MASTER

Analyzing the relationship between energy poverty and thermal living comfort, and the influence of a minor energy intervention on comfort improvement

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Analyzing the relationship between energy poverty and thermal living comfort, and the influence of a minor energy intervention on comfort improvement

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Preface

Before you lies my master thesis “Analyzing the Relationship between Energy Poverty and Thermal Living Comfort, and the Influence of a Minor Energy Intervention on Comfort Improvement.” This thesis has been written to fulfill the graduation requirements of the Architecture, Building, and Planning program, with a specialization in Urban Systems & Real Estate, at the Eindhoven University of Technology. The research and writing were conducted from September 2022 to July 2024.

I would first like to extend my gratitude to my main supervisor, Dr. Ioulia Ossokina, for helping me establish the research topic and for providing insightful feedback and guidance throughout the entire process. My thanks also go to the chair of my Graduation Supervision Committee, Prof. Dr. Theo Arentze, whose feedback and help with analytical methods were particularly beneficial in the latter stages of my project. I also want to thank my third supervisor, Dr. Ir. Pieter-Jan Hoes, from the Building Performance research group, for his valuable input on comfort-related aspects.

I would like to thank doctoral candidate Vincent Roberdel, who aided me in coding visualizations using the statistical analysis software R, a tool I was initially unfamiliar with. Furthermore, I wish to thank all the researchers, Klusbus participants, and students who contributed to creating a comprehensive and understandable survey.

A special acknowledgment is owed to Jantine Claus, project manager of the energy savings program at the Municipality of Eindhoven. She provided me with the opportunity to study the Klusbus case study and access to the necessary data. Without her, I could not have reached the target group as effectively.

Finally, I want to thank my friends for their support along the way. I also wish to express my gratitude to you, the reader. I hope you enjoy reading and uncover new insights into the subject matter.

Luc Snoeren

Eindhoven, July 1, 2024

Samenvatting

1. Inleiding

Energiearmoede staat hoog op de politieke agenda. Huishoudens in energiearmoede hebben niet voldoende financiële middelen om hun woning te verwarmen naar een comfortabele temperatuur. Energiearmoede komt dus vaker voor in slecht geïsoleerde woningen. Gemeenten proberen energiearmoede tegen te gaan met maatregelen, zoals bijvoorbeeld de Klusbus. Echter, niet veel is bekend over hoe energiearmoede precies is gerelateerd aan wooncomfort en op welke wijze de maatregelen zoals Klusbus het wooncomfort verbeteren.

Daarom is onderzoek gedaan naar de relatie tussen energiearmoede en comfort. Het onderzoek is gedaan gebruikmakend van de casestudy Eindhovense Klusbus.

De klusbus is een programma van de gemeente Eindhoven met als doel huishoudens te helpen die moeite hebben met het betalen van de energierekening. Dit gebeurt door gratis kleine aanpassingen aan de woningen uit te voeren om deze energiezuiniger te maken. Naast energiebesparing is het verbeteren van het wooncomfort een belangrijk doel van de Klusbus. Deze doelstelling en de doelgroep van het programma, energiearme huishoudens, komen samen in de onderzoeksvraag:

Wat is de relatie tussen energiearmoede en thermisch wooncomfort, en de invloed van een kleine energie-interventie op comfortverbetering?

Probleemstelling

Na het analyseren van bestaande onderzoeken is vastgesteld dat er een onderzoekskloof bestaat met betrekking tot het effect van energiearmoede op comfort. Bovendien is er beperkte kennis over de kenmerken van huishoudens in energiearmoede, het effect van energiearmoede op gedrag en de effecten van beleidsmaatregelen gericht op het verminderen van energiearmoede. Het doel van het onderzoek is om deze onderzoekskloof te overbruggen door de relatie tussen energiearmoede en het thermisch wooncomfort van bewoners te analyseren, en de invloed van een kleine energie-interventie op comfortverbetering.

Relevantie

Het onderzoek heeft als doel academische kennis toe te voegen over de vraag of energiearmen een lager thermisch wooncomfort ervaren en in welke mate. Daarnaast wordt kennis toegevoegd over de effectiviteit van kleine energie-interventies op het comfort. De resultaten van het onderzoek zijn waardevol voor gemeenten, woningcorporaties en andere organisaties die zich bezighouden met de bestijding van energiearmoede.

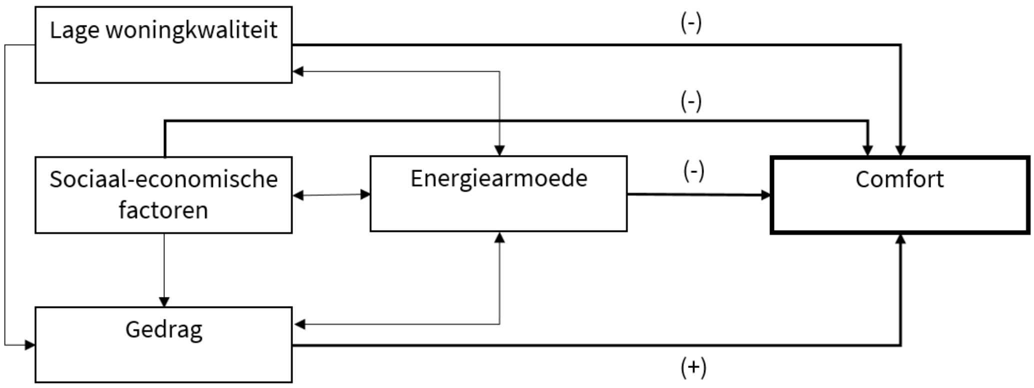
Het onderzoek streeft ernaar om inzicht te geven in de kenmerken van energiearme huishoudens en hoe zij hun comfort verlagen door hun gedragsaanpassingen om energieconsumptie te beperken. Ook wordt geëvalueerd of het gemeentelijke ‘energiefixer’-programma daadwerkelijk energiearme huishoudens bereiken en wat de effecten zijn op comfort, woningkwaliteit en gedrag. Daarnaast worden de meest effectieve energiemaatregelen binnen het programma samengevat. Gemeenten kunnen deze inzichten gebruiken om hun energiearmoedebeleid te verbeteren.

2. Theoretische achtergrond en literatuur

De literatuur stelt dat verschillende sociaaleconomische groepen onevenredig worden getroffen door energiearmoede, waaronder huurders (Mulder, Batenburg, & Dalla Longa, 2023), vrouwen (Clancy, Daskalova, Feenstra, Franceschelli, & Sanz, 2017) en kleine huishoudens (Legendre & Ricci, 2015). Bovendien is energiearmoede sterk afhankelijk van locatie (Mulder, Batenburg, & Dalla Longa, 2023) en woningkwaliteit (Mulder, Batenburg, & Dalla Longa, 2023). Slechte woonomstandigheden, zoals lage temperaturen en tocht, verminderen het comfort aanzienlijk (ISO, 2005).

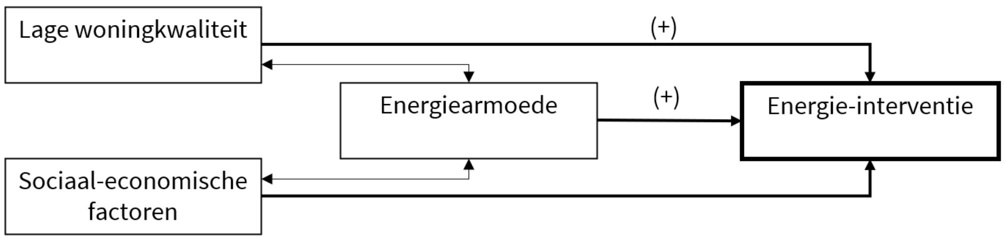
Om de energiekosten het hoofd te bieden, passen huishoudens vaak hun energieverbruikend gedrag aan, een fenomeen dat bekend staat als het prebound-effect (Boemi, Samarentzi, & Dimoudi, 2020). Veelvoorkomende strategieën zijn het verlagen van de thermostaat, korter verwarmen, het dragen van dikkere kleding en het uitschakelen van onnodige verlichting (Langevin, Gurian, & Wen, 2013; Brunner, Spitzer, & Christanell, 2012). Er is echter een gebrek aan onderzoek naar hoe de energiearmen zich in hun gedrag onderscheiden van de niet-energiearmen. Dergelijke gedragsaanpassingen worden verwacht het comfort negatief te beïnvloeden. Bovendien zijn sommige sociaaleconomische factoren bepalend voor het comfort, aangezien de beleving van comfort zeer individueel is (Andargie, Touchie, & O'Brien, 2019).

Ondanks dat er studies zijn over de factoren die verband houden met energiearmoede en factoren die verband houden met comfort, is onderzoek naar de relatie tussen energiearmoede en thermisch wooncomfort beperkt. De bestaande literatuur suggereert dat energiearmoede en thermisch wooncomfort met elkaar verbonden zijn door slechte woningkwaliteit, sociaaleconomische factoren en gedrag. Deze relaties worden geïllustreerd in Figuur S1, dat het eerste conceptuele model van deze scriptie weergeeft, dat zich richt op thermisch wooncomfort als afhankelijke variabele.



Figuur S1. Conceptueel model: thermisch wooncomfort.

Om energiearmoede te bestrijden, worden programma's opgezet om de energie-efficiëntie van woningen te verbeteren. Van energiearme huishoudens en degenen die in slechte woonomstandigheden verkeren, wordt verwacht dat zij de grootste verbeteringen in energie-efficiëntie ontvangen, aangezien zij deze het meest nodig hebben. Deze relaties worden weergegeven in Figuur S2, het tweede conceptuele model, met de energie-interventie als afhankelijke variabele.



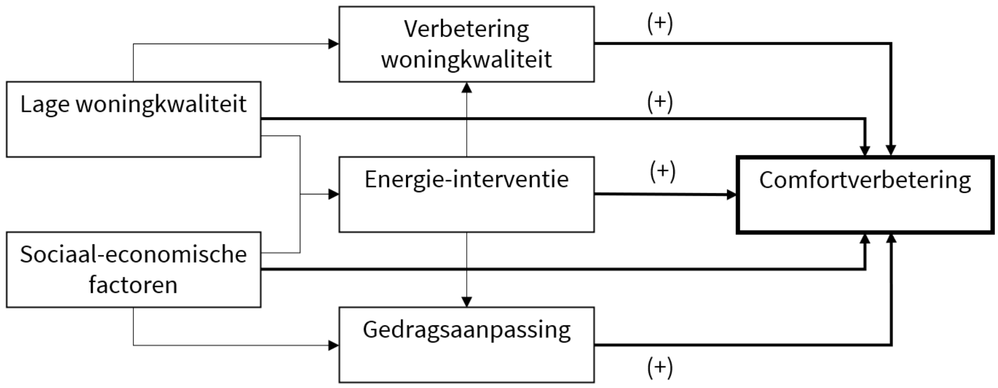
Figuur S2. Conceptueel model 2: de energie-interventie.

Slechts enkele studies hebben zich gericht op de effecten van programma's die energiearmoede aanpakken. De meeste studies onderzochten de impact van grootschalige renovaties en zagen vaak verbeteringen in de woningkwaliteit (Fisk, Singer, & Chan, 2020; Hong, Gilbertson, Oreszczyn, Green, & Ridly, 2009; Howden-Chapman, et al., 2007). Deze renovaties kunnen ertoe leiden dat bewoners hun gedrag veranderen en meer energie gaan verbruiken om het thermische wooncomfort te optimaliseren

(Roberdel, Ossokina, Karamychev, & Arentze, 2023), een fenomeen dat bekendstaat als het reboundeffect (Mizobuchi & Yamagami, 2022). Van der Wal et al. (2023) en Bashir (2013) bestudeerden de voordelen van kleinschaligere energiefixers- en energiecoachingsprojecten en constateerden verbeteringen in comfort, naast andere voordelen.

Veel lokale instellingen hebben echter hun eigen programma ontwikkeld om energiearmoede aan te pakken, elk met een andere benadering. Hierdoor variëren de resultaten sterk tussen de programma's, wat de behoefte aan verder onderzoek naar de effectiviteit van energiearmoedebeleid benadrukt. Deze studie onderzoekt daarom de effecten van een energiearmoedebeleid.

Na een verbetering in energie-efficiëntie wordt verwacht dat het comfort zal toenemen door betere woningkwaliteit en aangepast gedrag. Deze relaties worden weergegeven in Figuur S3, het derde conceptuele model, met de verbetering van comfort als afhankelijke variabele.



Figuur S3. Conceptueel model 3: comfortverbetering.

3. Casestudy: De Eindhovense Klusbus

Voor het onderzoek is gebruik gemaakt van het energiearmoedeprogramma 'De Eindhovense Klusbus'. Door de stijgende energieprijzen hebben veel huishoudens moeite om de energierekeningen te betalen. Om deze huishoudens te ondersteunen is de gemeente Eindhoven 'De Klusbus' gestart. Verschillende 'Klusbussen' bezoeken geselecteerde buurten in Eindhoven om de energiezuinigheid van woningen te verbeteren (Gemeente Eindhoven, 2022)om de energierekeningen te verlagen en het wooncomfort te verbeteren. De klussers, ook wel 'energiefixers' genoemd, voeren gratis kleine energiebesparende maatregelen uit. Zowel huurders als woningeigenaren komen in aanmerking voor deze ingrepen.

Tussen 7 december 2022 en 7 april 2023 heeft de Klusbus een aantal Eindhovense buurten met een hoog energiearmoedecijfer bezocht: Tivoli (28%), Doornakkers-West (11%), Kerstroosplein (16%) en Doornakkers-Oost (23%). 1,518 huishoudens hebben energiebesparende maatregelen ontvangen. Dat betekent dat 28.6% van de 5.305 huishoudens die in deze buurten wonen bereikt is. Deze huishoudens hadden voornamelijk last hadden van tocht, gevold door schimmel. De overgrote meerderheid woonde in een sociale huurwoning.

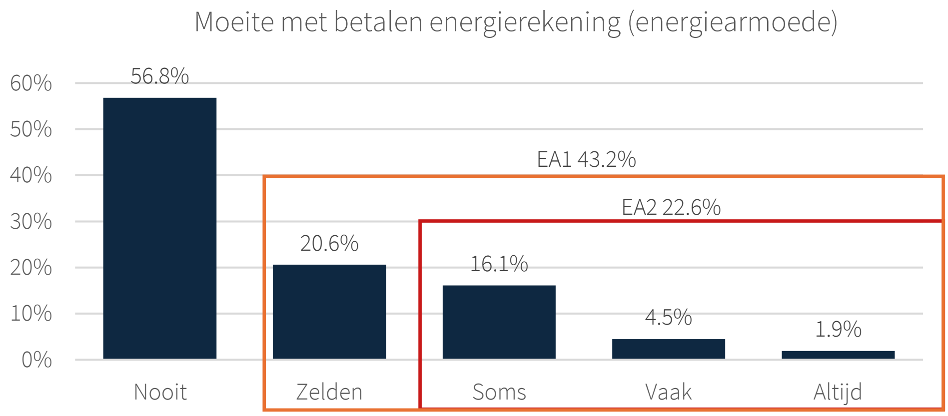
Gemiddeld hebben deze huishoudens een energie-interventie gekregen van 365,71 punten, wat overeenkomt met een waarde interventie-waarde van € 365,71. Gemiddeld zijn 10.52 losse maatregelen toegepast per woning. De meest toegepaste maatregelen zijn ledlampen en radiatorfolie, gevolgd door waterbesparende douchekoppen en tochtstrips. De overige maatregelen zijn tijdschakelaars, deurborstels, brievenbusborstels, tochtbanden, perlators, leidingisolatie, deurdrangers en kierafdichting.

4. Onderzoeksmethode

Om de relatie tussen energiearmoede en wooncomfort te onderzoeken, is een enquête opgezet. De survey bevat vragen over sociaal-economische eigenschappen, woningkwaliteit en gedrag, zowel voor als na de energie-interventie van de Klusbus. De verzamelde data is gekoppeld aan de data van de Klusbus en hiermee zijn vervolgens statistische en econometrische modellen geschat.

Survey en definitie energiearmoede

Van de 1.518 huishoudens die een interventie hebben ontvangen, hebben 632 aangegeven benaderd te mogen worden voor het vervolgonderzoek. Dit onderzoek werd gehouden in de vorm van een survey. Daar zijn 155 volledige reacties op gekomen, een responsgraad van 24,5%. De respondenten zijn onderverdeeld in energiearmen en niet-energiearmen, te zien in Figuur S4. Dit is gebaseerd op hoeveel moeite ze naar eigen zeggen hebben met het betalen van de energierekening. Huishoudens die nooit moeite hebben met het betalen van de energierekening zijn aangemerkt als niet-energiearm, niet-EA (88 respondenten). Huishoudens die zelden tot altijd moeite hebben met het betalen vallen in de brede definitie van energiearmoede, EA1 (67 respondenten). Huishoudens die soms tot altijd moeite hebben met het betalen behoren tot de smalle definitie van energiearmoede, EA2 (35 respondenten). In het vervolg van dit document wordt de EA2 definitie van energiearmoede gebruikt.



Figuur S4. Energiearmoede: frequentie van moeite met het betalen van de energierekening.

Multivariate analyse

De analyse is opgedeeld in drie delen, elk met een eigen afhankelijke variabele:

1) **Thermisch wooncomfort** (Conceptueel model 1): onderzoekt de relatie tussen energiearmoede, woningkwaliteit, gedrag en sociaal-economische factoren met comfort.
2) **Grootte van de energie-interventie** (Conceptueel model 2): onderzoekt hoe energiearmoede, woningkwaliteit en sociaal-economische factoren gerelateerd zijn aan de omvang van de ontvangen energie-interventie.
3) **Comfortverbetering na de interventie** (Comceptueel model 3): analyseert hoe woningkwaliteit, sociaal-economische factoren, de energie-interventie en verbeteringen in woningkwaliteit en gedragsaanpassingen na de interventie gerelateerd zijn aan comfortverbetering.

Meervoudige regressieanalyse is toegepast om de relatie tussen de onafhankelijke en afhankelijke variabelen te onderzoeken. De econometrische modellen zijn geschat met de Ordinary Least Squares (OLS)-methode, waarbij een significantieniveau van 10% is gehanteerd vanwege de beperkte steekproefgrootte. Voor de eindmodellen is de STEPWISE-methode gebruikt, waarbij de onafhankelijke variabelen iteratief zijn toegevoegd of verwijderd uit het model op basis van hun statistische significantie om overfitting te vermijden. De open-source analysetool R (The R Foundation, n.d.) is gebruikt voor de analyses.

Vanwege de beperkte steekproefgrootte (155 observaties) zijn kleine modellen nodig om overfitting te voorkomen. De richtlijn van minimaal 10 observaties per onafhankelijke variabele (Bujang, Sa'at, Sidik, & Joo, 2018) suggereert een maximum van 16 onafhankelijke variabelen per model. Door het gebruik van de STEPWISE-methode wordt overfitting vermeden, multicollineariteit verminderd en de modelinterpretatie verbeterd. Overige variabelen met een correlatie hoger dan 0,5 zijn verwijderd door gebruik van correlatiematrixen. Daarnaast zijn variabelen met minder dan 8 observaties niet opgenomen in de modellen.

Bivariate analyse: de kenmerken van energiearmen vergelijken met niet-energiearmen

Momenteel is er nog weinig bekend over wie de energiearmen precies zijn, maar het Klusbusprogramma probeert hen wel te bereiken. Daarom is het interessant om dieper in te gaan op de kenmerken van de energiearmen. Als verdieping zijn de energiearme respondenten vergeleken met de niet-energiearme respondenten. Met behulp van t-testen zijn de gemiddelde waarden van alle variabelen met elkaar vergeleken. Hierdoor is een beeld ontstaan van de kenmerken van de energiearmen in de steekproef op het gebied van sociaal-economische factoren, comfort, woningkwaliteit, energiebesparend en comfortverhogend gedrag, de energiebesparende maatregelen van de Klusbus, en comfortverbetering, verbetering van woningkwaliteit en gedragsaanpassingen na de interventie.

5. Resultaten

5.1 Wie had een lager comfort vóór de Klusbus?

Comfort is in de survey gemeten volgens de comfortladder in Tabel S1.

Tabel S1. Niveaus van comfort zoals gemeten in de enquête.

Comfort = Hoe vaak men last heeft van kou in de woonkamer in de winter				
-2	-1	0	1	2
Altijd	Vaak	Soms	Zelden	Nooit

De geschatte modellen laten zien dat: (i) energiearmen in lager comfort leven; (ii) comfortniveau ook gerelateerd is aan sociaal-economische eigenschappen, woningeigenschappen en gedrag. Tabel S2 toont de **groepen** die een hoger of lager comfortniveau hadden dan de referentiewaarde van 1.07 oftewel 'zelden kou hebben in de woonkamer'.

Tabel S2. Comfortniveau vóór de Klusbus, per bewonerssegment

Eigenschap	Gemiddeld comfort
Sociaal-economisch	
Energiearm EA2 (23% van de sample)	0,35
Sociale huurder (52%)	0,66
Jonger dan 35 (14%)	0,63
Woningtype en woningkwaliteit	
Appartement (13%)	1,59
Last van tocht in de woning	
Zelden (32%)	0,79
Soms (32%)	0,52
Vaak (18%)	0,24
Altijd (12%)	-0,04
Gebrek aan controle over het binnenklimaat	
Een beetje (29%)	0,91
Matig (27%)	0,75

Zeer (20%)	0,60
Totaal (4%)	0,44
Gedrag	
Ventileren slaapkamer	
3-4 keer per week (9%)	1,18
5-6 keer per week (5%)	1,30
1 keer per dag (30%)	1,42
Meer dan 1 keer per dag (10%)	1,53
Dikke kleding thuis dragen (12%)	0,53

*Opmerking: het comfort is berekend door de geschatte coëfficiënten (het aantal stappen in comfort per bewonerssegment) bij de referentiewaarde op te tellen. Variabelen met meerdere niveaus hebben een grotere relatie met comfort naarmate de waarde van de variabele groter wordt. Voorbeeld: comfort respondenten die zelden tocht ervoeren: 1.068 – 0.276 = 0.78; comfort respondenten die altijd tocht ervoeren: 1.068 + (4 * -0.276) = -0.04.*

Groepen waarvoor **geen** significant verschil in comfort t.o.v. de referentiewaarde is gevonden:	
Sociaal-economisch:	Ouder dan 64, huishouden met kinderen, werkt niet voltijds/niet met pensioen, vrouw, hoogopgeleid, energiebewust
Woningklachten:	Schimmel, droge lucht (<30% luchtvochtigheid), gebrek aan frisse lucht
Gedrag:	Kamertemperatuur, verwarmen woonkamer/slaapkamer, douchefrequentie/ -lengte, ventileren woonkamer, onnodige lichten uitzetten

5.2 Resultaten: Wie kreeg een grotere Klusbus interventie?

De Klusbusinterventie is gemeten in punten (euro).

Energiearmen kregen een grotere interventie (meer punten) van de Klusbus dan niet-energiearmen. Tabel S3 toont dat naast energiearmen ook andere **groepen** een grotere interventie kregen dan de referentiegroep (€ 293).

Tabel S3. Waarde energie-interventie, per bewonerssegment.

Eigenschap	Gemiddelde interventiepunten
Sociaal-economisch	
Energiearm EA2 (23% van de sample)	€ 375
Woningtype en woningkwaliteit	
Appartement (13%)	€ 232
Tocht	
Zelden (32%)	€ 309
Soms (32%)	€ 325
Vaak (18%)	€ 342
Altijd (12%)	€ 358
Droge lucht (<30% luchtvochtigheid) (20%)	€ 403

*Opmerking: de waarde van de interventie is berekend door de geschatte coëfficiënten (de extra interventiepunten per bewonerssegment) bij de referentiewaarde op te tellen. Variabelen met meerdere niveaus hebben een grotere relatie met de interventie naarmate de waarde van de variabele groter wordt. Voorbeeld: interventie respondenten die zelden tocht ervoeren: 293.04 + 16.16 = 309; interventie respondenten die altijd tocht ervoeren: 293.04 + (4 * 16.16) = 358.*

Groepen waarvan **geen** significant verschil met de referentie-interventie is gevonden.	
Sociaal-economisch:	Sociale huur, jonger dan 35, ouder dan 64, huishouden met kinderen, werkt niet voltijd/niet met pensioen, vrouw, hoogopgeleid, energiebewust
Woningklachten:	Schimmel, gebrek aan frisse lucht, geen controle over het binnenklimaat

5.3 Resultaten: Wie ervoer een grotere comfortverbetering en waardoor?

Comfortverbetering na de klusbus is gemeten volgens de ladder van comfortverbetering in Tabel S4. Gemiddeld is een comfortverbetering van 1, een beetje minder kou, gemeten.

Table S4. Niveaus van comfortverbetering zoals gemeten in de enquête.

Comfortverbetering = minder last van kou in de woning in de winter na de Klusbus				
0	1	2	3	4
Niet minder	Een beetje minder	Redelijk minder	Veel minder	Zeer veel minder

Wie ervoer een grotere comfortverbetering?

Energiearmen ervoeren geen grotere comfortverbetering dan niet-energiearmen. Tabel S5 toont dat andere **groepen** wel een grotere of kleinere comfortverbetering ervoeren dan de referentiewaarde van 0.56.

Tabel S5. Comfortverbetering ná de Klusbus, per bewonerssegment.

Eigenschap	Gemiddelde comfortverbetering
Sociaal-economisch	
Jonger dan 35 (14% van de sample)	1,41
Woningtype en woningkwaliteit	
Gebrek aan controle over binnenklimaat	
Een beetje (29%)	0,73
Matig (27%)	0,89
Zeer (20%)	1,06
Totaal (4%)	1,22

*Opmerking: de comfortverbetering is berekend door de geschatte coëfficiënten (het aantal stappen in comfortverbetering per bewonerssegment) bij de referentiewaarde op te tellen. Variabelen met meerdere niveaus hebben een grotere relatie met comfortverbetering naarmate de waarde van de variabele groter wordt. Voorbeeld: comfortverbetering respondenten die een beetje gebrek aan controle over het binnenklimaat hadden: 0.563 + 0.165 = 0.73; totaal gebrek aan controle: 0.563 + (4 * 0.165) = 1.22.*

Groepen waarvan **geen** significante relatie met de comfortverbetering is gevonden:	
Energierarmoede:	Energiearm
Sociaal-economisch:	Sociale huur, ouder dan 64, huishouden met kinderen, werkt niet voltijd/niet met pensioen, vrouw, hoogopgeleid, energiebewust
Woningkenmerken:	Appartement, tocht, schimmel, droge lucht (<30% luchtvochtigheid), gebrek aan frisse lucht, gebrek aan controle over binnenklimaat

Welke maatregelen zijn gerelateerd aan comfortverbetering?

Tabel S6 toont een aantal **maatregelen** dat is gerelateerd aan een grotere of kleinere comfortverbetering dan de referentiewaarde van 0.64.

Tabel S6. Comfortverbetering ná de Klusbus, per maatregel.

Maatregelen	Gemiddelde comfortverbetering
Antitocht maatregelen	
Tochtstrip op deur	
Een (38% van de sample)	0,97
Twee (14%)	1,29
Drie (3%)	1,62
Brievenbusborstel (29%)	0,97
Tochtband op deur	
Een (17%)	0,97
Twee (5%)	1,31
Drie (1%)	1,64
Efficiëntiemaatregelen	
Waterbesparende douchekop	
Een (65%)	0,31
Twee (2%)	-0,01

*Opmerking: de comfortverbetering is berekend door de geschatte coëfficiënten (het aantal stappen in comfortverbetering per maatregel) bij de referentiewaarde op te tellen. De relatie met comfortverbetering neemt toe naarmate meer maatregelen zijn toegepast. Voorbeeld: comfortverbetering respondenten die 1 tochtstrip hebben gekregen: 0.641 + 0.326 = 0.97; 3 tochtstrips: 0.641 + (3 * 0.326) = 1.62.*

Maatregelen waarvan **geen** significante relatie met de comfortverbetering is gevonden:	
Antitocht:	Deurborstel, tochtstrip raam
Efficiëntie:	Radiatorfolie, ledlamp, tijdschakelaar, perlator

Opmerking: leidingisolatie, deurdrangers en kierafdichting zijn niet onderzocht door het beperkt aantal toepassingen van deze maatregelen.

Welke verbeteringen van woningkwaliteit en gedragsaanpassingen zijn gerelateerd aan comfortverbetering?

Door de maatregelen werd de woningkwaliteit verbeterd en pasten mensen hun gedrag aan. Tabel S7 toont de **verbeteringen van woningkwaliteit** en **gedragsaanpassingen** ná de Klusbus die zijn gerelateerd aan een grotere of kleinere comfortverbetering dan de referentiewaarde van 0.23.

Tabel S7. Comfortverbetering ná de Klusbus, per bewonerssegment.

Verbetering van woningkwaliteit en gedragsaanpassing	Gemiddelde comfortverbetering
Verbetering woningkwaliteit	
Minder tocht	
Een beetje (29% van de sample)	0,77
Redelijk (19%)	1,31
Veel (8%)	1,85
Zeer veel (7%)	2,48
Gedragsaanpassingen	
Minder verwarmen (21%)	0,69
Minder (dikke) kleding (16%)	0,42

*Opmerking: de comfortverbetering is berekend door de geschatte coëfficiënten (het aantal stappen in comfortverbetering per bewonerssegment) bij de referentiewaarde op te tellen. Variabelen met meerdere niveaus hebben een grotere relatie met comfortverbetering naarmate de waarde van de variabele groter wordt. Voorbeeld: comfortverbetering respondenten die een beetje minder tocht ervoeren: 0.231 + 0.538 = 0.77; totaal gebrek aan controle: 0.231 + (4 * 0.548) = 2.48.*

Volgende ervaren woningverbeteringen en gedragsaanpassingen hebben we **niet** aan comfortverbetering kunnen relateren:	
Verbetering woningkwaliteit:	Minder schimmel
Gedragsaanpassingen:	Meer ventileren, vaker/langer douchen, minder onnodige lichten uitdoen

Opmerking: meer controle over het binnenklimaat en meer frisse lucht zijn niet onderzocht door correlatie tussen de variabelen.

5.4 Verdieping: Kenmerken van energiearmen vergeleken met niet-energiearmen

De energiearme respondenten in de steekproef verschilden significant van hun niet-energiearme tegenhangers wat betreft verschillende sociaaleconomische kenmerken. Ze ervaarden lagere comfortniveaus, woonden in slechtere woonomstandigheden en vertoonden meer energieverbruikend gedrag. De energiearme huishoudens waren vaker sociale huurders, hadden een lager opleidingsniveau, hadden hogere energiekosten, werkten minder vaak voltijds en waren minder vaak koppels zonder kinderen. Ze rapporteerden lager comfort vanwege meer klachten over de woningkwaliteit. In vergelijking met de niet-energiearme huishoudens ervaarden ze vaker kou en tocht, hadden ze vaker gebrek aan frisse lucht en hadden ze minder controle over het binnenklimaat. Vanwege hun lagere woningkwaliteit hadden ze meer verwarming nodig om een acceptabel comfortniveau te bereiken. Bijgevolg verwarmden de energiearme huishoudens hun slaapkamers meer gedurende de dag, hun woonkamers meer 's nachts en ventileerden ze hun woonkamers meer dan de niet-energiearme huishoudens.

Ondanks het feit dat ze al meer verwarmden, zouden de energiearme huishoudens hun gedrag nog verder aanpassen als financiële beperkingen werden opgeheven. Ze zouden hun huizen meer verwarmen, meer ventileren, vaker en langer douchen en lichtere kleding dragen dan de niet-energiearme huishoudens.

Daarnaast ontvingen de energiearme huishoudens waardevollere interventies (€419,03 vs €338,33) en meer energiemaatregelen (11,5 vs 10,2) dan de niet-energiearme huishoudens, met name gericht op het verminderen van tocht.

Echter, na de Klusbus-interventie ervoeren de energiearme huishoudens geen grotere verbetering in comfort. Wel ervoeren ze een grotere verbetering in de huisvestingskwaliteit, met name door een afname van schimmel en een toename van frisse lucht. Bovendien pasten de energiearme huishoudens hun gedrag meer aan na de interventie dan de niet-energiearme huishoudens. Ze begonnen vaker lichtere kleding te dragen, vaker en langer te douchen en minder vaak onnodige verlichting uit te doen dan de niet-energiearmen.

6. Conclusie

Bevindingen

Dit onderzoek gebruikte een survey en statistische en econometrische modellen om de relatie tussen energiearmoede en thermisch wooncomfort te onderzoeken, met als casestudy Eindhovense Klusbus.

Welke huishoudens hadden een lager comfort vóór de Klusbus?

Het onderzoek laat zien dat huishoudens die energiearm zijn (d.w.z. frequent moeite hebben met betalen van energierekeningen), ook last hebben van significant lager dan gemiddeld thermisch comfort in de woning. Naast het lagere comfortniveau, wonen de energiearmen ook in slechtere woningen, passen ze hun gedrag meer aan om hun comfort thuis te verhogen of energie te besparen, en zijn ze oververtegenwoordigd in diverse sociaal-economische groepen (vaker sociale huur, lager opleidingsniveau, hogere energiekosten, minder vaak voltijd werkzaam, en minder koppels zonder kinderen). Dit betekent dat energiearmoede verweven is met de andere factoren die invloed hebben op comfort, wat suggereert dat de relatie tussen energiearmoede en comfort niet alleen direct is, maar een onderliggend mechanisme vormt.

Verder hangt lager dan gemiddeld woningcomfort samen met woningklachten zoals tocht en een gebrek aan controle over het binnenklimaat, maar ook met bepaalde gedragsaanpassingen zoals weinig ventileren van de slaapkamer en het dragen van dikke kleding thuis. Ten slotte komt laag wooncomfort relatief vaker voor bij de volgende sociaal-economische groepen: sociale huurders, jongeren en bewoners van eengezinswoningen.

Welke huishoudens kregen een grotere interventie van de Klusbus?

Energiearme huishoudens ontvingen een kwart grotere energie-interventie (gemeten in termen van de totale maatregelkosten). Bepaalde woningkenmerken (klachten over tocht en droge binnenlucht en woningtype eengezinswoningen) waren ook geassocieerd met grotere interventies.

Welke huishoudens ervoeren een grotere comfortverbetering na de Klusbus en waardoor?

Alle huishoudens ervoeren een significante toename van wooncomfort en een afname van klachten na de Klusbus. Tegen de verwachting in vonden we echter geen relatie tussen energiearmoede en een grotere comfortverbetering na de interventie, dit ondanks een gemiddeld grotere interventie die energiearmen ontvingen.

Van alle toegepaste maatregelen hebben antitochtmaatregelen, (tochtstrips en tochtbanden voor deuren en brievenbusborstels) tot de grootste comfortverbeteringen geleid.

De belangrijkste drijvende factor in de verbetering van comfort na de interventie is de verbeterde woningkwaliteit, met name de vermindering van tocht. Daarna volgen aanpassingen in het gedrag na de interventie: minder verwarmen en lichtere kleding dragen. Dit impliceert een mechanisme waarbij energiemaatregelen tot een verbeterde woningkwaliteit en gedragsaanpassingen leiden, die samen bijdragen aan een verhoogd comfort.

Samenvattend vereist het aanpakken van energiearmoede een veelzijdige aanpak die zich richt op niet alleen energiezuinigheid, maar ook op woningkwaliteit, gedrag en sociaal-economische factoren. Door de onderlinge verbondenheid van deze factoren te begrijpen en doelgerichte interventies toe te passen, kunnen beleidsmakers, woningcorporaties en andere belanghebbenden energiearmoede effectief verminderen en het comfort en welzijn van kwetsbare huishoudens verbeteren.

Beperkingen

Het onderzoek heeft enkele beperkingen. Als eerste is het aantal deelnemers in het onderzoek relatief klein, met 155 respondenten, waaronder 35 energiearme en 88 niet-energiearme respondenten. Deze kleine steekproefomvang beperkte de statistische kracht en betrouwbaarheid van de bevindingen, vooral bij het vergelijken van verschillende groepen. Een grotere steekproefomvang zou robuuster bewijs kunnen leveren van relaties en effecten, en mogelijk statistisch significante relaties aan het licht brengen die in de kleinere steekproef niet waarneembaar waren.

Daarnaast is het onderzoek alleen uitgevoerd in vier buurten in Eindhoven. Dit gebrek aan geografische diversiteit en de relatief kleine steekproefomvang maken het moeilijk om de resultaten te generaliseren naar het hele land. De bevindingen moeten worden geïnterpreteerd binnen de context van de specifieke locatie en zijn mogelijk niet op bredere schaal toepasbaar.

Verder is de studie uitgevoerd tijdens een periode van fluctuerende energieprijzen. Het constante nieuws over energieprijsschommelingen kan de bewustwording van de deelnemers over energiebesparend gedrag hebben beïnvloed. Bovendien is de focus van de studie op energie-efficiëntieverbeteringen beperkt tot de interventies die zijn uitgevoerd door het Klusbus-programma, dat specifiek is voor Eindhoven. Andere gemeenten kunnen andere programma's of benaderingen hebben om energiearmoede aan te pakken en energiebesparende maatregelen te implementeren. Bovendien kan de bevolking in andere steden verschillen. Deze beperkingen beïnvloeden de externe validiteit van de studie en moeten in overweging worden genomen bij het interpreteren van de bevindingen.

Tenslotte, om het onderzoeksontwerp te versterken en meer robuust bewijs te leveren van het effect van de energie-efficiëntieverbeteringen, zou het nuttig zijn om een controlegroep op te nemen die de interventie niet heeft ontvangen. Een controlegroep zou een vergelijking mogelijk maken tussen degenen die de interventie hebben ontvangen en degenen die dat niet hebben gedaan, en een basislijn vaststellen voor het meten van de effecten van de interventie op comfort. Dit zou een beter begrip van de impact van de interventie bieden en helpen om waargenomen veranderingen in comfort nauwkeuriger toe te schrijven. Op deze manier kan rekening worden gehouden met de invloed van de tijdstrend. Het uitvoeren van de enquête in de lente, wanneer de temperaturen doorgaans warmer worden, kan verstorende factoren introduceren. Door een controlegroep te gebruiken, kunnen de effecten van de interventie beter worden geïsoleerd en kunnen waargenomen veranderingen in comfort worden toegeschreven aan de specifieke interventies uitgevoerd door de Klusbus. Door deze overwegingen aan te pakken, kan het onderzoek zijn interne validiteit versterken, het argument voor de veronderstelde causaliteit versterken en robuustere en generaliseerbare bevindingen opleveren.

Summary

1. Introduction

Energy poverty is a significant issue on the political agenda. Households experiencing energy poverty lack the financial resources to heat their homes to a comfortable temperature, which is more common in poorly insulated homes. Municipalities are attempting to combat energy poverty through measures such as the Klusbus. However, there is limited knowledge about how energy poverty is related to living comfort and how measures like the Klusbus improve this comfort.

This research examines the relationship between energy poverty and comfort, using the case study of the Eindhoven Klusbus. The Klusbus is a program by the municipality of Eindhoven aimed at helping households struggling to pay their energy bills by making small, free adjustments to their homes to make them more energy-efficient. In addition to energy savings, improving living comfort is a key goal of the Klusbus. This objective and the program's target group, energy-poor households, are encapsulated in the research question:

What is the relationship between energy poverty and thermal living comfort, and the influence of a minor energy intervention on comfort improvement?

Problem statement

After analyzing existing research, a research gap has been identified regarding the impact of energy poverty on comfort. Furthermore, there is limited knowledge about the characteristics of energy-poor households, the effect of energy poverty on behavior, and the effects of policy measures aimed at reducing energy poverty. The goal of this research is to bridge this gap by analyzing the relationship between energy poverty and residents' thermal living comfort, and the impact of a minor energy intervention on comfort improvement.

Relevance

Little is known in the literature about the relationship between energy poverty and living comfort. This research therefore aims to add academic knowledge about whether and to what extent the energy-poor compromise their thermal living comfort. Moreover, policies aimed at eradicating energy poverty are relatively new and their effects often unclear. Therefore, this study seeks to add knowledge about whether the municipal 'energy fixer' program effectively reached energy-poor households and whether minor energy interventions effectively influenced comfort, housing quality, and behavior. The results of this research are valuable for municipalities, housing associations, and other organizations working to combat energy poverty.

