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Supplementary Material

The Role of Solar Photovoltaics and Energy Storage Solutions in a 100% Renewable Energy System for Finland in 2050

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Table S1. Installed capacities of energy technologies for the 100% RE scenario for Finland in 2050

Technology	Installed capacity (GW_e)
Wind onshore	30
Wind offshore	5
Solar PV	30
Hydro - Run of river	3.5
CHP – District heating	9.4
Condensing[1]	0
Nuclear	0

[1]CHP plants could be run in condensing mode when heat requirements were low.

Table S2. Main scenario input parameters

Parameter	Unit	100% RE Finland 2050
Electricity demand	TWh_e	95
Transportation electricity demand	TWh_e	10
Other transport demand	TWh_{th}	25
Space heating demand	TWh_{th}	65
Cooling demand	TWh_{th}	3
Thermal storage	GWh_{th}	20
Stationary battery storage	GWh_e	20
V2G storage	GWh_e	150
Gas storage	GWh_{th}	3800

Table S3. Storage parameters

Technology	Efficiency [%]	Energy/Power Ratio [h]	Self-Discharge [%/h]
Batteries	90	6	0
TES	90	6	

Table S4. Technology efficiencies

	η_{el} [%]	η_{th} [%]
Water electrolysis		84
Methanation		77
CHP (backpressure mode)	40	50
CHP (condensing mode)	40	
Waste incinerator	40	50
Biogas upgrade		100

Table S5. Main cost parameters for 2050 Finland

Technology	**Capex [€/kW]**	**Opex fix [% of capex]**	**Opex var [€/kWh]**	**Lifetime [a]**
Onshore wind	900	4.5	0	30
Offshore wind	1800	4.5	0	30
PV ground mounted	300	2	0	40
PV rooftop	400	1	0	40
Hydro run-of-river	3060	4	0	50
Biomass gasification	300	4	0	30
Biodiesel plant	2770	3	0	30
Biopetrol plant	790	7.7	0	30
PtG plant (electrolysis +methanation)	870	3.3	0	30
SOEC electrolyser	480	2.5	0	30
Biogas plant	194	7	0	30
Biogas upgrading	240	15.8	0	25
CHP plant	1000	3.7	2.7	25
CHP boiler	100	3.7	0.15	35
CHP heat pump	2220	2	0.27	20
Waste CHP plant	540	7.4	0	20
	Capex [€/kWh]	**Opex fix [% of capex]**	**Opex var [€/kWh]**	**Life [a]**
Stationary battery	75	3.3	0	20
BEV battery	100	5	0	12
TES	3	0.7	0	30
Hydrogen storage	20	0.5	0	20
Gas storage	0.05	3.3	0	50

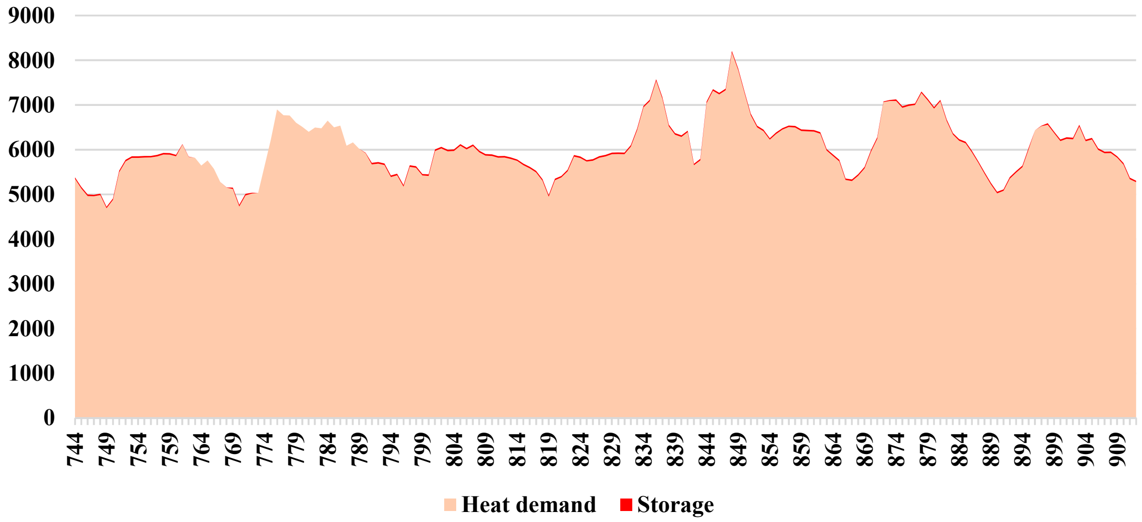

Figure S1. DH demand (MW_{th}): February 1-7. Demand for heat is relatively high during winter months.

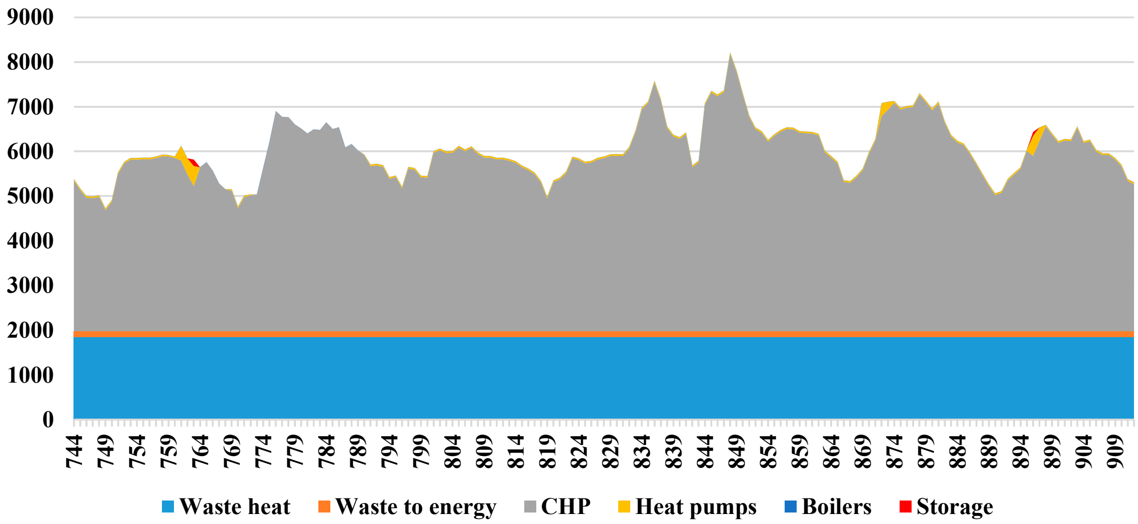

Figure S2. DH supply (MW_{th}): February 1-7. CHP plants operate near maximum capacity during winter months. Waste heat is supplied from PtG as a constant source due to a limitation of EnergyPLAN. In reality, this heat production would be much more variable.

