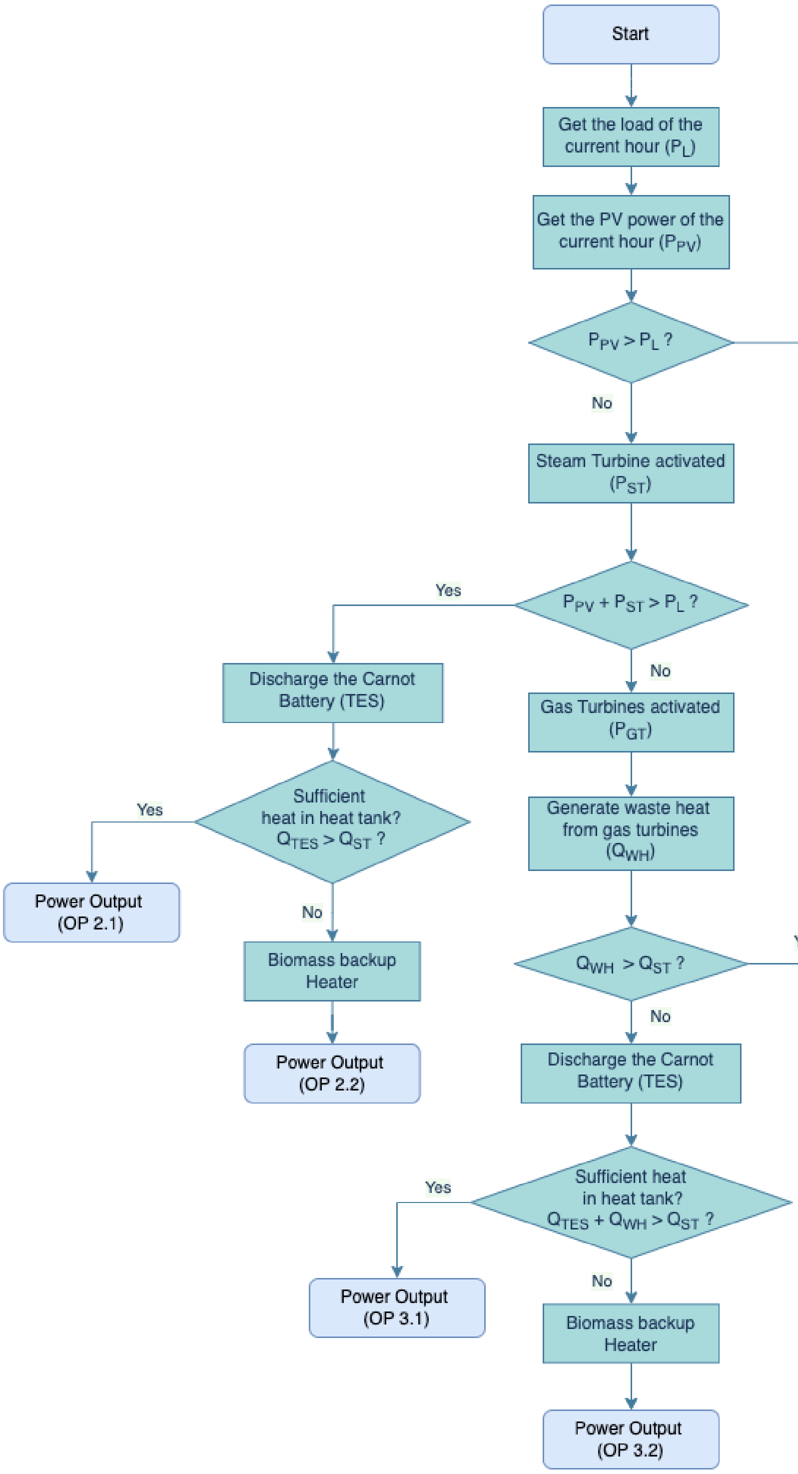

Figure 5: Logic Flow Chart of a basic TSPP model. Due to different operation conditions as well as loads, TSPP basically consists of six different operation modes. OP1: The PV plant delivers enough power to cover the load plus extra power to charge the Carnot Battery. OP2: PV power is not sufficient to cover the load. The steam turbine is activated and fills the gap, using heat from the storage (OP2.1) and, if necessary, from the biomass backup heater (OP2.2). OP3: PV and steam turbine capacity are not sufficient to cover the load. The gas turbines are activated and fill the gap, providing waste heat that is fed into the HRSG and used to run the steam turbine. If waste heat is not sufficient to provide maximum power of the steam turbine, the gap is filled with heat from the storage (OP3.1) and, if necessary, from the biomass backup heater (OP3.2). Otherwise, if waste heat is big enough to run the maximum of the steam turbine, the heat from the storage will not be used (OP3.3).

OP 1: Direct PV supply, Carnot battery charging and steam turbine stand-by

As far as the residual load allows for that, electricity from the photovoltaic plant is delivered directly to consumers. This usually happens in times with low solar radiation conditions, because then the additional PV capacity of the TSPP does not necessarily lead to grid surplus. An additional base load device connected to the TSPP helps to avoid surplus and curtailment, as it represents a minimum load even when the residual load is zero. Steam turbine and gas turbines remain idle or in standby. In case PV generation is higher than the total load, surplus (including grid surplus) can be fed to the heat storage via the electric heater. Charging power is limited by the maximum installed electric heater capacity and by the state of charge of the battery.

The following equations apply to Operation Mode 1 (Figure 6):

Operating Condition: $P_{PV}(t) \geq P_L(t) > 0$ Eq.1

TSPP Output: $P_{TSPP}(t) = P_L(t) = P_{PV,D}(t); \quad 0 \leq P_{TSPP}(t) \leq P_{L,max}$ Eq.2

Electric Heater Input: $P_{EH}(t) = P_{PV}(t) - P_L(t); \quad 0 \leq P_{EH}(t) \leq P_{EH,max}$ Eq.3

$Q_{EH}(t) = P_{EH}(t) \cdot \eta_{EH}$ Eq.4

Steam Turbine Output: $P_{ST}(t) = 0$ Eq.5

Gas Turbine Output: $P_{GT}(t) = 0$ Eq.6

Steam Turbine Input: $Q_{TES}(t) = Q_{ST,min}$ Eq.7

State of charge: $C(t+1) = MIN(C_{max};\ C(t) \cdot (1 - \gamma_{TES}) + Q_{EH}(t) - Q_{TES})$ Eq.8

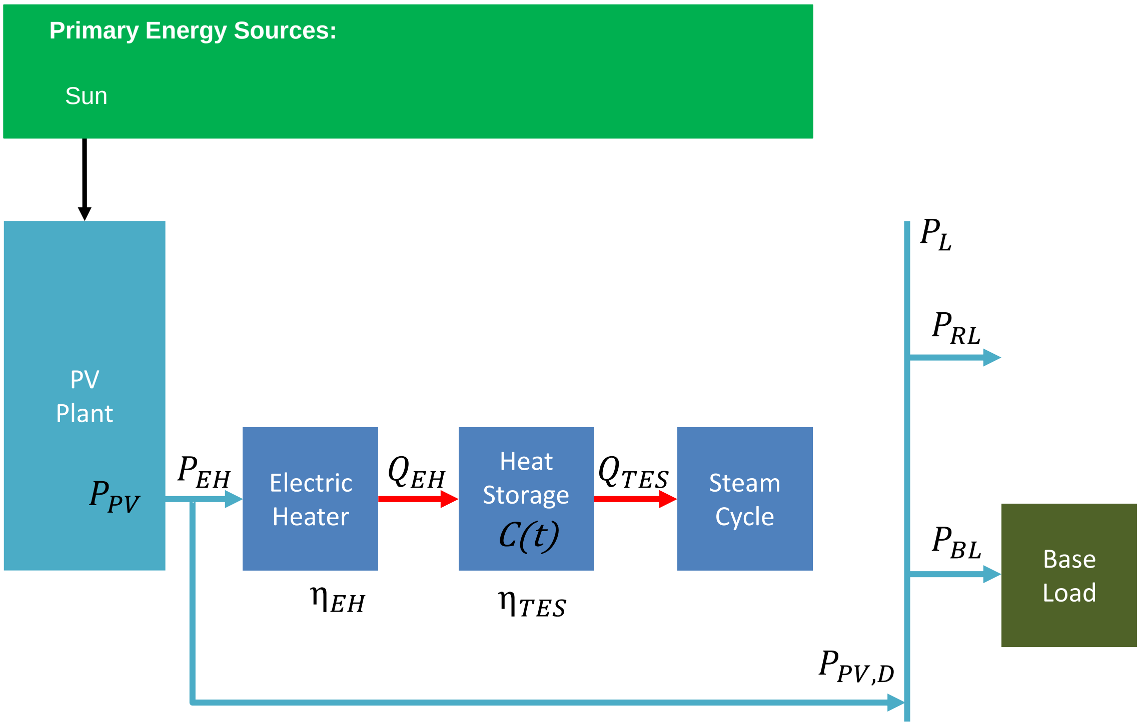

Figure 6: Operation Mode 1: Load is completely covered by direct PV supply and the heat storage is charged with surplus PV power. Steam turbine is in standby, gas turbine and backup heater are idle.

OP 2: Steam turbine operation

As soon as the load becomes larger than the available direct PV supply, the steam turbine enters into operation, in a first place powered by heat from the heat storage (Operation Mode 2.1). If the state of charge of the heat storage is too low to provide sufficient energy for the steam turbine, the biomass backup heater is activated and closes the respective gap (Operation Mode 2.2).

Operating Condition OP2: $0 < P_L(t) - P_{PV}(t) \leq P_{ST,max}$ Eq.9

OP 2.1: Steam turbine operation with non-critical state of charge of the Carnot battery

The following equations apply to Operation Mode 2.1 (Figure 7):

Operating Condition: $C(t) \geq Q_{TES}(t) > 0$ Eq.10

TSPP Output: $P_{TSPP}(t) = P_{PV}(t) + P_{ST}(t) = P_L(t)$ Eq.11

Gas Turbine Output: $P_{GT}(t) = 0$ Eq.12

Electric Heater Input: $P_{EH}(t) = 0$ Eq.13

Steam Turbine Output: $P_{ST}(t) = P_L(t) - P_{PV}(t)$ Eq.14

Heat from Storage: $Q_{TES}(t) = \frac{P_{ST}(t)}{\eta_{ST}(t) \cdot \eta_{TES}}$ Eq.15

State of charge: $C(t+1) = C(t) \cdot (1 - \gamma_{TES}) - Q_{TES}(t)$ Eq.16

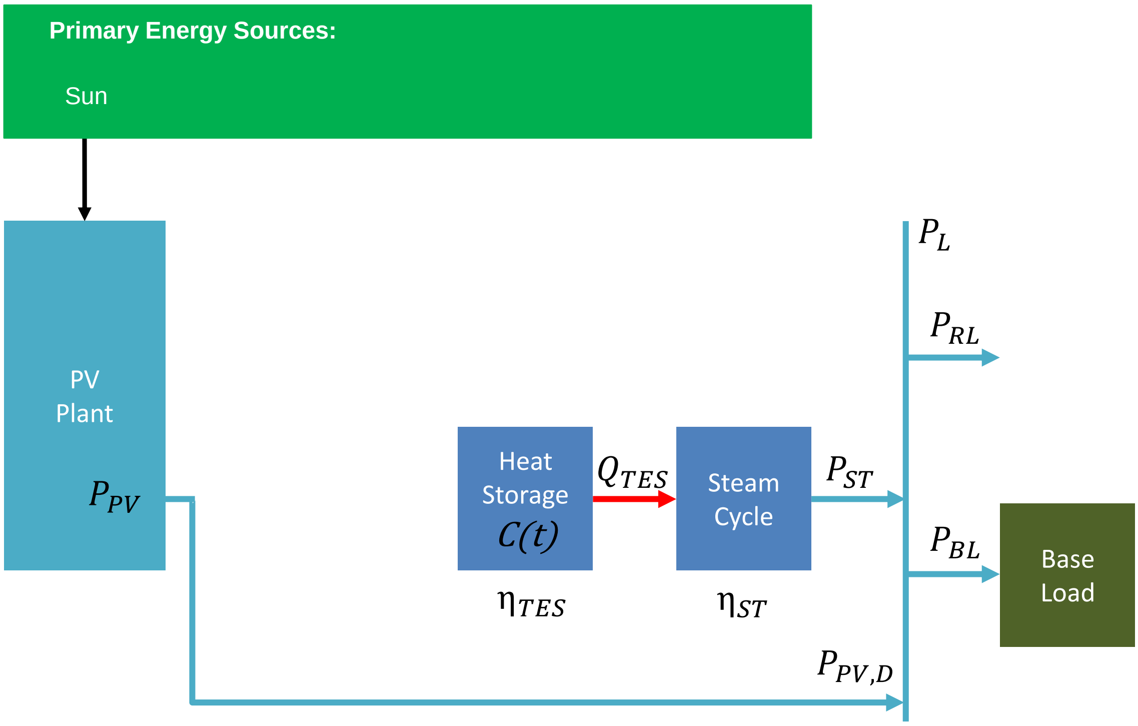

Figure 7: Operation Mode 2.1: Load is covered by direct PV and by the steam turbine powered by heat storage