Moreover, the study aims to provide insights into the characteristics of energy-poor households and whether they adjust their behavior to limit energy consumption. Furthermore, it summarizes the most effective energy measures within the program. Municipalities can use these insights to improve their energy poverty policies.

2. Theoretical background and literature

The literature states that various socioeconomic groups are disproportionately affected by energy poverty, including renters (Mulder, Batenburg, & Dalla Longa, 2023), women (Clancy, Daskalova, Feenstra, Franceschelli, & Sanz, 2017), and small households (Legendre & Ricci, 2015). Besides, energy poverty is highly dependent on location (Mulder, Batenburg, & Dalla Longa, 2023) and housing quality (van der Wal, van Ooij, & Straver, 2023). Poor housing conditions, such as low temperatures and drafts, significantly reduce comfort (ISO, 2005).

To manage energy costs, households often adjust their energy consumption behavior, a phenomenon known as the prebound effect (Boemi, Samarentzi, & Dimoudi, 2020). Common strategies include lowering the thermostat, reducing heating times, wearing thicker clothing, and turning off unnecessary lights (Langevin, Gurian, & Wen, 2013; Brunner, Spitzer, & Christanell, 2012). However, there is a lack of clear research on how the energy-poor differ in their behavior from the non-energy-poor. Such behavior adjustments are expected to negatively impact comfort. Furthermore, certain socioeconomic factors are significant determinants of comfort, as the experience of comfort is highly individual (Andargie, Touchie, & O'Brien, 2019).

Despite studies on the factors related to energy poverty and factors related to comfort, research on the relationship between energy poverty and thermal living remains limited. The existing literature suggests that energy poverty and thermal living comfort are interconnected through poor housing quality, socioeconomic factors, and behavior. These relationships are illustrated in Figure S1, which depicts the first conceptual model of this thesis, which focuses on thermal living comfort as the dependent variable.

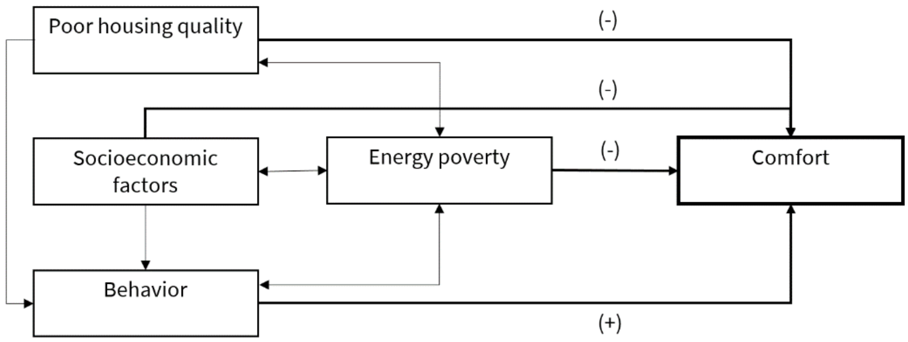


Figure S1. Conceptual model: thermal living comfort.

To combat energy poverty, programs are established to enhance the energy efficiency of homes. Energy-poor households and those residing in poor housing conditions are expected to receive the most substantial improvements in energy efficiency, as they most need it. These relationships are visualized in Figure S2, the second conceptual model, with the energy intervention as the dependent variable.

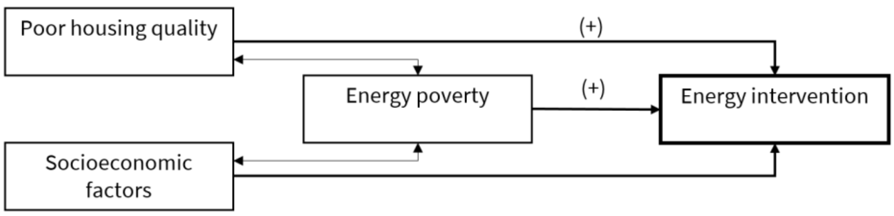


Figure S2. Conceptual model 2: the energy intervention.

Only a few studies have focused on the effects of programs targeting energy poverty. Most studies examined the impacts of large renovations and often find improvements in housing quality (Fisk, Singer, & Chan, 2020; Hong, Gilbertson, Oreszczyn, Green, & Ridly, 2009; Howden-Chapman, et al., 2007; Roberdel, Ossokina, Karamychev, & Arentze, 2023). These renovations can lead residents to change their behavior and consume more energy to optimize thermal living comfort (Roberdel, Ossokina, Karamychev, & Arentze, 2023) a phenomenon known as the rebound effect (Mizobuchi & Yamagami, 2022). Van der Wal et al. (2023) and Bashir (2013) studied the benefits of smaller-scale energy fixer and energy coaching projects, noting improvements in comfort among other benefits.

However, many local institutions have developed their own program to eradicate energy poverty, each with a different approach. Consequently, results vary widely across programs, highlighting the need for further research on the effectiveness of energy poverty policies. This study, therefore, examines the effects of an energy poverty policy.

Following an improvement in energy efficiency, comfort is expected to increase due to better housing quality and adjusted behavior. These relationships are depicted in Figure S3, the third conceptual model, focusing on comfort improvement as the dependent variable.

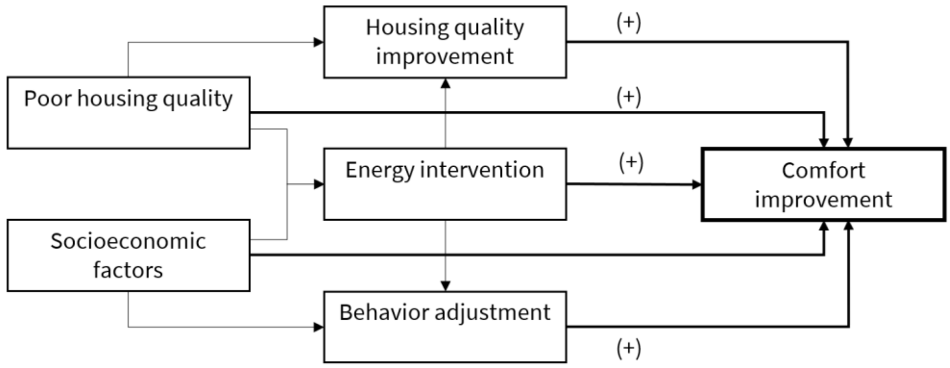


Figure S3. Conceptual model: comfort improvement.

3. Case study: De Eindhovense Klusbus

For this study, the anti-energy poverty program 'The Eindhoven Klusbus' was utilized. Due to rising energy prices, many households struggle to pay their energy bills. To support these households, the municipality of Eindhoven initiated 'The Klusbus.' Various 'Klusbuses' visit selected neighborhoods in Eindhoven to improve the energy efficiency of dwellings, aiming to lower energy bills and enhance living comfort (Gemeente Eindhoven, 2022). The workers, also known as 'energy fixers,' carry out small energy-saving measures entirely free of charge. Both renters and homeowners are eligible for these interventions.

Between December 7, 2022, and April 7, 2023, the Klusbus visited several Eindhoven neighborhoods with high energy poverty rates: Tivoli (28%), Doornakkers-West (11%), Kerstroosplein (16%), and Doornakkers-Oost (23%). A total of 1,518 households received energy-saving measures, meaning 28.6% of the 5,305 households in these neighborhoods were reached. These households mainly suffered from drafts, followed by mold issues. The vast majority lived in social housing.

On average, these households received an energy intervention worth 365.71 intervention points, equivalent to an intervention value of €365.71. An average of 10.52 individual measures were implemented per home. The most commonly applied measures were LED bulbs and radiator foil, followed by water-saving showerheads and draft strips. Other measures included timer switches, door brushes, mailbox brushes, draft tapes, aerators, pipe insulation, door closers, and gap seals.

4. Research method

To investigate the relationship between energy poverty and living comfort, a survey was conducted. The survey included questions about socio-economic characteristics, comfort, housing quality, and behavior, both before and after the Klusbus energy intervention. The collected data was then linked to the Klusbus data, and statistical and econometric models were estimated using this combined dataset.

Survey and definition of energy poverty

Out of the 1,518 households that received an intervention, 632 indicated their willingness to participate in a follow-up study. This follow-up was conducted in the form of a survey, which received 155 complete responses, resulting in a response rate of 24.5%. The respondents were categorized into energy-poor and non-energy-poor, as shown in Figure S4. This classification was based on their self-reported difficulty in paying energy bills. Households that never had trouble paying their energy bills were classified as non-energy-poor (non-EP), comprising 88 respondents. Households that rarely to always have trouble paying their energy bills fell under the broad definition of energy poverty (EP1), comprising 67 respondents. Households that sometimes to always have trouble paying were included in the narrow definition of energy poverty (EP2), comprising 35 respondents. In the remainder of this document, the EP2 definition of energy poverty is used.

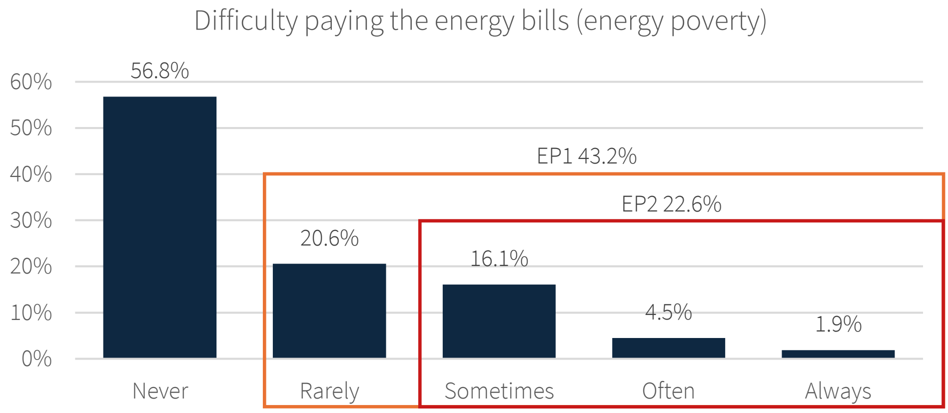


Figure S4. Energy poverty: frequency of difficulty paying the energy bills last winters. Source: survey.

Multivariate analysis

The analysis is divided into three parts, each one dependent variable:

1) Thermal living comfort (conceptual Model 1): This part examines the relationship between energy poverty, housing quality, behavior, and socioeconomic factors with comfort.
2) Size of the energy intervention (conceptual Model 2): This part investigates how energy poverty, housing quality, and socio-economic factors are related to the size of the received energy intervention.
3) Comfort improvement after the intervention (conceptual Model 3): This part analyzes how housing quality, socio-economic factors, the energy intervention, improvements in housing quality, and behavior adjustments post-intervention are related to comfort improvement.

Multiple regression analysis was applied to explore the relationship between the independent and dependent variables. The econometric models were estimated using the Ordinary Least Squares (OLS) method, with a significance level of 10% due to the limited sample size. The STEPWISE method was used for the final models, which iteratively adds or removes independent variables based on their statistical significance to avoid overfitting. The open-source analysis tool R (The R Foundation, n.d.) was used for the analyses.

Due to the limited sample size (155 observations), small models were necessary to prevent overfitting. The guideline of at least 10 observations per independent variable (Bujang, Sa'at, Sidik, & Joo, 2018) suggests a maximum of 16 independent variables per model. Using the STEPWISE method helps to avoid overfitting, reduces multicollinearity, and improves model interpretation. Other variables with a correlation higher than 0.5 were removed using correlation matrices. Additionally, variables with fewer than 8 observations were not included in the models.

Bivariate analysis: characteristics of the energy-poor compared to the non-energy-poor

Currently, little is known about who the energy-poor exactly are, but the Klusbus program does attempt to reach them. Therefore, it is interesting to delve deeper into the characteristics of the energy-poor. As an in-depth analysis, the energy-poor respondents were compared with the non-energy-poor respondents. Using t-tests, the mean values of all variables were compared. This provided insights into the characteristics of the energy-poor in the sample in terms of socio-economic factors, comfort, housing quality, energy-saving and comfort-enhancing behavior, the energy-saving measures of the Klusbus, and improvements in comfort, housing quality, and behavior adjustments post-intervention.

5. Results

5.1 Who had lower comfort before the Klusbus?

Comfort was measured in the survey using the comfort ladder shown in Table S1.

Table S1. Levels of comfort as measured in the survey.

Comfort = How often one experiences cold in the living room during winter				
-2	-1	0	1	2
Always	Often	Sometimes	Rarely	Never

The estimated models show that: (i) energy-poor households live in lower comfort; (ii) comfort level is also related to socio-economic characteristics, housing properties, and behavior. Table S2 displays the **groups** that had higher or lower comfort levels compared to the reference value of 1.07, meaning 'rarely experiencing cold in the living room'.

Table S2. Comfort level before the Klusbus, per resident segment

Characteristic	Average comfort
Socioeconomic	
Energy-poor EP2 (23% of the sample)	0.35
Social renter (52%)	0.66
Younger than 35 (14%)	0.63
Housing and housing quality	
Apartment (13%)	1.59
Experience of drafts in dwelling	
Rarely (32%)	0.79
Sometimes (32%)	0.52
Often (18%)	0.24
Always (12%)	-0.04
Lack of control over indoor climate	
Slight (29%)	0.91
Moderate (27%)	0.75
Very (20%)	0.60
Total (4%)	0.44
Behavior	
Ventilating bedrooms	
3-4 times per week (9%)	1.18
5-6 times per week (5%)	1.30
1 time per day (30%)	1.42
More than 1 time per day (10%)	1.53
Wearing thick clothing at home (12%)	0.53

*Note: Comfort is calculated by adding the estimated coefficients (the number of comfort steps per resident segment) to the reference value. Variables with multiple levels have a stronger relationship with comfort as their value increases. Example: comfort for respondents who rarely experienced drafts: 1.07 - 0.276 = 0.79; comfort for respondents who always experienced drafts: 1.07 + (4 * -0.276) = -0.04.*

Groups where **no** significant difference in comfort compared to the reference value was found:	
Socioeconomic:	Older than 64, households with children, not working full-time/not retired, female, highly educated, energy-conscious
Poor housing quality:	Mold, dry air (<30% humidity), lack of fresh air
Behavior:	Room temperature, heating living room/bedroom, shower frequency/duration, ventilating living room, turning off unnecessary lights

5.2 Results: Who received a larger Klusbus intervention??

The Klusbus intervention is measured in points (euros).

Energy-poor households received a larger intervention (more points) from the Klusbus compared to non-energy-poor households. Table S3 shows that besides energy-poor households, other **groups** also received a larger intervention compared to the reference group (€293):

Table S3. Value of energy intervention, per resident segment.

Characteristic	Average intervention points
Socioeconomic	
Energy-poor EP2 (23% of the sample)	€375
Housing and housing quality	
Apartment (13%)	€232
Drafts	
Rarely (32%)	€309
Sometimes (32%)	€325
Often (18%)	€342
Always (12%)	€358
Dry air (<30% humidity) (20%)	€403

*Note: The value of the intervention is calculated by adding the estimated coefficients (the additional intervention points per resident segment) to the reference value. Variables with multiple levels have a stronger relationship with the intervention as their value increases. Example: intervention for respondents who rarely experienced drafts: 293.04 + 16.16 = 309; intervention for respondents who always experienced drafts: 293.04 + (4 * 16.16) = 358.*

Groups where **no** significant difference with the reference intervention was found:	
Socioeconomic:	Social renter, younger than 35, older than 64, households with children, not working full-time/not retired, female, highly educated, energy-conscious
Poor housing quality:	Mold, lack of fresh air, lack of control over indoor climate

5.3 Results: Who experienced a greater comfort improvement and why?

Comfort improvement after the Klusbus was measured according to the comfort improvement ladder in Table S4. On average, an improvement of 1, indicating slightly less cold, was observed.

Table S4. Levels of comfort improvement as measured in the survey.

Comfort improvement = less cold in the home in the winter after the Klusbus				
0	1	2	3	4
Not less	Slightly less	Moderately less	Much less	Very much less

Who experienced a greater comfort improvement?

The energy-poor did not experience greater comfort improvement than the non-energy-poor. Table S5 shows that other **groups** did experience larger or smaller comfort improvement than the reference value of 0.56:

Table S5. Comfort improvement after the Klusbus, per resident segment.

Characteristic	Average comfort improvement
Socioeconomic	
Younger than 35 (14% of the sample)	1.41
Housing and housing quality	
Lack of control over indoor climate	
Slight (29%)	0.73
Moderate (27%)	0.89
Very (20%)	1.06
Total (4%)	1.22

*Note: Comfort improvement is calculated by adding the estimated coefficients (the number of steps in comfort improvement per resident segment) to the reference value. Variables with multiple levels have a stronger relationship with comfort improvement as the value of the variable increases. For example: comfort improvement for respondents who had a slight lack of control over the indoor climate: 0.563 + 0.165 = 0.73; total lack of control: 0.563 + (4 * 0.165) = 1.22.*

Groups for which **no** significant relationship with comfort improvement was found:

Socioeconomic:	Energy-poor, social rent, older than 64, household with children, does not work full-time / not retired, woman, highly educated, energy-conscious
Poor housing quality:	Apartment, drafts, mold, dry air (<30% humidity), lack of fresh air, lack of control over indoor climate

Which measures are related to comfort improvement?

Table S6 shows the **measures** that are related to greater or lesser comfort improvement than the reference value of 0.64:

Table S6. Comfort improvement after the Klusbus, per measure.

Measures	Average comfort improvement
Antidraft measures	
Door draft strip	
One (38% of the sample)	0.97
Two (14%)	1.29
Three (3%)	1.62
Mailbox brush (29%)	0.97
Door draft seal tape	

One (17%)	0.97
Two (5%)	1.31
Three (1%)	1.64
Efficiency measures	
Water-saving showerhead	
One (65%)	0.31
Two (2%)	-0.01

*Note: Comfort improvement is calculated by adding the estimated coefficients (the number of steps in comfort improvement per measure) to the reference value. The relationship with comfort improvement increases as more measures are applied. For example: comfort improvement for respondents who received 1 draft strip: 0.641 + 0.326 = 0.97; 3 draft strips: 0.641 + (3 * 0.326) = 1.62.*

Measures for which **no** significant relationship with comfort improvement was found:

Antidraft:	Door brush, draft strip at windows
Efficiency:	Radiator foil, LED light, timer switch, aerator

Note: pipe insulation, door closers, and draft sealing have not been studied due to the limited number of applications for these measures.

Which improvements in housing quality and behavioral adjustments are related to comfort improvement?

Through the measures, housing quality was improved and people adjusted their behavior. Table S7 shows the **improvements in housing quality** and **behavioral adjustments** after the Klusbus that are related to greater or lesser comfort improvement than the reference value of 0.23.

Table S7. Comfort improvement after the Klusbus, per resident segment.

Improvement in housing quality and behavioral adjustment	Average comfort improvement
Improved housing quality	
Less drafts	
Slightly (29% of the sample)	0.77
Moderately (19%)	1.31
Much (8%)	1.85
Very much (7%)	2.48
Behavior adjustments	
Heat less (21%)	0.69
Less (thick) clothes (16%)	0.42

*Note: Comfort improvement is calculated by adding the estimated coefficients (the number of steps in comfort improvement per resident segment) to the reference value. Variables with multiple levels have a stronger relationship with comfort improvement as the value of the variable increases. For example, comfort improvement for respondents who experienced a little less draft: 0.231 + 0.538 = 0.77; total lack of control: 0.231 + (4 * 0.548) = 2.48.*

The following experienced housing improvements and behavioral adjustments could **not** be related to comfort improvement.

Improved housing quality:	Less mold
Behavior adjustments:	Ventilating more, more frequent/longer showers, turning off unnecessary lights less

Note: more control over the indoor climate and more fresh air were not studied due to the correlation between the variables.

5.4 Bivariate analysis: characteristics of the energy-poor compared to the non-energy-poor

The energy-poor respondents in the sample differed significantly from their non-energy-poor counterparts in various socioeconomic characteristics. They experienced lower comfort levels, lived in poorer housing conditions, and engaged in more energy-consuming behaviors. The energy-poor were more often social renters, had lower education levels, faced higher energy costs, worked less full-time, and were less often couples without children. They reported lower comfort due to more complaints about housing quality. Compared to the non-energy-poor, they experienced cold and drafts more often, lacked fresh air more often, and had less control over the indoor environment. Due to their lower-quality housing, they required more heating to achieve an acceptable level of comfort. Consequently, the energy-poor heated their bedrooms more throughout the day, heated their living rooms more at night, and ventilated their living rooms more than the non-energy-poor.

Despite already heating more, the energy-poor would change their behavior even further if financial limitations were lifted. They would heat their homes more, ventilate more, shower more frequently and for longer durations, and wear lighter clothing compared to the non-energy-poor.

Additionally, the energy-poor received more valuable interventions (€419.03 vs €338.33) and more energy measures (11.5 vs 10.2) than the non-energy-poor, particularly aimed at reducing drafts.

However, after the Klusbus intervention, the energy-poor did not report a larger comfort improvement. They did experience a greater improvement in housing quality, notably through the reduction in mold and an increase in fresh air. Moreover, the energy-poor adjusted their behavior more after the intervention than the non-energy-poor. They more often started wearing lighter clothing, showering more frequently or for longer durations, and turning off unnecessary lights less frequently than the non-energy-poor.

6. Conclusion

Findings

This study used a survey and statistical and econometric models to investigate the relationship between energy poverty and thermal living comfort, with the Eindhoven Klusbus as a case study.

Which households had lower comfort before the Klusbus?

The study shows that energy-poor households (i.e., frequently have trouble paying energy bills) also suffer from significantly lower-than-average thermal comfort in their homes. In addition to lower comfort levels, energy-poor households also live in poorer housing, adjust their behavior more to increase their comfort at home or save energy, and are overrepresented in various socio-economic groups (more often social rent, lower educational levels, higher energy costs, less full-time employment, and fewer couples without children). This means that energy poverty is intertwined with other factors that affect comfort, suggesting that the relationship between energy poverty and comfort is not only direct but also forms an underlying mechanism.

Furthermore, lower-than-average housing comfort is associated with housing complaints such as drafts and a lack of control over the indoor climate, as well as with certain behavioral adjustments such as inadequate ventilation of the bedroom and wearing thick clothing at home. Finally, low housing comfort is relatively more prevalent among the following socio-economic groups: social renters, young people, and residents of single-family homes.

Which households received a larger Klusbus intervention?

Energy-poor households received a quarter larger energy intervention (measured in terms of total intervention costs). Certain housing characteristics (complaints about drafts and dry indoor air and the single-family dwelling type) were also associated with larger interventions.

Which households experienced greater comfort improvement after the Klusbus and why?

On average, all households experienced a significant increase in residential comfort and a decrease in housing complaints after the Klusbus. Contrary to expectations, however, no relationship between energy poverty and greater comfort improvement after the intervention was found, despite an average larger intervention received by energy-poor households.

Of all applied measures, anti-draft measures (draft strips and draft seal tape for doors and mailbox brushes) led to the greatest comfort improvements.

The main driving factor in the improvement of comfort after the intervention is the enhanced housing quality, particularly the reduction in drafts. Subsequently, adjustments in behavior post-intervention follow: reduced heating and wearing lighter clothing. This implies a mechanism where energy measures lead to improved housing quality and behavioral adjustments, collectively contributing to increased comfort.

In summary, addressing energy poverty requires a multifaceted approach that focuses not only on energy efficiency but also on housing quality, behavior, and socio-economic factors. By understanding the interconnectedness of these factors and implementing targeted interventions, policymakers, housing associations, and other stakeholders can effectively reduce energy poverty and enhance the comfort and well-being of vulnerable households.

Limitations

The research method has several limitations. Firstly, the sample size is relatively small, with 155 respondents, including 35 energy-poor and 88 non-energy-poor respondents. This small sample size limited the statistical power and reliability of the findings, especially when comparing different groups. A larger sample size could provide more robust evidence of relationships and effects, potentially revealing statistically significant relationships that were not detectable in the smaller sample.

Secondly, the study was conducted only in four neighborhoods in Eindhoven. This lack of geographical diversity and the relatively small sample size make it difficult to generalize the results to the entire country. The findings should be interpreted within the context of the specific location and may not be applicable on a broader scale

Furthermore, the study was conducted during a period of fluctuating energy prices. The constant news about energy price fluctuations could have influenced the participants' awareness of energy-saving behaviors. Moreover, the focus of the study on energy efficiency improvements was limited to the interventions carried out by the Klusbus program, which is specific to Eindhoven. Other municipalities may have different programs or approaches to addressing energy poverty and implementing energy-saving measures. Additionally, the population in other cities may differ. These limitations affect the external validity of the study and should be considered when interpreting the findings.

Finally, to strengthen the research design and provide more robust evidence of the effect of energy efficiency improvements, it would be beneficial to include a control group that did not receive the intervention. A control group would allow for a comparison between those who received the intervention and those who did not, establishing a baseline for measuring the effects of the intervention on comfort. This would provide a better understanding of the impact of the intervention and help attribute observed changes in comfort more accurately. In this way, the influence of the time trend can be considered. Surveying in the spring, when temperatures are generally warmer, might introduce confounding factors. Using a control group can better isolate the effects of the intervention and attribute observed changes in comfort to the specific interventions carried out by the Klusbus. Addressing these considerations can enhance the study's internal validity, strengthen the argument for the assumed causality, and yield more robust and generalizable findings.

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Acronyms:

EP =	Energy poverty, a situation when households must reduce their energy consumption to a degree that negatively impacts their health and well-being
EU =	European Union
EPAH =	Energy Poverty Advisory Hub, a collaborative network aiming to eradicate energy poverty and to accelerate the just energy transition of European local governments, an initiative run by the European Commission at the request of the European Parliament
EPOV =	Energy Poverty Observatory, the predecessor of the EPAH which developed national energy poverty indicators to diagnose energy poverty at the national level or to compare countries
EE =	Energy efficiency
EU-SILC=	European Union Statistics on Income and Living Conditions

1. Introduction

This chapter introduces the motivation and structure of this thesis. First, it outlines the background and motivation to describe the research's origins. Secondly, it describes the problem statement, research objectives, and research questions. Thirdly, it presents the research's scope, along with its academic and practical relevance. Lastly, it outlines the approach and structure of the study.

1.1 Background

Energy poverty (EP) is a rising problem worldwide. EP is a situation in which households are unable to access essential energy services and products (European Commission, 2022). For developed countries, the EP is further specified as a situation when households must reduce their energy consumption to a degree that negatively impacts their health and well-being (European Commission, 2023). This includes the financial inability to keep the home adequately warm. The European Commission (2022) states that "everyone depends on energy in their daily lives, as it is needed to have sufficient levels of heating or cooling, lighting, and energy to power appliances in people's homes to have a decent standard of living and help guarantee their health". Not having enough access to energy services in the dwelling can be related to the affordability of the energy bill, as some households do not have enough money to pay the bills (van der Wal, van Ooij, & Straver, 2023). Moreover, it can be related to the low energetic quality of the dwelling: dwellings with a low energy label are often badly insulated, which causes an unhealthy inner climate with dampness, and drafts (Balfour & Allen, 2014).

About 35 million citizens of the European Union (EU) (about 8% of the EU population) were unable to keep their homes adequately warm in 2020 (eurostat, 2021). The increase in energy prices, that started in 2021 (eurostat, 2022) and worsened by the invasion of Ukraine at the beginning of 2022 (International Monetary Fund, 2022), as well as the impact of the COVID-19 crisis, have worsened an already difficult situation for many EU citizens (European Commission, 2022). The Netherlands used to be one of the European countries with relatively low EP (eurostat, 2021). However, by 2022, the number of households suffering from EP has grown to 602 000 in the Netherlands (about 7.4% of the population), against 512 000 (6.4%) in 2020 (Mulder, Batenburg, & Dalla Longa, 2023). In comparison, about 15% of Dutch households were income-poor (Mulder, Dalla Longa, & Straver, 2021a). Income poverty is defined as an income under the low-income threshold, which differs per household type (CBS, 2023). Therefore, energy poverty and income poverty do not necessarily coincide. Severe energy poverty is much more spatially concentrated than income poverty (Mulder, Batenburg, & Dalla Longa, 2023). In only 5 municipalities and 7% of the districts more than 10% of the households are energy-poor, which implies the need for localized targeted policy.

Policies to tackle energy poverty

The European Union and national governments have set up several policies and programs with the aim of eradicating EP and protecting vulnerable consumers. An overview of policy instruments can be found in Table 1. In 2016, the Energy Poverty Observatory (EPOV) was set up to facilitate the measurement and monitoring of energy poverty in EU member states (Chlechowitz & Reuter, 2021). Later, the EPOV evolved into the Energy Poverty Advisory Hub (EPAH), which has become the "center of EP expertise in Europe for local governments and all stakeholders interested in taking action to combat EP in Europe (European Commission, n.d.)". It is a collaborative network aimed at eradicating energy poverty and accelerating the just energy transition of European local governments, an EU initiative run by the European Commission at the request of the European Parliament. The EPAH acknowledges that energy poverty is a multi-dimensional concept that is not easily captured by a single indicator (European Commission, 2022a). Therefore, a collection of 21 macro-indicators that had been set up by the EPOV have been made available to compare EU countries on energy poverty by providing insights, application limits, and recommendations within national contexts (EPAH, 2022).

The primary indicators for energy poverty on a national level include (EPAH, 2022):

- Arrears on utility bills
- Inability to keep home adequately warm
- High share of energy expenditure in income
- Low absolute energy expenditure

Table 1. Policies regarding energy poverty.

Policy	Authority	Year	Source
Energy Poverty Observatory (EPOV)	EU	2016	Chlechowitz & Reuter, 2021
Energy Poverty Advisory Hub (EPAH)	EU	2018	European Commission, n.d.
Energy rulebook 'Clean energy for all Europeans package'	EU	2019	European Commission, 2019
Regulation Reduction Energy Consumption (RRE)	NL national government	2019	RVO, 2019
Recommendation on energy poverty	EU	2020	EUR-Lex, 2020
Regulation Reduction Energy Consumption Homes (RREW)	NL national government	2020	RVO, 2020
'Fit for 55 package'	EU	2021	EUR-Lex, 2021
'Tackling rising energy prices: a toolbox for action and support'	EU	2021	EUR-Lex, 2021a
'Commission Energy Poverty and Vulnerable Consumers Coordination Group'	EU	2022	EUR-Lex, 2022
€300 million specific subsidy energy poverty	NL national government	2021-2022	Min. BZK, 2022
Reduction energy tax on electricity	NL national government	2022	Sgaravatti et al., 2023
Increase of energy tax refund	NL national government	2022	Sgaravatti et al., 2023
Increase of one-off energy allowance	NL national government	2022	Sgaravatti et al., 2023
€190 energy bill discounts for all households	NL national government	2022	Sgaravatti et al., 2023
National Insulation Program	NL national government	2023	Min. BZK, 2023
Energy VAT reduction	NL national government	2023	Sgaravatti et al., 2023
Energy price cap	NL national government	2023	Sgaravatti et al., 2023

In 2019, the EU adopted a new energy rulebook called the 'Clean Energy for All Europeans package' to help move away from fossil fuels and towards cleaner energy (European Commission, 2019). EP was made a key concept by defining and better monitoring EP in Europe (European Commission, 2019). Eradicating EP has also become increasingly important in energy efficiency, decarbonization, and clean energy policies to support a just energy transition for all (European Commission, 2022). Several EU countries have incorporated a specific plan into their national strategies and are creating their own measurement and monitoring techniques and policy solutions to address EP, as required by their obligation to evaluate EP in their National Energy and Climate Plans (NECPs) (European Commission, 2019a). In 2020, the European Commission published a recommendation on EP (EUR-Lex, 2020) to support EU countries in their efforts to tackle EP. It offers guidance on appropriate indicators for assessing EP, encourages the exchange of best practices among EU countries, and identifies opportunities to access EU funding programs that prioritize measures aimed at supporting vulnerable groups (EUR-Lex, 2020).

In 2021, the European Commission adopted the 'Fit for 55 package' (EUR-Lex, 2021), proposing specific measures to identify drivers of EP risks, such as high energy prices, low household income, and poor energy-efficient buildings and appliances. The same year, the European Commission listed a selection of short and medium-term initiatives to support the most vulnerable groups at the national level in the communication 'Tackling rising energy prices: a toolbox for action and support (EUR-Lex, 2021a).' A year later, the 'Commission Energy Poverty and Vulnerable Consumers Coordination Group (EUR-Lex, 2022)' was established to give the countries a space to exchange their experience and increase coordination of policy measures to support energy-poor households.

In the Netherlands, structural policy on tackling EP is still in its infancy (van Tilburg, Straver, & van Ooij, 2022). An important step taken was to develop a measure for EP. At the moment, the level of EP on a national scale is measured as the percentage of households with a low income and either high energy costs or a home of relatively low energetic quality (TNO, 2023). This is monitored yearly. 'Low income' is specified as a standardized disposable household income that does not exceed 130% of the low-income limit (Mulder, Batenburg, & Dalla Longa, 2023). 'High energy costs' is an energy bill higher than the average energy bill of a C-label dwelling (or the median energy bill) in the base year 2019. A dwelling is considered of 'low energetic quality' when the expected energy consumption of a home is higher than the average expected energy consumption for a C-label dwelling. A long-term strategy regarding EP is lacking (TNO, 2023). However, various policy experiments are performed, with ways to make the energy transition more social. Examples are the RRE (RVO, 2019) and RREW (RVO, 2020) schemes, which were created in 2019/2020. Using these schemes, municipalities can set up projects that stimulate homeowners to make small saving measures.

Since 2021, the Dutch national government has been offering additional support specifically to tackle EP (Rijksoverheid, 2021). Municipalities play a key role in the implementation of this support: they are expected to shape policy on accelerating the improvement of sustainability of the housing stock and are called in to get the energy allowance to the right households. The national support consists of several packages. It started in 2021 with a lump sum subsidy of €150 million for municipalities, which was used to tackle the problems in neighborhoods where EP is high (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022). The 2021 subsidy was later supplemented with an additional €150 million. Municipalities themselves determine how the money is spent exactly, also in consultation with Dutch public housing providers - housing associations – who own some 2.5 million houses where low-income people live. Example policies are: issuing vouchers for energy-efficient products; distributing energy boxes with small energy improvements; or giving energy advice by having 'energy teams' visit families (Rijksoverheid, 2021).

In 2022 - after substantial increases in energy prices – several fiscal responses took place in reaction to the energy crisis: a reduction of the energy tax on electricity; an increase of the energy tax refund from €560 to €785; an increase in the one-off energy allowance for benefit recipients and people earning up to 120% of the social minimum from €200 to €1300; an energy VAT (natural gas, electricity and district heating) reduction from 21% to 9%; a price cap on natural gas and electricity prices for households with an average consumption (which was set at the average energy price at January 2022); and a €190 discount on the energy bills for all households with a power connection in November and December 2022 (Sgaravatti, Tagliapietra, Trasi, & Zachmann, 2023).

Finally, in 2023 the National Insulation Program started, intending to insulate 2.5 million dwellings up until 2030 (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2023). A local approach will be used – the municipalities will collaborate with homeowners, owners' associations, landlords, tenants, and businesses - with an emphasis on improving dwellings with an E-, F-, or G-label. Meanwhile, several larger municipalities are working on the creation of a medium-term approach (van Tilburg, Straver, & van Ooij, 2022). In addition, more and more initiatives are set up for knowledge-building and exchange between municipalities (van Tilburg, Straver, & van Ooij, 2022).

On the level of local authorities (municipalities), various initiatives are undertaken. One of these is the 'Klusbus' program. For this program, the municipalities use funding from the national government, to assist households who face financial difficulties. This money is spent on offering energy-poor households small energy-saving measures for free. To implement the program, the municipalities collaborate with housing associations. The Klusbus program involves the deployment of specialized mobile units known as 'Klusbusses' with trained servicemen, also known as 'energy fixers'. These Klusbusses visit selected neighborhoods with a relatively EP high level to enhance the energy efficiency of all dwellings through cost-free minor energy efficiency adjustments (Gemeente Eindhoven, 2022). All residents of the neighborhood who are interested, both energy-poor and non-energy-poor, are allowed to participate. These adjustments include the installation of draft strips, mailbox brushes, radiator foil, and LED lights, among other measures. By targeting these neighborhoods, the program aims to assist households that may be struggling to pay their energy bills. The goal is to alleviate the financial burden on these households by reducing energy costs and simultaneously enhancing their overall living comfort.

Other municipalities have programs too, that differ slightly from the approach in Eindhoven. The 'FIXbrigade' in Amsterdam trains MBO interns, volunteers, and status holders (asylum seekers who obtained a residence permit (Rijksoverheid, 2024)) with technical knowledge as energy fixers. This way their opportunities in the labor market are improved while helping households with a low income to save money (Gemeente Amsterdam, 2023). Apart from among others sealing gaps and placing draft strips and radiator foil as done by the Klusbus, adjustments to central heating settings are made to make the system more efficient, and infrared scans are made to find heat leaks. Another program in Utrecht primarily focuses on advising people about energy-conscious behavior (Gemeente Utrecht, 2023), the so-called 'energy coaches'. This program is aimed at households with a low (minimum) income, particularly renters, and uses local job seekers to help with the program (van der Wal, van Ooij, & Straver, 2023). The energy coaches visit households once to twice, whereafter households receive an overview of energy-saving tips (and the associated financial savings) and an energy box with small energy-saving measures. The energy coaches do not install the measures themselves.

Apart from these municipal programs, social housing associations also take various actions to address energy poverty. Similar to the Klusbus program, some housing associations run a program to help households in neighborhoods selected on criteria such as low energy labels and high payment arrears (Leeuw, 2022). Trained professionals, engage in conversations with residents to determine if they qualify for energy allowances or require assistance. Rather than starting from scratch, it is recommended to learn from the experiences of other housing associations in tackling energy poverty (Leeuw, 2022). Proactive engagement is encouraged, and collaboration with municipalities, social partners, and colleagues who directly interact with tenants is highly advised (Leeuw, 2022).

The discussed policies are developed with the expectation that they will effectively reduce energy poverty. To optimally shape policy, one, however, needs to be able to predict its effects. Therefore, the way EP affects people's well-being needs to be understood. This among others happens via behavior.

As mentioned, many EU member states acknowledge the size of the problem of energy poverty and its negative consequences, such as severe health issues and social isolation. Recognizing energy poverty as a problem helps gain deeper insights into the specific difficulties faced by energy-poor households. EP is often part of a vicious circle of problems: energy poverty, poor living quality, bad health, high energy costs, unemployment, and possibly even overall income poverty (Straver & Mulder, 2020). Energy poverty has an independent impact on the physical and mental health, social life, and employment opportunities of those affected by it. Giving specific attention to energy poverty provides a clearer view of targeted solutions.

Behavioral consequences of energy poverty

For this thesis, energy poverty is operationalized as the difficulty with paying the energy bill. This financial constraint implies that people in EP accept a suboptimal (too low) level of living comfort, to minimize energy costs, so that money can be spent on goods of first necessity. This is called the prebound effect: when occupants adjust their behavior and consume less energy than is expected based on the energetic quality of the dwelling (Sunikka-Blank & Galvin, 2012). Behavior adjustments include dimming the lighting, putting on thicker clothes, adjusting fan settings to save energy, opening/closing windows, drinking warm/cold fluids to warm up or cool down, moving to a more comfortable room, adjusting the setting on personal heaters/air conditioning to save energy, going outside, and adjusting blinds to block sunlight (Langevin, Gurian, & Wen, 2013). These are adjustments performed by many people. The effects among the energy-poor are expected to be stronger, but not much is known about this yet.