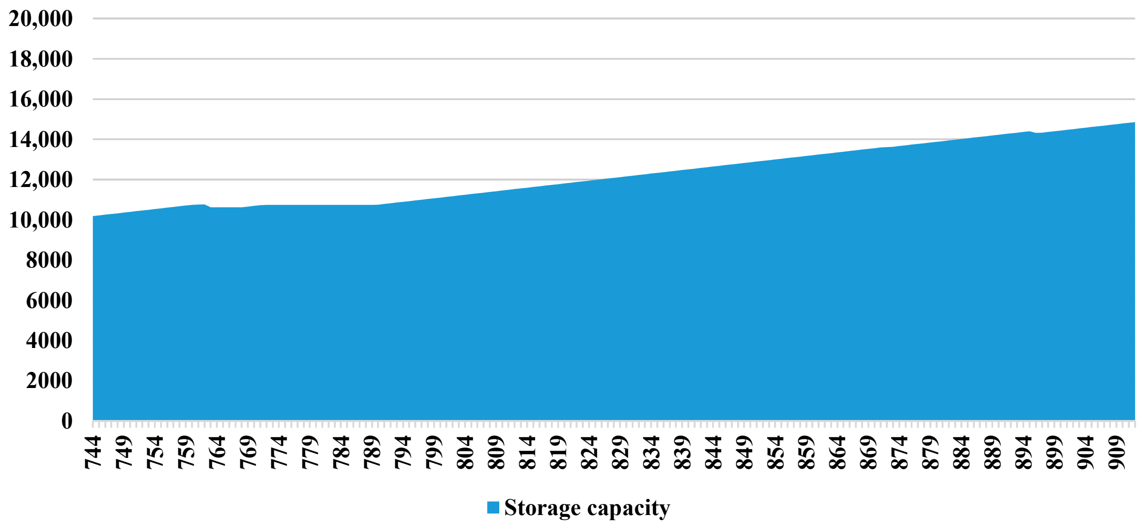

Figure S3. DH storage (MWh_{th}): February 1-7. Maximum storage is 20 000 MWh_{th}. Heat storage levels increase somewhat over the study period despite relatively high demands for heat. Power is a more limited commodity in the Finnish energy system. There appears to be an abundance of sustainable heat available throughout the year.

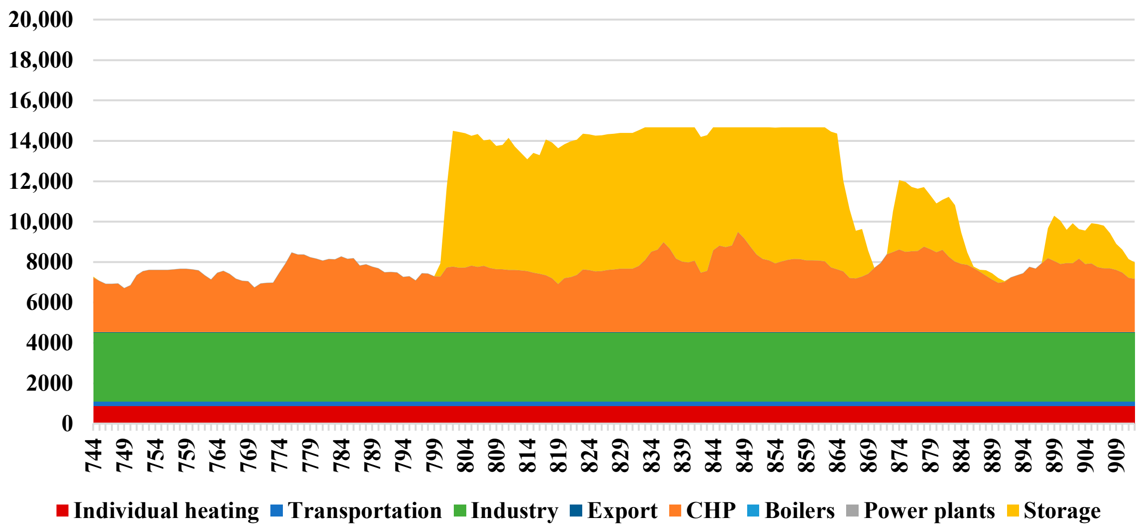

Figure S4. Grid gas demand (MW_{gas}): February 1-7. Demand for gas in thermal power plants is high during the study period. Excess gas production is allocated to storage.

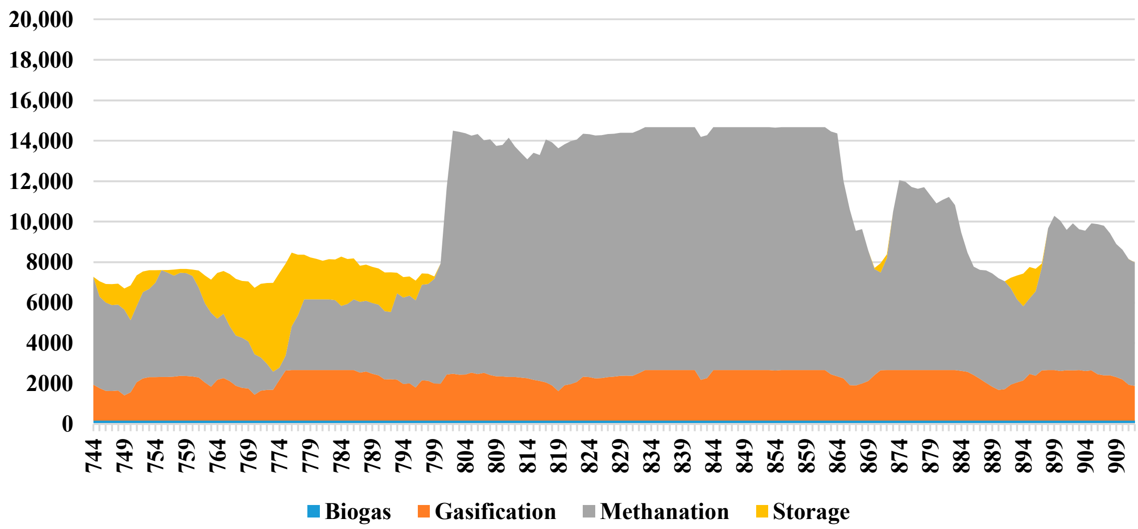

Figure S5. Grid gas supply (MW_{gas}): February 1-7. Production of PtG methane is high during periods of high wind production during the study week. PtG production as occurs during noon solar PV production peaks. Gasified biomass also contributes to the gas grid during winter months.

