Supporting Information for

Europe's adaptation to the 2022-2023 energy crisis: Reshaped gas supply-transmission-consumption structures and driving factors

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Supporting Information Text

1. Gas supply, storage, and consumption

The gas supply-consumption source for the EU27&UK was estimated in our previous study, and we provide the daily country- and sector-specific natural gas consumption dataset, EUGasSC (1). This open dataset is developed with a gas network flow simulation based on mass flow balance using ENTSO-G (European Network of Transmission System Operators for Gas) and other open gas data platforms, and it estimates the “real” supply sources by considering the intra-EU transmissions and storage supplies. EUGasSC quantifies daily gas consumption into five sectors (household heating, public heating, power, industrial, and others), and separates the supply sources into four major parts, pipeline imports from Russia, imports from LNG, EU local gas production, and pipeline imports from other countries (including Norway, Algeria, Azerbaijan, Libya, Serbia, and Turkey), which allows us to compare the supply and sector-specific gas consumption changes in winters. EUGasSC is used for the daily gas supply-consumption data with specified sources and sectors in this study. Note that the pipeline flow and import data collections have been included in the workflows of generating the EUGasSC dataset; they were extracted in this study to perform the net flow change analysis for the gas network.

Our previous study also predicted potential solutions, the EUGasRP dataset, to fill the gas supply gap caused by the cut-off of the Russian gas supply (1). In EUGasRP, we qualify the amount of Russian gas gap that can be resolved by gas saving in the heating sector, switching from gas-powered electricity to other sources, and gas supply increment by seeking potential boosting of gas supplies. We also estimate how the intra-EU transmission limits (if not well addressed) could result in relatively large gas shortages. EUGasRP is used in this study for comparing with the observed sectoral gas consumption changes to evaluate how the crisis was addressed during the winter of 2022-2023 and the future opportunities and challenges.

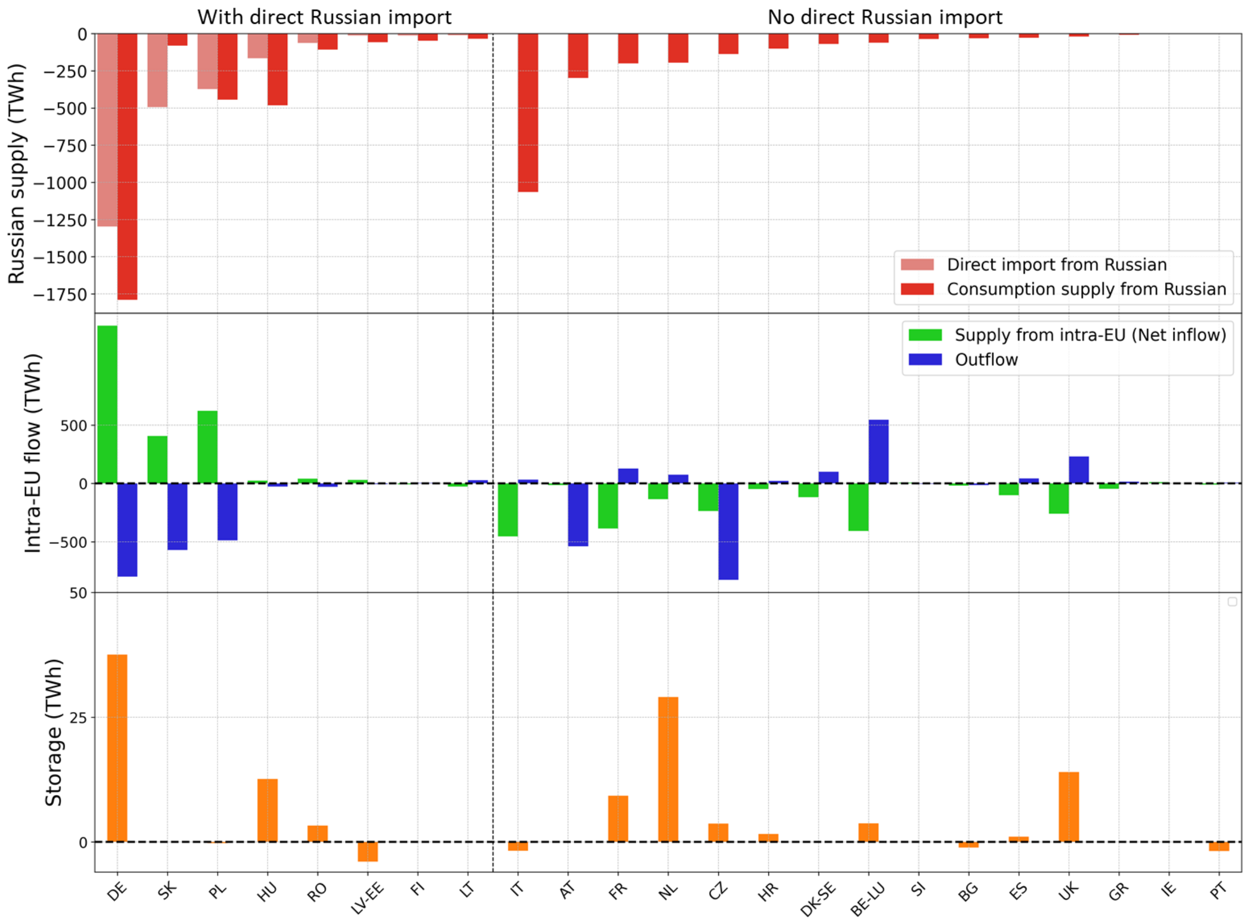

Fig S1. Post-invasion and pre-invasion comparisons in EU27&UK for 1) differences in Russian supply (top panel), 2) differences in intra-EU transmissions (middle panel), and 3) differences in flow to storage (bottom panel). The differences are calculated by subtracting the annual average of the pre-invasion period (2019-04-01 to 2022-03-3) values from the post-invasion period (2022-04-01 to 2023-03-31) values. The consumption supply from Russia is from the EUGasSC dataset (estimated with the gas network simulation). The supply from intra-EU transmissions (net inflow) is calculated by subtracting the total inflow from the total outflow.

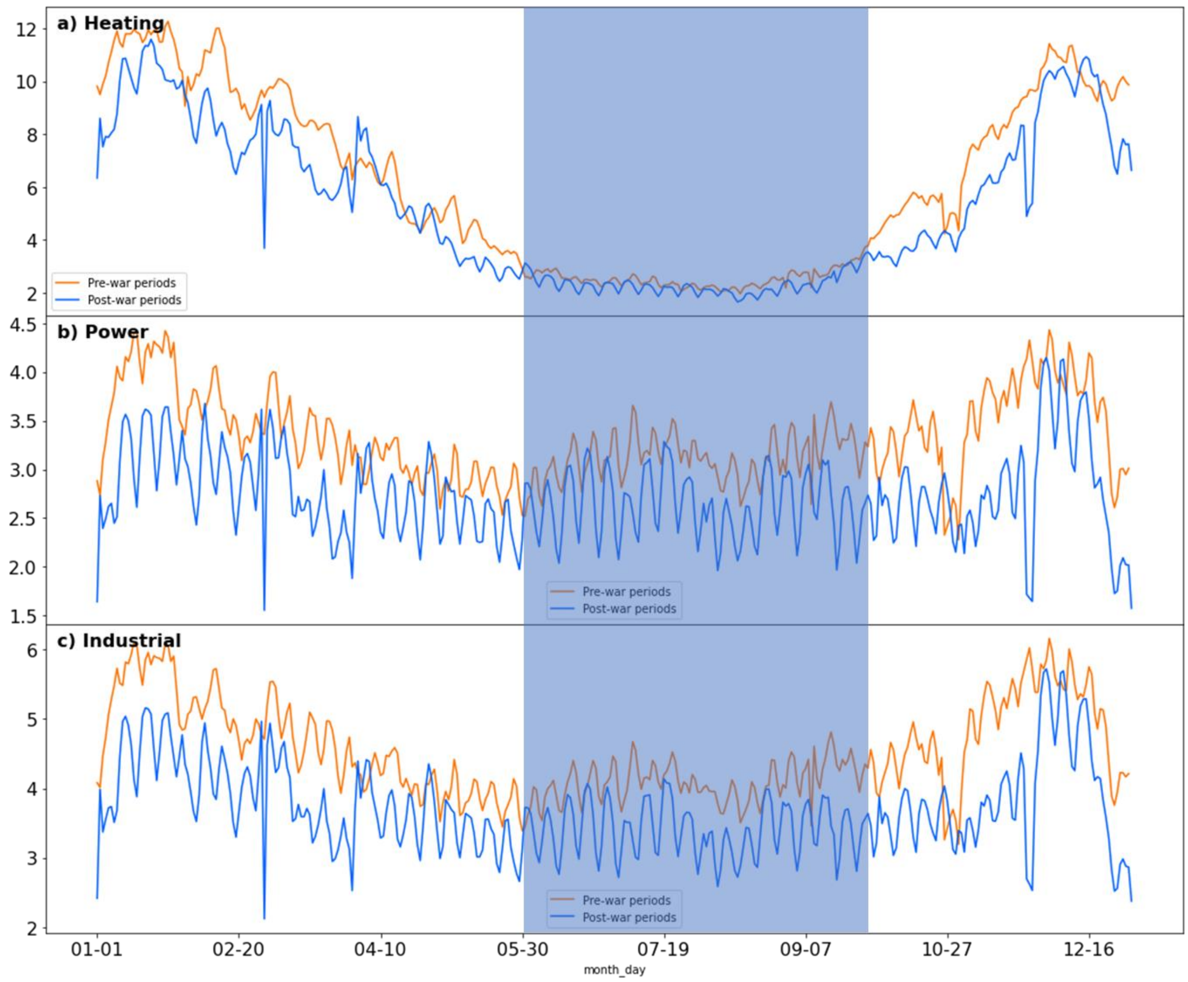

Fig S2. Mean daily gas consumption for a) residential heating, b) power, and c) industrial sectors in the pre-invasion periods (2019 to 2021) and the post-invasion periods (2022 to 2023). The periods with a blue background are non-heating seasons.

