The technical flexibility potential of heat pumps

Part 2: Extrapolation to the national level

Authors	Wolf Bracke Sam Hamels	UGent Building Physics Group UGent Energy Economics

Work Package	1	Theoretical foundations
Task	1.3	Expansion to the national level
Deliverable	1.3	Report on the realistic potential of flexibility on the national level

Partner responsible:	UGent BFG
Partners involved:	UGent BFG, UGent EELAB, UGent CEEM

Project / funding	This document is a deliverable of the FlexSys project ("A Flexible electricity System contributing to security of supply") funded by the Energy Transition Fund of the Belgian federal government, managed by the FPS Economy, SMEs, Self-employed and Energy.

TABLE OF CONTENTS

1. INTRODUCTION

In this part of the FlexSys project, we will estimate the heat pump flexibility potential of the Belgian residential building stock in 2030 and 2040. This work builds further on the work performed in D1.1 of the FlexSys project, where the flexibility potential of heat pumps on the individual building level is assessed.

2. RESEARCH METHODOLOGY

The total energy flexibility of the residential Belgian building stock can be regarded as the sum of the energy flexibility of every individual residential building in Belgium. The most precise methodology would be to calculate the energy flexibility of every individual dwelling, which is too computationally heavy and would require detailed geometric and physical properties of the buildings, which is not available.

As an alternative, a clustering methodology was developed, where the building stock is grouped in clusters which are represented by archetypical buildings with a variation in parameters as discussed in D1.1. An overview of the parameters is presented in Table 1. Note that the underfloor and radiator emission system are only combined with the air-water and geothermal heat pump. As a result, the building stock is grouped in 990 clusters with a unique combination of properties.

Table 1: Clustering parameters

geometry	*insulation level*	*heat pump type*	*heat emission system*	*heating schedule*
detached small	A	air-water	underfloor	24h
detached average	B	geothermal	radiators	16h
detached large	C	air-air		8h
semi-detached small	D			
semi-detached average	E			
semi-detached large	F			
terraced small				
terraced average				
terraced large				
apartment middle				
apartment roof				

3. BUILDING STOCK CONSTRUCTION

To extrapolate the results of the individual simulations to building stock level, we have to estimate the amount of buildings in each specific cluster. This requires a bottom-up approach where step by step more details are added until we reach the detail level of the clusters.

To estimate the building stock properties in 2030 and 2040, we first need a comprehensive understanding of the present building stock. This includes determining the total number of residential buildings, their typologies - be it detached homes, apartments, or other forms - and their sizes. We also need to gain insight in the current insulation level of these different groups of buildings.

Next, we must factor in new constructions and renovations anticipated between now and the target years of 2030 or 2040. It's not just the amount of renovations that's important; we must also predict the distribution between buildings' insulation level both before and after their respective renovations.

Finally, we have to estimate the number of heat pumps of different types that will be in use. We need to determine what building typologies and insulation levels will likely have a more significant amount of heat pumps and forecast the expected heating schedules for the different buildings.

3.1. Typology

We've examined building stock data from Statbel to determine the distribution of building typologies across different construction periods [1]. Current trends, which indicate a shift towards more apartments and fewer detached houses, are factored into our future scenarios. Figure 1 illustrates the current and estimated distribution across typologies.

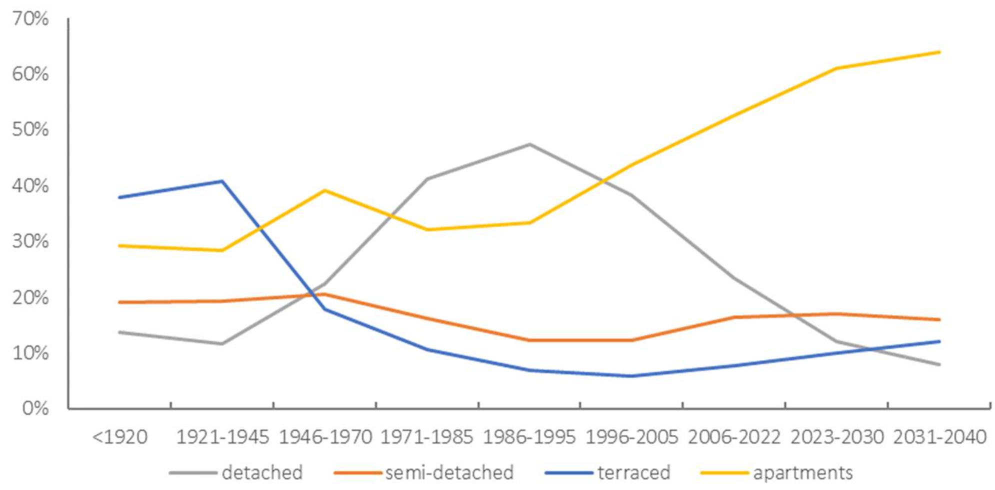


Figure 1: Building typologies distribution

For projecting the number of future constructions, we analysed Statbel's monthly building permit data [2]. The issuance of these permits has remained relatively consistent, with a mild upward trend, as can be regarded in Figure 2. Using this trend, we've made projections for the upcoming years to estimate the volume of forthcoming constructions.

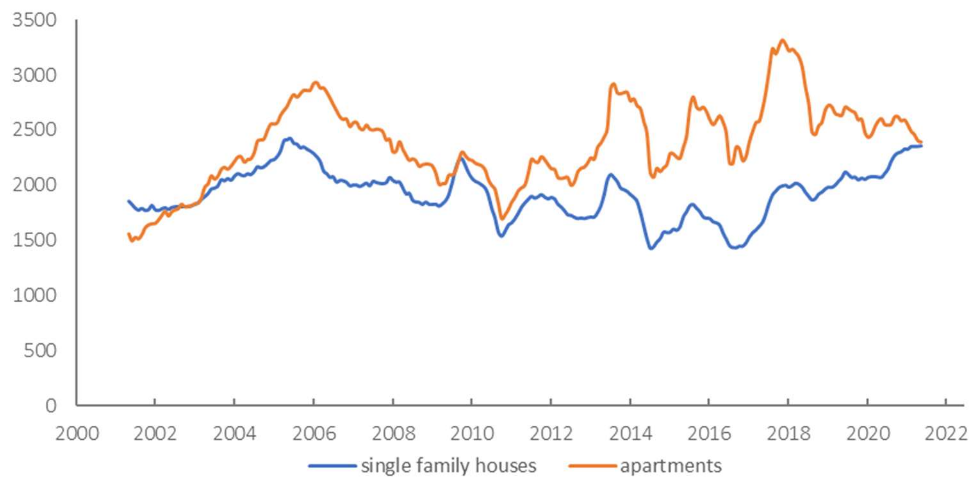


Figure 2: Monthly building permits

Combining the information from both sources, we come up with the following amount of residential buildings for different construction periods.

Table 2: Number of buildings according to typology and construction period

	<1920	*1921-1945*	*1946-1970*	*1971-1985*	*1986-1995*	*1996-2005*	*2006-2022*	*2023-2030*	*2031-2040*
detached	171 874	75 908	297 414	352 412	196 106	176 212	157 712	47 379	47 424
semi-detached	241 205	126 716	270 630	138 309	50 662	56 280	110 789	67 121	94 848
terraced	478 075	268 462	237 219	90 418	28 353	27 219	51 434	39 483	71 136
apartments	368 363	186 377	518 519	273 676	138 079	201 067	355 423	240 845	379 393

3.2. Building size

Given that our building clusters differentiate between the size of single family houses and the compactness of apartments, we've incorporated an additional analysis step.

The Flemish EPC database stores building properties of all energy performance certificates, providing insight in the building stock in Flanders for buildings with a construction period until the year 2005. Likewise, the EPB database stores the result of the building properties of buildings constructed since 2006, when the EPBD regulations were introduced. Various studies have been conducted analysing the properties of the building stock based on these databases [3][4][5][6][7].

Using these resources, we developed a method to divided the categories from Table 2 into more specific subcategories. While the EPC/EPB databases cover only a part of the Flemish building stock, the results are applied to complete Belgian building stock as found in the previous step. The outcome of this extrapolation is illustrated in Table 3.

Table 3: Number of buildings according to geometry and construction period

	<1920	1921-1945	1946-1970	1971-1985	1986-1995	1996-2005	2006-2022	2023-2030	2031-2040
detached small	71 586	33 437	131 903	111 715	49 909	36 916	24 367	7 320	7 327
detached average	42 797	21 937	95 619	113 124	63 440	52 599	45 658	13 716	13 729
detached large	57 492	20 533	69 892	127 573	82 757	86 696	87 688	26 343	26 368
semi-detached small	116 261	65 702	129 496	66 043	18 897	19 445	34 234	20 740	29 308
semi-detached average	63 919	36 748	91 473	44 674	16 313	19 585	37 391	22 653	32 011
semi-detached large	61 025	24 266	49 661	27 593	15 452	17 250	39 164	23 727	33 529
terraced small	238 081	134 097	99 632	34 856	9 016	9 581	16 948	13 010	23 439
terraced average	101 352	66 444	66 540	27 804	7 499	7 948	15 687	12 042	21 696
terraced large	138 642	67 921	71 047	27 758	11 837	9 690	18 799	14 431	26 000
apartment middle	153 792	61 318	221 667	137 659	61 238	88 067	116 756	79 118	124 631
apartment roof	214 571	125 059	296 852	136 017	76 841	113 000	238 667	161 727	254 762

3.1. Insulation level in 2022

To estimate the insulation level of the building stock in the year 2030 and 2040, we begin by establishing the baseline insulation level for 2022. Subsequent steps will account for new constructions and renovations.

We further refine the clusters from Table 3 according to the insulation levels we defined. To classify a building under insulation level A/B/C/D/E/F, we first calculate the total heat loss coefficient of the building models we simulated. The heat loss coefficient quantifies the heat loss (in W) through the building envelope for every K (or °C) difference between indoor and outdoor temperatures. It's important to note that the A to F insulation levels are linked to, but not directly related to the EPC-labels of a building, as classified by the Belgian EPBD regulations.

Table 4: Heat loss coefficients according to simulation model and insulation level

	A [W/K]	B [W/K]	C [W/K]	D [W/K]	E [W/K]	F [W/K]
detached small	145	292	417	709	891	1059
detached average	187	367	538	894	1117	1324
detached large	235	453	690	1116	1384	1642
semi-detached small	123	246	358	604	757	901
semi-detached average	140	267	417	670	829	980
semi-detached large	165	308	504	786	965	1145
terraced small	94	178	284	450	553	662
terraced average	133	240	382	569	686	821
terraced large	136	244	414	616	745	887
apartment middle	50	94	107	160	187	238
apartment roof	60	111	159	247	284	382

Next, we calculate the heat loss coefficient of the building envelope for the existing building stock, using the EPC/EPB database studies we introduced before. Each building is assigned an insulation level that aligns most closely with the criteria in Table 4. A distribution of the insulation levels is made for all typologies and construction periods. An example of the results can be found in Table 5, where we show the result for one specific construction period.

Table 5: Insulation level distribution for construction period 1921-1945

	detached			semi-detached			terraced			apartment	
	small	average	large	small	average	large	small	average	large	middle	roof
A	0.3%	2.1%	1.0%	3.2%	1.0%	0.5%	3.3%	3.9%	0.7%	36.0%	23.8%
B	2.7%	3.0%	3.5%	6.0%	4.8%	4.2%	8.2%	6.4%	2.5%	23.5%	20.0%
C	8.2%	10.2%	11.0%	13.1%	7.2%	7.9%	16.8%	14.9%	8.8%	12.2%	20.6%
D	22.1%	24.9%	19.6%	28.1%	21.1%	11.2%	25.7%	20.5%	15.3%	8.4%	12.7%
E	23.9%	18.0%	17.3%	23.4%	19.1%	12.4%	18.6%	21.1%	15.0%	6.7%	7.8%
F	42.7%	41.8%	47.6%	26.1%	46.7%	63.8%	27.4%	33.2%	57.7%	13.3%	15.0%

Integrating these findings with the clusters from Table 3, we calculate the total amount of buildings according to building type and insulation label for each construction period.

This leads to a detailed breakdown of building types and their respective insulation levels in the national building stock, as presented in Table 6.

Table 6: Number of buildings according to geometry and insulation level in 2022

	detached			semi-detached			terraced			apartment	
	small	average	large	small	average	large	small	average	large	middle	roof
A	29 328	49 907	85 188	42 228	38 294	36 371	29 191	22 671	19 972	423 933	347 938
B	41 075	49 747	70 462	34 668	20 463	19 064	39 471	23 319	16 679	131 646	319 383
C	94 128	122 796	150 472	86 909	52 850	38 017	99 565	58 806	48 158	90 447	203 480
D	109 489	96 615	101 442	116 637	64 762	34 650	134 840	61 095	57 223	75 104	116 500
E	75 572	49 590	47 580	84 144	46 811	25 031	98 773	50 542	51 616	55 618	78 098
F	110 240	66 519	77 487	85 492	86 924	81 276	140 370	76 841	152 046	63 749	135 607

3.2. Insulation level of new construction between 2022 and 2040

Given that the minimum insulation standard for all new constructions aligns with the A-level we defined, we assume that all new buildings, as outlined in Table 3, are categorised under insulation level A.

3.3. Insulation level of renovations between 2023 and 2040

The change in insulation level of buildings which will be renovated is less straightforward. We consulted building renovation permit data from Statbel and records of energy grants for individual insulation actions from the Flemish government [2][8]. However, both data sources present challenges. For instance, a building permit doesn't necessarily confirm that insulation improvements were undertaken. Moreover, conditions and appeal of energy grants schemes have evolved over time and the incentive to apply for grants has evolved with it. It's also worth noting that the total number of grants awarded doesn't clarify how many different insulation actions were combined within a single building.

To address these complexities, we developed a method to estimate the distribution of building insulation levels, considering both their original and post-renovation states.

As a starting point, we adopt the assumption from Elia's last Adequacy and Flexibility Study regarding the amount of energy renovations which will take place between 2022 and 2040 [9]. According to this projection, the renovation rate will grow linearly, rising from 0.7% today to 1.2% by 2035, then levelling off.

In a next step, we distribute the projected renovations across the defined insulation levels. We examined the distribution of insulation levels in our building stock. We assumed that buildings with A or B insulation level are unlikely to undergo renovations until 2040. Additionally, we introduced a correction factor, recognizing that buildings with higher insulation levels are more likely to be subjected to energy renovations. The processes described, along with the final distribution of energy renovations based on insulation level, are presented in Table 7.

Table 7: Energy renovation distribution according to insulation level

	A	*B*	*C*	*D*	*E*	*F*
% stock	19.9%	13.6%	18.5%	17.2%	11.8%	19.1%
% stock excl. A/B	0.0%	0.0%	27.9%	25.8%	17.7%	28.7%
correction	0.0%	0.0%	-7.5%	-2.5%	2.5%	7.5%
% renovations	0.0%	0.0%	20.4%	23.3%	20.2%	36.2%

We further assume that buildings with poor insulation levels are more likely to undergo deep energy renovations, encompassing multiple building elements simultaneously. Considering the four building elements - windows, roofs, walls, and floors - we anticipate the distributions for combined renovations to be as found in Table 8.

Table 8: Combined renovation distribution according to insulation level

	A	*B*	*C*	*D*	*E*	*F*
1	0%	0%	45%	25%	10%	5%
2	0%	0%	35%	40%	35%	30%
3	0%	0%	15%	25%	35%	40%
4	0%	0%	5%	10%	20%	25%

In every renovation, building elements are supposed to be insulated to match the A-level as defined in D1.3. Specifically, the U-value for windows stands at 1.50 W/(m².K) while roofs, walls and floors have a U-value of 0.24 W/(m².K)). Within the totality of buildings with a particular insulation level, renovation distribution is proportionally aligned with the prominence of the building type in that insulation category of the building stock.

Simulations were conducted for insulation levels C/D/E/F across all building types. In these scenarios, one, two, three, or all four building elements underwent insulation, and we monitored the resultant shift in insulation level. As an example, we illustrate the yearly changes for small detached houses in the period 2023-2030. Table 9 details the number of houses at a particular insulation level that experience a reduction in that level due to the anticipated renovations.

Table 9: Yearly decrease in insulation level

	A	B	C	D	E	F
0	0	0	380	121	0	0
- 1	0	0	785	740	217	64
- 2	0	0	112	461	368	124
- 3	0	0	0	168	272	384
- 4	0	0	0	0	172	191
- 5	0	0	0	0	0	724

Table 10 displays the resulting annual label shifts for this particular part of our building stock.

Table 10: Yearly change in labels

	A	B	C	D	E	F
increase	1175	1708	1492	341	64	
decrease	0	0	-897	-1369	-1028	-1486
net increase	1175	1708	595	-1028	-964	-1486

3.4. Insulation level in 2030/2040

Using the approach outlined earlier, we arrive at the projected building stock distribution for 2030 and 2040 , presented in Table 11 and Table 12 respectively.

Table 11: Number of buildings according to geometry and insulation level in 2030

	detached			*semi-detached*			*terraced*			*apartment*	
	small	*average*	*large*	*small*	*average*	*large*	*small*	*average*	*large*	*middle*	*roof*
A	46 051	70 371	119 140	71 246	67 661	65 609	53 970	40 977	44 487	509 191	521 571
B	54 738	63 537	86 355	47 995	28 717	24 611	55 435	31 815	25 404	142 689	340 999
C	98 888	122 446	148 501	92 250	56 568	40 233	107 024	61 736	53 827	91 557	201 092
D	101 264	88 688	93 085	107 672	60 140	32 489	124 884	56 835	54 051	69 442	107 860
E	67 857	44 500	42 760	75 381	42 119	22 684	88 672	45 397	46 703	49 859	70 227
F	98 354	59 347	69 133	76 274	77 551	72 512	125 236	68 556	135 653	56 875	120 986

Table 12: Number of buildings according to geometry and insulation level in 2040

	detached			*semi-detached*			*terraced*			*apartment*	
	small	*average*	*large*	*small*	*average*	*large*	*small*	*average*	*large*	*middle*	*roof*
A	69 473	95 651	158 534	114 723	111 165	108 570	97 557	73 396	87 750	644 334	796 714
B	78 127	87 143	113 560	70 808	42 846	34 105	82 761	46 358	40 341	161 593	378 002
C	107 037	121 847	145 128	101 393	62 933	44 024	119 793	66 753	63 532	93 456	197 003
D	87 185	75 120	78 779	92 326	52 229	28 790	107 839	49 544	48 620	59 751	93 069
E	54 651	35 788	34 510	60 381	34 087	18 665	71 382	36 589	38 293	40 002	56 751
F	78 007	47 069	54 831	60 495	61 508	57 511	99 327	54 374	107 589	45 109	95 956

As a result of renovation and new construction, the distribution of insulation levels across all building geometries evolves over the years as outlined in Table 13.

Table 13: Insulation level distribution

	A	B	C	D	E	F
2022	19.9%	13.6%	18.5%	17.2%	11.8%	19.1%
2030	26.7%	14.9%	17.8%	14.8%	9.9%	15.9%
2040	35.5%	17.1%	16.9%	11.7%	7.3%	11.5%

While the previous tables displayed consolidated data from all construction periods, we used three distinctive construction periods in our analysis. This methodology allows us to apply different properties such as renovation rates, heat pump distribution and heat emission distribution, which will be discussed in subsequent paragraphs. More specifically, we will handle buildings differently based on the building periods in Table 14.

