The energy and material related impacts of the transition towards low-carbon heating: a case study of the Netherlands

Verhagen, T.J.

Acknowledgements

Acknowledgements

Not everyone is given the opportunity to pursue a PhD. I am well aware of this and am deeply grateful to have been given this chance. There was a point in my life where I was doubting if I would be able to complete my bachelor's degree, making this PhD journey even more meaningful.

During this journey I have noticed that I am intrinsically driven, and that I want to contribute something positive to the world. This drive has resulted in the dissertation you are currently reading, and I aim to keep incorporating this positive contribution to the world in my career.

I was able to learn a lot from my supervisors, Ester van der Voet and Benjamin Sprecher. First of all, I would like to thank Benjamin for hiring me as a researcher at the CML and thereby bringing out my scientific interest. You taught me a lot about systems-thinking, writing and the ins and outs of the scientific world. Ester, thank you very much for your patience, knowledge, and wise words. You have proven to be a razor-sharp thinker and pragmatic at the right moments.

I would like to thank the CML support staff, Sammy, Suus and Kiki for all their help throughout the years. My more 'senior' colleagues Arnold, Rene, Mingming, Bernhard, Hauke, Maarten, Paul, Zhijie, Hale and Stefano. And of course, my fellow PhD's, giving me a group of people to joke around with and reflect on the perils of doing a PhD: Janneke, Sander, Glenn, Carlos, Sebastiaan, Franco, Bertram, Brenda, Yanan, Marc, Chen, Xining, Chunbo, Brenda and Bertram. I would like to thank my friends Simon and Tom, who have also made the controversial choice of doing a PhD.

I would like to thank my parents, Andra and Gerrit for their love and encouragement, without whom I would never have enjoyed so many opportunities in life. I also thank my aunt, Anneli, who keeps helping me reflect on the why and how for almost everything. I would also like to thank my little feline work-from-home colleagues, Lemon and Olive, who kept lowering my stress levels by demanding belly rubs.

To my wife Kaveri, who has taught me so much about the important things in life, thank you for supporting me through all the ups-and downs of a PhD. I promise I will return the favour with your PhD journey that started this year.

Curriculum Vitae

Curriculum Vitae

Teun Johannes Verhagen was born on the 14th of March 1992 in Zwolle, the Netherlands. After completing high school in 2010 at the Thorbecke Scholengemeenschap Zwolle, he went to study Industrial Design Engineering at the Delft University of Technology (TU Delft). He discovered his passion for sustainability with the minor Sustainable Energy Technologies. Shortly after, he joined the TU Delft Solar Boat Team to help design the solar array for the 2014 race. After completing the bachelor's degree, his thesis was selected for the TU Delft Best Graduate Award of 2016. The two-year master programme Industrial Ecology at Leiden University was for him the next logical step. During this master, he worked at the Rotterdam University of Applied Sciences as a policy advisor sustainability, and as a student assistant for the Resilient Cities Hub. In his master thesis, he analysed the trade-offs of low-carbon residential heating within the region of Leiden. Teun was then offered a research position in the field of Industrial Ecology at the Institute of Environmental Sciences (CML) to further pursue the topic of his master thesis. After one year, this position was converted into a full PhD. His research has been focussed on understanding the energy and material related impacts of the transition towards low-carbon heating in the Netherlands. He also contributed to multiple Circular Economy reports of the Dutch Planbureau voor de Leefomgeving (PBL).

C

List of publications

List of publications

Verhagen, Teun Johannes, Ester van der Voet, and Benjamin Sprecher. 2020. ‘Alternatives for Natural-Gas-Based Heating Systems: A Quantitative GIS-Based Analysis of Climate Impacts and Financial Feasibility’. Journal of Industrial Ecology n/a(n/a). doi: 10.1111/jiec.13047.

Verhagen, Teun Johannes, Marijn Sauer, Ester van der Voet, and Benjamin Sprecher. 2021. ‘Matching Demolition and Construction Material Flows, an Urban Mining Case Study’. Sustainability 13. doi: 10.3390/su13020653.

Verhagen, Teun Johannes, Cetinay, H. I., van der Voet, E., & Sprecher, B. (2022). Transitioning to Low-Carbon Residential Heating: The Impacts of Material-Related Emissions. Environmental Science & Technology. https://doi.org/10.1021/acs.est.1c06362

Verhagen, Teun Johannes, van Nielen, Sander., Sprecher, B., van der Voet, E., (2022). Legacy residential natural-gas infrastructure: urban mine or hydrogen infrastructure? (2022). Resources Conservation & Recycling. (under review)

Sander van Nielen, Benjamin Sprecher, **Teun Johannes Verhagen**, René Kleijn. (2022). Towards neodymium recycling: analysis of the availability and recyclability of European waste flows. Journal of waste management (under review)

Yang, Xining, Mingming Hu, Niko Heeren, Chunbo Zhang, **Teun Johannes Verhagen**, Arnold Tukker, and Bernhard Steubing. 2020. ‘A Combined GIS-Archetype Approach to Model Residential Space Heating Energy: A Case Study for the Netherlands Including Validation’. Applied Energy 280:115953. doi: 10.1016/j.apenergy.2020.115953.

Sprecher, Benjamin, **Teun Johannes Verhagen**, Marijn Louise Sauer, Michel Baars, John Heintz, and Tomer Fishman. 2021. ‘Material Intensity Database for the Dutch Building Stock: Towards Big Data in Material Stock Analysis’. Journal of Industrial Ecology n/a(n/a). doi: 10.1111/jiec.13143.