After an energy efficiency improvement of the dwelling – e.g., due to measures taken by municipalities or housing associations - people may turn back the behavioral adjustments they did because of EP. This is called the rebound effect: an increased demand for energy services caused by the reduction in energy costs following an energetic improvement to the dwelling (Mizobuchi & Yamagami, 2022).This often occurs to improve living comfort. Most studies measure the rebound effect as the difference in potential and actual energy savings after an efficiency improvement (Azevedo, 2014), but do not measure the improvement in comfort by the behavior adjustment. Common types of these behavioral adjustments are airing more frequently, paying less attention to keeping energy consumption low, increasing the internal temperature, heating sooner/later in the season, and not setting the thermostat lower when leaving the house (Hediger, Farsi, & Weber, 2018). Behavior is also related to socioeconomic factors. Low-income residents are found to be more likely to show rebound behavior (Milne & Boardman, 2000). A study by Roberdel, Ossokina, Karamychev, & Arentze (2023) in the Netherlands confirmed this. They found that following a comparable heating efficiency improvement, the poor had up to a one-third smaller reduction in natural gas consumption compared to the average. Instead, the poor reinvested up to 20% of their potential gas savings into enhancing their thermal comfort. Given that the poor live in more uncomfortable conditions, this reinvestment resulted in a larger increase in comfort. Consequently, the efficiency improvement may lead to a considerable comfort improvement for the poor, with a smaller energy-saving as a side effect.

So, energy-poor households may adjust their behavior to conserve energy more than non-EP households. Better insight into these behavior changes, both prebound and rebound, and their impact on people's well-being, will contribute to optimal policy choices.

Impacts on comfort

Adjusting behavior to reduce energy consumption influences living comfort and thus affects the well-being of people. For instance, having the heating on longer enables households to maintain a comfortable indoor environment. This thesis focuses on thermal quality and indoor air quality as they are the most influential factors on a person's comfort (Andargie, Touchie, & O'Brien, 2019).

Important factors of thermal comfort are among others air temperature, air velocity, humidity, drafts, and cold or warm floors (ISO, 2005). Nonetheless, the perception of thermal comfort is highly individual, and the importance of specific thermal and air conditions for comfort varies depending on the occupant. For example, elderly individuals and women tend to prefer warmer temperatures (Hwang & Chen, 2010). People often enhance their comfort by adjusting their clothing, increasing the temperature, improving ventilation, or initiating heating earlier in the season (Hediger, Farsi, & Weber, 2018).

The influence the residents have on the indoor environment of their home substantially influences comfort (Frontczak & Wargocki, 2011). They have an influence by, for instance, adjusting the thermostat. But on some other parts they do not have an influence (i.e., not in control) or a reduced influence, e.g., through drafts, bad insulation, or a malfunctioning heating system. Households facing energy poverty have limited financial capabilities and often reside in less energy-efficient dwellings. As a result, they have reduced control over the main parameters of thermal and air quality, leading to lower comfort levels.

Health

Having control over a comfortable indoor temperature is critical for the well-being and health of individuals, particularly vulnerable groups such as infants (Harker, 2006)the elderly (Balfour & Allen, 2014), and those with existing medical conditions (El-Ansari & El-Silimy, 2008). Exposure to cold temperatures can have detrimental effects on physical health, and having adequate heating systems in place helps prevent issues like hypothermia, cardiovascular and respiratory illnesses (Jessel, Sawyer, & Hernández, 2019), creating a healthier living environment. These diseases potentially cause death, especially among older people (Balfour & Allen, 2014). Living in cold conditions can also worsen pre-existing medical conditions, including diabetes, particular forms of ulcers, and musculoskeletal suffering (El-Ansari & El-Silimy, 2008). It could also cause asthma and bronchitis, which could evolve into long-term conditions (Barnes, Butt, & Tomaszewski, 2008).

Apart from physical health effects, living in low thermal comfort environments was also linked to mental health effects. A decrease in room temperature was linked to an increased experience of depression and anxiety (Green & Gilbertson, 2008). Moreover, especially young people with inadequately warm homes risked several mental health symptoms and a substantial part of children living in these conditions felt unhappy (Barnes, Butt, & Tomaszewski, 2008). Children living under poor housing conditions in general experience larger problems due to the conditions, such as depression and anxiety, are more likely to have slow physical and cognitive development, risk respiratory problems, long-term health problems, and disability (Harker, 2006). Ensuring sufficient heating contributes to a comfortable atmosphere where people can concentrate (Kolarik, Toftum, Olesen, & Shitzer, 2011), sleep better (Jessel, Sawyer, & Hernández, 2019), and generally enjoy their living space.

Furthermore, guaranteeing thermal living comfort is an increasingly important aspect in light of adapting to climate change (Jessel, Sawyer, & Hernández, 2019). The challenges faced by energy-poor households, who struggle to achieve minimum comfort levels, could increase with more extreme weather conditions resulting from climate change. Furthermore, enhancing the comfort of energy-poor households through measures like draft strips or insulation not only has positive implications for individuals' well-being but also directly benefits the environment by reducing heat loss and energy usage.

The health effects of energy poverty itself have hardly been studied. Pan, Biru, & Lettu (2021)found that on national levels EP is negatively related to public health. This negative relationship is less pronounced in countries with higher living standards. Comparable to the abovementioned negative effects of living in uncomfortable indoor environments, energy-poor people individuals experience a range of physical and mental health challenges Straver & Mulder (2020). For instance, they may suffer from health issues caused by drafts and humidity, particularly during cold winters. These conditions make it difficult to control the temperature. Moreover, financial difficulties often result in unpaid energy bills, inducing stress and worry that further contribute to health complaints, creating a cycle that can again impact income (Jessel, Sawyer, & Hernández, 2019). It is therefore now evident that EP is closely related to diminished comfort, and consequently, adverse health outcomes.

Conclusion

The literature suggests that there exists a complex mechanism between energy poverty and thermal comfort, through behavior, housing conditions, and socioeconomic factors.

At present, policies aimed at addressing energy poverty are still in the early stages, and their effectiveness has not yet been fully evaluated. Households experiencing energy poverty are expected to drastically sacrifice their living comfort as they adjust their behavior to save energy. It is crucial to gain insights into these behavioral changes, including prebound and rebound effects, their impact on people's well-being, and the complex relationship between behavior and comfort to make informed policy decisions. The influence of these behavioral aspects, and the impact of energy poverty on comfort, remains understudied. Current municipal policies (e.g., De Eindhovense Klusbus) offer a nice case study to get more insight into these effects, to better predict the possible effect of future policies by among others, municipalities and housing associations. This approach can help policymakers strive toward the goal of ensuring a decent standard of living for all Europeans and safeguarding their health (European Commission, 2022).

1.2 Problem statement, research objectives, & research questions

A gap in the literature is identified. This research aims to effectively address this gap and to accomplish the research objectives by answering the associated research questions.

Problem statement

After analyzing existing research, a gap in the literature is identified: what is the effect of energy poverty on living comfort? There is also limited knowledge of the effect of energy poverty on behavior, the effects of policies aimed at eradicating energy poverty, and the characteristics of energy-poor households. In this section, the research gap is further explained.

Comfort

Literature exists on all kinds of indoor environmental, socioeconomic, and behavioral aspects influencing comfort, such as temperature, humidity, drafts, warm or cold floors, age, gender, occupation patterns, controllability, heating, and ventilating (ISO, 2005; Andargie, Touchie, & O'Brien, 2019; Hwang & Chen, 2010; Hediger, Farsi, & Weber, 2018; Frontczak & Wargocki, 2011). Moreover, previous studies have focused on the importance of living comfort by studying the negative health effects of living in poor housing conditions, such as respiratory illnesses, hypothermia, depression, and anxiety (Jessel, Sawyer, & Hernández, 2019; Barnes, Butt, & Tomaszewski, 2008; Green & Gilbertson, 2008; Harker, 2006). Existing literature has shown that the energy-poor live in poorer housing conditions and suggests that the energy-poor have to adjust their behavior to save energy costs, both negatively affecting living comfort. However, research on the relationship between energy poverty and comfort is lacking.

Behavior

Sparse literature exists on what behaviors households engage in to save energy costs, such as changing clothing, adjusting the temperature, opening/closing windows, adapting lighting, and taking shorter showers (Langevin, Gurian, & Wen, 2013; Reaves, Clevenger, Nobe, & Aloise-Young, 2016; van der Wal, van Ooij, & Straver, 2023). Other studies focused on the behavior adjustments of households after an efficiency improvement to their dwelling (Hediger, Farsi, & Weber, 2018; Milne & Boardman, 2000; Walker, Lowery, & Theobald, 2014; Taylor, Jones, & Jennison Kipp, 2014; Boemi, Samarentzi, & Dimoudi, 2020). Other studies found that low-income residents adjusted their behavior more than the average after an energy efficiency improvement to enhance comfort (Milne & Boardman, 2000) (Roberdel, Ossokina, Karamychev, & Arentze, 2023). Based on their limited financial capabilities, the energy-poor too are expected to make larger behavioral adjustments to save costs. However, there is no clear research on how the energy-poor behave differently than the non-energy-poor. The same applies to the limited research on how the energy-poor adjust their behavior differently after an energy improvement.

Policies

Policies aimed at eradicating energy poverty are relatively new. Only since 2016 has the EU made the eradication of energy poverty a policy objective. Only a few studies have been performed aimed at finding the effects of programs targeting energy poverty. Most studies consider the effects of large renovations (Fisk, Singer, & Chan, 2020; Hong, Gilbertson, Oreszczyn, Green, & Ridly, 2009; Howden-Chapman, et al., 2007; Roberdel, Ossokina, Karamychev, & Arentze, 2023). Van der Wal et al. (2023) studied the effects of three energy fixers/coaches on living comfort, health, energy consumption and costs, financial worries, social cohesion and engagement, and sustainable behavior. Bashir (2013) studied the benefits of an energy coaching project in the UK. However, many local institutions have come up with their own program to eradicate energy poverty, each with a different approach. Different results are found for each program, and more research on the effect of energy poverty policies is therefore desired.

Energy-poor households

As energy poverty has only received attention as a problem and has been growing fast for a few years, there is no comprehensive insight into the characteristics of the energy-poor. The level of energy poverty is estimated on municipal, and sometimes neighborhood level, but there is limited information on household level. Mulder et al. (2023) tried to sketch a picture of the socioeconomic characteristics of the energy-poor in the Netherlands, but only considered tenure, dwelling type, and household composition. Other studies only covered the increased vulnerability to energy poverty based on certain socioeconomic factors such as gender, education level, migration background, employment, and urbanization level (Clancy, Daskalova, Feenstra, Franceschelli, & Sanz, 2017; Straver & Mulder, Energiearmoede en de Energietransitie, 2020; Phimister, Vera-Toscano, & Roberts, 2015; Mashhoodi, Stead, & van Timmeren, 2019). Further research comparing energy-poor to non-energy-poor on (socioeconomic) characteristics would give authorities a much better understanding of the people they are trying to target with their energy poverty policies.

Research objective

The research objective is to close the abovementioned research gap by analyzing the relationship between energy poverty and thermal living comfort and the influence of a minor energy intervention on comfort improvement. This will be applied to a case study, 'De Eindhovense Klusbus'. When analyzing this relationship, the socioeconomic characteristics, housing quality, behavioral adjustments, and thermal living comfort of the energy-poor are compared to that of the non-energy-poor. This comparison is made among participants in the case study before and after they have received a small energy efficiency improvement. The Klusbus is a municipal program where trained servicemen apply small energy-saving measures to dwellings for free to alleviate the problems of households that are struggling to pay the bills. These small measures include the placement of LED lights, radiator foil, draft strips, and water-saving showerheads, among others. More information on the use case can be found in Chapter 3.

Targeted outcomes

The study aims to add academic knowledge about whether and to what extent the energy-poor compromise their living comfort. Additionally, since policies targeting the eradication of energy poverty are relatively new and their effects are often uncertain, this study seeks to evaluate the effectiveness of a municipal 'energy fixer' program. Specifically, it investigates whether the program successfully reached its target group – energy-poor households – and whether minor energy interventions impact comfort, housing quality, and behavior.

The findings of this study will be valuable for municipalities, housing associations, and other organizations working to combat energy poverty. Moreover, it aims to provide insights into the characteristics of energy-poor households and whether they adjust their behavior to limit energy consumption. Furthermore, the study aims to identify the most effective energy measures within the program. Municipalities can use these insights to develop effective programs or improve existing energy poverty policies.

Research questions

This study aims to analyze the relationship between energy poverty and thermal living comfort, and the influence of a minor energy intervention on comfort improvement. The corresponding main research question will be answered:

What is the relationship between energy poverty and thermal living comfort and the influence of a minor energy intervention on comfort improvement?

The main research question hypothesizes a correlation between energy poverty and thermal living comfort. However, energy poverty is not the only factor influencing comfort. Therefore, other factors related to comfort are studied as well: housing quality, socioeconomic factors, and behavior. The relationships between these factors and comfort are studied by answering the subsequent sub-question:

1) *What is the relationship of a resident's socioeconomic characteristics, poor housing conditions, and energy-saving or comfort-enhancement behavior with the thermal living comfort in their dwelling?*

The relationship between energy poverty and thermal comfort is expected to be influenced by energy efficiency improvements to the dwelling. As a use case, the 'Eindhovense Klusbus' policy program aimed at reducing energy poverty is considered. As energy poverty is not the only factor that determined who received the largest improvement, other factors possibly influencing the energy intervention, housing quality, and socioeconomic factors, are studied as well. Therefore, the determinants of the size of the energy intervention received by a household are estimated by answering the following sub-question:

2) *What is the relationship of energy poverty, poor housing conditions, and a resident's socioeconomic characteristics with the received energy intervention in an anti-energy poverty program in a large Dutch city?*

Due to the energy intervention, the comfort is expected to be improved. However, the energy measures are not the only factors influencing comfort. Therefore, the relationship of the situation before the intervention, i.e., the socioeconomic characteristics and housing quality, with comfort improvement is studied. Second, the energy interventions themselves are related to comfort improvement. Finally, the improved housing quality and adjusted behavior after the intervention are related to comfort improvement. Therefore, the determinants of comfort improvement after a minor energy intervention are estimated by answering the following sub-question:

3) *What is the relationship of a resident's socioeconomic characteristics, poor housing conditions, the energy measures applied to a dwelling, improved housing conditions, and adjusted energy-saving or comfort-enhancement behavior with the thermal living comfort improvement in their dwelling after a minor energy intervention?*

Finally, an in-depth study into the characteristics of the energy-poor households is conducted. This creates an insight into their socioeconomic characteristics, poor housing conditions, and whether they adjust their behavior more than other households will be created. This relates to the following sub-question.

4) *Do energy-poor households differ in socioeconomic characteristics, live in poorer housing conditions, behave differently, receive a larger energy intervention in an anti-energy poverty program, experience a larger improvement in housing quality, and adjust their behavior more compared to non-energy-poor households?*

Goals of the sub-questions

The sub-questions zoom in on certain factors related to comfort and will indicate the size of these relationships. Moreover, they try to find out who benefited most from the 'Klusbus' energy interventions and what caused the largest comfort improvement. The first sub-question tries to find the factors related to comfort. It consists of three parts. First, it is prompted to control for possible effects of socioeconomic factors that may explain thermal living comfort. It could answer whether different social groups have different perceptions of comfort. Moreover, it aims to find the relative importance of housing quality on thermal living comfort. It tries to test whether comfort is lower when living in a low-quality dwelling. A further goal is to find the relative importance of behavior on thermal living comfort. It tries to test whether engaging in a lot of behaviors, for instance, heating, positively affects comfort.

Sub-question 2 is prompted to indicate who were reached by the 'Klusbus' program. The goal is to test whether the target group of the energy fixer program, the energy-poor in Eindhoven, was reached by the program and whether they received a larger intervention. It also aims to find whether poor-quality dwellings, which were most in need of improvement, also received a larger intervention. Finally, it aims to test whether certain social groups are reached more with the energy fixer program.

Sub-question 3 considers the comfort improvement after the energy intervention. First, it aims to find who felt the largest comfort improvement and therefore which social groups were reached most by the program. Moreover, it aims to find out whether the households living in the lowest quality dwellings also experienced the largest comfort improvement. A further goal is to find out what individual energy measures had the largest effect on comfort improvement. Finally, it intends to find out whether a larger improvement in housing quality and larger adjustment of behavior after the intervention also resulted in a larger comfort improvement.

The last sub-question aims to indicate whether there are significant differences between the energy-poor and non-energy-poor in socioeconomic characteristics, housing quality, and behavior. Better insights into the characteristics of the group the authorities try to target with their energy poverty policies are intended to be generated. This includes finding out whether the energy-poor live in poorer housing conditions and are therefore more in need of intervention. Moreover, it tests whether the energy-poor experienced larger improvements in housing quality after an intervention. Furthermore, it aims to study whether the energy-poor compromise on their behavior to save energy costs more than other residents, thereby sacrificing comfort. Finally, it tests whether the energy-poor adjusted their behavior more than other residents after an energy intervention.

1.3 Research scope and relevance

Scope

The study focuses on households living in neighborhoods in Eindhoven with high rates of energy poverty, whose dwellings have undergone an energy efficiency improvement. These efficiency improvements were part of a municipal program, called 'De Eindhovense Klusbus', aimed at alleviating the problems of households living in energy poverty. All households living in these neighborhoods could receive minor energy-saving measures, freely installed by the energy fixers of the 'Klusbus'. The improvements were carried out in the 2022/2023 winter, during the initial phase of the 'Klusbus' program. Households living in the first four neighborhoods visited by the 'Klusbus' will be included in this study. These include Tivoli, Doornakkers-West, Kerstroosplein, and Doornakkers-Oost.

These neighborhoods were selected to be visited by the 'Klusbus' due to the high energy poverty rates. These energy poverty rates were based on a study on energy poverty in Eindhoven (CBS/UDC Gemeente Eindhoven, 2022). To measure the energy poverty rates, the LILEK indicator was used, which is a selection method for all households with a low income and living in dwellings of low energetic quality (Mulder, Dalla Longa, & Straver, 2021a). According to LILEK, a household is energy-poor if the average income is lower than 130% of the social minimum income[1], and the average energy bill of similar dwellings is higher than the average energy bill in the Netherlands. More detailed information on the approach and selection method of the case study can be found in Chapter 3. The high EP rates make these four neighborhoods suitable for this study, as the thermal living comfort levels of energy-poor households are studied

Practical relevance

This study aims to enhance our understanding of how energy poverty affects household thermal comfort. Efforts are underway to improve both the energy efficiency of the housing stock to meet climate goals as well as to address energy poverty. This study evaluates the effectiveness of the 'De

[1] The minimum amount needed to provide for living expenses. When the income is lower than the social minimum, one may receive an allowance on their income (Rijksoverheid, 2024). Social minimum at 1 January 2024: gross income of €2,069.30 (married) and € 1,473.56 (single) per month (UWV, 2024).

Eindhovens Klusbus' program in addressing both issues. Analyzing the socioeconomic characteristics, housing conditions, and behavioral adjustments of energy-poor residents in Eindhoven, assists municipalities, housing associations, and relevant organizations in effectively understanding and supporting their target demographic. Moreover, the study identifies resident segments, including energy-poor households, who experience the lowest levels of comfort. The results can be used to shape policy measures to target groups in need of assistance to improve their living conditions. Furthermore, it assesses which socioeconomic groups and whether households with low housing quality received the largest interventions. These results could be used to optimize the approach if it turns out that the target groups are not effectively reached. Additionally, by evaluating the impact of energy efficiency improvements, the study identifies which measures most enhance comfort, offering insights to predict outcomes for energy policies and optimize the Klusbus program's effectiveness. Moreover, it can help future policies by selecting which energy measures to focus on in Eindhoven and other municipalities. In addition to municipalities, housing associations, as leaders in the energy transition, could utilize the results of this study to refine their approaches to retrofitting projects for their complexes.

Academic relevance

Several studies have been conducted on the magnitude of energy poverty and the factors that contribute to it, particularly in recent years as the issue has gained more attention. Additionally, extensive research has been conducted over the years to understand the various factors that influence living comfort. However, most research on EP has primarily focused on its financial aspects, neglecting its impact on living comfort. Therefore, this study aims to shed light on the effects of EP on living comfort, providing valuable insights that have not been previously examined. This includes the extent to which energy-poor households compromise on their behavior, sacrificing comfort, to reduce energy costs.

1.4 Research approach

The research process is presented in Figure 1. In the preparation phase, a literature review is conducted that defines the factors relevant to energy poverty, thermal living comfort, behavior, and small energy efficiency improvements. Moreover, data on the energy efficiency improvements that certain households received are gathered. In the execution phase, the conceptual models are constructed with expected relationships that are based on the outcomes of the literature review. A survey is set up and spread among certain households and the results are connected to the data on the energy interventions received by these households. In the analysis stage, the results of the survey and sample will be described. Furthermore, bivariate analysis will be performed to test the differences between the energy-poor and non-energy-poor. This is followed by analyzing the conceptual models by multiple regression analyses using the Ordinary Least Squares (OLS) method. These analyses are performed in statistical computing software R. In the report stage, conclusions will be drawn from the results of the analyses and the main and sub-questions will be answered. The conclusions, further recommendations, and a discussion will finally be presented in this report.

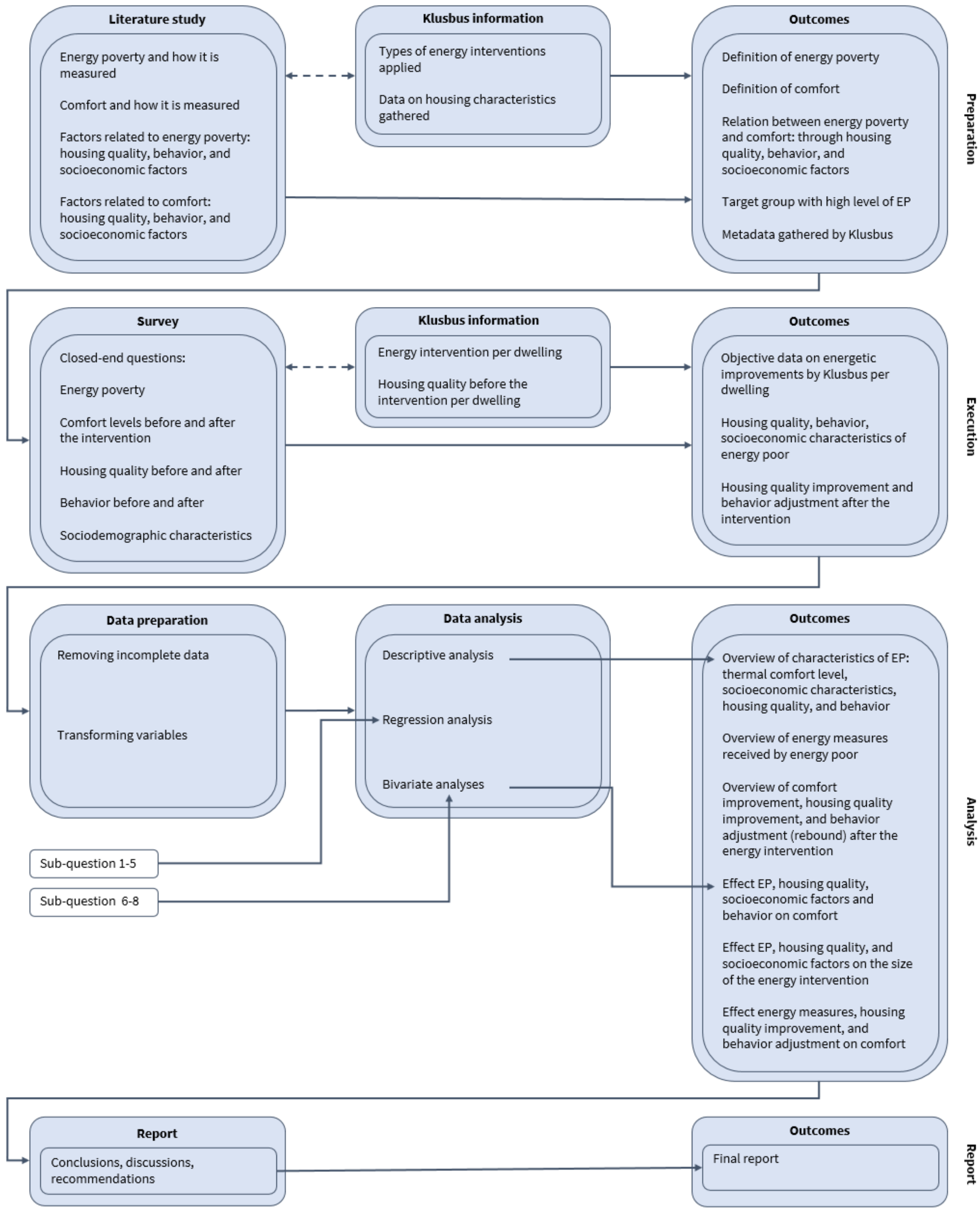

Figure 1. Research model.

1.5 Thesis structure

In the following chapter, the theoretical background is given, based on a literature review which is performed to find the factors that are relevant to this study. The outcomes of the literature review are translated into a conceptual research model. In Chapter 3, the use case, the 'Eindhovense Klusbus' is explained. In Chapter 4, the research method is described. This includes the survey design, data collection, and the definition of the statistical analysis models used. In Chapter 5, the sample, descriptive analysis of the survey, and technical information of the interventions are presented. This is followed by the results of the analyses, both the regression and bivariate analyses, in Chapter 6. The thesis is concluded in Chapter 7, where the research questions are answered, the implications of the results are discussed in relation to the literature, the limitations are acknowledged, and recommendations for future research are provided.

2. Theoretical Background & Literature

In this chapter, various factors that are related to energy poverty and comfort are described. Three conceptual models of the mechanism behind energy poverty and thermal comfort, and comfort improvement after an efficiency improvement are determined. The relevant factors are based on a literature review, discussed in this chapter, and the use case, which will be explained following chapter. Sections 2.2 and 2.3 give an overview of the existing literature. This literature review starts with an overview of characteristics related to energy poverty and the behavioral consequences of energy poverty. This is followed by the factors related to comfort, including behavior adjustments after an energy intervention and other effects of an energy intervention. It should be noted that the results of the mentioned studies are dependent on the context of each study. For example, energy poverty is defined in different ways in different studies. In addition, the perception of comfort, and the accompanying behavior varies by climate. The expected relationships between energy poverty and comfort identified in the literature are discussed in section 2.3.

2.1 Conceptual models

The use case (explained in the following chapter) constitutes the core of this thesis. This includes the thermal comfort of the energy-poor, a minor energy intervention, and the comfort improvement after the intervention. Other relevant factors in the relationship between energy poverty and comfort are identified by a literature review.

The literature suggests that energy poverty and thermal living comfort are related to each other through poor housing quality, socioeconomic factors, and behavior. After an energy efficiency improvement, comfort is expected to improve, as housing quality also improves, and behavior will be adjusted. These relationships can be found in Figures 2 to 4, which show the conceptual models of this thesis. There are three dependent variables that the study is focused on: (1) the thermal living comfort, (2) the energy intervention performed by the Klusbus, and (3) the thermal living comfort improvement after the Klusbus. The research is therefore split up into three parts, each focusing on one of the dependent variables. More detailed conceptual models of each of the research topics can be found in section 3.3.

The models show whether the expected relationship between the respective variable and the dependent variable is positive (+), neutral (0), negative (-), or unclear in line with the literature. The thick lines show the relationships that are analyzed in this thesis. The following paragraphs will provide a review of the literature that suggests the abovementioned expected relationships between energy poverty and comfort.

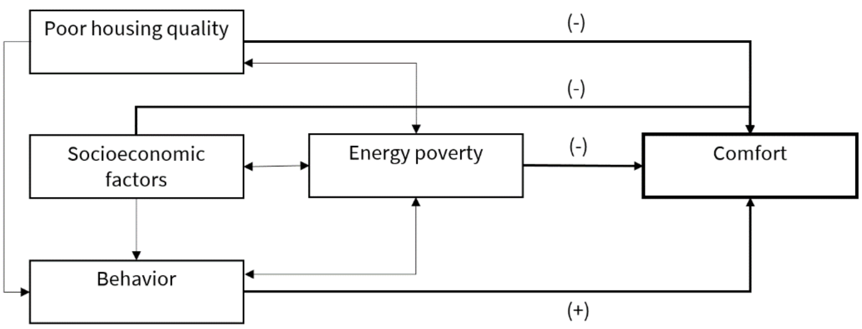

Figure 2. Conceptual model 1: thermal living comfort.

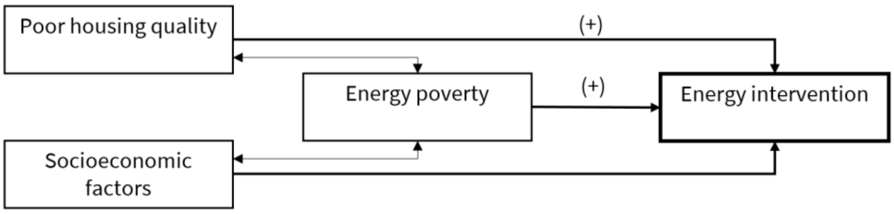

Figure 3. Conceptual model 2: the energy intervention.

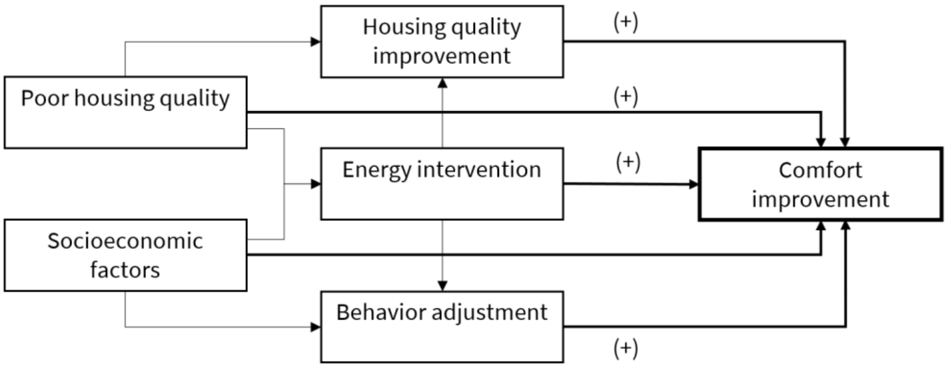

Figure 4. Conceptual model 3: comfort improvement.

2.2 Characteristics related to energy poverty

As the problem of energy poverty has only gained wide attention in recent years, there are only limited insights into the characteristics of energy-poor people. This section aims to give insights into personal and housing characteristics with an increased vulnerability to EP. It shows that the risk of EP is partly spatially determined. Moreover, the behavioral consequences of energy poverty are described.

Household and housing characteristics of the energy-poor

According to the definition given by van der Wal, van Ooij, & Straver (2023), energy poverty covers three dimensions: the affordability of energy ((high) energy costs, (low) household income); the (low) energetic quality of the dwelling; and the inability to independently make the dwelling more sustainable. A combination of the first two could lead to a situation where households are struggling to consume the energy they require or to pay the energy bills, which gets them into energy poverty. The latter makes it extremely difficult for households to get out of energy poverty once they have got into the situation.

The inability to make the dwelling more sustainable is largely related to tenure (Straver & Mulder, 2020). Renters, unlike owner-occupiers, have limited capabilities to decide about investing in making their homes more sustainable. Moreover, there are large differences between landlords. Housing associations differ from private landlords, but also among these categories there are differences. Some landlords may be more progressive towards making their housing stock more sustainable than others. Moreover, these three groups are subject to different subsidies and legislation and therefore differ in their options to invest in efficient energy technologies. In the Netherlands, approximately two-thirds of energy-poor households are tenants of housing associations; significantly higher than the national average of 29.1% of social renters (Mulder, Batenburg, & Dalla Longa, 2023). Almost 20% of the energy-poor live in a privately rented dwelling (compared to 10.3% for all households in the Netherlands), while around 12% are homeowners (in contrast to 60.4% for all households). In other countries, tenure is also found to be a risk factor regarding energy poverty. Homeowners are associated with lower exposure to EP in France (Legendre & Ricci, 2015). In New Zealand, too, energy-poor households tend to live in privately rented dwellings. This is largely due to the limited regulations landlords face to insulate or heat their properties, therefore resulting in vulnerable groups living in poor housing quality (Howden-Chapman, et al., 2012). That does not mean that homeowners cannot be energy-poor. There is also a group of homeowners who do not have the financial capabilities to improve the efficiency of their dwellings. This group could receive too little attention in energy poverty programs, as happened in South Korea (You & Kim, 2019). This group should therefore not be forgotten in energy poverty policies.

Moreover, energy poverty disproportionately affects households residing in multi-family dwellings, these make up 46.1% of energy-poor households compared to 32.7% of all households nationwide (Mulder, Batenburg, & Dalla Longa, 2023). Among the energy-poor living in dwellings with the lowest energetic quality, especially the group residing in terraced houses is growing rapidly. On the contrary, Besagni & Borgarello (2019) found that in Italy EP did not depend on dwelling type, but on construction period. That is also one of the reasons behind the spatial clustering of EP in Italy, as especially in areas with lower levels of EP, many newer (and energetically superior) dwellings were built. The building age and quality could also be a partial explanation of the spatial dependence of EP in the Netherlands. The spatial clustering will be further explained in section 3.3.1.

Single-person households and single-parent households are strongly overrepresented among the energy-poor (Mulder, Batenburg, & Dalla Longa, 2023). About half of the energy-poor households are single-person households, compared to only one-third for all households in the Netherlands. Moreover, there is a higher prevalence of energy poverty among single-parent families. This group accounts for 16.0% of energy-poor households compared to 7.6% for all households. However, the strongest growth of EP is among multi-person households including single-parent families, couples with children, and couples without children. Moreover, within the subgroup of energy-poor living in dwellings of the lowest energetic quality, especially families with children are increasing, with the proportion rising from 19% in 2020 to 33% in 2022. Comparable to the Netherlands, Legendre & Ricci (2015) found that in France too, single-person households are most vulnerable to EP, especially retired people living alone. In Italy, especially couples with one child were vulnerable to EP (Besagni & Borgarello, 2019). They also found that the probability of being energy-poor is negatively correlated with the floor area; the reason is that small households often live in small dwellings. A study in Vienna, Austria, found that the majority of energy-poor were single- or two-person households (Brunner, Spitzer, & Christanell, 2012).

Gender plays a significant role in energy poverty, with women being at a greater risk than men almost worldwide (Clancy, Daskalova, Feenstra, Franceschelli, & Sanz, 2017), primarily due to their lower average income. This gender disparity in energy poverty stems from three interconnected factors: economic, biological/physiological, and socio-cultural. Economically, women with low incomes are more likely to head households, particularly in single-parent families or during retirement due to their longer life expectancy. Biologically, women are more sensitive to thermal sensations than men. Socio-culturally, the traditional division of tasks in the household often results in differing energy needs and consumption of women compared to men. Among women, factors such as employment and marital status also influence energy consumption. Brunner, Spitzer, & Christanell (2012) also found substantially more women among the energy-poor than men in Austria. The majority of them as single parents, and many are divorced.

Straver (2020) identified several other factors with an increased vulnerability to EP. Time spent at home is a crucial determinant, as increased time spent at home, particularly during the day, leads to higher energy consumption and costs. This is often seen among multi-generation households, large families, pensioners, and the unemployed. Additionally, lower levels of education are associated with a higher risk of energy poverty, as education often correlates with low income and access to information, including information about subsidies for improving energy efficiency could apply for. Low education levels were also associated with EP in France and Greece (Legendre & Ricci, 2015; Boemi, Samarentzi, & Dimoudi, 2020). Low education level is also linked to functional illiteracy which is also a risk factor for EP (Straver & Mulder, 2020). Functional illiteracy means that someone's reading level is too low to survive in a literate society. Functional illiteracy and social isolation could cause difficulty with finding information or receiving advice on energy-saving. Besides that, energy-poor households are vulnerable to becoming more socially isolated as these households invite fewer guests over to their homes out of shame of the cold or poor state of their home (Baudaux & Bartiaux, 2020). That larger social isolation could then again ensure that households may have increased difficulty finding information, leading to larger energy poverty.

The difficulty with obtaining information could also occur for persons with a migration background. They may face language barriers, but they may also have different energy consumption patterns due to cultural habits regarding heating, cooling, or cooking patterns (Straver & Mulder, 2020). An overrepresentation of people with a migration background was also found among energy-poor in Austria (Brunner, Spitzer, & Christanell, 2012).

Mental health issues, such as stress related to energy bills and the inability to manage one's energy consumption, also contribute to increased vulnerability to energy poverty. Another group with an increased vulnerability to EP is the disabled. A study in England found that EP rates are higher among households containing disabled people (Snell, Bevan, & Thomson, 2015).

Location dependent

Energy poverty depends on and varies greatly by social and spatial factors, and therefore requires a contextualized policy approach that looks further than the simple criteria of household income and energy costs (You & Kim, 2019). A study in Italy even found that these spatial/geographic factors are more important when explaining energy poverty than sociodemographic characteristics (Besagni & Borgarello, 2019). Spatial heterogeneity of EP is found in the Netherlands, as the highest EP rates are observed in peripheral areas such as Groningen, South-Limburg, and Friesland, but also in major urban centers such as Amsterdam, Rotterdam, and The Hague (TNO, 2022). In Eindhoven, 9.6% of households experienced EP. The energy-poor living in dwellings of the lowest energetic quality are primarily concentrated in the Northeast of the country (Groningen and Friesland), but also in parts of Limburg, Rotterdam, The Hague, Arnhem, Almelo, and Enschede. The strongest growth of EP is found among several urban areas throughout the entire country, among which Helmond, Flevoland, Rotterdam, Schiedam, Vlaardingen, Amsterdam, Almelo, Assen, Enschede, Arnhem, and Heerlen.

A clear U-shaped relationship between energy poverty and urbanization level is observed (Mulder, Batenburg, & Dalla Longa, 2023). That means that on average EP occurs most frequently in both (very) strongly urban municipalities and non-urban municipalities. EP is much less common in moderately urban to somewhat urban municipalities. Notably, the steepest rise in EP is found in (strongly) urbanized areas. A study in Greece (Boemi, Samarentzi, & Dimoudi, 2020) also found that EP appeared primarily in more urbanized areas, but not so much in non-urban municipalities. In Italy, energy poverty is actually lower in the center of metropolitan cities compared to small municipalities (Besagni & Borgarello, 2019). They attribute this relationship to the urban heat island effect, which means the temperatures are higher in strongly urban areas than in surrounding areas, reducing the heating capacity at home in winter.

The are also large spatial differences regarding EP on a smaller scale. A study in Utrecht showed that the percentage of energy-poor households on the district level – which is a collection of a handful of neighborhoods – varies from 2.9% to 29.7% (Agterbosch, Wentrink, & Paenen, 2020). Spatial analysis indicated that sociodemographic, housing, and economic factors contribute to variations in EP across the different neighborhoods in the Netherlands (Mashhoodi, Stead, & van Timmeren, 2019). Mashoodi, Stead, & van Timmeren (2019) analyzed what factors have an equal effect on EP throughout the entire country and what factors have a different effect on EP across the neighborhoods of the country. It showed that two factors were equally important in each neighborhood. Low-income inhabitants (the lowest four income deciles) are at risk of EP across all neighborhoods of the Netherlands, as are pensioners. The vulnerability of pensioners stems from a heightened sensitivity to (indoor) climate conditions and increased time spent indoors, resulting in an increased heating demand, which increases energy consumption (Legendre & Ricci, 2015).

Apart from these homogenous effects, Mashoodi, Stead, & van Timmeren (2019) found five factors with varying local effects on EP. These variables were studied as they were already found to be effective predictors of EP in previous studies. They found that in 55% of the neighborhoods in the Netherlands, household size emerged as the main local determinant of EP. As mentioned before, larger households, often with more children, drive up energy usage (Middlemiss & Gillard, 2015; Anderson, White, & Finney, 2012).