Table 14: Construction period differentiation

construction year	description
< 2006	before EPBD regulations
2006-2022	since EPBD regulations
> 2022	increased heat pump uptake

3.5. Heat pumps in 2022

To estimate the amount of heat pumps in each cluster of our building stock, we start our analysis using Elia's assumption about the current number of heat pumps in the total Belgian building stock. According to Elia's recent Adequacy and Flexibility Study, there are approximately 230 000 heat pumps in Belgian residences serving as the primary source of heating [9].

Next, we have to make assumptions regarding the distribution of these heat pumps across the building stock. It's common knowledge that buildings with superior insulation levels tend to be equipped with heat pumps more frequently. Yet, there remain instances where buildings with suboptimal insulation levels also feature a heat pump. Since heat pump installation was in the past regarded as a relatively luxury product for people with higher budgets, heat pumps are more applied with building types such as detached houses. This brings us to the following distribution of heat pumps in Table 15.

Table 15: Number of heat pumps according to geometry and insulation level in 2022

	detached			semi-detached			terraced			apartment	
	small	average	large	small	average	large	small	average	large	middle	roof
A	17 821	32 530	57 059	9 308	9 556	9 192	2 830	2 508	2 692	17 600	15 929
B	3 938	4 616	10 539	1 110	832	1 492	435	264	340	754	13 164
C	2 093	2 730	3 345	588	358	257	258	152	125	39	87
D	1 063	938	985	345	191	102	153	69	65	17	27
E	276	181	174	94	52	28	42	22	22	2	2
F	177	107	124	42	42	40	26	14	28	2	4

3.6. Heat pumps in new construction between 2023 and 2040

We use Elia's latest report as a reference for the adoption of heat pumps in new constructions. In the Flemish region, starting 2025, new constructions not connected to a district heating network will be mandated to install heat pumps. Consequently, we anticipate the share of heat pumps in new constructions to increase from 30% in 2023 to 96% in 2025, maintaining that share in subsequent years. Since no regulation is in place in the Brussels and Walloon region, we see a delayed uptake of heat pumps with a starting point of 25% in 2023 and 96% adoption in 2028. We expect 75% of the new constructions to take place in Flanders, while only 25% takes place in Brussels and Wallonia.

Given that regulations don't specify heat pump requirements by building type, we do not adopt the differentiation we assumed in the 2022 building stock. Instead, we project an even distribution of heat pumps in line with the volume of new constructions for each building category.

3.7. Heat pumps in renovations between 2023 and 2040

Currently, there are no regulations in place that restrict the use of fossil fuel heating in existing buildings. Consequently, we've adopted and extrapolated Elia's projections on heat pump adoption: starting from 12% in 2023, increasing to 23% by 2030, and reaching 35% in 2035.

As previously mentioned in 3.5, buildings with superior insulation tend to be equipped with heat pumps more frequently in the current building practice. Over time, we foresee a shift with more heat pumps being installed in buildings with moderate insulation. This is likely due to the decreasing relative costs of heat pump installations compared to insulation measures. Furthermore, a potential tax shift from electricity to gas could make heat pump operations more economically attractive than gas boilers. Table 16 showcases the disparities between the current database observations and our projections for building renovations in 2030 and 2040.

Table 16: Heat pump distribution across insulation levels

	A	*B*	*C*	*D*	*E*	*F*
< 2022	77.0%	16.3%	4.4%	1.7%	0.4%	0.3%
> 2022	55.0%	25.0%	15.0%	3.5%	1.0%	0.5%

In line with our methodology for heat pumps in new construction, we assume an even distribution of heat pumps among building types with the same insulation level.

3.8. Heat pumps as end-of-life replacement between 2023 and 2040

In addition to the heat pumps installed during deep energy renovations, we anticipate heat pumps being adopted as replacements when current heating systems reach their end-of-life. Building upon Elia's assumptions, we project no such replacements in 2022, but a rise to 20% by 2030 and 27% by 2035. Given that most heating systems have an estimated lifespan of 20 years, we expect that 5% of buildings will replace their heating systems annually. The allocation of heat pumps for end-of-life replacements is projected to mirror the distribution seen in renovations.

3.9. Heat pumps in 2030/2040

Based on the assumptions previously outlined, we project the number of heat pumps for 2030 and 2040, as detailed in Table 16.

Table 17: Heat pumps in 2030/2040

	2022	2030	2040
existing	229 998	229 998	229 998
new construction		316 109	878 167
renovation		66 845	288 885
end-of-life		225 797	1007 617
total	229 998	838 749	2404 666

A comprehensive breakdown can be found in Table 18 and Table 21.

Table 18: Number of heat pumps according to geometry and insulation level in 2030

	detached			semi-detached			terraced			apartment	
	small	average	large	small	average	large	small	average	large	middle	roof
A	31 965	57 608	102 212	37 841	38 510	38 462	21 491	18 553	19 888	200 687	243 691
B	11 684	13 997	23 826	7 647	4 691	5 087	7 878	4 661	3 486	25 579	73 391
C	9 894	12 908	15 817	7 791	4 738	3 408	8 510	5 026	4 116	7 535	16 952
D	3 350	2 956	3 104	2 781	1 544	826	2 968	1 345	1 260	1 586	2 459
E	934	613	588	826	460	246	902	462	472	486	682
F	472	285	332	271	276	258	403	221	436	173	368

Table 18: Number of heat pumps according to geometry and insulation level in 2040

	detached			semi-detached			terraced			apartment	
	small	average	large	small	average	large	small	average	large	middle	roof
A	49 434	88 566	157 923	80 575	82 434	83 155	53 742	46 878	51 302	467 469	606 793
B	21 319	25 667	40 355	15 779	9 491	9 559	17 137	10 131	7 398	56 460	148 312
C	19 599	25 569	31 331	16 752	10 187	7 328	18 776	11 090	9 081	16 861	37 932
D	6 194	5 466	5 739	5 810	3 226	1 726	6 471	2 932	2 746	3 537	5 486
E	1 753	1 150	1 104	1 738	967	517	1 972	1 009	1 031	1 089	1 529
F	840	507	591	556	566	529	871	477	944	386	820

3.10. Heat pumps types in 2030/2040

We base our distribution of heat pump types for 2030 and 2040 on Elia's assumptions.

Table 19: Heat pump type distribution in 2030/2040

	air-water	geothermal	air-air
2030	61.1%	14.6%	24.3%
2040	66.4%	14.3%	19.2%

It's important to mention that the air-air heat pumps in our analysis only refer to those installed as primary heating systems. Air-air heat pumps used primarily for cooling, which can also function in reverse as a secondary heating system, are not considered in this study.

In deliverable D1.1, discussing the flexibility of heat pumps on the individual building level, only the application of air-water heat pumps is evaluated. To use the load reduction and load increase results for geothermal and air-air heat pumps, we apply a correction factor, based on typical COP's which can be expected.

Table 20: Heat pump correction factor

	COP	factor
air-water	4.00	1.00
geothermal	5.50	0.73
air-air	4.50	0.89

3.11. Heat emission systems in 2030/2040

For air-water and geothermal heat pumps, we've assessed both underfloor heating and radiator heating options.

For new construction, we anticipate the existing trend towards the application of underfloor heating to persist in the future, even more so when geothermal heat pumps are applied. This is largely attributed to the advantage of leveraging the free cooling feature, which necessitates underfloor heating.

For buildings constructed before 2005, we project a moderate rise in the adoption of underfloor heating. Yet, we also maintain a notable share for radiator heating, recognizing the end-of-life replacements that might occur outside comprehensive renovations where the heat emission system typically isn't altered.

For buildings erected between 2006-2022, we're not factoring in renovations.

The assumed distribution of emission systems for both air-water and geothermal heat pumps is illustrated in Table 21 and Table 22, respectively.

Table 21: Emission system distribution for air-water heat pumps in 2030/2040

	<2005		2006-2022		>2022	
	underfloor	radiators	underfloor	radiators	underfloor	radiators
2030	80%	20%	86%	14%	91%	9%
2040	83%	17%	86%	14%	94%	6%

Table 22: Emission systems distribution for geothermal heat pumps in 2030/2040

	<2005		2006-2022		>2022	
	underfloor	radiators	underfloor	radiators	underfloor	radiators
2030	95%	5%	98%	2%	99%	1%
2040	97%	3%	98%	2%	99%	1%

3.12. Heating regimes

Given the absence of dependable data sources to establish the heating regimes for various heat pump types and insulation levels in our building stock, we assume the following:

1. **Insulation and Heating Duration**: Buildings with superior insulation levels are more inclined towards continuous heating
2. **Floor Heating**: This system is mostly related to continuous heating due to its slow reaction time. If there's any intermittent heating with floor heating, it's assumed to be the 16-hour schedule.
3. **Radiator Heating**: With its faster reaction time, radiator heating tends to favor intermittent heating. For those with intermittent radiator heating, the heating schedules are assumed to be equally split between 16-hour and 8-hour heating.
4. **Air-Air Heating**: Being an extremely responsive system, air-air heating has a predominant leaning towards intermittent heating. The split between 16-hour and 8-hour heating for intermittent air heating is assumed to be even.
5. **Geothermal vs Air-Water Heat Pumps**: Geothermal heat pumps are believed to have a higher dominance of continuous heating than air-water heat pumps due to their lower energy consumption.
6. **Building Type Uniformity**: Our assumptions don't differentiate between building types.
7. **Time-Frame Uniformity**: The suppositions apply uniformly for both the 2030 and 2040 scenarios.

The distributions for all heat pumps and emission systems, using the aforementioned assumptions, are presented in Table 23.

Table 23: Heating regime distribution

	air-water						*geothermal*						*air-air*		
	underfloor			*radiators*			*underfloor*			*radiators*					
	24h	*16h*	*8h*	*24h*	*16h*	*8h*	*24h*	*16h*	*8h*	*24h*	*16h*	*8h*	*24h*	*16h*	*8h*
A	98%	2%	0%	20%	45%	45%	99%	1%	0%	24%	43%	43%	7%	47%	47%
B	95%	5%	0%	16%	46%	46%	97%	3%	0%	20%	45%	45%	5%	48%	48%
C	91%	9%	0%	12%	47%	47%	93%	7%	0%	15%	46%	46%	4%	48%	48%
D	89%	11%	0%	8%	48%	48%	91%	9%	0%	10%	47%	47%	3%	49%	49%
E	87%	13%	0%	4%	49%	49%	89%	11%	0%	5%	48%	48%	1%	50%	50%
F	85%	15%	0%	2%	50%	50%	87%	13%	0%	3%	49%	49%	1%	50%	50%

4. BUILDING STOCK RESULTS

In deliverable D1.3, we explained our definition of heat pump flexibility as well as the indicators we chosen to evaluate the flexibility. Additionally, we calculated and discussed the results for individual buildings taking into account a diverse range of building parameters. It's crucial for readers to first acquaint themselves with the methods and outcomes of D1.3 prior to delving into the aggregated building stock findings.

In Chapter 3, we broke down the building stock into clusters each characterized by unique attributes relating to geometry, insulation level, heat pump types, emission systems and heating regimes. Given that we've already simulated individualized results for each of these clusters, projecting these results onto the broader building stock level becomes a straightforward task. To calculate the building stock flexibility, we aggregate the load reductions or increases corresponding to the number of buildings represented by each cluster.

In the following paragraphs, we will discuss the building stocks in 2030 and 2040 for three climate years, representing a cold, average and warmer year. We also discuss three temperatures thresholds, which act as the minimum temperature before turning back on the heat pump in a flex event.

For clarity, we remind the readers of the monthly average outdoor temperatures in the climate years we studied in Table 24.

Table 24: Monthly average temperatures

	cold [°C]	average [°C]	warm [°C]
jan	0.1	5.0	6.1
feb	2.5	2.5	6.6
mar	6.7	7.3	9.3
apr	10.3	10.6	12.4
may	11.2	13.3	13.5
jun	17.4	18.2	16.5
jul	20.5	18.3	19.3
aug	17.1	16.7	16.2
sep	14.2	16.6	16.5
oct	10.6	14.2	13.6
nov	6.1	6.3	8.9
dec	-0.7	3.7	4.3

4.1. Duration

The duration on the individual level building was defined as the time it takes for the building to cool down to the minimum threshold, ending the load reduction phase and starting the load increase phase, or the ‘recovery period’.

In a building stock with a large variation of building properties, some buildings will cool down faster compared to others, resulting in a mixed situation of some buildings undergoing a load reduction, while others are already in the load increase phase. On the building stock level, all loads are aggregated, and the period of a net load reduction is defined as the duration of the flex event.

Table 25 offers insight in the average duration outcomes for of December, presenting the results for the different parameters examined. December was chosen, in accordance with report D1.1, since it represents a typical winter month for the average climate year. For the cold climate year, the month of December turns out to be the most critical month.

Table 25: Duration in December (values expressed in h)

	2030			2040		
	cold	average	warm	cold	average	warm
16°C	11.6	16.1	17.5	11.6	16.0	17.5
18°C	6.2	8.2	8.7	6.2	8.2	8.6
20°C	2.1	2.2	2.3	1.9	2.1	2.3

In Table 24, the following observations are made:

- The minimum temperature threshold is the most critical factor impacting the duration of the flex event, mirroring our observations at the individual building level.
- During a colder December month, the duration is significantly reduced. This effect is more pronounced with the lower temperature thresholds. The latter is related to the fast initial temperature drop we observed in D1.1.
- The rise in heat pump numbers in 2040 doesn't lead to a longer duration. Given our assumption that all buildings undergo the same flex event, they initiate the cooldown simultaneously. Intriguingly, 2040 shows a marginally shorter duration, which could be due to the adoption of heat pumps in buildings with inferior insulation in our proposed scenario.

While December's average monthly values might not perfectly capture the entirety of the year, a broader look at the yearly duration distribution is offered in Figure 3. Here, we focus on the building stock projections for 2040 in an average climate year, using the 18°C threshold. Echoing our findings from D1.1, there's an inverse correlation between duration and outdoor temperature. In the typical heating months, we see a concentration of low-duration values with an average value around 8h. During shoulder season, the average value increases to roughly 20h, but with significant fluctuations that coincide with varying outdoor conditions.

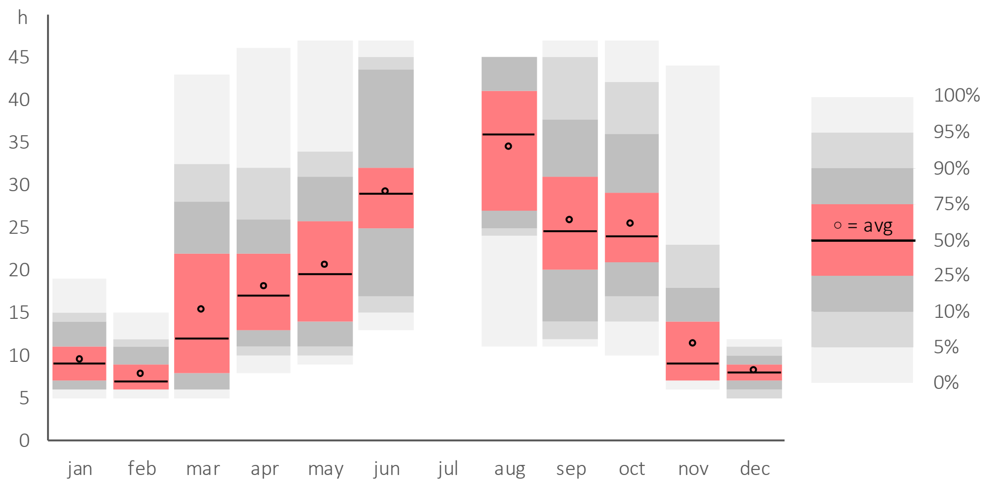


Figure 3: Distribution of the duration (2040 / average climate year / 18°C threshold)

4.2. Load reduction

Consistent with the D1.1 report, the load reduction of the aggregated building stock is examined for periods of 1h, 2h, 4h, 8h, and 24h post a flex event. The load reduction is quantified as the minimum amount of electricity which can be avoided during every hour of the specified timeframes.

Table 26 to Table 30 showcase the average load reduction for December during a 1h, 2h, 4h, 8h and 24h period, respectively.

It’s worth noting that the 1h load reduction for the 16°C threshold is virtually identical to the total electricity consumption of all heat pumps within the Belgian residential building stock, since very few buildings will experience a temperature drop from the 21°C setpoint to the 16°C minimum temperature within a single hour.

Table 26: 1h load reduction in December (values expressed in MW)

	2030			2040		
	cold	average	warm	cold	average	warm
16°C	1612	1255	1206	3240	2525	2428
18°C	1443	1158	1123	2948	2357	2282
20°C	1133	906	875	2414	1930	1857

Table 27: 2h load reduction in December (values expressed in MW)

	2030			2040		
	cold	average	warm	cold	average	warm
16°C	1342	1105	1065	2766	2258	2174
18°C	1134	952	932	2425	2000	1949
20°C	124	363	322	265	775	711

Table 28: 4h load reduction in December (values expressed in MW)

	2030			2040		
	cold	average	warm	cold	average	warm
16°C	1128	975	945	2391	2026	1958
18°C	938	819	796	2036	1757	1703
20°C	5	1	4	6	1	7

Table 29: 8h load reduction in December (values expressed in MW)

	2030			2040		
	cold	average	warm	cold	average	warm
16°C	779	768	748	1740	1649	1601
18°C	19	229	228	38	492	491
20°C	0	0	0	0	0	0

Table 30: 24h load reduction in December (values expressed in MW)

	2030			2040		
	cold	average	warm	cold	average	warm
16°C	0	4	55	0	8	115
18°C	0	0	0	0	0	0
20°C	0	0	0	0	0	0

Based on the data presented in the preceding tables, we conclude the following:

- Longer timeframes tend to result in smaller load reductions.
- The 20°C threshold provides a marginal load reduction after the initial hour.
- During a colder December month, higher load reductions can be achieved on short timeframes compared to the average December month. Since the buildings cool down faster, we observe the inverse phenomenon for longer timeframe load reductions.
- A higher load reduction is observed in 2040 relative to 2030, attributed to an increased number of installed heat pumps.
- The 24h load reduction is negligible in most scenarios.

In concordance with our analysis of the duration, we explore the yearly distribution of the load reduction values to learn more about the load reduction values expected during varying climate conditions. We focus again on the building stock projections for 2040 in an average climate year, using the 18°C threshold. Figure 4 through Figure 8 illustrate how higher load reductions relate to colder temperatures. The 1h, 2h and 4h load reductions are found to be in the same order of magnitude. Conversely, the 8h timeframe offers a significantly lower load reduction while the load reduction for the 24h period is virtually non-existent with the set of parameters we selected.

