Supply-storage-consumption of natural gas and potential solutions for Russian supply gaps in European Union (EU) countries: Can Russian gas be replaced in the EU?

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Supporting information

Gas network simulation

Our gas network simulation is based on graph analysis algorithms, which considers countries as nodes, and pipeline between counties as edges, as shown in the simulation netwrok graph in Fig S1. We consider gas storage as an attribute of each node. Note that Belgium and Luxembourg, Denmark and Sweden, Latvia and Estonia, were combined together as BE-LU, DK-SE, and LV-EE, respectively, which is based on the ENTSO-G balancing zone divisions. The simulation is constrained with the node mass balance Eq. (1), and also presented in Fig 1 (right) in the manuscript:

$$\begin{aligned}\text{Total gas supply} &= \text{Direct Supply (S)} + Inflow(IF) + Storage\ Supply\ (SI) \\ &= Consumption\ (C) + Outflow(OF) + To\ Storage(SO) = Total\ gas\ consumption\end{aligned} \tag{1}$$

We assume that mass balance of the gas supply sources is achieved daily for each node and edge. Therefore, the simulation iteratively solves the gas supply source shares for each node and edge based on Eq. (2) and Eq. (3).

$$r_{c,i} = \frac{total\ supply\ of\ source\ i}{total\ gas\ supply} = \frac{S \times RS_{c,\,i} + SI \times r_{c,s,i} + \sum if_c \times r'_{c,if,\,i}}{S + SI + IF} \tag{2}$$

$$\boldsymbol{r_{c,s,i} = of_{c,if,i} = r_{c,i}} \tag{3}$$

Where $r_{c,i}$ is the overall supply share of source *i* in country *c*, $RS_{c,\,i}$ is the supply share of direct supply for source *i* in country c, $r_{c,s,\,i}$ is the share of source i from storage (s) in country c, if_c are the edges that have flow into country c, $r'_{c,if,\,i}$ is the supply share of source i for edges that have flow into country c from the previous iteration, and $of_{c,if,i}$ is the share of source *i* for edges that have flow out from country *c*,.

The simulation stops until the convergence of all the nodes and edges, i.e. the differences for $r_{c,i}$ and $of_{c,if,i}$ between iterations are smaller than threshold value. Here we also assume that each county has no consumption preference of gas source, i.e., the consumption values from different sources are based on their supply shares.

