Earth's Future

Supporting Information for

Estimating Arctic Temperature Impacts from Select European Residential Heating Appliances and Mitigation Strategies

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Introduction

This supporting information provides data that were extracted from the 2016 European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) Air Pollutant Emissions Inventory Guidebook (EMEP, 2016) and country-specific 2018 inventory submissions, which reported 2016 emission inventory data (EMEP, 2018). Also included are the Arctic surface temperature response ratios derived from Sand et al., 2015. These data were used as inputs to derive the results as represented in the main article.

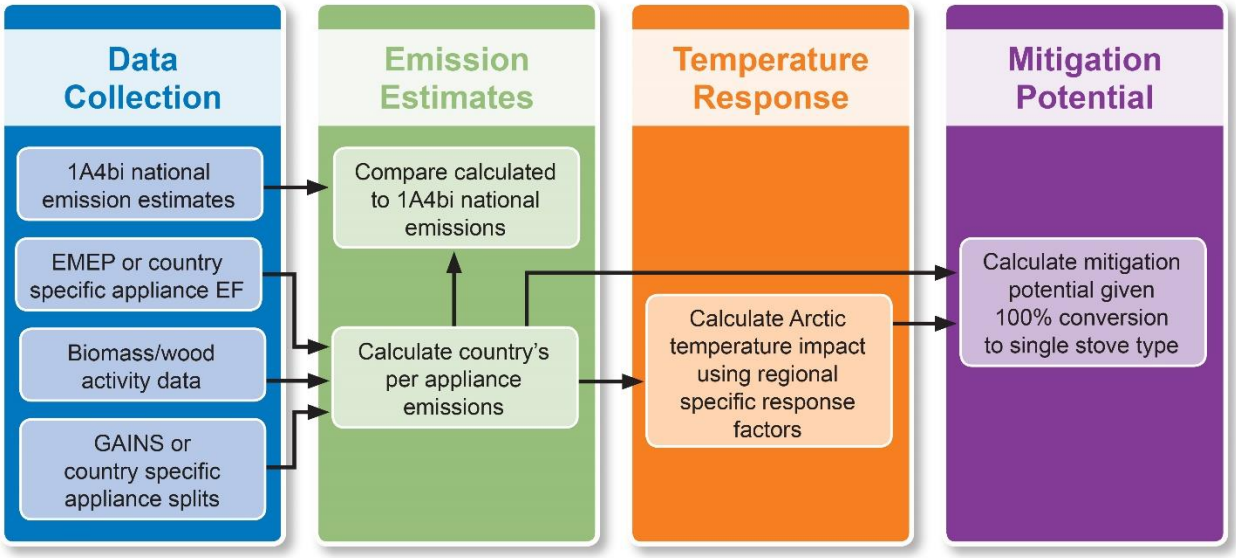

Figure S1. Flow chart process summary for data collection and analysis. The four main steps of the data analysis and methodological process, illustrated by the colored columns, were (blue) querying and extracting data from inventories and supplemental datasets, (green) disaggregating national reported emissions and deriving per appliance type mass emissions, (orange) translating emissions from each appliance type into Arctic temperature responses, and (purple) estimating aerosol emission and temperature response mitigation potentials provided hypothetical mitigation scenarios of 100% conversion to single stove types.