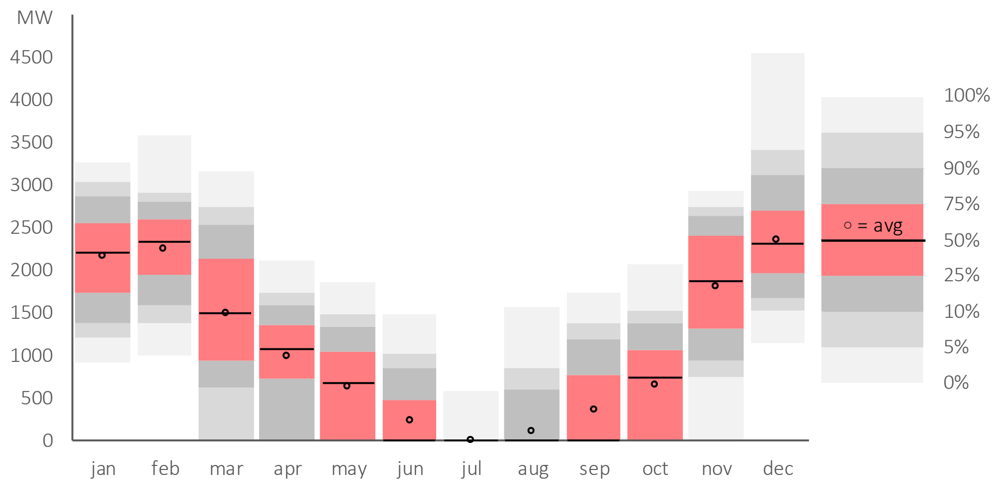


Figure 4: Distribution of the 1h load reduction (2040 / average climate year / 18°C threshold)

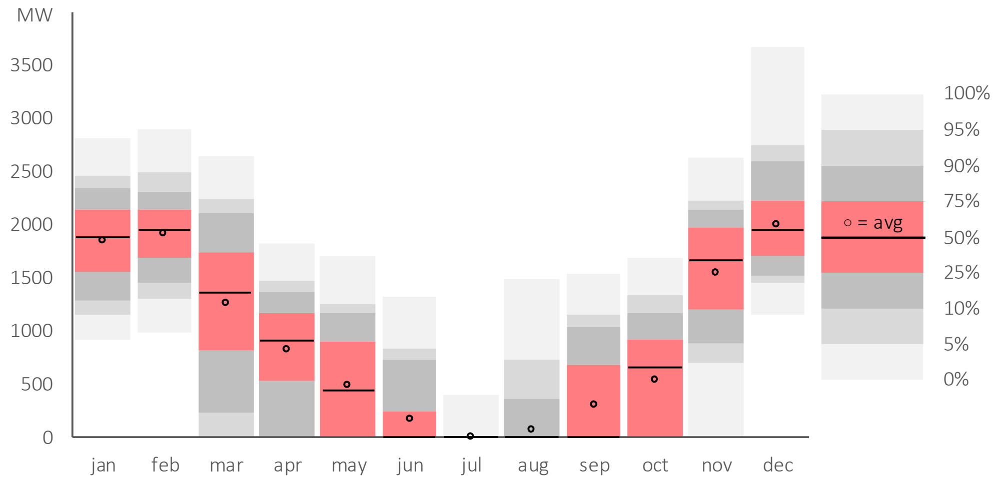


Figure 5: Distribution of the 2h load reduction (2040 / average climate year / 18°C threshold)

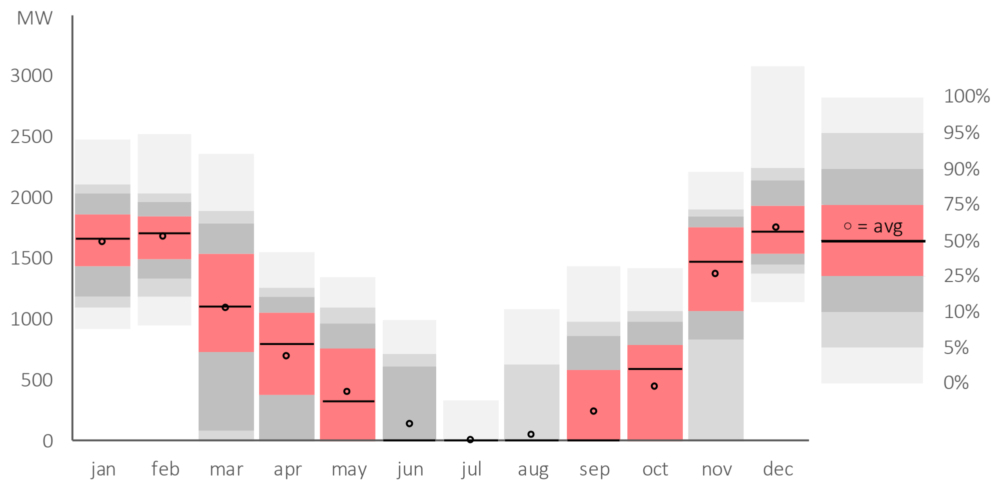


Figure 6: Distribution of the 4h load reduction (2040 / average climate year / 18°C threshold)

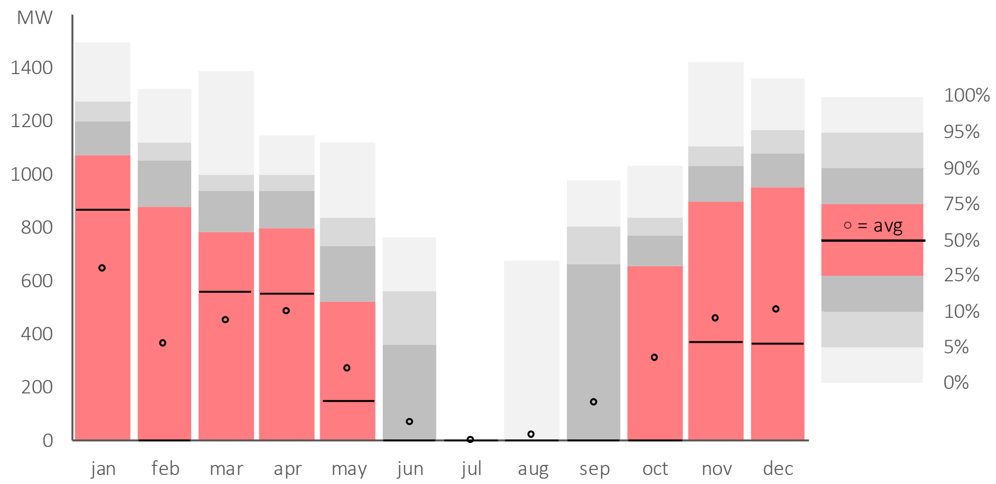


Figure 7: Distribution of the 8h load reduction
(2040 / average climate year / 18°C threshold)

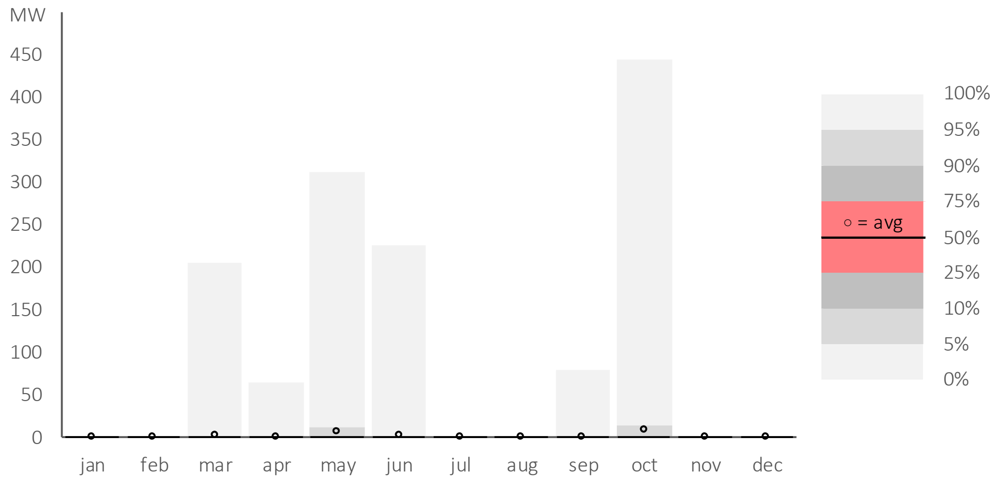


Figure 8: Distribution of the 24h load reduction
(2040 / average climate year / 18°C threshold)

4.3. Detailed analysis

For a more detailed analysis of the building stock flexibility under various climate and threshold assumptions, we use the flexibility curves as introduced in deliverable D1.1. These curves aggregate results for potential flexibility events that could arise at any hour within a month. For each flexibility event, the consequent load increase or reduction is determined for a span of 48 hours. Each post-event hour provides a percentile distribution, shedding light on both typical and extreme values.

To illustrate, we assess the flexibility curve for the building stock projected in 2040, referencing December in an average climate year, with an 18°C threshold. Figure 9 reveals several insights:

- **Initial response:** The initial load reduction averages 2500MW, but extreme values range between 1250 and 4250 MW. The core results, lying between the 25th and the 75th percentiles, are displayed in cyan. They are relatively concentrated between 2000 and 3000 MW.

- **Subsequent load:** Over the subsequent hours, the load reduction exhibits a declining trend, corresponding to certain buildings achieving the minimum temperature, prompting the heat pumps to reactivate.
- **Flex event duration:** On average, a flex event in December spans roughly 9 hours. However, specific events may last as briefly as 5 hours or extend up to 13 hours.
- **Recovery phase:** After the load reduction period, the recovery period begins where we observe load increases compared to the baseline scenario with normal heat pump operation. The average load increase peaks around 1000 MW, but extreme values go up to 2000 MW.
- **Extended recovery:** An extended 'tail' of minimal load increases is observed, extending beyond the 48-hour post-flex event period studied. Since the thermal mass of the buildings is cooled down during a flex event, it can take a long time to bring the building back to the original temperature.
- **Complex interaction:** Load reductions are sometimes witnessed during recovery. This stems from intricate interactions between the simulation results of the baseline and the flex scenarios. Disrupting the regular heating rhythm puts buildings in an altered state, even when they revert to the setpoint temperature. With the indoor temperature oscillating around this setpoint, occasional discrepancies in energy use arise, stemming from the temperature control algorithm coupled with the relatively extended 1-hour simulation timestep.
- **Percentile curve caveats:** It's pivotal to underscore that no specific flex event strictly adheres to the percentile curves' trajectory. For instance, the 100% percentile curve indicates the minimum load reduction or the maximum load increase found in the 744 hourly flex events during December. This maximum is gauged for each hour post intervention across the 48 hours. Evaluating the values from the 100% percentile, it's evident that a 5h load reduction of 1250 MW cannot demand a compensatory load surge of 2000 MW in the succeeding 10 hours.

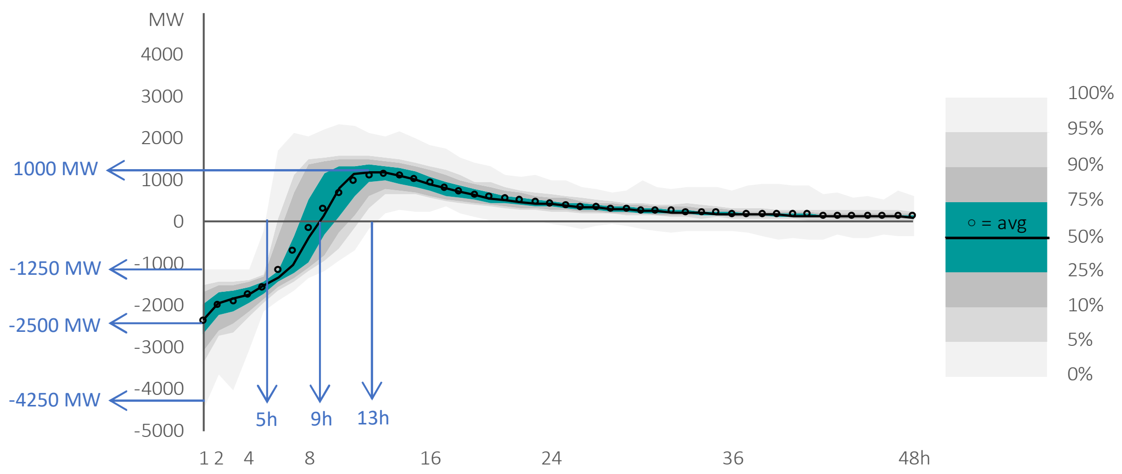


Figure 9: Flexibility curve December
(2040 / average climate year / 18°C threshold)

Flexibility curves have been produced for every projected building stock scenario spanning all months, offering a holistic view of annual flexibility. Detailed results for each scenario are catalogued in the Annexes, as outlined in Table 31.

Table 31: Annex scenario overview

Annex	year	climate	threshold
A	2030	cold	16°C
B	2030	cold	18°C
C	2030	cold	20°C
D	2030	average	16°C
E	2030	average	18°C
F	2030	average	20°C
G	2030	warm	16°C
H	2030	warm	18°C
I	2030	warm	20°C
J	2040	cold	16°C
K	2040	cold	18°C
L	2040	cold	20°C
M	2040	average	16°C
N	2040	average	18°C
O	2040	average	20°C
P	2040	warm	16°C
Q	2040	warm	18°C
R	2040	warm	20°C

In the subsequent sections, we will highlight key observations in our scenario analysis. Using the previously discussed flexibility curve as our reference point, we will compare it against curves from varied scenarios.

4.3.1. Threshold

Using the 2040 building stock in an average climate year as a reference, we emphasize the significance of the minimum temperature threshold, specifically for the month of December. Figure 10, Figure 11 and Figure 12 present the flexibility curves for thresholds of 16°C, 18°C, and 20°C, respectively. From these figures, we can deduce the following insights:

- A lower threshold primarily leads to flexibility events that have extended durations. Correspondingly, the recovery periods are prolonged.
- Analysing the scenarios for 16°C and 18°C thresholds, it's evident that a lower threshold doesn't necessarily translate to notably increased load reductions or increments. However, for the 20°C threshold, the load reduction is diminished, as certain buildings don't exhibit any flexibility due to their rapid cooldown within the initial hour.

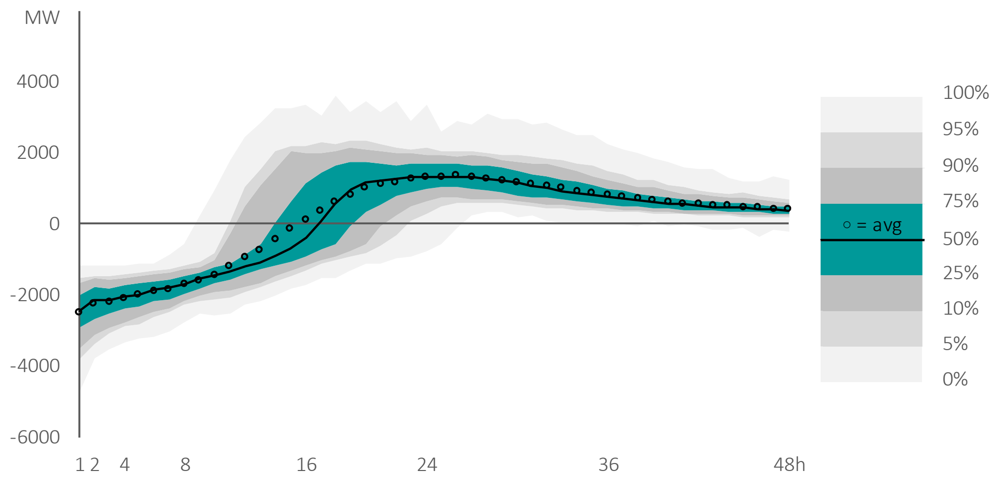


Figure 10: Flexibility curve December (2040 / average climate year / 16°C threshold)

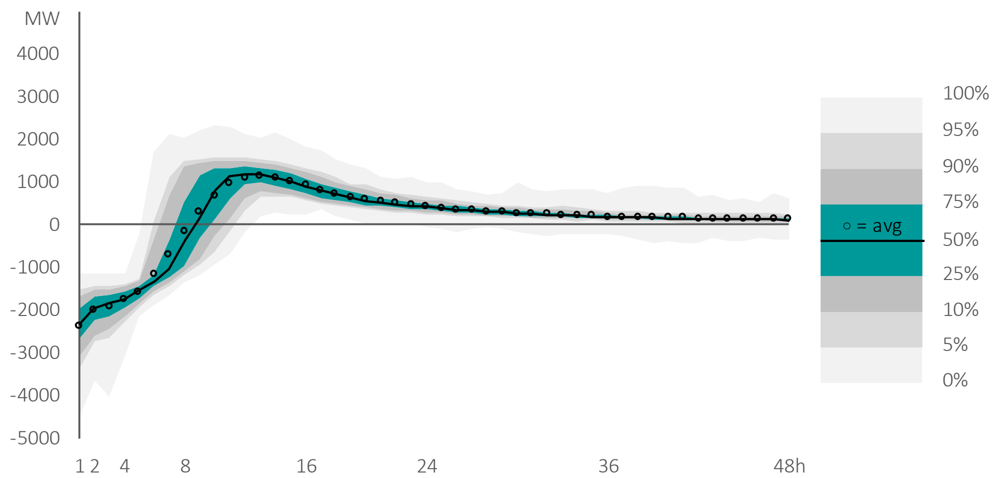


Figure 11: Flexibility curve December (2040 / average climate year / 18°C threshold)

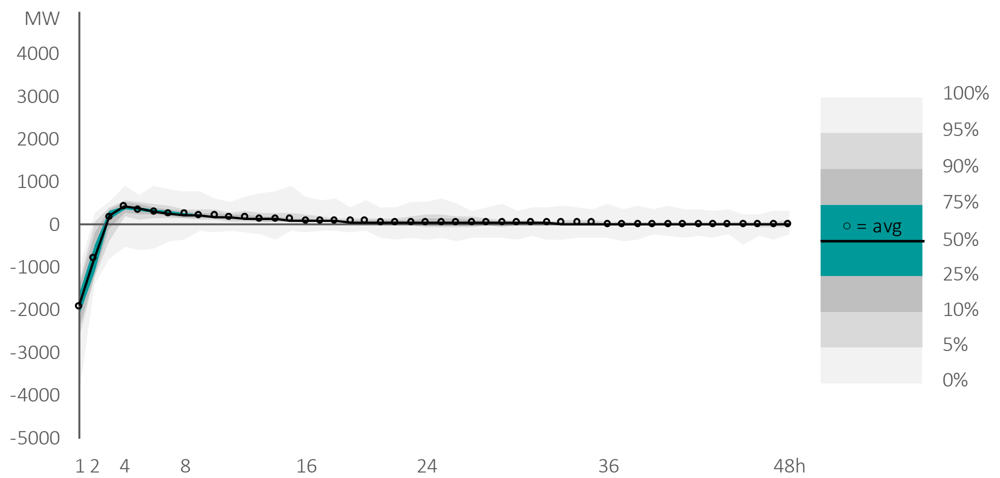


Figure 12: Flexibility curve December (2040 / average climate year / 20°C threshold)

4.3.2. Climate year

In this analysis, we once again center our attention on the month of December for the 2040 building stock, using the 18°C threshold. Observing the effects of an average, cold, and warm climate year in Figure 13, Figure 14 and Figure 15, the following insights can be drawn:

- During colder December months, there's a pronounced increase in both load reductions and load surges.
- Simultaneously, a colder December month correlates with flexibility events that are more time-limited in duration.