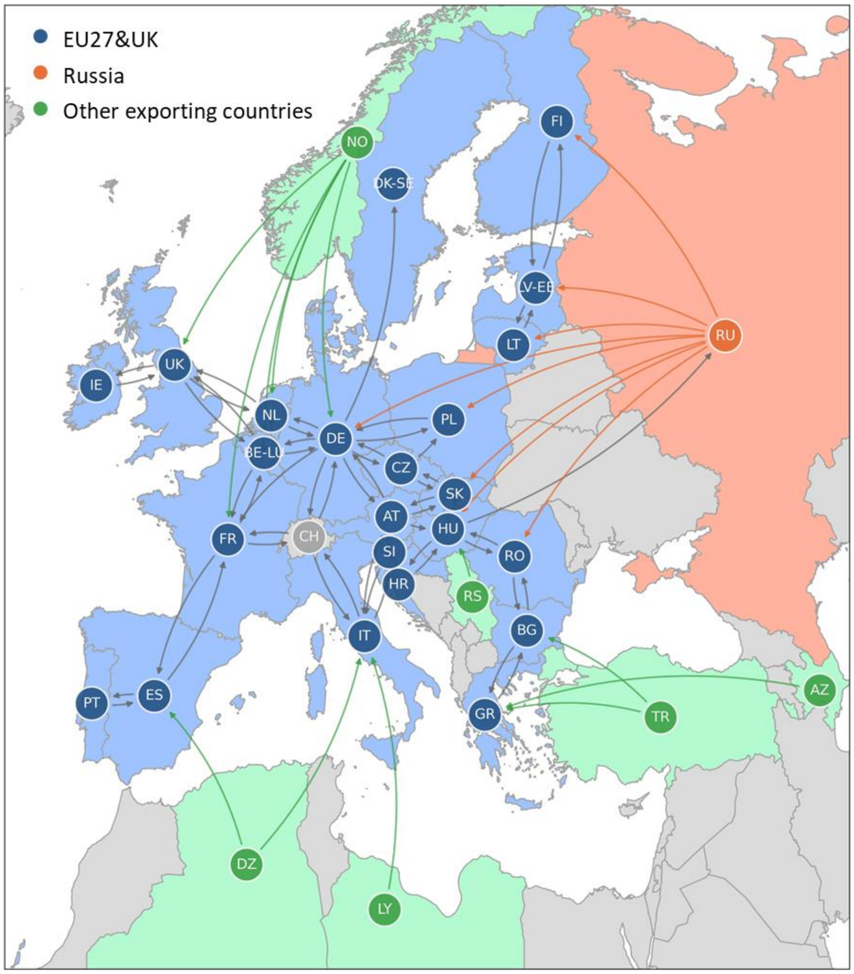

Figure S1. Simulation network graph.

Sectoral splitting validation

ENTSO-G datasets provide a rough splitting for consumption sectors as distribution (DIS), which is considered as heating and others sectors, and final consumer (FNC), which is considered as power and industrial sectors. However, the splitting is not available for all countries. On the other hand, Eurostat energy balance datasets (Eurostat, 2022b, c) provide more detailed monthly gas consumption in detailed sectors, therefore, we use the variables from Eurostat to split the consumption from ENTSO-G into five sectors: 1) *FC_OTH_HH_E* as household heating, 2) *FC_OTH_CP_E* as public building heating, 3) *TI_E* as power sector, 4) *FC_IND_E + FC_IND_NE* as industrial, 5) *IC_OBS- sum of the other four sectors* as others.

We validate this splitting approach with those counties that have DIS and FNC data from ENTSO-G, including Germany, France, Portugal, Italy, Romania, the UK, the Netherlands, Poland, Greece, and Belgium-Luxemburg. We firstly split the total consumption from ENTSO-G into the five sectors with Eurostat as mentioned above. Then we compare the original DIS values from ENTSO-G with the calculated DIS values from the Eurostat sectors (household heating + public building heating + others). Similarly, compare the original FNC values from ENTSO-G with the calculated FNC values from the Eurostat sectors (power sector + industrial). The compassion results are shown in Fig. S2. The good r2 and low differences indicate that our approach provides good qualities of the splitting for DIS and FNC, which implies our splitting approach for the five sectors would be reasonable.