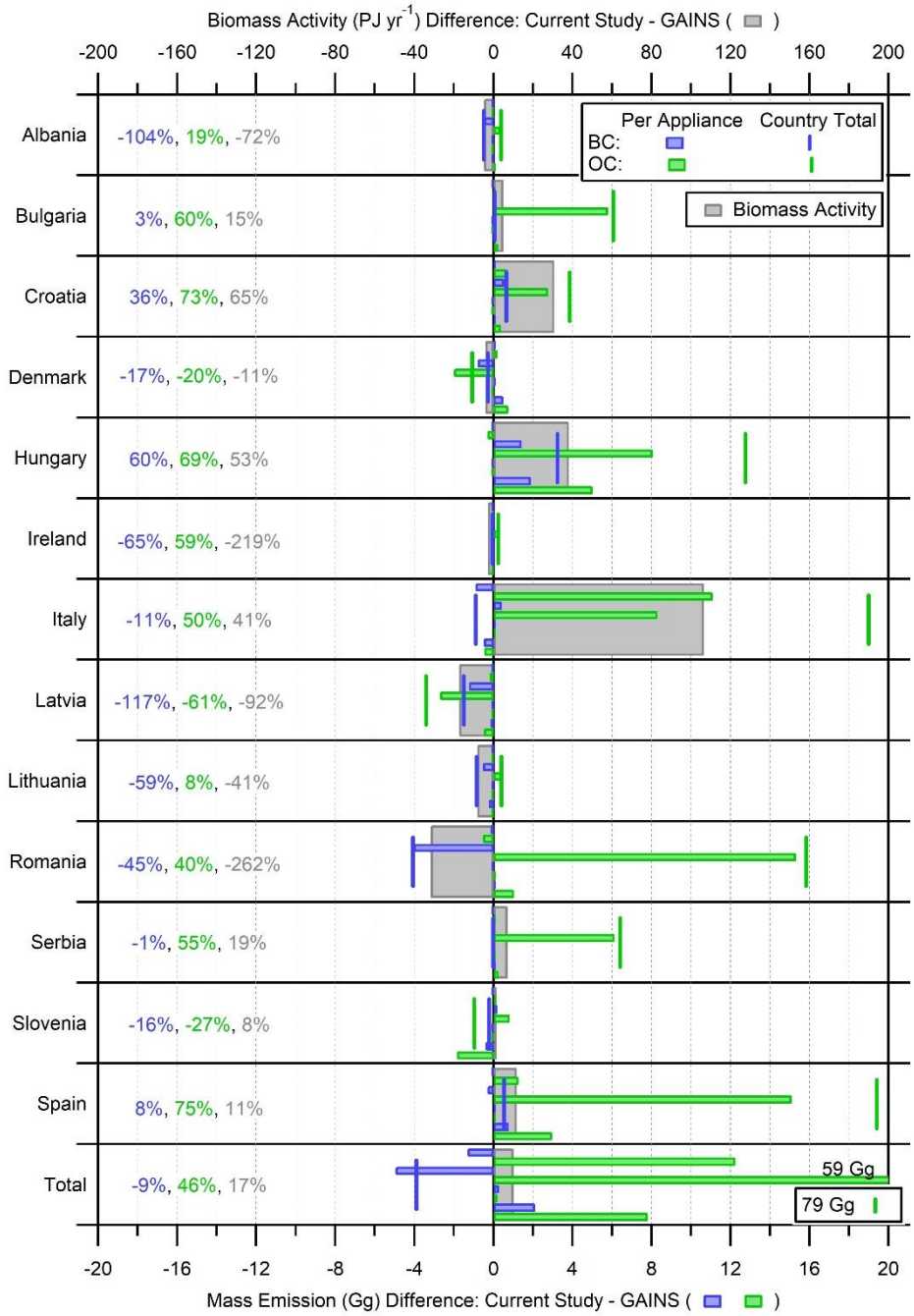

Figure S2. Per country difference (bars) and percent change (text along left y-axis) of BC mass (blue), OC mass (green), and biomass activity (grey) between the current study and GAINS Europe model. Bars (from top to bottom) for each country compare open fireplaces, heating stoves, pellet stoves and boilers, and conventional boilers. For the current study, heating stove mass is a summation of conventional, high-efficiency, and advanced/ecolabelled stoves. Note that two data points for the total mass emissions difference for OC extend past the upper bound of the x-axis and are illustrated in overlayed text on the figure. Bars extending to the left of the zero line (negative values on x-axis) and negative percent change values indicate the GAINS model had higher values compared to this study and vice versa.