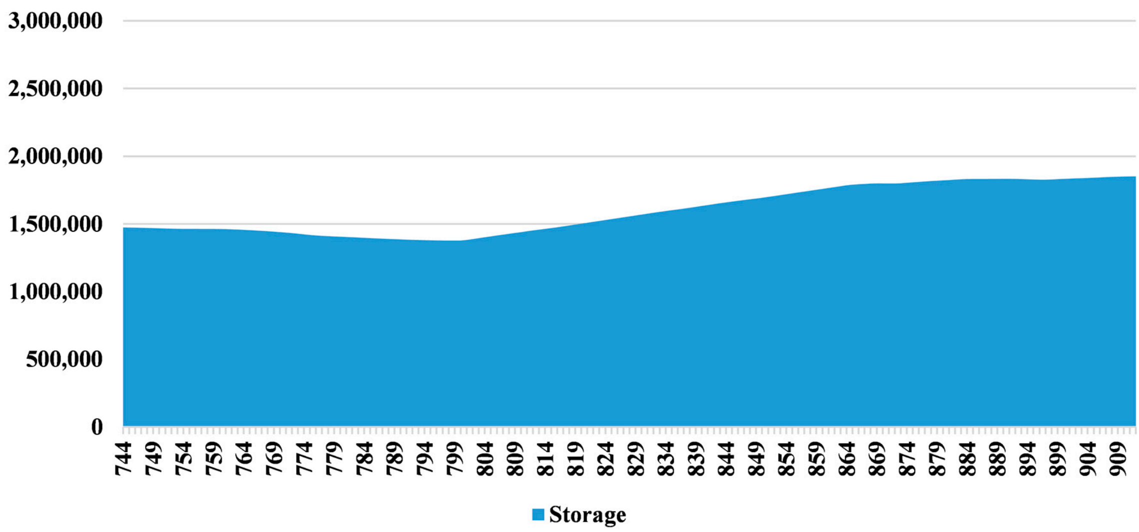

Figure S6. Grid gas storage (MWh_{gas}): February 1-7. Maximum storage is 3 800 000 MWh_{gas}. Storage levels of grid gas slightly increase during one of the weeks of highest gas demand due to high levels of PtG production that resulted from relatively high wind power production.

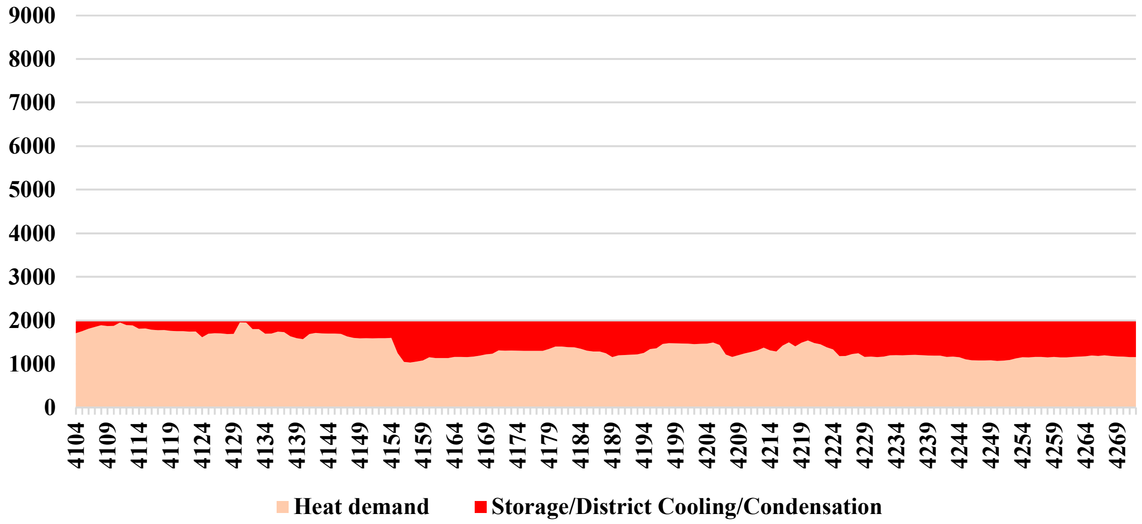

Figure S7. DH demand (MW_{th}): June 20-26. Heat demand is low during the summer months. This study period also represents a time of reduced industrial heat use due to summer holidays. A significant amount of excess heat is therefore condensed.

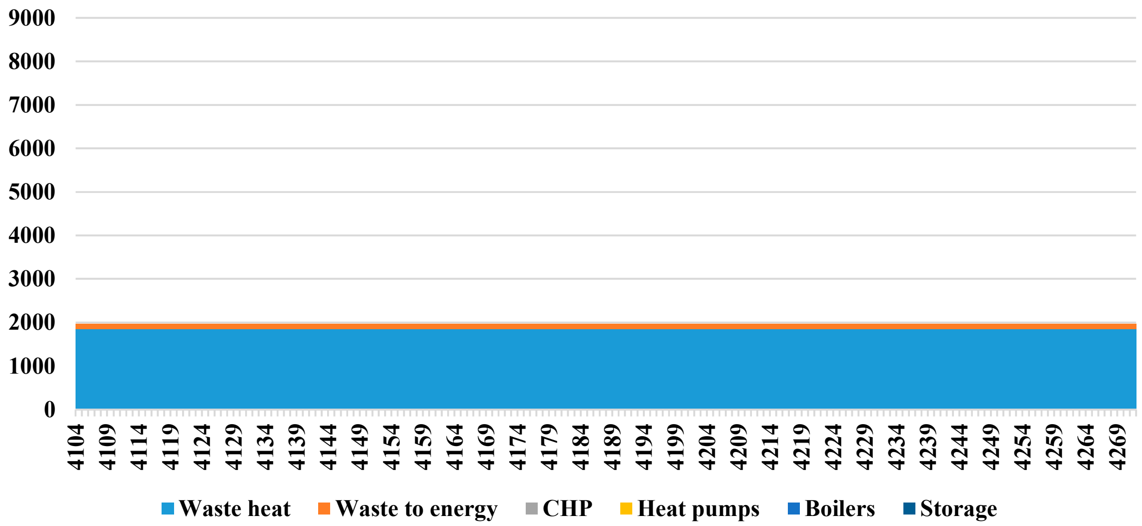

Figure S8. DH supply (MW_{th}): June 20-26. Supply of heat mostly comes from waste heat resulting from the PtG process.

