Investigating pathways to a net-zero emissions building sector in the European Union. What role for the Energy Efficiency First principle?

Supplementary material | Model input data

The data annex of this publication provides detailed descriptions of the data sources used in the analysis presented in the main text. These data sets included in the annex are available to readers for further exploration and replication of the study's findings.

Energy demand

Building retrofits

Table S 1. Specific investments for renovation of building envelopes

Category	Cost type	Retrofit base expenditure $[EUR/m^2]$	Additional expenditure per cm insulation thickness and m² component area $[EUR/(cm \cdot m^2)]$	Refurbishment expenditure [a] $[EUR/m^2]$
Buildings constructed since 1945	Ceiling incl. roof	190	2.97	136
	Ceiling flat roof	174	0.70	118
	Exterior walls	96	2.67	37
	Building base	29	1.14	0
Buildings constructed before 1945	Exterior walls	125	3.47	48
	Building base	38	1.48	0
	Ceiling	228	3.56	163

Values for Germany, excluding subsidies | Source: Hummel et al. (2020); Hummel et al. (2023) | [a] Activities to maintain or enhance building's aesthetics, functionality and safety, without explicitly improving thermal energy performance

Table S 2. Specific investments for renovation of windows

Category	Unit	U-value $[W/m^2K]$					Refurbishment [a]
		2.7	1.7	1.3	0.95	0.65	
Residential	$[EUR/m^2_{component}]$	-	359	379	427	475	201
Non-residential		-	285	308	367	425	160
Buildings before 1945		461	467	492	555	1,190	216

Values for Germany, excluding subsidies | Source: Hummel et al. (2020), Hummel et al. (2023) | [a] Activities to maintain or enhance building's aesthetics, functionality and safety, without explicitly improving thermal energy performance

Table S 3. Construction cost index for building renovation activities

Member State	**Index [*Germany* = 100]**
Austria	104
Belgium	92
Bulgaria	50
Croatia	57
Cyprus	62
Czech Republic	63
Denmark	150
Estonia	61
Finland	118
France	108
Germany	100
Greece	66
Hungary	55
Ireland	82
Italy	97
Latvia	60
Lithuania	61
Luxembourg	102
Malta	82
Netherlands	85
Poland	68
Portugal	52
Romania	48
Slovakia	53
Slovenia	83
Spain	73
Sweden	139

Source: Eurostat (2022e)

Heating systems

Table S 4. Specific investments for building heating systems

Technology	Capacity level [kW_{th}]									
	7.5	**10**	**12.5**	**15**	**25**	**50**	**100**	**200**	**500**	**1000**
District heating substation	261	196	180	169	142	106	80	61	50	46
Oil condensing boiler	736	552	514	489	392	265	205	142	105	91
Gas condensing boiler	431	323	294	274	226	164	123	94	77	71
Wood log boiler	1142	856	788	743	623	474	-	-	-	-
Wood chips boiler	2003	1502	1311	1183	911	676	550	425	350	323
Wood pellets boiler	1463	1097	1040	1002	832	604	501	-	-	-
Air/water heat pump	1205	904	867	843	773	660	581	479	-	-
Brine/water heat pump	1983	1487	1428	1389	1247	1040	923	728	612	570

[EUR/kW_{th}]

Values for Germany, excluding subsidies | Source: Hummel et al. (2020); Hummel et al. (2023)

Electrical Appliances

Table S 5. Techno-economic parameters of electrical appliances

Technology	Investment [$EUR/Appliance$]	Energy use [$kWh/Appliance/a$]
Air conditioning	305 – 992	196.7 – 283.2
Computer screens	218 – 327	14.2 – 18.2
Desktop computers	397 – 518	72.0 – 97.1
Dishwashers	394 – 686	154.7 – 289.6
Dryers	376 – 666	100.6 – 266.0
Freezers	213 – 956	163.6 – 766.4
Laptop computers	762 – 883	35.6 – 44.3
Lighting	8 – 23	1.6 – 3.3
Modems	65 – 97	34.3 – 49.7
Refrigerators	165 – 762	150.2 – 703.5
Set-top boxes	81 – 101	43.3 – 43.3
Stove	590 – 767	497.7 – 681.8
Televisions	651 – 963	20.3 – 101.1
Washing machines	281 – 571	110.0 – 227.1