Appliance (efficiency) [a]	Description	Aerosol wood combustion EFs [e]			
		$PM_{2.5}$, g/GJ [b]	BC, g/GJ (%) [c]	OC, g/GJ (%) [c]	SO_x, g/GJ
Open fireplaces (20%)	Simplest combustion device, including a basic combustion chamber directly connected to a chimney and a large opening to the fire bed. Devices are characterized by high, non-adjustable excess of combustion air.	820	57.4 (7)	352.6 (43)	11
Conventional stoves (45%)	Includes both closed fireplaces and conventional radiative stoves. Closed fireplaces are equipped with front doors and have air flow control systems. Because of their design and combustion principles, they more closely resemble and are grouped with conventional stoves rather than open fireplaces. Conventional radiative stoves include both downburning and upburning techniques with poorly organized combustion processes.	740	74 (10)	333 (45)	11
Conventional boilers < 50 kW (60%)	Devices that heat water for indirect heating. Over-fire boilers are characterized by non-optimal supply of combustion air caused by natural draft, which causes incomplete combustion. Under-fire boilers include manual feed systems, stationary grates, and a two-part combustion chamber.	470	75.2 (16)	178.6 (38)[d]	11
High-efficiency stoves (65%)	Covers traditional stoves with improved utilization of secondary air in the combustion chamber. Also includes catalytic converter stoves, which reduce emissions from incomplete combustion.	370	59.2 (16)	140.6 (38)[d]	11
Advanced / ecolabelled stoves and boilers (70%)	Characterized by multiple air inlets and pre-heating of secondary combustion air by heat exchange with hot flue gases. Ecolabelling schemes assign a standard for improved efficiency and reduced emissions and are largely based around European standards. Also includes state of the art downdraft multi-chamber boilers.	93	26.04 (28)	28.83 (31)	11
Pellet stoves and boilers (85%)	An advanced stove that uses an automatic feed for pelletized fuels, which are distributed to the combustion chamber by a fuel feeder. These stoves are often equipped with active control systems for combustion air supply. Category also includes automatic pellet-fired boilers, which include fully automatic systems for feeding fuel and for supply of combustion air.	60	9 (15)	7.8 (13)	11

Table S1. Residential Heating Appliance Type Summary

[a] Combustion technology and efficiency improves from top to bottom of the table. Stove efficiencies were extracted from 2016 EMEP/EEA Guidebook (EMEP, 2016). If an efficiency range was provided in the Guidebook (e.g., 50-70%), then an average was applied here and in subsequent calculations (e.g., 60%). It is important to note that combustion efficiencies of stove types can range depending on a variety of factors (i.e., manufacturer, user operation, fuel moisture content, maintenance, etc.) and therefore individual stoves may vary from the combustion efficiencies presented here.

[b] The $PM_{2.5}$ EFs are comprised of both the solid/filterable particles and the gases that form particles upon cooling, i.e., the condensables. The BC and OC percentages of $PM_{2.5}$ would be considerably higher if only the solid particles were considered in the $PM_{2.5}$ EF values but the EF values in units of g/GJ would not change.

[c] Values in parentheses represent the percentage of $PM_{2.5}$ EF that are BC or OC.

[d] OC EFs for conventional boilers and high-efficiency stoves were not available from EMEP guidance documents. These values were calculated by averaging between $PM_{2.5}$ EF percentages from conventional stoves and advanced/ecolabelled stoves and boilers.

[e] All appliance-specific information extracted from 2016 EMEP/EEA Guidebook (EMEP, 2016). The EFs for each aerosol/appliance will vary based on the wood species that is burned. In the absence of country-specific information, it is assumed these EFs provide an average over all wood species.

Country	Open fireplace	Conventional stove	High-efficiency stove	Advanced / ecolabelled stoves and boilers	Pellet stoves and boilers	Conventional boilers < 50 kW
Albania	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	9, 7.8, 11	75.2, 178.6, 11
Bulgaria	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	9, 7.8, 11	75.2, 178.6, 11
Croatia	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	4.4, 3.8, 11	75.2, 178.6, 11
Denmark	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	4.4, 3.8, 11	75.2, 178.6, 11
Georgia	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	9, 7.8, 11	75.2, 178.6, 11
Hungary	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	9, 7.8, 11	75.2, 178.6, 11
Ireland	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	9, 7.8, 11	75.2, 178.6, 11
Italy	28.7, 176.3, 12.4	37, 166.5, 12.4	45.6, 108.3, 12.4	5.3, 5.9, 12.4	9, 7.8, 12.4	37.6, 89.3, 12.4
Latvia	57.4, 352.6, 40	74, 333, 40	59.2, 140.6, 40	26.0, 28.8, 40	4.4, 3.8, 40	75.2, 178.6, 40
Lithuania	57.4, 352.6, 40	74, 333, 40	59.2, 140.6, 40	26.0, 28.8, 40	9, 7.8, 40	75.2, 178.6, 40
Romania	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	9, 7.8, 11	75.2, 178.6, 11
Serbia	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	9, 7.8, 11	75.2, 178.6, 11
Slovenia	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	9, 7.8, 11	75.2, 178.6, 11
Spain	57.4, 352.6, 11	74, 333, 11	59.2, 140.6, 11	26.0, 28.8, 11	9, 7.8, 11	75.2, 178.6, 11