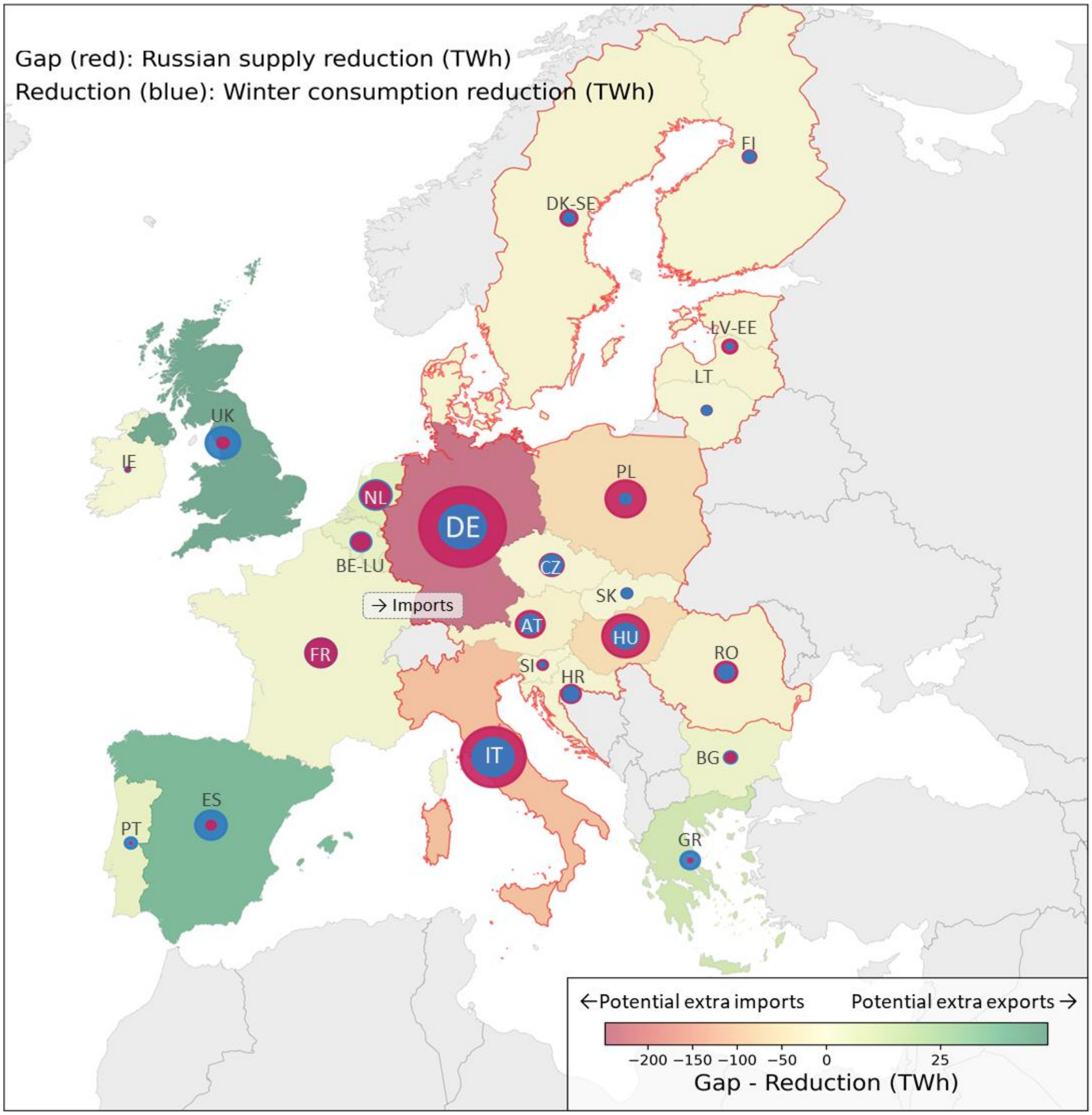

Fig S3. Map of gas supply-consumption status. The red circles indicate the gas supply gap caused by the reduction of Russian supply, while the blue circles indicate the consumption reduction between post-invasion and pre-invasion winter. The differences between the supply gap and consumption are presented by the map colors. If the differences were negative (red on the map), the countries require extra gas imports. If the differences were positive(green on the map), the countries can export extra gas to other countries.

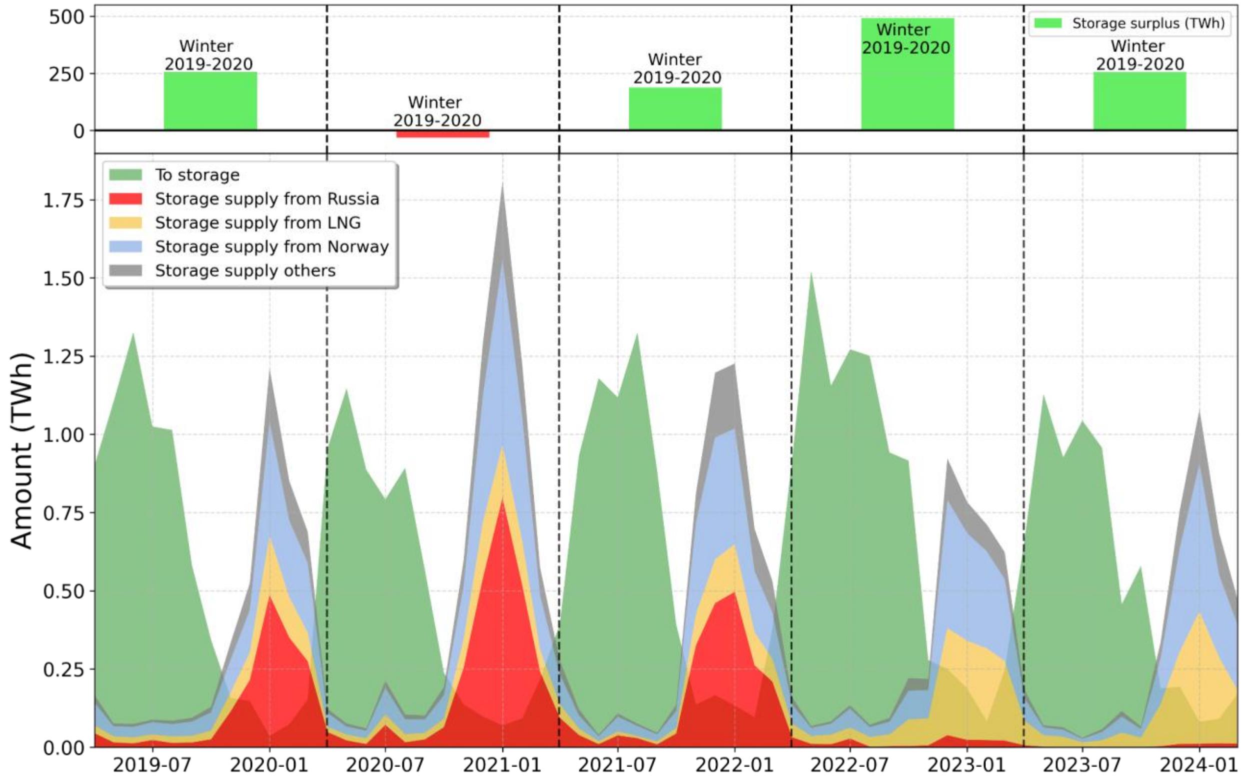

Fig S4. Monthly gas supply from storage and gas flow to storage facilities from 2019-04 to 2023-04 in EU27&UK. The supply source is from the EUGasSC dataset (estimated with the gas network simulation based on flow mass balance).

Table S1. Gas exports from Russia to EU27&UK during the post-invasion winters.

Country	The last date of direct flow from Russia	Flow from Russia in post-invasion winters (TWh)	Flow to Russia in post-invasion winters (TWh)
RO	2022-04-01	/	1.5
LV-EE	2023-07-24	0.0	/
FI	2022-05-21	/	/
DE	2022-09-01	/	/
PL	2024-03-30	19.0	5.1
HU	2024-01-18	0.19	16.8
LT	2024-03-31	25.4	/
SK	2024-03-31	236.1	/
Total		280.7	23.4
Net total		257.3	

Table S2. LNG for intra-EU transmission (exports to other EU countries) and local consumption in the major LNG import countries.

Country	Transmission over consumption ratio for the pre-invasion periods*	Transmission over consumption ratio for the post-invasion periods*
BE-LU	2.14	5.53
NL	2.29	3.40
UK	0.28	0.68
FR	0.25	0.58
PT	0.06	0.21
ES	0.03	0.14
Overall	0.36	1.08

* Transmission over consumption ratio is estimated with EUGasSC and EUGasNet for the local LNG consumption and LNG transmission, respectively.

Table S3. Current and planned LNG facilities in EU27&UK. The country order is based on the current LNG capacity. The data is collected from https://www.gem.wiki/Kiyanly_LNG_Terminal

Country	Current LNG terminal capacity (bcm/yr) *	Planned LNG terminal capacity (bcm/yr)
ES	67.1	/
UK	48.3	/
FR	34.5	5.0
NL	21.5	/
IT	16.2	8.0
DE	12.0	5.0
BE	11.4	/
PL	8.3	/
PT	7.6	/
GR	7.0	13.5
LT	4.0	/
HR	2.6	/
FI	0.6	/
Total	241.1	31.5

* bcm/yr is billion cubic meter LNG per year

2. Economic

With the profound structural change in EU gas supply, the Dutch TTF (Title Transfer Facility) natural gas price (**Fig. S5**) reached its peak when Russia completely halted the Nord Stream in 2022-08 with several critical events, such as when Russia invaded Ukraine in 2022-02 and started to reduce its Nord Stream supply in 2022-06. (2) (3) Nevertheless, the EU gas price was gradually back to the pre-invasion levels probably because the intra-EU transmission “bottlenecks” were resolved. The “bottlenecks” involved addressing gas transmission from France to Germany and developing German LNG facilities, which will be discussed later. Based on the price trends, we classified the counties into four different groups (**Fig S6**).