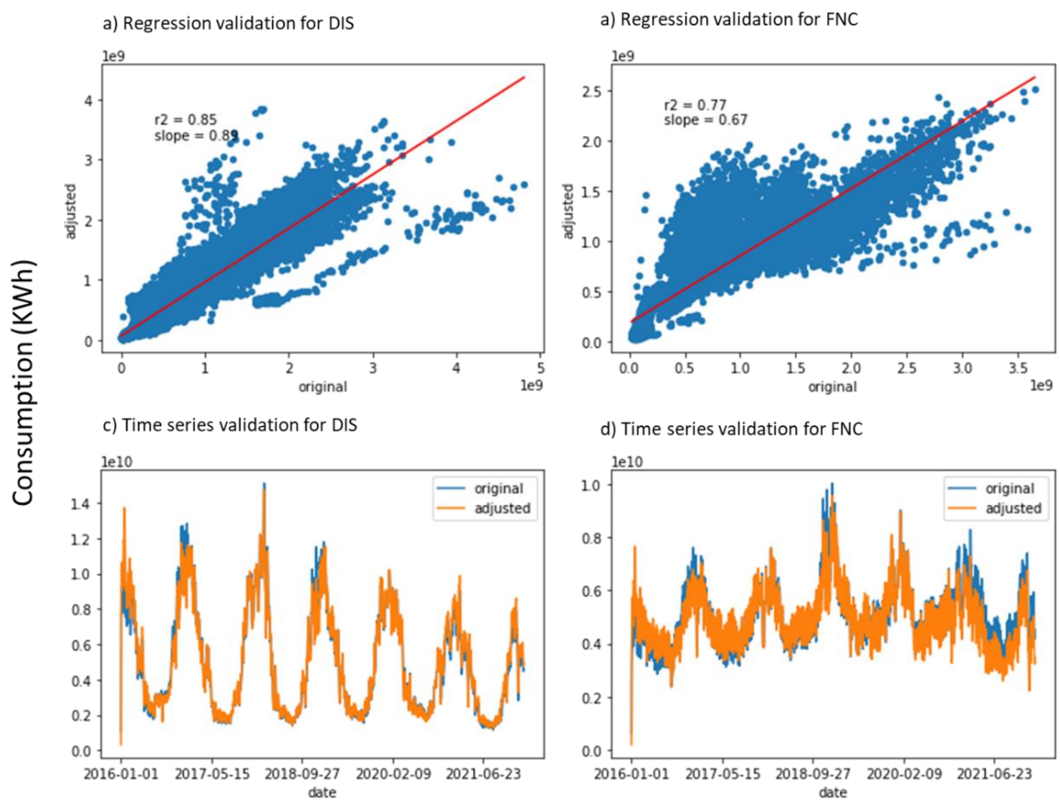

Figure S2. Comparisons between the original values and the estimated values based on Eurostat for the distribution (DIS) and final consumer (FNC).

Heating reduction

The detailed approach of the reduction capacity estimation based on empirical temperature-gas-consumption (TGC) curves is presented in section 2.3.1 of our manuscript. Here, we presented the plots for TGC curves fittings and reduction estimations of each country, as shown in Fig S3 for the household heating weekdays, Fig S4 for the household heating weekends, and Fig S5 for the public buildings, respectively.