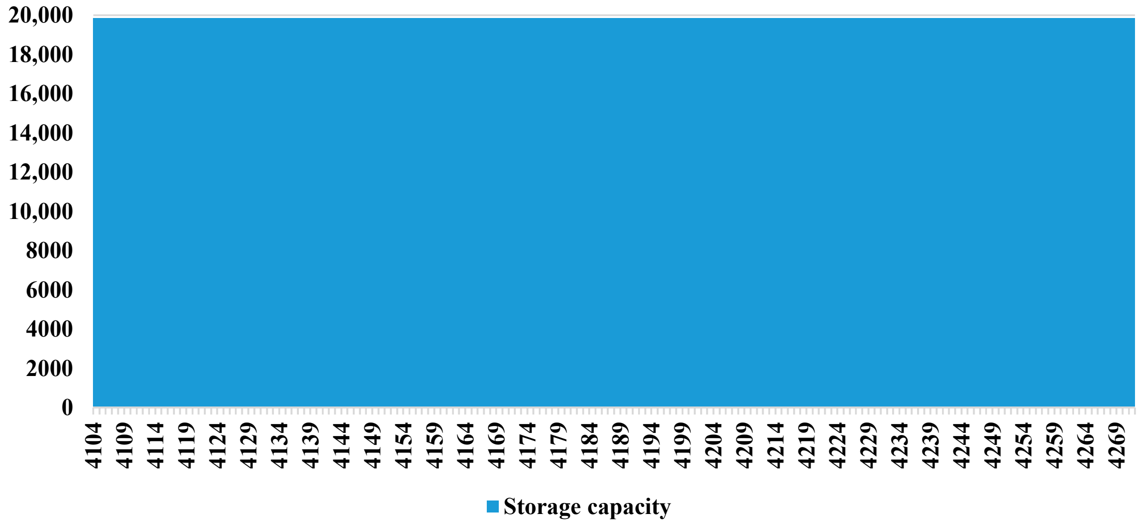

Figure S9. DH storage (MWh_{th}): June 20-26. Maximum storage is 20 000 MWh_{th}. Heat storage remains full throughout the study period due to very low demand for DH.

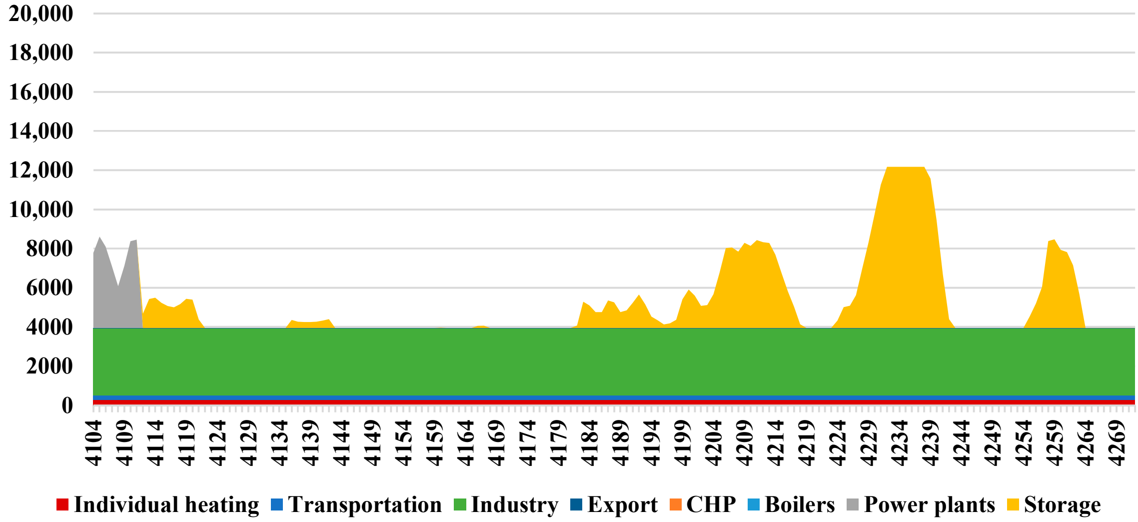

Figure S10. Grid gas demand (MW_{gas}): June 20-26. Demand for grid gas is relatively low during the study period. Excess gas is allocated to storage.

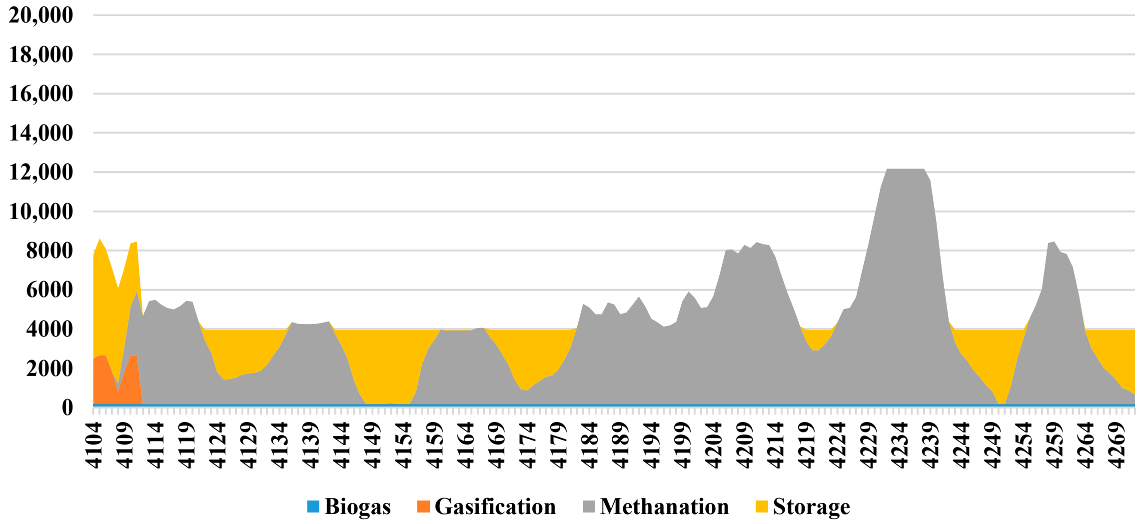

Figure S11. Grid gas supply (MW_{gas}): June 20-26. PtG methane production corresponds to peaks in solar PV production during the study period. Gasification of biomass is unnecessary during most of the study period.