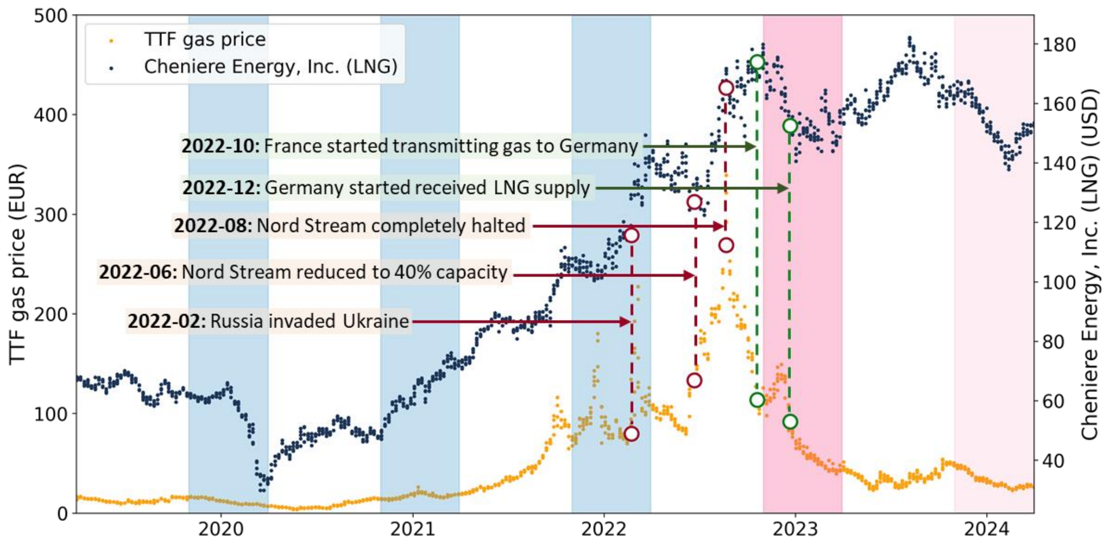

Fig S5. Dutch TTF (Title Transfer Facility) natural gas price from 2019 to 2023 and the stock price of LNG industrial.

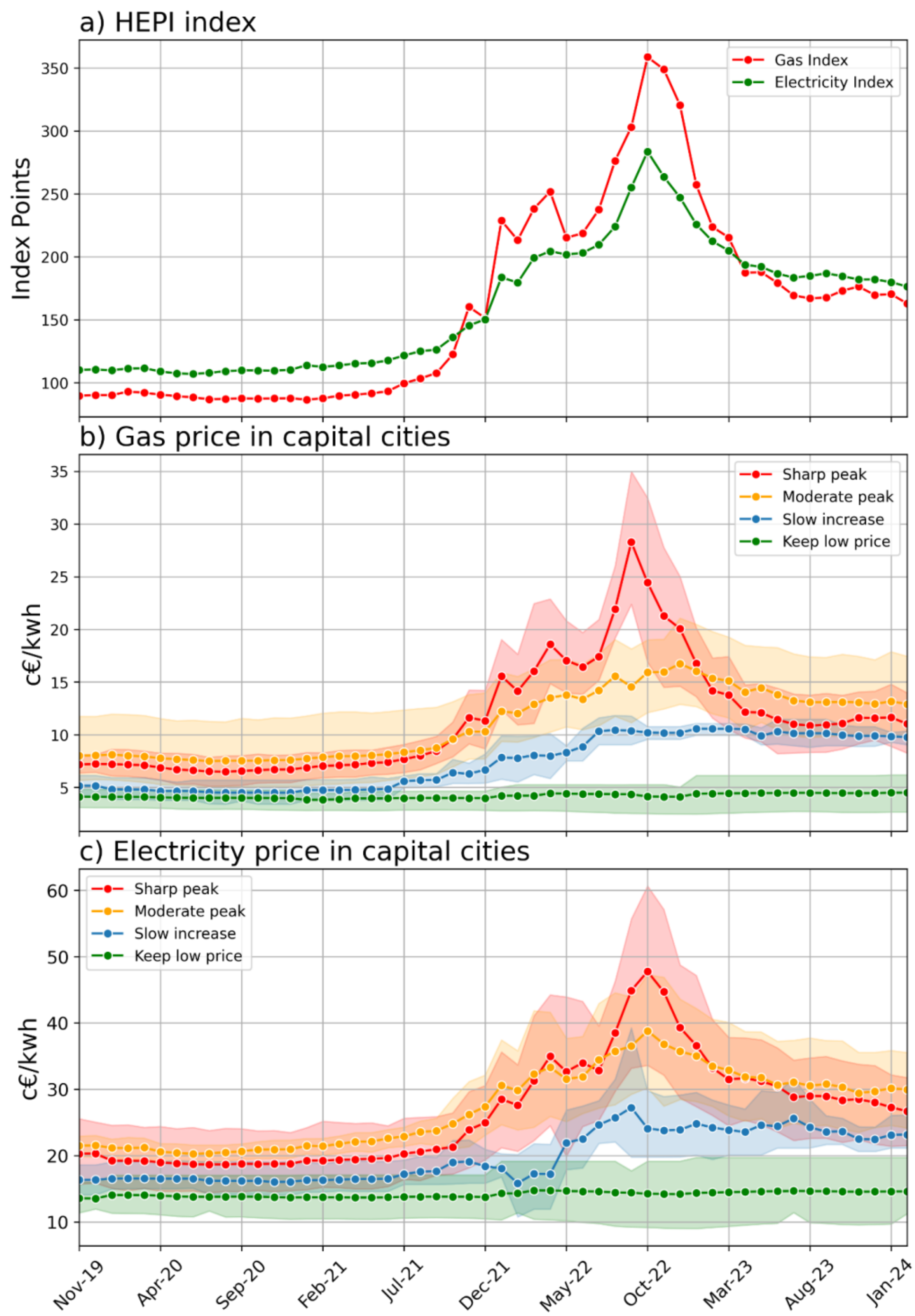

Fig S6. Time series of household energy price index (HEPI) in EU27 (a), gas price in capital cities (b), and electricity price in capital cities (c). The group "Sharp Peak" includes Austria, Bulgaria, Denmark, Estonia, Greece, Germany, Italy, and the Netherlands. The group "moderate peak" includes Belgium, Czechia, Ireland, France, Portugal, Poland, Spain, Sweden, and the UK. The group "slow increase" includes Latvia, Lithuania, Luxembourg, and Slovenia. The group "keep low price" includes Croatia, Hungary, and Slovakia.

3. Intra-EU gas transportation

The intra-EU gas transmissions graph network was developed with the ENTSO-G physical pipeline flow from 2019-04-01 to 2023-03-31 by aggregating the bi-directional flow data and LNG import data (**Fig. S7 b and c**), as follows:

$$E_{i,j} = \sum_{date} flow_{from\ i\ to\ j,date} \quad (1)$$

Where $E_{i,j}$ is the graph edge between country (or supply source, i.e., LNG) i and j, which indicates the annual physical flow from country i to country j, and $flow_{from\ i\ to\ j,date}$ is the daily physical flow from country i.

The annual flow differences (**Fig. S7 a**) were then compared between the post-invasion period (from 2022-04-01 to 2023-03-31) and the pre-invasion period (from 2019-04-01 to 2022-03-31), as follows:

$$\Delta E_{i,j} = E_{i,j,post-war} - E_{i,j,pre-war} \quad (2)$$

Where $\Delta E_{i,j}$ is the edge of the flow difference graph. As mentioned above, we use the annual flow differences to include the flow difference caused by storage.

Finally, the graph of the net flow difference of the intra-EU transmissions and imports (**Fig. 2**) can be developed by aggregating the bi-directional flow differences, as follows:

$$E_{net,i,j} = \Delta E_{i,j} - \Delta E_{j,i} \quad (3)$$

$$N_{net,i} = \sum_{n} E_{i,n,post-war} - \sum_{n} E_{i,n,pre-war}$$

(4)

Where $E_{net,i,j}$ is the edge of the net flow difference graph, $N_{net,i}$ is the node of the graph, which indicates the outgoing flow difference of country i, and n is a list of countries that are connected to country i.