The weather – i.e., the number of frost days or summer days – was the most important local determinant in 23.7% of the neighborhoods. When these extreme temperatures occur more frequently, inhabitants are exposed to climate conditions they are not used to, which affects energy consumption by heating or cooling (Wiedenhofer, Lenzen, & Steinberger, 2013). In 12.8% of the neighborhoods, privately rented dwellings constitute the main local determinant. A higher proportion of privately rented dwellings is related to more EP as landlords are less likely to invest in the maintenance of their rented-out dwellings compared to owner-occupiers and publicly rented dwellings (Robinson, Bouzarovski, & Lindley, 2018; Howden-Chapman, et al., 2012). In 5% of the neighborhoods, the energy efficiency of the buildings had the largest local influence. Building age was considered a proxy for energy efficiency in their study (Brunner, Spitzer, & Christanell, 2012). So, the more relatively old buildings, the more EP found in these neighborhoods. In only 0.4% of the neighborhoods, unemployment was the main local determinant. Unemployment indicates a low-income level and lack of motivation to invest in energy efficiency of the dwelling, but unemployed are also more at home, having to heat the dwelling longer (Phimister, Vera-Toscano, & Roberts, 2015). Brunner, Spitzer, & Christanell (2012), also found a high proportion of unemployed, many long-term unemployed, among the energy-poor in Austria. Spatial dependence and other factors make energy poverty differ from absolute poverty. It was therefore also found in Italy that absolute poverty cannot be used to correctly estimate energy poverty (Besagni & Borgarello, 2019).

These results clearly showed that the factors influencing EP differ greatly among neighborhoods. This confirms that the mechanisms behind EP are complex and multidimensional. This underscores that effective policy aimed at eradicating EP should therefore consider nuance, location specific interventions (Straver & Mulder, 2020).

The energy transition

The ongoing energy transition towards more renewable energy sources is expected to further worsen EP and widen the gap between energy-poor and non-energy-poor. As the transition progresses, households not participating in it will face escalating energy expenses. The main reason behind the increase in energy costs is the need to invest in new technologies (Straver & Mulder, 2020). Households must invest to make use of renewable energy sources – for instance installing a heat pump to switch from gas to electricity. Energy grid operators also must invest in more capacity to connect solar and wind parks to the grid. Carley & Konisky (2020) found that the switch to sustainable energy technologies - as electric vehicles, solar panels, efficient devices, and LED lights – are often exclusively made by high income households.

Households that cannot invest in sustainable technologies will have to deal with higher energy costs. They will remain dependent on fossil fuels that will become more heavily taxed to stimulate households to switch to sustainable energy (Straver & Mulder, 2020). The transition away from natural gas for heating is anticipated to push more households into spending over 10% of their income on energy bills (Schellekens, Oei, & Haffner, 2019), with estimates suggesting that this could become up to 18% of Dutch households. Thus, there is a significant risk that the energy transition will lead to growing inequality and energy poverty. Energy transition policies should therefore specifically target households that do not have the financial capability to improve their dwelling themselves to prevent a further growth in inequality.

As shown above, many energy-poor households lack the means to improve the energetic quality of their residences. Some households depend on their landlord for energy-related improvements. This considers the 13.1% of all households in the Netherlands that are renters of a dwelling with low energetic quality (Mulder, Batenburg, & Dalla Longa, 2023). Moreover, about 4.5% of all households are homeowners with insufficient financial resources to enhance the energy efficiency of their homes. This adds up to about 1.4 million households in the Netherlands that are incapable of energetically improving their own dwelling, also putting them at risk to missing out on participating in the energy transition, even worsening their situation. Consequently, this group of households could be extra likely to look at look at other things to do to save on energy costs. These energy-poor may therefore opt to adjust their behavior.

Behavioral consequences of energy poverty

In order to cope with the energy costs, households adjust their behavior. This section delineates various behaviors exhibited by energy-poor households to save energy costs, thereby often negatively influencing living comfort.

Prebound

Financial constraints imply that people living in EP change their energy consumption behavior drastically, sometimes sacrificing optimal comfort levels to minimize energy costs so that money can be spent on goods of first necessity. The situation when occupants adjust their behavior and consume less energy than is expected based on the energetic quality of the dwelling, is called the prebound effect (Sunikka-Blank & Galvin, 2012). These behavior adjustments vary based on factors such as geographical location, climate, available resources, and socioeconomic circumstances.

An example of prebound behavior was found in Greece. Due to the last financial crisis and the decreased household income, many energy-poor households have reduced their energy expenses substantially (Boemi, Samarentzi, & Dimoudi, 2020). This is done in several ways. Langevin, Gurian &

Wen (2013) studied what behaviors low-income households in Philadelphia, USA perform to conserve energy. Major behavior changes frequently conducted by the residents were to adapt the lighting in their home (86% of the residents), change clothing (78%), adjust fan settings (73%), open/close windows (70%), and drink warm/cool fluids (68%). Other behaviors conducted less frequently were moving to a more comfortable room (47%), adjusting personal heater/air-conditioner settings (50%), going outside (50%), and adjusting the blinds. These behaviors range from simple actions as changing clothes to more complex and skill-needed tasks as operating personal heaters, which may require understanding of complicated control interfaces and understand their impact on the indoor environment (Wood & Newborough, 2003). This complexity may hinder certain lower socioeconomic groups. The Philadelphia residents indicated that they primary adjusted their behavior adjustment to enhance comfort rather than solely focusing on energy conservation (Langevin, Gurian, & Wen, 2013). The ones paying the bills did find saving energy more important. This difference was also found when purchasing energy efficient appliances. The ones paying the bills considered a new appliance in terms of potential savings, while the ones not paying the bills looked at it in terms of perceived product quality. This difference in attitude between the ones paying the bills and the ones who do not was already seen much earlier by Verhallen & van Raaij (1981).

A study by Reaves et al. (2016) identified several behaviors that were considered optimal for reducing energy consumption for an affordable housing facility in northern Colorado. They found a top five behaviors with the highest overall energy reduction potential for their case study: (1) taking shorter showers (to 4 min); (2) in summer, opening windows at night and shutting during the day to reduce cooling loads; (3) hanging clothes to dry instead of using a dryer; (4) replacing incandescent bulbs with fluorescents; and (5) washing clothes in cold water rather than hot or warm water. Additionally, they suggested behaviors such as avoiding the use of AC and using fans and reducing heating when sleeping or away (by 6°C) to further reduce energy usage.

The study in Colorado also found actions that affordable housing residents were highly willing to perform. These were: the installation of low-flow aerators to reduce hot water usage; in summer, opening windows at night and shutting during the day to reduce cooling loads; using the economy settings on the dishwasher; (4) the installation of water-efficient showerheads; and using natural light rather than electric light during the day.

Brunner, Spitzer, & Christanell (2012) found that the most common coping strategy to reduces costs among energy-poor in Vienna was only heating one room of a flat. This was followed by putting one different layers of clothing, this includes several layers at the upper part of the body, often wearing two pairs of socks, and sometimes even long underpants. Moreover, many energy-poor also reduced the use of lights. This includes turning off lights in empty rooms, using small lights instead of larger lights, only using the TV's light emission as illumination source in the evening. Low-income households were even found to have less lights in their dwelling than better-off households, but with a higher share of energy efficient lights.

Prebound behavior is also see observed in the 2022/2023 winter in the Netherlands, the winter also studied in this research. As mentioned in the introduction, before this winter energy prices had increased substantially. Theron, van der Wal et al. (2023) found that people used energy rather consciously. On average households set their thermostat to 17.5 ˚C in the 2022/2023 winter, some even completely turned it off. Almost all wore a sweater or took a blanket when cold, regularly took showers shorter than 5 minutes, and turned off the lights in empty rooms to keep energy costs low. The low temperature at home and low energetic quality of the dwelling resulted in many households regularly facing cold, drafts, and mold, which had negative health effects. Van der Wal et al. (2023) did not study the participant's behavior before this winter, so it is unclear to what extent they adjusted their behavior in response to the increased energy prices.

The above paragraphs clearly demonstrate that people modify their behavior in loads of different ways to save on energy costs, a practice not exclusive to the energy-poor. Households throughout all income deciles engage in them. However, the degree of discomfort tolerated may differ across income levels (Langevin, Gurian, & Wen, 2013). For instance, one could refuse to put on more blankets to save on energy for heating. Energy-poor are expected to often endure greater discomfort to minimize expenses. Energy-poor are therefore expected to engage in these behaviors much more strongly, but further research is needed to understand the extent of this phenomenon.

Behavioral differences

Not all energy-poor are expected to cope with the energy costs in the same way, as the differences in characteristics among households also lead to different behavioral reactions. Due to large variations in lifestyle and preferences, behavior of residents is an important contributor to energy use in dwellings (Guerra-Santin & Itard, 2010). A study in Utrecht Leidsche Rijn and The Hague Wateringse Veld revealed that households with a high presence at home, elderly residents, higher education levels, and single-family dwellings tend to maintain higher thermostat settings and longer heating durations. The limited sacrifice in comfort was also seen among a group of single mothers in Austria, who refused to limit their consumption too much, disregarding the energy costs, for the benefit of their children (Brunner, Spitzer, & Christanell, 2012).

On the contrary, households with lower education level, living in a multi-family dwelling, and equipped with manual radiator valves tend to maintain a lower temperature and shorter heating durations. Notably, the duration of heating usage had a larger effect on energy consumption than the temperature the thermostat was set to.

In terms of ventilation practices, households with children or elderly tend to ventilate the dwelling less by relying less on opening windows (Guerra-Santin & Itard, 2010), possibly due to increased home presence. Window and grille ventilation also have a strong effect on energy consumption. As heating and ventilation have a strong effect on energy consumption, energy-poor are likely to severely curtail these activities to minimize costs.

Guerra-Santin & Itard (2010) also state that various socioeconomic factors and housing characteristics also shape occupants' behavior in the Utrecht. Occupant behavior and housing characteristics thereon influence energy use. A study in Germany also found different consumption patterns depending on age, with elderly individuals generally consuming less energy compared to younger participants (Preisendörfer, 1999). Elderly individuals tend to conserve energy through behavioral adjustments, such as cooking activities, whereas younger individuals often opt for technological solutions. This discrepancy could stem from generational differences, as older individuals grew up in an era emphasizing frugality while younger generations are more inclined towards technological reliance. Contrarily, Meier & Rehdanz (2010) found that elderly in Great Britain consumed more energy compared to younger generations.

So, numerous socioeconomic factors influence occupant behavior, consequently impacting energy consumption. Energy-poor households may exhibit more pronounced adjustments in behavior to conserve energy compared to non-energy-poor households. Enhanced understanding of these behavioral changes, and their implications for individual well-being, will contribute to optimal policy choices.

2.3 Impacts on comfort

Adjusting behavior to reduce energy consumption impacts living comfort and thus affects well-being of people. For instance, prolonged heating usage allows households to maintain a comfortable indoor environment. However, in their efforts to reduce energy costs, energy-poor households often change their behavior, therewith possibly drastically sacrificing living comfort. Living comfort encompasses thermal comfort, visual comfort, acoustic comfort, and indoor air quality (IAQ) (Andargie, Touchie, & O'Brien, 2019). Among these, thermal quality and IAQ emerge as the most influential factors affecting a person's comfort (Andargie, Touchie, & O'Brien, 2019). Thermal comfort refers to the balance between a person's body and the surrounding environment (ISO, 2005). It relates to the subjective satisfaction with the thermal conditions and significantly impacts health and potential long-term illnesses (Polimeni, Simionescu, & Iorgulescu, 2022).

Thermal comfort

This research focuses primarily on indoor environmental quality, particularly the thermal environment, as it is the main adjustable component. Thermal comfort can be categorized into factors that affect the overall thermal balance of the body as a whole and factors that influence the local thermal balance of parts of the body. The former includes physical activity, clothing, and environmental parameters such as air temperature, mean radiant temperature, air velocity, and air humidity (ISO, 2005). The latter refers to localized discomfort caused by undesirable cooling or heating of parts of the body, such as drafts at the feet, vertical air temperature differences between head and feet, radiant temperature asymmetry, and cold or warm floors (ISO, 2005).

The perception of thermal comfort is highly individual, and the significance of specific thermal and air conditions for comfort varies depending on the occupant (Andargie, Touchie, & O'Brien, 2019). Several biological or physiological factors are relevant to the experience of comfort (Clancy, Daskalova, Feenstra, Franceschelli, & Sanz, 2017). For instance, age is an important factor when dealing with cold or heat stress. Young children and the elderly are particularly vulnerable to heat stress. Moreover, women are more sensitive to thermal sensations than men.

Hediger, Farsi, & Weber (2018) studied behavior adjustments among the Swiss population. They found that people often enhance their comfort by adjusting their clothing, increasing the temperature, improving ventilation, or initiating heating earlier in the season. Households not experiencing energy poverty can generally engage in comfort-enhancing behaviors whenever desired. However, households living in energy poverty often need to modify their behavior after making energy efficiency improvements to their dwellings, which can lead to the rebound effect (Milne & Boardman, 2000).

The various methods people employ to adjust their comfort interact with each other. For instance, opening windows to improve thermal comfort and indoor environmental quality often results in increased noise levels, thereby negatively impacting acoustic comfort (Dahlan, 2015). Consequently, the relationship between behavior and comfort is likely to be a complex mechanism rather than a simple causal link.

The controllability of the indoor environment significantly influences comfort (Frontczak & Wargocki, 2011). This relates to the influence the residents have on the indoor environment of their homes. They have an influence by, for instance, adjusting the thermostat. But on some other parts they do not have an influence (i.e., they are not in control) or a reduced influence, e.g., through drafts, bad insulation, or a malfunctioning heating system. Households facing energy poverty have limited financial capabilities and often reside in less energy-efficient dwellings. As a result, they have reduced control over the main parameters of thermal sensation and air quality, leading to lower comfort levels.

Temperature control was also found to be a very important factor regarding the use of heating and ventilation systems (Guerra-Santin & Itard, 2010). Households living in dwellings with a programmable thermostat had the radiator on more often. They also had a higher temperature in the bedroom(s) at night. Moreover, households with a programmable thermostat were more likely to open windows for a longer duration, while households with a manual thermostat were more likely to turn off the heating or close the windows/grilles when the heating was on. So, the controllability of the indoor environment is also related to energy consumption.

Effects energy interventions

As energy-poor households are confronted by poor thermal comfort due to poor housing conditions and limited energy efficiencies in their homes, energy efficiency improvements potentially improve thermal comfort and indoor environmental conditions and reduce energy costs (Hernandez & Phillips, 2015). This section delves into the impacts of minor efficiency improvements on comfort, energy poverty, and related factors.

Multiple studies have been conducted on the effect of energy efficiency retrofits. Fisk, Singer, & Chan (2020) reviewed the effects of energy retrofits on environmental quality, comfort, and health in several studies performed across Europe and the United States. On average, households increased their indoor air temperature in winter by less than 1.5˚C after a retrofit. The largest temperature improvement was found by Hong, Gilbertson, Oreszczyn, Green, & Ridly (2009), who studied the effect of England's Warm Front energy efficiency improvement program on thermal comfort in low-income dwellings in winter. The program consisted of the implementation of insulation and an energy-efficient heating system. This resulted in an average indoor temperature increase of 1.9˚C, from 17.1˚C to 19.0˚C. Moreover, the proportion of households that felt thermally comfortable increased from 36.4% to 78.7%.

Fisk, Singer, & Chan (2020) also found that recipients of retrofits reported a decrease in dampness and mold in almost all studies they reviewed. An almost 50% reduction in households suffering from mold was measured after insulating low-income dwellings in New Zealand (Howden-Chapman, et al., 2007). Moreover, Fisk, Singer, & Chan (2020) found that in the majority of studies, recipients of retrofits experienced an improvement in thermal comfort. Furthermore, the participants also reported an improvement in general and mental health in almost all studies.

Some of the aforementioned studies show substantial improvements in thermal comfort and other factors after an energy intervention. However, most of the studies only focus on large renovations. For an overview look at (Fisk, Singer, & Chan, 2020). Only a few studies are performed that consider minor energy efficiency improvements, as studied in this thesis. Minor energy efficiency improvements are improvements that at maximum cost several hundreds of euros. The positive results of larger interventions do suggest that minor interventions also have positive effects – but smaller - on comfort, housing conditions, and energy costs.

Hernandez & Phillips (2015) studied the effects of small to medium energy efficiency measures among 20 low-income households in New York City. These measures ranged from window and door sealing, efficient lights, and low-flow showerheads to boiler replacements, window and door replacements, and roof insulation. They found that the measures improved thermal comfort, health, and safety, and reduced energy costs. The most common improvement is the improvement in comfort. This was followed by a reduction in energy costs, which apart from the energy measures themselves also attributed to energy-conscious behavior performed by some households after the upgrade. Among the renters, the reduced energy costs did not all flow back to the households. Landlords usually use these improvements as a basis by which to increase rents beyond the annual increases. These upgrades therefore do not necessarily help households out of energy poverty, although now living in a more comfortable home. Moreover, differences were found among low-income renters and homeowners. Homeowners have more control over the comfort and indoor environment in their homes, but they also encounter larger costs related to the maintenance, repair, heating, and cooling of their homes. Renters do not have these costs and responsibilities regarding maintenance and building operation but depend on the landlord who sometimes sacrifices the tenants' comfort to save costs. For instance, by regulating boilers automatically and remotely.

(Grey, et al., 2017) studied the effects of poor-quality low-income dwellings in Wales that received an intervention as part of an energy poverty policy. Measures such as wall insulation, heating system upgrades, and connecting off-gas communities to the main gas network were freely applied. They found that the interventions led to increased thermal satisfaction, and participants suffered less from cold due to the inability to pay for the desired level of heating in the dwelling. Moreover, they were more satisfied with the reduction of damp-related housing problems.

The measures implemented in the above studies are, however, still bigger than the measures studied in this thesis. In the case study of this thesis, the effect of energy fixers on comfort is studied. Energy fixers are professional servicemen who apply minor energy efficiency improvements to dwellings for free, often employed by the authorities to help energy-poor households. This includes the placement of LED lights, sealing of doors and windows, and placing water-saving showerheads, timer switches, and door brushes, among others.

So far, only limited research has been performed about the effects of energy fixers. A few studies do suggest that energy-saving measures and energy advice can enhance living conditions. Bashir (2013) reported benefits in comfort, home temperature, warmth, and physical and mental well-being among vulnerable people targeted by their UK-based program. While participants anticipated to see reduced energy bills from the energy coach/fixer program, this expectation was not met. However, participants did experience increased control over their indoor environment. Furthermore, the results suggested that social connections improved in socially isolated households. The participants attributed these improvements not only to the applied saving measures but also to the advice received.

The study by van der Wal et al. (2023) is one of the few studies with an elaborate investigation of the effects of energy fixer/energy coach programs and renovation programs on among others living comfort, energy consumption/costs, and sustainable behavior. They found that, the larger the efficiency improvement, the larger the comfort improvement. Renovations therefore yielded the greatest comfort enhancements. Energy fixers had a positive effect on comfort too by reducing cold and drafts but only when the fixer applied the energy-saving interventions to the dwelling themselves. Especially households that suffered a lot from cold and drafts before the efficiency improvement were (partly) helped by the energy fixer. However, there seems to be a maximum of what a fixer can do. While fixers provided relief, households continued to suffer from cold and drafts to some extent after the intervention. The reduction of mold and heat problems was also studied, but no improvement was found.

Dutch households who received an energy-saving intervention experienced fewer respiratory problems compared to those without a fixer visit (van der Wal, van Ooij, & Straver, 2023). This is likely due to the improved housing quality, as respiratory problems often coincide with cold and drafts experienced in the dwelling. Moreover, energy fixers directly affected energy poverty by reducing energy costs. Households that were visited by energy fixers that applied energy-saving measures saw an average monthly reduction of €23 in energy expense, potentially increasing to €46 per month with extensive energy-saving measures. Households that saw their energy bill decline also experienced fewer financial worries than households that were not visited by a fixer. Other effects on mental health as sadness, stress, and anger were not found.

The effectiveness of energy fixer programs depends largely on the method behind the energy fixers/energy coach program. Positive outcomes in comfort, health, energy costs, and financial worries were only observed when the energy fixers directly implemented the interventions (van der Wal, van Ooij, & Straver, 2023). One of the programs that were studied considered energy coaches, who only advise on energy savings. Here, residents received a report with saving tips and an energy box with minor energy-saving measures after an inspection of their homes. The coaches, however, did not apply those measures themselves. This resulted in no reduction in cold, drafts, respiratory problems, energy costs, or financial worries compared to the control group.

The various measures studied - energy fixers, renovations, but also white goods schemes - improved living conditions but did not solve energy poverty completely. After the intervention, households still suffered from low living comfort, but to a lesser extent, and physical and mental health problems did not disappear completely. Therefore, a holistic approach to tackling energy poverty is necessary, of which the employment of energy fixers could be a substantial element.

Rebound behavior

The following paragraphs show that an energy improvement can influence household behavior in two ways. Firstly, there's the rebound behavior, where individuals increase consumption to enhance comfort after an efficiency enhancement. Conversely, people may have become more aware of their energy consumption behavior which may prompt individuals to adopt more energy-conscious behaviors compared to the ones who did not receive an energy improvement.

The existence of prebound behavior suggests that, following an improvement in the energetic quality of the home – such as through renovation, people may turn back the behavioral adjustments made due to EP. This is called the rebound effect: an increased energy demand caused by the reduction in energy costs after an energetic improvement to the dwelling (Mizobuchi & Yamagami, 2022). This often occurs to improve living comfort. After any energetic improvement, a rebound effect potentially follows. It can be measured through the difference between potential and actual energy savings after an efficiency improvement (Azevedo, 2014). Common types of rebound behavior are airing more frequently, paying less attention to keeping energy consumption low, increasing the internal temperature, heating sooner or later in the season, and not setting the thermostat lower when leaving the house (Hediger, Farsi, & Weber, 2018). Behavior is also related to socioeconomic factors.

Lower actual energy savings than predicted after an efficiency improvement to the home are found in many places. For instance studies in several cities across the USA (Allcott & Greenstone, 2017), the Netherlands (Aydin, Kok, & Brounen, 2017), and England and Wales (Penasco & Diaz Anadon, 2023). Most studies, however, focus primarily on energy savings. This thesis, however, does not focus on the effects of an efficiency improvement on energy savings, but on the improvement in comfort. Most studies find that the energy savings of the intervention are lower than expected, primarily caused by households adjusting their behavior to optimize comfort.

Low-income residents are found to be more likely to show rebound behavior (Milne & Boardman, 2000; Aydin, Kok, & Brounen, 2017). This was confirmed by a study by Roberdel, Ossokina, Karamychev, & Arentze (2023) in the Netherlands. They found that after a heating efficiency improvement, the natural gas consumption reduced by 22% on average. However, for the poor, this was only 16%. That means that with a comparable efficiency improvement, the poor still have an up to one-third lower reduction of gas consumption than the average. This difference can be explained by the rebound effect. The results suggest that the poor reinvested up to 20% of their potential gas savings into an improvement of thermal comfort, which means they set a higher temperature in their home. The average reinvestment in the improvement of thermal comfort was only 5%, indicating that the poor adjust their behavior more after an efficiency improvement. This is due to the lower thermal comfort that the poor lived in, i.e. the lower temperature. After an efficiency improvement, households will increase the temperature to optimize thermal comfort. For the poor, this increase will be larger, as they live in more uncomfortable conditions. So, the effect of an efficiency improvement on energy savings may be smaller for the poor, but the effect of an efficiency improvement on comfort is larger for the poor.

Moreover, renters are found to be more likely to rebound than owner-occupiers in several studies, as in Switzerland and the Netherlands (Hediger, Farsi, & Weber, 2018; Aydin, Kok, & Brounen, 2017). Aydin, Kok, & Brounen (2017) found that the rebound effect was almost twice as large among renters than among homeowners.

Galassi & Madlener (2018) studied whether individuals in Germany would adjust their behavior to improve thermal comfort after a large efficiency improvement to their dwelling. They found that the respondents attached a positive value to opening the window or tilting the window compared to not adjusting indoor comfort. Moreover, half of the respondents also preferred to wear lighter clothes indoors. Furthermore, they found that the respondents would choose the adjustment solution - e.g. opening windows, thermostats, or radiator valves – that requires the least effort and resulted in the shortest adjustment time of indoor comfort. That is the time in which the indoor conditions have adjusted to the preferred comfort level.

The previously mentioned study by van der Wal et al. (2023) also studied post-intervention behaviors. The behaviors studied were: using a blanket or sweater when cold, turning off lights in unused spaces, showering for less than 5 minutes, and setting the temperature of the thermostat. They studied different energy efficiency improvements, ranging from large to small: renovations, the visits of an energy fixer or energy coach, and participation in a white goods scheme. Households whose dwellings received a (large) renovation seemed to turn off the lights in spaces where no residents resided more after the renovation than households whose dwelling was not renovated. Thereby behaving even more energy consciously. Contrarily, households whose homes received a renovation more often afforded themselves to take longer showers than households whose homes had not been renovated, thereby consuming more energy. Conversely, minor interventions like an energy fixer/coach or participation in a white goods scheme showed no significant impact on behavior change. It was found that households that participated in a white goods scheme already often behaved sustainably, leaving little room for improvement.

Nevertheless, energy coach projects, focusing on providing advice for energy savings, demonstrated effectiveness in promoting energy-conscious behaviors. In some studies, a behavior change was measured that reduced households' costs, as heating and cooking behavior (Walker, Lowery, & Theobald, 2014; Straver, et al., 2017). An energy coach seems to be more effective when they visit the household more often and have technical and social skills (Straver, et al., 2017). Moreover, it is most effective when the advice is tailored to the household. Furthermore, households that consumed more energy before the advice of an energy coach also started saving more after the advice than households that already consumed less energy (Taylor, Jones, & Jennison Kipp, 2014).

Overall, the literature suggests that extensive renovations may lean towards inducing rebound effects, while energy advice tends to foster energy-conscious behaviors. Nonetheless, predicting household behaviors and their changes after an intervention remains challenging as every household behaves differently. One relevant factor in the different behavior of households is the occupancy pattern.

2.4 Hypotheses

The literature discussed in previous sections suggests that energy poverty and thermal living comfort are related to each other through poor housing conditions, socioeconomic factors, and behavior, as visualized in section 2.1 Conceptual model. This section will give a more detailed representation of the variables studied in this research. Moreover, the relationships of the included variables expected from the literature are further described.

Detailed conceptual models

As mentioned, the research is split up into three parts, each focusing on one of the dependent variables: (1) thermal living comfort, (2) the energy intervention, and (3) comfort improvement after the intervention. Detailed conceptual models of each of the three research topics with the selected research variables can be seen in Figure 5 – 7.

Thermal living comfort

Figure 5 shows that thermal living comfort is expected to be negatively dependent on energy poverty and complaints about housing quality, positively dependent on behavior, and dependent on certain socioeconomic characteristics of the resident. These factors are expected to have a direct relationship with comfort. However, housing quality and behavior are also expected to be negatively related to energy poverty. Moreover, certain socioeconomic characteristics make one more prone to energy poverty. The more detailed expected relationships are explained in the section 'Expected relationships'. The exact variables included in the model were found to be related to comfort or energy poverty in the literature. Moreover, some variables are included to test whether they are also relevant. This is also the case for Figures 5 and 6.

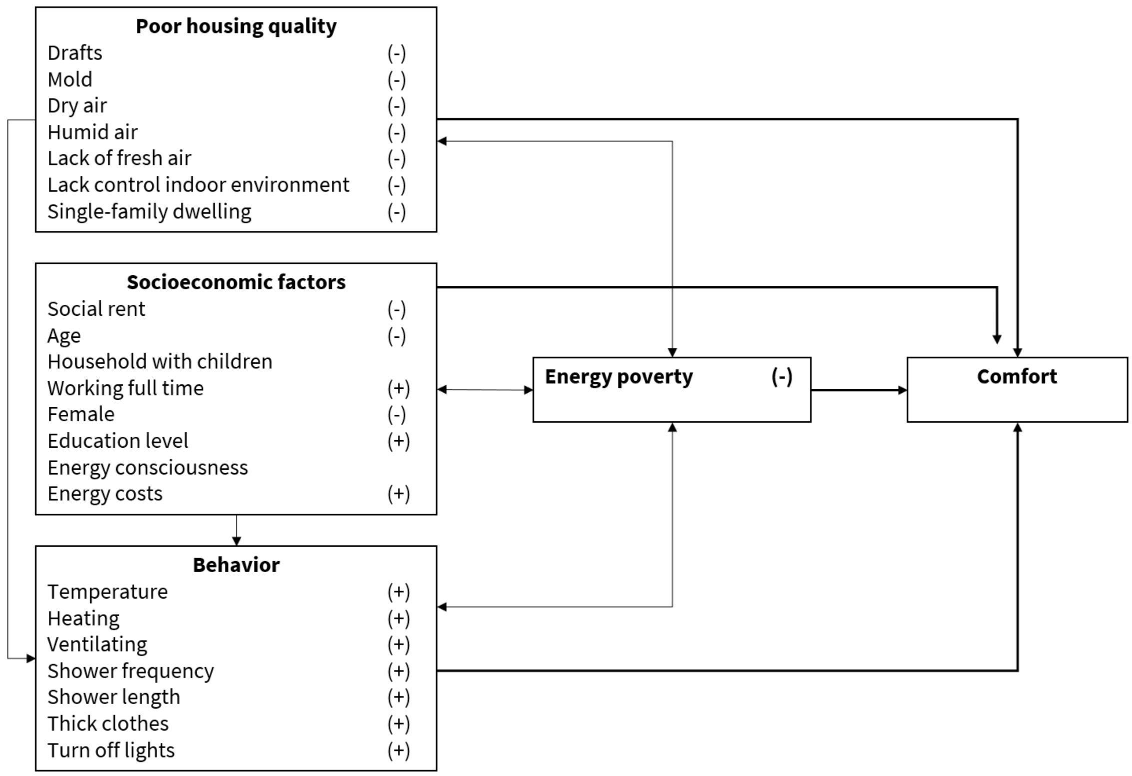

Figure 5. Detailed conceptual model: thermal living comfort.

The energy intervention

As mentioned before, the participants of this study all received an energy efficiency improvement, for instance, LED lights, water-saving showerheads, and draft strips. These efficiency improvements are offered by the municipality completely cost-free, to help households who are struggling to pay the bills. Figure 6 shows that the size of the energy intervention performed by the Klusbus is expected to be positively dependent on the degree of energy poverty and negatively dependent on housing quality. Socioeconomic characteristics of the resident also play a role. However, housing quality and socioeconomic factors are also expected to be related to energy poverty. The exact relationships expected are explained in the section 'Expected relationships'.

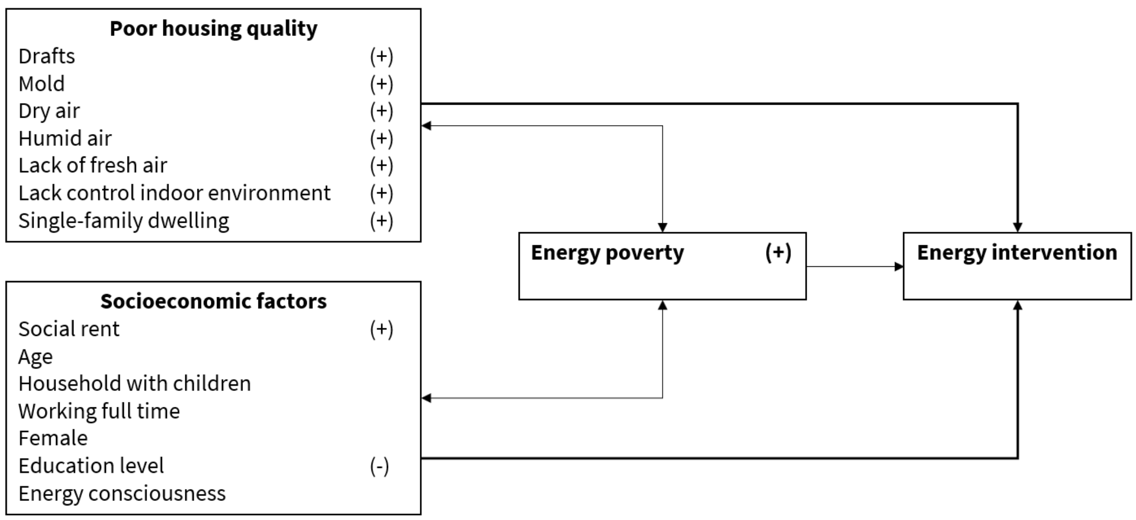

Figure 6. Detailed conceptual model: the energy intervention.

Comfort improvement

Figure 7 shows that the comfort improvement after the Klusbus is to be partly determined by the situation before the intervention: energy poverty, housing quality, and socioeconomic characteristics. The energy interventions are expected to positively affect comfort. Just as the indirect effect of the intervention on comfort through the improvement of housing quality and the adjustment of behavior.

However, housing quality (improvement), socioeconomic factors, the size of the intervention, and behavior adjustment are also expected to be related to energy poverty. The exact relationships expected are explained in the section 'Expected relationships'.

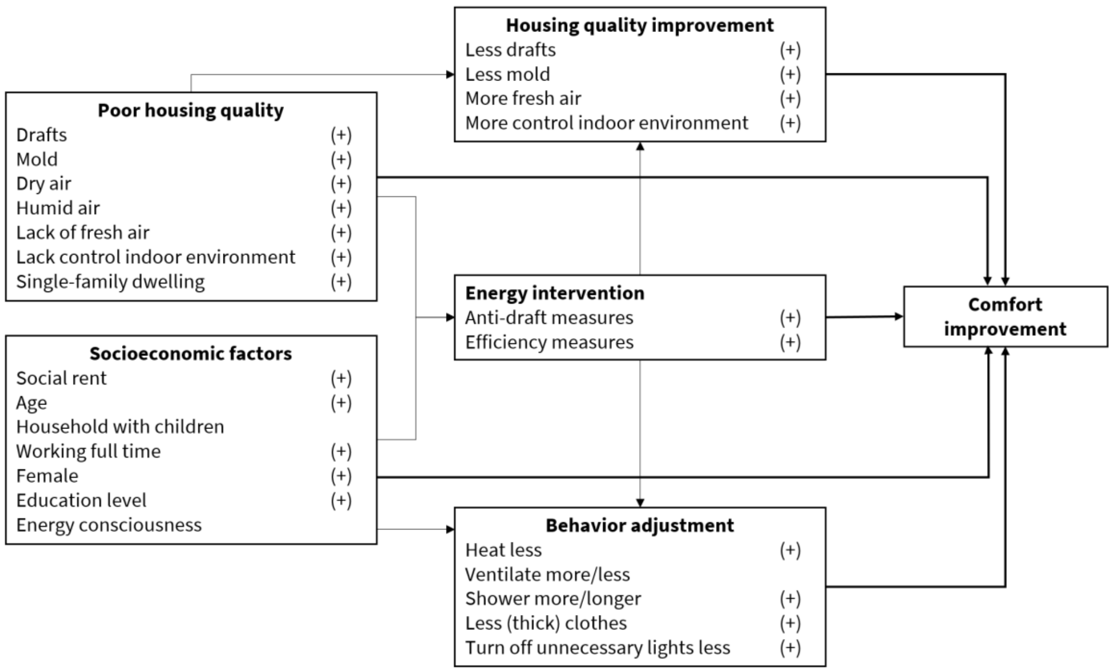

Figure 7. Detailed conceptual model: comfort improvement.

Expected relationships

Expectations about the relationships between relevant variables and the respective dependent variable are made based on the literature review. This is divided into three parts: (1) the expected relationships between thermal living comfort and its determinants; (2) the expected relationship between the size of the energy intervention and its determinants; and (3) the expected relationship between comfort improvement after the interventions and its determinants. Only the relationships between the independent variables and the respective dependent variables are considered. The models do not consider the relationships between the groups of independent variables.

Energy poverty

People living in energy poverty face difficulty with paying their energy bills and are expected to be negatively related to housing quality as a large group of energy-poor live in dwellings of low (energetic) quality. Moreover, EP is expected to negatively relate to behavior and comfort. They are expected to adjust their consumption behavior to save costs e.g. heat and ventilate less, which together with low housing quality could result in suboptimal (thermal) living comfort. Moreover, some socioeconomic groups as women and households with children are more prone to energy poverty.

As the energy-poor are expected to have lower housing quality and less financial capabilities to improve the situation, they are expected to receive a larger intervention. They are therefore also expected to experience a larger comfort improvement. So, the energy-poor are expected to experience a larger reduction of drafts and mold and a bigger improvement in fresh air and control over the indoor environment. Moreover, energy-poor are expected to make a different behavior adjustment than non-energy-poor. As mentioned, the energy-poor are expected to minimize their consumption behavior. An improvement in energy efficiency could lead to the rebound effect, where people start consuming more after an efficiency improvement to improve comfort while staying at a comparable cost level. This effect is expected to be larger for the energy-poor, as they restrict their behavior much more than non-energy-poor.

As energy-poor are expected to differ from non-energy-poor on a wide range of factors, including housing quality, socioeconomic factors, and behavior, the effects of these factors may also differ for energy-poor compared to non-energy-poor.

Housing quality (improvement)

A lower housing quality is expected to lead to a low experience of comfort. The more complaints one has regarding the quality of the house – i.e. the more drafts, mold, dry or humid indoor air, lack of fresh air, and lack of control over the indoor environment - the lower the expected comfort. All housing quality variables – or actually the lack of housing quality – are therefore expected to negatively relate to comfort. Moreover, housing quality is expected to negatively relate to energy poverty in two directions. Energy-poor have lower housing quality, and persons living in lower housing quality have a higher chance of living in energy poverty.

Housing quality is also expected to affect the energy intervention received. The lower the housing quality, the more in need of an intervention, the larger the expected energy intervention. The latter also means that improved housing quality is expected to cause a comfort improvement, albeit small due to the relatively small intervention.

Socioeconomic factors

Socioeconomic factors are related to both energy poverty and comfort. The experience of comfort was found to be highly individual. Among others, the elderly, females, and households with children are expected to be more sensitive to the thermal environment. Persons not working full time, thus being home more often, experience the comfort level in their dwelling more intensively. Moreover, some groups were found to be more prone to EP as single-person households, social renters, elderly, female, and unemployed. An energy-conscious person limiting their energy consumption for environmental causes could behave similarly and consume as little energy as an energy-poor person who is forced to behave this way by financial constraints. They could, however, experience their comfort differently. Persons living in single-family dwellings have more difficulty keeping the heat in their homes compared to apartments and are expected to have lower thermal comfort. Moreover, highly educated are expected to be less prone to energy poverty.

Socioeconomic factors are also expected to influence the energy intervention. Certain socioeconomic factors such as energy costs, employment, and education level may limit the household’s capacity to improve the housing quality themselves. It could therefore be that certain socioeconomic groups receive a larger energy intervention. This suggests that some groups may experience a larger comfort improvement.

Behavior (adjustment)

Households are expected to behave in certain ways to enhance comfort or reduce energy consumption. That includes heating certain spaces for a certain duration, ventilating certain spaces for a certain duration, setting the thermostat to a certain temperature, showering (in)frequently, showering long/short, wearing thick/thin clothes, and turning off/down unnecessary lights. Therefore, engaging more in a certain behavior is expected to positively influence comfort. Energy-poor are expected to reduce energy consumption behavior to a minimum, reducing comfort.

After the energy intervention, residents – especially energy-poor - are expected to make a rebound. In reaction to the improved efficiency of the house, there may be more financial room to, for instance, ventilate a bit more. This adjustment of behavior is aimed at improving comfort and it is therefore also expected that an improvement of comfort is experienced by the residents that adjusted their behavior after the intervention. However, as the energy intervention is small, the behavior change is also expected to be small. As the energy-poor were more restricted in their behavior (by costs), the adjustment of behavior may have a different effect on comfort improvement for the energy-poor than for the non-energy-poor.

Energy interventions

The municipal program aimed to alleviate the problems of households facing difficulty paying the bills. The energy-poor are therefore expected to receive a larger energy intervention. This could also mean that certain socioeconomic groups related to energy poverty may receive a larger intervention. Households with many complaints about the housing quality are expected to receive a larger intervention as they are more in need of improvement. The more drafts, mold, bad air quality, and lack of control over the indoor environment, the larger the energy intervention expected.

The energy interventions are expected to improve the housing quality. The anti-drafts measures – i.e., door draft strips, door brushes, mailbox brushes, door draft seal tape, window draft strips, door closers, and gap sealing - are expected to reduce drafts specifically. The efficiency measures – i.e., radiator foil, LED lights, water-saving showerheads, timer switches, low-flow aerators, and pipe insulation - are expected to improve the energy efficiency of the dwelling. Moreover, in reaction to the energy efficiency improvement, residents are expected to adjust their behavior, the rebound effect found in the literature. Through the immediate change in housing quality and behavior, the energy interventions are expected to lead to an increase in comfort.