OP 2.2: Steam turbine operation with critical state of charge of the Carnot battery

If the state of charge of the heat storage is not sufficient to provide energy for the steam turbine, the biomass backup heater is activated. The following equations apply to Operation Mode 2.2 (Figure 8):

Operating Condition: $C(t) < Q_{TES}(t) > 0$ Eq.17

TSPP Output: $P_{TSPP}(t) = P_{PV}(t) + P_{ST}(t) = P_L(t)$ Eq.18

Electric Heater Input: $P_{EH}(t) = 0$ Eq.19

Gas Turbine Output: $P_{GT}(t) = 0$ Eq.20

Steam Turbine Output: $P_{ST}(t) = P_L(t) - P_{PV}(t)$ Eq.21

Heat from Storage: $Q_{TES}(t) = \frac{P_{ST}(t)}{\eta_{ST}(t) \cdot \eta_{TES}}$ Eq.22

Biomass Backup: $Q_{BB}(t) = Q_{TES}(t) - C(t) \cdot (1 - \gamma_{TES})$ Eq.23

State of Charge $C(t+1) = C(t) \cdot (1 - \gamma_{TES}) - Q_{TES}(t) + Q_{BB}(t) = 0$ Eq.24

Biomass Consumption: $F_{BB}(t) = \frac{Q_{BB}(t)}{\eta_{BB}}$ Eq.25

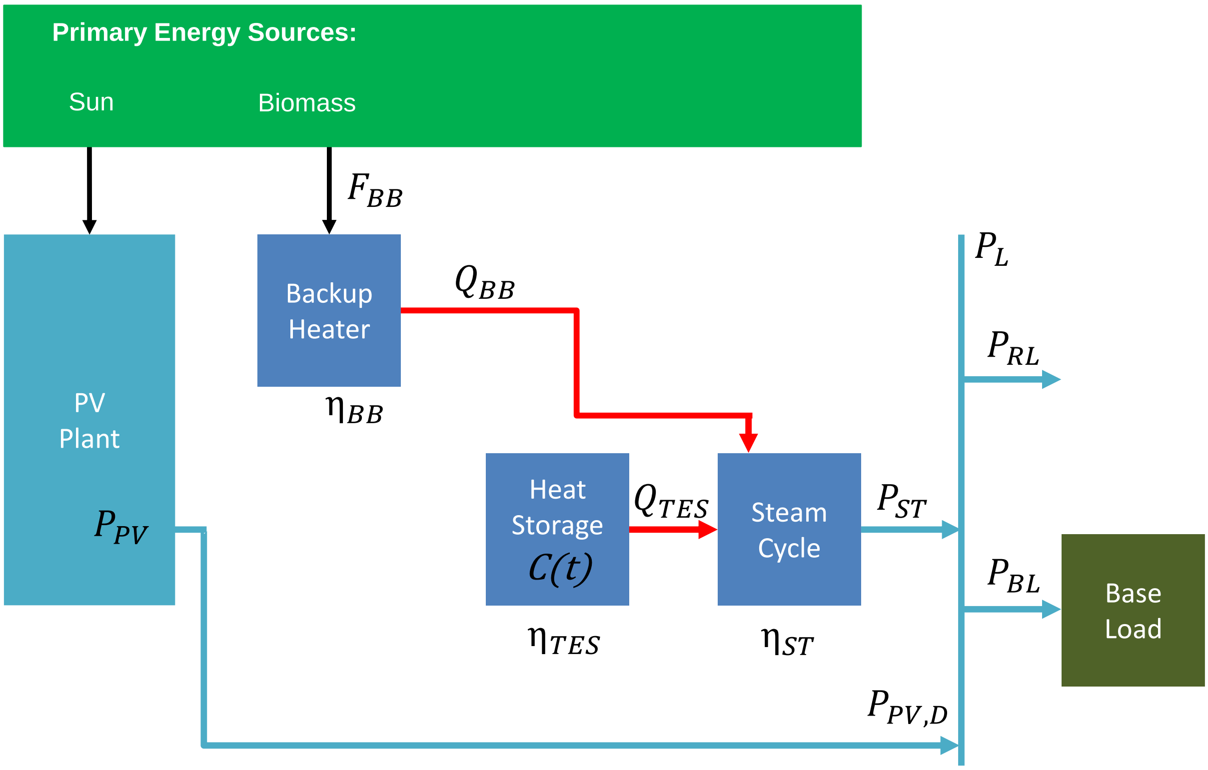

Figure 8: Operation Mode 2.2: Load is covered by direct PV and by the steam turbine powered by heat storage and biomass backup

OP 3: Steam and gas turbine operation

As soon as the load becomes larger than the maximum capacity of the steam turbine, the gas turbine enters into operation, providing waste heat that is fed into the HRSG and used to run the steam turbine. If waste heat is not sufficient to provide maximum power of the steam turbine, the gap is filled with heat from the storage (OP3.1) and, if necessary, from the biomass backup heater (OP3.2). Otherwise, if waste heat is big enough to run the maximum of the steam turbine, the heat from the storage will not be used (OP3.3).

Operating Condition OP3: $P_{ST,max} < P_L - P_{PV} \leq P_{L,max}$ Eq.26

OP 3.1: Gas turbine with steam turbine operated by waste heat and heat storage

If the state of charge of the heat storage is enough to provide sufficient energy for the steam turbine, it is preferably operated by waste heat from the gas turbine and by heat from the storage (Figure 9):

Operating Condition: $C(t) \geq Q_{TES}(t) - Q_{HRSG}(t)$ Eq.27

TSPP Output: $P_{TSPP}(t) = P_{PV}(t) + P_{ST,max}(t) + P_{GT}(t) = P_L(t)$ Eq.28

Gas Turbine Output: $P_{GT}(t) = P_L(t) - P_{PV}(t) - P_{ST,max}$ Eq.29

Gas Turbine Waste Heat: $Q_{HRSG}(t) = [\frac{P_{GT}(t)}{\eta_{GT}(t)} - P_{GT}(t)] \cdot \eta_{HRSG}$ Eq.30

TSPP Input: $P_{EH}(t) = 0$ Eq.31

Biomass Backup: $Q_{BB}(t) = 0$ Eq.32

Steam Turbine Output: $P_{ST}(t) = P_{ST,max}$ Eq.33

Heat from Storage: $Q_{TES}(t) = \frac{P_{ST,max}}{\eta_{ST}(t) \cdot \eta_{TES}}$ Eq.34

State of Charge: $C(t+1) = C(t) \cdot (1 - y_{TES}) - Q_{TES}(t) + Q_{HRSG}(t)$ Eq.35

Biomethane Consumption: $F_{GT}(t) = \frac{P_{GT}(t)}{\eta_{GT}(t)}$ Eq.36

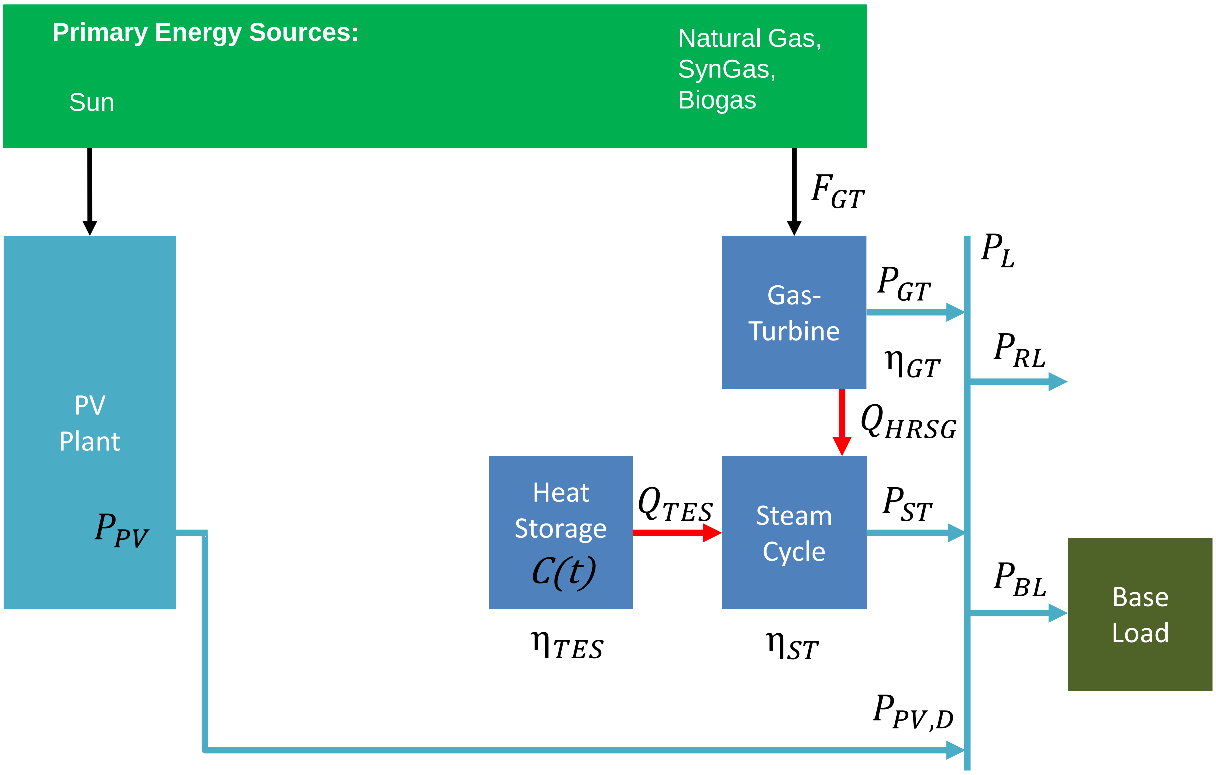

Figure 9: Operation Mode 3.1: Load is covered by direct PV, by the steam turbine at maximum capacity and by the peaking gas turbine. The steam turbine operates with waste heat from the gas turbine and heat from the storage.

OP 3.2: Gas turbine with steam turbine operated by waste heat, heat storage and backup heater

If the state of charge of the heat storage is not sufficient to provide energy for the steam turbine, the biomass backup heater is activated (Figure 10):

Operating Condition: $C(t) < Q_{TES}(t) - Q_{HRSG}(t)$ Eq.37

TSPP Output: $P_{TSPP}(t) = P_{PV}(t) + P_{ST,max}(t) + P_{GT}(t) = P_L(t)$ Eq.38

Gas Turbine Output: $P_{GT}(t) = P_L(t) - P_{PV}(t) - P_{ST,max}$ Eq.39

Gas Turbine Waste Heat: $Q_{HRSG}(t) = [\frac{P_{GT}(t)}{\eta_{GT}(t)} - P_{GT}(t)] \cdot \eta_{HRSG}$ Eq.40

Steam Turbine Output: $P_{ST}(t) = P_{ST,max}$ Eq.41

Storage Plant Input: $P_{EH}(t) = 0$ Eq.42

Heat from Storage: $Q_{TES}(t) = \frac{P_{ST,max}}{\eta_{ST,max} \cdot \eta_{TES}}$ Eq.43

Biomass Backup: $Q_{BB}(t) = Q_{TES}(t) - Q_{HRSG}(t) - C(t) \cdot (1 - \gamma_{TES})$ Eq.44

State of charge: $C(t+1) = C(t) \cdot (1 - \gamma_{TES}) - Q_{TES}(t) + Q_{HRSG}(t) + Q_{BB}(t) = 0$ Eq.45