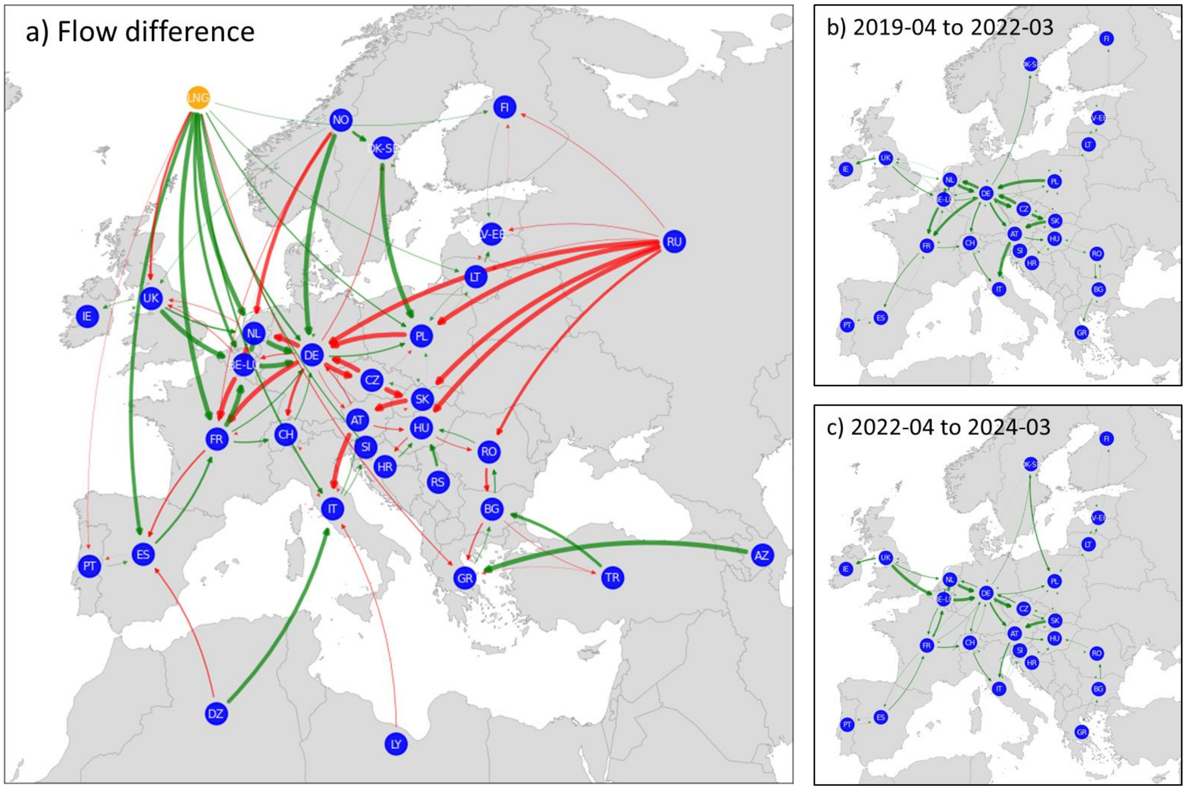

Fig S7. Bi-directional intra-EU transmission flow network: a) net flow changes between post-invasion (2022-04-01 to 2023-03-31) and pre-invasion (2019-04-01 to 2022-03-3), b) the annual averaged physical flow in pre-invasion periods (2019-04-01 to 2022-03-31), and c) physical flow in post-invasion periods (2022-04-01 to 2023-03-31). The differences are calculated by subtracting the annual average of pre-invasion from post-invasion values. The red arrows indicate the changes were negative, and the green arrows indicate the changes were positive. The width of the arrows indicates the amount of the flow changed.

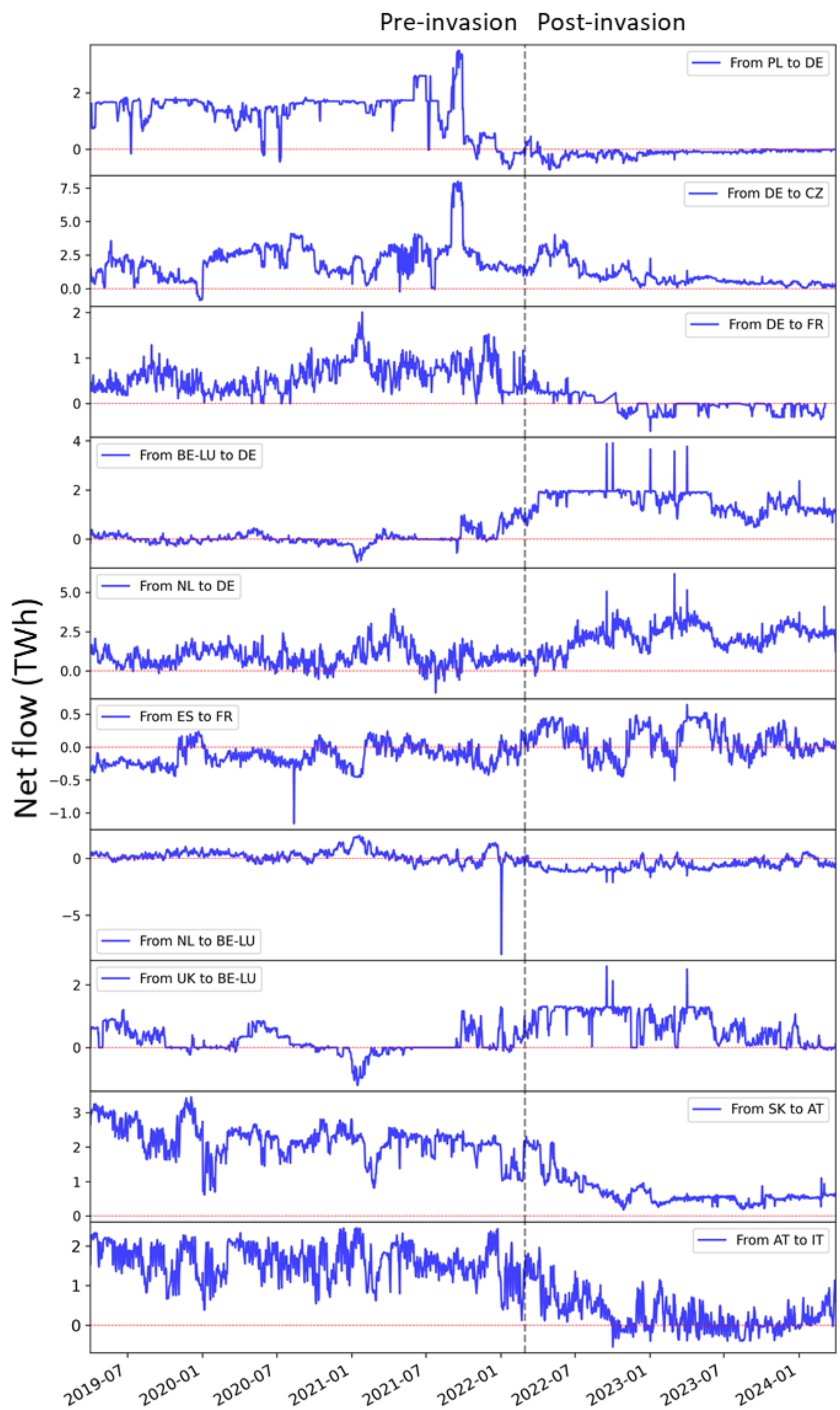

Fig S8. The daily net flow of several important intra-EU connections. The negative netflow indicates the reversed transmission between the connections. For example, the negative flow from PL to DE indicates the transmission from DE to PL (top panel).

Consumption reduction attributions

The discrepancy between the decreased Russian gas supply and the increment of supplies from other sources is defined as the "Russian gas gap", which caused the consumption reduction for the post-invasion winter:

$$\Delta Consumption = \Delta Russian\ imports - \sum_{source} \Delta Supply_{source} \quad (5)$$

Where $\Delta Russian\ imports$, and $\Delta\ Supply_{source}$ were estimated with gas supply differences between the post-invasion winter and the mean gas supply of the pre-invasion winters for Russian imports, LNG imports, pipeline imports from other countries, and the EU local gas productions. The gas supply source data is from the EUGasSC dataset.

We then disaggregated the consumption difference ($\Delta Consumption$) into residential heating, power, and industrial sectors:

$$\Delta Consumption = \Delta Heating + \Delta Power + \Delta Industrial \quad (6)$$

Where $\Delta Heating$ is the heating consumption changes that can be further attributed to the gas saving due to the temperature ($saving_{temperature}$) and the behavior changes ($saving_{behavior}$):

$$\Delta Heating = \sum_{date} (saving_{behavior} + saving_{temperature}) \quad (7)$$

The $\Delta Power$ is the change of gas consumption in power generation, which includes the shifting to other sources for generating electricity ($power_{replaced,source}$) and the electricity generation drop due to the lack of gas ($power_{drop}$):

$$\Delta Power = \sum_{date,source} (power_{replaced,source} + power_{drop}) \quad (8)$$

And $\Delta Industrial$ is the change of gas consumption in the industrial sector, which can be separated into the reduction that likely had a negative impact on industrial production ($Industrial_{non-negative}$) and the reduction that unlikely had a negative impact on industrial production ($Industrial_{negative}$)

$$\Delta Industrial = \sum_{date} (Industrial_{negative} + Industrial_{non-negative}) \quad (9)$$

Residential heating sector

The gas consumption in the heating sector can be estimated with empirical TGC curves, which have been discussed in our previous research (1) (4). In this study, we focused on the winter periods with low temperatures, therefore, the two-segment TGC curves can be simplified by only considering the segment with temperatures lower than the start-heating temperature:

$$Heating\ consumption_{date} = TGC(T_{date}) = T_{date} * a + b \quad (10)$$

Where T_{date} is the daily air temperature, a and b are the coefficients of the linear regression.

The TGC curves of household heating and public heating were fitted for the pre-invasion and post-invasion winters (**Fig S9 a and b**). Then the daily gas consumption changes due to the behavior and temperature can be defined with day-to-day comparisons:

$$change_{behavior,date} = TGC_{pre}(T_{post\_date}) - TGC_{post}(T_{post\_date}) \quad (11)$$

$$change_{temperature,date} = TGC_{post}(Mean(T_{prev\_date})) - TGC_{post}(T_{post\_date}) \quad (12)$$

Where $change_{behavior,date}$ and $change_{temperature,date}$ are the daily gas changes due to the behavior and the temperature (positive values means gas consumption is reduced in the post-invasion winter), TGC_{prev} and TGC_{post} are the country-based TGC curved fitted for the pre-invasion and post-invasion winters, T_{post_date} and $Mean\ (T_{prev\_date})$ are the daily air temperature in the post-invasion winter and the daily mean temperature in the pre-invasion winters for a particular date, respectively. This dual approach allowed us to isolate and quantify the distinct impacts of behavioral shifts and temperature changes on residential gas consumption.