Values for EU-27 in 2020. Investments transferred to Member State level using price level indices (Table S 6) | Ranges (Min – Max) across efficiency classes | Source: various, see Elsland (2016)

Table S 6. Price level index for electrical appliances

Member State	Index [$EU27 = 100$]
Austria	100
Belgium	106
Bulgaria	101
Croatia	101
Cyprus	107
Czech Republic	96
Denmark	118
Estonia	90
Finland	104
France	106
Germany	102
Greece	94
Hungary	80
Ireland	97
Italy	95
Latvia	88
Lithuania	93
Luxembourg	115
Malta	134
Netherlands	105
Poland	79
Portugal	105
Romania	93
Slovakia	98
Slovenia	103
Spain	99
Sweden	123

Source: Eurostat (2022d)

Demographic trends

Table S 7. Assumed demographic trends in the building sector

Country | Year	Buildings [1000 *buildings*]		Dwelling [1000 *dwellings*]		Floor area [1000 m^2]	
	2020	**2050**	**2020**	**2050**	**2020**	**2050**
Austria	2,222	2,594	5,482	6,673	716,782	848,919
Belgium	2,770	3,199	5,039	5,799	736,934	861,271
Bulgaria	1,533	1,413	2,604	2,343	256,520	253,322
Croatia	1,084	982	1,652	1,475	197,689	185,589
Cyprus	221	286	1,474	1,556	57,869	73,075
Czech Republic	1,667	1,788	4,374	4,564	486,658	526,774
Denmark	1,623	1,830	2,838	3,268	472,054	552,807
Estonia	199	203	678	665	72,654	75,292
Finland	1,442	1,463	2,618	2,642	384,458	408,933
France	18,370	20,579	30,890	33,802	4,629,150	5,253,451
Germany	22,112	23,108	50,579	52,925	5,920,603	6,250,607
Greece	1,989	2,073	3,893	3,982	637,207	681,190
Hungary	2,913	2,821	4,267	4,090	577,941	595,944
Ireland	1,374	1,745	1,761	2,227	253,367	322,432
Italy	11,598	11,672	29,282	29,108	4,146,791	4,168,585
Latvia	203	198	820	743	90,533	91,310
Lithuania	540	481	1,343	1,160	139,512	132,192
Luxembourg	192	294	272	432	53,949	79,367
Malta	104	149	138	199	21,563	30,588
Netherlands	4,667	5,416	7,813	8,998	1,266,001	1,493,424
Poland	6,710	7,200	14,568	15,715	1,811,518	2,037,959
Portugal	3,416	3,404	5,331	5,243	664,311	681,291
Romania	4,904	5,008	7,381	7,480	626,735	656,399
Slovakia	752	773	1,674	1,687	177,329	188,174
Slovenia	516	559	779	840	110,422	123,708
Spain	9,117	10,228	18,544	21,588	1,798,196	2,087,644
Sweden	2,987	3,892	5,929	7,586	931,468	1,234,493
Total EU-27	**105,226**	**113,358**	**212,023**	**226,789**	**27,238,213**	**29,894,740**