Biomass Consumption: $F_{BB}(t) = \frac{Q_{BB}(t)}{\eta_{BB}}$ Eq.46

Biomethane Consumption: $F_{GT}(t) = \frac{P_{GT}(t)}{\eta_{GT}(t)}$ Eq.47

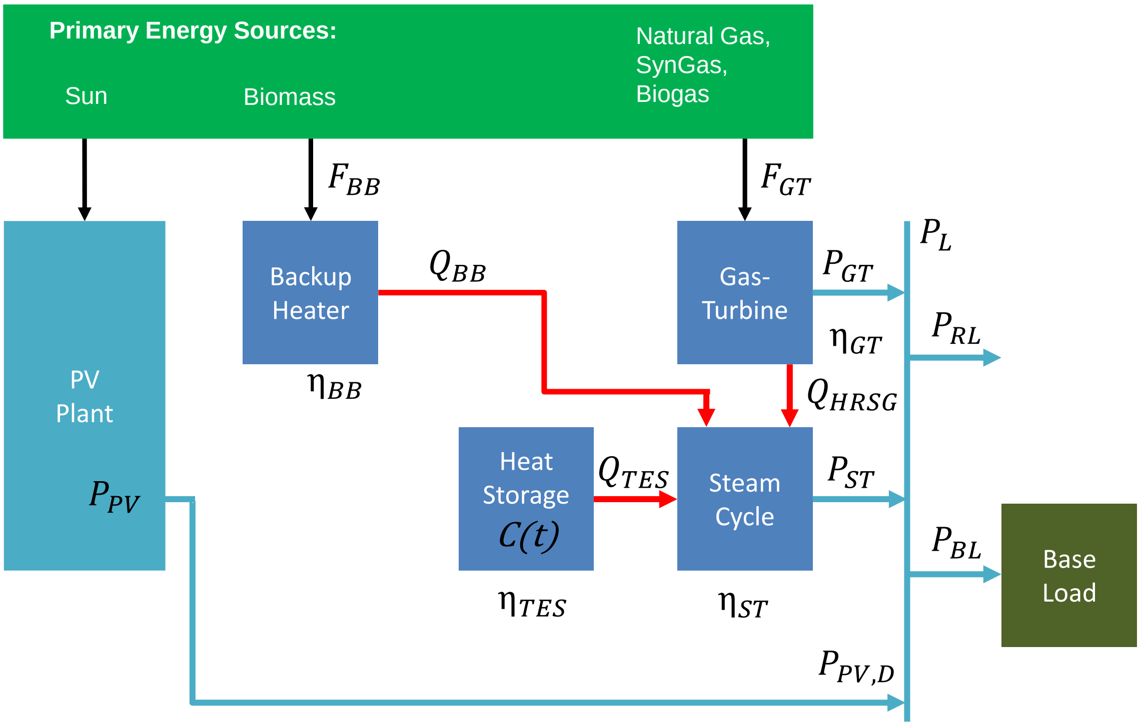

Figure 10: Operation Mode 3.2: Load is covered by direct PV, by the steam turbine at maximum capacity and by the peaking gas turbine. A critical state of charge of the heat storage requires additional heat from the backup heater.

OP 3.3: Gas turbine with steam turbine operated only by waste heat

If the waste heat from gas turbine is enough to provide sufficient energy for the steam turbine, it is preferably operated by waste heat from the gas turbine (Figure 11):

Operating Condition: $Q_{HRSG}(t) \geq \frac{P_{ST,max}}{\eta_{ST}(t)}$ Eq.48

TSPP Output: $P_{TSPP}(t) = P_{PV}(t) + P_{ST,max}(t) + P_{GT}(t) = P_L(t)$ Eq.49

Gas Turbine Output: $P_{GT}(t) = P_L(t) - P_{PV}(t) - P_{ST,max}$ Eq.50

Gas Turbine Waste Heat: $Q_{HRSG}(t) = [\frac{P_{GT}(t)}{\eta_{GT}(t)} - P_{GT}(t)] \cdot \eta_{HRSG}$ Eq.51

TSPP Input: $P_{EH}(t) = 0$ Eq.52

Biomass Backup: $Q_{BB}(t) = 0$ Eq.53

Steam Turbine Output: $P_{ST}(t) = P_{ST,max}$ Eq.54

Heat from Storage: $Q_{TES}(t) = 0$ Eq.55

State of Charge: $C(t+1) = C(t)$ Eq.56

Biomethane Consumption: $F_{GT}(t) = \frac{P_{GT}(t)}{\eta_{GT}(t)}$ Eq.57

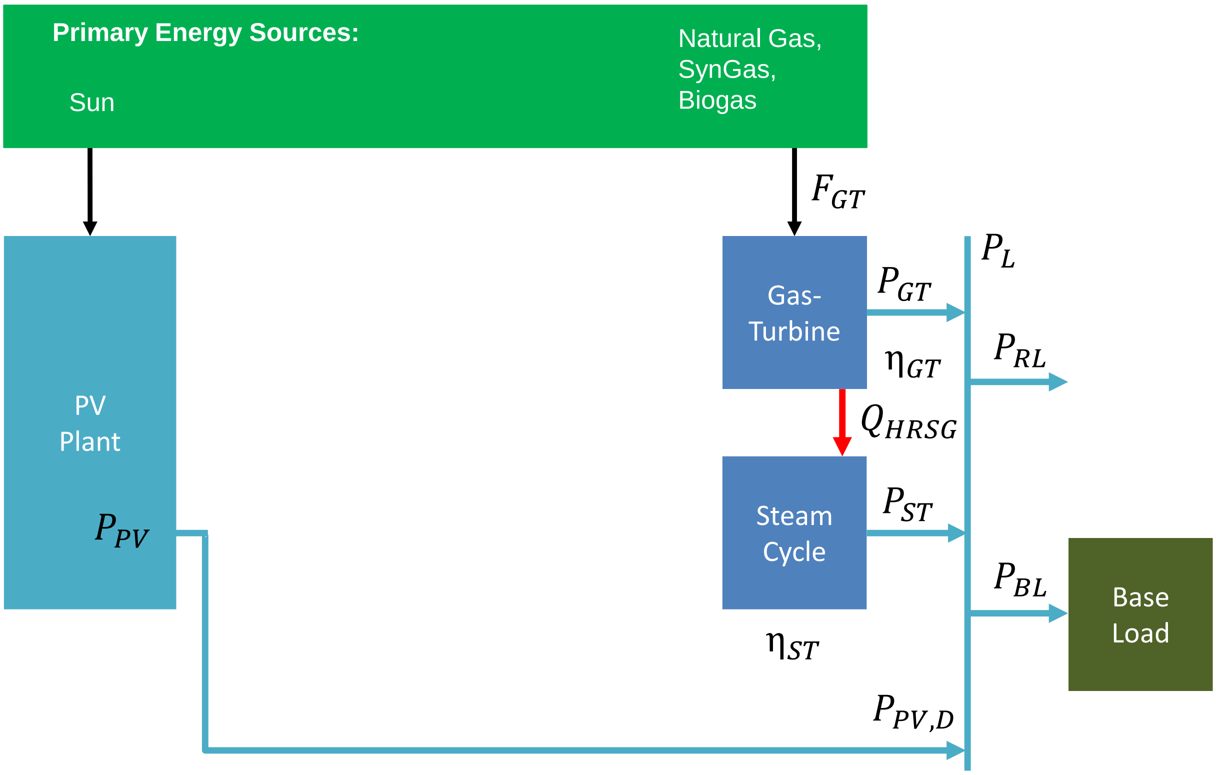

Figure 11: Operation Mode 3.3: Load is covered by direct PV, by the steam turbine at maximum capacity and by the peaking gas turbine. The steam turbine operates only with waste heat from the gas turbine.

3. Data and assumptions

3.1 Annual hourly residual load curve

In the model case presented here, the TSPP is in charge of covering the annual residual load curve of the German power plant park expected in 2040, following a scenario presented earlier by Trieb and Thess [17]. Due to considerable presence of wind and PV power in this scenario, the residual load in Germany reaches from a maximum 82.5 GW during a period with little wind and solar power availability in February to a series of events over the whole year with zero residual load, where sufficient wind and solar power resources are available. The scope of this analysis was to assess whether this obvious challenge for any conventional thermal power plant could be solved theoretically by TSPP that are supposed to be able to provide the total spectrum from standby to continuous base load supply. In order to come to realistic plant sizes, the maximum power of the reference TSPP plant was set to 70 MW, and the residual load curve from the scenario was scaled down accordingly (Figure 12). Dividing annual electricity consumption by peak load, the residual load curve shows 2700 equivalent full load hours per year.

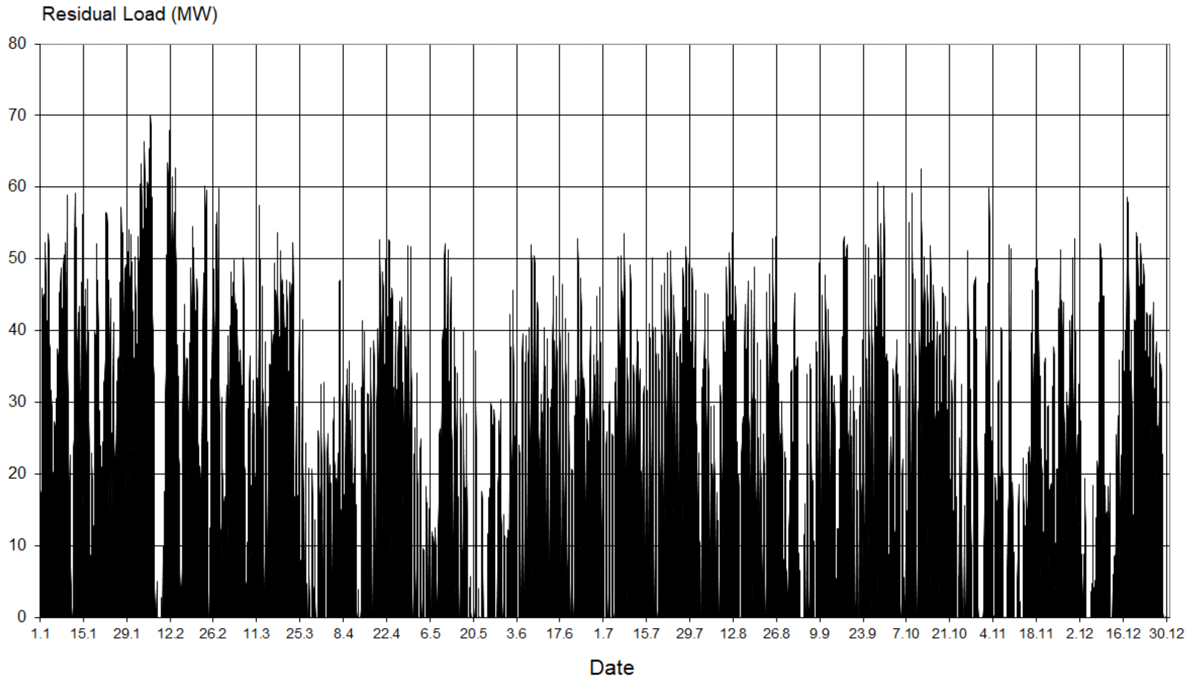

Figure 12: Hourly residual load curve of Germany in 2040 [17] scaled down to a maximum TSPP-capacity of 70 MW.

3.2 Annual hourly PV availability

The annual hourly PV availability curve is characterized by a total of 900 equivalent full load operating hours per year and by an average 2.4 full load operating hours per day, respectively. It can be seen that an hourly average value of 100%, which represents the nominal installed peak capacity, is never achieved. For this reason, the maximum capacity of the TSPP's electric heater that is in charge of absorbing the generated PV-power has been set to 67% of the installed PV peak capacity as will be explained later in Section 3.3.

The curve shows a typical maximum and fairly regular daily availability of PV power in summer and a considerable reduction of maximum output as well as more frequent and longer intermittence in winter (Figure 13).