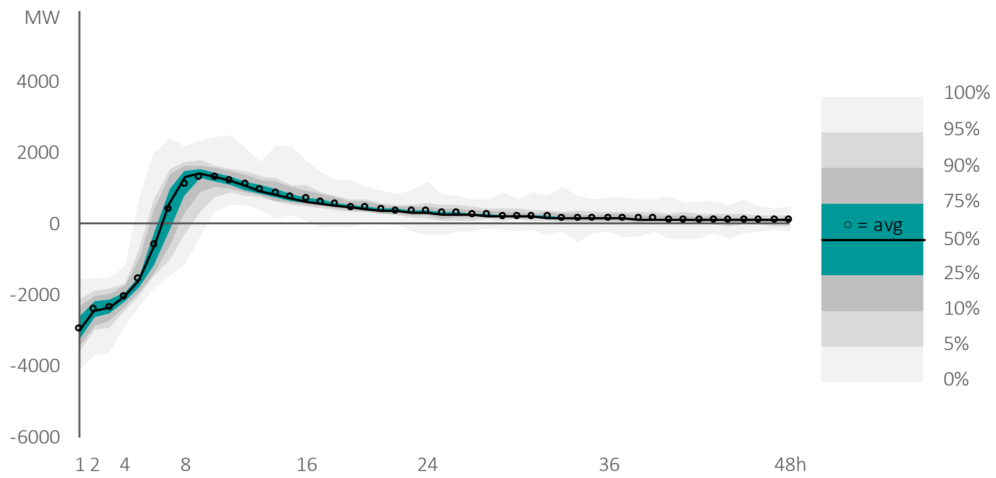


Figure 13: Flexibility curve December
(2040 / cold climate year / 18°C threshold)

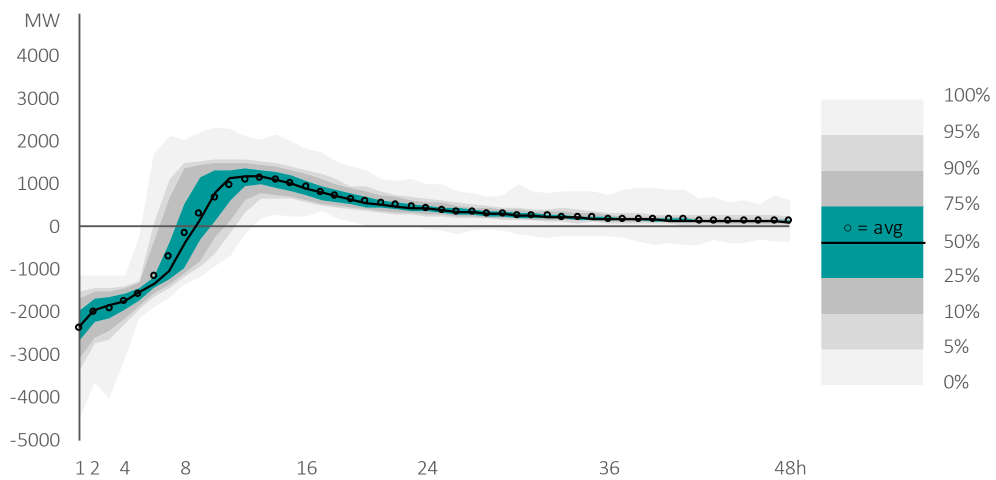


Figure 14: Flexibility curve December
(2040 / average climate year / 18°C threshold)

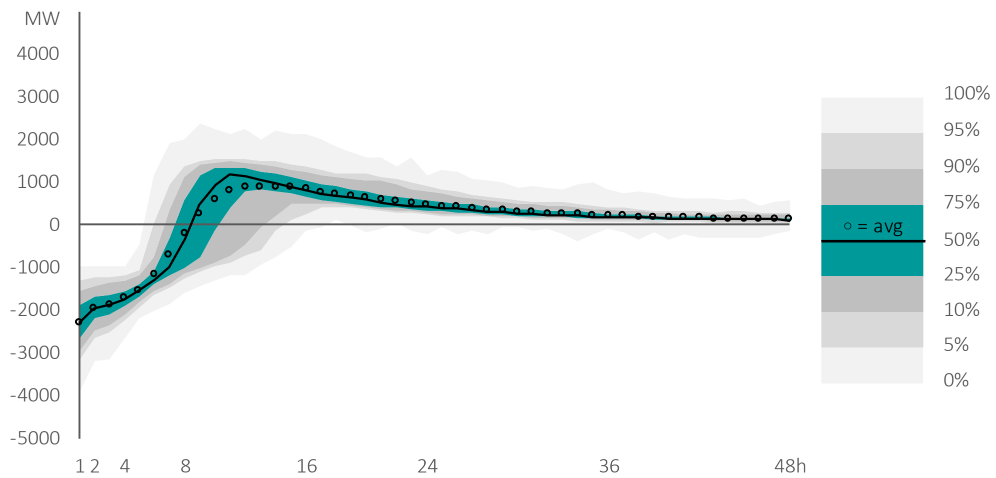


Figure 15: Flexibility curve December
(2040 / warm climate year / 18°C threshold)

4.3.3. Seasonal variation

Our focus has been primarily anchored to the December month due to the more pronounced electricity usage by heat pumps during winter, resulting in a higher flexibility potential. However, it's also important to consider what possibilities exist during the shoulder seasons and summer. Through Figure 16, Figure 17 and Figure 18, we compare the flexibility curves in December, March and August for the 2040 building stock during an average climate year using the 18°C threshold. The following observations can be made:

- For December, the curve displays the typical profile we previously elaborated upon.
- The average load reductions and increases for March are lower compared to the December results. As a result of the broad fluctuations in outdoor temperatures, we observe a wide-ranging distribution in both the duration as well as the magnitude of load reductions and increases.
- In August, the flexibility potential is nearly negligible. The core results, depicted in cyan, are conspicuously absent, which indicates that in over 75% of all flex events, neither load reductions nor increases were registered. A few sporadic load increases and reductions can be noted; these are reflective of certain atypical cooler nights when some buildings, in theory, might necessitate heating to maintain an ambient 21°C according to our simulations. However, such a scenario is slightly counter-intuitive in the real world. More often than not, heating systems would likely be turned off, resulting in a null flexibility provision during these periods.

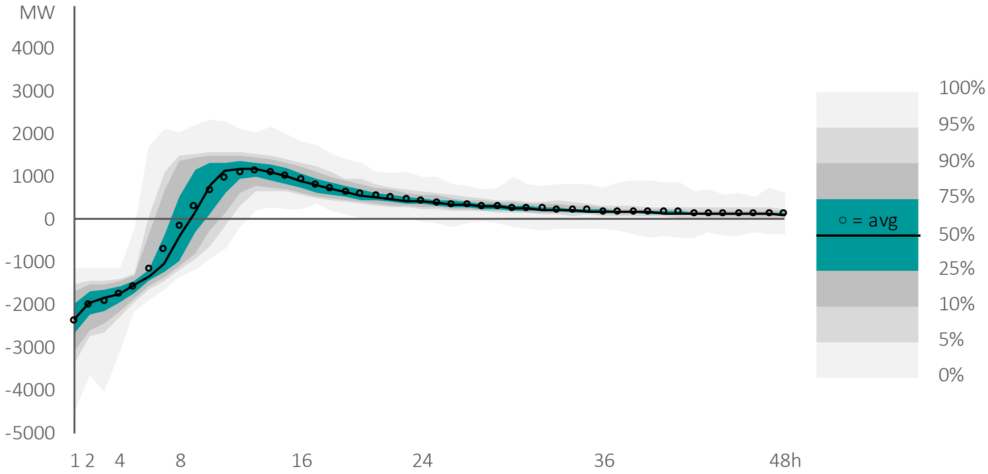


Figure 16: Flexibility curve December
(2040 / average climate year / 18°C threshold)

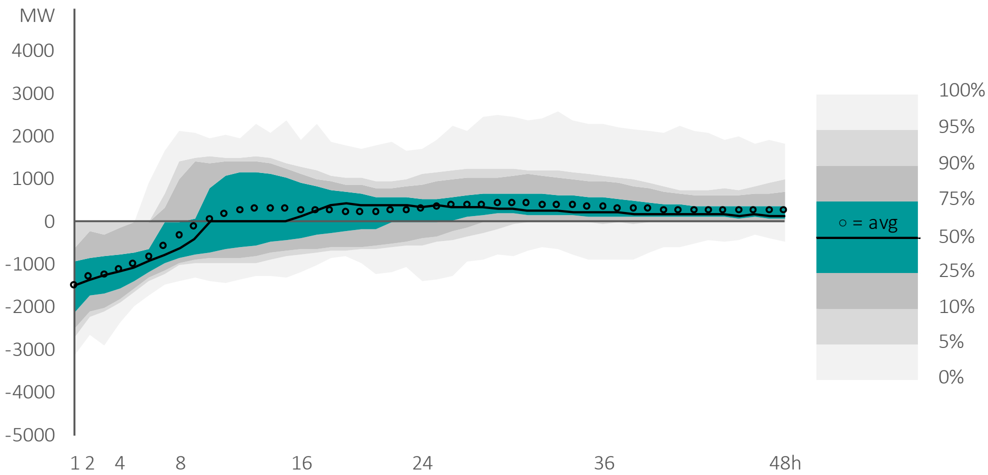


Figure 17: Flexibility curve March
(2040 / average climate year / 18°C threshold)

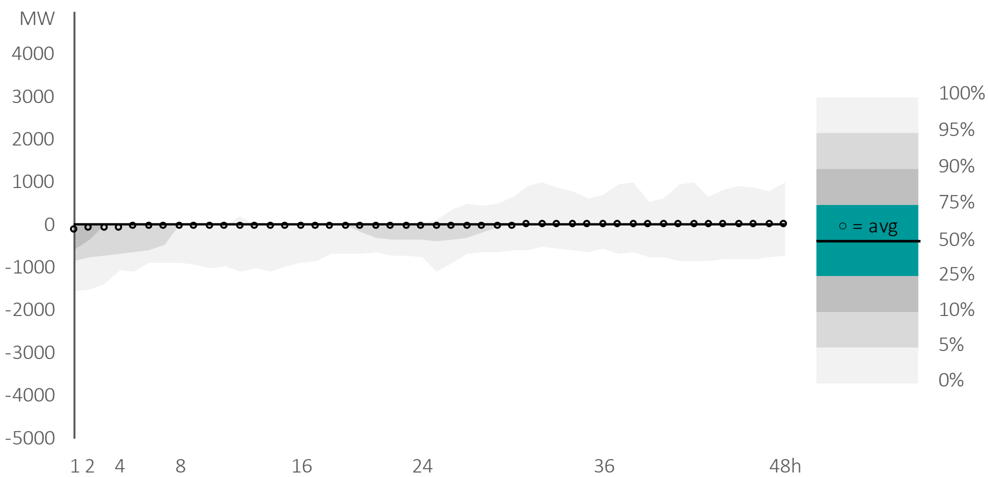


Figure 18: Flexibility curve August
(2040 / average climate year / 18°C threshold)

4.3.4. 2030 vs. 2040

Revisiting the scenario characterized by an average climate year and an 18°C threshold, we examine the December month for the 2030 and 2040 building stocks as depicted in Figure 19 and Figure 20. The patterns appear notably consistent across both figures, though they vary in terms of absolute values for load reductions and increases. Naturally, with a larger number of heat pumps installed, the flexibility potential is elevated.

Theoretically, the different mix in 2030 and 2040 of building types, insulation levels, heat pump types and heat emission systems should have an impact of the aggregated flexibility curve, but the effect is not easily observed in the charts.

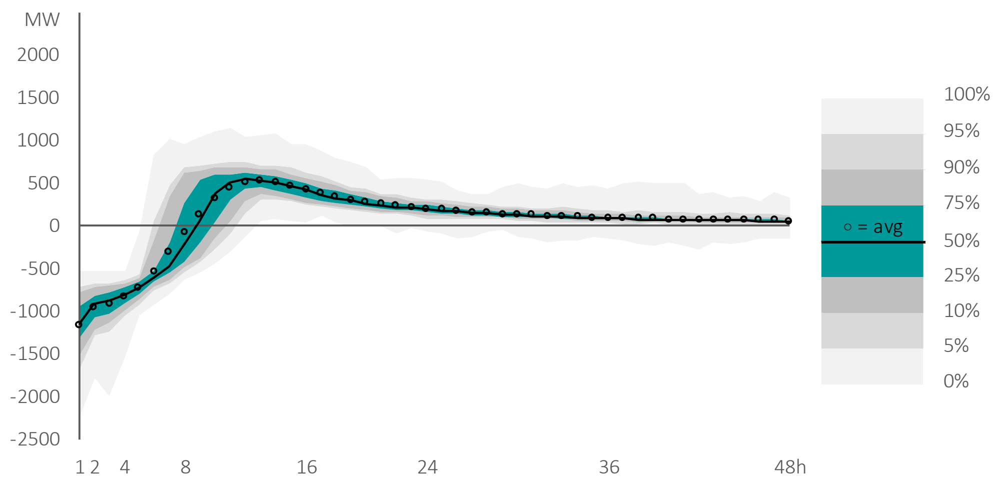


Figure 19: Flexibility curve December
(2030 / average climate year / 18°C threshold)

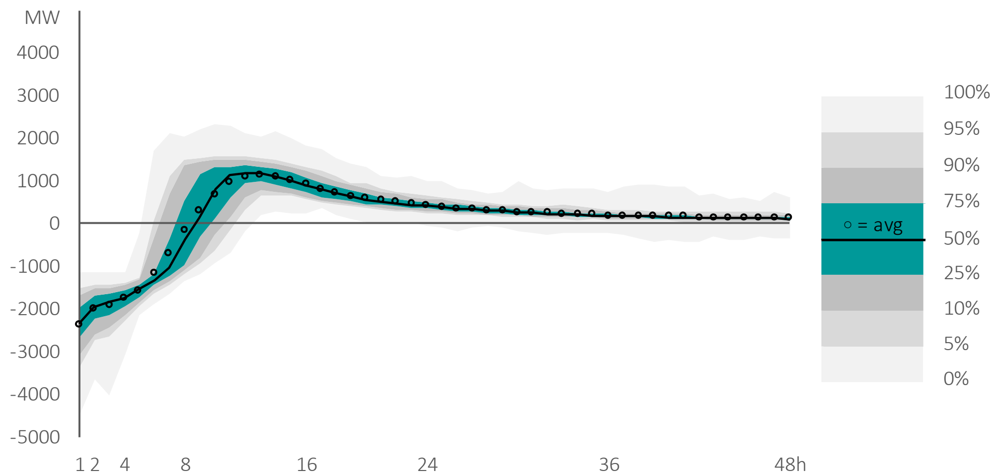


Figure 20: Flexibility curve December
(2040 / average climate year / 18°C threshold)

5. CONCLUSIONS

The flexibility potential of the future Belgian residential building stock was evaluated in this report. A clustering methodology was developed to group all residential buildings according to specific attributes such as building geometry, insulation level, heat pump type, heat emission system and heating regime. Though we capitalized on existing data repositories to envisage the upcoming building stock, it's imperative to recognize that projections inherently embody certain assumptions - specifically concerning renovation trajectories, heat pump adoption rates, and the employment of particular heat emission systems.

In the FlexSys deliverable D1.1, we dissected the technical flexibility potential of heat pumps on the individual building level. We aggregated the results from the individual building simulations and calculated the total building stock flexibility based on the estimated amount of dwellings in each specific cluster.

The technical flexibility potential of the building stock is evaluated by deactivating all heat pumps until a minimum threshold temperature is reached in the buildings. After the initial load reduction phase, a load increase phase follows, where the buildings are reheated back to the original 21°C setpoint.

As we already discussed in the D1.1, the individual building simulations are impacted significantly by assumptions made in the building model, introducing some uncertainty in the results. In this phase of the research, we add another layer of uncertainty with our building stock assumptions. Consequently, the most important take-aways of this research are the relative variation across the scenarios we studied, and the overarching trends identified. When interpreting the results of the flexibility indicators, it's more prudent to consider the order of magnitude rather than fixate on the exact numerical values.

The 18°C threshold is regarded as a realistic lower temperature limit before reactivating the heat pumps. It results in a limited comfort loss, yet offers in a significant amount of flexibility. This threshold ensures a balanced compromise – ensuring comfort isn't extensively compromised while still reaping appreciable flexibility benefits. Taking the December month in a typical climate year as an example, we noted an immediate load reduction approaching 2500 MW for the 2040 scenario. This value progressively diminishes, eventually nullifying after a span of approximately 9 hours. Following this phase, a discernible load increase materializes relative to the standard scenario, peaking at 1000 MW around 4 hours into the recovery. This surge tapers off, extending well beyond the flex event's inception. In the context of the 2030 scenario, it's appropriate to slash these values by half.

Studying a large variation of building stock scenarios, we highlighted the importance of the temperature threshold and outdoor temperatures. Lower thresholds are related to flexibility events with a longer load reduction and load increase phase. Lower outdoor temperatures amplify the load reduction potential, but result in flexibility events with a shorter duration.

6. LIMITATIONS AND PERSPECTIVES

Certain limitations in our research methodology concerning individual building flexibility were already outlined in D1.1. These constraints reverberate in our extrapolation to the Belgian building stock. To recap, we noted constraints in:

- Building model: Our approach simplifies the building's geometry, its physical attributes, and the heating system.
- Simulation parameters: We didn't distinguish between thermal capacity and heat pump types.
- Flexibility indicators calculation: The research primarily zeroes in on the period post-flex event that registers energy savings, less so on the energy consumption during temperature recovery. Furthermore, our flexibility measurement leans towards the conservative side.

In addition to these, several other constraints concerning our building stock methodology surface:

- Building stock construction
  - Our analysis rests on reports regarding Flemish EPC/EPB data, which we've extrapolated to the broader Belgian building stock, including the Brussels and Walloon regions.
  - Renovation rates and the proportion of deep energy renovations come with significant uncertainty.
  - Similar uncertainty surrounds the uptake rate of heat pumps during renovations and at the end-of-life replacements.
  - We've largely estimated the heat pump distribution across different building types and insulation levels.
  - Our assessment regarding the split between underfloor and radiator heating at varying insulation levels is based on our estimations.
  - Given the absence of data on heating regimes, we've had to rely on assumptions.
- Result aggregation
  - We aggregated the results for the individual simulations, using weightings derived from our building stock construction. By mixing flexibility events with a longer and shorter duration, the recovery phase of one building type may take place during the flexibility phase of another building type. As such, we are adding negative values (load reductions) with positive values (load increases), resulting a number which might be net negative or positive. While we didn't study the recovery phase of the flexibility events in de individual simulations, it has a significant effect on the aggregated flexibility curves.

It's important to highlight that our approach involves a simplified control strategy. Specifically, we deactivate all heat pumps across the building stock simultaneously during a flex event. However, this might not necessarily align with the optimal strategy in real-world scenarios, where grid requirements may vary.