Energy demand in non-building sectors

Table S 8. Assumed development of electricity demand in non-building sectors

Country / Demand in *TWh*	Electric vehicles			Other transport			Other sectors		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Austria	0.7	3.3	7.7	3.1	3.2	3.3	65.6	73	78.9
Belgium	1	4.3	10.1	1.9	2.2	2.4	80.5	94	109.3
Bulgaria	0.1	0.9	2.8	0.7	0.6	0.6	29.6	31.7	34.3
Croatia	0.1	0.4	1.1	0.5	0.5	0.6	13.3	14.4	15.3
Cyprus	0	0.1	0.3	0	0	0	3.3	3.9	4.7
Czech Republic	0.3	1.8	4.9	3.2	3.5	3.6	56.5	65.4	73
Denmark	1.2	3.5	7.3	0.8	2	3.8	33.7	38.1	42.1
Estonia	0.1	0.3	0.9	0.1	0.1	0.2	7.3	7.8	8.3
Finland	0.4	2.1	5.6	1.4	1.9	2.7	76.3	84.5	89.8
France	4.1	28.6	93.4	13.8	15.6	17.5	372.8	428.7	475.4
Germany	5.1	35.7	101.4	23.2	39.2	59.9	511.7	542.6	573.1
Greece	0.4	2.4	5.9	0.1	0.1	0.1	44.9	50.1	53.1
Hungary	0.1	1	2.7	1.8	1.9	1.9	39	44.2	47.7
Ireland	0.2	1	2.7	0.1	0.1	0.2	23.3	26.7	29.9
Italy	1.7	12.2	34.1	7.5	7.7	7.3	271.3	301	330.9
Latvia	0	0.2	0.6	0.3	0.4	0.5	7.5	8.5	8.9
Lithuania	0.1	0.3	0.9	0.5	0.5	0.5	10.2	11.1	12.5
Luxembourg	0	0.2	0.5	0.1	0.1	0.1	7.6	8.9	9.2
Malta	0	0	0.1	-	-	-	2.1	2.3	2.4
Netherlands	3.9	10.4	19.2	1.8	2.4	3.2	116.5	134.3	150.3
Norway	3	7.7	14.4	0.9	1.1	1.5	132.4	148.3	148
Poland	0.9	5.1	14.1	7.2	7.5	7.8	164.5	186.9	201.6
Portugal	0.5	2.7	7.1	0.5	0.4	0.4	52.1	57.6	59.7
Romania	0.3	1.7	5.6	2.5	2.8	2.9	52.5	61.2	68.9
Slovakia	0.1	0.5	1.8	1.4	1.4	1.4	29.6	34.7	36.2
Slovenia	0.1	0.8	1.8	0.5	0.6	0.6	13.8	14.7	15.6
Spain	0.9	6.4	17.6	4.1	4.8	5.6	247.8	269.6	285.3
Sweden	3.2	12.3	22.7	3.2	4	5.3	120.1	132.1	141.9
Switzerland	0.3	2.2	5.6	3	3	2.8	68.1	76.3	76.1
United Kingdom	6.3	28.1	67.1	4.4	6.1	6.7	300.9	330.4	359

Based on 1.5TECH scenario (European Commission 2018). Distribution between countries based on Diversification pathway of SET-Nav project (Hartner et al. 2019)

Table S 9. Assumed development of hydrogen and related fuel demand in non-building sectors