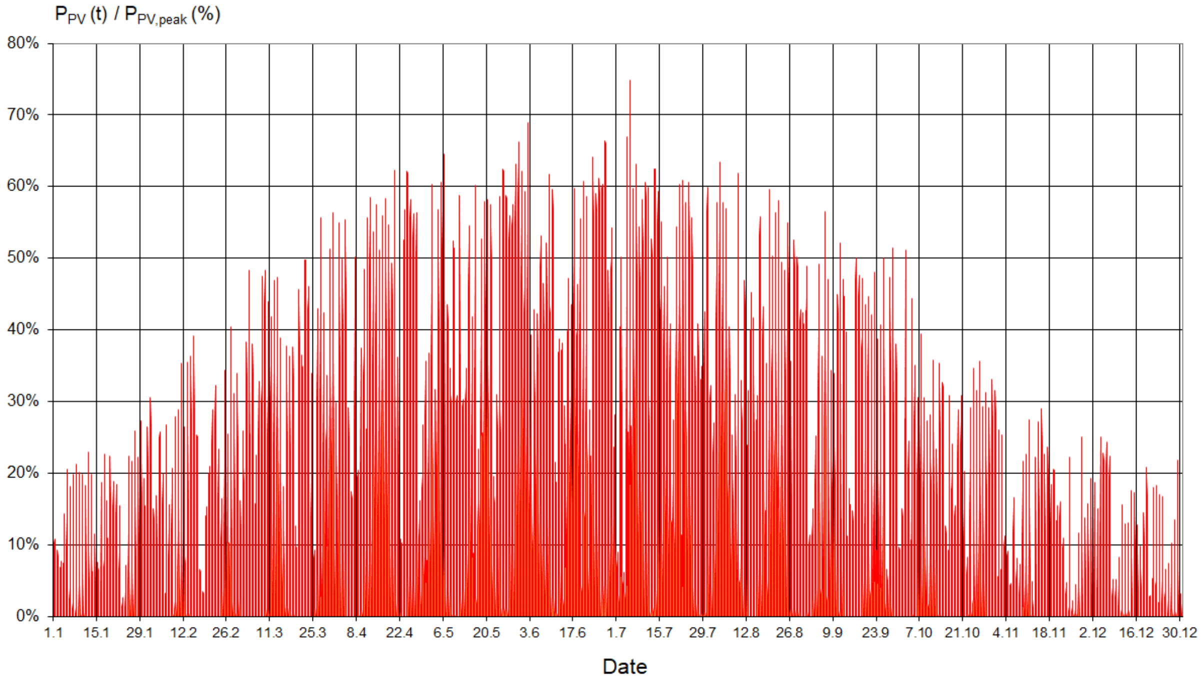

Figure 13: Annual hourly PV availability relative to installed nominal PV capacity used for the TSPP model.

3.3 TSPP design parameters

The maximum load that is to be covered defines the size of the TSPP (Eq.58). As an example, if the maximum share of the residual load to be covered is 70 MW and a low-temperature heat pump with 15 MW electrical capacity is added to the system as base load device for sector coupling, the total capacity of the TSPP, composed of the capacity of the steam turbine plus that of the gas turbine, must be 85 MW. If a 30 MW steam turbine is selected for the Carnot Battery, then in this case it must be complemented by 55 MW peaking gas turbines (Eq.59).

The maximum output power capacity of the Carnot Battery is identical to the nominal capacity of the steam turbine (Figure 4). The related size of the PV plant, of the electric heater and of the heat storage are scaled directly proportional to the nominal steam turbine capacity $P_{ST,max}$, using the scaling factors Solar Plant Power Ratio (SPR), Electric Heater Power Ratio (EPR) and the Maximum Equivalent Full Load Hours (h_{max}) of the heat storage:

Nominal capacity of the TSPP: $$P_{TSPP,max} \equiv P_{L,max} = P_{GT,max} + P_{ST,max} \qquad \text{Eq.58}$$

Nominal capacity of the peaking gas turbines: $$P_{GT,max} \equiv P_{L,max} - P_{ST,max} \qquad \text{Eq.59}$$

Solar Plant Power Ratio: $$SPR \equiv \frac{P_{PV,peak}}{P_{ST,max}} = \frac{h_{max}}{h_{PV,d}} = 5 \qquad \text{Eq.60}$$

Electric Heater Power Ratio: $$EPR \equiv \frac{P_{EH,max}}{P_{ST,max}} = SPR \cdot \frac{P_{PV,max}}{P_{PV,peak}} = 3.3 \qquad \text{Eq.61}$$

Storage Full Load Hours (h): $$h_{max} \equiv \frac{C_{max}}{Q_{TES,max}} = \frac{C_{max} \cdot \eta_{ST,max} \cdot \eta_{TES}}{P_{ST,max}} = 12 \text{ h} \qquad \text{Eq.62}$$

Those values have been derived from scenario evaluation, where they have been found to lead to low curtailment of solar power and low overall cost of electricity supply [17]. As alternative to scenario optimization, which can be a rather complex process, first estimates of these parameters can also be obtained in a simpler way, revealing their logical background: the term h_{max} can be sized according to the average gap that has to be bridged when using solar energy as primary energy source, which corresponds world-wide to about 12 hours of storage capacity. The Solar Plant Power Ratio SPR can be estimated by dividing h_{max} by the average daily full load hours of a PV plant obtained at a respective site $h_{PV,d}$ that can be obtained for most countries from the World Bank's Global Solar Atlas [23]. Finally, the necessary Electric Heater Power Ratio EPR can be estimated by multiplying SPR with the ratio of the maximum power $P_{PV,max}$ delivered by the photovoltaic plant and its nominal installed capacity $P_{PV,peak}$. The time series used here reveals a ratio of $\frac{P_{PV,max}}{P_{PV,peak}} = 67\%$ for German weather conditions. Other design parameters can be calculated from the estimated efficiencies of the related TSPP components from Table 2:

Biomass Backup Heater Capacity: $$Q_{BB,max} \equiv \frac{P_{ST,max}}{\eta_{ST,max} \cdot \eta_{BB}} \qquad \text{Eq.63}$$

Heat Recovery Steam Generator: $$Q_{HRSG,max} \equiv P_{GT,max} \cdot \left(\frac{1}{\eta_{GT,max}} - 1\right) \cdot \eta_{HRSG} \qquad \text{Eq.64}$$

All components of the TSPP can be scaled up and down with the abovementioned factors departing from the size of the steam turbine. The same scaling factors are used here just as those used for scenario modelling, assuming that all TSPP covering the residual load in that scenario would have a similar configuration, and all of them together would cover the residual load in Germany. Of course, in reality this simplistic approach leaves much room for optimizing design and operation of single TSPP units and of the total supply system. Nevertheless, this simplified approach gives a first impression on whether TSPP could theoretically cope with the residual load paradigm or not.

As an example, using the scaling factors above, a 30 MW steam turbine used as output device of the Carnot Battery would imply a 150 MW photovoltaic plant as primary energy source, a 99 MW electric heater to insert photovoltaic power to the heat storage and a capacity of the molten salt heat storage of $C_{max} = 856$ MWh$_{th}$ considering 42.5% efficiency for the steam turbine, 99% storage efficiency and 0.05% hourly self discharge of the thermal energy storage (Table 2, Table 3).

Table 2: Model design efficiencies of TSPP components. Storage losses include average conversion losses and hourly self discharge. The efficiencies of the steam cycle and of the gas turbines are a function of their load (Figure 14).

Name	Electric Heater Efficiency	Steam Cycle Efficiency	Thermal Energy Storage Efficiency	Storage Self-Discharge Rate	Biomass Backup Unit Efficiency	Heat Recovery Steam Generator Efficiency	Gas Turbine Efficiency
Parameter	η_{EH}	$\eta_{ST,max}$	η_{TES}	γ_{TES}	η_{BB}	η_{HRSG}	$\eta_{GT,max}$
Value	98%	42.5%	99%	0.05%/h	85% *	85%	35%

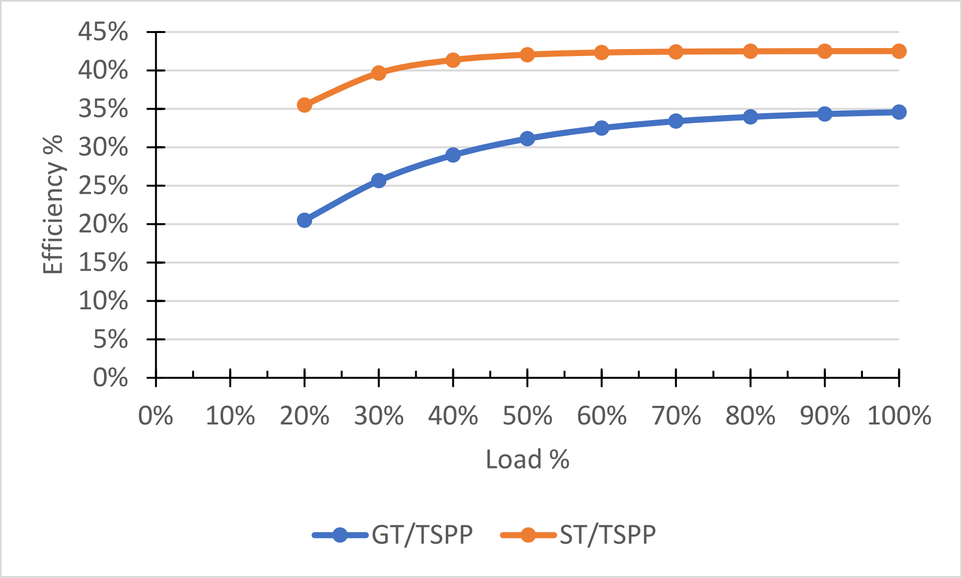

Figure 14: Efficiency of the TSPP's steam cycle (ST/TSPP) and gas turbine (GT/TSPP) as function of load. Below their minimum capacity of 20% the turbines are either shut down or kept at minimum power, in this case producing surplus.

The efficiencies of the steam cycle and of the gas turbines are assumed to be a function of load (Figure 14). All other efficiencies are for simplicity considered as constants. Gas turbines are operated down to rather low part load situations, where their efficiency is considerably reduced. Nevertheless, as the exhaust heat is recovered, and because those situations are not very frequent, the overall system efficiency is not significantly affected by this. Gas turbines are assumed to operate with natural gas or with biomethane, in this case depending 100% on renewable energy. The backup heater is assumed to be fired with solid biomass.

3.4 Economic model parameters

Table 3 (top section) gives the size of the TSPP components for this example and provides the specific cost estimates for each unit. A TSPP with a total firm capacity of 85 MW and all components inclusive a large solar photovoltaic collector field would result in a specific investment cost of about 3500 €/kW. This value may be considered high when compared to the investment of conventional power plants, but it is fairly acceptable when compared to the investment of comparable renewable energy utilities like e.g. concentrating solar power stations or biomass power plants, that range in the same order of magnitude [24] [25]. This is not surprising, considering that biomass and solar power are the main primary energies used in TSPP. The calculation includes a lump sum addition of 25% of surcharges covering contingencies and project costs not directly related to each component. The cost decreasing potential considering economies of scale and massive introduction of TSPP, especially regarding future storage materials, is yet not considered hereunder and will increase feasibility in a mentionable manner.

In the example mentioned before, biomethane at a cost of 75 €/MWh$_{th}$ is used as complementary fuel for the gas turbines. This means that the example configuration works completely free of carbon emissions and does not have to cover any carbon cost. Besides that, the calculation of the levelized cost of electricity (LCOE) includes a capital cost share proportional to a fix charge rate of 8% of the investment per year, annual operation and maintenance cost of 2% of the investment and fuel cost depending on the type of fuel used as backup and for the peaking gas turbines (Table 3, lower section). Of course, economic parameters can be selected individually for each concrete project.

The resulting LCOE for this specific layout amounts to 168 €/MWh, which lies within the range of contemporary electricity costs of concentrating solar power plants and biomass power plants [25].

Table 3: Parameter assumptions and exemplary calculation of investment cost and levelized cost of electricity (LCOE) for a TSPP configuration with additional base-load added to the residual load.

Investment Cost Items	**Specific Values**		**Unit Size**		**Investment**	
Steam Cycle	800	€/kW	30	MW	24,0	M€
Gas Turbine	550	€/kW	55	MW	30,3	M€
Photovoltaic Plant	600	€/kWp	150	MWp	90,0	M€
Electric Heater	100	€/kW	99	MW	9,9	M€
Thermal Energy Storage	25	€/kWh_th	856	MWh_th	21,4	M€
Backup Heater	450	€/kW_th	84	MW_th	37,7	M€
Backup Steam Generator	100	€/kW_th	84	MW_th	8,4	M€
Storage Steam Generator	100	€/kW_th	71	MW_th	7,1	M€
Heat Recovery Steam Generator	100	€/kW_th	92	MW_th	9,2	M€
Total Surcharges	25%				59,5	M€
TSPP Total Investment					**297,4**	**M€**
TSPP Specific Investment (SC + GT)			85	MW	**3499**	**€/kW**

Annual Cost Items	**Specific Values**		**Unit Size**		**Annual Cost**	
Fix Charge Rate	8%	/a	297,4	M€	23,8	M€/a
O&M Cost	2%	/a	297,4	M€	5,9	M€/a
Fuel Cost Biomass	25	€/MWh_th	229	GWh_th/a	5,7	M€/a
Fuel Cost Biomethane	75	€/MWh_th	249	GWh_th/a	18,7	M€/a
Fuel Cost Natural Gas	35	€/MWh_th	0	GWh_th/a	0,0	M€/a
Carbon Cost	50	€/t	0	t/a	0,0	M€/a
TSPP Total Annual Cost					**54,1**	**M€/a**
TSPP LCOE			322	GWh/a	**168**	**€/MWh**

4. Results

4.1 Power supply patterns

The six operation modes result in different supply patterns that are illustrated as examples in Figure 15 and Figure 16. Figure 15 shows an hourly time series between April and May for the selected model year 2040 in Germany [17]. The residual load curve assumed here is the result of scaling down the total national residual load for that year. The electrical load for this specific TSPP configuration is increased by covering the residual load plus delivering extra power to a base load device, for example an electrolysis unit or a heat pump that continuously delivers heat to industrial consumers. This creates a base load band and increases the TSPP's load factor, efficiency and economic performance. During a windy period that reduces the residual load to minimum in the center-right part of the figure, the sequential (vertical) structure of supply mentioned before becomes noticeable.