In a theoretical context, there's potential for improved flexibility over extended periods. For instance, by excluding building types with shorter flexibility durations, we could prevent the overlapping of additional energy consumption in some buildings with energy savings in others. Additionally, by segmenting the building stock and deactivating heat pumps in a staggered fashion, we might achieve extended flexibility events with lesser load reduction. But it's important to note that such an approach would demand a larger second group of buildings, ensuring that energy savings neutralize the recovery energy consumption of the initial group.

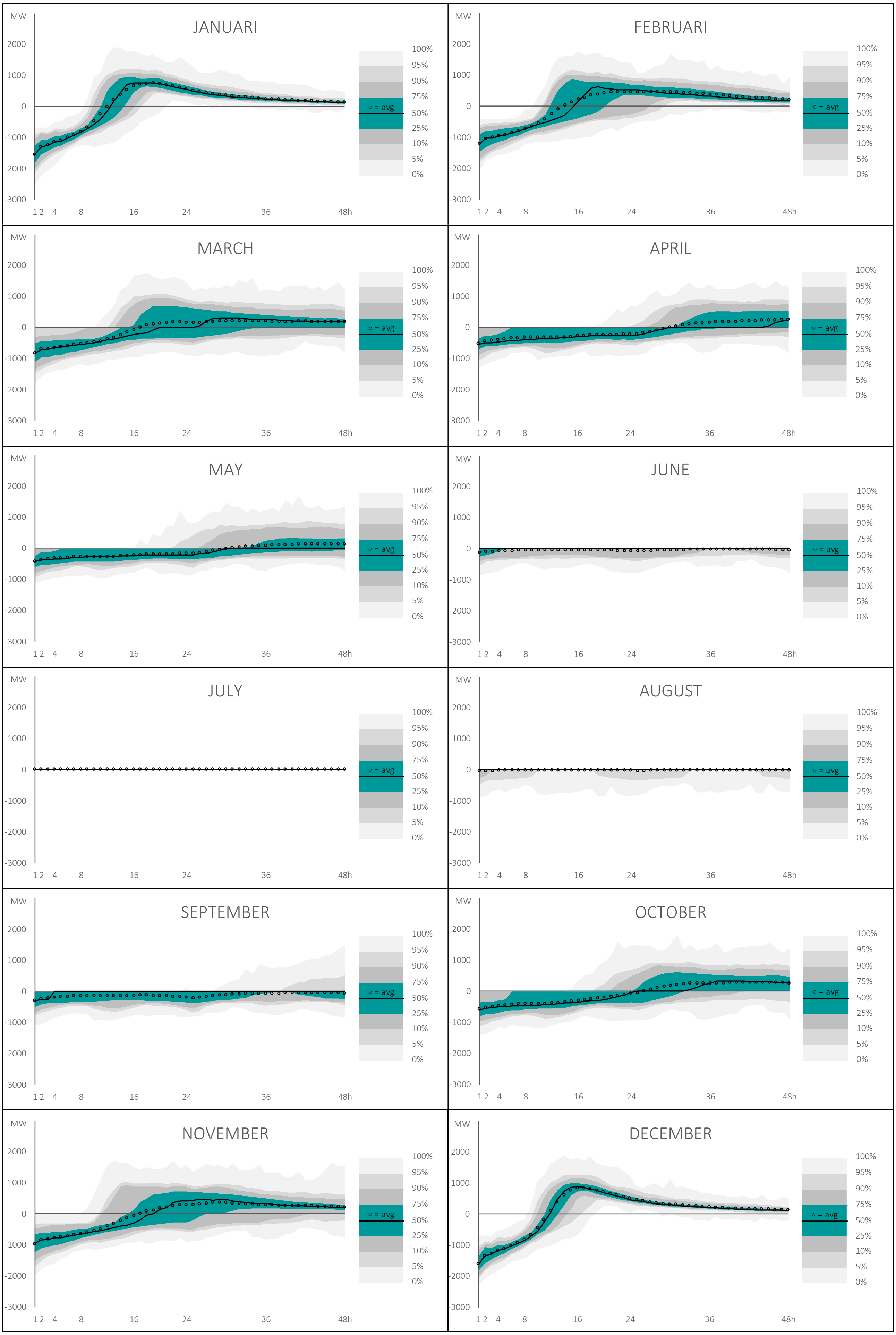
However, we didn't delve into these advanced strategies within this research. The computational intensity and the need for intricate control mechanisms over the building stock made them out of scope of this project.

While our analysis focuses on the technical potential of heat pump flexibility across the building stock, it presupposes that all heat pumps will function as distributed assets. However, practical challenges exist. For instance, several older heat pumps might not be equipped for smart grid integration. Furthermore, only a select number of heat pumps might be integrated into home energy management systems. It's also worth noting that even if heat pumps are technically primed for flex events, they might not participate if occupants override or halt the event.

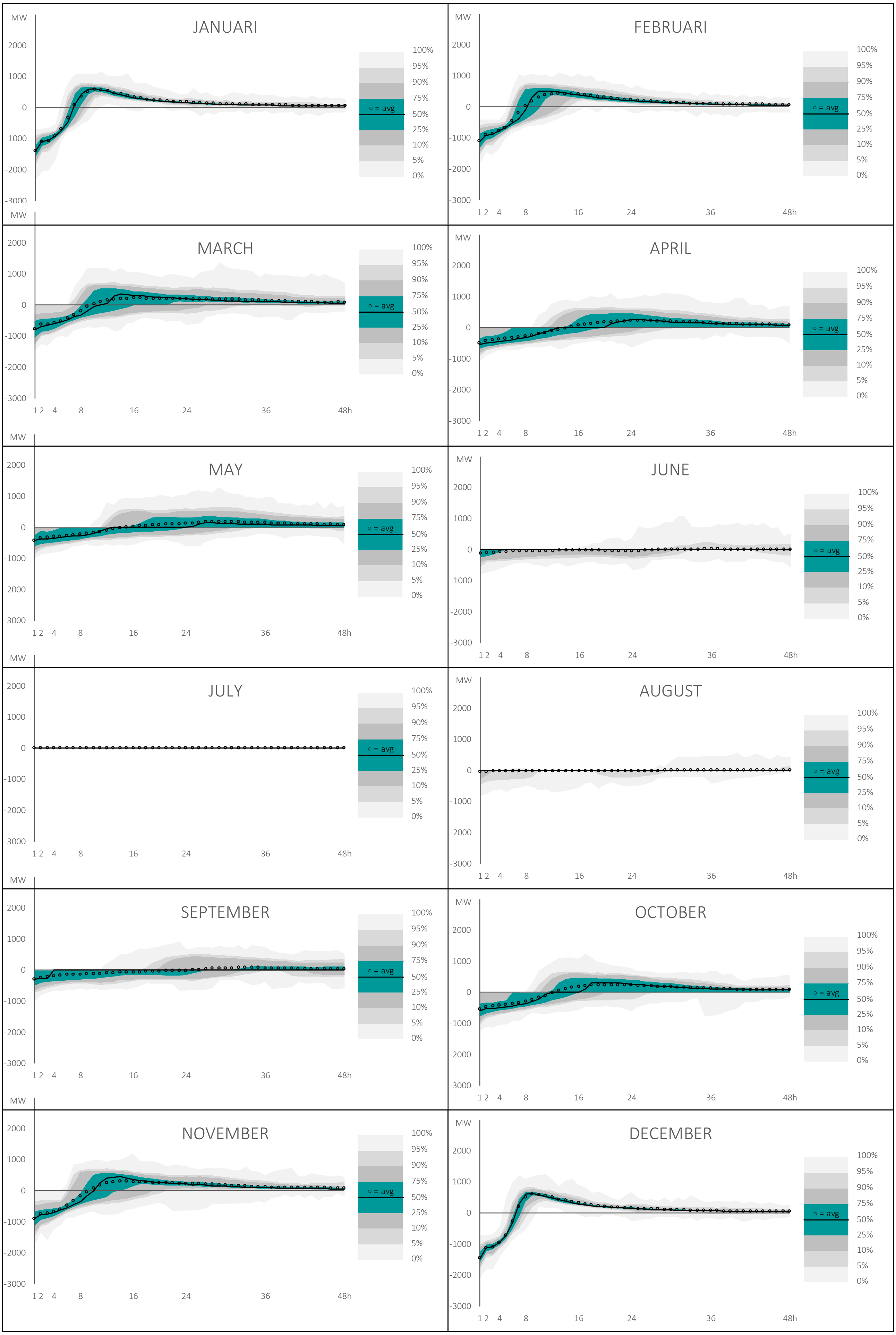
7. REFERENCES

1 https://statbel.fgov.be/en/open-data/cadastral-statistics-building-stock
2 https://statbel.fgov.be/en/themes/housing/building-permits
3 Cijferrapport: 10 jaar energieprestatieregelgeving. Procedures, resultaten en energetische karakteristieken van het Vlaamse gebouwenbestand – periode 2006 – 2015, Vlaams Energieagentschap, april 2016.
4 https://www.vlaanderen.be/epb-pedia/epb-beleid/epb-in-cijfers
5 Studiedag 5 jaar Renovatiepact: Vlaamse renovatiestrategie 2050: de weg naar energiezuinige en koolstofarme gebouwen, december 2019.
6 Heylen, K. & Vanderstraeten, L. (2019). Wonen in Vlaanderen anno 2018. Leuven: Steunpunt Wonen.
7 Van Hove M., Delghust M., Janssens A. (2021). Analyse naar de haalbaarheid van statistische modellen die energiegebruik in woningen kunnen voorspellen op basis van gebouwparameters.
8 https://apps.energiesparen.be/energiekaart/vlaanderen/premies-res-tijdreeks-algemeen
9 Adequacy and flexibility study for Belgium 2024-2034. Elia. https://elia.group/ADEQFLEX-EN

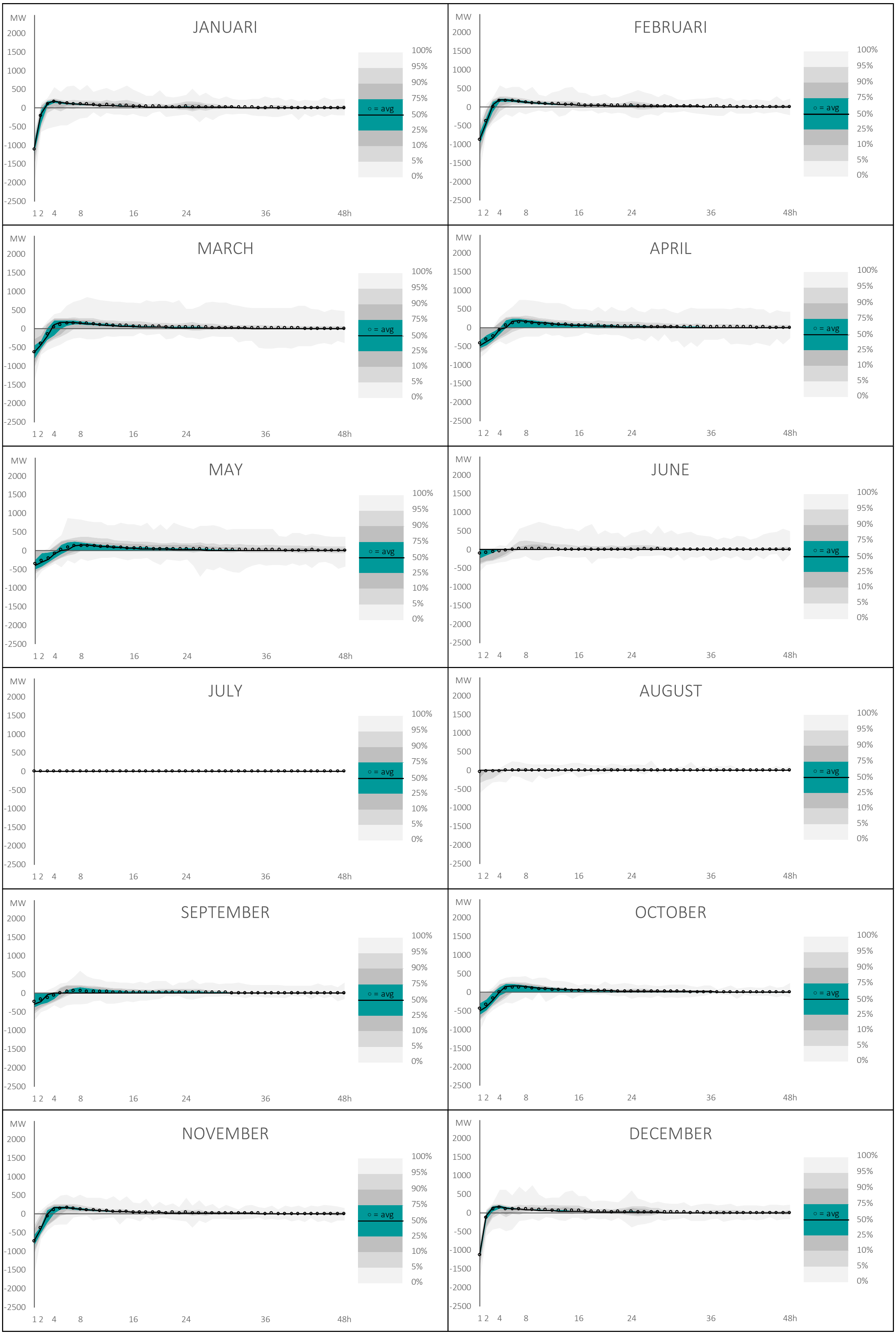
ANNEX A: FLEXIBILITY CURVES 2030 / COLD YEAR / 16°C



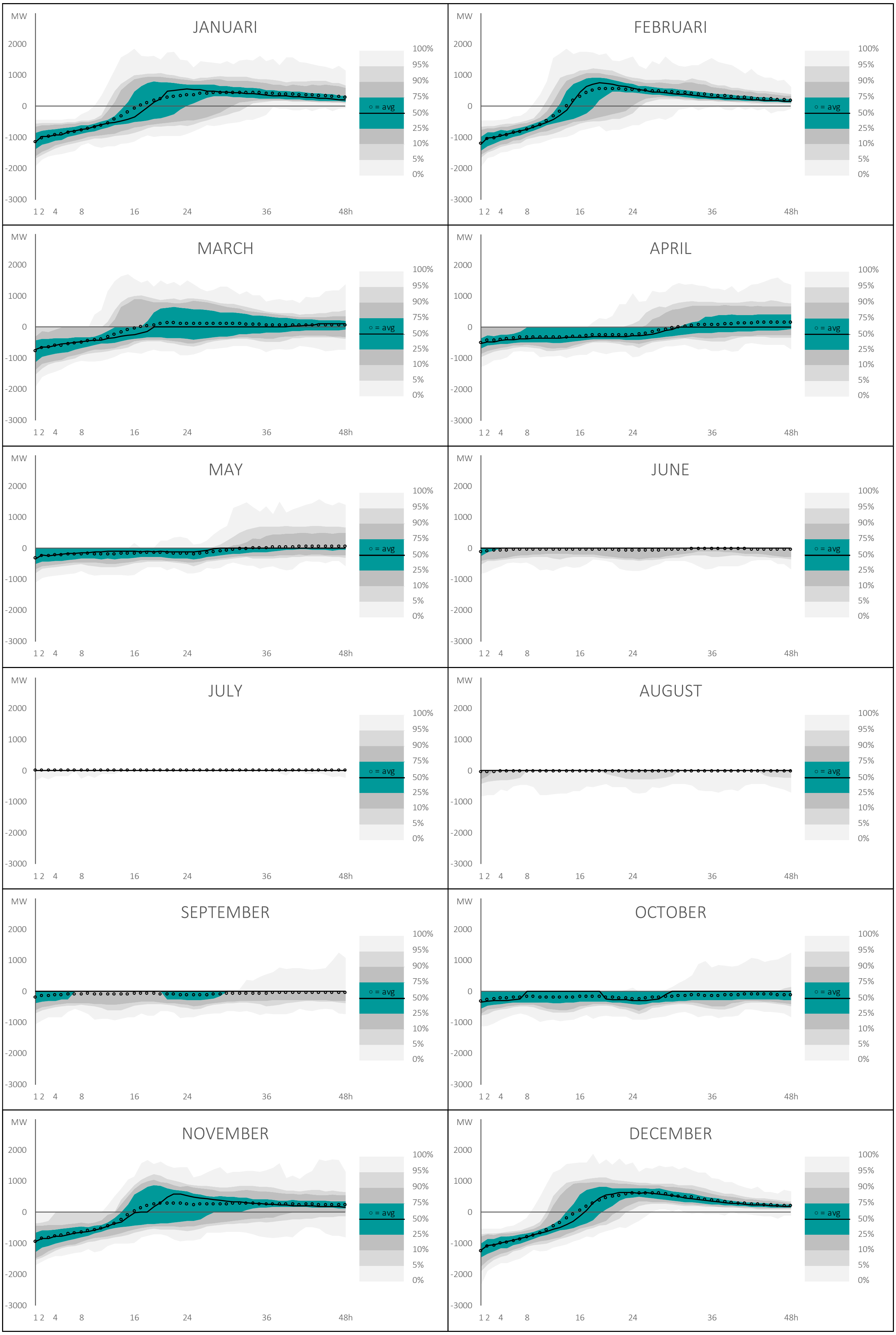
ANNEX B: FLEXIBILITY CURVES 2030 / COLD YEAR / 18°C



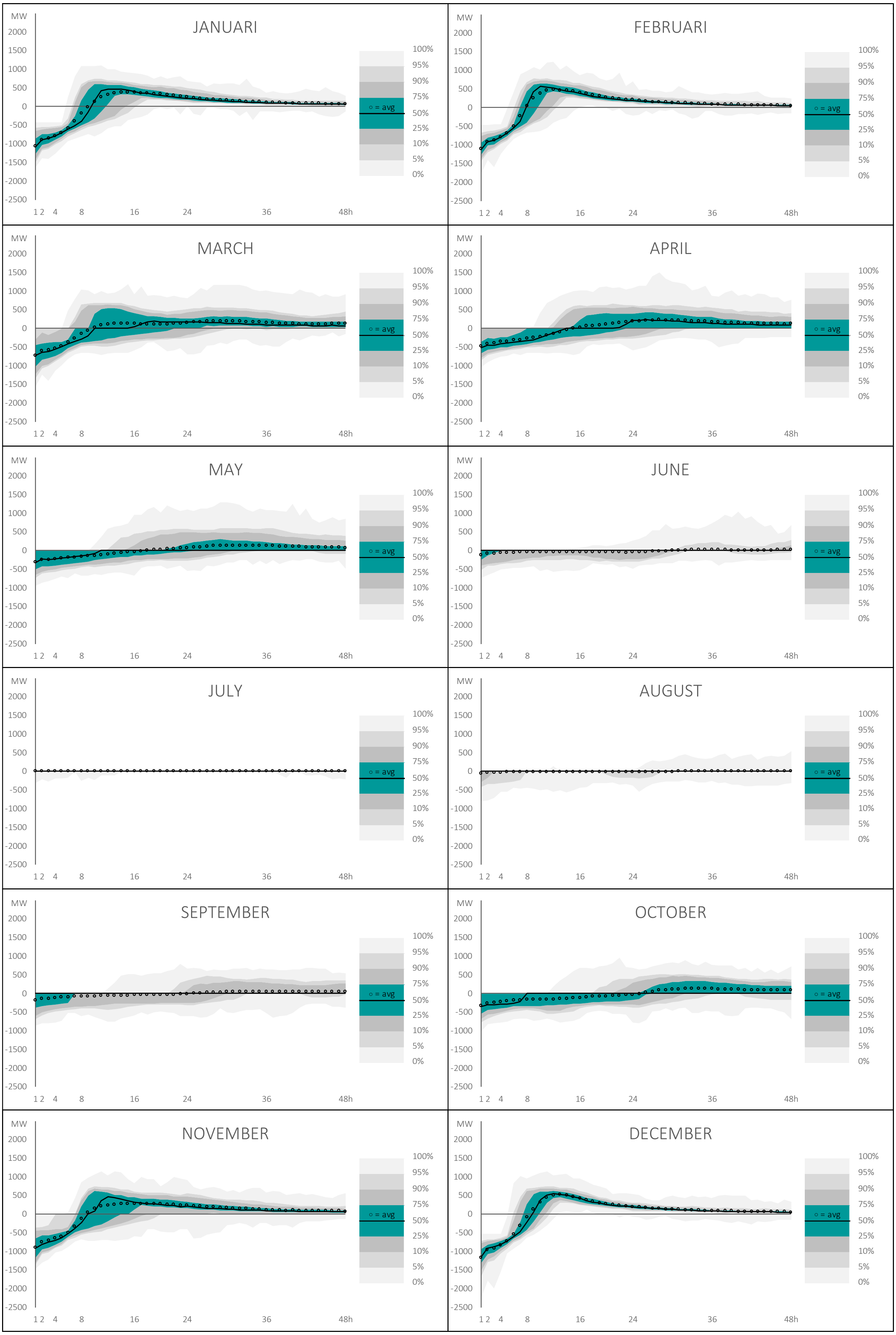
Annex C: Flexibility curves 2030 / Cold year / 20°C