Country / Demand in *TWh*	Hydrogen			Synthetic methane			Synthetic liquid hydrocarbons		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Austria	1.3	9.2	27	0.5	3.4	10.2	0.9	6.1	18
Belgium	3.9	26.7	74.5	1.5	10.1	28.1	2.6	17.9	49.9
Bulgaria	0.5	3.1	7.8	0.2	1.2	3	0.3	2.1	5.2
Croatia	0.1	0.4	0.8	0	0.1	0.3	0.1	0.2	0.5
Cyprus	0	0.1	0.2	0	0	0.1	0	0	0.1
Czech Republic	1	5.9	14.2	0.4	2.2	5.3	0.7	4	9.5
Denmark	0	0.1	0.3	0	0	0.1	0	0	0.2
Estonia	0	0.2	0.5	0	0.1	0.2	0	0.1	0.4
Finland	0.5	2.7	6.6	0.2	1	2.5	0.3	1.8	4.4
France	5.9	47.8	148	2.2	18	55.8	4	32	99.1
Germany	9.8	57.2	143.6	3.7	21.6	54.1	6.6	38.3	96.1
Greece	0.2	2	6.5	0.1	0.7	2.4	0.1	1.3	4.3
Hungary	0.9	4.8	11.8	0.3	1.8	4.5	0.6	3.2	7.9
Ireland	0.1	0.8	2.4	0	0.3	0.9	0	0.5	1.6
Italy	3.5	19.6	50.4	1.3	7.4	19	2.3	13.1	33.8
Latvia	0	0	0	0	0	0	0	0	0
Lithuania	0.4	2.2	5.5	0.1	0.8	2.1	0.3	1.5	3.7
Luxembourg	0	0	0	0	0	0	0	0	0
Malta	0	0	0.1	0	0	0	0	0	0.1
Netherlands	4	22.6	56.7	1.5	8.5	21.3	2.7	15.1	37.9
Norway	0	0.1	0.3	0	0	0.1	0	0	0.2
Poland	1.9	9.8	23.4	0.7	3.7	8.8	1.3	6.5	15.7
Portugal	0.5	3	7.4	0.2	1.1	2.8	0.4	2	5
Romania	1.6	9.2	22.7	0.6	3.5	8.5	1.1	6.2	15.2
Slovakia	0.9	4.6	9.2	0.3	1.7	3.5	0.6	3.1	6.2
Slovenia	0	0	0	0	0	0	0	0	0
Spain	2	11.2	29.2	0.7	4.2	11	1.3	7.5	19.5
Sweden	0.8	4.6	11.4	0.3	1.7	4.3	0.5	3.1	7.6
Switzerland	0	0.7	2.6	0	0.3	1	0	0.5	1.8
United Kingdom	3.2	17.6	44.1	1.2	6.6	16.6	2.1	11.8	29.5

Based on 1.5TECH scenario (European Commission 2018). Distribution between countries based on Diversification pathway of SET-Nav project (Hartner et al. 2019)

Energy supply

Fuel prices

Table S 10. Wholesale fossil fuel price trends

Fuel	Year	Price in EUR/MWh
Crude oil	2030	32.3
	2040	30.7
	2050	29.2
Natural gas	2030	21.7
	2040	21.7
	2050	21.7
Steam coal	2030	6.0
	2040	6.2
	2050	6.5

Source: World Energy Outlook 2019 Sustainable Development scenario (IEA 2019)

Electricity generation

Table S 11. Techno-economic properties of conventional power plants

Technology	Year	Lifetime $[a]$	Investment $[EUR/kW_{el}]$	Fixed O&M $[EUR/(kW_{el} \cdot a)]$	Variable O&M $[EUR/MWh]$	Efficiency el
Battery storage	2030	10	228	6	0.0	95%
	2040	10	216	6	0.0	95%
	2050	10	204	6	0.0	95%
Coal	2030	20	1,600	26	2.4	43%
Combined cycle gas turbine	2030	20	775	12	3.0	60%
	2040	10	750	11	3.0	60%
Gas turbine	2030	20	400	8	1.5	41%
	2040	10	400	8	1.5	41%
Hydrogen	2030	30	400	8	1.5	41%
	2040	30	400	8	1.5	41%
	2050	30	400	8	1.5	41%
Lignite	2030	40	1,700	57	1.5	47%
Nuclear	2030	40	3,500	20	1.0	35%
	2040	40	3,500	20	1.0	35%
	2050	40	3,500	20	1.0	35%
Oil	2030	30	800	11	3.0	58%
Pumped hydro	2030	40	1,000	23	0.0	91%
	2040	40	900	20	0.0	91%
	2050	40	887	20	0.0	91%

Source: DeVita et al. (2018), DEA (2021) | Note: The capacity expansion of nuclear, geothermal and solar thermal plants was set exogenously for each modelled country. Coal phase-out plans were considered at country level.