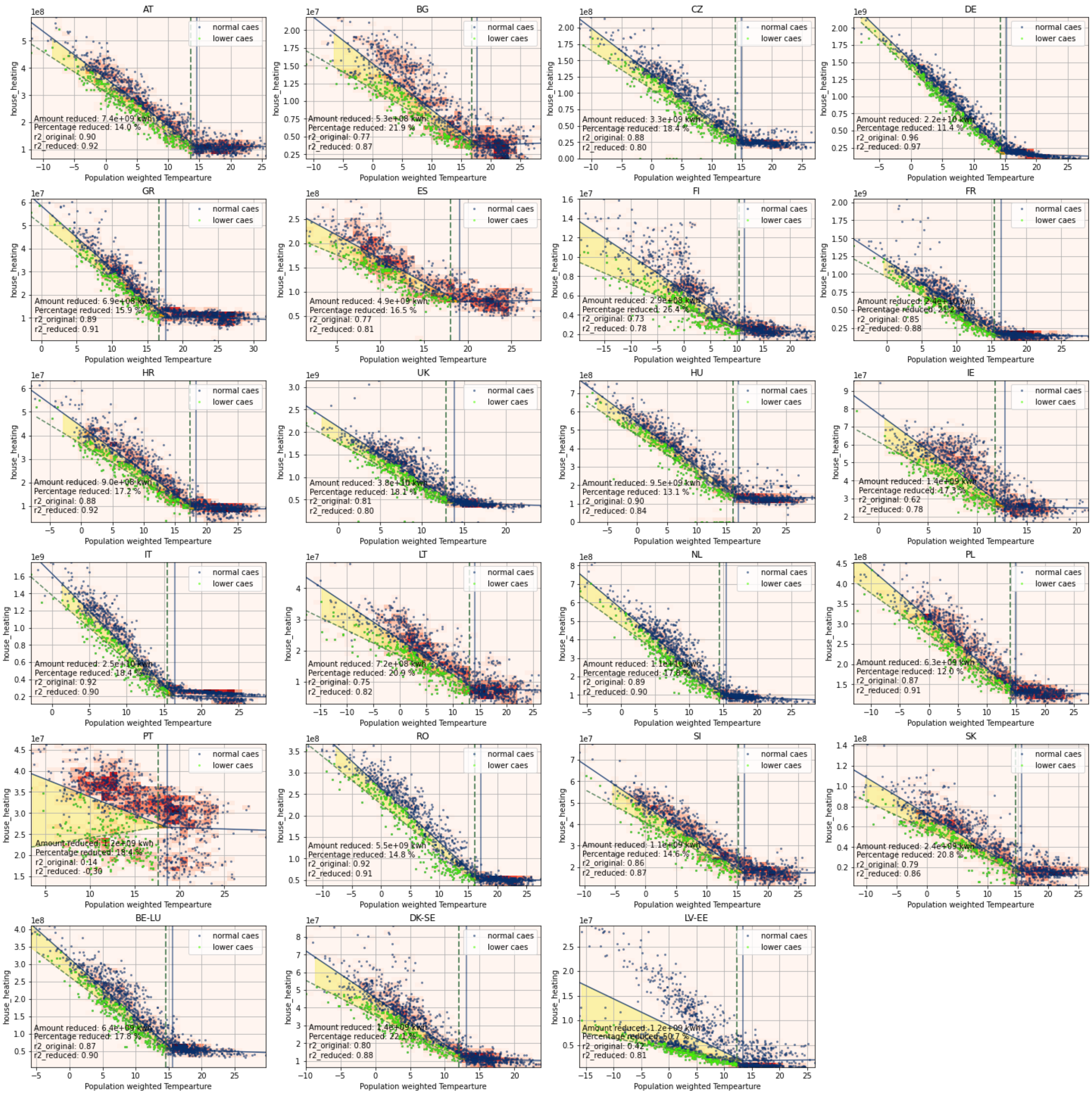

Figure S3. Reduction based on TGC for household heating weekdays. The figure shows a moderate scenario adopt a 1 °C lower critical temperature and the lower 30th percentile of the TGS curve.