Ballatore, Andrea, **Teun Johannes Verhagen**, Zhije Li, and Stefano Cucurachi. 2021. ‘This City Is Not a Bin: Crowdmapping the Distribution of Urban Litter’. Journal of Industrial Ecology n/a(n/a). doi: 10.1111/jiec.13164.

Zhang, Chunbo, Hu, Mingming, Sprecher, Benjamin, Yang, Xining, **Verhagen, Teun Johannes**, Tukker, Arnold. 2021. 'Integrated material-energy efficiency renovation of housing stock in the Netherlands: Economic and environmental implications'. Energy & Environmental Science. (under review)

Berghe, Karel, **Verhagen, Teun Johannes**. 2021 'Making it concrete: analyzing the locations of concrete plants in achieving, or failing, urban circular policy goals' Frontiers in Built Environment, section Urban Science

Appendix I

Based on supplementary information provided with chapter 2:

Verhagen, T. J., Nielen, S. van, Voet, E. van der, & Sprecher, B. (2022). Legacy residential natural-gas infrastructure: urban mine or hydrogen infrastructure? *Resources conservation & Recycling*, *n/a*(n/a). (In review)

AI.I – Network provider data

Table A1.1, network operators and their infrastructure length extracted from the GIS-datasets, for Rendo and Coteq the numbers are based on Netbeheer Nederland and are marked in italics:

Network operator	Gas infrastructure length (km)	Number of pipeline segments
Stedin	23,345	555,368
Liander	63,585	5,675,329
Enexis	49,431	968,147
Enduris	3,924	57127
Westland infra	6	248
Rendo	*3,492*	N.a.
Coteq	*4,389*	N.a.
Total	**148,172**	**7,256,219**

I

AI.II – Natural gas production installations:

Table A1.2, kg of material required for the production of a m3 of natural gas (EcoInvent, 2010):

	Steel	Cement	Concrete
Onshore natural gas well	4.24E-04	4.04E-04	
Pipeline infrastructure	1.00E-03		
Natural gas processing plant	2.00E-03		9.29E-04
Total:	3.42E-03	4.04E-04	9.29E-04

With an annual onshore production of 7.77+E09 Nm3 of natural gas in the Netherlands for 2020, we calculated the following material stock for the natural gas production installations:

	Steel (ton)	Cement (ton)	Concrete (ton)
Total:	2.66E+04	3.14E+03	7.22E+03

AI.III – Eindhoven case study data

Table A1.3, residential buildings in the GIS dataset of Eindhoven:

All residential buildings in Eindhoven	Residential buildings built before 1965	Residential buildings built before 1948
73,138	32,829	14,869
100%	45%	20%

Table A1.4, materials in the natural gas infrastructure around residential buildings in Eindhoven.

	All residential buildings (tonnes)	Residential buildings built before 1965 (tonnes)	Residential buildings built before 1949 (tonnes)
Steel	6,930	5,180	2,060
PCV + SPVC	2,880	1,160	573
PE	36	13	6
Grey iron + ductile iron	2,140	1,520	1,340
Asbestos cement	21	8	1
Total	12,000	7,880	3,980

Figure A1.1, natural gas infrastructure in Eindhoven in 2020 (left), the situation in 2050 with 45% of buildings still connected to the gas grid (middle) and the situation in 2050 with 20% of buildings connected to the gas grid (right):

AI.IV – Lifetime distributions & material intensity per dwelling

Table A1.5, Weibull distribution parameters used in the Dynamic Stock Model:

	Scale	Shape	Source
Natural gas boilers	2	17	(Oliver-Solà et al., 2009a)
Pipelines	2	38	(Mukherjee et al., 2015)
Natural gas production installations	2	32	(Rijksoverheid, 2021)

Table A1.6, materials intensity of the natural-gas-based heating system per dwelling:

	Steel	(S)PVC	Copper	Cast iron	Concrete	Cement	Brass	PE	Bronze	Total
Natural gas production installations	4.2	0.0	0.0	0.0	1.1	0.5	0.0	0.0	0.0	5.8
Infrastructure	57.7	42.5	0.0	11.3	0	0	0.0	3.6	0.0	115.1
CV-boilers	27.3	6.6	8.4	0.2	0.0	0.0	1.9	0.0	0.3	44.6

AI.V – Pipelines suitable for the distribution of hydrogen

Table A1.7, materials in the Dutch natural-gas infrastructure deemed suitable for the distribution of hydrogen by the Dutch network providers:

Material	(S)PVC	Steel	PE	Cast iron	Asbestos cement	Total
Stock (kilotons)	277.0	376.5	23.7	73.8	1.4	752.5
Length (km)	103,188	22,449	18,732	3,462	245	148,172
Mass percentage	37%	50%	3%	10%	0%	100%
Length percentage	69.8%	15.2%	12.5%	2.3%	0.2%	100%
Suitable for hydrogen distribution	Yes	Yes	Yes	No	No	

Appendix II

Based on supplementary information provided with chapter 3:

Verhagen, T. J., Voet, E. van der, & Sprecher, B. (2020). Alternatives for natural-gas-based heating systems: A quantitative GIS-based analysis of climate impacts and financial feasibility. *Journal of Industrial Ecology*, *n/a*(n/a). https://doi.org/10.1111/jiec.13047

AII.I – Model variables

Table A2.1, variables used in the model:

Variable	Value	Unit	Source
2018 price per m3 gas	0.67	Euro	(Milieu centraal, 2019)
2018 price per kWh electricity	0.21	Euro	(Milieu centraal, 2019)
2018 price per kWh network heat	0.065	Euro	(Milieu centraal, 2019)
Cost insulation per kWh/m2	1.47	Euro	Supplementary data 4
Kg CO_2 per kWh gas	0.178	Kg	
Lifetime heat pump	15	Years	(Technische Unie, 2018)
Lifetime heat exchangers	15	Years	(RVO, 2014)
Lifetime CV	15	Years	(RVO, 2014)
Infrastructure cost heat pumps	10000	Euro	(Rijksoverheid, 2018c)
Infrastructure cost heating networks	12800	Euro	(Province of Zuid-Holland, 2018)
Cost heat pump	10000	Euro	(Rijksoverheid, 2018c)
Cost heat exchanger	850	Euro	(RVO, 2014)
Cost boiler	2000	Euro	(RVO, 2014)
COP heat pump	3.5	kWh heat / kWh of the system	(Greenhome, 2017)
COP low temperature	0.88	kWh heat / kWh of the system	(Lund et al., 2014)
COP high temperature	0.76	kWh heat / kWh of the system	(Lund et al., 2014)
CO_2 intensity heat pumps	2.14	kg CO_2 per kWh	Supplementary data 1
CO_2 intensity LT	0.468	kg CO_2 per kWh	Supplementary data 1
CO_2 intensity HT	0.674	kg CO_2 per kWh	Supplementary data 1

II

AII.II – Investment per building and insulation

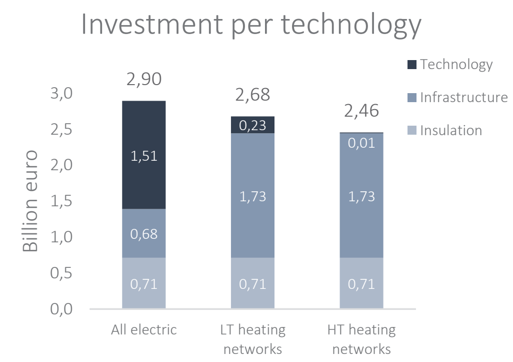

Figure A2.1, investment per building and technology in the baseline scenario for the whole case study:

AII.III – Insulation calculations

Table A2.2, overview of the investment and energy reduction of a Dutch residential building (Milieu centraal, 2018):

	Investment	Annual reduction kWh/m2	Euro per kWh/m2
Wall insulation (5-8cm)	€ 817.00	44.82	18.23
Wall insulation (8-10cm)	€ 4,388.00	4.37	1004.36
Floor insulation (8-10cm)	€ 1,165.00	14.08	82.76
Floor insulation (13-20cm)	€ 503.00	4.69	107.19
Roof insulation (8-10cm)	€ 3,692.00	19.74	187.02
Roof insulation (13-20cm)	€ 950.00	9.87	96.25
HR++ glass living rooms	€ 2,307.00	8.09	285.15
HR ++ glass bedrooms	€ 1,912.00	6.80	281.34
Total:	**€ 15,734.00**	**112.46**	**139.91**

95 m2

1.47 euro/kWh/m2 energy reduction

AII.IV – Case study GIS-maps

Figure A2.2, reduction of CO2 emissions with different heating technologies in the case study:

AII.V – CO_2 emissions per building

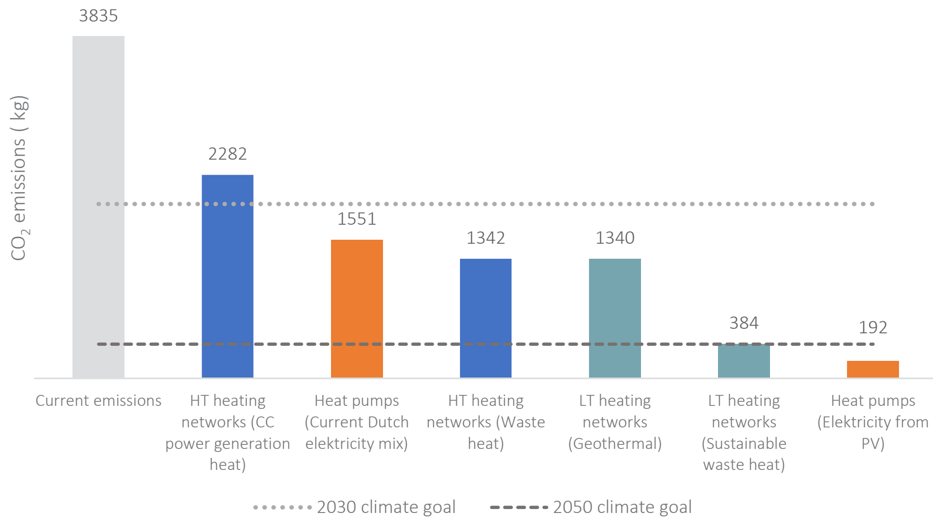

Figure A2.3, average annual urban heating CO_2 emissions per building and technology:

2030 climate goal - 50% reduction in heating-related CO_2 emissions

2050 climate goal - 90% reduction in heating-related CO_2 emissions

Appendix III

Based on supplementary information provided with chapter 4:
Verhagen, T. J., Sauer, M. L., van der Voet, E., & Sprecher, B. (2021). Matching Demolition and Construction Material Flows, an Urban Mining Case Study. *Sustainability, 13*(2), 653. https://doi.org/10.3390/su13020653

AIII.I – Construction and demolition in Leiden for the 2020-2030:

Table A3.1, planned demolition in m2 for the municipality of Leiden, 2020-2030:

	Row house	Offices	High rise	Commercial	Other	Detached	Apartment
2019	0	1,845	52,613	0	22,706	1,831	14,511
2020	4,096	1,590	52,114	0	3,796	1,298	48,733
2021	12,082	1,321	978	15,124	32,317	0	2,340
2022	0	41,122	35,755	0	50,443	0	2,725
2023	0	6,115	0	2,747	48,875	0	0
2024	0	0	0	0	13,468	0	0
2025	0	18,249	0	0	31,542	97	16,599
2026	2,311	10,035	20,209	2,553	29,021	461	12,130
2027	2,311	10,035	20,209	2,553	29,021	461	12,130
2028	2,311	10,035	20,209	2,553	29,021	461	12,130
2029	0	0	0	0	11,925	0	0
2030	0	0	0	0	35,526	0	0

Table A3.2, planned construction in m2 for the municipality of Leiden, 2020-2030:

	Row house	Offices	High rise	Commercial	Other	Detached	Apartment
2019	0	0	23,080	0	25,890	1,640	11,760
2020	7,600	1,440	60,910	0	5,860	1,760	32,400
2021	13,120	7,200	3,520	10,240	95,920	0	3,280
2022	0	68,160	26,300	0	75,560	0	0
2023	0	52,920	0	4,000	95,880	0	0
2024	0	0	0	0	48,300	0	0
2025	0	40,000	0	0	32,300	49,280	32,000
2026	2,960	24,246	16,259	2,034	54,244	7,526	11,349
2027	2,960	24,246	16,259	2,034	54,244	7,526	11,349
2028	2,960	24,246	16,259	2,034	54,244	7,526	11,349
2029	0	0	0	0	65,160	0	0
2030	0	0	0	0	100,000	0	0

Total demolition: 814,640 m2

Total construction: 1,351,331 m2

III

AIII.II – Construction and demolition waste in Leiden

Table A3.3, demolition waste supply per year (tonnes):

	Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
2019	80,838	26,734	5,539	1,269	642	1,133	1,931	1,572	1,087	984	338	347
2020	119,258	41,645	7,229	278	700	567	2,222	2,282	789	1,468	521	154
2021	44,605	11,570	3,000	2,520	531	1,853	1,431	541	1,518	1,063	75	587
2022	97,802	21,724	5,513	4,731	1,054	3,490	3,183	1,219	2,669	1,595	189	1,109
2023	43,104	9,725	2,084	2,983	516	2,118	1,373	254	1,650	796	-	678
2024	10,112	2,474	481	696	120	493	309	59	393	171	-	158
2025	62,330	15,585	2,834	2,573	548	1,888	1,615	575	1,475	1,028	82	600
2026	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
2027	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
2028	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
2029	8,954	2,190	426	616	107	436	273	52	348	151	-	140
2030	26,675	6,525	1,268	1,836	317	1,300	815	156	1,036	451	-	417

Table A3.4, construction material demand per year (tonnes):

	Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
2019	55,949	18,063	3,537	1,338	455	1,073	1,310	889	964	740	179	335
2020	103,818	36,222	7,109	377	695	619	2,194	2,212	813	1,272	503	173
2021	96,705	23,948	5,495	5,857	1,135	4,228	3,048	921	3,408	1,875	98	1,349
2022	125,109	23,653	6,513	7,426	1,446	5,365	4,355	1,190	3,990	2,230	129	1,711
2023	113,084	20,658	5,330	7,895	1,366	5,611	3,925	672	4,190	2,180	0	1,796
2024	36,266	8,871	1,724	2,496	431	1,767	1,108	213	1,409	613	0	567
2025	152,889	57,208	16,781	3,736	1,147	2,978	3,572	2,050	2,462	2,309	398	921
2026	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
2027	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
2028	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
2029	48,925	11,968	2,326	3,367	582	2,384	1,494	287	1,901	827	0	765
2030	75,085	18,367	3,570	5,167	893	3,659	2,293	440	2,917	1,269	0	1,175

Table A3.5, material supply from demolition and demand from construction per year (tonnes):

		Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
2019	Supply	80,838	26,734	5,539	1,269	642	1,133	1,931	1,572	1,087	984	338	347
	Demand	55,949	18,063	3,537	1,338	455	1,073	1,310	889	964	740	179	335
	Balance	24,889	8,670	2,002	-69	187	60	621	683	123	245	159	12
2020	Supply	119,258	41,645	7,229	278	700	567	2,222	2,282	789	1,468	521	154
	Demand	103,818	36,222	7,109	377	695	619	2,194	2,212	813	1,272	503	173
	Balance	15,440	5,424	120	-99	5	-52	27	69	-24	196	17	-19
2021	Supply	44,605	11,570	3,000	2,520	531	1,853	1,431	541	1,518	1,063	75	587
	Demand	96,705	23,948	5,495	5,857	1,135	4,228	3,048	921	3,408	1,875	98	1,349
	Balance	-52,100	-12,378	-2,495	-3,338	-605	-2,375	-1,617	-380	-1,890	-812	-22	-762
2022	Supply	97,802	21,724	5,513	4,731	1,054	3,490	3,183	1,219	2,669	1,595	189	1,109
	Demand	125,109	23,653	6,513	7,426	1,446	5,365	4,355	1,190	3,990	2,230	129	1,711
	Balance	-27,307	-1,929	-1,000	-2,695	-391	-1,875	-1,172	29	-1,321	-635	60	-603
2023	Supply	43,104	9,725	2,084	2,983	516	2,118	1,373	254	1,650	796	-	678
	Demand	113,084	20,658	5,330	7,895	1,366	5,611	3,925	672	4,190	2,180	0	1,796
	Balance	-69,980	-10,933	-3,246	-4,912	-850	-3,493	-2,553	-418	-2,540	-1,384	-	-1,117
2024	Supply	10,112	2,474	481	696	120	493	309	59	393	171	-	158
	Demand	36,266	8,871	1,724	2,496	431	1,767	1,108	213	1,409	613	0	567
	Balance	-26,154	-6,398	-1,244	-1,800	-311	-1,275	-799	-153	-1,016	-442	-	-409
2025	Supply	62,330	15,585	2,834	2,573	548	1,888	1,615	575	1,475	1,028	82	600
	Demand	152,889	57,208	16,781	3,736	1,147	2,978	3,572	2,050	2,462	2,309	398	921
	Balance	-90,559	-41,623	-13,947	-1,163	-599	-1,089	-1,957	-1,475	-987	-1,282	-316	-322
2026	Supply	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Balance	-32,253	-8,452	-2,830	-2,011	-366	-1,443	-1,064	-235	-1,094	-588	-15	-460
2027	Supply	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Balance	-32,253	-8,452	-2,830	-2,011	-366	-1,443	-1,064	-235	-1,094	-588	-15	-460
2028	Supply	65,436	18,494	3,811	2,150	587	1,649	1,723	929	1,369	1,015	172	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Balance	-32,253	-8,452	-2,830	-2,011	-366	-1,443	-1,064	-235	-1,094	-588	-15	-460
2029	Supply	8,954	2,190	426	616	107	436	273	52	348	151	-	140
	Demand	48,925	11,968	2,326	3,367	582	2,384	1,494	287	1,901	827	0	765
	Balance	-39,971	-9,778	-1,901	-2,751	-476	-1,948	-1,221	-234	-1,553	-676	-	-625
2030	Supply	26,675	6,525	1,268	1,836	317	1,300	815	156	1,036	451	-	417
	Demand	75,085	18,367	3,570	5,167	893	3,659	2,293	440	2,917	1,269	0	1,175
	Balance	-48,410	-11,842	-2,302	-3,331	-576	-2,359	-1,478	-284	-1,881	-818	-	-757

AIII.III – Annual collected and recycled demolition waste in Leiden

Table A3.6, material recycling per material and year (tonnes, extrapolated values in dark blue):

Year		Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
	Collection rate (%)	85%	95%	95%	0%	95%	95%	95%	95%	95%	50%	95%	100%
	Recycled content (%)	50%	50%	90%	0%	50%	85%	91%	80%	40%	50%	96%	0%
2019	Supply	68,712	25,397	5,262	-	610	1,077	1,835	1,493	1,032	492	321	347
	Demand	55,949	18,063	3,537	1,338	455	1,073	1,310	889	964	740	179	335
	Recycled content limit	27,974	9,032	3,183	-	228	912	1,192	711	386	370	172	-
	Recycled	27,974	9,032	3,183	-	228	912	1,192	711	386	370	172	-
2020	Supply	101,369	39,563	6,867	-	665	538	2,111	2,167	750	734	495	154
	Demand	103,818	36,222	7,109	377	695	619	2,194	2,212	813	1,272	503	173
	Recycled content limit	51,909	18,111	6,398	-	348	526	1,997	1,770	325	636	483	-
	Recycled	51,909	18,111	6,398	-	348	526	1,997	1,770	325	636	483	-
2021	Supply	37,914	10,991	2,850	-	504	1,761	1,359	514	1,442	532	72	587
	Demand	96,705	23,948	5,495	5,857	1,135	4,228	3,048	921	3,408	1,875	98	1,349
	Recycled content limit	48,352	11,974	4,945	-	568	3,594	2,773	737	1,363	937	94	-
	Recycled	37,914	10,991	2,850	-	504	1,761	1,359	514	1,363	532	72	-
2022	Supply	83,132	20,637	5,238	-	1,002	3,315	3,024	1,158	2,536	797	179	1,109
	Demand	125,109	23,653	6,513	7,426	1,446	5,365	4,355	1,190	3,990	2,230	129	1,711
	Recycled content limit	62,554	11,826	5,862	-	723	4,560	3,963	952	1,596	1,115	124	-
	Recycled	62,554	11,826	5,238	-	723	3,315	3,024	952	1,596	797	124	-
2023	Supply	36,638	9,239	1,980	-	490	2,012	1,304	241	1,568	398	-	678
	Demand	113,084	20,658	5,330	7,895	1,366	5,611	3,925	672	4,190	2,180	-	1,796
	Recycled content limit	56,542	10,329	4,797	-	683	4,769	3,572	538	1,676	1,090	-	-
	Recycled	36,638	9,239	1,980	-	490	2,012	1,304	241	1,568	398	-	-
2024	Supply	8,596	2,350	457	-	114	468	293	56	373	85	-	158
	Demand	36,266	8,871	1,724	2,496	431	1,767	1,108	213	1,409	613	-	567
	Recycled content limit	18,133	4,436	1,552	-	216	1,502	1,008	170	564	306	-	-
	Recycled	8,596	2,350	457	-	114	468	293	56	373	85	-	-