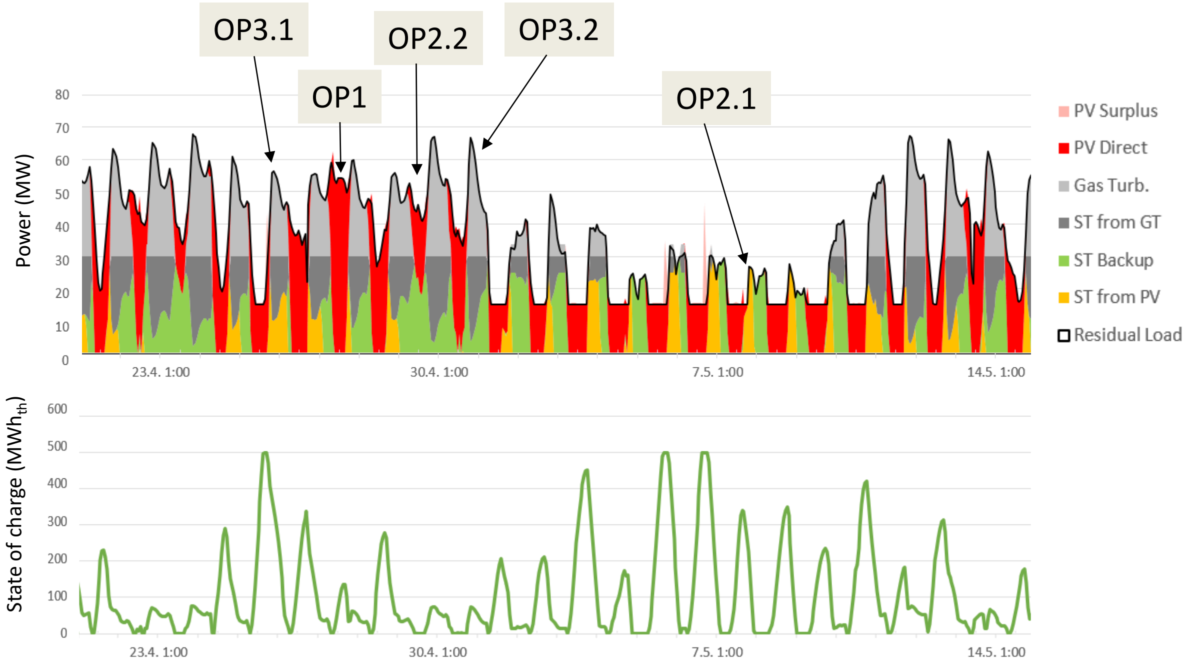

Figure 15: Hourly time series of TSPP operation (upper graph) between April 21 and May 14 of the selected model year, showing days with different dominating operation modes and the respective state of charge of the Carnot Battery (lower graph). Maximum load is the sum of a continuous base load demand for sector coupling (15 MW) and the varying residual load (< 70 MW). The maximum capacity of the steam turbine (ST) is 30 MW, that of the gas turbines (GT) is 55 MW. Installed PV capacity is 150 MW. The electric heater has a capacity of 100 MW. Storage capacity is 856 MWh$_{th}$ equivalent to 12 hours of full load operation of the steam turbine. The left part of the picture shows a period with little wind energy on the grid that leads to significant residual load at night. During the day, the residual load is reduced by the regular availability of solar power. The center part represents a period with strong wind energy and minimum residual load, again followed by a low wind period with high residual load (right side).

Figure 16 shows the same time series for the same configuration covering the residual load without additional base-load. It can be seen that base load demand band has disappeared, and the maximum load has decreased. As a consequence of this, the installed capacity of all components inclusive heat storage has been reduced. The utilization (annual full load hours) of the TSPP is reduced significantly compared to a system with additional base-load for sector coupling. As can be appreciated in the center of the graph, the windy period between 1st and 10th of May leads to zero electricity demand and increased curtailment of surplus PV power during daytime. Such periods significantly reduce the technical and economic performance of any plant that tries to cover the residual load.

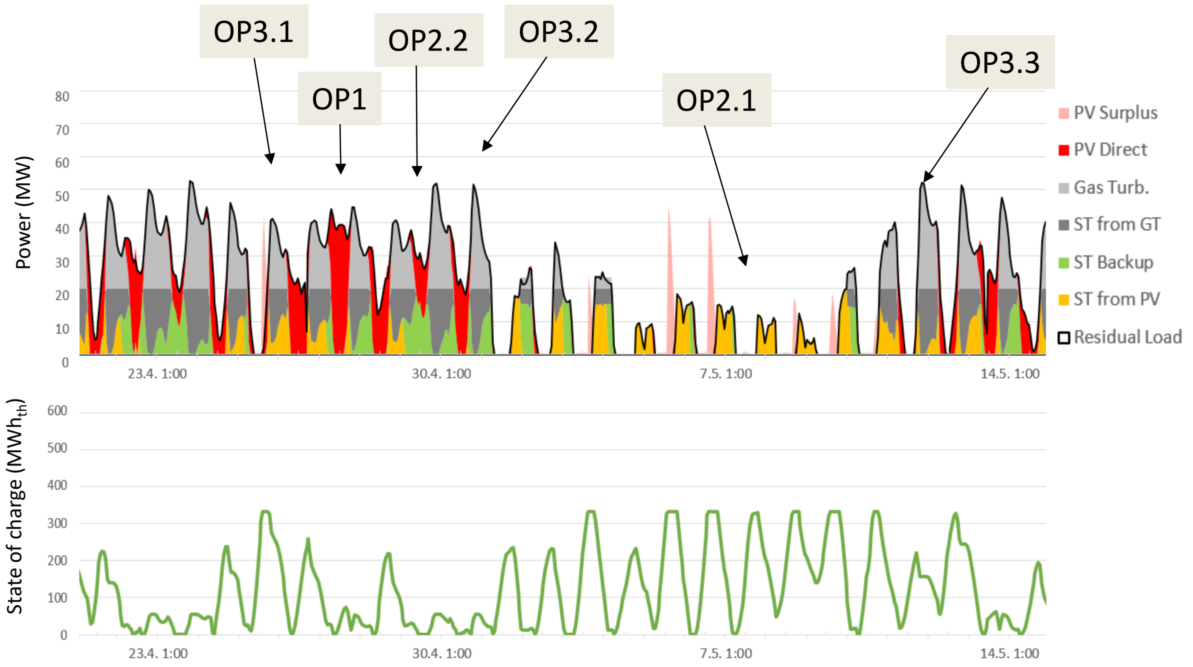

Figure 16: Time series for the same period as in Figure 4, but without additional base load. In this example, the maximum capacity of the steam turbine (ST) is reduced to 20 MW, that of the gas turbines (GT) is 50 MW. Installed PV capacity is 100 MW. Storage capacity is 570 MWh_{th}.

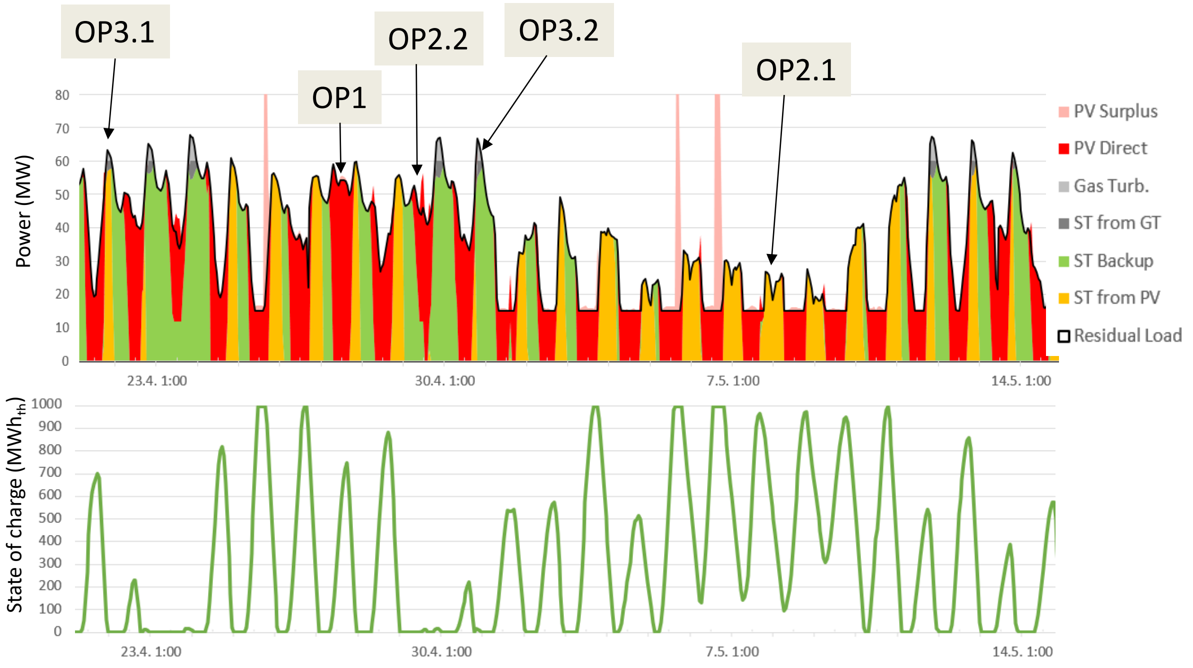

Figure 17: Time series for the same period as in Figure 15 with 15 MW additional base load. In this example, the maximum capacity of the steam turbine (ST) is 60 MW, almost covering the complete load. Gas turbine capacity is reduced to 25 MW, only active in few occasional peak load situations. Installed PV capacity is 300 MW. Storage capacity is 1700 MWh_{th}. In this case, gas demand is almost reduced to zero. The picture vividly illustrates the "vertical" demand response of TSPP.

TSPP provide two alternatives of covering the residual load: the first alternative, as described before, includes peaking gas turbines with waste heat recovery to cope with short-term peaks of electricity demand. A second alternative is to just increase the capacity of the steam turbine and reduce the capacity of the gas turbines so that most of the load will be covered by the steam turbine (and related components) alone, strongly reducing its load factor (Figure 17). Such plant will consume very little gas (only for extreme load peaks) and will primarily work with direct and stored PV power plus biomass backup. In this case the vertical (sequential) structure of covering the residual load becomes clearly visible.

The change of paradigm related to a change from a traditional horizontal supply structure that was based on the merit order of the marginal cost of different types of power plants and fuels, to a vertical supply structure that is expected to rely on renewable energy, is not easy to fulfil. Disruptions in the power sector like cost escalation, curtailment and the need for idle reserve and grid stabilization capacity already become visible today and will most probably increase further, unless better solutions are found.

The strength of a TSPP is that it can adapt to any load profile, as it can adapt to any load situation ranging from standby and extracting power from the grid to base load or peak load supply. The load profile will have a major impact on economy. This is a challenge for any technology aiming to cover the present and future residual load, because the residual load profile will change dramatically in the coming years, and the technology in place must adapt its performance to the significant variable renewable share added in every year. At the same time, it must in the long term provide 100% renewable power itself. A TSPP is suited to solve this challenge satisfyingly and is able to bridge the gap towards 100% renewable share.

A significant advantage of covering such “vertical” load structure with one integrated system rather than with different disconnected power supply units is obvious: system control and optimization lies in one hand, which is that of the TSPP operator. Synergies between the different components (like e.g. waste heat recovery of the gas turbine and enhanced load factor of the steam turbine) can be fully exploited. Different TSPP operators will compete for covering the residual load in the most efficient and economical way possible and will individually decide, which primary energy source they will use in a specific situation, fully complying with modern market mechanisms.

Whether one or the other alternative is more profitable will depend on the cost of the TSPP’s components and the utilized fuels, especially the cost of PV, biomass and the type of fuel gases used by the gas turbines. A systematical analysis of the impact of the size of the Carnot Battery on system performance and cost will be presented in the following section of this paper.