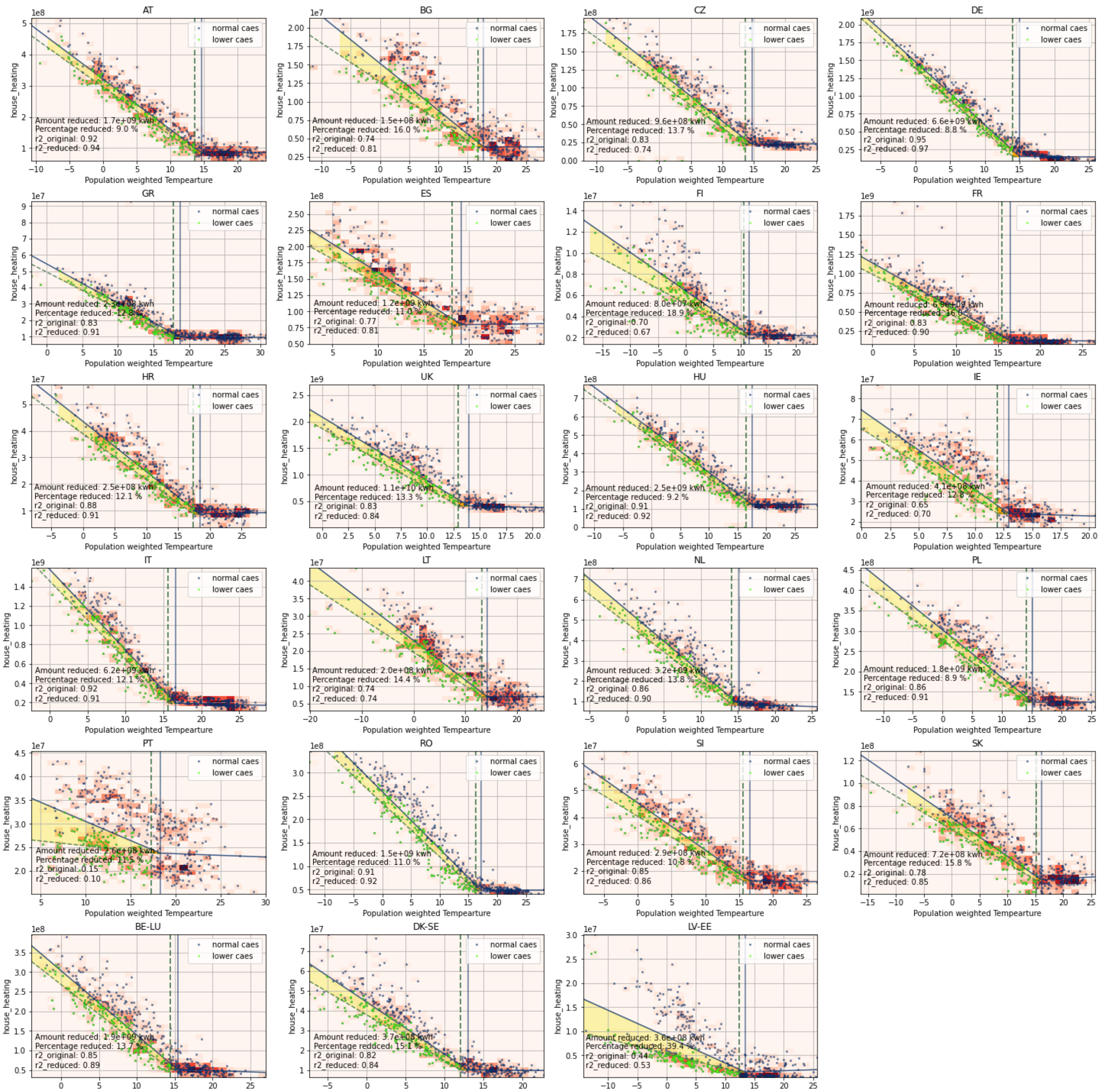

Figure S4. Reduction based on TGC for household heating weekends. The figure shows a moderate scenario adopt a 1 °C lower critical temperature and the lower 50th percentile of the TGS curve.