Table A3.6, Continued

		Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
2025	Supply	52,980	14,806	2,693	-	520	1,794	1,534	546	1,402	514	78	600
	Demand	152,889	57,208	16,781	3,736	1,147	2,978	3,572	2,050	2,462	2,309	398	921
	Recycled content limit	76,444	28,604	15,103	-	573	2,531	3,251	1,640	985	1,155	382	-
	Recycled	52,980	14,806	2,693	-	520	1,794	1,534	546	985	514	78	-
2026	Supply	55,620	17,569	3,621	-	558	1,566	1,637	882	1,300	508	163	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Recycled content limit	48,844	13,473	5,977	-	477	2,628	2,537	931	985	801	179	-
	Recycled	48,844	13,473	3,621	-	477	1,566	1,637	882	985	508	163	-
2027	Supply	55,620	17,569	3,621	-	558	1,566	1,637	882	1,300	508	163	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Recycled content limit	48,844	13,473	5,977	-	477	2,628	2,537	931	985	801	179	-
	Recycled	48,844	13,473	3,621	-	477	1,566	1,637	882	985	508	163	-
2028	Supply	55,620	17,569	3,621	-	558	1,566	1,637	882	1,300	508	163	519
	Demand	97,688	26,946	6,641	4,161	954	3,092	2,787	1,164	2,462	1,603	187	979
	Recycled content limit	48,844	13,473	5,977	-	477	2,628	2,537	931	985	801	179	-
	Recycled	48,844	13,473	3,621	-	477	1,566	1,637	882	985	508	163	-
2029	Supply	7,611	2,081	404	-	101	415	260	50	330	76	-	140
	Demand	48,925	11,968	2,326	3,367	582	2,384	1,494	287	1,901	827	-	765
	Recycled content limit	24,463	5,984	2,094	-	291	2,027	1,360	229	760	413	-	-
	Recycled	7,611	2,081	404	-	101	415	260	50	330	76	-	-
2030	Supply	22,673	6,199	1,205	-	301	1,235	774	148	984	225	-	417
	Demand	75,085	18,367	3,570	5,167	893	3,659	2,293	440	2,917	1,269	-	1,175
	Recycled content limit	37,542	9,183	3,213	-	447	3,110	2,087	352	1,167	635	-	-
	Recycled	22,673	6,199	1,205	-	301	1,235	774	148	984	225	-	-

Table A3.7, summarized recycling of materials (tonnes):

	Concrete	Brick	Wood	Roof gravel	Aluminium	Steel	Glass	Ceramic	Gypsum	Bitumen	Cast Iron	Other materials
Supply	586,487	183,970	37,817	-	5,983	17,315	17,405	9,022	14,318	5,377	1,634	5,747
Demand	1,100,894	299,796	72,309	50,141	11,011	36,960	31,661	12,366	29,441	18,122	1,867	11,731
Recycled	455,383	125,053	35,269	-	4,760	17,138	16,648	7,636	10,865	5,156	1,418	-

Supply of demolition waste: 1,033,029 metric tonnes
Supply of demolition waste after collection: 885,074 metric tonnes

Demand: 1,676,298 metric tonnes
Recycled: 679,327 metric tonnes
66% of demolition waste recycled as secondary materials, 41% lower primary material demand
14% material of demolition waste not suitable for collection, 20% mismatch

III

Appendix IV

Based on supplementary information provided with chapter 5:
Verhagen, T. J., Cetinay, H. I., van der Voet, E., & Sprecher, B. (2022). Transitioning to Low-Carbon Residential Heating: The Impacts of Material-Related Emissions. *Environmental Science & Technology*. https://doi.org/10.1021/acs.est.1c06362

In this document, we included the consequences of the heating transition for the electricity demand in detail (I), the input data used in the model (II), excluded materials (III), and the output data of the model per scenario (IV).

AIV.I – Consequences of the heating transition for the electricity demand

Figure A4.1 represents a typical low voltage grid in a neighbourhood in Europe (IEEE, 2020). The network has *N = 906* lv connections (nodes), that are connected by *L = 905* lv cables (links) and 1 mv/lv transformer. Figure is the graphical representation of the grid, where the nodes represent the lv connections and the links are the cables between the connections.