Table S 12. Techno-economic properties of solar technologies in 2050

Technology	Investment $[EUR/kW]$	Fixed O&M $[EUR/(kW \cdot a)]$	Lifetime $[a]$
Ground-mounted PV	500	5.0	20
Rooftop PV	764	11.0	20
CSP	2,410	40.0	20

Source: Lux et al. (2023)| PV = photovoltaics; CSP = concentrated solar power

Table S 13. Techno-economic properties of three representative offshore wind turbines in 2050

Turbine	Hub height $[m]$	Specific area power $[W/m^2]$	Investment $[EUR/kW]$	Fixed O&M $[EUR/(kW \cdot a)]$	Lifetime $[a]$
1	120	370	3,559	66.5	20
2	120	380	3,542	66.3	20
3	120	390	3,526	66.3	20

The offshore wind potential calculations in ENERTILE take 16 different turbine configurations into account. In 2050, hub heights in the range of 100–120 m and specific area outputs of 370–450 W/m² are considered. Table shows representative combinations. See Lux et al. (2023).

Table S 14. Techno-economic properties of eight representative onshore wind turbines in 2050

Turbine	Hub height $[m]$	Specific area power $[W/m^2]$	Investment $[EUR/kW]$	Fixed O&M $[EUR/(kW \cdot a)]$	Lifetime $[a]$
1	120	270	1,293	23.1	20
2	120	280	1,277	23.0	20
3	120	290	1,261	22.8	20
4	140	350	1,229	22.9	20
5	150	280	1,374	25.4	20
6	150	350	1,262	23.7	20
7	160	270	1,423	26.4	20
8	160	350	1,294	24.5	20

The onshore wind potential calculations in ENERTILE take 59 different turbine configurations into account. In 2050, hub heights in the range of 80–160 m and specific area outputs in the range of 270–500 W/m² are considered. Table shows representative combinations. See Lux et al. (2023).

Electricity networks

Table S 15. Specific investment for electricity transmission technologies

Technology	Unit	Year		
		2030	2040	2050
DC line ground	$[EUR/(MW \cdot km)]$	440	469	830
AC line ground		1,214	1,307	2,760
DC line submarine		1,361	1,361	993
AC/DC converter		75,750	75,750	90,900

Source: Held et al. (2018), Sensfuss et al. (2019)

Table S 16. Specific electricity distribution network charges

Country / EUR/kWh	Residential electricity demand	Non-residential electricity demand
Austria	0.053	0.023
Belgium	0.092	0.013
Bulgaria	0.021	0.011
Croatia	0.033	0.021
Cyprus	0.021	0.014
Czech Republic	0.041	0.027
Denmark	0.039	0.014
Estonia	0.033	0.016
Finland	0.047	0.016
France	0.042	0.016
Germany	0.068	0.026
Greece	0.021	0.007
Hungary	0.034	0.019
Ireland	0.072	0.022
Italy	0.048	0.010
Latvia	0.043	0.027
Lithuania	0.038	0.022
Luxembourg	0.075	0.018
Netherlands	0.054	0.019
Poland	0.042	0.023
Portugal	0.040	0.017
Romania	0.036	0.015
Slovakia	0.040	0.034
Slovenia	0.036	0.013
Spain	0.061	0.021
Sweden	0.040	0.018

Network charges as of 2020 | Source: Eurostat (2022a), Eurostat (2022b), Eurostat (2022f)

District heating generation

Table S 17. Techno-economic properties of combined heat and power technologies

Technology	Year	Lifetime [a]	Investment [EUR/kW]	Fixed O&M [$EUR/(kW \cdot a)$]	Variable O&M [EUR/MWh]	Efficiency el (CHP)
Biomass CHP	2030	25	3,200	115	2.1	30% (71%)
	2040	25	3,050	109	2.1	30% (71%)
	2050	25	2,900	103	2.1	30% (71%)
Coal CHP	2030	40	1,802	45	1.5	36% (89%)
Combined cycle gas turbine CHP	2030	20	950	30	3.5	48% (88%)
	2040	10	950	30	3.5	48% (88%)
Gas turbine CHP	2030	20	730	30	2.7	33% (85%)
	2040	10	730	30	2.7	33% (85%)
Hydrogen CHP	2030	30	950	30	3.0	48% (88%)
	2040	30	950	30	3.0	48% (88%)
	2050	30	950	30	3.0	48% (88%)
Lignite CHP	2030	40	1,952	45	1.5	36% (89%)