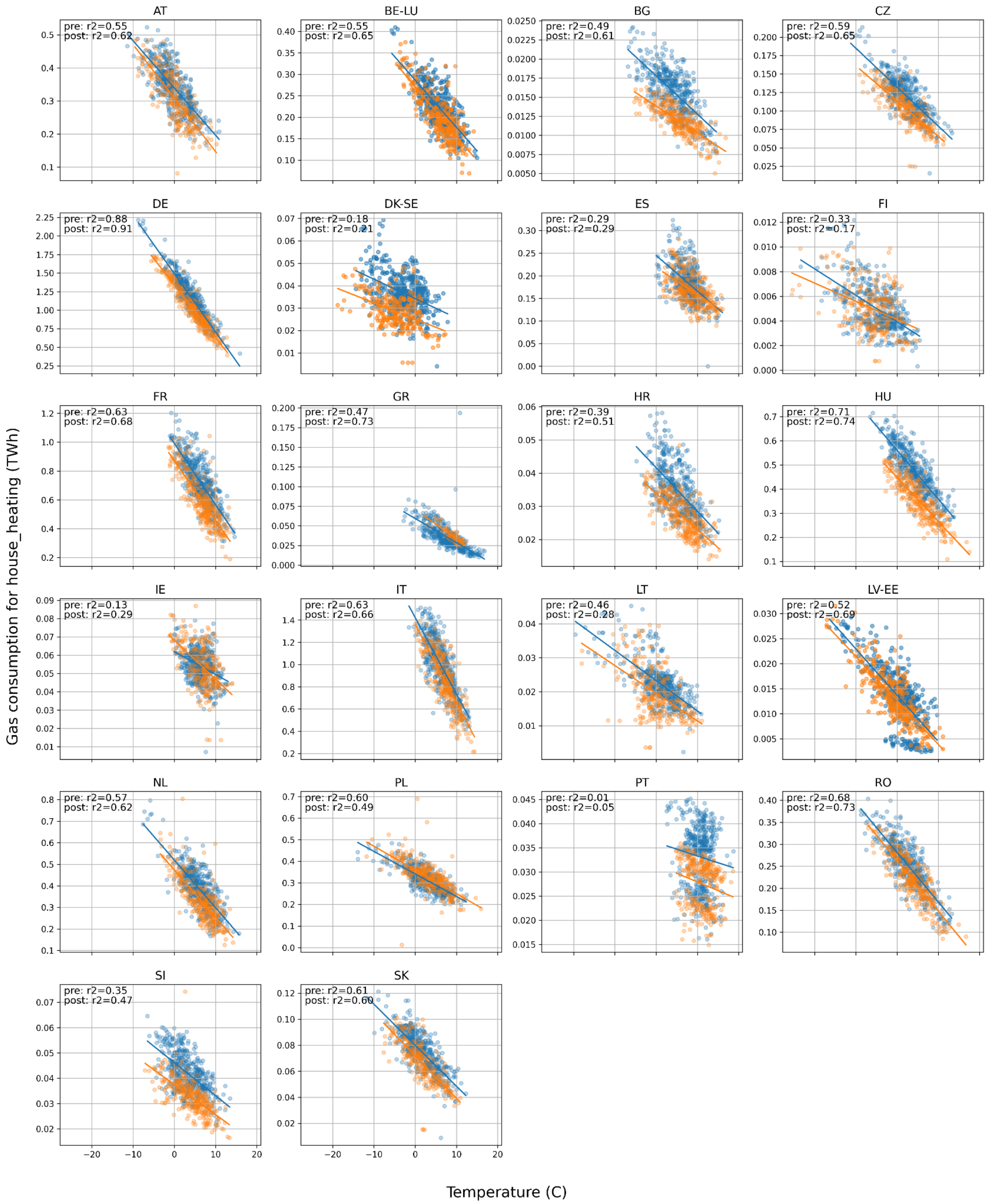

Fig S9 a. Temperature-gas-consumption (TGC) curves for household heating in the pre-invasion winters (2019-2022) and post-invasion winter (2022-2023).

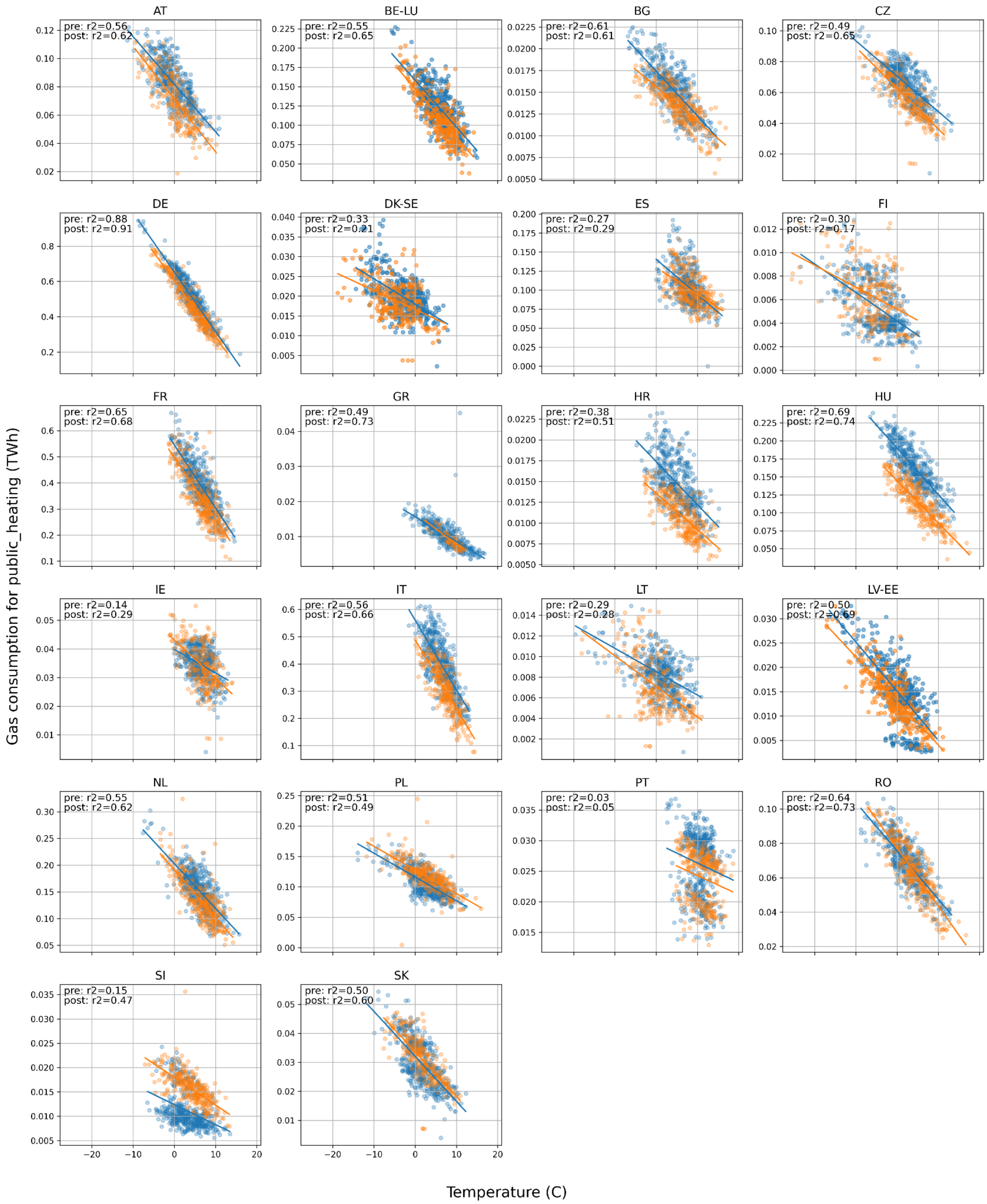

Fig S9 b. Temperature-gas-consumption (TGC) curves for public heating in the pre-invasion winters (2019-2022) and post-invasion winter (2022-2023).

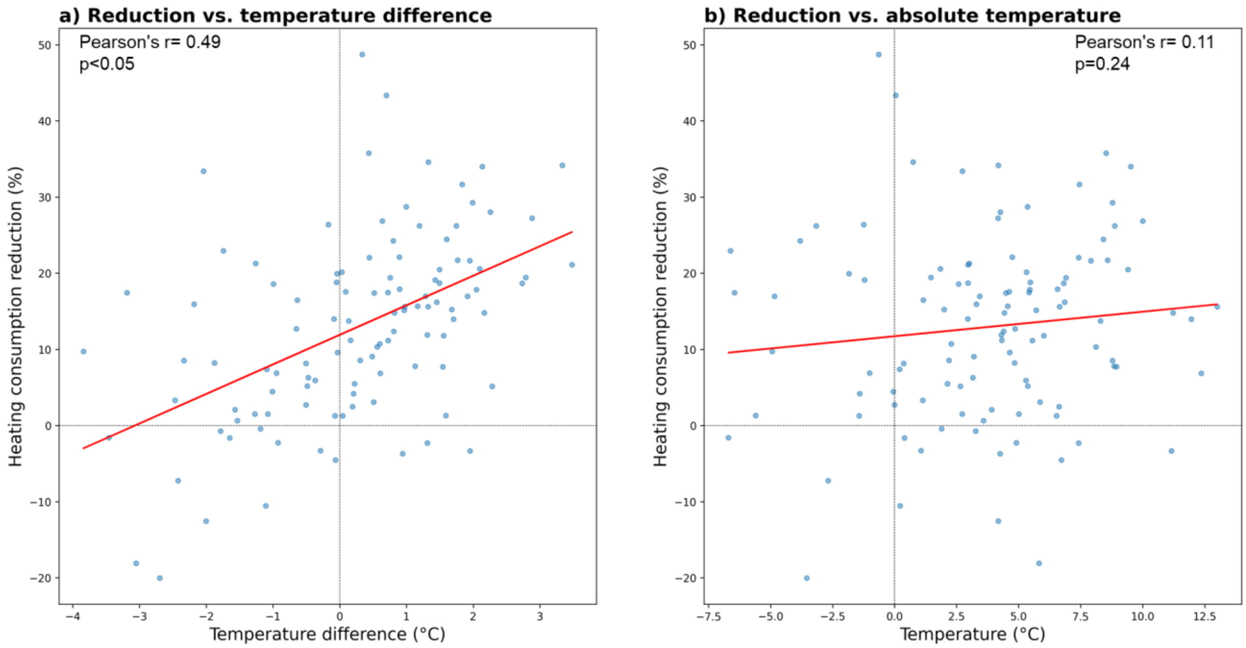

Fig S10. Correlation between (a) monthly household heating reduction vs. temperature difference, and (b) monthly household heating reduction vs. absolute temperature.