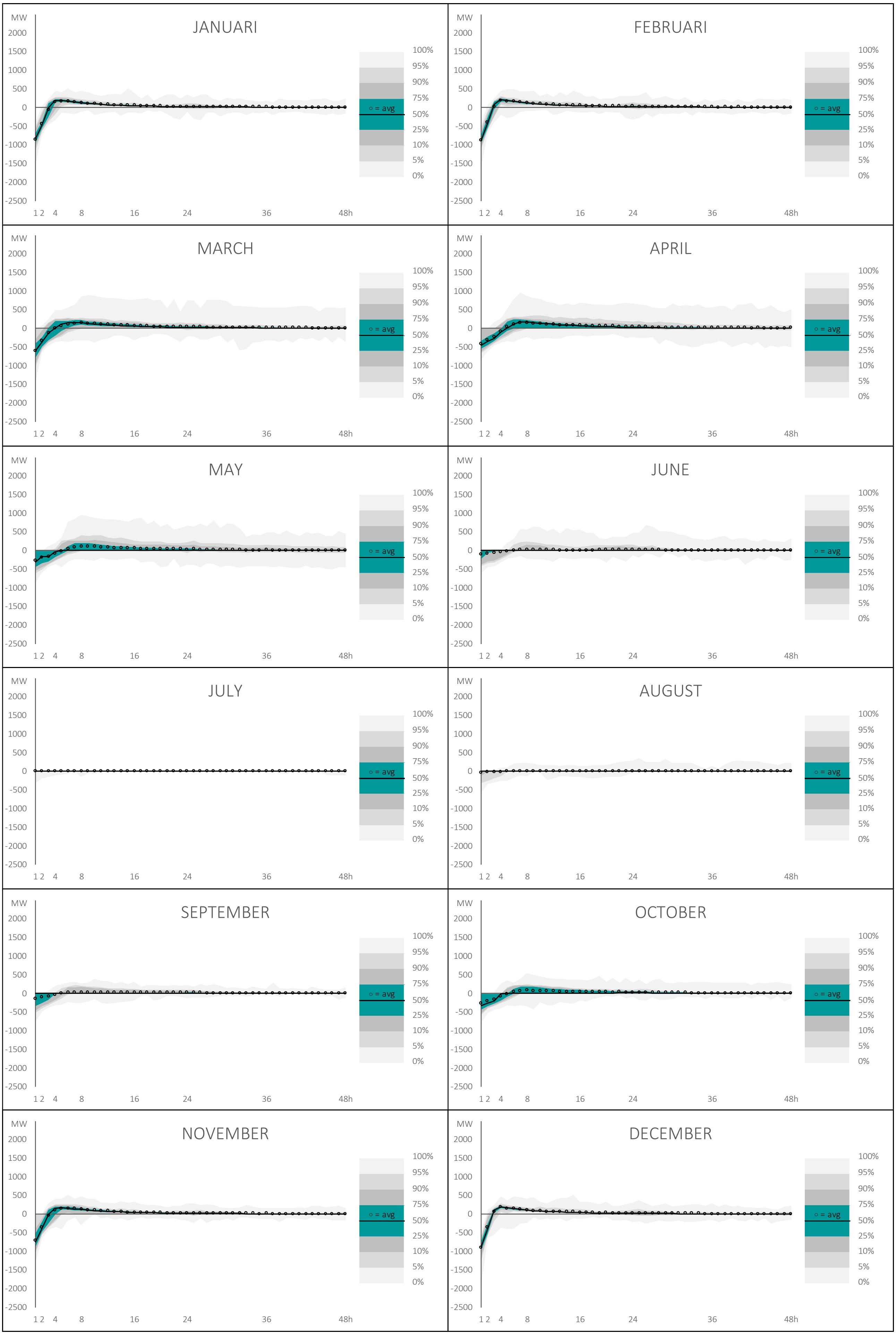
ANNEX D: FLEXIBILITY CURVES 2030 / AVERAGE YEAR / 16°C



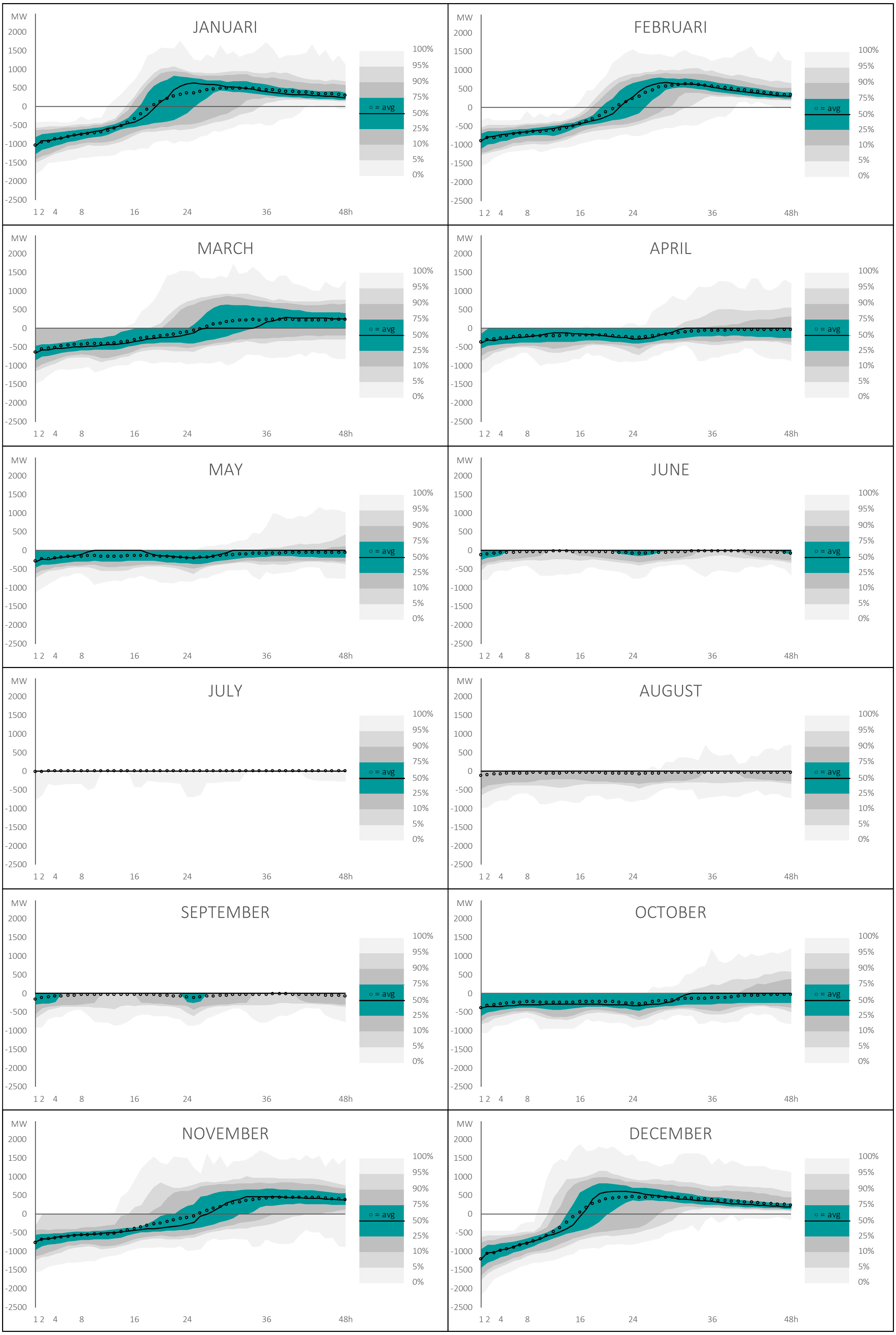
ANNEX E: FLEXIBILITY CURVES 2030 / AVERAGE YEAR / 18°C



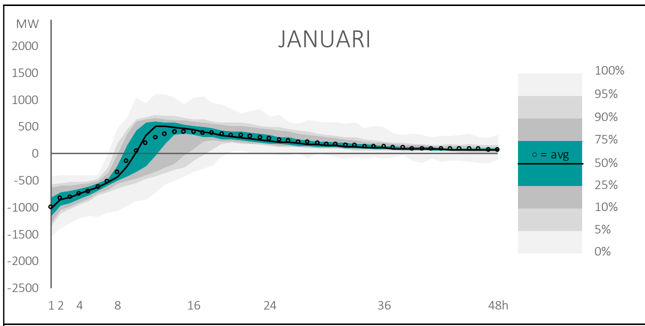
ANNEX F: FLEXIBILITY CURVES 2030 / AVERAGE YEAR / 20°C

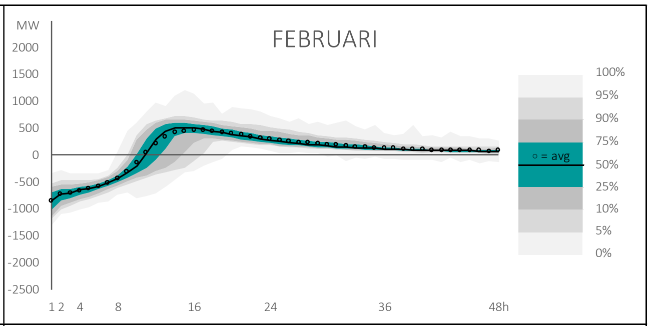


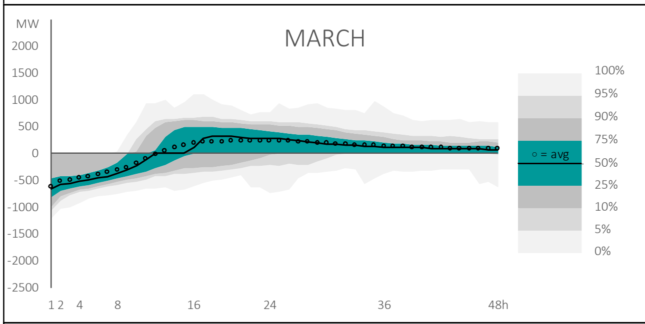
ANNEX G: FLEXIBILITY CURVES 2030 / WARM YEAR / 16°C

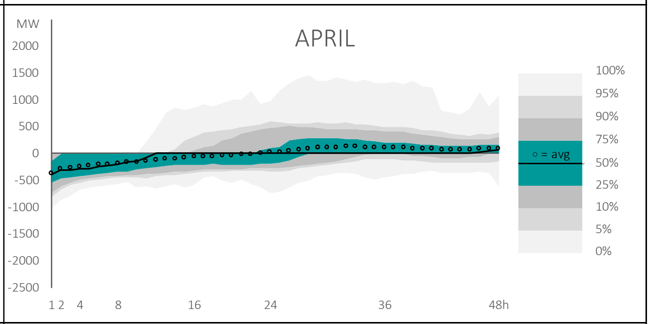


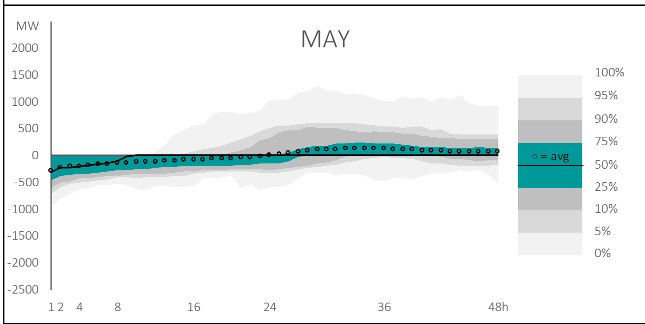
Annex H: Flexibility curves 2030 / Warm year / 18°C