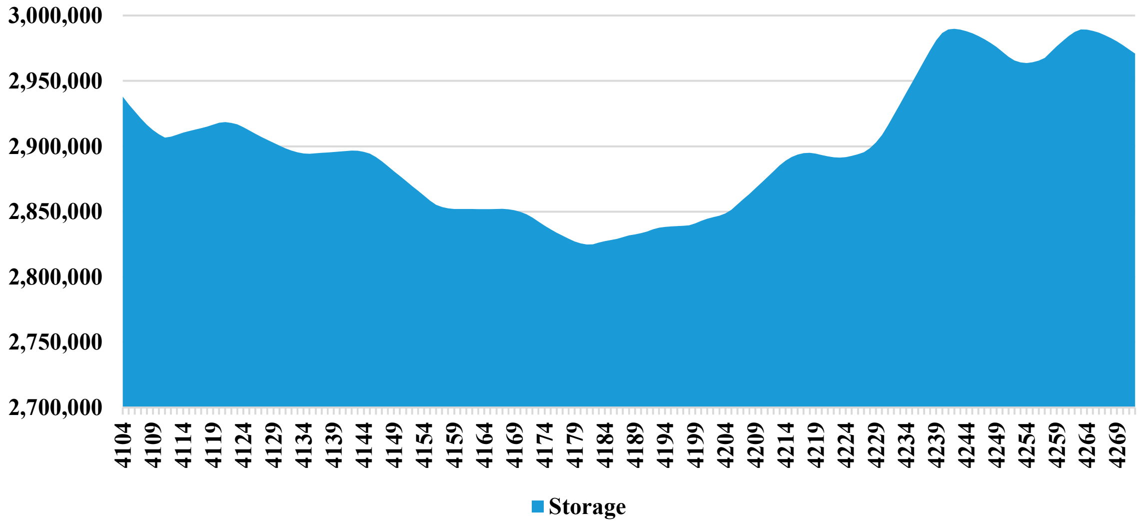

Figure S12. Grid gas storage (MWh_{gas}): June 20-26. Maximum storage is 3 800 000 MWh_{gas}. Small, daily increases in grid gas storage correspond to peaks in solar PV production. Small amounts of gas are used during the evening hours to produce power in CHP plants. Grid gas storage is close to maximum during the study period.

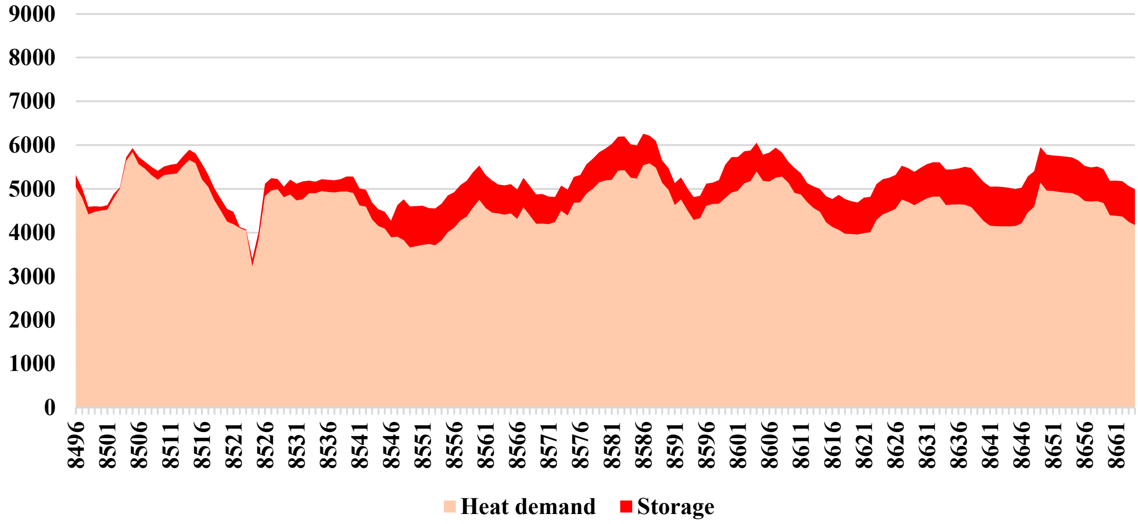

Figure S13. DH demand (MW_{th}): December 20-26. Demand for heat is somewhat high during the Winter solstice/Christmas period, especially during evening hours.

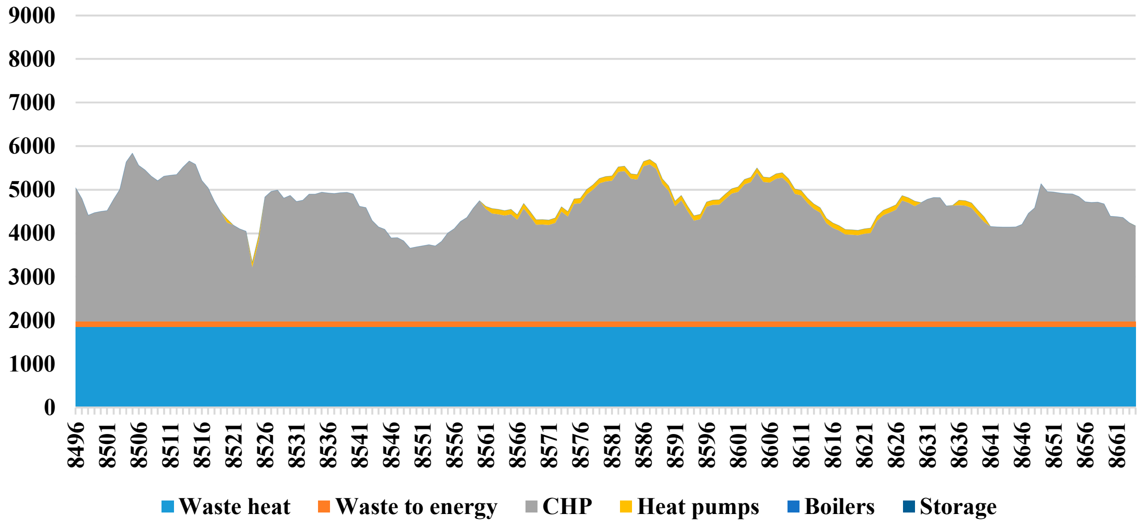

Figure S14. DH supply (MW_{th}): December 20-26. CHP plants run at close to maximum capacity during this period. Colder temperatures during the mid-week necessitate the use of heat pumps for the DH system.