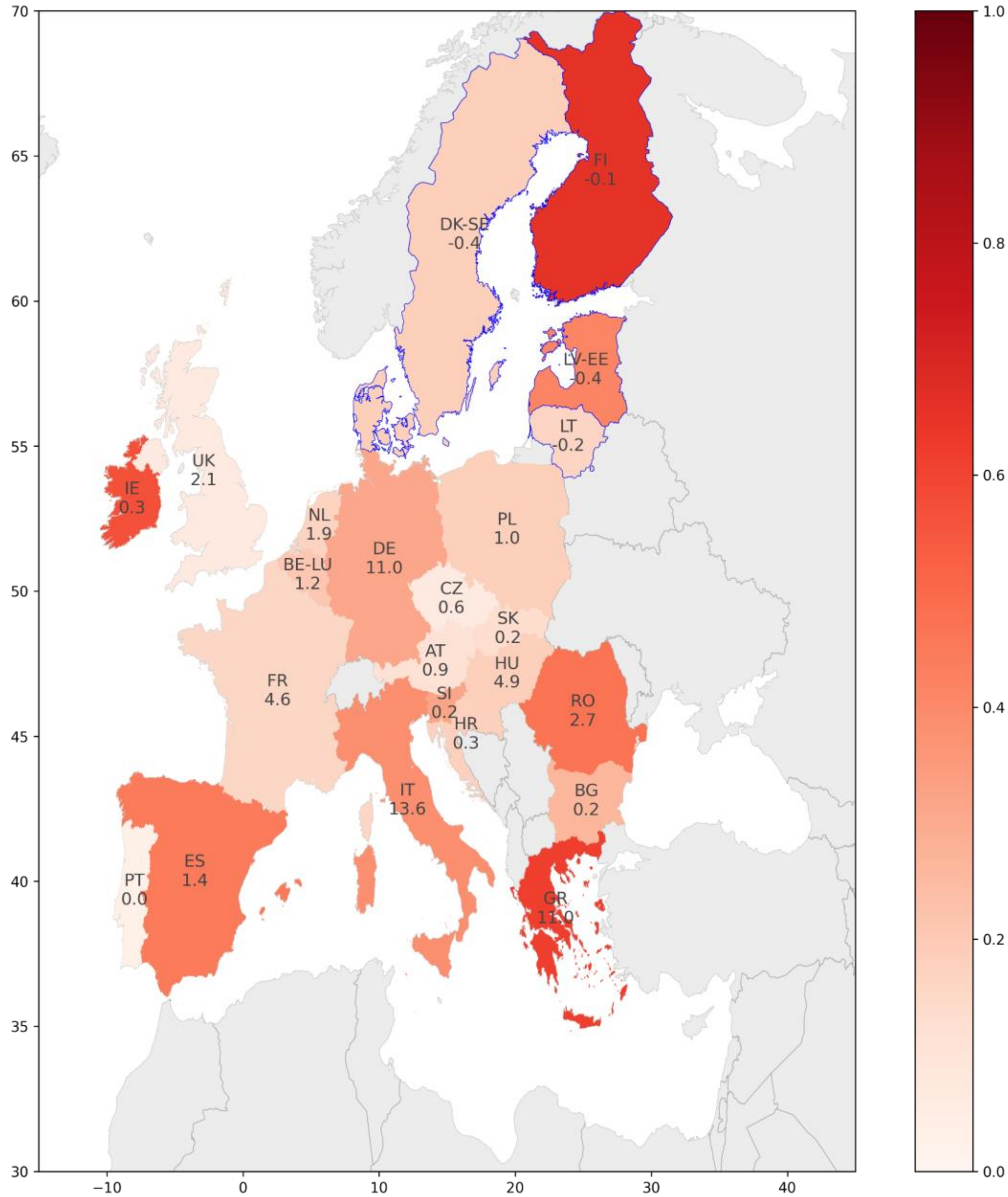

Fig S11. Map of temperature importance for consumption change in the heating sector, choropleth maps indicate the ratios of temperature change compared with the behavior change, and the number shows the changed amount (TWh) because of the temperature change. The temperature changes are negative (more consumption due to the temperature) for the countries with blue contours.

Power sector

The power structure changes after the cut-off of the Russian gas supply were analyzed based on daily power generations with different sources from the Carbon Monitor Power dataset (5). To avoid the weekly variation, we performed 7-day aggregated difference comparisons for power generated by different energy sources including gas, coal, oil, nuclear, wind, solar, hydro, and others in the EU27&UK as follows:

$$\Delta power_{source,date} = \left(\sum_{i=0}^{6} power_{source,post\_date-i} - \sum_{i=0}^{6} Mean(power_{source,prev\_date-i})\right)/7 \quad (13)$$

Where $\Delta power_{source,date}$ is the daily electricity generation changes for particular date-source combinations, $power_{source,post\_date}$ and $Mean(power_{source,prev\_date})$ are the daily electricity generation in the post-invasion winter and the daily electricity generation in the pre-invasion winters for the corresponding date and source, respectively.

Then the reduction of gas-powered electricity that would probably be replaced by other energy sources ($power\ replaced_{date}$) and probably not be replaced by other energy sources ($power\ dropped_{date}$) can be estimated as follows:

$$power\ dropped_{date} = 0\ if\ (\Delta power_{gas,date} + power\ replaced_{date} > 0)$$

$$else\ -(\Delta power_{gas,date} + power\ replaced_{date}) \quad (14)$$

$$power\ replaced_{date} = \sum_{source \neq gas} \Delta power_{source,date}\ \ if\ (\Delta power_{source,date} > 0)\ else\ 0 \quad (15)$$

When the increment of daily electricity generation from other sources exceeds the decrement of gas-powered electricity generation ($\Delta power_{gas,date} + power\ replaced_{date} > 0$), $power\ dropped_{date}$ will be set to 0, and the supply source shares in $power\ replaced_{date}$ will be maintained. This approach allowed us to assess the daily potential for alternative energy sources to replace gas-powered electricity and the risk of electricity supply shortages due to reduced gas usage.

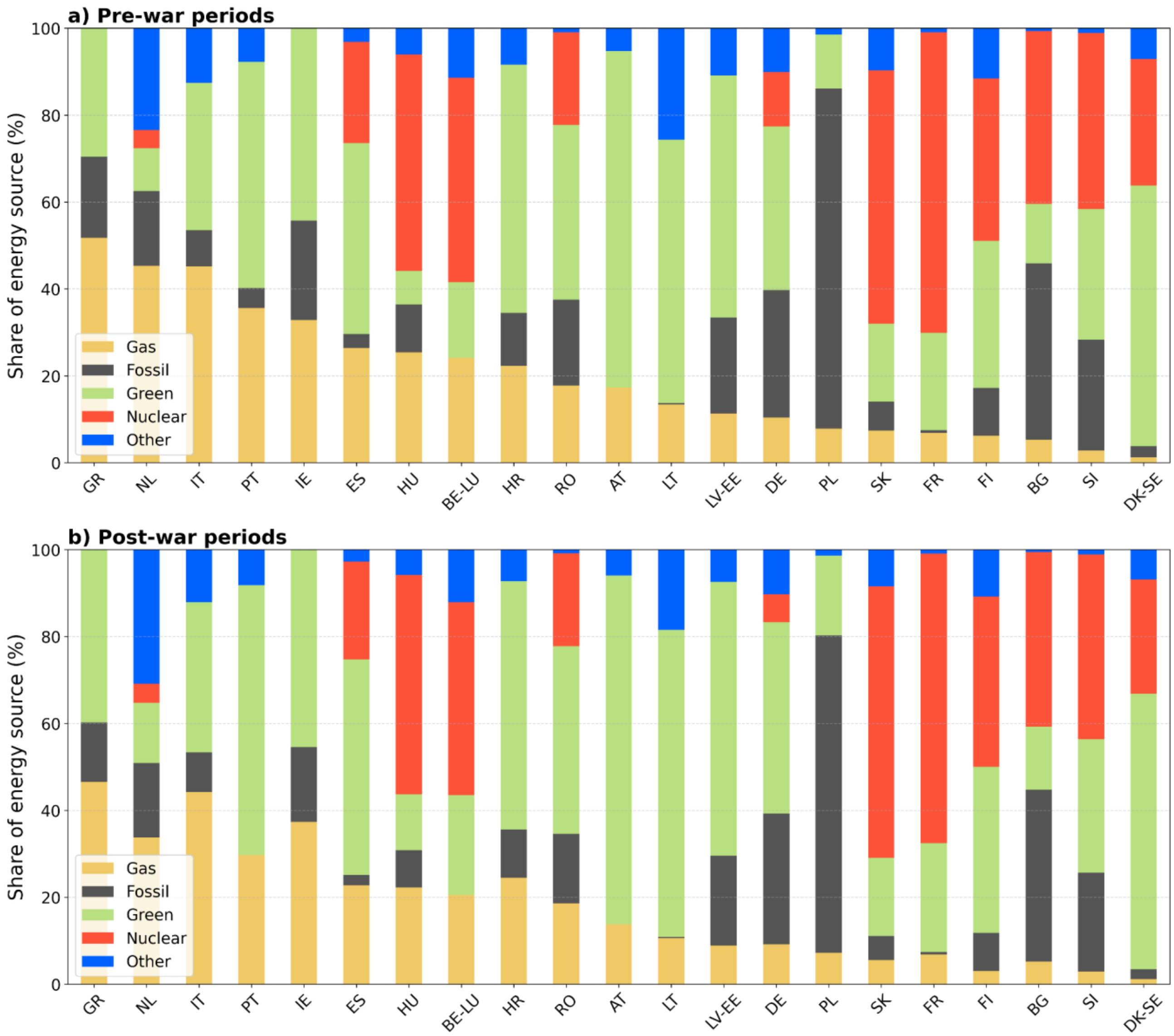

Fig S12. Pre-invasion (a) and post-invasion (b) energy structure in power generation for pre-invasion and post-invasion periods.