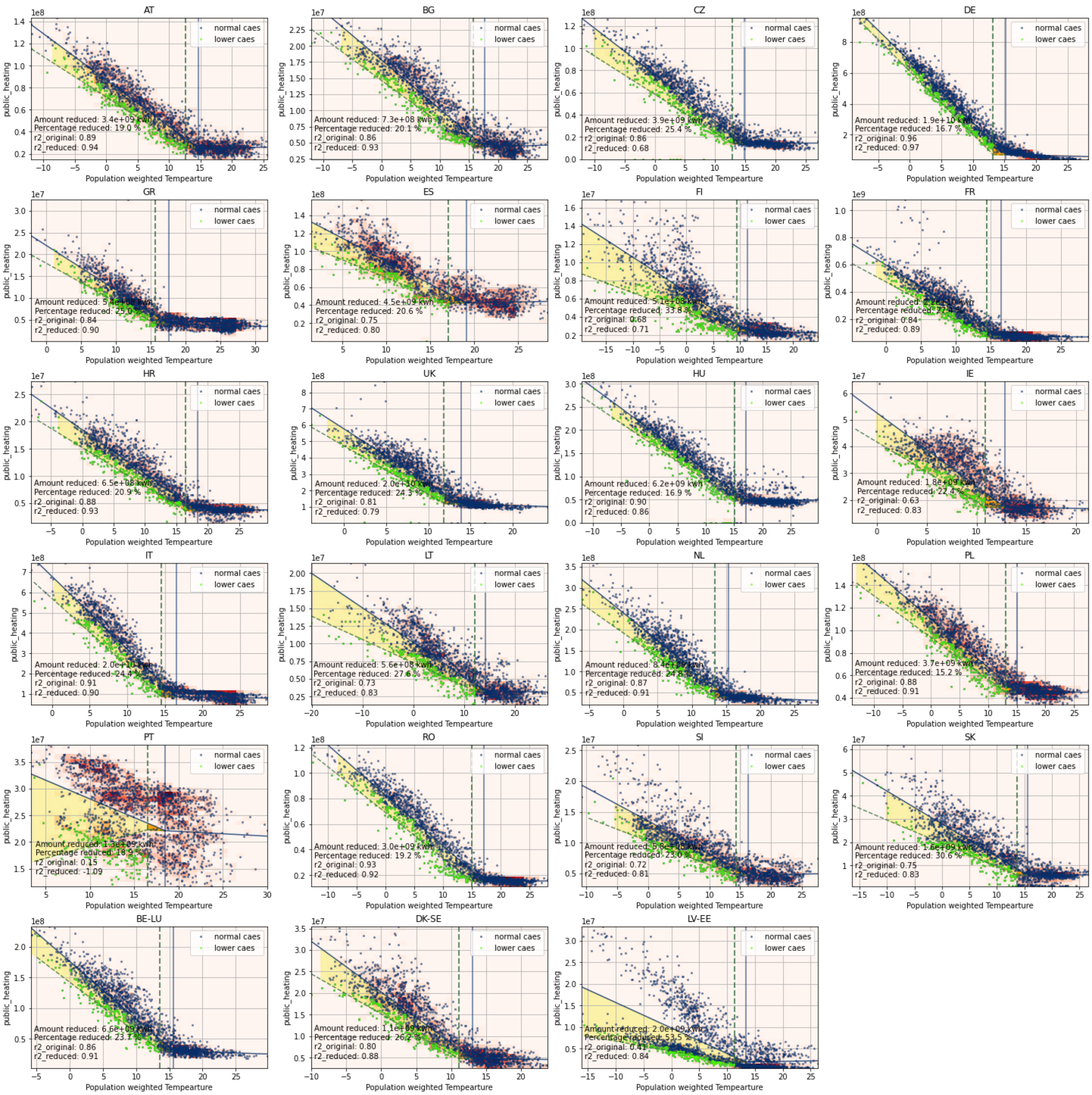

Figure S5. Reduction based on TGC for public building heating. The figure shows a moderate scenario adopt a 2 °C lower critical temperature and the lower 30th percentile of the TGS curve.

Power sector

We estimate that the gas can be saved in the power sector by substituting it with coal, nuclear, and biomass. We analyze the diurnal capacities (75% and 95% as moderate and severe cases) for those alternative electricity sources in each country as shown in Fig S6. The extra capacities from alternative sources will be used to replace the electricity generated by gas-fired power plants. Then the substituted electricity from ENTSO-E is converted to gas form as ENTSO-G considering gas-fired power plant efficiency. We estimate the average efficiencies of gas-fired power plants in each country by calculating the overall correlations between gas consumed in the FNC (gas form, from ENTSO-G) and gas-powered electricity generated (electricity form, from ENTSO-E), as shown in Table S1. The slopes are used as average efficiencies, and we also limit the efficiencies from 0.4 to 0.6.