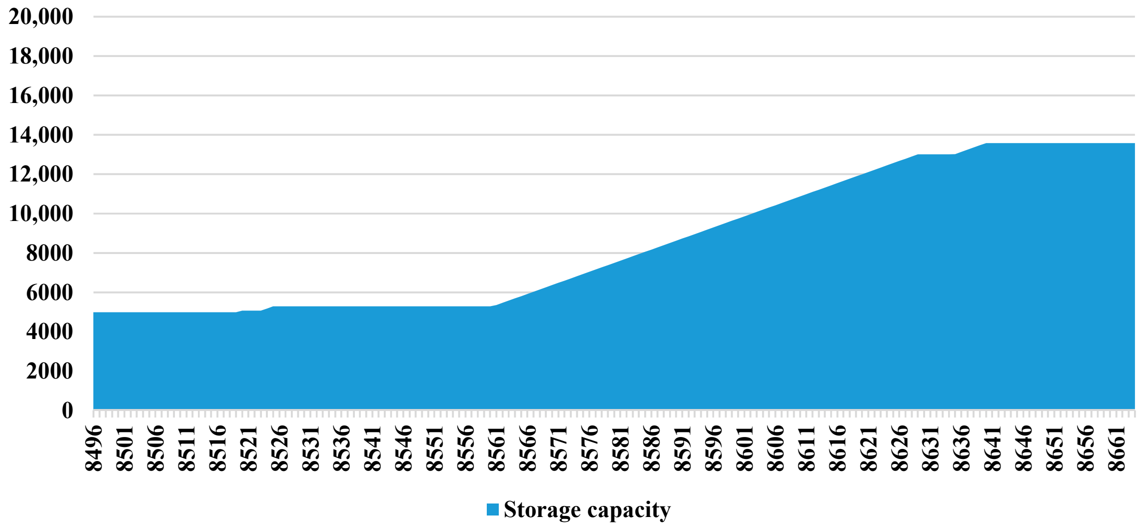

Figure S15. DH storage (MWh_{th}): December 20-26. Maximum storage is 20 000 MWh_{th}. Thermal storage approaches its lowest levels for the year during the study period due to relatively high demand. High demand for electricity during a windy and cold period in the middle of the study period results in high CHP production. This is also a time of high electricity demand during Christmas. Heat storage levels moderately increase as a result of excess heat production during the daytime.

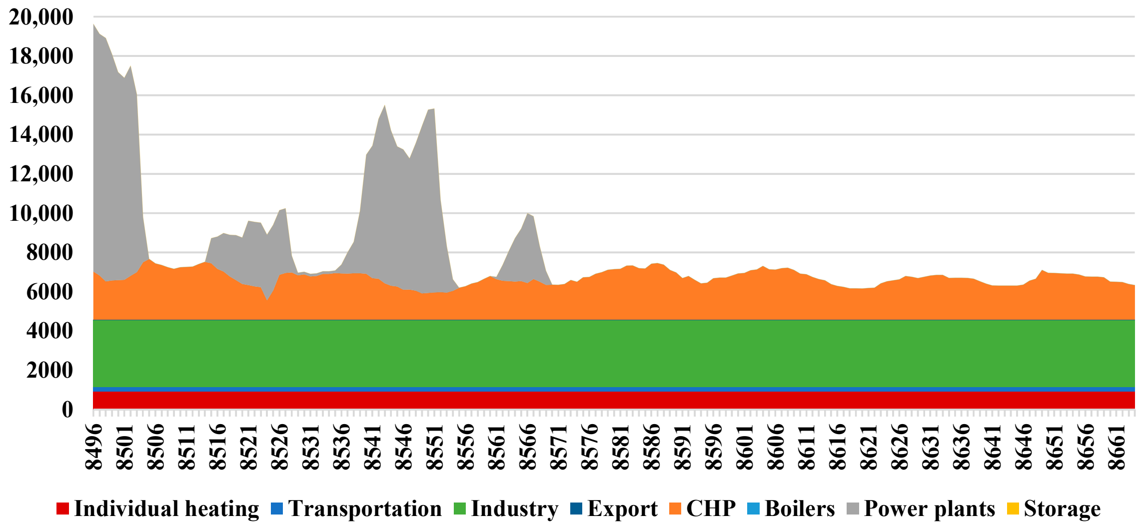

Figure S16. Grid gas demand (MW_{gas}): December 20-26. Demand for grid gas in thermal plants is high during evening hours over the first half of the study period.