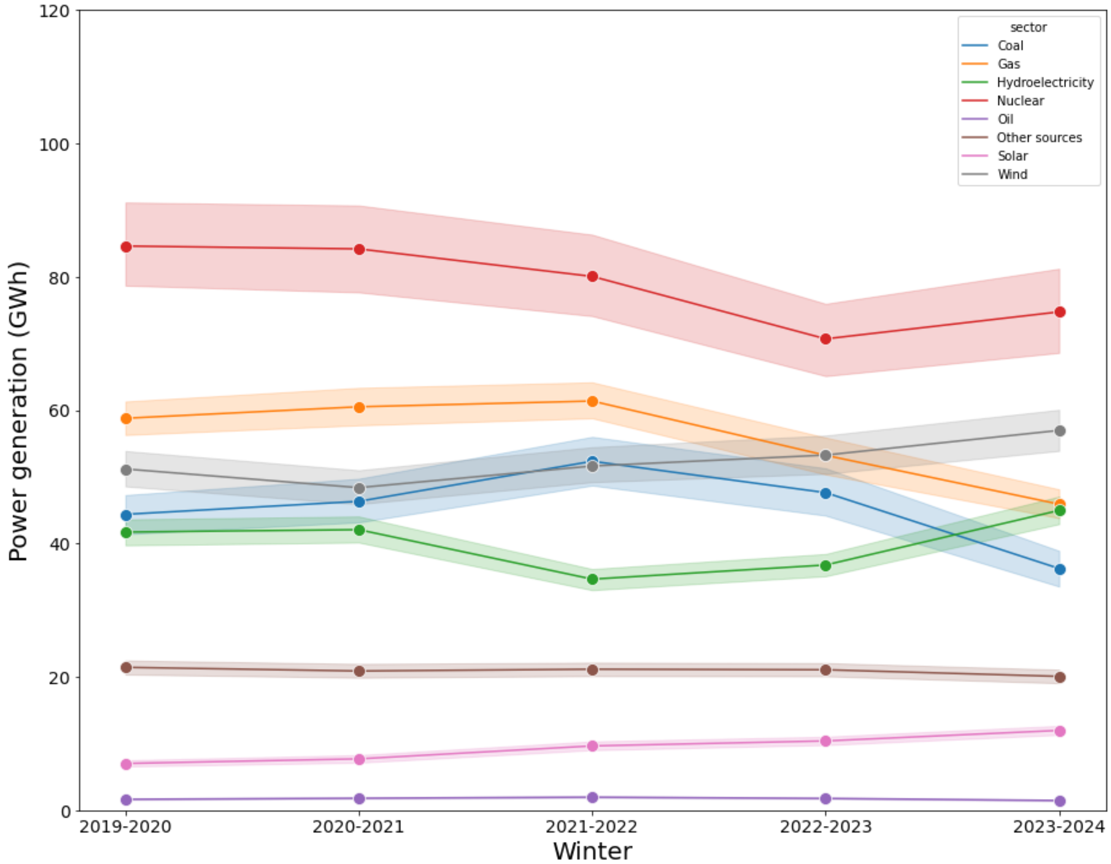

Fig S13. Monthly power generation in the pre-invasion and post-invasion winters in each energy sector (from the Carbon Monitor power dataset).

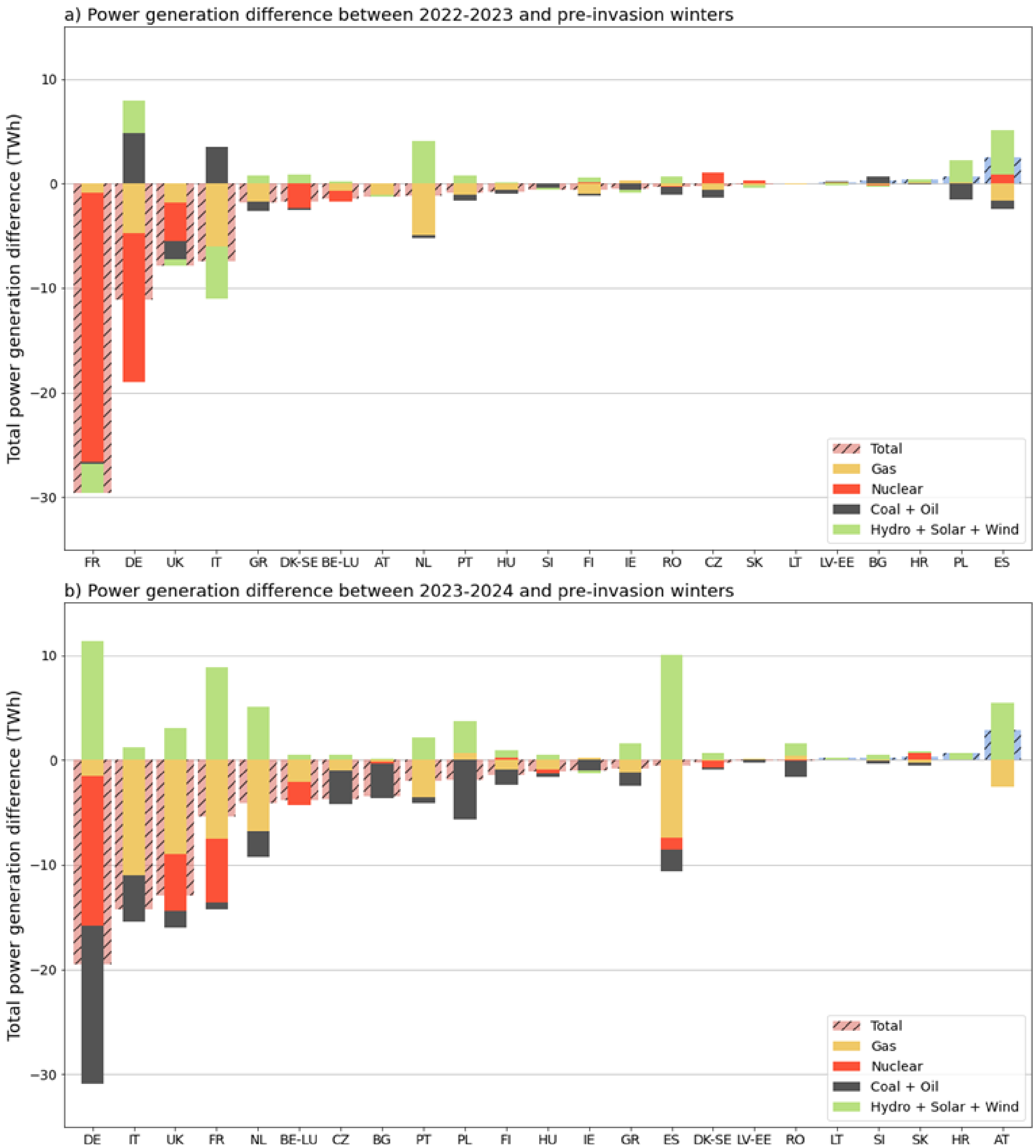

Fig S14. Daily mean power generation changes in the post-invasion and pre-invasion winters (from the Carbon Monitor power dataset).

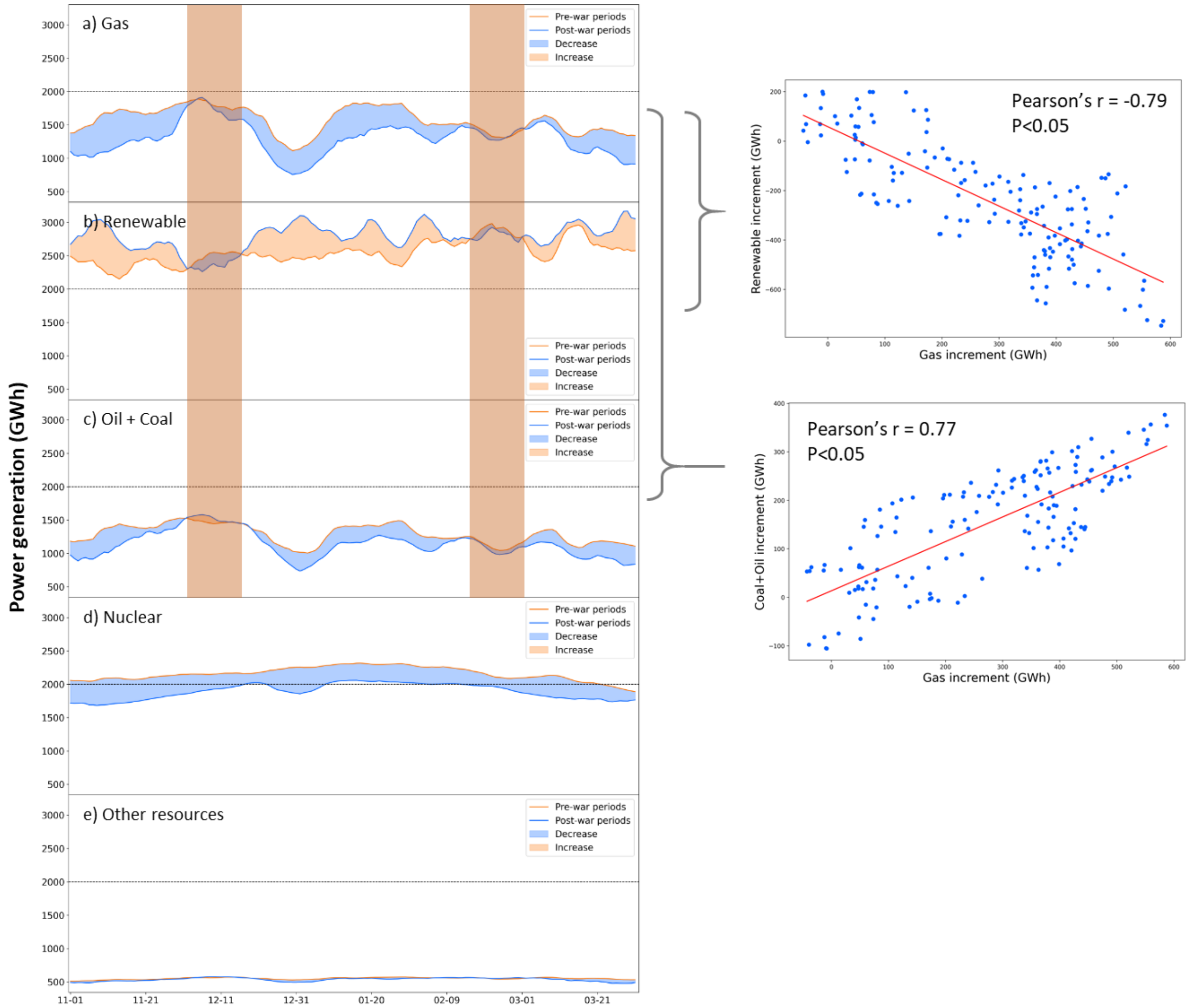

Fig S15. Daily power generation changes based on sources, a) gas, b) renewable, c) oil+coal, d) nuclear, and e) other resources in EU27&UK. The renewable include hydro, wind, and solar electricity. The periods with orange backgrounds indicate that gas-powered electricity was not able to be replaced by renewable electricity.