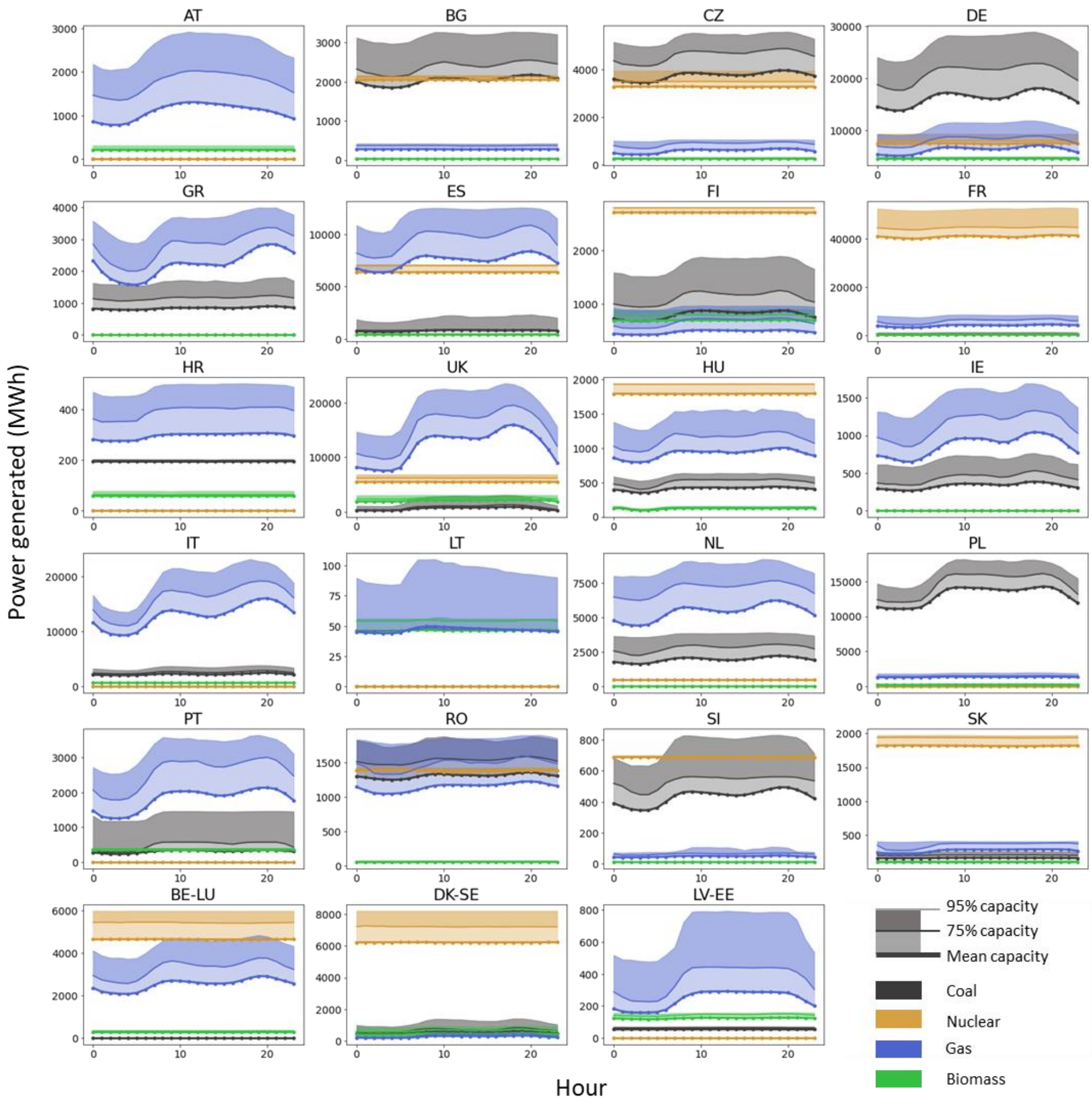

Figure S6. Diurnal hourly capacities (75% and 95%) for coal, gas, nuclear, and biomass based on ENTSO-E electricity production from 2019 to 2021. Those capacities will be used for gas reduction capacities estimations.

Table S1. Linear regression between gas (MWh) used in power sector (from EUGasSC) and the electricity (MWh) generated with gas power plant (from ENTSO-E).

	r2[1]	Slope[1]	Efficiency[2]
AT	0.87	1.72	0.6
BG	0.75	0.15	0.4
CZ	0.11	0.19	0.4
DE	0.45	0.29	0.4
GR	0.69	0.65	0.6
ES	0.52	0.5	0.5
FI	0.27	0.66	0.6
FR	0.8	1.17	0.6
HR	0.4	0.11	0.4
UK	0.64	0.7	0.6
HU	0.33	0.17	0.4
IE	0.13	0.36	0.4
IT	0.66	0.52	0.52
LT	0.09	0.04	0.4
NL	0.62	0.71	0.6
PL	0.51	0.72	0.6
PT	0.68	0.74	0.6
RO	0.66	0.84	0.6
SI	0.52	0.91	0.6
SK	0.01	0.02	0.4
BE-LU	0.71	1.06	0.6
DK-SE	0.41	0.51	0.51
LV-EE	0	0	0.4

[1] R^2 presents whether the power consumption from EUGasSC correlated to ENTSO-E. The slope indicates the average gas power plant efficiency if all the gas consumption from EUGasSC were fully used for electricity generations.