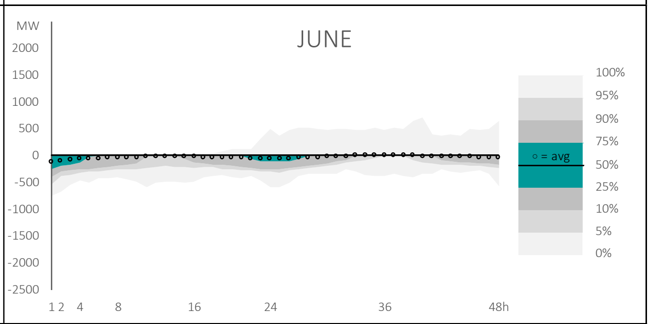


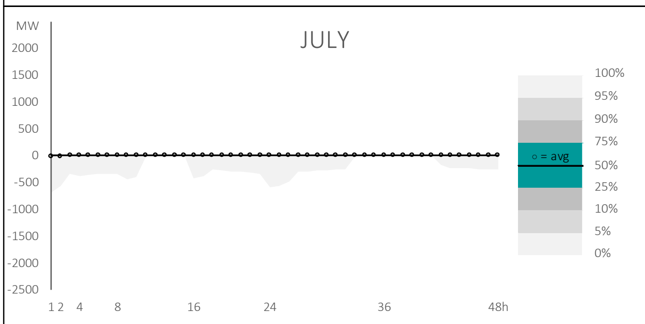


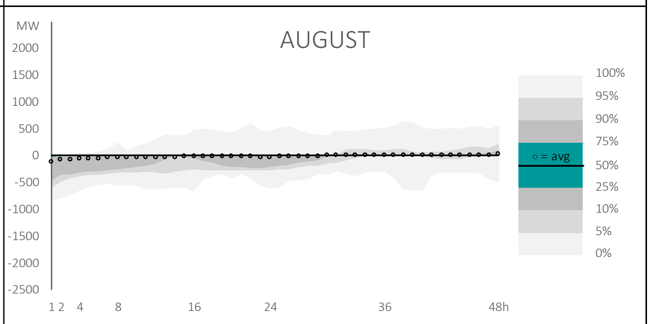


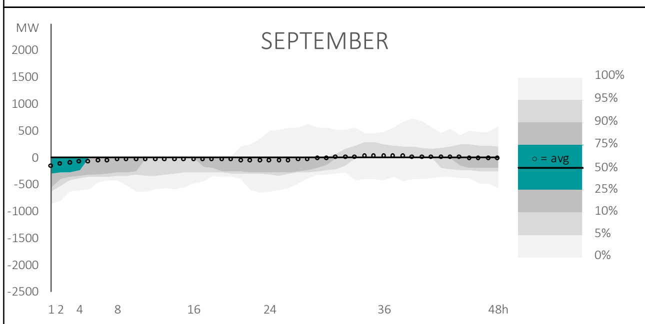


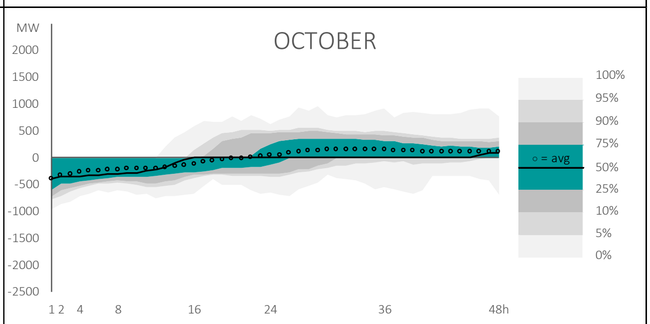


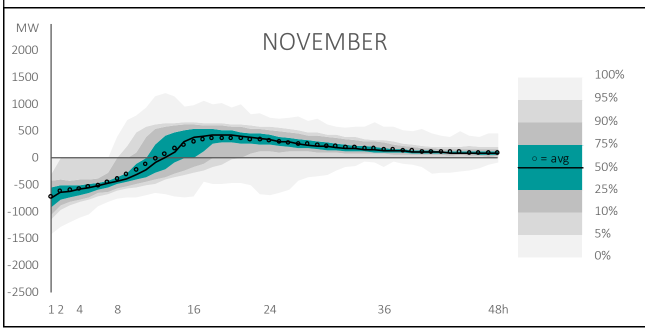


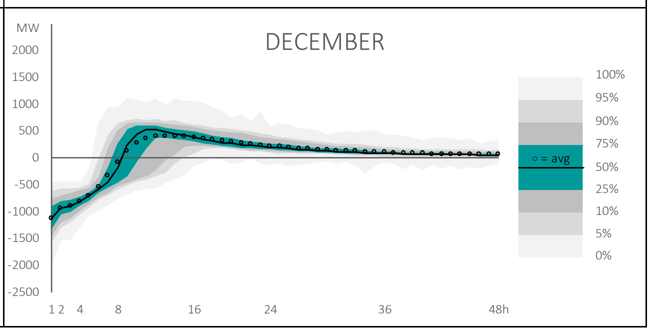




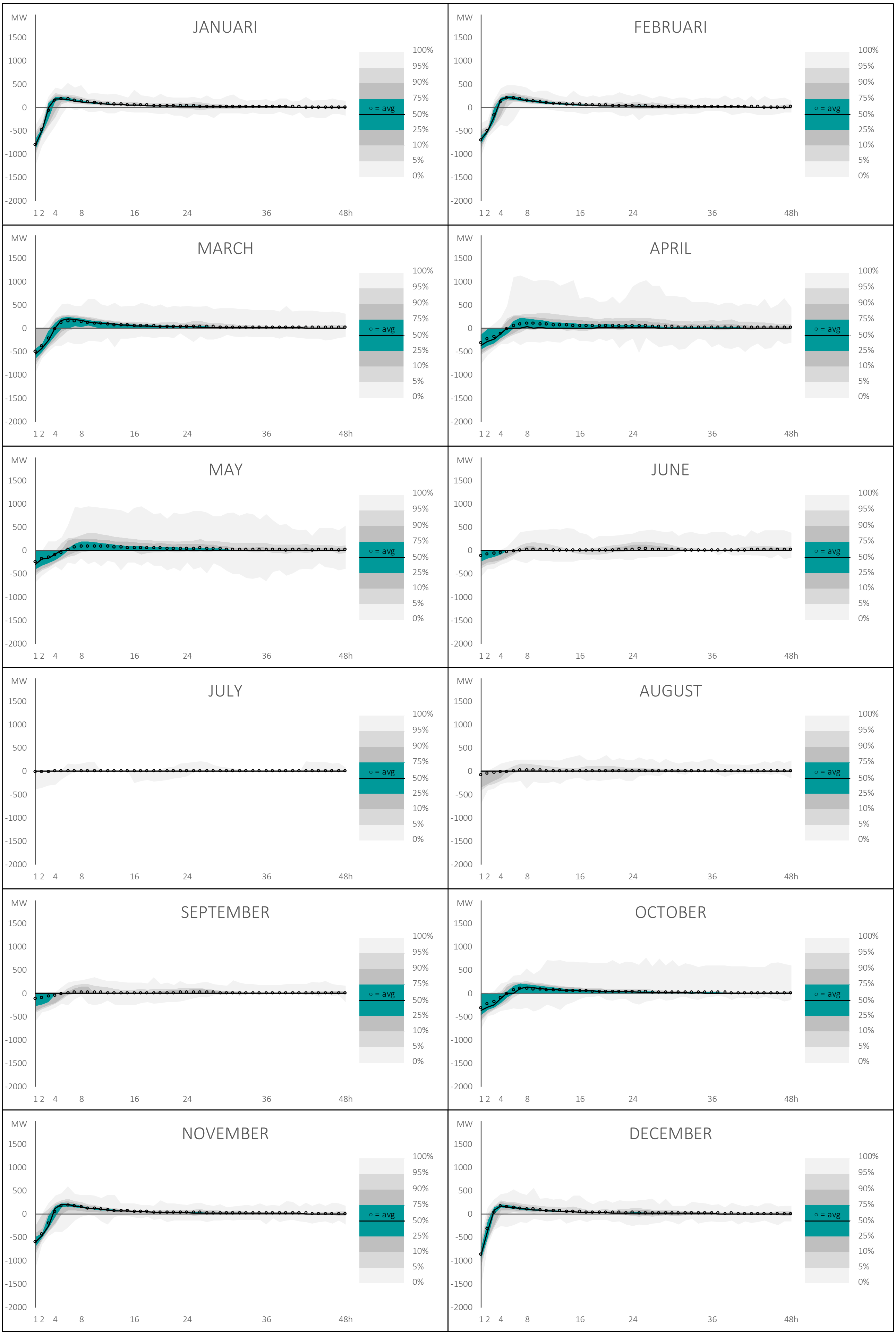




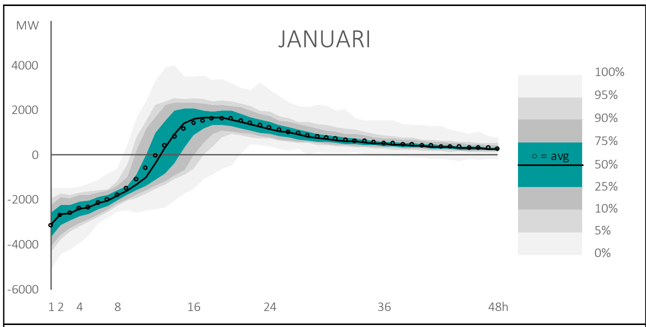


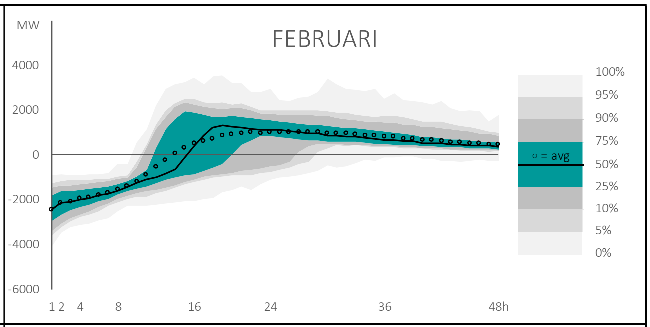


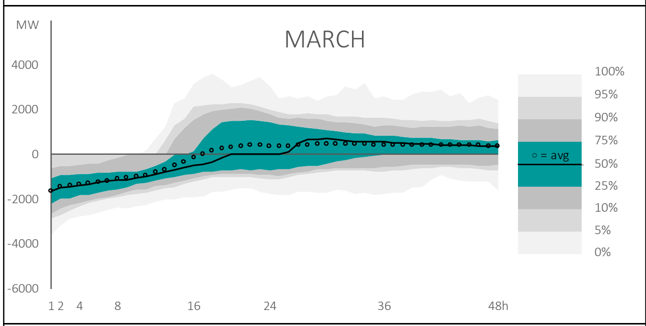
Annex I: Flexibility curves 2030 / Warm year / 20°C

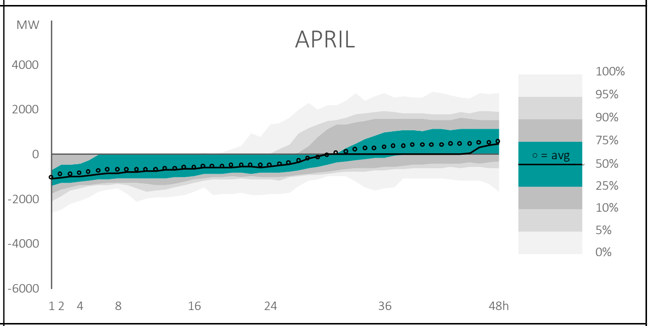


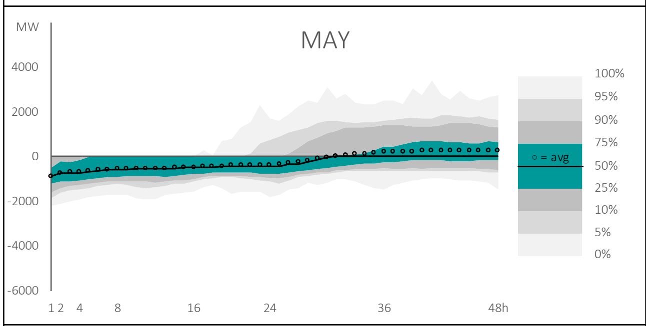
ANNEX J: FLEXIBILITY CURVES 2040 / COLD YEAR / 16°C