Table S2. Per Country BC, OC, and SO_x Emission Factors (g/GJ) for the six Appliance Types

Note. Each cell contains three emission factors for a given country and appliance. The first value is for BC, followed by OC, and SO_x.

Country	Biomass activity (TJ NCV / yr)	Open fireplace (%)	Conventional stove (%) [a]	High-efficiency stove (%) [a]	Advanced / ecolabelled stoves and boilers (%) [a]	Pellet stoves and boilers (%)	Conventional boilers < 50 kW (%)
Albania [d]	6581.7 [b]	1.1	92.1	0	0	1.1	5.7
Bulgaria [d]	31737	1.2	92	0	0	1.2	5.7
Croatia [c]	47220.8	6.2	17.8	0	66.4	3.4	6.2
Denmark [c, f]	39731	2.4	23.4	4.0	12.2	37.4	20.7
Georgia [d, e]	15955.3	1.1	85.2	0	0	2.3	11.4
Hungary [c]	71976	0	50	0	0	0	50
Ireland [d]	1335.2	15.7	76	0	0	5.2	3.1
Italy [c]	258501	51	23	16	6	4	0
Latvia [d]	18864	7.0	75.4	0	0	7.0	10.5
Lithuania [c]	20260	7	50	0	0	3	40
Romania [c]	124547	0	91	0	0	2	7
Serbia [d]	36557	1.1	92.1	0	0	1.1	5.7
Slovenia [c]	20241.1	1	15	0	13	4	67
Spain [d]	105589	6.3	56.3	0	0	18.8	18.8
Average	**57078.3**	**7.2**	**59.9**	**1.4**	**7.0**	**6.5**	**18.0**

Table S3. Per Country Activity Data and Splits for the six Appliance Types

[a] If no information was provided on the activity split between conventional, high-efficiency, and advanced/ecolabelled stoves, we applied all heating stove activity data from the GAINS model to conventional stoves following EMEP recommendations (EMEP, 2016).

[b] Albania biomass activity data were not directly provided in their EMEP submission. This activity value was derived from the mass of firewood provided and net caloric value (NCV) for fuel woods with an assumed moisture content of 20% and ash content of 1%.

[c] Country provided their own appliance splits.

[d] Country did not provide appliance splits in EMEP submission. Therefore, the 2015 GAINS splits data (using ECLIPSE_V5a_CLE_base data set) were used.

[e] No activity splits information was provided by GAINS, in which case it is good practice to select a country most resembling the country in question (EMEP, 2016). Therefore, activity split estimates for Turkey were used for Georgia.

[f] Denmark's EMEP submission defined and provided splits for 13 different appliances. Here, these 13 appliances were aggregated into the appropriate six EMEP appliance types.

Region	BC direct	BC snow/ice	OC direct	OC indirect	SO_x direct	SO_2 indirect
Nordic Countries	1.10E-04	2.15E-04	-9.92E-07	-4.38E-05	-4.07E-06	-1.45E-05
Rest of Europe	4.60E-05	8.22E-05	-9.45E-08	-1.56E-05	-3.31E-06	-4.82E-06
Rest of World	5.73E-05	7.77E-06	-1.64E-06	-4.85E-06	-3.42E-06	-4.77E-06

Table S4. Model Mean Arctic Surface Temperature Forcer Response Ratios (K/Gg)

Note. Domestic sector response ratios are based on results from Sand et al. (2015). Ratios are calculated as the domestic sector's annual Arctic equilibrium surface temperature responses (Table S7; Sand et al., 2015) divided by 2010 emissions (Table S2a; Sand et al., 2015) for each region and pollutant.