2.5 Conclusion

To conclude, households experiencing energy poverty are expected to drastically sacrifice their living comfort as they adjust their behavior to conserve energy. Several factors are related to energy poverty. They often are renters, females, and small households among others. Apart from socioeconomic factors, energy poverty is highly location-dependent. Energy poverty occurs mostly in highly urbanized or non-urban areas and depends greatly on housing quality. Energy-poor are expected to live in poor-quality dwellings. Poor housing conditions as low temperatures and drafts negatively influence comfort. To cope with the energy costs, households adjust their energy consumption behavior, which is known as the prebound effect. They often turn down the thermostat, heat less long, wear thicker clothes, and turn off unnecessary lights. These behavioral adjustments also differ per household, for instance, households with children tend to cut their energy consumption behavior less strongly for the well-being of the children. The adjustment of behavior is namely expected to have a negative influence on comfort, especially thermal comfort. Moreover, certain socioeconomic factors are important determinants of comfort, as the experience of comfort is found to be highly individual.

The anti-energy poverty program 'Eindhovense Klusbus' is considered. The energy-poor and the ones living in poor housing conditions are expected to receive a larger energy efficiency improvement as they are most in need of improvement. Energy efficiency improvements are found to improve thermal comfort, particularly for low-income households. They often change their behavior after an improvement and start consuming more energy to optimize thermal living comfort, called the rebound effect. Based on the relationships found in the literature, three conceptual models are set up. Model (1) incorporates the relationship of energy poverty with comfort. Model (2) focuses on the relationship of energy poverty with a minor energy intervention. Model (3) focuses on the determinants of comfort improvement after the intervention. The case study used to test these hypotheses is explained in the following chapter. The method of testing the expected mechanism behind energy poverty and comfort, before and after an efficiency improvement, is explained in Chapter 4.

3. Case Study: De Eindhovense Klusbus

The households under study have all undergone a small energy efficiency improvement and are highly likely to be energy-poor. This target group is reached by using a case study: 'De Eindhovense Klusbus'. This chapter outlines what this municipal program does, and how participants are selected.

The approach

The municipality of Eindhoven has received funding from the national government to aid households facing financial struggles (Gemeente Eindhoven, 2022). Due to rising energy prices, many households have difficulty paying or cannot pay the bills. In Eindhoven alone, this affects approximately 14,000 households. The aim is therefore to take minor energy-saving measures in 14,000 residences to reduce the energy bills and improve living comfort.

To achieve this objective, several 'Klusbusses' drive around selected neighborhoods in Eindhoven to enhance the energy efficiency of the dwellings. Trained servicemen, also called energy fixers, apply minor energy interventions for free. Both renters and homeowners are eligible for these interventions. The buses operate on weekdays between 7:30h and 16:00h. In each neighborhood visited by the Klusbus, a so-called 'Klusbus stop' is set up. Residents can visit these stops for all their questions regarding the Klusbus, energy-saving tips, municipal benefits, and more. While residents can schedule an appointment to have the measures applied to their dwelling, the servicemen also conduct door-to-door visits (Gemeente Eindhoven, 2023b). Participation in the Klusbus is entirely free for households in the selected neighborhoods (Gemeente Eindhoven, 2022). Moreover, participation in the Klusbus may not result in a rent increase, as the dwellings are only improved with small energy-saving measures.

The energy measures implemented include radiator foil, LED lights, water-saving showerheads, door draft strips, timer switches, door brushes, mailbox brushes, door draft seal tape, low-flow aerators, window draft strips, pipe insulation, door closers, and/or gap sealing (Gemeente Eindhoven, 2023). The demand for interventions is high, particularly among households with a limited budget and tenants of social housing, who often do not know what they can do and what is allowed in their home (Hoekstra, 2023). The scale of intervention applied to each dwelling is determined by a point system. Each dwelling receives an intervention with a maximum of 500 points (with a few exceptions for dwellings in large need of energy efficiency improvements). These points correspond to the monetary value of each measure. For instance, a water-saving showerhead is valued at 65 points (euros) and radiator foil at 50 points (euros). Residents can decide together with the servicemen what measures are the most effective for their home. Apart from implementing energy-saving measures, the Klusbus servicemen also collect information by measuring and asking about housing complaints. These include the frequency of drafts and mold problems, the humidity, and the desired and actual temperature in the living room.

Unfortunately, well-intentioned (government) measures and incentives often fail to reach the people for whom they are intended. To involve all residents in the program an Energy Team has been set up that goes door to door to explain to residents what the Klusbus can do for their households and help them schedule an appointment (Bureau Cocosmos, 2023). Their approach focuses specifically on people who may be reluctant to participate on their own, for example, due to a language barrier, low trust in (government) authorities, or skepticism regarding effectiveness. It is precisely these people who can often benefit most from energy-saving measures.

To reach all residents, a user-friendly booking platform has been set up, allowing residents to schedule a Klusbus visit when it suits them. Everyone who has not yet scheduled an appointment is visited to schedule an appointment. The Energy Team speaks eight languages, so that information is transferred properly. Moreover, the Klusbus stop and stop signs make the project visible in the neighborhood, encouraging neighbors to talk to each other about the Klusbus. This lowers the threshold for participating in and trusting this project. Finally, walk-in consultation hours are organized. In each neighborhood, three moments are organized when people can visit the Klusbus stop to ask for information about the Klusbus. Welfare and financial partners are also present during these sessions to address additional questions.

Residents of neighborhoods not visited by the Klusbus but interested in getting started with small energy-saving measures can still receive assistance through alternative channels (Gemeente Eindhoven, 2022). These residents can request an energy box. , which includes personalized advice from an energy coach and a box with small energy-saving materials that the residents can apply themselves. Moreover, they could visit the 'Energy Desk' for guidance on suitable measures for their home, to arrange financing, find a specialist, or find available local promotions (Regionaal Energieloket, 2024).

Unfortunately, assisting households in other ways is not possible. For instance, municipalities are not allowed to insulate dwellings owned by housing associations. That could be considered state aid, which is a situation where an organization that receives governmental support gains an advantage over its competitors (European Commission, 2024). State aid is therefore generally prohibited in the EU. Besides the fact that municipalities are not allowed to insulate the dwellings of housing associations, the received funding is not nearly enough for that (Gemeente Eindhoven, 2022). That is why they have opted for a simple method where households immediately notice the comfort improvement and energy savings.

The Klusbus is made possible by the Sustainability Pact, a collaboration between the municipality of Eindhoven, the Platform Eindhoven Customer Councils (PEK), and local housing associations 'thuis, Wooninc., Trudo, and Woonbedrijf. Contracting companies Caspar de Haan, Van der Meijs, and Van Asperd execute the interventions. Bureau Cocosmos goes door to door to inform residents what the Klusbus can do for their households and assist them in scheduling an appointment.

Measurement method energy poverty

The neighborhoods have been selected based on a study into energy poverty in Eindhoven (Eindhoven Open data, 2024). This study, conducted by the CBS/Urban Data Center (UDC) Eindhoven (2022), aimed to provide the municipality with insights into the districts and neighborhoods where individuals with low income reside in poorly insulated homes. Furthermore, the municipality sought to understand the housing characteristics associated with EP in Eindhoven. Due to privacy considerations, municipalities do not know which households exactly are affected by EP. However, connections between EP and various housing and regional characteristics were established.

For the definition of energy poverty, this study adheres to the criterion outlined in the TNO report 'The facts about energy poverty in the Netherlands' (Mulder, Dalla Longa, & Straver, 2021a). A household is deemed energy-poor if it has a relatively low income and lives in a dwelling of relatively low energetic quality. This corresponds with the indicator Low Income & Low Energetic Quality (LILEK). According to LILEK, a household qualifies as energy-poor if its average income falls below 130% of the social minimum income[2], and the average energy bill of similar dwellings[3] is higher than the average energy

[2] The minimum amount needed to provide for living expenses. When the income is lower than the social minimum, one may receive an allowance on their income (Rijksoverheid, 2024). Social minimum at 1 January 2024: gross income of €2,069.30 (married) and € 1,473.56 (single) per month (UWV, 2024).

[3] All dwellings are categorized in 440 different dwelling classes, based on 5 dwelling types, 11 construction year classes, and 8 surface area classes (Mulder, Dalla Longa, & Straver, 2021a).

bill in the Netherlands. This metric for Low Energetic Quality equates to roughly all houses with an energy label of D or lower.

The study found that nationally, 7% of households living in dwellings for which EP can be calculated are deemed energy-poor (CBS/UDC Gemeente Eindhoven, 2022). In the Brainport region, this figure stands at 6%, whereas within the municipality of Eindhoven, 8% of households are energy-poor. On the neighborhood level, it is noteworthy that over 30 neighborhoods report energy poverty rates of 10% or higher. Particularly high rates of EP are observed in the neighborhoods Tivoli (28%), Doornakkers-Oost (23%), Lievendaal (18%), Jagershoef (17%), Kerstroosplein (16%), Vaarbroek (16%), Drents Dorp (16%), and Eckart (15%).

Selected neighborhoods

Based on the findings of this study, several neighborhoods were selected to be visited by the Klusbus. Figure 8 shows the neighborhoods first visited by the Klusbus: Tivoli, Doornakkers-West, Kerstroosplein, and Doornakkers-Oost (Gemeente Eindhoven, 2023). These neighborhoods were visited in the first four months, from December 2022 until April 2023, and will be studied in this thesis.

Later Eckart, Vlokhoven, Jagershoef, Prinsejagt, Rapenland, Mensfort, Gildebuurt, Limbeek-Noord, Lievendaal, Genderdal, Blaarthem, Bennekel-West Gagelbosch, Bennekel-Oost, Bloemenplein, Burghplan were visited (Eindhoven Open data, 2024). Future plans involve visits to Vaartbroek, Drents Dorp, Oude Toren, Woensel West, Woenselse Heide, Hanevoet, Limbeek Zuid, 't Hool, and Generalenbuurt.

During the initial four months, the Energy Team documented visits to 2,278 households, with 1,518 of them receiving an energy intervention, representing a participation rate of 66.6%. Others either declined participation or were not at home during the visit. According to CBS, these neighborhoods comprise a total of 5,305 households (Gemeente Eindhoven, 2023a), indicating that 28.6% of all households in these neighborhoods were helped.

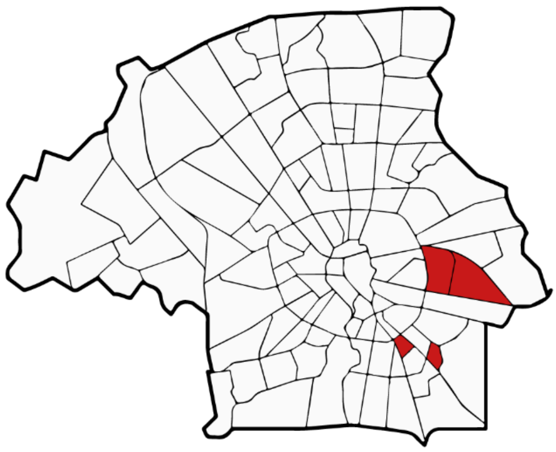

Figure 8. Studied neighborhoods: first neighborhoods visited by the Klusbus in Eindhoven.

Table 2A gives an overview of the information documented by the Klusbus servicemen about the housing conditions. Housing conditions were asked and measured for this research, to study the effectiveness of the Klusbus program. Table 2A shows that the occupants indicated to the Klusbus servicemen that on average they *often* suffered from drafts and *regularly* suffered from mold. Indoor humidity levels measured mostly fell between 30%-60%, which is considered not too dry and not too humid. The average temperature in living rooms, measured at 18.4˚C, was one degree Celsius lower than the desired temperature of 19.4˚C. Table 2B outlines the ownership of the dwellings that received an intervention. It shows that the majority of households that received an intervention were occupants of social rental dwellings, followed by homeowners and a small portion of commercial renters. Appendix A gives more detailed information about the socioeconomic composition of the studied neighborhoods.

Table 2A and 2B. Average housing conditions and ownership of the first households participating in the Klusbus program.

Table 2A

Housing conditions (range)	Mean / frequency distribution
Drafts (0,4)	2.95
0. Never	6%
1. Rarely	28%
2. Sometimes	41%
3. Often	15%
4. Always	10%
Mold (0,4)	1.83
0. Never	45%
1. Rarely	35%
2. Sometimes	13%
3. Often	4%
4. Always	3%
Humidity (-1,1)	-0.13
-1. <30%	14%
0. 30%<->60%	84%
1. >60%	2%
Temperature living room	18.39(˚C)
Desired temperature	19.43(˚C)

Table 2B

Ownership	Percentage
Homeowner	23.8%
Social rent	73.0%
'thuis	*0.3%*
Trudo	*2.3%*
Woonbedrijf	*64.2%*
Wooninc	*6.2%*
Other rent	3.2%

Source both tables: (Gemeente Eindhoven, 2023) *Data from the Klusbus visits commissioned by the municipality of Eindhoven, data processed by the author.*

A wide variety of energy measures were applied among the first participating households. Table 3 gives an overview of the energy measures applied to the dwellings in the selected neighborhoods. Column 2 shows the average number of measures per dwelling. Column 4 shows the percentage of dwellings where each measure was applied at least once. It shows that the average intervention was worth €365.71. The smallest intervention at a single dwelling was the placement of draft seal tape at just one door, only worth €15.-. The largest intervention consisted of the placement of radiator foil behind six radiators, one water-saving showerhead, and the sealing of gaps at twelve window/door frames, worth €1385.-. On average, households received more than 10 energy measures in their dwelling.

Popular measures were radiator foil, LED lights, water-saving showerheads, and draft strips at the doors. Column 4 shows that these measures were implemented in the majority of households. The least applied measures included gap sealing, door closers, pipe insulation, and draft strips at windows.

Table 3. The average number of energy measures received by the first households participating in the Klusbus program and the percentage of households that received at least one piece per type of energy measure.

Energy measures	Mean	Range	Percentage
Tot points	365.71	15 – 1385 points	-
Tot measures	10.52	1 – 27 measures	-
Radiator foil	2.50	0 – 9 pcs (per radiator)	76.3%
LED lights	4.53	0 – 23 lights	72.5%
Water-saving showerheads	0.62	0 – 3 showerheads	61.4%
Door draft strips	0.79	0 – 5 pcs (per door)	59.4%
Timer switches	0.51	0 – 4 switches	44.9%
Door brushes	0.42	0 – 4 doors	37.5%
Mailbox brushes	0.33	0 – 2 pcs (per mailbox)	33.1%
Door draft seal tape	0.31	0 – 7 doors	21.8%
Low-flow aerators	0.24	0 – 4 taps	16.8%
Window draft strips	0.09	0 – 5 pcs (per window)	6.0%
Pipe insulation	0.07	0 – 14 meters	5.9%
Door closers	0.08	0 – 5 pcs (per door)	1.3%
Gap sealing	0.03	0 – 12 frames	0.9%

Source: (Gemeente Eindhoven, 2023) *Data from the Klusbus visits commissioned by the municipality of Eindhoven, data processed by the author.*

Table 4 provides additional insights into the socioeconomic characteristics of the four neighborhoods in comparison to the citywide average Eindhoven. These neighborhoods exhibit similar household compositions in terms of household type and age distribution. Migration backgrounds align closely with the citywide average, with a slightly higher representation of individuals with a non-western background. However, the disposable income, at €35,100, is notably lower compared to the citywide average of €45,800. Almost double as many households fall below the low-income threshold (<€9250), or express worries about money.

Moreover, education levels are below the citywide average. Housing ownership is predominantly held by housing associations, doubling the citywide average, while commercially rented dwellings are half as prevalent. Single-family dwellings comprise three-quarters of the housing stock, substantially more than the citywide average.

Energy consumption levels are comparable to the city average. The neighborhoods are characterized by a strong urbanization level, slightly lower than the city average, as the studied neighborhoods are situated on the city's periphery. Safety perceptions in these neighborhoods are somewhat lower, and health issues are only marginally more prevalent than the citywide average.

Table 4. Distribution of the socioeconomic characteristics in the four studied neighborhoods compared to the average neighborhood in Eindhoven. Source: (Gemeente Eindhoven, 2023a).

Theme	Neighbor-hoods	EHV
EP rate	18%	8%
Households		
Mean no. of households	1,326	1,093
Single-person	52%	49%
Hh without children	21%	25%
Hh with children	27%	26%
Household size	1.9	1.9
Age		
0-14	14.4%	13.6%
15-64	70.6%	70.0%
>64	15.0%	16.4%
Migration background		
Dutch	54.2%	57.8%
Western	15.3%	16.8%
Non-western	30.5%	25.4%
Income		
Disposable hh income (€)	35,100	45,800
High income (upper 20%)	7.5%	16.5%
Max 120% social minimum	22.7%	13.6%
Low income (<€9250)	9.7%	5.4%
Worries about money	18%	9%
Has debts	25%	21%
WW allowance	2%	1%
UWV registered job seeker	4%	6%

Theme	Neighbor-hoods	EHV
Education		
Low	34.6%	24.1%
Medium	37.7%	35.0%
Highly	27.7%	40.9%
Tenure		
Commercial rent	11%	20%
Homeowners	29%	43%
Social housing	60%	37%
Dwelling type		
Multi-family	25%	41%
Single-family	75%	59%
Energy consumption		
Electricity use (kWh)	2,422	2,580
Gas use (m3)	943	910
Neighborhood		
Urbanization level	Strongly urban	Vergy strongly urban
Sometimes feels unsafe in the neighborhood	27%	20%
Social nuisance	18%	18%
Health		
Mediocre/bad health	15%	12%
At home through illness	7%	5%
(very) unhappy	6%	6%
Limited social network	13%	11%

4. Methodology

In this chapter, the research methodology is described. First, the variables stated in the conceptual models are operationalized. The structures of both datasets – the municipality dataset and the survey dataset – are defined. The process of data collection, management, and preparation then are discussed. Finally, several analysis methods are proposed to estimate the relationships hypothesized in the conceptual models.

4.1 Research design

In this section, an overview is provided of all data gathered through the survey and the Klusbus dataset. This includes the way the variables have been asked and measured.

Table 5 gives an overview of the involved variables, their data source, and the corresponding research question. Based on the overview, a questionnaire is set up to measure the variables. In Appendix B, the completed questionnaire can be found. A further explanation of the measurement of the variables is given below.

The levels/categories of each variable are based on literature and practicality. Note that the target group of this study consists of relatively many low SEC persons and persons who do not speak the language very well. To make the survey understandable, many questions have been structured similarly and recognizable.

The survey was tested among fellow students and Klusbus participants before the final survey was sent out.

Table 5. Overview of collected data in survey and municipal Klusbus dataset.

Survey		
(sub) question	Factor	Variable
Main question	Energy poverty	Energy poverty
2, 4, 8, 11	Housing quality	Lack of fresh air
		Control indoor environment
Main question	(Comfort)	Cold in the living room
1, 5, 9, 12	Socioeconomic factors	Tenure
		Age
		Household composition
		Energy costs
		Employment status
		Gender
		Education
		Dwelling type
		Energy consciousness
3, 6	Behavior	Heating
		Shower frequency
		Shower length
		Ventilating frequency
		Clothing
		Turn off unnecessary lights
2, 14	Housing quality improvement	Less drafts
		Less mold
		More fresh air

10 - 15	(Comfort improvement)	More control indoor environment Less cold in the dwelling
3, 15	Behavior adjustment	Heat more/less Ventilate more/less Shower more/longer Less (thick) clothes Turn off unnecessary lights less New temperature
3	Desired behavior	Prefer heating more/less Prefer ventilating more/less Prefer showering more Prefer less (thick) clothes
Klusbus dataset		
(Sub) question	Factor	Variable
2, 3, 8, 11	Housing quality	Drafts Mold Humidity
3, 6	Behavior	Actual temperature
2, 7, 8, 9, 13	Energy interventions	Radiator foil LED lights Water-saving showerheads Draft strips door Timer switches Door brushes Mailbox brushes Door draft seal tape Low-flow aerators Draft strips window Pipe insulation Door closers Gap sealing
	Desired behavior	Desired temperature

Energy poverty

To determine whether someone is energy-poor, the respondents are asked whether the household had difficulty paying the energy bills in the winters before the Klusbus. This metric is defined after an analysis of several EP indicators, as no standardized definition of energy poverty has been universally adopted across the EU (Chlechowitz & Reuter, 2021). As mentioned in section 1.1, the four primary indicators of energy poverty are (EPAH, 2022):

(1) Arrears on utility bills
(2) Inability to keep home adequately warm
(3) High share of energy expenditure in income
(4) Low absolute energy expenditure

EP metrics can be subdivided into two approaches: expenditure-based and consensual-based (Rademaekers, Yearwood, & Ferreira, 2016). Expenditure-based metrics hinge on household energy spending compared to income, while consensual metrics identify households struggling to meet essential energy services.

The first two primary indicators rely on self-reported experiences of energy service limitations, adhering to the consensual-based approach. These indicators are based on questions from the EU-wide national surveys of the European Union Statistics on Income and Living Conditions (EU-SILC). Which is a survey aimed at collecting comparable cross-sectional and longitudinal data on income, poverty, social exclusion, and living conditions within the EU (European Commission, 2020). The latter two indicators were calculated using household income and data on energy expense, adhering to the expenditure based (EPAH, 2022). These indicators are calculated using data from household budget surveys (Eurostat, 2020).

Metric (1) relates to the question "In the past twelve months, has the household been in arrears, i.e. has been unable to pay the utility bills (heating, electricity, gas, water, etc.) of the main dwelling on time due to financial difficulties (European Commission, 2020)? In the EU-SILC survey the answer options are limited to 'yes once', 'yes, twice or more', or 'no'. This metric represents one possible dimension of energy poverty, namely households struggling to pay for vital energy services. However, this metric has some limitations as some households intentionally under-consume energy but don't exhibit payment arrears due to energy-saving behaviors (Cong, Nock, Qiu, & Xing, 2022). Moreover, the answer options 'yes once,' 'yes, twice or more,' or 'no' may oversimplify experiences (Thomson, Bouzarovski, & Snell, 2017). In some instances, non-payment might result from neglect or forgetfulness. Additionally, a single arrear could stem from an income shock, like unexpectedly high energy costs during cold weather (Rademaekers, Yearwood, & Ferreira, 2016). Importantly, borrowing money for bill payments from banks, relatives, or friends isn't deemed an inability to pay (European Commission, 2020), although it signifies payment challenges.

The second metric relates to the EU-SILC question "Can your household afford to keep its home adequately warm?", with answer options yes and no. This metric also comes with some limits. The binary answer options fail to capture the varying degrees of energy poverty intensity. Moreover, different interpretations of what 'adequate warmth' is can exist among gender, age, and other sociodemographic groups. Individual responses per household member may give a more accurate representation of vulnerability to EP (Sintov, White, & Walpole, 2019). This metric could also be seen as too specific, primarily focusing on a single energy service, namely space heating (Rademaekers, Yearwood, & Ferreira, 2016; Castaño-Rosa, Solís-Guzmán, Rubio-Bellido, & Marrero, 2019)

Metric 3 considers households with a share of energy expenditure compared to income that is higher than a certain threshold. An internationally applied threshold is twice the national median (EPAH, 2022). By using this metric households with disproportionately high energy costs are identified. The metric does require that rather sensitive data on both income and energy costs must be asked of respondents. It however does not include energy-poor households that are under-consuming to save energy. Moreover, it does not differentiate on what type of energy use energy costs are made. One household with a dwelling of low energetic quality could for instance spend it on basic needs while another household with a dwelling of high energetic quality could be spending it on leisure. Moreover, households with a high income can still be indicated as energy-poor using this metric, and the two-median threshold seems rather arbitrary. Are households that fall shortly under the threshold not energy-poor? It does not consider differences in energy demands for different household sizes, composition, and income (EPAH, 2022).

The fourth metric considers households with energy expenditure below a certain threshold. The threshold applied internationally is half the national mean (EPAH, 2022). Households with disproportionately low expenditure can be identified, therefore focusing on cases of hidden energy poverty (Rademaekers, Yearwood, & Ferreira, 2016). It should therefore be combined with the metric 3 to also capture households with specifically high energy costs. It is easy to calculate but does not consider other factors such as the energy efficiency of the dwelling, household size, and income. Therefore, for instance, a high-income household with a highly energy-efficient home could be considered energy-poor (Barrella, et al., 2022). An income threshold could be set to prevent this.

To conclude, there is no international metric yet that accurately captures all households that live in energy poverty. There probably will never be, due to the complexity of the problem. The two expenditure-based approaches ignore other factors such as household composition, energy efficiency of the dwelling, and income thresholds. Furthermore, they should be combined to capture both households with high energy costs and under-consuming households. A consensual-based approach seems more suitable for studying the effect of energy-saving behavior.

Selected energy poverty metric

As energy poverty is the main research concept of this study, the definition or metric used in the survey is very important. Due to the complexity of the problem, one metric will probably not encounter the entire group of energy-poor. For analysis purposes, however, it would be easiest to include one question (one metric) to define whether a respondent is considered energy-poor. Therefore, a metric is selected, based on the literature review and understandability of the target group, that tries to mitigate the limitations of the current metrics used on an international scale. This final metric considers one's difficulty in paying the energy bills. The accompanying survey question: "Think about last winters. Did your household have difficulty paying the energy bills?". The 5-point ordinal scale ranging from 'never' to 'always' gives a scale of energy poverty ranging from 'not energy-poor' to 'very much'.

This metric focuses on the important dimension of households struggling to pay for vital energy services. It will result in a wider group than when looking a payment arrears. Contrary to payment arrears, households that under-consume (hidden energy poverty) may still be captured by this metric to some extent. However, their level of energy poverty will not be fully captured, as their payment difficulties are already mitigated by their behavior. Furthermore, households that had to borrow money to pay the bills are also included, as needing to borrow inherently implies difficulty with paying the energy bills.

Sociodemographic influences as relevant for 'the inability to keep home adequately warm' are excluded as the difficulty to pay the bills is influenced less by sociodemographic factors than the opinion on adequate warmth. The metric does only consider households that have difficulty in winter. Households that may have difficulty cooling their homes in summer are not per se included, but that is not part of this research. The scope of the research is limited to thermal comfort in winter.

This metric also prevents certain problems with expenditure-based approaches. No sensitive data on exact income and energy costs should be acquired. Households with a high income will probably not be included as energy-poor using this metric. The ordinal scale also prevents the exclusion of households that may suffer energy poverty to a certain extent like binary variables or (arbitrary) expenditure thresholds may do. A risk may still be that the energy-poor could still downplay their financial problems.

Comfort

To determine thermal living comfort, the respondents are asked whether they suffered from cold in their living room in the winters before the Klusbus. To select a measurement method for comfort appropriate for this study, several measurement methods have been analyzed.

A common metric is thermal sensation. Melikov, Pitchurov, Naydenov, & Langkilde (2005) asked the experience of thermal sensation in the dwelling with a 7-point Likert scale answer options ranging: 'Cold; Cool; Slightly cool; Neutral; Slightly warm; Warm; Hot'. It seems intuitive that 'neutral' is the most comfortable sensation but it is not. People seem to prefer a slightly warmer environment (Pellering & Candas, 2003).

The next metric is the acceptability of the indoor environment. This relates to the question of whether the thermal environment is acceptable to the respondent, with answer options yes and no (Lai, Mui, Wong, & Law, 2009). The binary answer options, however, limit the degree to which the environment is (un)comfortable.

A third metric is the satisfaction or dissatisfaction with the thermal sensation. Respondents can indicate their satisfaction on an ordinal scale ranging from 'very dissatisfied' to 'very dissatisfied'. Satisfaction seems to be one of the most used ways to measure comfort (Mlecnik, et al., 2012). The international standard for thermal comfort uses a combination of metric 1 thermal sensation and metric 3 satisfaction. (ISO, 2005) predicts the percentage of people who would be dissatisfied, based on their rating of the thermal sensation (metric 1).

A fourth metric is personal preference. Respondents are asked whether they prefer the environment to be colder, warmer, or the same environment (Melikov, Pitchurov, Naydenov, & Langkilde, 2005). The ones indicating they would prefer the same environment would live in comfortable conditions.

Selected comfort metric

The selected comfort metric is tailored to the study. The study namely considers the comfort in the winters before and after an intervention. Therefore, comfort is interpreted as the thermal sensation in winter, in other words, the degree of cold, see Table 6. Most of the above metrics ask about the comfort the person experiences in the environment he is in at that moment. However, when studying the comfort in a complete winter, the comfort is not the same every day. Therefore, the respondents are not questioned whether they feel cold, or to what extent, but to what frequency.

The accompanying survey question: "Think about last winters. Did you suffer from cold in the living room in the winters?". The 5-point ordinal scale ranging from 'never' to 'always' gives a scale of energy poverty ranging from 'not energy-poor' to 'very much'. To measure the comfort improvement after the energy intervention, a comparative question has been asked. The following statement has been added to the survey: "After the Klusbus, I suffer less from cold in the living room".

Table 6. Levels of the comfort variables before and after the energy intervention.

Variable	Categories
Cold in dwelling	Never, Rarely, Sometimes, Often, Always
Less cold in the dwelling	Not less at all, Slightly less, Moderately less, Much less, Very much less

Housing and housing quality (improvement)

Questions regarding housing and housing quality before the Klusbus visit were also considered: dwelling type, drafts, mold, humidity, lack of fresh air, and control indoor environment. Table 7 gives an overview of the housing quality variables asked in the survey or by the Klusbus. Most questions in the survey are asked on an ordinal scale, based on a Likert scale of frequency (Likert, 1932). Drafts, mold, and humidity were asked of the residents by the mechanics of the Klusbus. The levels were therefore predefined in the dataset received. The same levels, based on the frequency of occurrence of a housing complaint, are used for lack of fresh air. Fresh air was also added as indoor air quality was found to be important to one's comfort (Andargie, Touchie, & O'Brien, 2019). The categories of dwelling type are based on Mulder, Batenburg, & Dalla Longa (2023) who described the characteristics of the energy-poor using these classifications.

Many questions have the same or comparable answer options, so that the respondents recognize the way of questioning, making the survey user-friendlier. This is also the case for control over the indoor environment, which was found to be an important factor by Frontczak & Wargocki (2011).

Table 7. Categories of the variables about housing (quality) before the energy intervention.

Variable	Categories
Dwelling type	Multi-family house (apartment), In-between house, Corner house. Semi-detached house, Detached house
Drafts *	Never, Rarely, Sometimes, Often, Always
Mold *	Never, Rarely, Sometimes, Often, Always
Humidity *	<30%, 30%<->60%, >60%
Lack of fresh air	Never, Rarely, Sometimes, Often, Always
Control indoor environment	Never, Rarely, Sometimes, Often, Always

**Variable is part of the Klusbus dataset.*

Moreover, questions are asked about the improvement of housing quality after the energy intervention. Table 8 gives an overview of the variables regarding housing quality improvement included in the survey: fewer drafts, less mold, more fresh air, a more controlled indoor environment, and less cold in the dwelling.

These are the same housing quality factors as asked in the survey about the situation before the intervention. The respondents are asked to what extent the problems were reduced after the intervention, measured on an ordinal scale. The same scale, depending on the direction change, was used for every variable. The difference in humidity is not considered, as this was measured by the Klusbus servicemen before the intervention. The dwellings are not visited when doing the survey, making a new measurement impossible.

Table 8. Categories of the variables about housing quality improvement after the energy intervention.

Variable	Categories
Less drafts	Not less at all, Slightly less, Moderately less, Much less, Very much less
Less mold	Not less at all, Slightly less, Moderately less, Much less, Very much less
More fresh air	Not more at all, Slightly more, Moderately more, Much more, Very much more
More control indoor environment	Not more at all, Slightly more, Moderately more, Much more, Very much more

Socioeconomic factors

Questions about socioeconomic factors were considered: tenure, age, household composition, employment status, gender, education, and energy consciousness. Table 9 gives an overview of the variables asked in the survey. Education levels are based on classifications by the Dutch Bureau of Statistics (CBS, 2021). Tenure and household composition are based on Mulder, Batenburg, & Dalla Longa (2023) who described the characteristics of the energy-poor using these classifications. Age and energy costs are based on the Dutch National Housing Survey (CBS, 2020). For energy costs, the distribution among Dutch households has been divided into equal intervals. Employment status is based on the research by Karigar (2022). Energy consciousness is added to control for a possible effect on energy consumption.

Table 9. Categories of the socioeconomic variables.

Variable	Categories
Tenure	Homeowner, Social rent, Other rent,
Age	Younger than 25, 25 – 34, 35 – 44, 45 – 54, 55 – 64, 65 – 74, 75 or older
Household composition	Single, Couple without child(ren) (living at home), Single parent with child(ren) living at home, Couple with child(ren) living at home, Other
Energy costs	Less than 60 per month, 61 to 120 per month, 121 to 180 per month, 181 to 240 per month, 241 to 300 per month, More than 300 per month, I don't know
Employment status	All adults work full time (32 hours a week or more), One adult works full time (32 hours a week or more), All adults are retired, Other
Gender	Male, Female, Prefer not to say / other
Education	Primary school, vmbo, lower half havo/vwo, mbo level 1 or 2, Mbo, havo, or vwo completed, Hbo/wo bachelor, Wo master or PhD
Energy consciousness	Extremely, Very, Moderately, Slightly, Not at all

Behavior (adjustment)

The next questions aim to describe the behavior and energy consumption patterns of the studied households before the Klusbus visit. Table 10 shows that the variables include heating duration of the living room and bedroom(s), ventilating frequency of the living room and bedroom(s), shower frequency and length, clothing, and turning off unnecessary lights.

According to the literature, residents alter their behavior to conserve energy. In the survey, the respondents were asked at which frequency they engage in each behavior. The selected behaviors are considered rather simple behaviors. This is due to the target group, which is primarily persons of lower socioeconomic class who are not expected to make complex behavior changes. Furthermore, the same behaviors are asked after the intervention.

Heating and ventilation were found to have the strongest effect on energy consumption and are therefore included (Guerra-Santin & Itard, 2010). Heating duration is asked for both the living room and bedroom(s). Hueber, et al. (Hueber, et al., 2021) asked the number of hours the heating was on per day. For simplicity of the survey participant, it has been adapted to the parts of the day the heating was on and whether the heating was on all the time during that part of the day or partly. Ventilating frequency was based on Guerra-Santin & Itard, 2010 (Guerra-Santin & Itard, 2010), who also asked the hours per day the windows were opened. This too has been adjusted to a more understandable categorization. Shower length was added as Reaves et al. (2016) found that the energy-poor often shower for less than 5 minutes. Extra 5-minute intervals were added to create ordinal answer options. Shower frequency was also added. It was not found in the literature that energy-poor shower less, but it could be expected as they were found to shower shorter. Turning off unnecessary lights was found to be often done by the energy-poor (Brunner, Spitzer, & Christanell, 2012). Therefore, it has been added as a variable with the same answer options as for housing quality. Clothing was based on the research by Hillman-Eady (2022), where respondents can see a picture and tick all the garments they usually wear. Temperature was measured by the Klusbus servicemen.

Table 10. Categories of the variables about behavior before the energy intervention.

Variable	Categories
Heating living room	Morning: Yes / Partly / No Afternoon: Yes / Partly / No Evening: Yes / Partly / No Night: Yes / Partly / No
Heating bedroom(s)	Morning: Yes / Partly / No Afternoon: Yes / Partly / No Evening: Yes / Partly / No Night: Yes / Partly / No
Ventilating frequency living room	2 or less times per week, 3 - 4 times per week, 5 - 6 times per week, 1 time per day, More than 1 time per day
Ventilating frequency bedroom(s)	2 or less times per week, 3 - 4 times per week, 5 - 6 times per week, 1 time per day, More than 1 time per day
Shower frequency	2 or less, 3 – 4, 5 – 6, 7 or more
Shower length	Less than 5 minutes, 5 - 9 minutes, 10 - 14 minutes, 15 minutes or more
Clothing	Top, T-shirt, Long-sleeved shirt, Sweater-blazer, Dress, Trousers, Skirt, Jacket, Open shoes, Shoes, Boots, Scarf,
Turn off unnecessary lights	Never, Rarely, Sometimes, Often, Always
Temperature	˚C

For the four behaviors with the largest expected effects on energy consumption and/or comfort, an extra question is asked. Namely, whether the respondent would prefer to engage in this behavior more or less than they are currently doing if they would be financially capable. Once more, the answer options are ordinal, as seen in Table 11. This way, it can be tested whether the energy-poor adjust their behavior more than the non-energy-poor. The desired temperature was asked by the Klusbus servicemen.

Table 11. Levels of the variables about preferred behavior if the respondents were financially able.

Variable	Categories
Heat more / less	Much less, Less, Not more / not less, More, Much more
Ventilate more / less	Much less, Less, Not more / not less, More, Much more
Shower more / longer	Never, Rarely, Sometimes, Often, Always
Less (thick) clothes	Never, Rarely, Sometimes, Often, Always
Desired temperature	˚C

Table 12 gives an overview of the questions asked in the survey regarding behavior adjustment after the intervention. Based on the literature, the improvement of housing quality is expected to lead to adjustments in household energy consumption behavior. Participants are expected to change the heating hours and temperature, ventilating frequency, showering length or frequency, and lights use. These are the same behavior factors asked in the survey about the situation before the intervention to compare the behavior after the intervention with the situation before. The answer options are again based on the 5-point Likert scale. Heating more/less is centered around no behavior change as the improvement of housing quality may for some households lead to heating more for better comfort, and for others heating less because heating is less necessary than before. The same applies to ventilating. The adjustment of showering, clothes, and turning off unnecessary lights is only considered in one direction (i.e., lighter clothes) as the other direction does not seem to apply in this situation.

Table 12. Levels of the variables about behavior adjustment after the energy intervention.

Variable	Categories
Heat more / less	Much less, Less, Not more / not less, More, Much more
Ventilate more / less	Much less, Less, Not more / not less, More, Much more
Shower more / longer	Never, Rarely, Sometimes, Often, Always
Less (thick) clothes	Never, Rarely, Sometimes, Often, Always
Turn off/down unnecessary lights less	Not less at all, Slightly less, Moderately less, Much less, Extremely less
New temperature	10˚C - 30 ˚C

Klusbus energy intervention

Besides the subjective data about the improvement after the energy intervention, objective technical information about the energy intervention itself is taken from the Klusbus database (Gemeente Eindhoven, 2023). It consists of an overview of the energy interventions applied and is provided by the municipality of Eindhoven. The included variables can be seen in Table 13. The number of energy measures per dwelling and the total monetary value of the energy intervention at each dwelling (points renovation) are included.

Table 13. Categories of the energy measures variables.

Variable	Categories
Radiator foil	No. of radiators
LED lights	No. of lights
Water-saving showerheads	No. showerheads
Draft strips door	No. of doors
Timer switches	No. of switches
Door brushes	No. of doors
Mailbox brushes	No. of mailboxes
Door draft seal tape	No. of doors
Low-flow aerators	No. of water taps
Draft strips window	No. of windows
Pipe insulation	No. of meters
Door closers	No. of doors
Gap sealing	No. of frames
Total points renovation	No. of points

4.2 Data collection

This section elaborates on the data collection. First, the target group is explained. This is followed by the data collection and data management procedure. Moreover, the way the data is prepared for analysis is discussed, as are the limitations of the data regarding reliability and validity.

Target group

The defined variables are collected from two sources. The first data source considers information about energy interventions applied to several dwellings in Eindhoven by the municipal program called the 'Klusbus' (Gemeente Eindhoven, 2023). The second data source is an online survey distributed among residents who have received such an energy intervention and have indicated their willingness to participate in follow-up research on the energy interventions.

To define the target group, the first dataset on the Klusbus dataset is used. This dataset has data on the dwellings that received an energy intervention by the Klusbus between December 7, 2022, and April 7, 2023. This dataset is provided by the municipality of Eindhoven. Not all households/dwellings in the dataset are suitable for the study. Households that received an intervention were asked by the energy fixers if they were open to being approached for follow-up research on the intervention. Therefore, only the households that indicated their willingness to participate could be approached for this study. This results in a mix of energy-poor and non-energy-poor households living in these four neighborhoods who all received an intervention, but of different size.