4.2 Technical, economic and environmental performance

This section describes the results of a systematical variation of the size of the Carnot Battery represented by the steam turbine capacity, and its impact on technical and economic performance of the TSPP. For this purpose, four different system configurations have been analyzed:

1. TSPP covering the residual load with PV, biomass backup and biomethane as gaseous energy source: TSPP (Biomethane).
2. TSPP covering the residual load with PV, biomass backup and natural gas as gaseous energy source: TSPP (Natural Gas).
3. TSPP with added base-load (BL) for sector coupling with PV, biomass backup and biomethane as gaseous energy source: TSPP + BL (Biomethane).

4. TSPP with added base-load (BL) for sector coupling with PV, biomass backup and natural gas as gaseous energy source: TSPP + BL (Natural Gas).

For all four configurations, levelized cost of electricity LCOE, specific carbon emissions and total consumption of biomass including solid biomass for backup and biomethane for the gas turbine were calculated as function of the installed steam turbine capacity (Figure 18 to Figure 20). Configurations using biomethane in the gas turbine are considered free of carbon emissions.

The cost of solid biomass was assumed to be 25 €/MWh$_{th}$, that of biomethane 75 €/MWh$_{th}$ and that of natural gas 35 €/MWh$_{th}$. The cost of carbon dioxide emissions was assumed to be 50 €/t (Table 3). These assumptions are also valid for the natural gas combined cycle plant used as reference for our calculations.

In order to calculate total biomass consumption (Figure 20), a conversion factor of 65% from original biomass to biomethane was considered when adding the consumption of solid biomass of the backup heater and the consumption of biomethane of the gas turbines.

The size of the steam turbine has been varied from zero to almost complete coverage of the load, leaving only extreme peaking events to be covered with gas turbines (like in the example in Figure 17) and reducing gas turbine capacity as well as the consumption of biomethane or natural gas. When varying steam turbine capacity, all other components are scaled proportionally according to the scaling factors defined in Section 3.3.

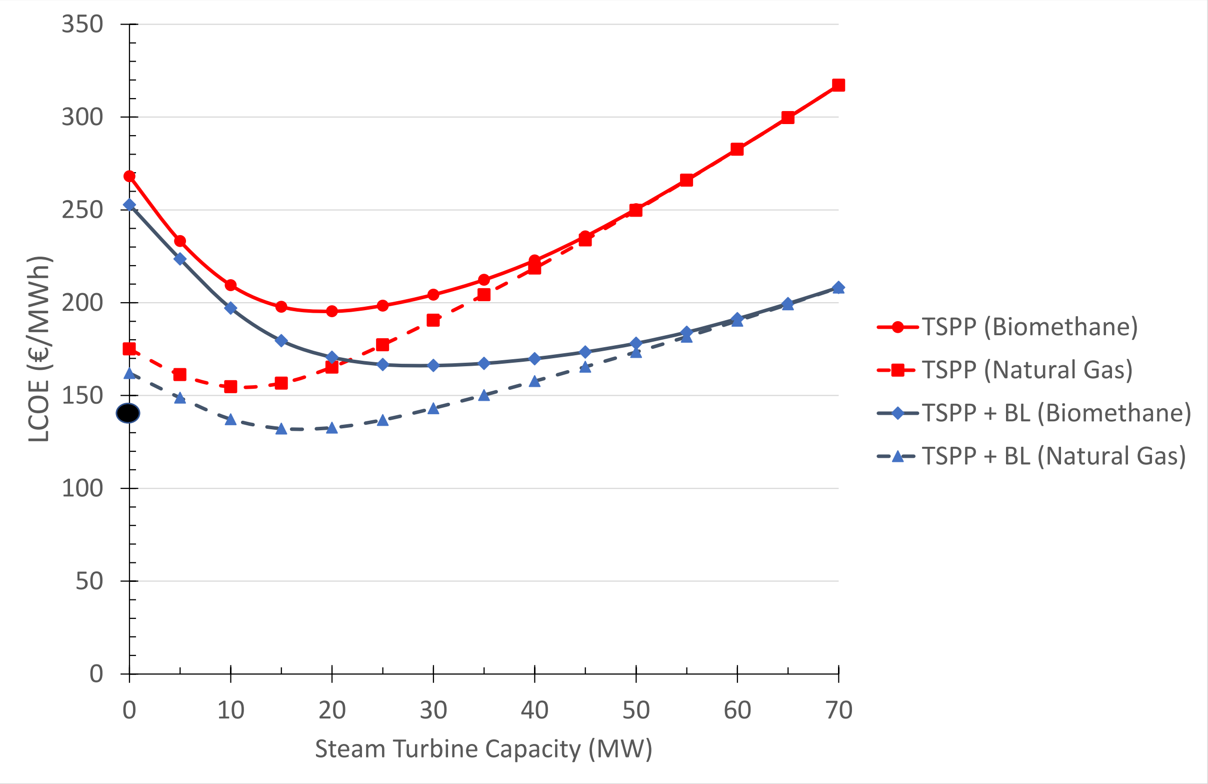

Figure 18: Impact of steam turbine capacity of a TSPP on the levelized cost of electricity (LCOE). The graph shows the results for four configurations that differ as follows: TSPP without base load (red lines) and with base load (blue lines). Gas turbines of the TSPP are alternatively fired by natural gas (dashed lines) or biomethane (bold lines). The black dot represents the cost of a natural-gas-fired combined cycle power plant covering the residual load.

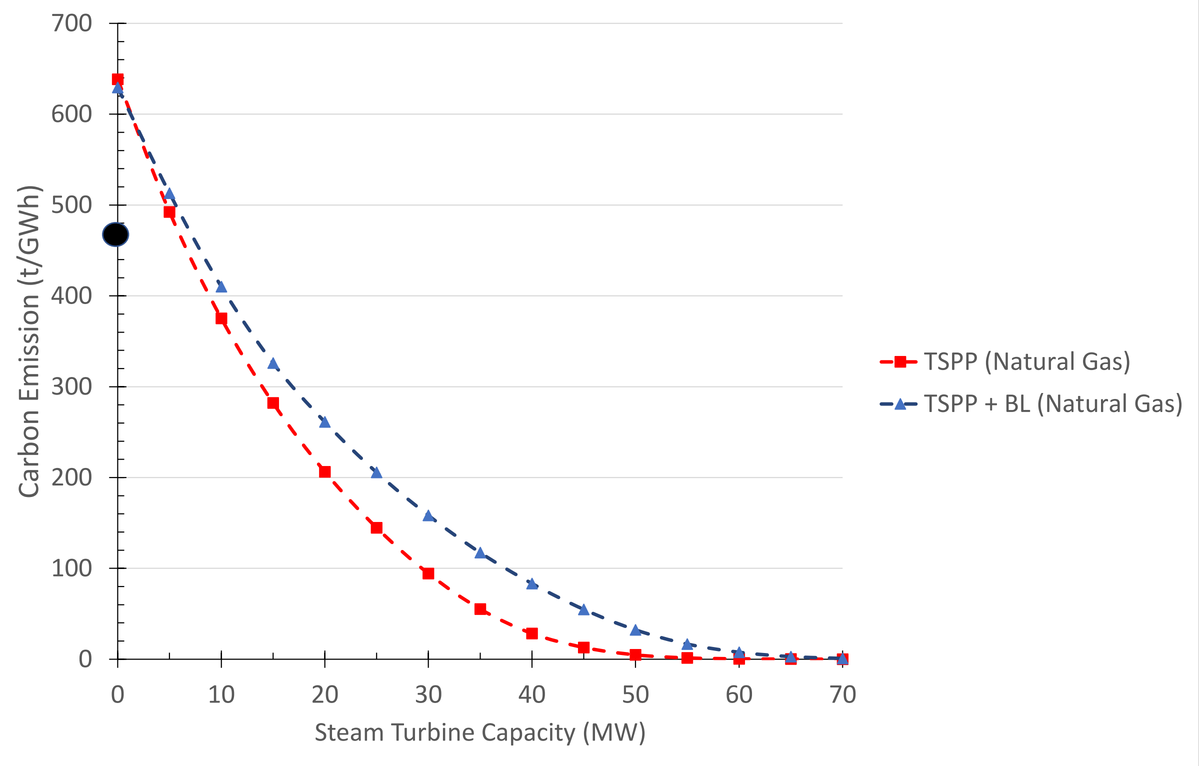

Figure 19: Impact of steam turbine capacity of a TSPP on carbon emissions. The graph shows the results for TSPP without base load (red line) and with base load (blue line). TSPP using biomethane instead of natural gas have zero emissions and are not displayed here. When using natural gas, carbon free operation is achieved at steam turbine sizes larger than 60 MW, because operation is then dominated by PV and biomass co-firing. The black dot represents the specific carbon emission of a natural-gas-fired combined cycle reference plant covering the residual load.

The analysis reveals that TSPP can achieve zero carbon emissions in two alternative ways:

The first one is using biomethane for the peaking gas turbines. In this case and with the model parameters described before, the analysis yields a cost minimum of 198 €/MWh at an installed steam turbine capacity of 20 MW when only covering the residual load, and a cost optimum of 168 €/MWh at 30 MW steam turbine capacity when adding a 15 MW base load to the residual load (Figure 18). The cost difference of 30 €/MWh is due to better technical and economic performance of the TSPP when adding a base load device to the system. Adding a heat pump or other base load devices leads to higher full load operating hours and to less curtailment of surplus PV power, resulting in a significant reduction of electricity cost. Added value for providing process heat as well as additional cost for the base load device have not been included in this calculation. Depending on cost and revenue of sector coupling, this could further enhance economic system performance.

The second option for achieving zero emissions is increasing the size of the steam turbine until it is able to cover the load alone. In this case electricity will be solely generated by PV and solid biomass. No peaking gas turbines and no biomethane will be needed. This seems to be an attractive alternative, as biomethane is about three times more expensive than solid biomass. Moreover, increasing steam turbine capacity will also reduce the total consumption of biomass, considering the losses of converting biomass to biomethane (Figure 20). On the other hand, covering peak load situations with the Carnot Battery rather than with peaking gas turbines will reduce the annual average utilization of the expensive steam cycle and will thus impact the economic performance of the system. Increasing the size of the steam turbine will increase LCOE, particularly in the case of covering the residual load without additional base load device (Figure 18).

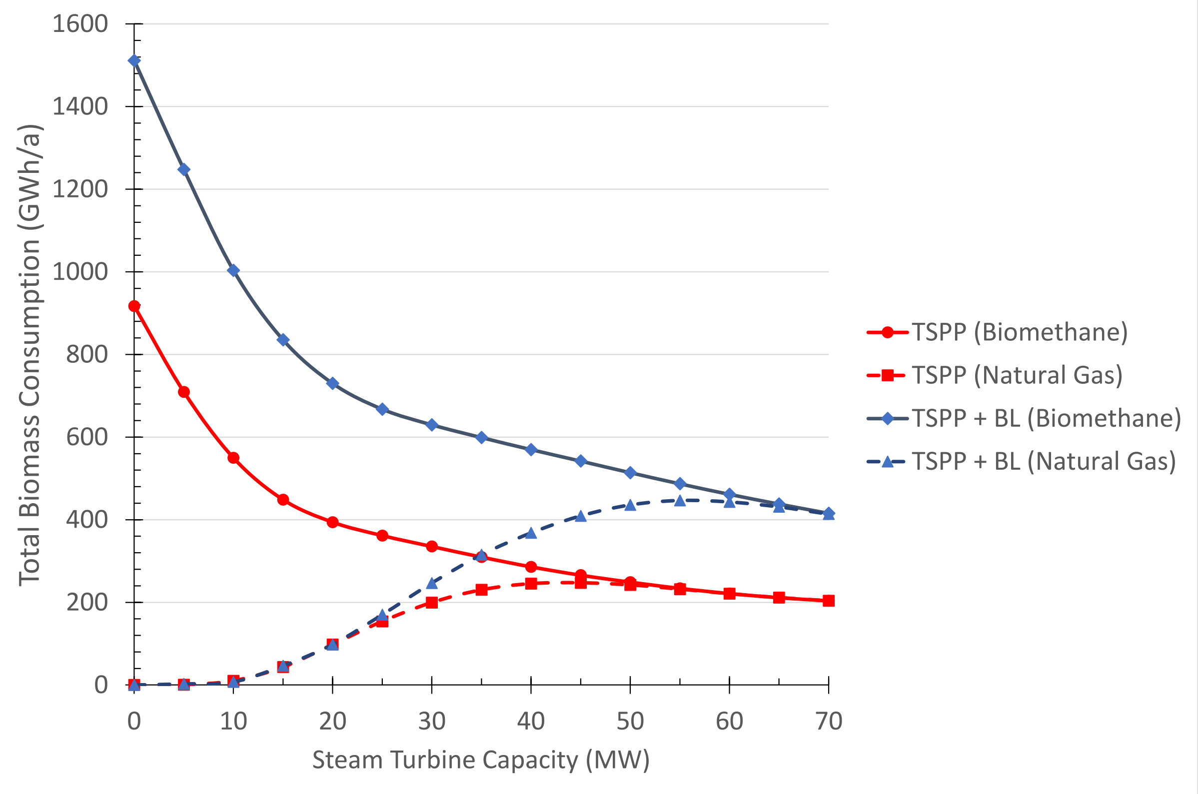

Figure 20: Impact of steam turbine capacity of a TSPP on total biomass consumption. The graph shows the results for four configurations that differ as follows: TSPP without base load (red lines) and with base load (blue lines). Gas turbines of the TSPP are alternatively fired by natural gas (dashed lines) or biomethane (bold lines).