Source: DeVita et al. (2018), DEA (2021)

Table S 18. Techno-economic properties of heat supply technologies

Technology	Year	Lifetime [a]	Investment [EUR/kW]	Fixed O&M [$EUR/(kW \cdot a)$]	Variable O&M [EUR/MWh]	Efficiency th
Biomass boiler	2030	25	830	48	0.7	103%
	2040	25	790	45	0.7	103%
	2050	25	750	43	0.7	103%
Electric boiler	2030	20	60	1	0.5	99%
	2040	20	60	1	0.5	99%
	2050	20	60	1	0.4	99%
Gas boiler	2030	19	50	2	0.9	104%
	2040	9	50	2	0.9	104%
Geothermal	2030	20	2,250	85	1.3	100%
	2040	20	2,250	85	1.3	100%
	2050	20	2,250	85	1.3	100%
Heat storage	2030	20	22	0	0.0	99%
	2040	20	22	0	0.0	99%
	2050	20	22	0	0.0	99%
Hydrogen boiler	2030	25	50	2	0.9	104%
	2040	25	50	2	0.9	104%
	2050	25	50	2	0.9	104%
Large-scale heat pump	2030	25	590	2	1.7	variable *
	2040	25	560	2	1.7	variable *
	2050	25	530	2	1.6	variable *
Solarthermal	2030	20	950	10	0.7	100%
	2040	20	950	10	0.7	100%
	2050	20	950	10	0.7	100%

*Source: DeVita et al. (2018), DEA (2021) | * Endogenously determined in ENERTILE model, see Bernath et al. (2019)*

District heating networks

Table S 19. General parameters for modelling of district heating networks

Indicator	Value	Unit
Investment lifetime	30	a
Average building access pipe length	10	m
Average supply temperatures	90	$°C$
Average return temperatures	60	$°C$
Average full load hours	2,000	h
Average pump efficiency	75	%
Average pipe differential pressure loss	150	Pa/m
Specific maintenance cost factor	15	%

Table S 20. Labour costs, construction price levels, and specific investment for district heating pipes

Country	Construction sector hourly labour cost in 2019 [EUR/h]	Construction price level index in 2019 [$EU27 = 100$]	Calculated specific pipe investment* [EUR/m]
Austria	35.7	114	959
Belgium	36.4	99	872
Bulgaria	4.7	52	402
Croatia	9.9	49	418
Czechia	12.1	69	570
Denmark	41.6	135	1,131
Estonia	14.6	75	629
Finland	35	148	1,178
France	33.4	101	864
Germany	29.6	144	1,116
Greece	10.3	61	504
Hungary	8.3	61	490
Ireland	27.8	109	963
Italy	24	81	742
Latvia	10.4	69	558
Lithuania	8.4	67	534
Luxembourg	28	110	886
Netherlands	37.1	122	1,022
Poland	10.1	66	535
Romania	6.1	47	377
Slovakia	10.3	74	596
Slovenia	15.3	64	561
Spain	20.2	79	704
Sweden	36.5	146	1,172

** Weighted average costs from the NetHEAT model results | Sources: Eurostat (2022c), Eurostat (2022e)*

Hydrogen generation

Table S 21. Techno-economic properties of hydrogen generation technologies

Technology	Year	Lifetime	Investment [EUR/kW]	Fixed O&M [$EUR/(kW \cdot a)$]	Variable O&M [EUR/MWh]	Efficiency
H_2 electrolyser	2030	20	481	22	0.0	66%
	2040	20	404	21	0.0	68%
	2050	20	327	19	0.0	71%
Methanation reactor	2030	20	1,275	49	0.0	47%
	2040	20	948	36	0.0	49%
	2050	20	832	32	0.0	52%

Source: Lux and Pfluger (2020), own assumptions

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