Data collection and preparation

A survey was created in the online survey environment LimeSurvey (LimeSurvey GmbH, 2024) and was distributed among the residents who agreed to be approached. The survey was distributed via email on April 26, 2023. A reminder was sent on May 9. A physical letter was sent to the households that had not responded yet on May 19.

Combining the datasets

The survey data should be matched with the Klusbus data from the municipality with housing data. Therefore, the two datasets will have to be linked on address level. Sensitivity arises because (low-risk) personal data can be traced to the address level. To guarantee the privacy of the respondents, precautions will be taken so that the address data are stored separately from the other data in the research and are never merged directly to survey answers. This is done by the following steps, also visible in Figure 9:

Database 1: Addresses & unique identifier (UID). Each address will receive a unique identifier (UID). The matching table Address-UID will be stored on a secure BE-project drive and is only accessible by the researcher and the TU/e supervisor.

Database 2 (intermediate): UID & housing characteristics. Database 1 will be merged with the housing characteristics from the municipality, after which the addresses will be removed from the resulting table. The resulting database includes UID and housing characteristics of the dwellings. Individual households cannot be traced.

Database 3: (Intermediate) UID & survey answers. Invitations are sent to the residents to participate in the survey with a personalized survey link. The survey is in the online environment Limesurvey and the answers are stored with the UID and identification. Individual households can this way not be traced.

Database 4 (final): UID & housing characteristics & survey answers. By merging databases 2 and 3, the final database will be created to perform the statistical analysis. Individual households cannot be traced.

So, there is no single dataset in which personal data can be traced to the address. Further, all data that can be used to identify an individual will be removed as soon as possible. Only the overall descriptive data and the results of the regression analysis will be visible in the final report. No data on the level of the dwelling or household will be shared. The data will be stored at the TU/e facilities for 10 years as part of the Master thesis documentation. The supervisors may keep the data for future research. The raw data will not be shared with anyone else.

Respondents needed to give permission to participate in the survey. The survey starts by providing an informed consent form, as can be seen in Appendix B. This way, participants are provided with information on which data from the participant is used, what is used for, that it is voluntary, and that the participant can refuse to participate or stop during making the survey. The Ethical Review Board of the Eindhoven University of Technology approved the survey and informed consent form on April 24, 2023.

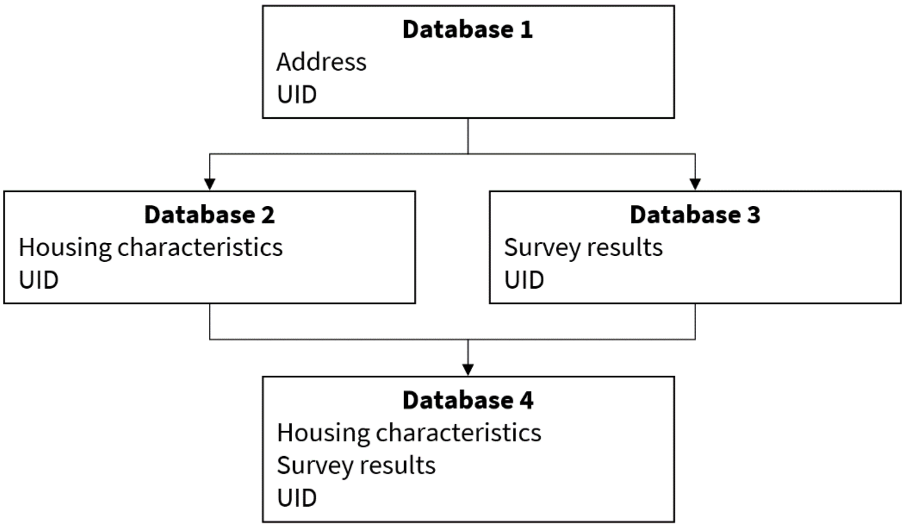

Figure 9. Precautions taken to pseudonymize the data.

Data preparation

Several steps of data preparation have been performed to enable proper analysis. First, only respondents who filled in the full survey were selected. That also excludes everyone who had lived in the dwelling for less than a year. Thermal comfort was measured as the level of cold in the dwelling in the winter. To be able to determine the comfort improvement after the intervention, it is necessary that the studied households already lived in the same dwelling in the winter before the intervention. Therefore, the households considered in the study should have lived in their dwelling for at least one year. The removal of these respondents leaves no missing cases for the survey data.

The Klusbus dataset did miss some data for some households. Therefore, the missing values for *temperature*, *desired temperature*, *drafts*, *mold*, and *humidity* are replaced by the mean. Moreover, some variables are transformed, or new variables are created from existing variables for further analysis. For instance, energy-poor has been recoded into a dichotomous variable which is 1 for all respondents who sometimes to always have difficulty paying their energy bills. A further explanation of the exact recoding can be found in Appendix C.

Moreover, all variables with less than 8 observations are not considered in the regression analyses. In general, 10 observations are taken as the minimum. However, this study only has a small sample. Setting a relatively high threshold could result in the omitting of possible interesting effects. Table 14A lists all variables that have been excluded due to limited observations. D*raft strip window* was also excluded, despite more than 8 observations, as it has been applied to substantially fewer dwellings than the second-least applied measure *low-flow aerators* (33). The limited application of draft strips window could therefore distort the results. Moreover, the interaction effects of several variables with energy poverty have been excluded due to limited observations. The excluded interaction effects are listed in Table 14B.

Table 14A and 14B. Excluded variables due to limited observations (less than 8).

Table 14A Variable	N
Housing (quality)	
Humid (humidity >60%)	5
Energy measures	
Gap sealing	1
Door closer	1
Pipe insulation	4
Draft strips window	10
Housing quality improvement	
More fresh air	3
Behavior adjustment	
Heat more	5
Ventilate less	6

Table 14B Interaction effect with EP2	N
Socioeconomic	
Younger than 35	5
Housing (quality)	
Apartment	4
Dry (humidity <30%)	4
Behavior	
Light clothes	4
Thick clothes	6
Behavior adjustment	
Turn off unnecessary lights less	

Table 15. Excluded variables due to multicollinearity (p. cor. > 0.5).

Removed variable	Cluster	Correlated with	Pearson correlation coefficient (p-value)
Is single	Socioeconomic factors	Household with children	-0.526 (0.000)
Heat living room afternoon	Behavior	-	-
Heat living room night	Behavior	Heat bedrooms night	0.551 (0.000)
Hea bedrooms morning	Behavior	Heat bedrooms afternoon Heat bedrooms evening Heat bedrooms night	0.599 (0.000) 0.632 (0.000) 0.634 (0.000)
Heat bedrooms afternoon	Behavior	Heat bedrooms morning Heat bedrooms evening	0.599 (0.000) 0.570 (0.000)
Heat bedrooms evening	Behavior	Heat living room night Heat living room morning Heat bedrooms evening	0.551 (0.000) 0.634 (0.000) 0.538 (0.000)
More control indoor environment	Housing quality improvement	Less drafts	0.586
More fresh air	Housing quality improvement	Less mold	0.576

Furthermore, for the regression analyses, several variables that correlated with other variables within the same cluster of independent variables had to be removed to avoid multicollinearity, as explained in section 4.3 Analysis method. Pearson correlation matrices for each cluster can be found in Appendix D. Table 15 gives an overview of the excluded variables, the cluster of variables to which they belonged, and what respective variables they correlated with.

4.3 Analysis

This section will give an overview of the analyzed subjects and the method of analysis. Moreover, the econometric model used, and the corresponding model equations are explained. Finally, the limitations of the selected analysis method are discussed.

Analyzed variables

Several regression analyses are performed to find the relationship between energy poverty and thermal living comfort. They are divided into three parts, each belonging to one of the conceptual models, each with one dependent variable:

Part 1) Thermal living comfort (conceptual model 1, Figure 5). How are energy poverty, housing quality, behavior, and socioeconomic factors related to comfort? To answer sub-questions 1.
Part 2) Size of the energy intervention (conceptual model 2, Figure 6). How are energy poverty, housing quality, and socioeconomic factors related to the size of the energy intervention received? To answer sub-questions 2.
Part 3) Comfort improvement after the energy intervention (conceptual model 3, Figure 7). How are housing quality, socioeconomic factors, energy measures, housing quality improvement, and behavior adjustment related to comfort improvement? To answer sub-question 3.

This corresponds to the following storyline throughout the analyses:

Who suffers from low comfort and is most in need of an energy intervention? Did the ones most in need also receive the largest energy intervention? Did the ones most in need and/or the ones who received the largest energy intervention also experience the largest comfort improvement? To what extent do the improvement of housing quality and behavior adjustment after the intervention determine the experienced comfort improvement?

Thermal living comfort

The first part examines how much comfort energy-poor households consume (conceptual model 1, Figure 5) to answer sub-question 1. Moreover, it is studied which other socioeconomic groups under-consume comfort and whether housing quality and behavior are also related to comfort. Comfort here refers to the frequency of suffering from cold in the living room in winter. The analysis is split up into intermediary models of each cluster to test whether the clusters indeed relate to comfort. First, the relationship of energy poverty with comfort is analyzed in a linear regression model (intermediary model 1). This will result in the level of comfort which the energy-poor under-consume compared to the non-energy-poor.

As EP is not the only variable influencing comfort, other factors are also considered. These other factors are controlled for in the other regressions. Comfort is estimated on socioeconomic factors (intermediary models 2-4), housing quality (intermediary models 5-7), and behavior (intermediary models 8-10) separately. For every cluster of independent variables, three linear regressions are performed.

In the first regression, comfort is estimated on all variables of the respective category, e.g. housing quality variables. This is done to find the relationship between this cluster and comfort. In the second regression, energy poverty is added to the model. This is done to compare EP's relationship with comfort to that of the other variables. In the third regression, interaction effects between EP and the other independent variables, e.g. behavior, are included. This way the relationship of EP with the other factors is studied. Possibly, some variables may relate to comfort differently among the energy-poor than among the non-energy-poor. This is for instance expected for behavior, as energy-poor tend to behave differently than non-energy-poor.

If all clusters are found to be related to comfort, they are included in the final regression model (model 11). This model enables a better comparison of the strength of these relationships.

The energy intervention

The second part relates to conceptual model 2 (Figure 6) to answer sub-question 2. This part examines what factors – i.e., EP, housing quality, and socioeconomic factors - determined who received the most valuable energy intervention to answer sub-question 2. This part is structured similarly to Part 1, but the dependent variable is the value of the received energy intervention. This refers to the value of the energy intervention received by the participants to their dwelling worth in euros.

It starts with finding the relationship between EP and the energy intervention (intermediary model 12). Did the energy-poor receive a larger energy intervention? This is followed by studying the relationship between housing quality (intermediary models 13-15) and socioeconomic factors (intermediary models 16-18) with the energy intervention. The separate models allow testing whether the clusters are indeed related to the received intervention.

These models are built up in the same way as explained in Part 1. In the first regression, the cluster of independent variables is related to the dependent variable, in this case, the energy intervention. Then EP is added in the second regression, followed by the addition of the interaction effect of EP with the independent variables in the third regression.

If all clusters are found to be related to the energy intervention, they are included in the final regression model (model 19). This model enables a better comparison of the strength of these relationships.

Comfort improvement

The third part of the analysis relates to conceptual model 3 (Figure 7) and considers the factors related to comfort improvement after the intervention to answer sub-question 3. Comfort improvement here refers to the extent to which the respondents suffer less from cold in their dwelling after the energy intervention. The relationships between comfort improvement and housing quality, socioeconomic factors, energy measures, improved housing quality, and behavior adjustment are analyzed.

Part 3 starts with examining to what extent the situation before the intervention – i.e., housing quality (intermediary models 20-22) and socioeconomic characteristics (intermediary models 23-25) – determine the comfort improvement. If these clusters do relate to comfort improvement, they are added to one final model (26). It answers whether the ones most in need of an intervention and the ones who received the largest intervention also experienced the largest improvement.

This is followed by determining the relationships of the individual energy measures (intermediary models 27-29) on comfort improvement. Model (27) divides the energy measures into two distinct categories: anti-draft and efficiency measures. It compares the effect of each of the two types of measures on comfort. Model (28) zooms in on the individual effect of the anti-draft measures on comfort improvement. The final model (29) includes both the individual anti-draft measures and the efficiency measures, allowing for a comprehensive comparison of the effects of all individual energy measures. This part of the analysis gives valuable information about the effectiveness of the Klusbus program, particularly which measures were most effective.

Finally, the relationship between the improved situation after the intervention and comfort improvement is analyzed. This refers to the influence of improved housing quality (intermediary models 30-32) and behavior adjustments (intermediary models 33-35). What factors are the biggest determinants of comfort improvement? If both clusters are found to be related to comfort improvement, they are included in the final regression model (model 36). This model enables a better comparison of the strength of these relationships.

The intermediary models in Part 3 (except for models 27-29 about the energy measures) are built in the same way as in Parts 1 and 2. Three regressions are performed, one only considering the cluster of independent variables, one adding EP, and one adding the possible interaction effect of EP with the independent variables. A difference between Parts 1 and 2 is that Part 3 does not start with a regression of comfort improvement on energy poverty. This is not done as the bivariate analysis, section 6.4, showed that the energy-poor did not experience a larger comfort improvement.

Econometric model

To find the relationships between the relevant independent variables and the respective dependent variable, an economic model is constructed based on Rosen's (1974) model of project differentiation. In this model, goods are valued for their utility-bearing characteristics. The dependent variable is utility, which stands for the satisfaction or pleasure that is derived from the goods. In this study, the good is the resident's dwelling. The dependent variable differs per regression.

For part 1 comfort is interpreted as utility. It is assumed that people derive utility from comfort in their dwelling because the higher the comfort, the higher the pleasure. Thermal comfort is measured as one variable that indicates the resident's frequency of cold in the dwelling influenced by several (dwelling) conditions. As utility is often measured on an ordinal scale, comfort is also measured on an ordinal scale. Residents who always experience cold are expected to report the lowest value of comfort, and residents who never experience cold are expected to report the highest value on the comfort scale

In part 3 the dependent variable is the comfort improvement after an energy intervention. Residents who did not experience less cold are expected to report the lowest value of comfort improvement, while residents who experienced extremely less cold are expected to report the highest value of comfort improvement.

In part 2, not comfort but the size of the energy intervention is studied. The households are expected to derive utility from a larger intervention. The size of the intervention was measured in renovation points, which reflect the total value of the intervention in euros. The lowest possible value is having received no intervention.

The conceptual models identify all variables that are expected to relate to comfort, the energy intervention, and comfort improvement respectively. Based on these models, the dependent variables are predicted on a set of variables that differ per dependent variable and a random error that estimates the effect of unobserved characteristics of comfort, the intervention, and comfort improvement, respectively.

The expected relationships explained in the previous sections translate into the model equation mentioned below. The (clusters of) variables included in each model can be found in Table 16 (thermal living comfort), Table 17 (the energy intervention), and Table 18 (comfort improvement).

$$Y = \beta_0 + \sum_{i=1}^{N} \beta_i X_i + \varepsilon$$

Y = Dependent variable
β_0 = Intercept (constant term)
β_i = Regression coefficients for the predictor variables
X_i = Independent variables where i ranges from 1 to N.
ε = error term

Table 16. Part 1, thermal living comfort: variables included in each regression model.

Dependent variable: thermal living comfort		
Model	Independent variables	Variable selection
1. Intermediary	Energy-poor	ENTER
2. Intermediary	Housing quality	ENTER
3. Intermediary	Housing quality Energy-poor	ENTER
4. Intermediary	Housing quality Energy-poor Interaction effect: housing quality and EP	ENTER
5. Intermediary	Socioeconomic factors	ENTER
6. Intermediary	Socioeconomic factors Energy-poor	ENTER
7. Intermediary	Socioeconomic factors Energy-poor Interaction effect: socioeconomic factors and EP	ENTER
8. Intermediary	Behavior	ENTER
9. Intermediary	Behavior Energy-poor	ENTER
10. Intermediary	Behavior Energy-poor Interaction effect: behavior and EP	ENTER
11. Final	Energy-poor Socioeconomic factors Housing quality Behavior	STEPWISE

Table 17. Part 2, size of the energy intervention: variables included in each regression model.

Dependent variable: energy intervention points		
Model	Independent variables	Variable selection
12. Intermediary	Energy-poor	ENTER
13. Intermediary	Housing quality	ENTER
14. Intermediary	Housing quality Energy-poor	ENTER
15. Intermediary	Housing quality Energy-poor Interaction effect: housing quality and EP	ENTER
16. Intermediary	Socioeconomic factors	ENTER
17. Intermediary	Socioeconomic factors Energy-poor	ENTER

18. Intermediary	Socioeconomic factors Energy-poor Interaction effect: socioeconomic factors and EP	ENTER
19. Final	Energy-poor Socioeconomic factors Housing quality	STEPWISE

Table 18. Part 3, comfort improvement: variables included in each regression model.

Dependent variable: comfort improvement		
Model	Independent variables	Variable selection
20. Intermediary	Housing quality	ENTER
21. Intermediary	Housing quality Energy-poor	ENTER
22. Intermediary	Housing quality Energy-poor Interaction effect: housing quality and EP	ENTER
23. Intermediary	Socioeconomic factors	ENTER
24. Intermediary	Socioeconomic factors Energy-poor	ENTER
25. Intermediary	Socioeconomic factors Energy-poor Interaction effect: socioeconomic factors and EP	ENTER
26. Final	Energy-poor Socioeconomic factors Housing quality	STEPWISE
27. Intermediary	Sum of anti-draft measures Sum of efficiency measures	ENTER
28. Intermediary	Individual anti-draft measures	ENTER
29. Final	Individual anti-draft measures Individual efficiency measures	STEPWISE
30. Intermediary	Housing quality improvement	ENTER
31. Intermediary	Housing quality improvement Energy-poor	ENTER
32. Intermediary	Housing quality improvement Energy-poor Interaction effect: housing quality improvement and EP	ENTER
33. Intermediary	Behavior adjustment	ENTER
34. Intermediary	Behavior adjustment Energy-poor	ENTER
35. Intermediary	Behavior adjustment Energy-poor Interaction effect: behavior adjustment and EP	ENTER
36. Final	Energy-poor Housing quality improvement Behavior adjustment	STEPWISE

Analysis method

Multiple regression analysis is applied to analyze the relationship between the independent variables and the respective dependent variable. For instance, the relationship between energy poverty and thermal living comfort can be estimated while controlling for other socioeconomic factors. The economic models defined in the previous section are estimated using multiple regression analyses with the Ordinary Least Squares (OLS) method. Given the study's limited sample size, a 10% significance level is used to judge the statistical significance of the results, to avoid overly conservative testing.

Two methods of variable selection are used.

1) Intermediary models – ENTER Method: The ENTER or 'standard' method is used for the intermediary models. In this procedure, all specified independent variables are entered into the regression model simultaneously. This ensures that all selected variables are included in the analysis. This method is used to test the theory: to test whether the hypothesized clusters indeed relate to the dependent variables. If the clusters are found to be related, they are included in the final model.
2) Final models – STEPWISE Method. The STEPWISE method is applied to the final models. This approach iteratively adds or removes independent variables from the model based on their statistical significance. It results in a model with a subset of independent variables that provide the best fit to the data without overfitting.

The open-source analysis tool R (The R Foundation, n.d.) is used for the analyses described in this chapter. Accurate estimation of the OLS models is possible when the model's bias is constrained. However, bias might be introduced due to two factors: multicollinearity and the existence of external effects.

Mitigating multicollinearity and overfitting

Accurate estimation of Ordinary Least Squares (OLS) in regression models requires the absence of multicollinearity. Multicollinearity is the phenomenon where two or more independent variables are strongly correlated, which makes it difficult to accurately determine the individual effect of each independent variable on the dependent variable. Literature suggests various expected relationships among groups of independent variables; for example, individuals with lower education levels and those living in apartments tend to use heating at lower temperatures and for shorter durations. This shows that independent variables – in this case, socioeconomic characteristics and behavior - could have a strong correlation with each other and therefore create a risk of multicollinearity.

In the intermediary models, the risk of inter-group multicollinearity is mitigated by analyzing each cluster of independent variables separately. This isolates relationships such as socioeconomic factors with comfort from potential correlations with behavior, thereby eliminating inter-group correlations. Each model focuses on only one group of independent variables alongside energy poverty and the dependent variable. Possible correlations with energy poverty are allowed, as this interaction effect is one of the effects studied.

However, within-group multicollinearity remains a concern, such as correlations between different behavioral adjustments. To address this, Pearson correlation matrices are computed for each cluster of independent variables (see Appendix D). Correlations stronger than 0.5 are mitigated by removing one of the correlated variables.

For the final models, inter-group multicollinearity remains possible. Nevertheless, correlation analyses within these models indicate that no variables are correlated following the exclusion of within-group correlations, as explained in section 4.2 Data preparation.

This methodological approach of separately analyzing clusters and integrating them into a STEPWISE final model enhances model interpretability. Separate models provide detailed insights into each cluster's relevant factors, while the final model facilitates comparison across clusters, offering a clearer and more interpretable understanding of the relationships between independent variables, energy poverty, and the dependent variable.

Given the limited sample size, it is essential to use small models to prevent overfitting. This is assured by conducting separate analyses of clusters and employing the STEPWISE approach in the final model, which includes all relevant variables. Overfitting is a phenomenon where a statistical model describes the random error in the data instead of the relationship between the variables (Frost, 2024). When this occurs, the regression coefficients describe the noise rather than the genuine relationships. Overfitting arises when a model incorporates too many variables relative to the number of observations. With only 155 observations, the guideline of at least 10 observations per independent variable (Bujang, Sa'at, Sidik, & Joo, 2018) suggests a maximum of 16 preferred independent variables. That is not enough to include all the relevant independent variables in one model. However, this challenge is addressed through separate intermediary models and final STEPWISE models. Therefore, the analysis approach achieves the following:

- Mitigates multicollinearity
- Enhances model interpretability
- Avoids overfitting due to limited data observations

This strategy ensures robust and insightful regression analyses despite the data limitations.

Bivariate analysis characteristics of the energy-poor

As a deeper analysis, the characteristics of respondents experiencing energy poverty were examined. Mean values for each variable are provided for both the energy-poor and non-energy-poor. T-tests were used to compare the means of these groups to determine whether they were significantly different from each other. These tests provided insights into the characteristics of the energy-poor in the sample in terms of socio-economic factors, comfort, housing quality, behavior, and the received energy interventions.

Limitations

Validity and reliability are important concepts used to evaluate the quality of research. They demonstrate how well the research method measures what is intended to measure. Reliability is the consistency of a measure, whether the results can be reproduced when the research is repeated under the same conditions (Middleton, 2019). Validity refers to the accuracy of a measure, indicating whether the results truly reflect what they are intended to measure.

The proposed research methodology has several limitations that need to be acknowledged. Firstly, the sample size is relatively small, with 155 respondents, including 35 energy-poor and 88 non-energy-poor respondents. This small sample size limited the statistical power and reliability of the findings, especially when comparing different groups. A larger sample size could provide more robust evidence of relationships and effects, potentially revealing statistically significant relationships that were not detectable in the smaller sample.

Secondly, the study was conducted only in four neighborhoods in Eindhoven. This lack of geographical diversity and the relatively small sample size make it difficult to generalize the results to the entire country. The findings should be interpreted within the context of the specific location and may not be applicable on a broader scale.

Furthermore, the study was conducted during a period of fluctuating energy prices. The constant news about energy price fluctuations could have influenced the participants' awareness of energy-saving behaviors. Moreover, the focus of the study on energy efficiency improvements was limited to the interventions carried out by the Klusbus program, which is specific to Eindhoven. Other municipalities may have different programs or approaches to addressing energy poverty and implementing energy-saving measures. Additionally, the population in other cities may differ. These limitations affect the external validity of the study and should be considered when interpreting the findings.

Finally, to strengthen the research design and provide more robust evidence of the effect of energy efficiency improvements, it would be beneficial to include a control group that did not receive the intervention. A control group would allow for a comparison between those who received the intervention and those who did not, establishing a baseline for measuring the effects of the intervention on comfort. This would provide a better understanding of the impact of the intervention and help attribute observed changes in comfort more accurately. In this way, the influence of the time trend can be considered. Surveying in the spring, when temperatures are generally warmer, might introduce confounding factors. Using a control group can better isolate the effects of the intervention and attribute observed changes in comfort to the specific interventions carried out by the Klusbus. Addressing these considerations can enhance the study's internal validity, strengthen the argument for the assumed causality, and yield more robust and generalizable findings.

4.4 Conclusion

To conclude, a description is given of the data that has been collected. A survey was set out among recipients of an energy intervention. This survey has been combined with data from the municipality about the received energy intervention and some other housing characteristics. The variables included in both datasets, the way the data are securely managed, and the data preparation necessary for the analyses have been explained. The data is used to perform several econometric analyses, which have also been explained. Finally, the reliability and validity of the data and the approach are described. In the following chapter, the results of the survey will be described.

5. Data Description

In this section, the survey results are described, and an overview of the respondent's characteristics is provided. The survey has resulted in a better overview of the level of comfort, housing quality, and energy conservation behavior of the households studied. Moreover, the comfort improvement, housing quality improvement, and behavior adjustments after the Klusbus are described. Statistical tests are performed to test the representativeness of the sample.

5.1 Energy poverty

In the survey, energy poverty was assessed by asking households if they had difficulty paying their energy bills during the last winters. This assessment was categorized into five distinct levels. Figure 10 shows the percentage of the respondents in the energy poverty category. It reveals that most respondents reported *never* facing difficulties in paying their energy bills. About one-fifth indicated *rarely* experiencing difficulties, while another fifth reported varying degrees of challenges, ranging from *sometimes* to *always*.

To investigate the distinguishing characteristics of energy-impoverished households and to compare them with those not experiencing energy poverty, the sample was categorized into three groups. The first group comprises households that reported any degree of difficulty in paying their energy bills, regardless of frequency, forming the broad definition of energy-poor households. The second group defines a more stringent criterion for energy poverty, encompassing households that reported struggling with energy bill payments "sometimes" to "always". Households that stated they "never" experienced such difficulties are classified as non-energy-poor.

This classification results in a sample consisting of 67 respondents within the broad definition (referred to as "EP1") of energy poverty, 35 respondents in the narrow definition (referred to as "EP2"), and 88 respondents classified as non-energy poverty. In the next sections, the socioeconomic composition, comfort levels, housing quality, and behavioral adjustments before and after the energy intervention by the Klusbus are compared between these distinct groups.

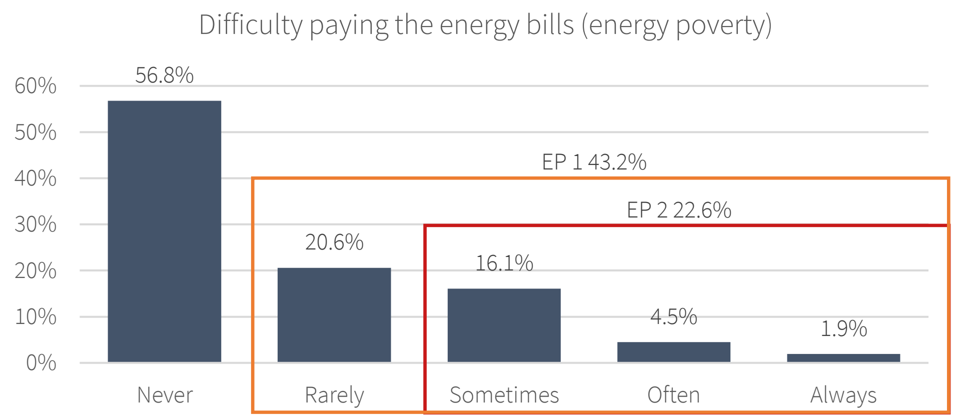

Figure 10. Energy poverty: frequency of difficulty paying the energy bills last winters. Source: survey.

5.2 Sample description

During the study period from December 7, 2022, to April 7, 2023, 1518 dwellings underwent energy efficiency enhancements facilitated by the Klusbus initiative. Figure 11 indicates that the dwellings are exclusively located within four neighborhoods: Tivoli, Doornakkers-West, Kerstroosplein, and

Doornakkers-Oost. The energy poverty rates in these neighborhoods were 28%, 11%, 16%, and 24% respectively (CBS/UDC Gemeente Eindhoven, 2022).

Among these households, 632 expressed their willingness to participate in a follow-up visit or survey. In April and May 2023, a survey was conducted among these households. This resulted in 155 complete responses, yielding a response rate of 24.5%. Households that had not resided in their current home long enough to facilitate a meaningful before-and-after comparison were excluded in advance. Figure 12 illustrates the period during which the interventions were applied to the dwellings and when the survey was answered for each energy poverty group. The colored bars (December - March) represent the implementation of the intervention, while the dashed bars (April – May) represent the survey responses.

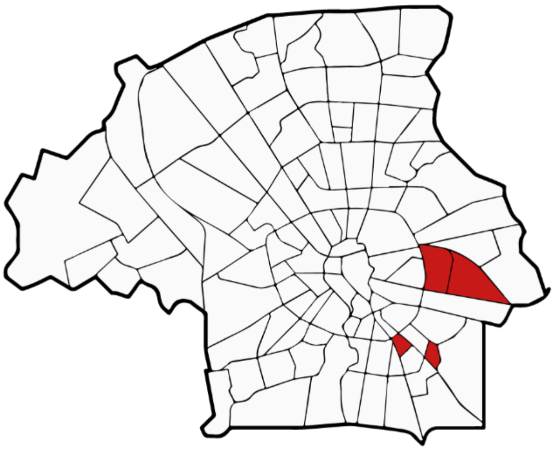

Figure 11. Studied neighborhoods: first neighborhoods visited by the Klusbus in Eindhoven.

The average duration between the completion of the Klusbus renovations and the submission of the survey was 77 days. A further breakdown shows that this time frame was 77 and 89 days for the 'EP 1' and 'EP 2' groups, respectively, and 74 days for the non-energy-poor group. The line in Figure 12 represents the average temperature in the Netherlands, shown on the secondary axis. It indicates that the temperature was higher when most respondents answered the survey, which could have influenced their responses regarding cold and housing conditions.

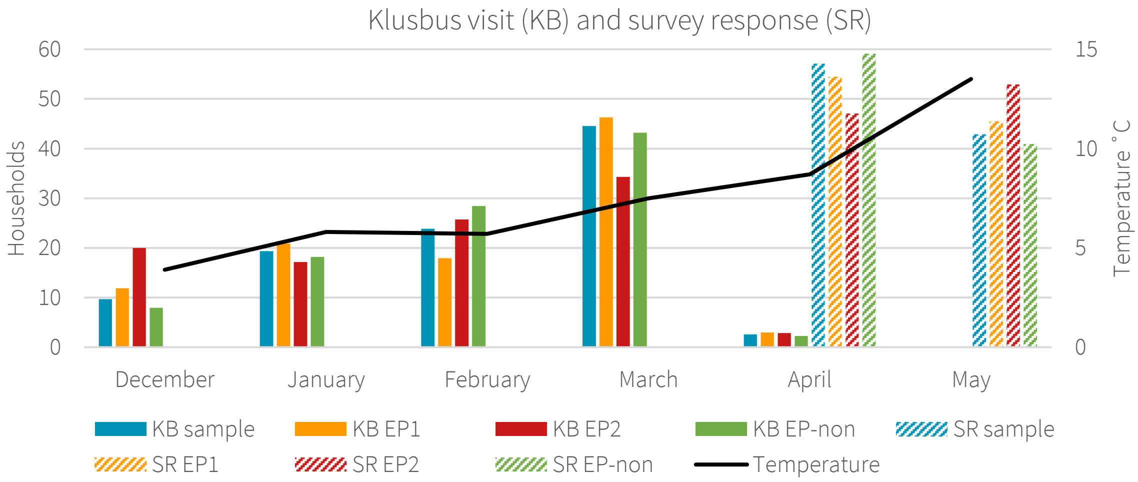

Figure 12. Klusbus visit (KB, colored) and survey response (S, dashed) per energy poverty group.

5.3 Socioeconomic factors

This section provides an overview of the socioeconomic characteristics of the sample and compares them to the national average.

Representativeness of the sample

This section aims to compare the socioeconomic characteristics of the sample to the average socioeconomic composition of the Netherlands. Table 19 presents the most notable socioeconomic characteristics of the complete sample and compares them to the national average. T-tests were performed to determine whether there are significant differences between the socioeconomic composition of the sample and the national average. A p-value of less than 0.10, shown in the penultimate column, indicates that the socioeconomic characteristic is over- or underrepresented in the sample compared to the national average.

Table 19. The most notable socioeconomic characteristics of the sample compared to the national average. Source sample: survey. The source of the national averages is given in the last column.

Variable (range)	Sample	Netherlands	p-value sample vs NL	Source
Younger than 35	13.5%	27.5%	0.000 ***	(CBS, 2021)
Older than 64	31.6%	27.5%	0.137	(CBS, 2021a)
Highly educated	39.4%	35.5%	0.165	(CBS, 2022a)
Low educated	29.1%	25.8%	0.189	(CBS, 2022a)
Single-person household	45.2%	28.7%	0.000 ***	(CBS, 2021a)
Female	58.7%	50.3%	0.012 **	(CBS, 2021a)
Terraced house	84.6%	39.3%	0.000 ***	(CBS, 2021a)
Social rent	52.3%	28.6%	0.000 ***	(CBS, 2023a)
Homeowner	38.7%	56.6%	0.000 ***	(CBS, 2023a)

*Note: ***, **, *: Statistical significance level 1%, 5%, 10%*

The table indicates that there are relatively few young individuals (under 35 years of age) in the sample, approximately half the proportion found at the national level. The remainder of the age distribution closely mirrors the national distribution.

The sample has a relatively average education level. 60.6% do not have a higher professional (hbo) or university degree, comparable to the national average of 64.5%.

In the overall sample, the largest group consists of single-person households, significantly more than the national average. Moreover, the representation of females is much higher than that of males, whereas nationally, approximately half of the population is female.

The far majority of respondents live in terraced houses, more than double the national average. This overrepresentation is due to the focus on four residential neighborhoods where terraced houses are most prevalent. Most of the remaining respondents live in multi-family houses, while only a very small portion reside in (semi-)detached houses.

Finally, most respondents reside in social rental dwellings, followed by homeowners, whereas at the national level, the opposite is true. The high prevalence of social rental housing confirms that the dwellings are situated in disadvantaged neighborhoods.

Socioeconomic characteristics

Table 20 outlines the average socioeconomic characteristics collected in the survey: age, education level, household type, energy costs, gender, employment status, tenure, and energy consciousness. The socioeconomic characteristics were measured in binary (no-yes) or on an ordinal Likert scale.

Table 20. Socioeconomic characteristics of the sample. Source: survey.

Variable	Sample	Variable	Sample
Age		*Household type*	
Younger than 25	2%	Single	45%
25 - 34	12%	Couple without children	26%
35 - 44	16%	Single parent with children	8%
45 - 54	20%	Couple with children	17%
55 - 64	19%	Other	4%
65 - 74	23%	*Employment status*	
75 or older	8%	All adults work full-time	23%
Education		One adult works full-time	20%
Low educated	29%	All adults are retired	27%
Medium educated	8%	Other	30%
Highly educated	39%	*Tenure*	
Energy costs		Homeowner	39%
Less than 60 per month	3%	Social rent	52%
61 to 120 per month	21%	Other rent	9%
121 to 180 per month	32%	*Energy consciousness*	
181 to 240 per month	32%	Not at all	1%
241 to 300 per month	10%	Slightly	10%
More than 300 per month	10%	Moderately	39%
I don't know	3%	Very	46%
Gender		Extremely	5%
Male	41%		
Female	59%		

5.4 Before the Klusbus

The situation studied before the Klusbus renovations considers factors regarding comfort level, housing quality, and behavior to conserve energy.

Comfort

Table 21 presents the thermal living comfort before the Klusbus intervention. Comfort was assessed in the survey and is measured as the frequency of experiencing cold in the living room. On average, the respondents *sometimes* experienced cold in their living room.

Table 21. Comfort of the sample. Source: survey.

Variable	Sample
Cold in living room (comfort)	
Always	14%
Often	19%
Sometimes	25%
Rarely	33%
Never	9%

Housing and housing quality

This section aims to understand the extent to which the Klusbus participants experienced issues with housing quality. Several complaints (i.e., about drafts, mold, and humidity) were asked or measured by the Klusbus servicemen during the intervention. The other complaints and dwelling types were surveyed after the intervention.

Tables 22A and 22B give the dwelling type and complaints about the housing quality of the sample. The sample consists of particularly many terraced houses. Moving on to housing quality, one particular housing complaint that led to discomfort was drafts. On average, the participants *sometimes* experienced drafts. Draft-related discomfort may be linked to air quality in the dwelling. On average, the sample *rarely* to *sometimes* lacked fresh air. Related to fresh air is the humidity level. Less than 30% is considered dry, 30%-60% is considered neutral, and more than 60% is considered humid, which can lead to mold formation (Clean Air Optima, 2023). Three-quarters of the sample had neutral humidity levels. As mentioned, humid air conditions could lead to mold formation. Mold was a less prevalent issue, with the average respondent experiencing it *never* to *rarely*. Moreover, on average, the respondents had a *slight* to *moderate* lack of control over the indoor environment.

The assessments of indoor environmental quality discussed above undoubtedly influence individuals' overall satisfaction with their dwelling, the average satisfaction level being *neutral*.

Table 22A and 22B. Housing quality of the sample. Source 3A: (Gemeente Eindhoven, 2023). Source 3B: survey.

22A. Klusbus data

Variable	Sample
Dwelling type	
Apartment	13%
In-between house	67%
Corner house	18%
Semi-detached house	2%
Detached house	6%
Drafts	
Never	5%
Rarely	32%
Sometimes	32%
Often	18%
Always	12%
Humidity	
<30%	20%
30%<->60%	77%
>60%	3%
Mold	
Never	68%
Rarely	19%
Sometimes	8%
Often	3%
Always	3%

22B. Survey data

Variable	Sample
Lack of fresh air	
Never	36%
Rarely	47%
Sometimes	11%
Often	7%
Always	0%
Lack control indoor environment	
Not at all	21%
Slightly	29%
Moderately	27%
Very	20%
Totally	4%
Satisfaction	
Very unsatisfied	6%
Unsatisfied	16%
Neutral	33%
Satisfied	41%
Very satisfied	5%

Behavior

Table 23 outlines the behaviors performed by the sample population. The behaviors were asked in the survey, indoor temperature was measured by the Klusbus servicemen.

Most households only heat their living room (or partly), and only throughout the day. The heating of bedrooms is much less common. The sample ventilated their bedrooms more frequently (at least once per day) than their living rooms (4 to 5 times per week) on average. The respondents showered 4-5 times per week and stepped out of the shower after 5 to 9 minutes on average. They turned off unnecessary lights *often* and three-quarters wore medium-thick clothing inside.

The average temperature in the living room was about 18.3˚C. When examining climate effects, it was noted that the average room temperature remained relatively consistent across different months, regardless of outside temperatures. Table 24 shows that the exception was in April, where room temperatures appeared slightly lower. However, this observation was based on a limited number of measurements (4 measurements from April 1 to 7) and therefore does not accurately depict the average room temperature for the entire month.

Table 23. Behavior of the sample. Source: survey and (Gemeente Eindhoven, 2023).

Variable	Sample	Variable	Sample
Heating		*Shower frequency*	
Living room morning	85%	2 or less per week	19%
Living room afternoon	80%	3 - 4 per week	29%
Living room evening	95%	5 - 6 per week	23%
Living room night	21%	7 or more per week	29%
Bedrooms morning	21%	*Shower length*	
Bedrooms afternoon	19%	Less than 5 minutes	23%
Bedrooms evening	34%	5 - 9 minutes	56%
Bedrooms night	17%	10 - 14 minutes	16%
Ventilate living room		15 minutes or more	6%
2 or less times per week	47%	*Turn off lights*	
3 - 4 times per week	9%	Never	6%
5 - 6 times per week	5%	Rarely	12%
1 time per day	30%	Sometimes	24%
More than 1 time per day	10%	Often	26%
Ventilate bedrooms		Always	33%
2 or less times per week	19%	*Clothes*	
3 - 4 times per week	10%	Thick clothes	12%
5 - 6 times per week	11%	Medium clothes	77%
1 time per day	37%	Light clothes	11%
More than 1 time per day	24%	Temperature	18.28 ˚C

Table 24. Average measured temperatures (and count of measurements) per month. Source: (KNMI, 2023) and (Gemeente Eindhoven, 2023).