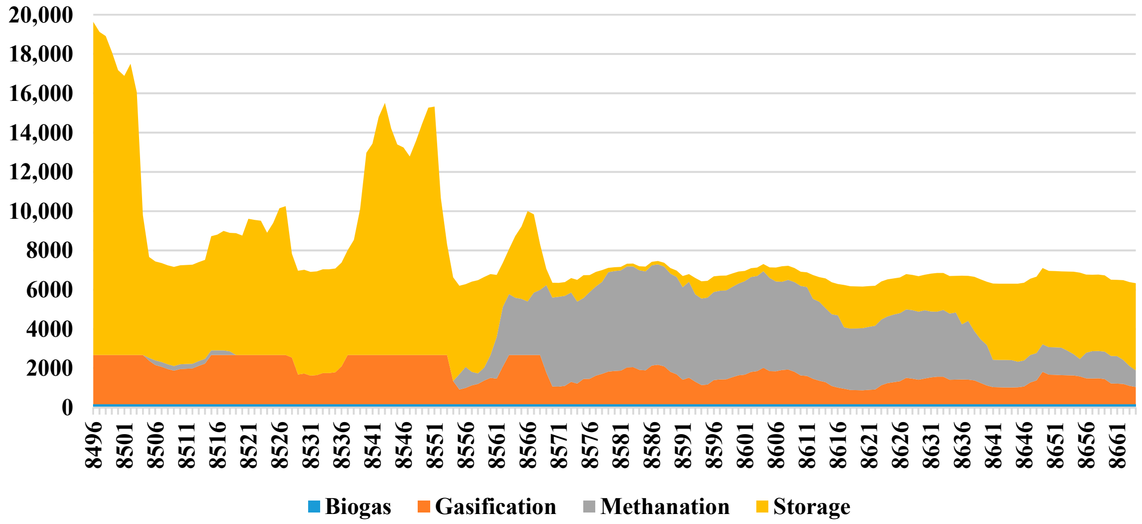

Figure S17. Grid gas supply (MW_{gas}): December 20-26. High grid gas demand is mostly provided by storage over the study period. Relatively high PtG methane production is utilized directly after midweek. Biomass gasification is relatively strong during this period of high gas demand.

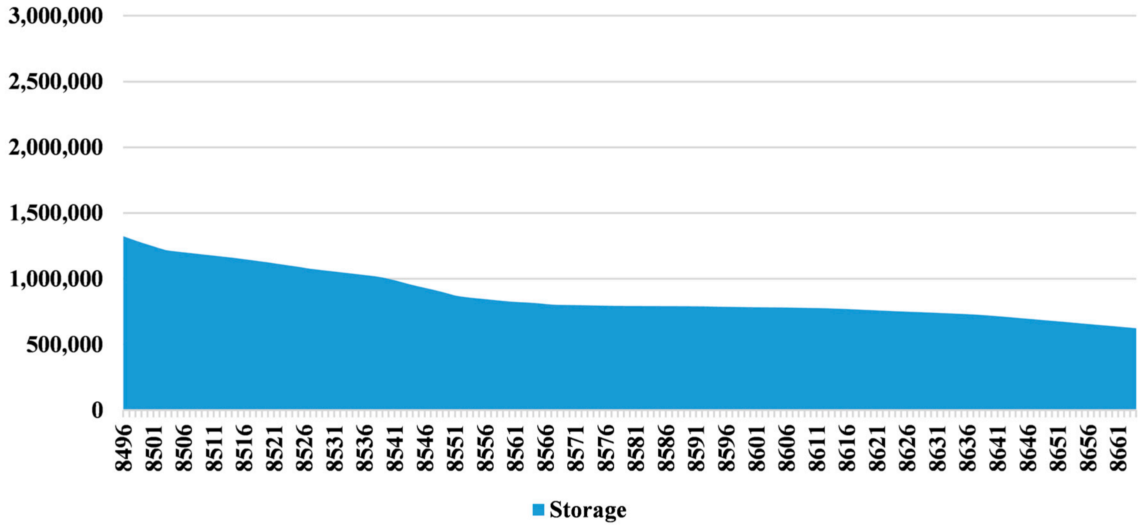

Figure S18. Grid gas storage (MWh_{gas}): December 20-26. Maximum storage is 3 800 000 MWh_{gas}. Grid gas storage is at relatively low levels for the year due to high demand. Storage levels decrease smoothly, however, due to variable production of synthetic methane from gasification of biomass and PtG.

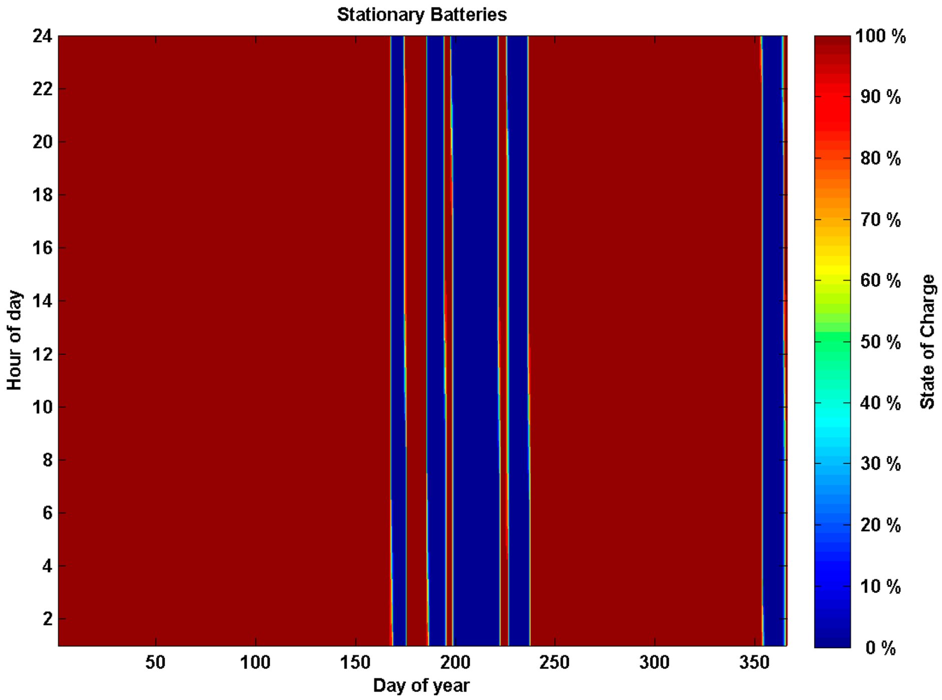

Figure 1. State of charge of stationary batteries. The utilization of stationary batteries by EnergyPLAN seems at odds with how such energy storage devices would be used in reality. EnergyPLAN used stationary batteries as a storage of lowest priority, while future prosumers may use them with the highest priority.