There is also the option to use natural gas instead of biomethane in TSPP as an interim stage of decarbonization of the power sector (Figure 19). In order to reduce initial costs, first of a kind TSPP could start using natural gas for peaking supply and later subsequently increase the share of biomethane until reaching 100% renewable power production. Another option is increasing the size of the Carnot Battery until supply is dominated by PV and biomass backup.

As a consequence of those findings, a strategy for using TSPP for a transition to 100% renewable energy in the power sector including sector coupling could look as follows:

1. In the first place, it makes very much sense to include an additional load in order to increase system utilization, preferably a base load device like a heat pump or an electrolysis unit. This will open many opportunities for sector coupling and will enhance efficiency and economic performance of TSPP.
2. The expected cost and availability of PV power, solid biomass and biomethane will define their optimal share for least cost system performance.
3. Depending on the cost of natural gas, it might be reasonable to start in the near term with natural gas for peaking and sooner or later replace it by biomethane or synthetic fuels from renewable sources.
4. Subsequently substituting natural gas by biomethane will result in zero carbon emission and will increase the biomass consumption of the TSPP.
5. As alternative to the use of biomethane or other carbon free gases, the Carnot Battery can be sized large enough to cover the complete load only with PV and biomass and without gas. This will result in higher LCOE and lower biomass consumption (Figure 21).

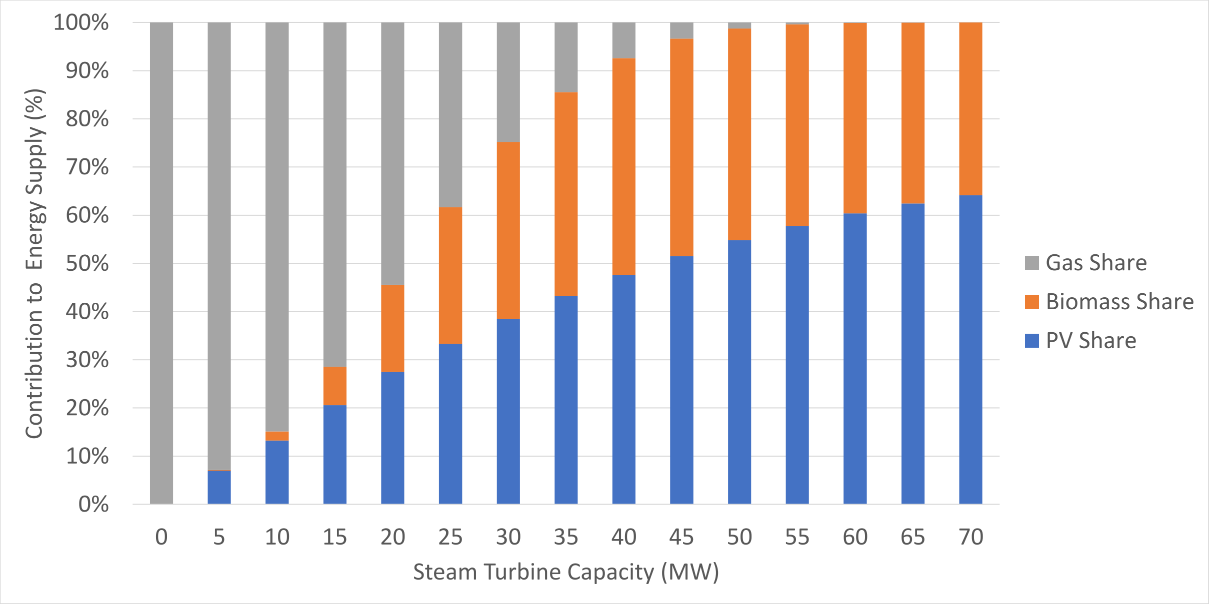

Figure 21: Share of PV, biomass and natural gas or biomethane as function of steam turbine capacity of a TSPP that covers a highly variable residual load and additional base load for sector coupling. It can be appreciated how the consumption of gas and biomass can be reduced by increasing the size of the Carnot Battery and the PV plant, both sized directly proportional to the capacity of the steam turbine.

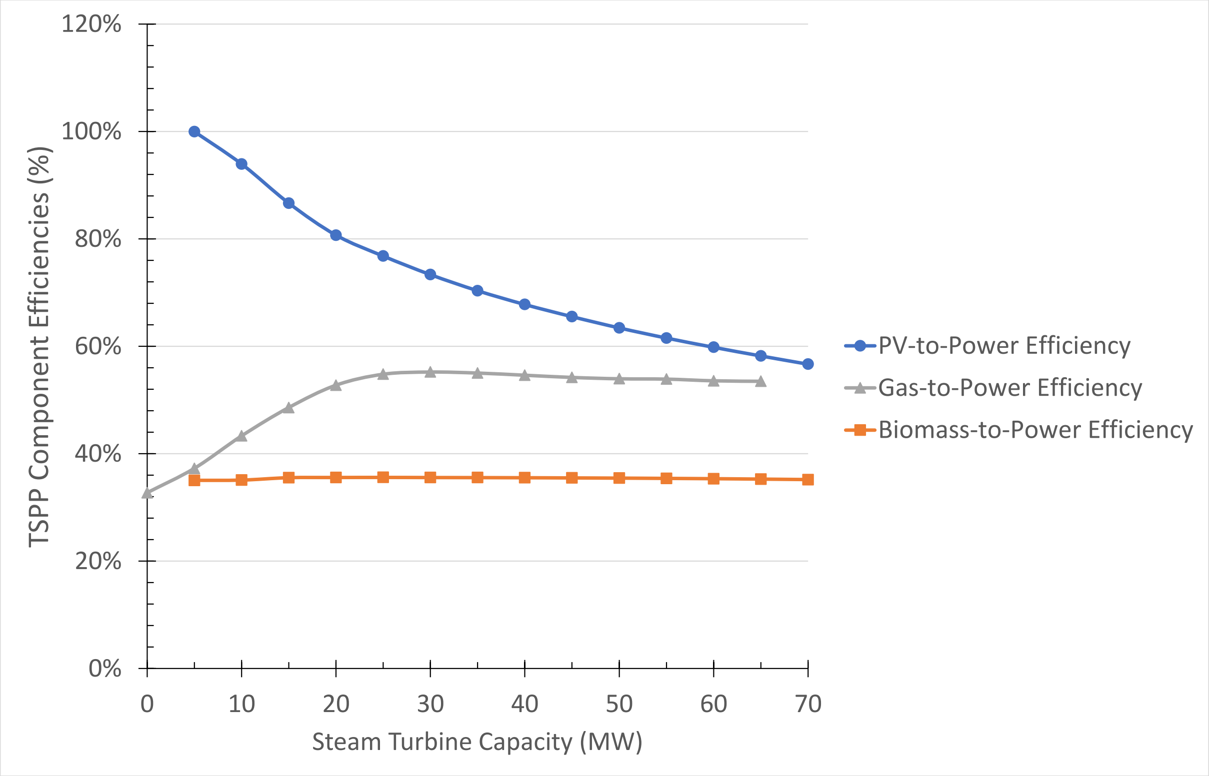

Figure 22: Efficiencies of the system components of a TSPP that covers the residual load and an additional base load for sector coupling, as function of the size of the steam turbine (Configuration: TSPP + BL).

The analysis of the system component's efficiencies reveals a very high effectiveness of TSPP: the PV-to-Power efficiency ranges from 100% when all PV power is directly supplied to consumers to 60% with maximum share of stored PV. In the optimum case for the configuration – TSPP + BL at 30 MW steam turbine size – the PV-to-Power efficiency reaches a value of 73%, which is the weighted average of directly supplied and stored PV contributions to the load (Figure 22).

The gas-to-power efficiency ranges in the order of 55% except for configurations with very small Carnot Battery, where gas-turbines cover the load almost alone. This is within the same order of magnitude as the efficiency of conventional combined cycle gas turbines. The biomass-to-power efficiency in the order of 36% is fairly constant for all configurations.

This simplified analysis shows that it is possible to find an optimal layout of a TSPP depending on specific local frame conditions like annual solar electricity yield of a PV plant and the availability and cost of solid biomass, biomethane and natural gas. Further optimization and fine tuning are possible and necessary by individually adapting the scaling factors described in Section 3.3 in order to fit to the specific frame conditions of concrete TSPP projects world wide.

It must be considered that the assumptions and parameters used here are estimates corresponding to first TSPP installed under German frame conditions around 2025. Further cost reductions and improvements are expected when introducing TSPP in large scale and on global level under better solar radiation conditions [26].

5. Review of TSPP variants and sector coupling options

The variant described and analyzed within this paper is considered as basic TSPP configuration, that would require relatively little technical innovation for its realization [27] [28]. The Carnot Battery consists of a molten-salt electric heater, a molten-salt heat storage and a molten salt steam generator to power the steam cycle. Today, 21 GWh_{th} of molten-salt storage technology are installed world wide in concentrating solar power plants [29]. Molten-salt electric heaters and molten-salt steam generators are also commercial state of the art [21] [26]. Gas turbines with HRSG and biomass steam generators are components of conventional combined cycle and biomass power plants [30].

In principle, the following variants are possible and will be assessed in future work:

Instead of an electric heater, a high temperature heat pump could be used to heat the storage, making use of surplus electricity and waste heat from other processes as primary energy sources [31] [32]. Such innovation could elevate the efficiency of the Carnot battery from about 40% to 70%. High-temperature heat pumps are presently being developed by several industrial players and by a new institute founded in Cottbus by the German Aerospace Center DLR [33].

In the long-term, the backup heater could be integrated to the thermal energy storage instead of being directly integrated to the steam cycle [17]. In this case, backup heater operation would be independent from the highly dynamic operation of the steam turbine. This would significantly increase overall system flexibility and would allow for a smaller and more efficient heater. Due to the minimum temperature of the molten salt cycle of 280°C the flue gas temperature of the backup heater would be limited to 300°C. In this case it will be necessary to use an economizer in order to preheat combustion air, or use other options of energy integration in order to recover the waste heat.

Instead of a molten salt, solid state materials like concrete, pebbles or ceramics can be used as heat storage together with air as heat transfer fluid [34]. When using a backup heater, solid state heat storage would allow for lower minimum temperature levels of the flue gases than molten salt storage, in this case not requiring an economizer. Solid state storage has an early stage of development and is most interesting for smaller unit sizes [35].

TSPP offer many opportunities for sector coupling that are related to mass flows of base materials like carbon dioxide and hydrogen, heat from involved combustion processes and reject heat from the steam turbine, and of course electricity for heat pumps, electrolysis or other purposes (Figure 23).

One option is to include a low temperature heat pump that uses electricity and reject heat from the steam turbine for district or process heating, a concept that has already been realized in a conventional power plant in Vienna [36] [37]. In this case, a heat pump with 27 MW_{th} thermal capacity provides district heat to 25000 households, making use of the reject heat of the Simmering biomass power plant. The power demand of such a largescale heat pump or of any other device used for sector coupling adds to the residual load covered by the TSPP, significantly increasing the load factor and the economic performance of the plant.

Another option is to include an electrolysis unit for the continuous production of hydrogen and oxygen that would also increase the full load hours of the plant and provide important base materials for the energy transition. As an example, the oxygen could be used to enhance the combustion processes involved and to reduce or avoid NO_x-Emissions. At the same time, CO_2 and water from combustion processes could be used together with hydrogen from electrolysis for the production of synthetic renewable fuels in a similar way that has also been proposed for concentrating solar power plants [38].