Month	Outside temperature	Indoor temperature	No. of measurements
December	3.9˚C	18.40˚C	15
January	5.8˚C	18.43˚C	30
February	5.7˚C	18.43˚C	37
March	7.5˚C	18.16˚C	69
April	8.7˚C	17.50˚C	4
Average		18.28˚C	
Range		13 - 22˚C	
Std Dev		1.666˚C	

5.5 Preferred behavior

This section aims to find out whether the respondents would adjust their behavior if they were financially able. A desire to behave differently suggests that a household restricts its energy consumption behavior due to financial limitations. The survey posed five questions to gauge potential changes in behavior if participants had the financial capacity to do so. These questions addressed considerations about heating the home more frequently or for extended durations, adjusting ventilation habits, prolonging or increasing the frequency of showers, opting for lighter clothing, and turning up the thermostat.

Table 25 outlines the behavior preferred if the respondents were financially able. On average, the respondents would heat their home *not* more to *more* if they were financially able. Moreover, they would not ventilate more or less, rarely shower more or longer, and rarely wear lighter clothes on average. Finally, the desired temperature that the respondents indicated was 19.43˚C, 1.15˚C higher than the measured temperature before the intervention.

Table 25. Preferred behavior of the respondents if they were financially able. Source: survey.

Variable	Sample	Variable	Sample
Heating less/more		*Shower more/longer*	
Much less	1%	Never	47%
Less	1%	Rarely	19%
Not more / not less	57%	Sometimes	14%
More	35%	Often	11%
Much more	6%	Always	9%
Ventilating less/more		*Less (thick) clothes*	
Much less	1%	Never	49%
Less	3%	Rarely	25%
Not more / not less	72%	Sometimes	15%
More	20%	Often	8%
Much more	5%	Always	3%
Desired temperature	19.43˚C		
Delta temperature	-1.15˚C		

5.6 The Klusbus interventions

This section outlines which measures were applied most. The municipality provided data on the energy measures applied by the Klusbus. Table 26 gives the average intervention size, the number of applications for each measure per household, and the percentage of households that received at least one piece per type of energy measure. The intervention size was measured in points, which represent the monetary value of the intervention. On average, the respondent received 10.68 energy measures with a value of €358.09.

A total of thirteen distinct types of energy efficiency measures were implemented in the selected dwellings. They are categorized into anti-draft measures and other efficiency measures, with efficiency measures as the predominant type of measures applied. The most applied were LED lights, radiator foil, door draft strips, and water-saving showerheads. Less frequently implemented measures included gap sealing (only applied 1 time), door closers (1), pipe insulation (4), and draft strips at doors (10).

Table 26. Energy measures applied among the sample. Source: (Gemeente Eindhoven, 2023).

Variable	Average per dwelling	Percentage of dwellings	Range
Intervention points	358.09	100%	25 – 630
Tot measures	10.68	100%	0 – 23
Anti-draft measures	1.82	74.8%	0 – 7
Draft strips door	0.74	54.8%	0 – 3 pcs (per door)
Door brushes	0.42	37.4%	0 – 2 doors
Mailbox brushes	0.29	29.0%	0 pc (per mailbox)
Door draft seal tape	0.29	22.6%	0 – 3 doors
Draft strips window	0.08	6.5%	0 – 2 pcs (per window)
Door closers	0.01	0.6%	0 pc (per door)
Gap sealing	0.01	0.6%	0 frame
Efficiency measures	8.63	96.8%	0 – 23
Radiator foil	2.34	78.1%	0 – 8 pcs (per radiator)
LED lights	4.81	74.2%	0 – 23 lights
Water-saving showerheads	0.69	67.1%	0 – 2 showerheads
Timer switches	0.49	43.2%	0 – 2 switches
Low-flow aerators	0.30	21.3%	0 - 3 aerators
Pipe insulation	0.23	2.6%	0 - 14 meter

5.7 After the Klusbus

The Klusbus renovations are expected to enhance living comfort, improve housing quality, and influence residents' energy-saving and comfort-enhancing behavior. This section elaborates on the observed changes.

Comfort improvement

Table 27 outlines the comfort improvement of the sample following the intervention. Comfort improvement was measured as the extent to which the respondents experienced less cold in their dwelling after the Klusbus. Column 1 shows that 74% of the participants experienced comfort improvement after the Klusbus, with an average reduction of *slightly* less cold in their dwelling.

Table 27. Comfort improvement of the respondents. Source: survey.

Variable	Sample
Less cold (comfort)	
Not less at all	36%
Slightly less	40%
Moderately less	16%
Much less	7%
Very much less	2%

Housing quality improvement

This section aims to ascertain whether the participants experienced an improvement in housing quality after the Klusbus intervention. The survey included questions about the housing quality improvements: a reduction in drafts and mold, and an increase in fresh air and control over the indoor environment. Table 28 gives the housing quality improvements of the sample.

The most notable impact was observed on drafts, with 73% of the sample experiencing a reduction of drafts, resulting in *slightly fewer* drafts on average. The impact on mold and fresh air was much smaller, with only 12% and 17%, respectively, indicating an improvement. Furthermore, 27% of the respondents experienced more control over the indoor environment after the Klusbus, with an average of *not more* to *slightly more* control.

Table 28. Housing quality improvement of the sample. Source: survey.

Variable	Sample	Variable	Sample
Less drafts		*More fresh air*	
Not less at all	37%	0. Not more at all	83%
Slightly less	29%	1. Slightly more	10%
Moderately less	19%	2. Moderately more	5%
Much less	8%	3. Much more	1%
Very much less	7%	4. Very much more	1%
Less mold		*More control indoor environment*	
Not less at all	88%	0. Not more at all	73%
Slightly less	4%	1. Slightly more	17%
Moderately less	3%	2. Moderately more	8%
Much less	2%	3. Much more	1%
Very much less	3%	4. Very much more	1%

Behavior adjustment

The last section aims to determine if participants changed their behavior after the energy intervention to optimize comfort. Participants were surveyed regarding six behavior adjustments post-intervention. Table 29 presents the distribution across each level of the behavior adjustments.

Most respondents did not alter their heating or ventilation habits post-intervention. 22% started *heating* less, and only 4% started *heating* more, while 4% started *ventilating* less, and 7% started *ventilating* more. 13% started showering more/longer. A small group indicated a decreased tendency to shower more (13%), wear lighter clothes (16), or turn off unnecessary lights (14%).

The mean temperature in the living room did not increase significantly compared to the pre-intervention level of 18.28˚C. The average post-intervention temperature was 18.4˚C, still below the desired temperature of 19.4˚C.

Table 29. Behavior adjustments of the respondents. Source: survey.

Variable	Sample
Heating less/more	
Much less	2%
Less	19%
Not less / not more	76%
More	3%
Much More	1%
Ventilating less/more	
Much less	1%
Less	3%
Not less / not more	90%
More	6%
Much More	1%
Shower more/longer	
Not more at all	87%
Slightly more	11%
Moderately more	2%
Much more	1%
Very much more	0%

Variable	Sample
Less (thick) clothes	
Not at all	84%
Slightly less thick / less layers	13%
Moderately less thick / less layers	3%
Much less thick / less layers	0%
Very much less thick / less layers	1%
Turn off unnecessary lights less	
Not less at all	86%
Slightly less	8%
Moderately less	3%
Much less	2%
Very much less	1%
Temperature	18.40 °C

6. Results Analysis

This chapter summarizes the results of the analyses, with each section addressing one of the sub-questions, in ascending order. Sections 6.1 to 6.3 present the findings from the regression analyses belonging to the three conceptual models. The final section provides the outcomes of the bivariate analysis, focusing on the characteristics of energy-poor households.

6.1 Thermal Living Comfort

This section aims to find a relationship between energy poverty and comfort and the mechanisms behind it, as hypothesized in conceptual model 1, to answer sub-question 1. First, the general relationship between EP and comfort is reported. Next, the focus shifts to housing quality, followed by an examination of socioeconomic factors and behavior as potential mechanisms. Finally, comfort is related to all these clusters in one (stepwise) model. This results in an overview of the people most in need of an energy intervention.

Comfort was measured with a five-step 'thermal comfort ladder' measured on a five-point Likert scale. So, it is important to note that when the term (dis)comfort is mentioned in this section, this stands for (not) suffering from cold in the living room.

Energy poverty

Table 30 shows the relationship between thermal comfort (how often a person experiences cold in the living room) and energy poverty. The frequency of cold was measured on a five-point Likert scale, centered at zero. The intercept here represents the average thermal comfort level of the reference group, that is all non-energy-poor respondents, this is around zero (*sometimes-rarely*). The coefficient for energy-poor indicates that they experience a one-point lower comfort, suffering from cold *almost often* (-0.800).

Table 30. Results regression analyses: thermal living comfort predicted on energy poverty.

Variable (range)	(1) Energy poverty
(Intercept)	0.292 (0.101) ***
Energy-poor	-1.092 (0.213) ***
Multiple R^2	0.146

*Note: (SE) and ***, **, *: Statistical significance level 1%, 5%, 10%.*

In further sections, the possible mechanisms of why the energy-poor experience lower comfort are examined. Is it because of poor quality houses, the socio-economic characteristics, or because of their behavioral adjustments (heating less)?

Housing and housing quality

This section explores the extent to which housing quality explains the feeling of lower comfort, for both energy-poor and not energy-poor individuals. The analysis aims to determine whether the lower housing quality score of the energy-poor explains the previous section's finding that the energy-poor report lower levels of comfort.

Table 31 relates the comfort to dwelling type and complaints about the house: drafts, mold, dry air, lack of fresh air, and lack of control over the indoor environment. Column 2 relates the complaints to thermal living comfort, not accounting for energy poverty. The complaints have been measured on a five-point Likert scale from 0 to 4 (never-..-always), or as a binary statement (no-yes). Therefore, the intercept can be interpreted as the comfort for an average person never experiencing the named complaints and with complete control over the indoor environment. This person scores almost one on the comfort ladder, which translates to *rarely* suffering from cold in the living room. Figure 13 provides a detailed explanation of how to read the table.

Some complaints are negatively related to comfort. Drafts have the largest negative relationship with comfort. That means that the ones *rarely* experiencing drafts make a 0.375 step down the comfort ladder relative to the ones *never* experiencing drafts, while the ones *always* experiencing drafts make a 1.500 step down the comfort ladder (0.375 * 4). Furthermore, a lack of control over the indoor environment also has a negative relationship with comfort, about two-thirds the size of drafts, followed by mold, albeit a third of the size of drafts.

Column 3 relates energy poverty, next to complaints, to comfort. The intercept here represents the average comfort level of a non-energy-poor person without complaints. The person scores above one (*rarely experiencing cold*), which is a bit higher than a similar person with undefined energy poverty (column 2). The energy-poor make a 0.776 step down the comfort ladder compared to non-energy-poor without complaints. The relationships of drafts and lack of control with comfort are smaller than without considering EP. Furthermore, in this extended model, the statistical significance of the relationship between mold and comfort is lost (probably due to a limited sample size), but the point estimate stays of the same magnitude.

Reading instructions Table 31-33, 35-37, 39-40 & 43-44.
The tables in this and the next chapter can be interpreted as follows:

Each table shows the relationship of a cluster of characteristics (e.g. housing quality) with the dependent variable (e.g. comfort).

- Column 1 lists the characteristics that belong to the relevant cluster.
- The other columns display the results of three different models by displaying the regression coefficients of each model.
- Column 2 relates the dependent variable to a cluster of variables that was expected to be related to the dependent variable based on the theory.
- Column 3 relates the dependent variable to the variables in the cluster and compares the relationships to that of energy poverty.
- Column 4 adds possible interaction effects of energy poverty to the model. It shows whether the variables in the cluster are related to the dependent variable differently for energy-poor compared to non-energy-poor households.
- The intercept on the second row gives the average level of the dependent variable (e.g. comfort) for a person without any of the characteristics to which it is related in each model.
- The coefficients indicate how much each variable is related to dependent variable with respect to the intercept. A p-value below 0.10 indicates a significant statistical relationship.
- Variables that are underlined have a p-value below 0.20. These variables may show a significant relationship in studies with a larger sample size.

Figure 13. Explanation of how to read the tables in this chapter.

These relationships indicate that an energy-poor person who always experiences drafts and has no control over the indoor environment scores -1.834 (*always*). That is three steps down the comfort ladder compared to the reference category.

Column 4 also considers the possible interaction effects of energy poverty with the complaints. This shows whether certain housing complaints may be more important for comfort for the energy-poor than the non-energy-poor. The results, however, do not show any statistically significant differences. This means that complaints about housing quality do not impact thermal living comfort differently for the energy-poor than for the non-energy-poor. The interaction effects of 'apartment' and 'dry air' were excluded due to limited observations.

Table 31. Results regression analyses: thermal living comfort predicted on housing quality and energy poverty.

Variable (range)	(2) Complaints	(3) .. + EP 2	(4) .. + cross-effects
(Intercept)	0.887 (0.425) **	1.123 (0.412) ***	0.965 (0.497) *
Apartment (0/1)	0.280 (0.256)	0.239 (0.246)	0.269 (0.252)
Drafts (0,4)	-0.375 (0.080) ***	-0.333 (0.077) ***	-0.396 (0.090) ***
Mold (0,4)	-0.171 (0.094) *	<u>-0.147</u> (0.090)	-0.090 (0.106)
Dry air (<30% humidity) (0,1)	0.061 (0.213)	-0.039 (0.206	-0.011 (0.207)
Lack of fresh air (0,4)	0.111 (0.104)	0.048 (0.101)	0.111 (0.121)
Lack of control indoor environment (0,4)	-0.252 (0.076) ***	-0.212 (0.074) ***	-0.186 (0.087) **
Energy-poor (0,1)		-0.776 (0.206) ***	-0.362 (0.891)
Drafts: EP			<u>0.251</u> (0.176)
Mold: EP			-0.225 (0.207)
Lack of fresh air: EP			-0.233 (0.234)
Lack of control: EP			-0.082 (0.167)
Multiple R^2	0.249	0.315	0.333

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: See Figure 13 for table reading instructions.

Socioeconomic factors

Apart from issues related to housing quality, it was hypothesized that certain socioeconomic factors could affect thermal comfort as the experience of thermal sensation is highly personal.

Table 32 shows the relationship between comfort and socioeconomic factors: social rent, young or old, household with children, adults not working full time, female, highly educated, and (very) energy conscious.

Column 2 relates socioeconomic factors to thermal living comfort, not accounting for energy poverty. Because the socioeconomic factors were measured binary (no-yes), the intercept represents the average comfort level of the reference group, that is all persons not having any of the aforementioned socioeconomic factors.

Some socioeconomic factors are related to comfort. Social renters score 0.599 lower on the comfort ladder than the reference category, followed by young respondents (-0.569). For both, this suggests they live in lower-quality dwellings.

Column 3 includes energy poverty as one of the socioeconomic factors. The intercept here represents the average comfort level of the reference group, that is persons with the same socioeconomic factors as in column 1 and who are also non-energy-poor. This is 0.632 (*sometimes*-*rarely*). The energy-poor take a full step down the comfort ladder compared to the reference category. The same relationships as in column 2 are found, but slightly smaller. Therefore, the relationship between energy poverty and comfort is about twice the size of that of all other socioeconomic factors.

An energy-poor social renter, younger than 35, scores -0.896 (*often*). While a non-energy-poor, non-social renter, medium-aged will only *sometimes* to *rarely* (0.632) experience cold in the living room.

Column 4 considers, apart from socioeconomic factors and energy poverty, also the interaction effect between them. The reference group is the same as for column 3. The elderly score half a step higher on the comfort ladder than the reference category. Suggestive evidence is seen that energy-poor elderly have much lower comfort than non-energy-poor elderly. This may indicate that the elderly only report lower comfort when they cannot afford the higher temperature they prefer (i.e., when they are energy-poor). This relationship may be visible in future studies. The interaction effect of 'younger than 35' was excluded due to limited observations.

Table 32. Results regression analyses: thermal living comfort predicted on socioeconomic factors.

Variable (range)	(5) Socioeconomics	(6) .. + EP 2	(7) .. + cross-effects
(Intercept)	<u>0.488</u> (0.296)	0.632 (0.278) **	0.397 (0.341)
Social rent (0,1)	-0.599 (0.215) ***	-0.503 (0.202) **	<u>-0.377</u> (0.236)
Younger than 35 (0,1)	-0.569 (0.295) *	-0.516 (0.276) *	-0.563 (0.284) **
Older than 64 (0,1)	0.307 (0.253)	<u>0.330</u> (0.236)	0.546 (0.270) **
Household with children (0,1)	-0.066 (0.241)	0.018 (0.226)	0.038 (0.264)
Work not full-time / not retired (0,1)	-0.055 (0.228)	0.090 (0.215)	0.284 (0.257)
Female (0,1)	-0.192 (0.193)	-0.235 (0.180)	-0.230 (0.208)
Highly educated (0,1)	0.018 (0.228)	-0.071 (0.214)	0.074 (0.251)
Very energy conscious (0,1)	-0.020 (0.196)	0.017 (0.183)	0.001 (0.207)
Energy-poor (0,1)		-1.025 (0.217) ***	-0.233 (0.593)
Social rent: EP			<u>-0.705</u> (0.488)
Older than 64: EP			<u>-0.850</u> (0.556)
Household with children: EP			0.048 (0.554)
Work not full-time / not retired: EP			<u>-0.805</u> (0.494)
Female: EP			0.300 (0.456)
Highly educated: EP			-0.235 (0.544)
Very energy conscious: EP			0.321 (0.466)
Multiple R^2	0.108	0.226	0.269

*Note: (SE) and ***, **, *: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: See Figure 13 for table reading instructions.

Behavior

This section shows to what extent behavior explains the feeling of lower comfort, for energy-poor and non-energy-poor.

Column 2 of Table 33 relates comfort to behavior: temperature in the living room relative to the mean, heating the living room and bedroom(s), shower frequency, shower length, ventilating the living room and bedroom(s), clothing, and turning off unnecessary lights. Because behavior was measured on a Likert scale from 0 to 3/4 (*not to a lot*) or binary, the intercept can be interpreted as the comfort for an average person who engages in the named behaviors the least possible. This person scores 0.208 on the comfort ladder, which translates to *sometimes* suffering from cold. It is, however, important to note that the intercept is not statistically significant.

Some behaviors are related to comfort. Heating the living room (or partly) in the morning is positively related to comfort (0.548) while heating the bedroom(s) (or partly) in the night is strongly negatively related to comfort (-0.520). People generally do not heat their bedroom(s) during the night. The latter relationship may therefore indicate that people heating the bedroom(s) at night have such low-quality dwellings that heating is necessary and that comfort in their home generally is low. People wearing thick clothes also feel lower comfort (-0.569), and the longer one showers (-0.242), or the more one ventilates their living room (-0.140), the lower the experienced comfort. Conversely, the more often one ventilates their bedroom(s), the higher the experienced comfort (0.186). The shower frequency, wearing light clothes, and turning off unnecessary lights do not seem to affect comfort.

Column 3 compares behavior with energy poverty. The intercept represents the average person that engages the least possible in each behavior and is energy-poor, this is around a half (*sometimes*-*rarely*, but again not significant). The coefficient for energy-poor (-0.918) indicates that they are a nearly full step down the comfort ladder compared to non-energy-poor. Ventilating the living room does not show a significant relationship anymore.

Table 33. Results regression analyses: thermal living comfort predicted on behavior and energy poverty.

Variable	(8) Behavior	(9) .. + EP 2	(10) .. + cross-effects
(Intercept)	0.208 (0.555)	0.478 (0.528)	0.011 (0.635)
Temperature (-5.3,3.72)	0.059 (0.055)	0.041 (0.053)	0.039 (0.648)
Heat living room morning (0,1)	0.548 (0.263) **	0.517 (0.249) **	0.640 (0.289) **
Heat living room evening (0,1)	-0.323 (0.429)	-0.358 (0.406)	-0.123 (0.470)
Heat bedroom night (0,1)	-0.520 (0.245) **	-0.313 (0.237)	-0.120 (0.307)
Shower frequency (0,3)	-0.078 (0.083)	-0.101 (0.078)	-0.120 (0.088)
Shower length (0,3)	-0.242 (0.118) **	-0.251 (0.111) **	-0.213 (0.140)
Ventilate living room (0,4)	-0.140 (0.069) **	-0.084 (0.066)	-0.105 (0.072)
Ventilate bedrooms (0,4)	0.186 (0.075) **	0.161 (0.071) **	0.158 (0.079) **
Thick clothes (0,1)	-0.569 (0.288) *	-0.467 (0.273) *	-0.547 (0.290) *
Light clothes (0,1)	0.305 (0.297)	0.285 (0.281)	0.212 (0.292)
Turn off lights (0,4)	-0.020 (0.078)	-0.029 (0.074)	0.029 (0.086)
Energy-poor (0,1)		-0.918(0.215) ***	0.646 (1.163)
Temperature: EP			-0.033 (0.121)
Heat living room morning: EP			-0.389 (0.720)
Heat living room evening: EP			-0.998 (1.120)
Heat bedroom night: EP			-0.685 (0.537)
Shower frequency: EP			0.115 (0.251)
Shower length: EP			0.029 (0.252)
Ventilate living room: EP			0.248 (0.229)
Ventilate bedrooms: EP			-0.070 (0.233)
Turn off lights: EP			-0.245 (0.174)
Multiple R^2	0.194	0.286	0.321

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: See Figure 13 for table reading instructions.

The lowest expected average comfort is -1.660 (*often-always*) for an energy-poor person showering 15 minutes or more and wearing thick clothes. The highest expected average comfort is 1.538 (*rarely-never*) corresponds to a non-energy-poor person (partly) heating the living room in the morning and ventilating the bedroom(s) more than once per day.

Furthermore, column 4 shows that no interaction effects between behavior and energy poverty are found. That means that behavior does not affect thermal living comfort differently for the energy-poor than for the non-energy-poor. The interaction effects of 'thick clothes and 'light clothes were excluded due to limited observations.

Final model: stepwise

The models in the previous sections indicated that the three clusters (i.e., housing quality, socioeconomic factors, and behavior) and energy poverty were indeed related to the experience of comfort. Table 34 relates comfort with each of the abovementioned clusters and energy poverty, by adding them all in one stepwise model. This method identifies the best-fitting model by adding or removing variables. Variables with a significant relationship with comfort in one of the previous models in this chapter may have been removed or have lost their significant relationship. This means that other variables from different clusters may now better explain the relationship with comfort.

The intercept in column 2 can be interpreted as the average comfort for a non-energy-poor person, without any of the named socioeconomic factors, without complaints about the housing quality, and who engages in the named behaviors the least possible. This person scores 1.068 on the comfort ladder, which translates to *rarely* suffering from cold in the living room.

Compared to this reference category, an energy-poor person scores 0.714 lower on the comfort ladder. Two socioeconomic factors are related to comfort: social renters and young respondents experienced a half-step lower comfort.

Interestingly, residents of apartments experienced a half-step higher comfort while this was not observed in the models that only included housing variables. However, a positive relationship was expected, as it seems explainable by the fact that apartments are easier to heat than single-family dwellings due to limited cold surface areas (walls, roofs, floors). Furthermore, two complaints about housing quality were negatively related to comfort. Drafts have the largest negative relationship with comfort, ranging from -0.276 for individuals *rarely* experiencing drafts, to -1.104 for individuals *always* experiencing drafts. The relationship of comfort a lack of control over the indoor environment is about half the size of that of drafts. Residents who are *very* in control over the indoor environment make a 0.157 step down the comfort ladder, and residents *not at all* in control make a 0.561 step down the comfort ladder, compared to the ones *totally* in control.

Moreover, two behaviors were related to comfort. Ventilating the bedroom(s) was positively related to comfort, with a 0.116 to 0.464 higher comfort (*3-4 times per week* to *more than once per* day resp.), compared to twice or less per week. Moreover, individuals who had to wear thick clothes at home experienced lower comfort.

The lowest comfort is predicted for the average energy-poor person, under the age of 35, living in a social rental single-family dwelling, always experiencing drafts, not in control over the indoor environment, and wearing thick clothes. This is -2.762 (MoE 0.816). The highest comfort is predicted for the average non-energy-poor, non-social renter living in an apartment, older than 35, never suffering from drafts, totally in control over the indoor environment, ventilating the bedroom(s) more than once a day, and not wearing thick clothes. This is 2.051 (MoE 0.639).

Table 34. Results final regression analysis: thermal living comfort predicted on socioeconomic factors, housing quality, and behavior.

Variable (range)	(11) Unstandardized coefficient (SE)	Standardized coefficient
(Intercept)	1.068 (0.264) ***	
Socioeconomic		
Energy-poor (0/1)	-0.714 (0.197) ***	-0.250 ***
Social rent (0/1)	-0.407 (0.176) **	-0.170 **
Younger than 35 (0,1)	-0.443 (0.251) *	-0.127 *
Housing and housing quality		
Apartment (0/1)	0.521 (0.252) **	0.146 *
Drafts (0,4)	-0.276 (0.076) ***	-0.253 ***
Mold (0,4)	<u>-0.133</u> (0.087)	-0.104
Lack of control indoor environment (0,4)	-0.157 (0.072) **	-0.149 **
Behavior		
Ventilate bedrooms (0,4)	0.116 (0.059) *	0.138 *
Thick clothes (0/1)	-0.536 (0.253) **	-0.144 **
Multiple R^2	0.371	0.371

*Note: (SE) and ***, **, *: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: Standardized coefficients show the change in standard deviations of the outcome variable (comfort) associated with a one-standard-deviation change in each predictor variable.

Column 3 includes the standardized regression coefficients, which provide insight into the relative importance of each variable in explaining comfort by placing them on a common scale. To assess the overall importance of each cluster, the absolute values of the standardized coefficients within each cluster are summed. This method allows for the comparison of the relative importance of each cluster concerning comfort, regardless of the units of measurement.

The standardized coefficients indicate that drafts and energy poverty are the most critical factors related to comfort. The aggregate measures show that the clusters of housing (quality) (0.548) and socioeconomic factors (0.547) are the most strongly related to comfort, followed by behavior (0.282). Notably, almost half of that relationship of the socioeconomic factors is driven by energy poverty.

Conclusion

The intermediary models in the first sections proved that the three clusters hypothesized to influence thermal living comfort – housing quality, behavior, and socioeconomic factors – are all three related to comfort. They are therefore included in the final model. This leaves the conclusion that several factors in each cluster are related to comfort. Figure 14 shows the average comfort for each resident segment based on the final model. It shows that regarding housing (quality), the ones living in an apartment experienced much less cold. Moreover, drafts and a lack of control over the indoor environment are negatively related to experienced comfort. Certain behaviors people perform in reaction to their housing quality are also related to comfort. Having to wear thick clothes is negatively related to comfort. Contrarily, ventilating the bedroom(s) more often was positively related to comfort. Regarding socioeconomic factors, social renters and younger respondents experienced substantially lower comfort levels. When considering the analysis of the three clusters, one conclusion keeps coming back. No matter what factors are considered, energy poverty keeps emerging as one of the dominant factors. Mostly showing an almost complete step lower on the comfort ladder compared to non-energy-poor.

Socioeconomic factors, housing conditions, and behavior were not found to relate to comfort differently for the energy-poor compared to the non-energy-poor.

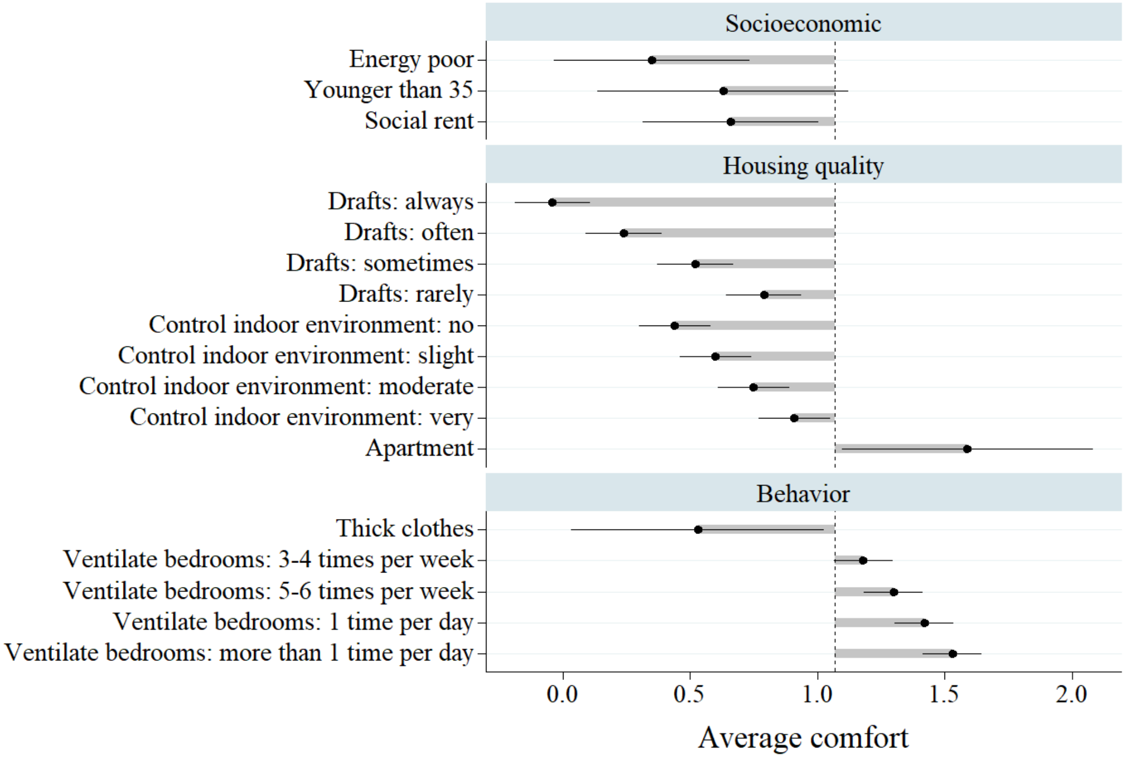

Figure 14. Comfort per resident segment.
*Notes: The dashed line represents the reference category. This indicates the average comfort of a person who does not possess any of the mentioned characteristics (i.e., 1.068: rarely cold in the living room). The gray bars show the average comfort. Comfort is calculated by adding the estimated coefficients (the number of steps in comfort per resident segment) to the reference value. Variables with multiple levels have a greater relationship with comfort as the value of the variable increases. Example: Comfort of respondents who rarely experienced drafts: 1.068 – 0.276 = 0.78; Comfort of respondents who always experienced drafts: 1.068 + (4 * -0.276) = -0.04.The black lines show the 95% margin of error.*

6.2 The energy intervention

This section aims to find out which households received the largest energy interventions from the Klusbus program. Did the program reach the households who were most in need of the intervention? The relationship of the energy intervention with energy poverty, housing quality, and socioeconomic factors is reported, as hypothesized in conceptual model 2, to answer sub-question 2. Behavior is not included, as behavior is not expected to influence the received intervention.

The households studied in this research all underwent an energy intervention. Each household underwent a different intervention tailormade to their highest needs. Some households for instance received LED lights and a water-saving showerhead, while others received anti-draft measures. The size of each intervention was measured in two ways: the number of measures per dwelling and the number of points per dwelling. These points refer to the value of the renovation in euros. That is the value of the materials of the measures plus that of the assembly. The participating households on average received 10.7 energy measures in their dwelling, worth €358.10.

The bivariate analysis (section 6.4) indicated that energy-poor households received larger interventions than non-energy-poor households, especially when considering the intervention points. Therefore, in this section, the size of the interventions was measured by looking at points, i.e. the value of the intervention.

Energy poverty

The previous chapter showed that energy poverty was the strongest indicator of low comfort. Did they also receive the largest energy intervention?

Table 35 shows the relationship between the energy interventions (the value of the renovation) and energy poverty. The intercept here represents the average value of the energy intervention of the reference group, that is all non-energy-poor respondents, this is €340.32. The coefficient for energy-poor indicates that they received an intervention on average worth €78.71 more.

Table 35. Results regression analyses: energy intervention points predicted on energy poverty.

Variable (range)	(12) Energy poverty
(Intercept)	340.32 (12.22) ***
Energy-poor	78.71 (25.72) ***
Multiple R^2	0.058

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%.*

In further sections, the analysis delves into other socioeconomic factors and examines whether housing quality determined the size of the intervention participants received.

Housing and housing quality

Table 36 relates the size of the energy interventions to dwelling type and complaints about the house, to find whether dwellings of lower quality received a larger intervention. Column 2 relates the size of the intervention to housing and housing quality. The intercept shows that households living in a single-family dwelling without complaints about housing quality on average receive a home improvement worth €81.58.

Table 36. Results regression analyses: energy intervention points predicted on housing quality and energy poverty.

Variable (range)	(13) Complaints	(14) .. + EP 2	(15) .. + cross-effects
(Intercept)	281.58 (51.44) ***	257.89 (50.61) ***	245.64 (61.49) ***
Apartment (0/1)	-65.41 (31.00) **	-61.26 (30.18) **	-53.26 (31.15) *
Drafts (0,4)	18.85 (9.63) *	<u>14.63</u> (9.46)	14.11 (11.11)
Mold (0,4)	13.92 (11.39)	11.55 (11.11)	15.65 (13.11)
Dry air (<30% humidity) (0,1)	98.07 (25.80) ***	108.08 (25.30) ***	108.62(25.58) ***
Lack of fresh air (0,4)	0.00 (12.61)	6.24 (12.43)	11.16 (15.01)
Lack control indoor environment (0,4)	12.92 (9.19)	8.98 (9.03)	5.14 (10.82)
Energy-poor (0,1)		77.86 (25.29) ***	129.20 (110.18)
Drafts: EP			0.64 (21.81)
Mold: EP			-19.21 (25.57)
Lack of fresh air: EP			-24.52 (28.94)
Lack of control: EP			17.28 (20.69)
Multiple R^2	0.166	0.217	0.226

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: See Figure 13 for table reading instructions.

Interestingly, dwellings with dry air conditions on average received a €98.07 larger intervention, while section 6.1 showed that persons living with dry air did not experience lower comfort. Drafts were related to lower comfort. Correspondingly, dwellings with various levels of drafts on average received a €18.85 to €75.40 larger intervention. Notably, households experiencing mold and a lack of control did report lower comfort but apparently did not receive a larger intervention. Residents of apartments received a smaller intervention, which could be linked to the greater comfort observed in section 6.1.

Column 3 apart from housing quality, also relates energy poverty to the size of the energy interventions. It indicates that the size of these relationships is partly explained by the presence of energy poverty. The energy-poor received a €77.86 larger intervention. Interestingly, in this extended model, the statistical significance of the relationship between drafts and the energy intervention is lost (probably due to the limited sample size), but the point estimate stays of the same magnitude.

The largest average intervention is therefore received by an energy-poor person living in a single-family dwelling with dry air: €443.84. Column 4 shows that no interaction effects between housing quality and energy poverty were found. The interaction effects of 'apartment' and 'dry air' were excluded due to limited observations.

Socioeconomic factors

Apart from housing quality, the applied interventions may also be related to socioeconomic factors.

Table 37 examines the relationship between the size of energy interventions and socioeconomic factors. In column 2, the intercept indicates that the reference group – individuals without any of the considered socioeconomic factors – received an average intervention worth €322.27.

Table 37. Results regression analyses: energy intervention points predicted on socioeconomic factors.

Variable (range)	(16) Socioeconomics	(17) .. + EP 2	(18) .. + cross-effects
(Intercept)	322.27 (35.31) ***	311.14 (34.63) ***	333.86 (43.20) ***
Social rent (0,1)	6.77 (25.62)	-0.69 (25.10)	-19.95 (29.89)
Younger than 35 (0,1)	56.70 (35.19)	52.55 (34.33)	49.85 (35.99)
Older than 64 (0,1)	48.30 (30.12)	46.53 (29.37)	42.28 (34.13)
Household with children (0,1)	53.06 (28.78) *	46.55 (28.14)	47.02 (33.43)
Work not full-time / not retired (0,1)	2.21 (27.22)	-8.97 (26.80)	3.07 (32.47)
Female (0,1)	-8.02 (22.98)	-4.68 (22.43)	-17.90 (26.32)
Highly educated (0,1)	4.90 (27.16)	11.80 (26.58)	-11.01 (31.77)
(Very) energy conscious (0,1)	-3.69 (23.34)	-6.62 (22.77)	-0.48 (26.19)
Energy-poor (0,1)		79.53 (27.05) ***	39.38 (75.08)
Social rent: EP			36.41 (61.71)
Older than 64: EP			4.13 (70.32)
Household with children: EP			-4.00 (70.05)
Work not full-time / not retired: EP			-36.08 (62.53)
Female: EP			37.46 (57.69)
Highly educated: EP			72.17 (68.76)
(Very) energy conscious: EP			-17.66 (58.97)
Multiple R^2	0.039	0.093	0.113
Error	138.45	134.96	136.74

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: See Figure 12 for table reading instructions.

Households with children, on average, received €53.06 more. Additionally, there is suggestive evidence that both younger and older respondents received larger interventions. Column 3 incorporates energy poverty as one of the socioeconomic factors. Here, the reference group consists of non-energy-poor individuals without any of the named socioeconomic factors. The intercept indicates that this group received a slightly smaller intervention on average compared to the initial model. Energy-poor households, on average, received interventions worth €79.53 more. In this extended model, the statistical significance of the relationship between households with children and the size of the intervention is lost (likely due to the limited sample size), though the point estimate remains of similar magnitude. Consequently, the largest average intervention, €390.67, is received by an energy-poor individual.

Column 4 shows whether some socioeconomic factors are only related to the size of the interventions for energy-poor respondents. However, no cross-effects were identified. The interaction effect of 'younger than 35 was excluded due to limited observations.

Final model: stepwise

The models in the previous sections indicated that the two clusters (i.e., housing quality and socioeconomic factors) and energy poverty were indeed related to the size of the intervention that households received. Table 38 relates the size of the energy intervention to each of the abovementioned clusters and energy poverty, by adding them all in one stepwise model. This method identifies the best-fitting model by adding or removing variables. Variables with a significant relationship with comfort in one of the previous models in this chapter may have been removed or have lost their significant relationship. This means that other variables from different clusters may now better explain the relationship with comfort.

The intercept in column 2 can be interpreted as the average intervention received by a non-energy-poor person without any of the named socioeconomic factors, and without complaints about the housing quality. This person received an intervention worth €293.04 (MoE 43.63).

Compared to this reference category, an energy-poor person on average received an €82.00 more valuable intervention. Apart from energy poverty, no socioeconomic factors were related to the intervention. Housing conditions were related strongly to the intervention. Residents of an apartment received a €60.60 smaller renovation. Individuals experiencing drafts received a €16.16 (*rarely* suffering from drafts) to €64.64 (*always*) large renovation. Notably, dwellings with dry indoor air received the largest intervention, +€110.15.

Table 38. Results final regression analysis: energy intervention points predicted on socioeconomic factors and housing quality.

Variable (range)	(19) Unstandardized coefficient (SE)	Standardized coefficient
(Intercept)	293.04 (22.26) ***	
Socioeconomic		
Energy-poor (0/1)	82.00 (24.43) ***	0.250
Housing and housing quality		
Apartment (0/1)	-60.60 (29.86) **	-0.148
Drafts (0,4)	16.16 (9.28) *	0.129
Dry air (<30% humidity) (0,1)	110.15 (25.13) ***	0.322
Multiple R^2	0.206	

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: Standardized coefficients show the change in standard deviations of the outcome variable (the intervention) associated with a one-standard deviation change in each predictor variable.

The largest average renovation is predicted for the average energy-poor person, living in a single-family dwelling, *always* experiencing drafts, with dry indoor air. They received an intervention worth €549.83 (MoE 66.73). The smallest average intervention is predicted for a non-energy-poor person living in an apartment, never experiencing drafts, and no dry indoor conditions. This is €232.44 (MoE 63.88).