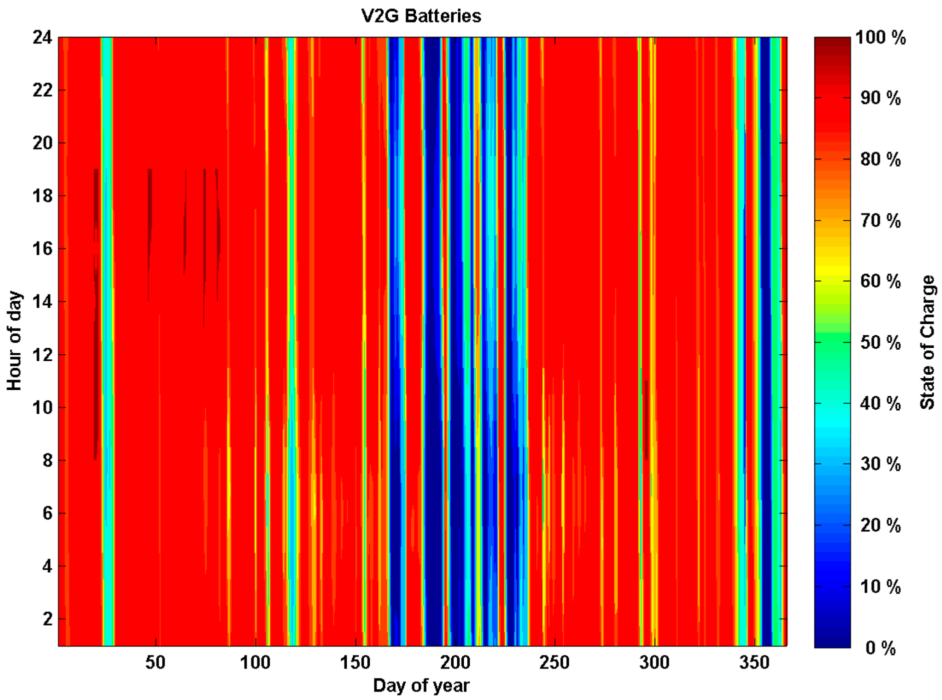

Figure 2. State of charge of V2G batteries. V2G batteries were a high priority storage solution for EnergyPLAN.

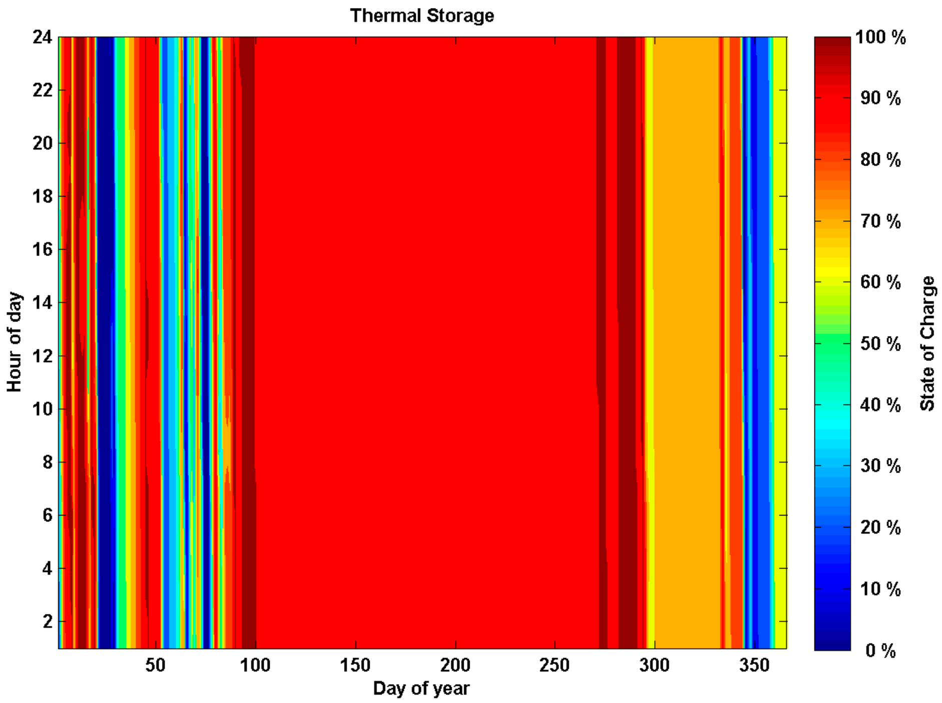

Figure 3. State of charge of DH storage. Finland currently has high levels of thermal energy storage associated with the DH system. Much of it is unused during the summer months, but it has an important function during the winter.

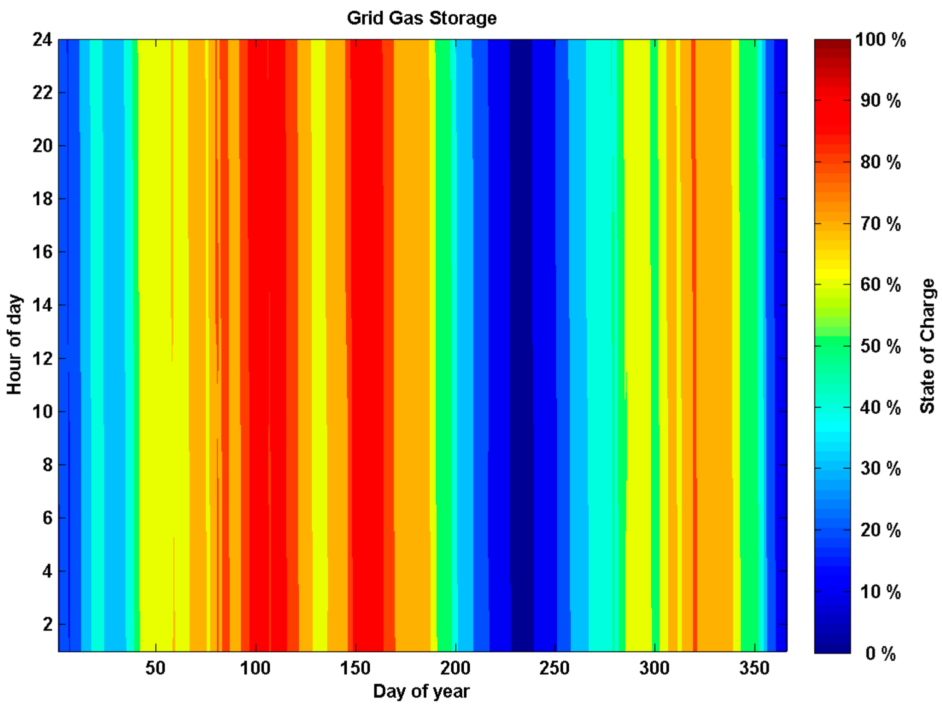

Figure 4. State of charge of grid gas storage. The grid gas storage is used as a seasonal balancing component for the energy system, as documented by the seasonal charging and discharging pattern.