Another opportunity of sector coupling with TSPPs is related to the production of synthetic hydrocarbon fuels and will be assessed in further research. The flue gases from biomass and biomethane could be re-used by carbon capture. In this case the TSPP would act as a carbon sink instead of just a carbon neutral power plant. The captured carbon dioxide could be used for a hydrocarbon synthesis process together with hydrogen from electrolysis, that could add base-load to the residual load just like the heat pump in the former example and open many opportunities for integrated heat flow management, thus improving the TSPP’s overall performance.

TSPP can also be integrated with the production of biomass for backup heating of the plants. As an example, reject heat and electricity from a TSPP can be used for drying and processing raw biomass [39] [40]. The production of bio-coal from hydrothermal carbonization of biomass waste requires some startup heat and also electricity input, although being an exothermal transformation process that results in a coal product that is similar to, but usually cleaner than lignite [39] [41].

6. Conclusions and outlook for further work

The scope of the modelling work at hand was to find out whether TSPP can theoretically cope with the rigorous flexibility requirements and subsequently reduced load factors that are related to the decarbonization of the power sector after introducing large variable renewable power capacities.

Although a TSPP as defined here is more complex and sophisticated than conventional power plants and requires large investment, a unique selling point is its outstanding flexibility and the many fold degrees of freedom for its design and operation.

TSPP solve several challenges of future transition towards renewable power supply:

- TSPP allow for massive expansion of additional PV capacity without creating grid fluctuations, but on the contrary smoothening variable renewable supply in the energy mix.

- TSPP operate in the whole range from standby to base-load, interacting flexibly with increasing variable renewable supply shares and flexibly covering the residual load.
- TSPP lead to economically optimal utilization of turbomachinery required for firm capacity, ranging from about 5000 full load hours for steam turbines to 1500 full load hours for gas turbines.
- Making use of turbomachinery like steam and gas turbines, TSPP are ideally suited for sector coupling and de-carbonization of both the power sector and the industrial and district heating sectors.

A TSPP is not only a thermal storage device for surplus grid electricity similar to a battery, but a full-scale thermal power plant that transforms raw primary energy into firm power on demand (Figure 23). TSPP integrate three forms of primary energy: first of all, a large photovoltaic power generator that regularly provides renewable energy surplus to be fed to the Carnot Battery, secondly solid biomass for backup and in the third place and optionally, some kind of renewable, synthetic or (only during transition) fossil combustion gas for peak load events.

The core of a TSPP is a Carnot Battery composed of electric heater, thermal energy storage and steam turbine. This element gives it the flexibility that is required to react to any situation on the electricity grid, ranging from excess power that must be taken off the grid to either long-lasting or short-term residual load events that must be reliably bridged, preferably with renewable power. In this context, a TSPP is a suitable device to balance the electricity grid and to cover the strongly fluctuating residual load.

Thermal energy storage can either consist of liquid molten-salt or of solid-state material (ceramics, pebbles, etc.) and air as heat transfer fluid. Solid-state ceramic storage operated with air as a heat transfer medium has already been demonstrated successfully and also shows positive perspectives, especially at lower plant sizes up to 100 MW capacity and in combination with gas turbines, as the exhaust heat can be combined with heat from the storage. This system is especially advantageous when combined with existing municipal or industrial CHP plants with waste heat recovery.

Firm and secure power capacity can be guaranteed at any time by a backup heater, even if the Carnot Battery is empty. This makes the big difference to conventional storage systems, because this makes a TSPP a full-fledged thermal power plant that is independent from the state of charge of the storage. Carnot Battery, steam generation and power production can be separated from combustion, allowing for much higher flexibility to cover strongly variable load patterns. And of course, due to additional energy from the photovoltaic generator, a TSPP requires much less fuel.

Temperature level and flexibility are limited when using biomass as backup. Molten salt heat storage opens room for coupling rather nonflexible biomass combustion with highly flexible steam turbine operation and fits well to the typical steam temperature of biomass plants of about 450 °C - 550 °C. On the other hand, the minimum temperature of the molten salt heat storage of 280°C limits the efficiency of the backup heater and also that of waste heat recovery from the gas turbine. Further research could lead to the possibility of running the backup heater in semi-continuous mode and to increase process efficiency by means of a better integration of backup and waste heat.

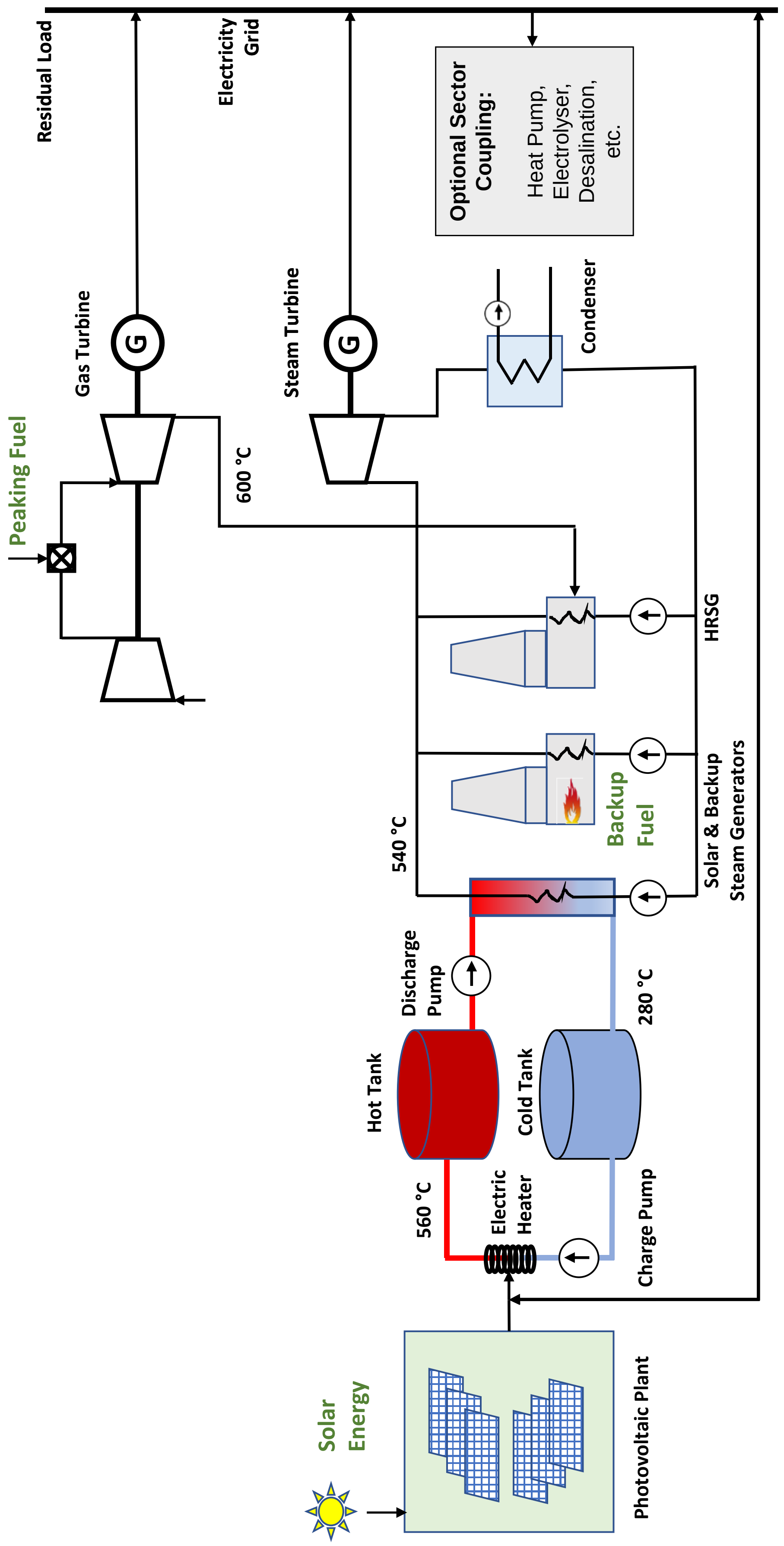

Figure 23: Simplified sketch of a TSPP with three corridors for solar energy input (PV, Biomass and Biomethane).

Short-term peak demand is usually not covered by steam turbines, but by more flexible and lower cost gas turbines. Therefore, the TSPP can be complemented by gas turbines that take over demand peaks that exceed the capacity of the steam turbine. In this context, the Carnot Battery provides an opportunity to disconnect gas turbine peaking operation – usually required for a few hundred full load hours per year – and steam turbine operation that for economic reasons rather aims to achieve several thousand full load hours per year. Moreover, the heat recovery steam generator allows to achieve gas-to-power efficiencies similar to those of combined cycle gas turbine systems, in spite of only providing peaking power with the gas turbines. TSPP offer many opportunities for integration and modernization of all energy sectors, ranging from district heating to industrial processes of sustainable fuel production departing from biomass and electricity. A core advantage of a TSPP is the possibility of integrating several renewable energy sources (solar power, biomass, bio-coal, biomethane, hydrogen) and key products of the energy transition related to the Power-to-X concept like hydrogen, recycled carbon dioxide, heat, power and other derivatives like liquid or gaseous hydrocarbon fuels [42]. A comprehensive and detailed assessment of those opportunities will be published at a later stage.

Due to the high investment cost of a TSPP including its primary renewable energy resources, a high utilization rate is crucial for economic performance. This is difficult to achieve considering that for example in the analyzed scenario for Germany in the year 2040, the expected residual load makes up for only about 2700 equivalent full load hours per year. Sector coupling can therefore be considered as economic must-have for TSPPs, and particularly using base load devices like a heat pump or electrolysis for this purpose is a very attractive option that enhances technical and economic system performance. Adding internal base load demand has a significant positive impact on LCOE by increasing utilization, reducing PV curtailment and adding value.

The status of development of TSPP technology is yet theoretical, although all components can be considered as state of the art. The main technical challenge is their integration and optimization of their design. Another challenge is related to solar radiation intensity and availability of land area for PV collector fields, particularly in northern countries like Germany. However, although land resources in Germany are indeed scarce, it has been found that enough PV potential would be available for the transformation described here, particularly when integrating photovoltaics and agriculture [43] [44].

Another challenge is related to the financing of TSPPs. The cost level of 160 - 170 €/MWh for first-of-a-kind TSPP in Germany resulting from the analysis at hand seems rather high, but it is in fact questionable whether cheaper alternatives exist at all that would be able to cover the highly variable residual load with flexible, secure and at the same time renewable power. As an example, an alternative way to cover the residual load could be achieved by a combination of batteries acting as buffer storage for variable renewables, biomass plants for firm capacity and combined cycle or simple cycle gas turbines operating with renewable fuel gases for peaking. While alternative solutions based on such conventional power technologies would face the same challenges as TSPP, they would probably provide less opportunities for integrated operation. Further research will show a technical and economic comparison of TSPP and alternative concepts when facing the challenge of the future residual load curve in Germany with 90-100% renewable share.

Electricity markets with price levels of 50-100 €/MWh that do neither provide benefit for firm and flexible power capacity nor for renewable supply are a difficult platform for TSPP development - just as for any other renewable power technology that would be able to cope with the residual load paradigm. Good chances and possible business cases only appear in those cases, where conventional power plants that cover the residual load have already become rather expensive, and on the other hand where primary renewable energy is cheap. As an example, under very good solar radiation conditions and with high market prices for coal and natural gas, first TSPP projects are already on the verge of realization in Chile [26].

In the case of Germany, with low solar radiation level, high prices for biomass and a conventional electricity market based on the marginal cost of fossil fuels with average revenues of around 50 €/MWh in the year 2020, TSPP – similar to all other type of electrical energy storages like pump storage and electrical Batteries – up to now had little chance to be realized unless a national regulation was imposed that forces the residual load to be covered securely by firm capacity from renewable sources. While still present, nuclear and lignite base load plants will keep market prices low until taken out of the market. On the other hand, with quickly increasing gas- and carbon prices and in view of the nuclear (2022) and coal (2038) phase out ultimately imposed by the German government, market prices have recently emerged up to a level of 185 €/MWh, finally opening market opportunities for TSPPs in the near- to mid term future [45] [46].

A big advantage of TSPP is the immediate possibility to gradually convert existing power plants and CHP plants into renewable power plants and to make use of sites with permits in place, thus reducing implementation periods and giving existing infrastructure a new perspective.

Last but not least, further research will be dedicated to the use of a high temperature heat pump replacing the electric heater. Such innovation could elevate the efficiency of the Carnot battery from at present 40% to about 70% [31] [32].

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