Industrial sector

The gas consumption in the industrial sector can be divided into energy use and non-energy use (6). In energy use, gas is mainly used for heating and electricity generation, and in non-energy use, gas is mainly used as chemical feedstocks or as raw materials (7).

Similar as the power sector, 7-day aggregated difference comparisons are used for industrial gas consumption and total electricity generation comparison as well. The potential impact of industrial gas change on industrial production can be estimated (**Fig S16**): 1) low possibility of having negative impacts if the industrial gas change is positive (post-invasion consumed more gas in the industrial sector), 2) low possibility of having negative impacts if the industrial gas change is negative, and the positive electricity change can cover the decrement with a low conversion efficiency (0.3), 3) medium possibility of having negative impacts if the industrial gas change is negative, and the positive electricity change cannot cover the decrement with a medium conversion efficiency (0.3~0.7), 4) high possibility to have a negative impact if the industrial gas change is negative, and the positive electricity change cannot cover the decrement with a high conversion efficiency (0.7), 5) high possibility to have a negative impact if both the industrial gas change and electricity generation are negative. Then the amount of industrial gas reduction ($industrial\ dropped_{date}$) that would potentially have negative impacts on industrial production can be estimated:

$$industrial\ dropped_{date} = \Delta industrial_{date} + \Delta power_{date}/efficiency$$

$$if\ \Delta industrial_{date} < 0\ and\ \Delta power_{date} > 0 \qquad (16)$$

Where $\Delta industrial_{date}$ and $\Delta power_{date}$ are the 7-day aggregated differences between industrial gas consumption and total electricity generations.

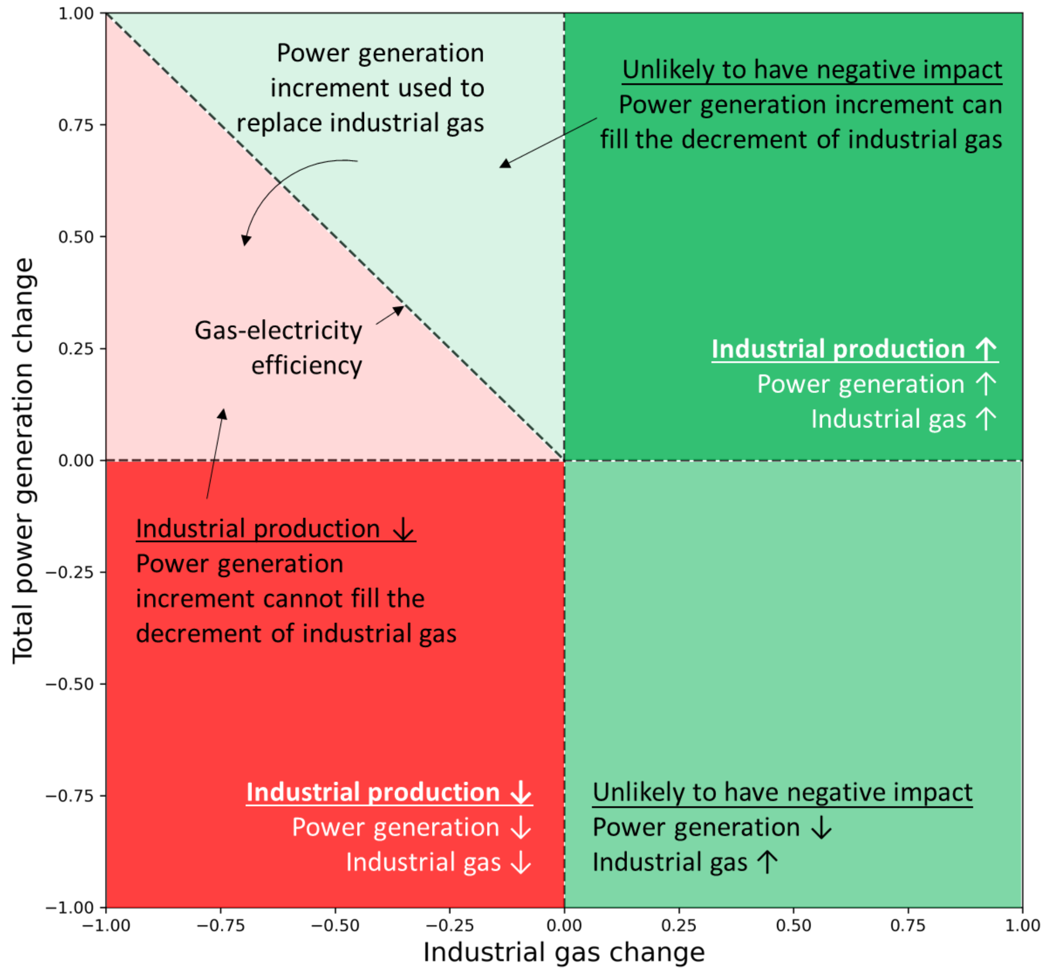

Fig S16. Concept figure of the estimation of the potential impact of industrial gas change on industrial production.

GHG emission related

CO_2 emission estimations for the power sector

We estimate the CO_2 emission changes from the coal-fired and gas-powered power plants based on emission factors from the US EPA report (8), the emission factor for coal-fired power plants and gas-fired power plants is 2180 pound CO_2/MWh and 898 pound CO_2/MWh, respectively. Despite the CO_2 emission in production, we assume the CO_2 emission from solar, wind, hydro, and nuclear is zero.

The CO_2 emission from the electricity generation can be estimated as follows:

$$emission = \sum_{source} power\ generation_{source} \times Emssion\ Factor \quad (1)$$

Therefore, we estimated, that in the EU27&UK, the CO_2 emission from power generation for the pre-invasion and post-invasion winters are 294 Mt CO_2 /yr and 283Mt CO_2/yr, and the carbon density for the pre-invasion and post-invasion winters are 0.233 and 0.237 Kg CO_2/MWh.

The CO_2 emission reduction caused by replacing gas-powered electricity in the post-invasion winter is 8.5 Mt CO_2, estimated as follows:

$$\Delta emission = \sum_{source} replaced_{source} \times (Emission\ Factor_{source} - Emission\ Factor_{gas}) \quad (2)$$

Where the $replaced_{source}$ is the reduction of gas-powered electricity that would probably be replaced by other energy sources (see **method 2.5.2**).

Based on equation (2), we estimate 16.3 Mt CO_2 emission can be reduced if French Nuclear power generation is back to the pre-invasion levels to replace the gas-powered electricity.

CO_2 emission estimations for gas transportation

We estimate the CO_2 emission from the LNG and pipeline transportation based on the Global Warming Potential (GWP) of 100-year periods. On-site research estimated that LNG carriers will emit about 100 Kg CO_2 eq/ tonne of LNG transported (9). And the potential leakage of pipeline transportation is about 1.4%. (10) We use a conversion factor for natural gas at 0.2 Kg CO_2 eq/kWh of gas. (10, 11), and the tonne-KWh conversation factor for LNG at 15222 KWh/tonne of LNG. (12)

The increased LNG supply from this study is **593.3 TWh.**

The CO_2 emission from LNG transportation is (13):

593.3 TWh * 10^9 / 15222 KWh/tonne of LNG * 100 Kg CO_2 eq/ tonne of LNG = 38.9 Mt CO_2 eq

The CO_2 emission from the pipeline transportation is:

593.3 TWh * 10^9 * 1.4% * 0.2 Kg CO_2 eq/KWh = 16.6 Mt CO_2 eq

The CO_2 emission from LNG transportation would be able to allow leakage from pipeline transportation up to 3.3%.

Table S4. Descriptions of column headers and units of EUGasNet and EUGasImpact.

Dataset	Header	Description	Unit
EUGasNet	date	Transmission date	DateTime
	fromCountry	Start country key	CountryKey
	toCountry	End country key	CountryKey
	LNG_share	Supply ratio from LNG	0-1
	PRO_share	Supply ratio from EU Production	0-1
	RU_share	Supply ratio from Russian Production	0-1
	AZ_share	Supply ratio from Azerbaijan	0-1
	DZ_share	Supply ratio from Algeria	0-1
	NO_share	Supply ratio from Norway	0-1
	RS_share	Supply ratio from Serbia	0-1
	TR_share	Supply ratio from Turkey	0-1
	LY_share	Supply ratio from Libya	0-1
	TotalFlow	Total transmission ammount	KWh
EUGasImpact	date	date	DateTime
	country	country	CountryKey
	house_heating	Consumption of house heating	GWh
	house_heating_diff_total	Consumption difference compared to pre-invasion periods	GWh

	house_heating_diff_T	Consumption differences caused by temperature	GWh
	house_heating_diff_behavior	Consumption differences caused by behavior	GWh
	house_heating_residual	Consumption differences residual	GWh
	public_heating	Consumption of public heating	GWh
	public_heating_diff_total	Consumption difference compared to pre-invasion periods	GWh
	public_heating_diff_T	Consumption differences caused by temperature	GWh
	public_heating_diff_behavior	Consumption differences caused by behavior	GWh
	public_heating_residual	Consumption differences residual	GWh
	power_generated_with_gas	Power generated with gas	GWh
	power_generated_with_gas_diff	Differences in power generated with gas compared to pre-invasion periods	GWh
	power_dorp_filled_with_fossil	Gas-powered electricity reduction (if exists) replaced by fossil electricity	GWh
	power_dorp_filled_with_green	Gas-powered electricity reduction (if exists) replaced by green electricity	GWh
	power_dorp_filled_with_nuclear	Gas-powered electricity reduction (if exists) replaced by nuclear electricity	GWh
	power_dorp_can_not_filled	Gas-powered electricity reduction (if exists) can not be replaced	GWh
	industrial	Consumption of industrial	GWh
	industrial_diff	Consumption difference	GWh

		compared to pre-invasion periods	
	reduced_impact_industrial_production	Consumption reduction (if exists) might reduce industrial production	GWh

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