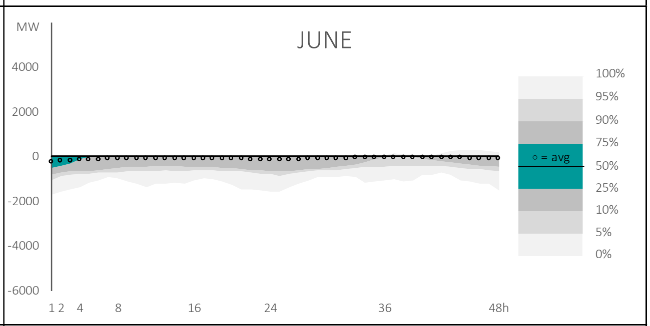


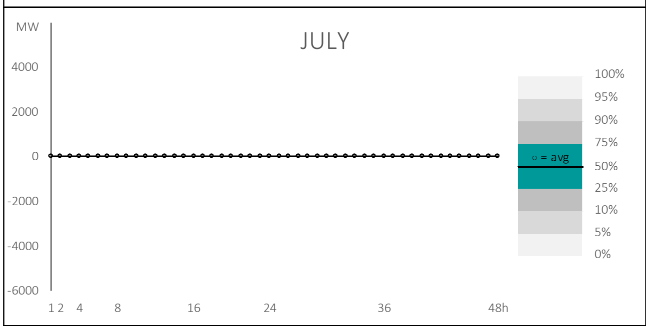


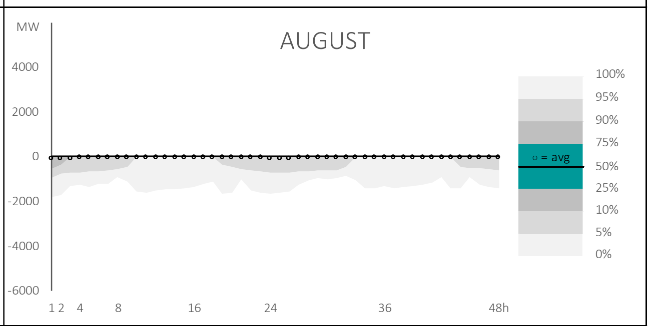


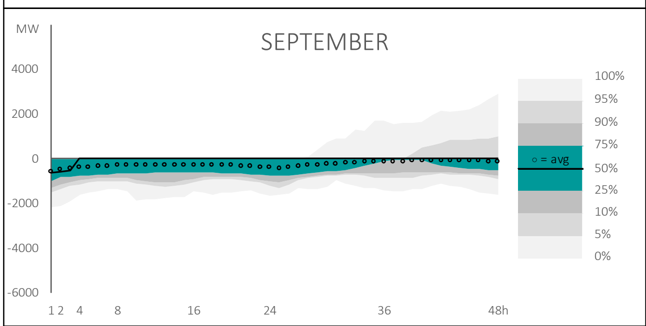


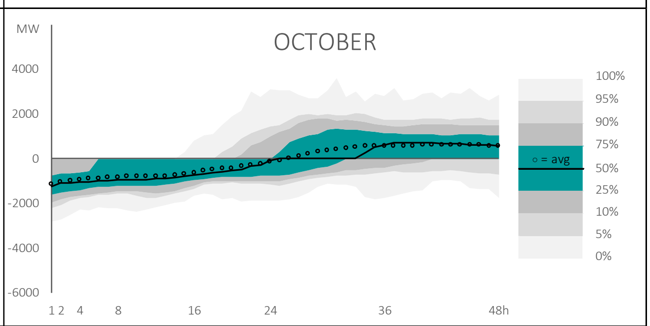


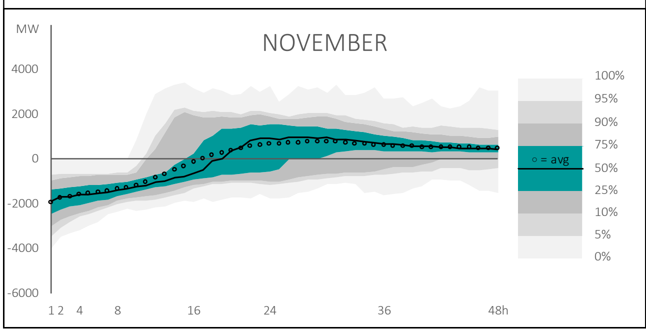


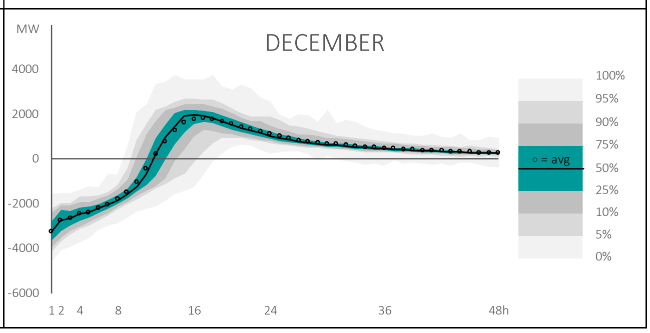




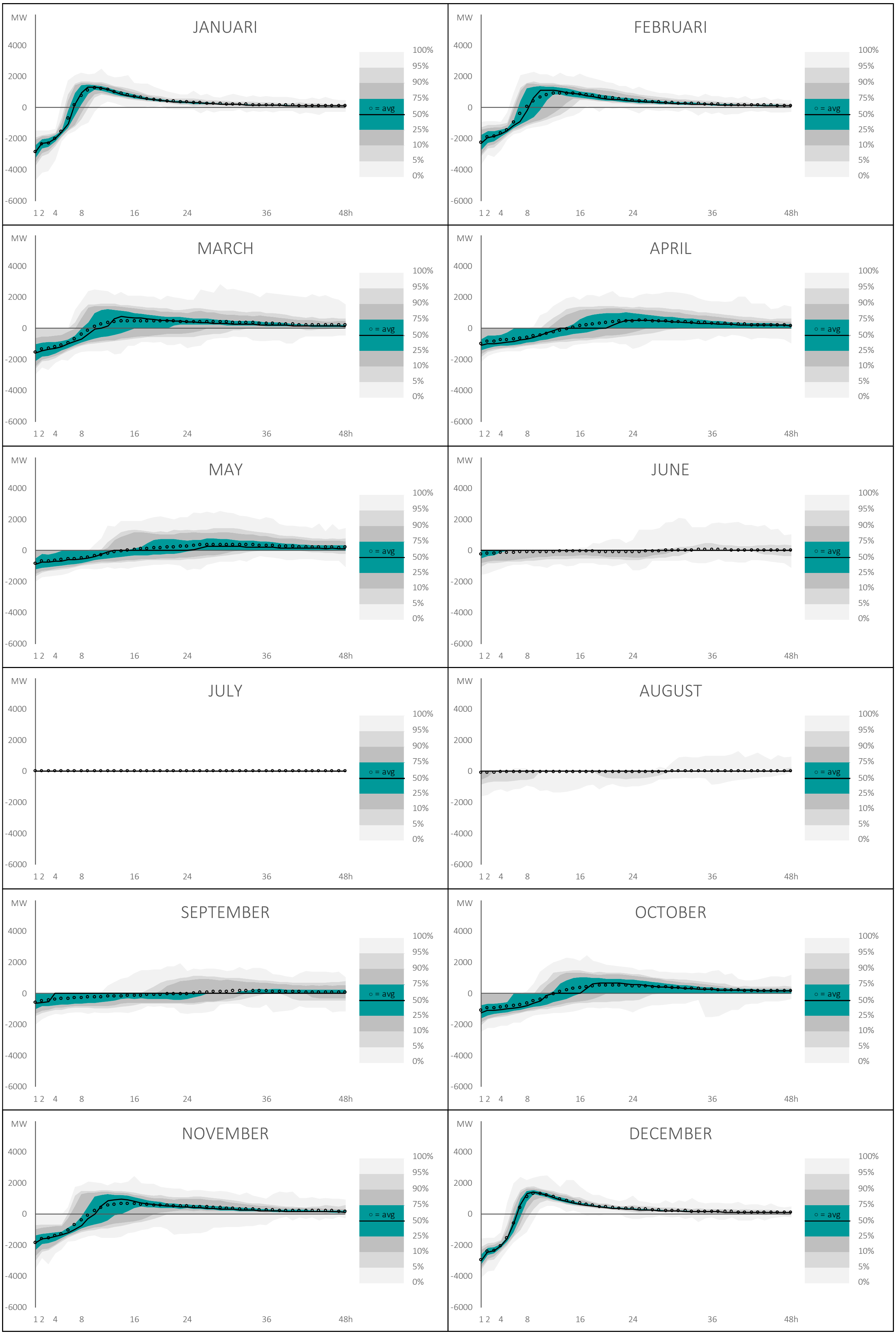




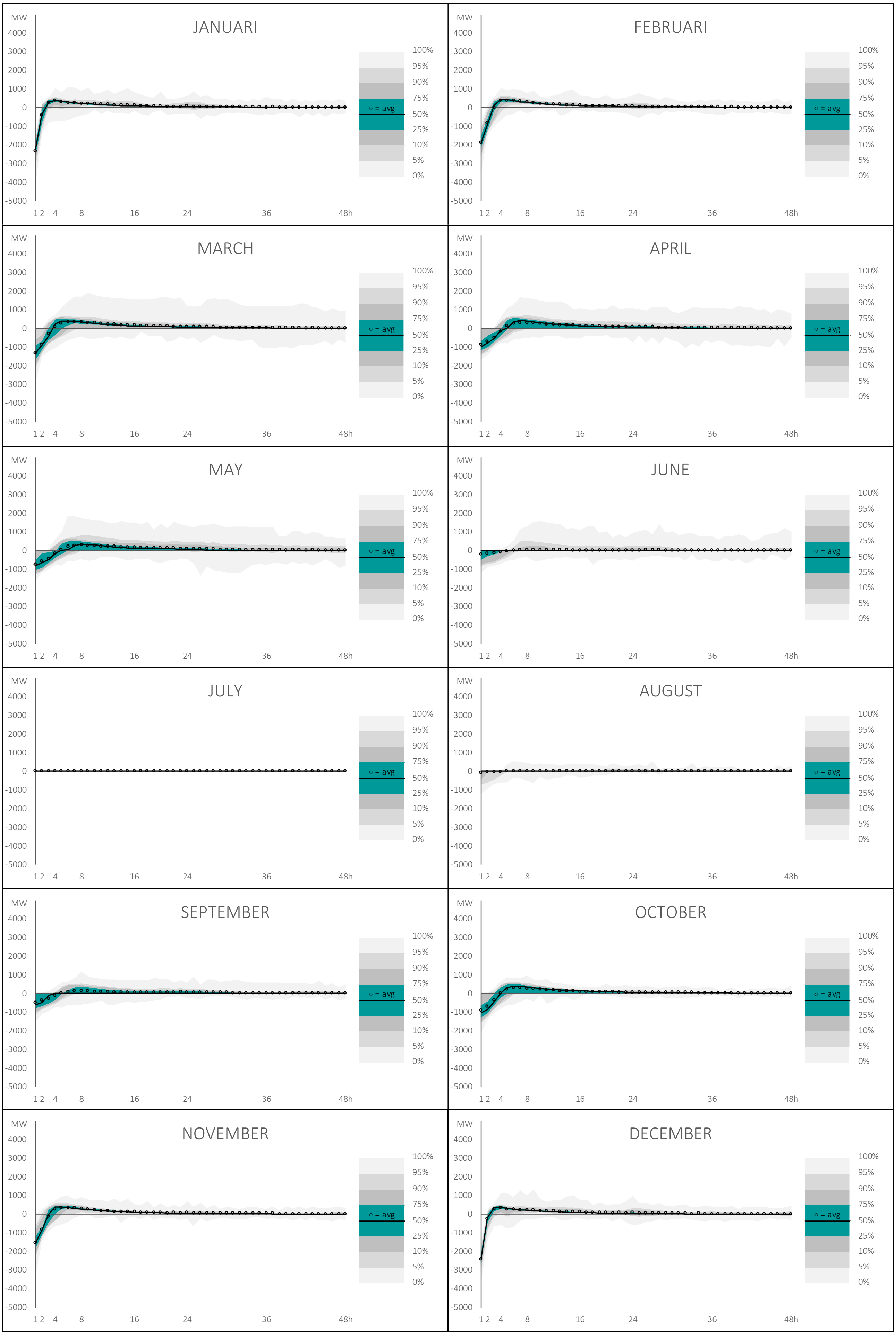




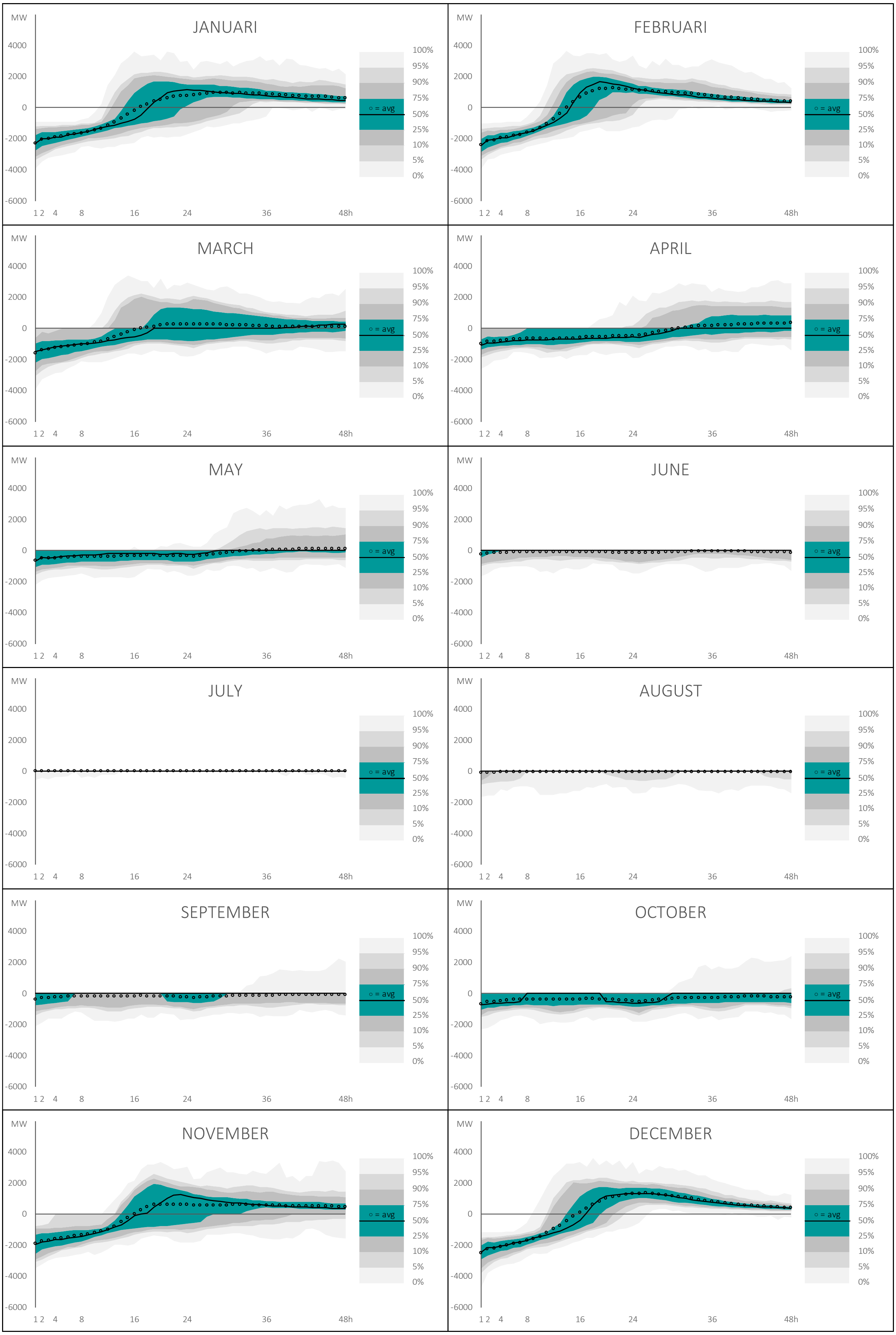
Annex K: Flexibility curves 2040 / Cold year / 18°C



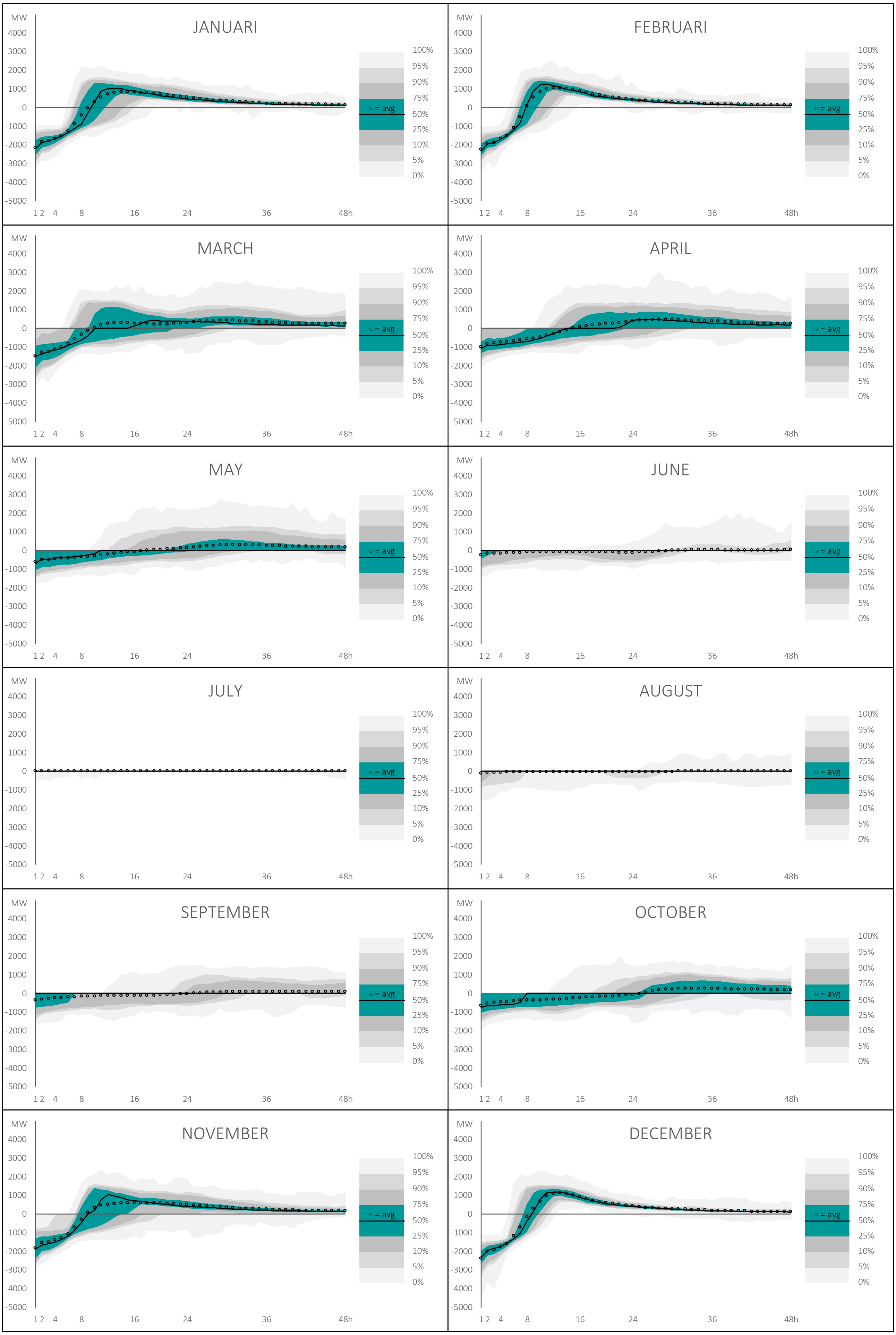
ANNEX L: FLEXIBILITY CURVES 2040 / COLD YEAR / 20°C



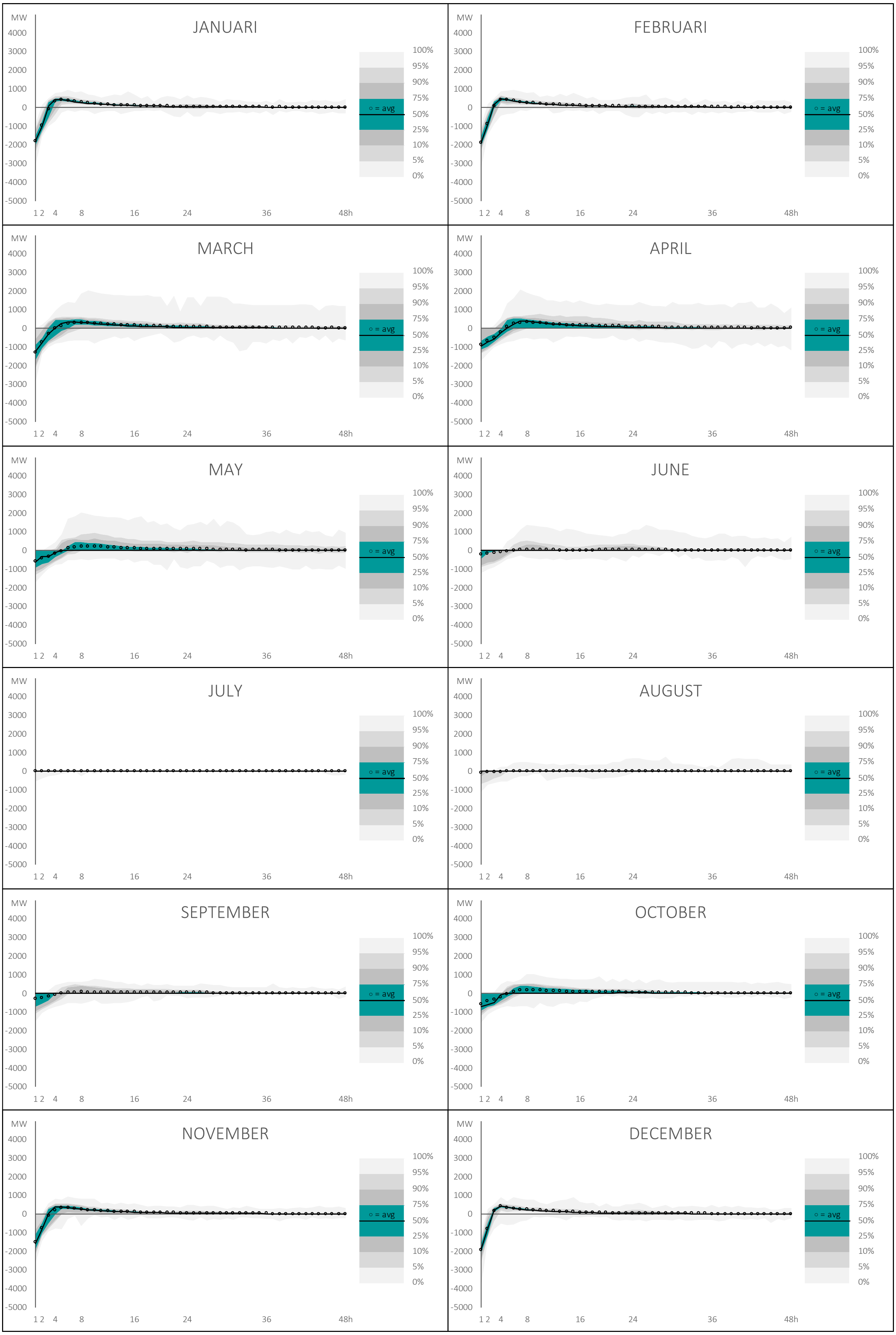
ANNEX M: FLEXIBILITY CURVES 2040 / AVERAGE YEAR / 16°C



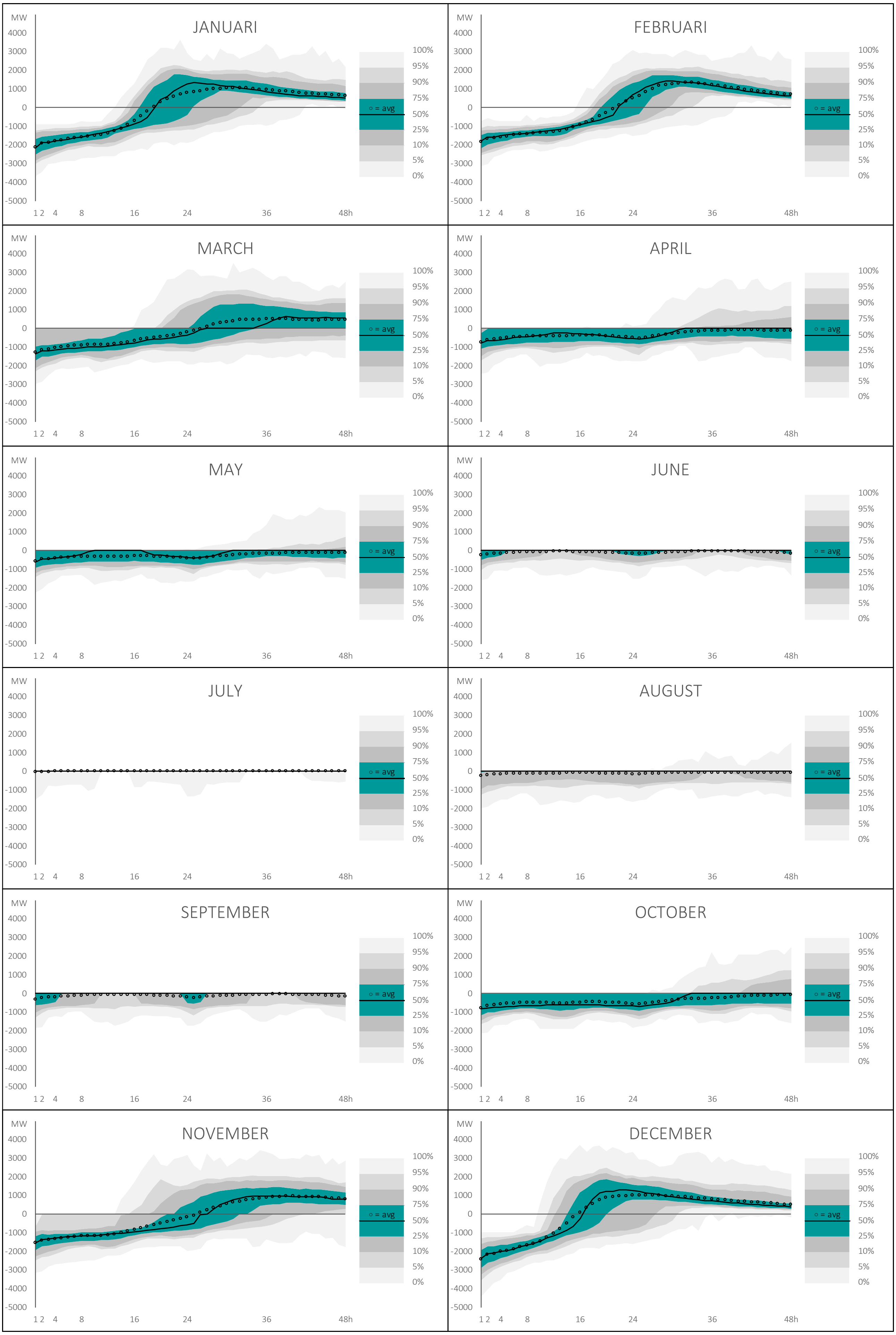
ANNEX N: FLEXIBILITY CURVES 2040 / AVERAGE YEAR / 18°C



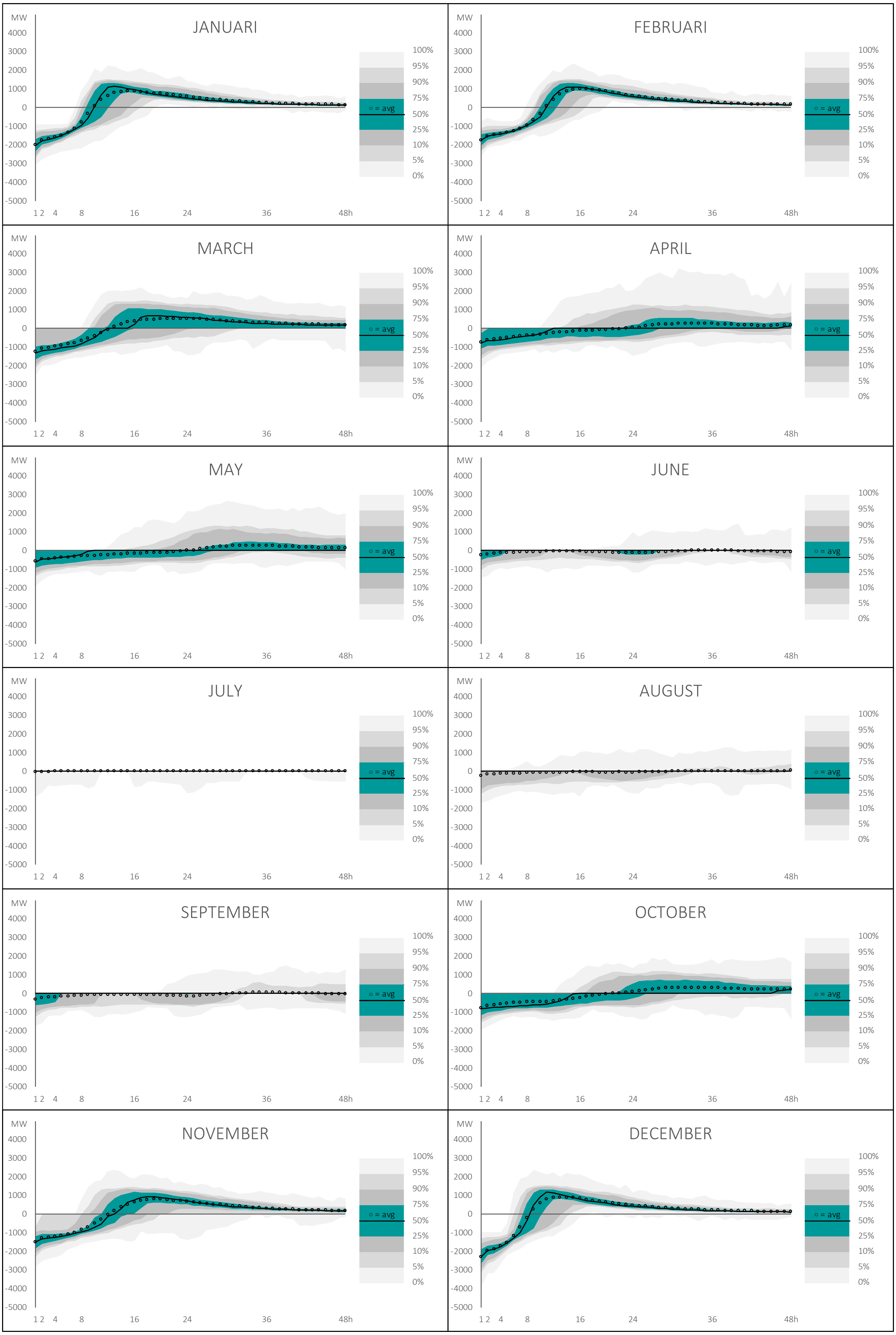
ANNEX O: FLEXIBILITY CURVES 2040 / AVERAGE YEAR / 20°C



ANNEX P: FLEXIBILITY CURVES 2040 / WARM YEAR / 16°C



Annex Q: Flexibility curves 2040 / Warm year / 18°C



ANNEX R: FLEXIBILITY CURVES 2040 / WARM YEAR / 20°C