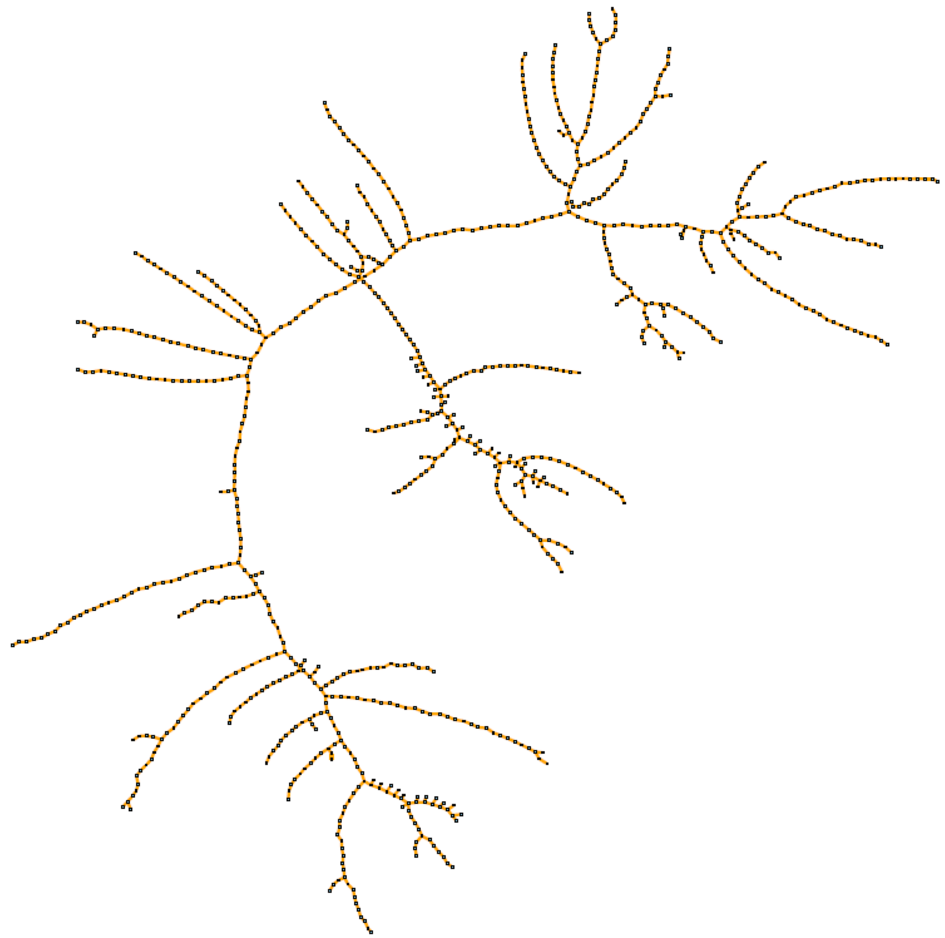

Figure A4.1. European low voltage grid with N = 906 nodes and L = 905 links. The grid is a tree network, in other words, there are no loops. The network starts from the low voltage side of the distribution transformer (node 1).

We use electricity consumption behavior profiles from the vereniging Nederlandse Energie-Data Uitwisseling (NEDU), which is as an umbrella organization of the Dutch electricity companies, to represent an average lv connection in the Netherlands (NEDU, 2020). We use the profile E1A profile, which represent a lv connection smaller than 3x25A. A typical household electricity consumption in the Netherlands is taken as 6000 kwh. The planning for the electricity grid investments are mainly based on the peak-load conditions, in other words when the electricity consumption demand is maximum. According to the NEDU profile, the peak load happens at the first week of January with the maximum peak load of 1.55 kw per household as shown in Figure A4.2.

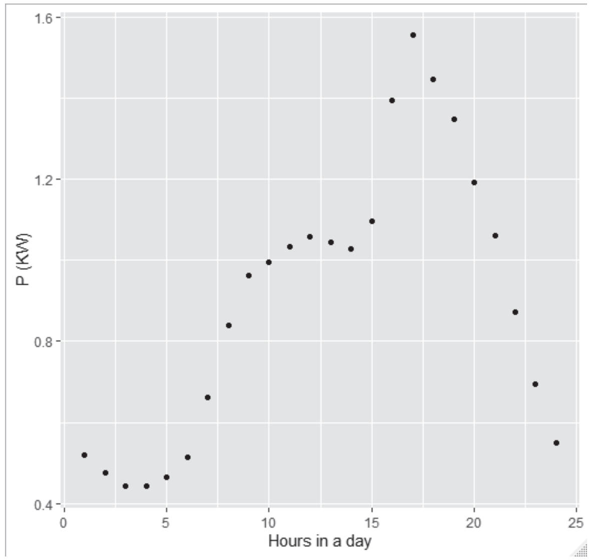

Figure A4.2. The electricity consumption of an average household at the peak day. The x axis represent the hours in a day whereas the y axis in the electricity demand in kw.

We will use the linearized DC power flow equations to find the flow of each link in network at the peak load conditions (Cetinay, Kuipers, et al., 2018). Following (Cetinay, Soltan, et al., 2018). we assume that the thermal capacity c_l of a link l is $c_l = \min\{\text{mean(flows)}, (1+\alpha) \times f_l\}$ and an investment decision is made when the flow f_l of a link is higher than its thermal capacity c_l. In this paper we take α = 0.5.

We assume that in our test grid, initially, there are no houses with heat pumps, i.e. the number of total heat pumps is zero. Next, we add the heat pump load on the regular house hold electricity demand. We choose a heat pump of size 4 kw. Focusing at the peak day, we assume that the heat pump will work on a full capacity with COP=1 making the electrical load of a heat pump 4 kw (Nyers & Nyers, 2011). We take the simultaneity factory of the heat pumps as 1, meaning that most people are likely have heat pump working at this winter peak day. If we the probability that a house hold getting a heat pump is h_i , the total load of a household with heat pump P^{HP}_{max} becomes

$$P^{HP}_{i,max} = P^{0}_{i,max} + h_i \times s_i$$

where S_i is the size of the heat pump at connection (node) i and P^{0}_{max} = 1.55 is the initial peak load of the connection i.

We assume a uniform distribution of the heat pump among the houses, in other words, every house has an equal probability h_i to obtain a heat pump. Under these assumptions, we re-solve the dc power flow again to calculate the flow of each link in the network and we compare these new flows of the links with their thermal capacities to find the overloaded links. In addition, using the lengths of the cables in the datasets, we also calculate the total length of the overloaded links.

In order to calculate the average additional investment of lv cables and the number of distribution transformers per household in this example neighborhood, we normalize the heat pump integration effects with the number of households N. For the distribution transformers, we see that it becomes overloaded when h_i = 0.2 thus its investment decision becomes a step function. Table presents the average investments per customer in the example grid. To assess the whole Netherlands, we can scale up this average neighborhood for each city and their ambition for the heat pump integration.