The EUGasSC dataset might systematically underestimate the gas consumption in the power sector if the slope is large than 0.6 with a good r^2. Smaller r^2 with the lower slope ceases might indicate bad estimations of the power sector from EUGasSC.

[2] We use the slope as the average gas power efficiency with the limits from 0.4 to 0.6.

Extra CO_2 emission

We estimate the extra CO_2 that will be emitted by replacing gas-fired power plants with coal-fired power plants based on average efficiencies and emission factors from the US EPA report (https://www.epa.gov/sites/default/files/2020-12/documents/power_plants_2017_industrial_profile_updated_2020.pdf). We assume that the average efficiency for gas-fired power plants is 0.5, the reported emission factor for gas-fired power plants is 898 pound CO_2/MWh, and the reported emission factor for coal-fired power plants is 2180 pound CO_2/MWh. Then the extra CO_2 emission can be calculated as:

$$\text{Extra } CO_2 = gas_{replaced} \times gas_{efficiency} \times (coal_{emission} - gas_{emssion}) \quad (4)$$

Table S2. Remaining gaps in the Russia-dependent countries with redistribution from Russian-independent countries using the current network and assuming bi-directional transmission network possibilities.

Regions	Remaining gap without redistribution (TWh) [1]	Remaining gap with redistribution using current network (TWh)	Remaining gap with redistribution using bi-directional network (TWh)
Germany	348.9	295.8	137.4
Italy	309.4	285.1	265.5
Hungary	147.9	145.0	122.9
Poland	120.2	119.1	117.1
Austria	138.9	131.4	101.8
Baltic	36.1	33.0	32.9
Other	77.8	84.9	66.6
Total	1179.2	1094.2	844.1

[1] The remaining gaps shown in this table are evaluated with upper bound capacities for heating, power generations, and imports.

Table S3. Descriptions of column headers and units of EUGasSC and EUGasRP.

	Column header	Description
Common	date	Date of the row
	country	Country of the row
EUGasSC*	TOTAL	Total gas consumption
	RU	Gas supply from Russia imports
	LNG	Gas supply from LNG imports
	PRO	Gas supply from EU production
	AZ	Gas supply from Azerbaijan imports
	DZ	Gas supply from Algeria imports
	NO	Gas supply from Norway imports
	RS	Gas supply from Serbia imports
	LY	Gas supply from Libya imports
	TR	Gas supply from Turkey imports
	RU_from_storage	Gas supply from stored Russia imports
	LNG_from_storage	Gas supply from stored LNG imports
	PRO_from_storage	Gas supply from stored EU production
	AZ_from_storage	Gas supply from stored Azerbaijan imports
	DZ_from_storage	Gas supply from stored Algeria imports
	NO_from_storage	Gas supply from stored Norway imports
	RS_from_storage	Gas supply from stored Serbia imports
	LY_from_storage	Gas supply from stored Libya imports
	TR_from_storage	Gas supply from stored Turkey imports
	house_heating	Gas consumption in household heating
	public_heating	Gas consumption in public building heating
	others	Gas consumption in others sector
	industrial	Gas consumption in industrial sector
	power	Gas consumption in power generation
EUGasRP*	publich_building	Capacity from reducing public building heating
	household	Capacity from reducing household heating
	coal	Capacity from increasing power generation by coal
	biomass	Capacity from increasing power generation by biomass
	nuclear	Capacity from increasing power generation by nuclear

* Units are KWh.