IV

Table A4.1 Average investment length of lv cables and distribution transformers per household versus the probability of integration of heat pumps

Probability of integration of heat pumps h_i	Additional investment length of lv cables (m)	Additional investment of distribution transformers (units)
0	0	0
0.1	0.04	0
0.2	0.42	0.0011
0.3	0.42	0.0011
0.4	0.44	0.0011
0.5	0.45	0.0011
0.6	0.47	0.0011
0.7	0.48	0.0011
0.8	0.5	0.0011
0.9	0.51	0.0011
1	0.52	0.0011

A similar analysis has been done also for the hybrid heat pumps, with the assumption that the heat pump peak load is 3 kw (due to the switching to gas). Compared to the full electric heat pumps, we see the transformer is overloaded when h_i = 0.3 and the additional investments in the lv cables are slightly lower.

Table A4.2 Average investment length of lv cables and distribution transformers per household versus the probability of integration of hybrid heat pumps

Probability of integration of hybrid heat pumps h_i	Additional investment length of lv cables (m)	Additional investment of distribution transformers (units)
0	0	0
0.1	0.01	0
0.2	0.05	0
0.3	0.42	0.0011
0.4	0.42	0.0011
0.5	0.44	0.0011
0.6	0.45	0.0011
0.7	0.45	0.0011
0.8	0.47	0.0011
0.9	0.47	0.0011
1	0.49	0.0011

AIV.II – Model input data

Table A4.3a, mean lifetimes for each low-carbon heating technology subcomponent (years):

	Building adjustments	Insulation materials	Infrastructure	Electricity and heat production	Sources
HT heating networks	25	75	50	20	(Oliver-Solà et al., 2009b; Sullivan, 2010)
LT heating networks	25	75	50	30	(Basosi et al., 2020; Oliver-Solà et al., 2009b)
Heat pumps	25	75	40	25	(Greening & Azapagic, 2012; Jorge et al., 2012; Spath & Mann, 2000; Vestas, 2019)
Hybrid heat pumps	25	75	40	25	(Greening & Azapagic, 2012; Jorge et al., 2012; Spath & Mann, 2000; Vestas, 2019)

Table A4.3b, Weibull function parameters used in the Dynamic Stock Model based on the mean lifetimes from Table A4.3a:

	Building adjustments		Insulation materials		Infrastructure		Electricity and heat production	
	Scale	Shape	Scale	Shape	Scale	Shape	Scale	Shape
HT heating networks	2	28	67	2	2	57	2	23
LT heating networks	2	28	67	2	2	57	2	34
Heat pumps	2	28	67	2	2	45	2	28
Hybrid heat pumps	2	28	67	2	2	45	2	28

Table A4.4a, distribution of market share of low-carbon heating technologies for the Dutch built environment in 2050, based on the *warmtescenario* report by Berenschot (Berenschot, 2020a):

	Scenario 1 (Mix LT+ heat pump)	Scenario 2 (High heat pump)	Scenario 3 (High hybrid heat pump)
HT heating networks	5 %	5 %	10 %
LT heating networks	40 %	20 %	25 %
Heat pumps	35 %	55 %	25 %
Hybrid heat pumps	20 %	20 %	40 %

Table A4.4b, electricity generation composition for each scenario in 2050, based on the *klimaatneutrale energiescenarios* report by Berenschot (Berenschot, 2020b), (PBL, 2019; Rijksoverheid, 2017):

	Scenario 1 (Mix LT + heat pump)	Scenario 2 (High heat pump)	Scenario 3 (High hybrid heat pump)
Biogas power plant	26 %	35 %	31 %
Wind onshore	10 %	7 %	12 %
Wind offshore	26 %	20 %	21 %
Solar power (PV)	38 %	38 %	36 %

Table A4.5a and A4.5b are input data used from from our previous paper for the calculation of the operational emissions over time (Verhagen et al., 2020).

Table A4.5a, CO_2 intensity per kWh of supplied heat for heating networks and heat pumps sources (MRA & TNO, 2017) (Stimular, 2016):

	Gram CO_2/GJ	gram CO_2/ kWh heat	CO_2 intensity (natural gas = 1)	Temperature
Natural gas		192.8	1	N/A
Biomass	13000	46.8	0.24	LT
Waste heat without additional burning	8800	31.7	0.16	LT
Geothermal	25050	90.1	0.47	LT
Heat from burning waste	26000	93.6	0.49	HT
Waste heat Tata Steel	26000	93.6	0.49	HT
Waste heat from gas fired power plant	32000	115.2	0.60	HT
Waste heat from coal fired power plant	45000	162.0	0.84	HT

Table A4.5b, CO_2 intensity per kWh of supplied heat for heat pumps (COP = 3.5):

	Gram CO_2/ kWh electricity	gram CO_2/ kWh heat	CO_2 intensity (natural gas = 1)
PV	50	14.3	0.07
'Grey' electricity	365.83	104.5	0.54

Table A4.6, materials included and quantified in the model:

Other materials	Metals	Plastics
Cement	Aluminium	ABS
Ceramic brick	Brass	HDPE
Concrete	Bronze	PE
Limestone	Cast iron	Polyurethane (foam)
Sand	Copper	PVC
Wood fibreboard	Galvanized steel	Synthetic rubber
Mineral wool	Stainless steel	Glass fiber
	Steel	Polystyrene
	Nickel	
	Manganese	
	Chromium	
	Molybdenum	
	Tungsten	
	Niobium	
	Vanadium	
	Titanium	
	Cobalt	
	Tantalum	
	Neodymium	

IV