Column 3 includes the standardized regression coefficients, which provide insight into the relative importance of each variable in explaining the size of the intervention by placing them on a common scale. To assess the overall importance of each cluster, the absolute values of the standardized coefficients within each cluster are summed. This method allows for the comparison of the relative importance of each cluster concerning the intervention, regardless of the units of measurement.

The standardized coefficients indicate that dry air and energy poverty are the most critical factors related to the intervention. Additionally, the analysis shows that the housing quality cluster (aggregate measure 0.599) is the most strongly related to the size of the intervention. In contrast, socioeconomic factors exhibit roughly half the strength of the relationship (0.250), with energy poverty being the only significant variable within this cluster.

Conclusion

The intermediary models in the first sections proved that the two clusters hypothesized to influence thermal living comfort – socioeconomic factors and housing quality – and energy poverty are related to the size of the interventions. They are therefore included in the final model. The results indicate that the target group of the Klusbus – energy-poor – has received a larger intervention than non-energy-poor, see Figure 14. Furthermore, people with certain personal characteristics that reported lower comfort and were therefore in higher need of intervention also received a larger intervention: persons living in a single-family dwelling, and persons experiencing drafts. On the other hand, larger interventions have been received by people with dry indoor air conditions, who did not per se report lower comfort. So, the people helped by the program did not all experience above-average levels of cold. No interaction effects with energy poverty were observed.

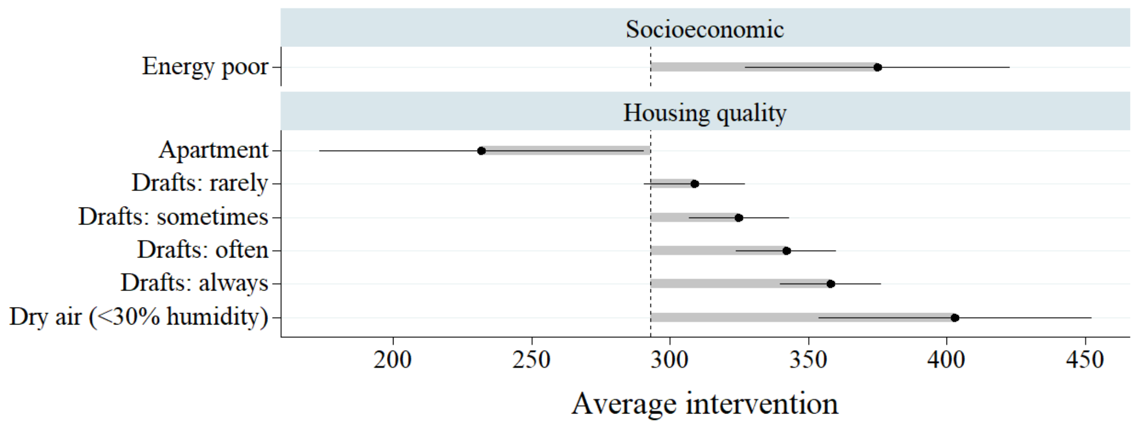

Figure 14. Intervention value per resident segment.
*Notes: The dashed line represents the reference category. This indicates the average intervention points of a person who does not possess any of the mentioned characteristics (293.04). The gray bars show the average intervention value. The value of the intervention is calculated by adding the estimated coefficients (the extra intervention points per resident segment) to the reference value. Variables with multiple levels have a greater relationship with the intervention as the value of the variable increases. Example: Intervention for respondents who rarely experienced drafts: 293.04 + 16.16 = 309; Intervention for respondents who always experienced drafts: 293.04 + (4 * 16.16) = 358. The black lines show the 95% margin of error.*

6.3 Comfort improvement

This section aims to explain the factors related to the size of the comfort improvement after the Klusbus as hypothesized in conceptual model 3, to answer sub-question 3. First, the relationship between the situation before the intervention as – i.e., housing quality, socioeconomics, and energy poverty – and the comfort improvement is reported. This is followed by reporting the effect of each measure on comfort improvement. Finally, the analysis examines the improvement of housing quality and behavior adjustments after the interventions as possible mechanisms behind the comfort improvement.

After the energy interventions from the Klusbus, most households experienced an improvement in comfort. This comfort improvement was measured with a five-step 'ladder of comfort improvement' ranging from *not less* to *very much less*. So, it is important to note that when the term comfort improvement is mentioned, this stands for suffering less from cold in the dwelling.

The situation before the intervention

Before the energy intervention, the participants on average suffered *sometimes* from cold in their living room. After the intervention, the participants made an average improvement of 1.000, which means they experienced *slightly less* cold in their dwelling. This is a minor improvement, which was expected due to the relatively small interventions.

How much did the quality of the dwellings and socioeconomic factors explain the feeling of this improved comfort, for the energy-poor and the non-energy-poor? Did the ones who suffered from lower comfort and the ones who received larger interventions also experience the largest improvement?

Housing and housing quality

Column 2 of Table 39 relates the thermal comfort improvement to complaints about the house. The intercept shows that an average person never suffering from the considered complaints experienced a comfort improvement of 1.446 (*slightly less–moderately less* cold in the dwelling). Counterintuitively, persons experiencing a lack of fresh air reported a 0.206 to 0.824 lower comfort improvement. Persons with a lack of control of the indoor environment did report a higher comfort improvement, 0.166 to 0.664.

Table 39. Results regression analyses: comfort improvement predicted on housing quality and energy poverty.

Variable (range)	(20) Complaints	(21) .. + EP 2	(22) .. + cross-effects
(Intercept)	1.446 (0.386) ***	1.442 (0.392) ***	1.336 (0.472) ***
Apartment (0/1)	-0.125 (0.232)	-0.124 (0.233)	-0.153 (0.239)
Drafts (0,4)	-0.031 (0.072)	-0.032 (0.073)	-0.081 (0.085)
Mold (0,4)	-0.068 (0.085)	-0.069 (0.086)	-0.018 (0.101)
Dry air (<30% humidity) (0,1)	0.249 (0.193)	0.251 (0.196)	0.273 (0.196)
Lack of fresh air (0,4)	-0.206 (0.095) **	-0.205 (0.096) **	-0.179 (0.115)
Lack control indoor environment (0,4)	0.166 (0.069) **	0.165 (0.070) **	0.228 (0.083) ***
Energy-poor (0,1)		0.013 (0.196)	0.251 (0.845)
Drafts: EP			0.205 (0.167)
Mold: EP			-0.173 (0.196)
Lack of fresh air: EP			-0.053 (0.222)
Lack of control: EP			-0.236 (0.159)
Multiple R^2	0.090	0.090	0.116

*Note: (SE) and ***, **, *: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: See Figure 12 for table reading instructions.

The largest average improvement is therefore found for a person with a complete lack of control: 2.109 (*moderately less*). The smallest improvement is for a person with a complete lack of fresh air: 0.623 (*not less-slightly less*).

Column 3 also relates energy poverty to comfort improvement. The bivariate analysis (section 6.4) revealed that the energy-poor did not experience a larger comfort improvement than non-ep. However, some factors may have a different effect for the energy-poor than non-energy-poor. Column 4 therefore also considers possible interaction effects of EP with the complaints, but no interaction effects were found. The interaction effects of 'apartment' and 'dry air' were excluded due to limited observations.

Socioeconomic factors

Apart from the housing quality, persons with certain personal characteristics may have experienced a larger thermal comfort improvement.

Column 2 of Table 40 shows the relationships between socioeconomic factors and comfort improvement. Persons without any of the considered characteristics score a comfort improvement of 1.188 (*slightly less*). One socioeconomic factor is related to comfort improvement. Young respondents take an almost complete step (0.828) up the improvement ladder compared to middle-aged respondents.

Column 3 also relates EP to comfort improvement and column 4 considers possible interaction effects between EP and the other socioeconomic factors. No relationships between improvement and EP nor interaction effects of EP with socioeconomic factors were found. The interaction effect of 'younger than 35 was excluded due to limited observations.

Table 40. Results regression analyses: comfort improvement predicted on socioeconomic factors.

Variable (range)	(23) Socioeconomics	(24) .. + EP 2	(25) .. + cross-effects
(Intercept)	1.188 (0.241) ***	1.171 (0.243) ***	1.262 (0.303) ***
Social rent (0,1)	-0.040 (0.175)	-0.050 (0.176)	-0.045 (0.209) ***
Younger than 35 (0,1)	0.828 (0.240) ***	0.822 (0.241) ***	0.817 (0.252) *
Older than 64 (0,1)	-0.264 (0.205)	-0.266 (0.206)	-0.429 (0.239)
Household with children (0,1)	0.206 (0.196)	0.197 (0.197)	0.205 (0.234)
Work not full-time / not retired (0,1)	-0.181 (0.186)	-0.197 (0.188)	-0.229 (0.227)
Female (0,1)	-0.089 (0.157)	-0.084 (0.157)	-0.153 (0.184)
Highly educated (0,1)	-0.166 (0.185)	-0.156 (0.186)	-0.193 (0.223)
Energy conscious (0,1)	-0.148 (0.159)	-0.153 (0.160)	-0.108 (0.183)
Energy-poor (0,1)		0.116 (0.190)	-0.088 (0.526)
Social rent: EP			-0.044 (0.432)
Older than 64: EP			0.617 (0.493)
Household with children: EP			-0.056 (0.491)
Work not full-time / not retired: EP			0.179 (0.438)
Female: EP			0.237 (0.404)
Highly educated: EP			-0.045 (0.482)
Very energy conscious: EP			-0.299 (0.413)
Multiple R^2	0.133	0.135	0.156
Error	0.944	0.946	0.958

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: See Figure 12 for table reading instructions.

Final model: Stepwise

The intermediary models in the previous sections proved that the situation before the intervention (i.e., housing quality and socioeconomic factors) was indeed related to the improved experience of comfort. Energy poverty was not. Table 41 relates the comfort improvement to both socioeconomic factors and housing quality before the energy intervention, by adding them all in one stepwise model. This method identifies the best-fitting model by adding or removing variables. Variables with a significant relationship with comfort in one of the previous models in this chapter may have been removed or have lost their significant relationship. This means that other variables from different clusters may now better explain the relationship with comfort.

The results indicate that only a few factors of the existing situation (before the intervention) are related to the improvement of comfort. The intercept shows the average comfort improvement for the reference category: a person without any of the named socioeconomic factors and complaints about housing quality. That is a person older than 35 without a lack of control over the indoor environment. This is 0.563 (MoE 0.261), *no* to *slightly less* cold in the dwelling. Only one socioeconomic factor and one housing complaint are related to comfort improvement. Young respondents made an almost complete point larger comfort improvement compared to the reference category. Residents with a lack of control over the indoor environment made a 0.165 to 0.660 larger improvement (*slight* - .. - *total lack* resp.).

The lowest comfort improvement is predicted for the reference group. The highest comfort improvement is predicted for a person younger than 35 with a total lack of control over the indoor environment. This person is expected to make a comfort improvement of 2.073 (MoE 0.498), which translates to *moderately less* cold in the dwelling after the Klusbus.

Table 41. Results final regression analysis: comfort improvement predicted on socioeconomic factors and housing quality.

Variable (range)	(26) Unstandardized coefficient (SE)	Standardized coefficient
(Intercept)	0.563 (0.133) ***	
Socioeconomic		
Younger than 35 (0,1)	0.849 (0.217) ***	0.295
Household with children (0,1)	0.245 (0.171)	0.108
Housing and housing quality		
Lack control indoor environment (0,4)	0.165 (0.066) **	0.191
Multiple R^2	0.146	

*Note: (SE) and ***, **, *: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: Standardized coefficients show the change in standard deviations of the outcome variable (the intervention) associated with a one-standard deviation change in each predictor variable.

Column 3 includes the standardized regression coefficients, which provide insight into the relative importance of each variable in explaining comfort improvement by placing them on a common scale. To assess the overall importance of each cluster, the absolute values of the standardized coefficients within each cluster are summed. This method allows for the comparison of the relative importance of each cluster concerning comfort improvement, regardless of the units of measurement.

The standardized coefficients indicate that young respondents are the most strongly related to comfort improvement, followed by a lack of control over the indoor environment, which has about two-thirds the strength of the relationship, and households with children, which has one-third the strength of the relationship. The aggregate measures indicate that socioeconomic factors (0.403) are the most strongly related to comfort improvement, followed by housing quality (0.191).

Energy measures

The previous section explained who experienced the largest improvement. However, this prior housing and socioeconomic situation did not cause the improvement. The energy intervention is the main cause of the comfort improvement. Therefore, this section explores what energy interventions applied by the Klusbus caused the largest comfort improvement.

The energy measures can be divided into two categories. (1) Measures that reduce draft: draft strip at door and window, door brush, mailbox brush, and door draft seal tape. (2) Other measures that improve energy and water efficiency: radiator foil, LED light, water-saving showerhead, timer switch, and low-flow aerators.

Table 42 relates the size of the comfort improvement to the energy interventions. Column 2 relates the two categories – drafts and efficiency - of energy measures to comfort improvement. The reference category is the average comfort improvement for a person who lives in a dwelling that received no energy intervention. This is 0.613, which means that without intervention, one would suffer *not less* to *slightly less* from cold. This may sound contradictory, but other factors, such as the warmer weather, also had an effect. The relationships may therefore not be interpreted as the total causal effect of the intervention on comfort improvement. Measures aimed at alleviating drafts are positively related to comfort improvement, the efficiency measures are not.

Column 3 zooms in on the most effective measures: the individual anti-draft measures. Three interventions were positively related to comfort improvement. For each door where draft seal tape was placed, a 0.311 comfort improvement was experienced. For each door at which draft strips were placed and each door where a mailbox brush was placed a 0.302 improvement was made. These three measures seem to be comparably effective concerning the size of the comfort improvement.

Column 4 shows the final model. This model relates, apart from anti-draft measures, also the efficiency measures to comfort improvement. One individual efficiency measure is related to comfort improvement. Interestingly, smaller comfort improvements are identified among the dwellings where water-saving showerheads were placed. Using these results, a household that received draft strips and seal tape at three doors and one mailbox brush would on average score a comfort improvement of 2.952 (MoE 1.026) (*much less cold*). That is more than two steps up the improvement ladder compared to no interventions. Interestingly, a household that received two water-saving showerheads would experience the lowest average comfort improvement. This is -0.014 (MoE 0.595) (*not less cold at all*)

In theory, the comfort improvement could be much higher than predicted. The range of the variables in this case does not represent the minimum and maximum number of applications of each measure. It represents the maximum number of each measure that has been applied in the Klusbus program. In reality, for instance, draft strips could be applied to more than three doors, if a dwelling has more doors. However, a more optimistic prediction on the largest intervention has not been made. The observed range of applications is assumed to be a realistic representation of the number of applications for average dwellings.

Other energy measures that were applied were pipe insulation, door closers, and gap sealing. They were applied too limitedly to measure the effect.

Table 42. Results regression analyses: comfort improvement predicted on the energy measures.

Variable (range)	(27) Drafts vs efficiency	(28) Drafts	(29) Drafts + efficiency
(Intercept)	0.613 (0.180) ***	0.589 (0.118) ***	0.641(0.220) ***
Anti-draft measures (0,7)	0.208 (0.049) ***		
Draft strip door (0,3)		0.302 (0.106) ***	0.326 (0.108) ***
Door brush (0,2)		0.045 (0.141)	0.027 (0.141)
Mailbox brush (0,1)		0.302 (0.172) *	0.333 (0.177) *
Door draft seal tape (0,3)		0.311 (0.129) **	0.333 (0.133) **
Window draft strip (0,2)		-0.115 (0.251)	-0.170 (0.255)
Efficiency measures (0,23)	0.001 (0.017)		
Radiator foil (0,8)			0.054 (0.044)
LED light (0,23e)			-0.001 (0.020)
Water-saving showerhead (0,2)			-0.327 (0.160) **
Timer switch (0,2)			0.049 (0.139)
Low-flow aerators (0,3)			0.025 (0.143)
Multiple R^2	0.108	0.131	0.167

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*

Furthermore, the interventions that were most widely applied (see Table 26 in Data description) did not per se lead to the largest comfort improvement. Radiator foil (78.1% of dwellings) and LED lights (74.2%) were most applied but did not affect comfort improvement. Third was water-saving showerheads (67.1%) which related negatively to comfort improvement. Fourth is the first intervention that relates positively to comfort improvement, with 54.8% of dwellings receiving draft strips for at least one door.

Apart from the direct effect of the interventions on the experience of cold, certain specific aspects of the improved housing quality may explain the improved comfort. This is zoomed in on in the next section.

The situation after the intervention

The Klusbus interventions resulted in improved housing quality and residents adjusting their behavior. This section aims to find how much the changed situation explains the feeling of comfort improvement.

Housing quality improvement

After the energy intervention by the Klusbus, the participants reported an improvement in housing quality: less cold, less drafts, more control over the indoor environment, better air quality, and less mold. To what extent does this improvement in housing quality explain the feeling of higher comfort?

Column 2 of Table 43 relates the comfort improvement to a reduction of complaints about the house: less drafts and less mold. Because the reduction of complaints was measured on a five-point Likert scale from 0 to 4 (*not less/more at all-..-very much less/more*) the reference category is a person who did not experience a reduction of drafts or mold. This person scores 0.272 on the improvement ladder (*not less cold at all*).

Less drafts is the dominant factor related to comfort improvement. Depending on the extent to which drafts were reduced, a 0.610 to 2.439 average comfort improvement is made. A reduction in mold is not significantly related to an improvement in comfort. The average person with *very much less* drafts scores a comfort improvement of 2.712(*much less cold*). That is three steps up the improvement ladder compared to the average person who did not experience a reduction in housing complaints.

Other housing factors that were asked for were improved control over the indoor environment and an increase in fresh air. However, these factors were also related to the aforementioned factors (less drafts and less mold), a problem called multicollinearity, see Appendix D (correlation matrices). Adding them to the model as displayed in Table 8 (Research design) would lead to an overestimation of the relationship between the housing quality improvements and comfort improvement. More control and an increase in fresh air had a smaller relationship with health than their correlating variables, therefore they are left out.

The R-squared shows that 58.0% of the comfort improvement predictions based on these housing complaints reductions are correct. This is very high, meaning that the improvement in housing quality explains the improvement in comfort very well.

Columns 3 and 4 show that no relationships between energy poverty and comfort improvement, nor interaction effects of energy poverty with housing quality improvement respectively, were found.

Table 43. Results regression analyses: comfort improvement predicted on housing quality improvement and energy poverty.

Variable (range)	(30) Complaints reduction	(31) .. + EP 2	(32) .. + cross-effects
(Intercept)	0.272 (0.072) ***	0.241 (0.078) ***	0.224 (0.082) ***
Less drafts (0,4)	0.610 (0.044) ***	0.614 (0.044) ***	0.622 (0.051) ***
Less mold (0,4)	0.032 (0.065)	0.016 (0.067)	0.058 (0.086)
Energy-poor (0,1)		0.134 (0.127)	0.248 (0.179)
Less drafts: EP			-0.060 (0.110)
Less mold: EP			-0.106 (0.137)
Multiple R^2	0.580	0.583	0.586

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: See Figure 12 for table reading instructions.

Behavior adjustment

Apart from the improved housing quality, people have adjusted their behavior after the Klusbus interventions. They heated less (some more), wore less (thick) clothes, turned off/down unnecessary lights less often, took more/longer showers, and ventilated more (some less). This section tries to find how much these behavior adjustments explain the feeling of improved comfort.

Table 44 shows the relationship between thermal living comfort improvement and behavior adjustments. Column 2 does not account for energy poverty. Because behavior adjustments were measured on a five-point Likert scale from 0 to 4 (*not less/more-..very much less/more*) or binary, the intercept can be interpreted as the comfort improvement for an average person who did not engage in the named behavior adjustments. This person *does not suffer less* or *suffers slightly less* from cold (0.667 comfort improvement). Two behavior adjustments are positively related to comfort improvement. People who started to heat less made an almost full step up the comfort improvement ladder. People wearing less (thick) clothes made an almost half step up the ladder for each step of less (thick) clothes worn. As identified in section 5.7 13.5% started showering more or longer after the intervention, possibly due to the placement of a water-saving showerhead. The table shows that this change in showering behavior did not lead to a larger comfort improvement.

These findings mean that a person who started to heat less and wore extremely less (thick) clothes had an average comfort improvement of 5.985 (*extremely less cold*). A person who did not change their behavior had an average comfort improvement of 0.667. An immense difference.

Column 3 shows that the energy-poor did not experience a larger comfort improvement than the non-energy-poor, as found earlier. Column 4 shows that there are no interaction effects between EP and behavior adjustments either. This means that behavior adjustments are related to comfort improvement similarly for energy-poor as for non-energy-poor. The interaction effect of 'turning off unnecessary lights less' was excluded due to limited observations.

Table 44. Results regression analyses: comfort improvement predicted on behavior adjustments and energy poverty.

Variable (range)	(33) Behavior adjustment	(34) .. + EP 2	(35) .. + cross-effects
(Intercept)	0.667 (0.084) ***	0.679 (0.089) ***	0.648 (0.095) ***
Heat less (0,1)	0.866 (0.176) ***	0.863 (0.177) ***	0.871 (0.196) ***
Ventilate more (0,1)	0.262 (0.284)	0.264 (0.285)	0.349 (0.336)
Shower more/longer (0,4)	0.041 (0.156)	0.050 (0.158)	0.068 (0.208)
Less (thick) clothes (0,4)	0.464 (0.141) ***	0.473 (0.144) ***	0.607 (0.179) ***
Turn off unnecessary lights less (0,4)	0.139 (0.103)	0.141 (0.103)	0.158 (0.111)
Energy-poor (0,1)		-0.069 (0.171)	0.096 (0.213)
Heat less: EP			0.271 (0.510)
Ventilate more: EP			-0.560 (0.738)
Shower more/longer: EP			0.014 (0.336)
Less (thick) clothes: EP			-0.524 (0.318)
Multiple R^2	0.278	0.279	0.295

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: See Figure 12 for table reading instructions.

Final model: stepwise

The previous sections showed that the adjusted situation after the Klusbus intervention (i.e. the improved housing quality and the adjusted behavior) hypothesized to influence comfort improvement were strongly related to the improved experience of comfort. They are therefore added in one final STEPWISE model. Table 45 relates the comfort improvement to both the housing quality improvement and behavior adjustment after the energy intervention. This method identifies the best-fitting model by adding or removing variables. Variables with a significant relationship with comfort in one of the previous models in this chapter may have been removed or have lost their significant relationship. This means that other variables from different clusters may now better explain the relationship with comfort.

The large R-squared shows that the housing quality improvement and behavior adjustment explain the improved experience of comfort much better than the preexisting situation (Table 41) and the energy measures themselves (Table 42). The intercept in column 2 can be interpreted as the average comfort improvement for a person who reported no improvement in housing quality and did not adjust their behavior. This person made a 0.231 (MoE 0.134) comfort improvement (*not* to *slightly less* cold).

The most dominant factor is the improvement of housing quality. The reduction of drafts was most strongly related, with a 0.538 to 2.152 larger comfort improvement (*slightly* to *very much* less drafts resp.) compared to the reference category. Moreover, two behavior changes related to a larger comfort improvement. Persons heating less made a 0.455 larger comfort improvement, while persons wearing less (thick) clothes made a 0.191 larger improvement.

The highest comfort is therefore predicted for the average person who experienced very much less drafts, heated less, and wore lighter clothes after the Klusbus. They experienced a 3.030 (0.278) comfort improvement (*much less* cold). The lowest improvement is predicted for the average person without improved housing quality and adjusted behavior, the reference category.

Table 45. Results final regression analysis: comfort improvement predicted on housing quality improvement, behavior adjustments and energy poverty.

Variable (range)	(36) Unstandardized coefficient (SE)	Standardized coefficient
(Intercept)	0.231 (0.069) ***	
Housing quality improvement		
Less drafts (0,4)	0.538 (0.045) ***	0.665
Behavior adjustment		
Heat less (0/1)	0.455 (0.129) ***	0.187
Less (thick) clothes (0/1)	0.191 (0.097) *	0.105
Multiple R^2	0.624	

*Note: (SE) and ***,**,*: Statistical significance level 1%, 5%, 10%. Underlined coefficients are significant at 20%.*
Note: Standardized coefficients show the change in standard deviations of the outcome variable (the intervention) associated with a one-standard deviation change in each predictor variable.

Column 3 includes the standardized regression coefficients, which provide insight into the relative importance of each variable in explaining comfort improvement by placing them on a common scale. To assess the overall importance of each cluster, the absolute values of the standardized coefficients within each cluster are summed. This method allows for the comparison of the relative importance of each cluster concerning comfort improvement, regardless of the units of measurement.

The standardized coefficients indicate that the reduction of drafts is the most critical factor related to comfort improvement. The aggregate measures show that the housing quality improvement cluster (0.665) is the most strongly related to comfort. This is followed by behavior adjustment (0.292), which is only about half as influential as housing quality improvement.

Conclusion

Individuals' situation before the Klusbus intervention, i.e., housing quality and socioeconomics, only limitedly explain their comfort improvement, visualized in Figure 15. Participants who lacked control over their indoor environment and young participants experienced a greater comfort improvement. The energy-poor did not experience a larger comfort improvement than non-energy-poor participants.

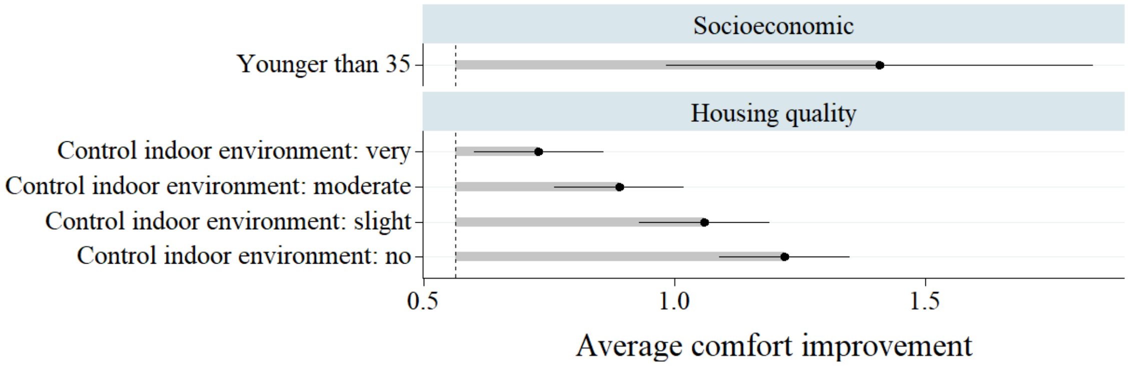

*Figure 15. Comfort improvement after the Klusbus, per resident segment. Notes: The dashed line represents the reference category. This indicates the average comfort improvement of a person who does not possess any of the mentioned characteristics (i.e., 0.563: not to slightly less cold in the dwelling). The gray bars show the average comfort improvement. Comfort improvement is calculated by adding the estimated coefficients (the number of steps in comfort improvement per resident segment) to the reference value. Variables with multiple levels have a greater relationship with comfort improvement as the value of the variable increases. Example: Comfort improvement for respondents who had a slight lack of control over the indoor climate: 0.563 + 0.165 = 0.73; complete lack of control: 0.563 + (4 * 0.165) = 1.22. The black lines show the 95% margin of error.*

Figure 16 illustrates that the Klusbus interventions positively related to comfort improvement were exclusively anti-draft measures: draft seal tape, door draft strips, and mailbox brushes. In contrast, water and energy efficiency enhancement measures did not positively impact comfort improvement. Notably, among these efficiency measures, only water-saving showerheads were negatively related to comfort improvement.

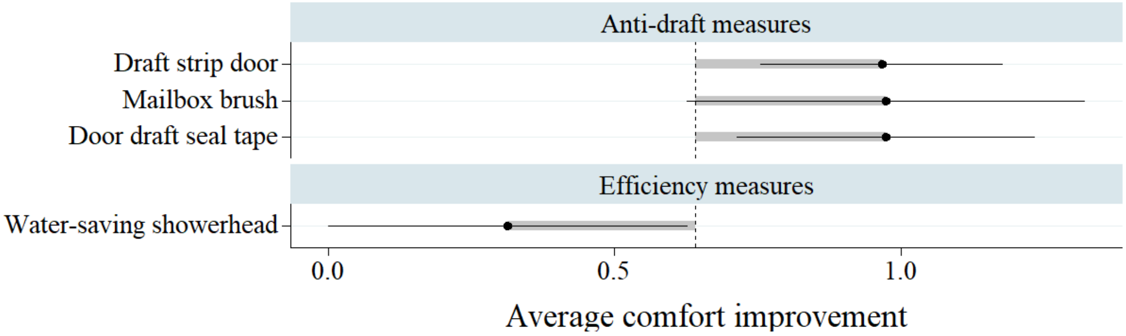

Figure 16. Comfort improvement after the Klusbus, per energy measure.
*Notes: The dashed line represents the reference category. This indicates the average comfort improvement of a person who did not receive any of the mentioned energy measures (i.e., 0.641: not to slightly less cold in the dwelling). The gray bars show the average comfort improvement. Comfort improvement is calculated by adding the estimated coefficients (the number of steps in comfort improvement per measure) to the reference value. The relationship with comfort improvement increases as more measures are applied. Example: Comfort improvement for respondents who received 1 draft strip: 0.641 + 0.326 = 0.97; 3 draft strips: 0.641 + (3 * 0.326) = 1.62.. The black lines show the 95% margin of error.*

However, the factor that best explains comfort improvement is the improved housing quality after the Klusbus intervention. Figure 17 shows that the reduction in drafts is the strongest indicator of comfort improvement.

Behavior adjustments also explained improvement very well, though to a lesser extent than housing improvements. Individuals who started to heat less and wear less (thick) clothes made the largest comfort improvement.

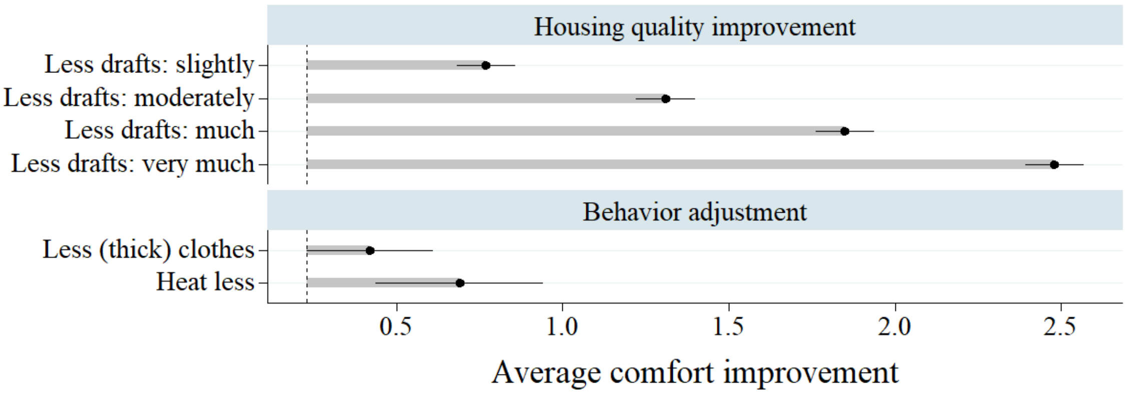

Figure 17. Comfort improvement after the Klusbus, per resident segment.
*Notes: The dashed line represents the reference category. This indicates the average comfort improvement of a person who does not possess any of the mentioned characteristics (i.e., 0.231: not less cold in the dwelling). The gray bars show the average comfort improvement. Comfort improvement is calculated by adding the estimated coefficients (the number of steps in comfort improvement per resident segment) to the reference value. Variables with multiple levels have a greater relationship with comfort improvement as the value of the variable increases. Example: Comfort improvement for respondents who experienced slightly less draft: 0.231 + 0.538 = 0.77; complete lack of control: 0.231 + (4 * 0.548) = 2.48.. The black lines show the 95% margin of error.*

6.4 Bivariate Analysis: Characteristics of the Energy-Poor

Currently, the exact profile of the energy-poor population remains unclear, as this issue has only recently gained political attention and research on it has been limited. However, policy initiatives like the Klusbus aim to reach and help this group. Therefore, diving into the characteristics of the energy-poor is crucial. What notable traits distinguish the energy-poor?

To address this, statistical tests were performed to compare the energy-poor respondents with the non-energy-poor respondents across various dimensions: socio-economic factors, comfort, housing quality, energy-saving and comfort-enhancing behavior, the Klusbus energy measures, and improvements in comfort, housing quality, and behavior post-intervention. A comprehensive bivariate analysis of these differences between the energy-poor and the non-energy-poor is presented in Appendix F, offering deeper insights into the target group. This also helps verify whether the Klusbus program effectively reached its intended audience.

This chapter highlights the key findings from the bivariate analysis, summarizing the characteristics of the energy-poor. Differences between EP2 and non-EP and EP1 and non-EP were statistically tested using t-tests. In most cases, the differences are larger between EP2 and non-EP, compared to EP1 and non-EP. Therefore, the characteristics of the energy-poor discussed here refer to EP2 unless stated otherwise. The statistical analysis points to the following findings.

Who are the energy-poor?

The energy-poor respondents in the sample are more often social renters, have lower education levels, higher energy costs, work less full-time, and are less often couples without children. No difference in energy consciousness was observed between the energy-poor and non-energy-poor.

Do the energy-poor compromise on living comfort?

The energy-poor appear to experience cold and drafts more often. Moreover, they lack fresh air more often and have less control over the indoor environment. Logically, they reported lower general satisfaction with their dwelling too. So, the energy-poor have lower comfort due to more complaints about housing quality compared to the non-energy-poor.

Do the energy-poor adjust their behavior (prebound) to conserve energy?

The energy-poor heat the bedrooms more throughout the day and heat the living rooms more at night compared to the non-energy-poor. They also ventilate their living rooms more. However, they do not ventilate the bathroom more often, shower more frequently or longer, turn off unnecessary lights more often, or wear extra thick clothing compared to the non-energy-poor. So, despite the higher energy costs, the energy-poor heat more to achieve a somewhat acceptable comfort level (which is still lower than the comfort level of non-energy-poor individuals), indicating lower-quality housing. They do not seem to drastically change their behavior to conserve energy.

Despite already heating more, the energy-poor would increase their energy-consuming behavior more if financial limitations were lifted than the non-energy-poor (resulting in higher energy costs). If financially able, the energy-poor would start heating more, ventilating more, showering more frequently and longer, and wearing lighter clothing compared to the non-energy-poor.

Have the energy-poor received a larger energy intervention by the Klusbus?

The energy-poor received more extensive interventions and energy measures than the non-energy-poor, particularly aimed at reducing drafts. They received more energy measures (EP1 11.31, EP2 11.51, non-EP 10.20) than the non-energy-poor. This resulted in more valuable interventions (EP1 €384.04, EP2 €419.03, non-EP €338.33). Specific measures that were applied more often in energy-poor households include radiator foil, draft strips at doors, and door brushes, although draft tape at doors was applied less compared to the non-energy-poor.

Have the energy-poor experienced a larger comfort improvement after the energy intervention?

The energy-poor did not report a greater reduction in cold but did experience a greater improvement in housing quality compared to the non-energy-poor. They reported a greater reduction in mold and a greater improvement of fresh air. No greater improvements in drafts or indoor climate control were observed.

Have the energy-poor adjusted their behavior (rebound)?

The energy-poor have adjusted their behavior more after the Klusbus intervention compared to the non-energy-poor. They started wearing less thick clothing, showering more frequently or for longer durations, and turning off unnecessary lights less frequently.

7. Discussion & Conclusion

In this concluding chapter, the research questions are answered, the results are related to the literature, and their implications are discussed. Moreover, the limitations of the research are stated to assess the quality of the study, the practical applications are explored and suggestions for future research are made.

7.1 Answers to research questions

A survey was conducted among a sample comprising a substantial proportion of energy-poor households. The survey covered various aspects including energy poverty, socioeconomic characteristics, comfort levels, housing quality, behavior, and comfort improvement, housing quality improvement, and behavior adjustments after a minor energy intervention. These survey results were integrated with data on housing conditions and the specific energy measures implemented among each household. The primary objective of this research was to determine the relationship between energy poverty and thermal living comfort. The main and sub-questions are answered in subsequent sections.

Thermal living comfort

Several linear regression analyses were conducted to find the relationship between energy poverty and comfort, and the influence of a minor energy intervention on comfort improvement. This analysis was divided into three parts, each studying one main topic. These were factors related to (1) thermal living comfort, (2) a minor energy intervention, and (3) thermal living comfort improvement after the energy intervention. To start with the first part in this section.

Comfort was measured on a five-step 'comfort ladder', ranging from *never* to *always* suffering from cold in the living room. Table 46 gives an overview of the groups with the lowest comfort (the findings from section 6.1), the largest intervention groups (section 6.2), and the largest comfort improvement groups (section 6.3).

> *Sub-question (1): What is the relationship of a resident's socioeconomic characteristics, poor housing conditions, and energy-saving or comfort-enhancement behavior with the thermal living comfort in their dwelling?*

Energy poverty, several socioeconomic characteristics, housing complaints, and behavior are primarily negatively associated with comfort.

Column 1 of Table 46 reveals that several socioeconomic factors are related to comfort. Social renters and young participants (aged under 35) reported lower comfort levels. No relationship with comfort was observed for tenure, age, household type, employment, gender, education level, and energy consciousness.

Living in an apartment was associated with higher comfort. Moreover, the table indicates that poor housing quality is the most important determinant of comfort, depending strongly on the level of housing problems. Complaints about drafts are negatively related to comfort, followed by a lack of control over the indoor environment. Mold, dry air, and a lack of fresh air were not associated with comfort. The poor housing quality likely prompts individuals to adjust their behavior.

Finally, two behaviors were related to comfort. Regularly ventilating the bedrooms was associated with enhanced comfort, depending on the frequency of this behavior. Conversely, needing to wear thick clothes at home was negatively related to comfort. The strength of these relationships varied based on the extent of engagement in these behaviors. Heating, showering, turning off unnecessary lights, and indoor temperature were not found to be linked to comfort.

When compared to the impact of these clusters on comfort, energy poverty emerged as one of the strongest indicators of low comfort. Energy-poor individuals were found to be a step lower on the comfort ladder compared to non-energy-poor individuals.

Table 46. Overview of the groups with the lowest comfort, largest interventions, and largest comfort improvements. Coefficients of final models (models 11, 19, and 26).

Who experienced lower comfort? Benchmark: 1.068	Who received a larger intervention? €293.04	Who experienced a larger improvement? 0.563
Socioeconomics		
Energy-poor (-0.714)	Energy-poor (+€82.00)	-
Social rent (-0.407)	-	-
Younger than 35 (-0.251)	-	Younger than 35 (+0.849)
Housing and housing quality		
Apartment (+0.252)	Apartment (-€60.60)	-
Drafts (-0.276 to -1.104)	Drafts (+€16.16 to +€64.64)	
Lack control indoor environment (-0.157 to – 0.628)		Lack control indoor environment (+0.165 to +0.660)
-	Dry air (<30% humidity) (+€110.15)	-
Behavior	*NA*	*NA*
Ventilating bed (+0.116 to + 0.464)		
Thick clothes (-0.536)		

Note: The benchmark is the average comfort, intervention, or comfort improvement for a person without any of the listed characteristics in this table. Each characteristic indicates a lower or higher value compared to the benchmark.

The energy intervention

It is now known which households experienced the lowest comfort levels and were therefore most in need of improvement in their housing situation. This section answers whether these households benefited most from the energy interventions provided by the Klusbus, designed to enhance comfort and reduce energy costs.

> Sub-question (2): *What is the relationship of energy poverty, poor housing conditions, and a resident's socioeconomic characteristics with the received energy intervention in an anti-energy poverty program in a large Dutch city?*

All households studied received tailored interventions based on their highest needs. On average, the interventions were valued at €358.09. Column 2 of Table 46 shows that the target group of the Klusbus – energy-poor – were in greater need of intervention and consequently received interventions worth €82.00 more than those provided to non-energy-poor households.

Housing conditions also determined the size of the intervention. Residents of apartments, who generally experienced higher comfort, received interventions worth €60.60 less than those living in single-family dwellings. Households experiencing drafts, who reported lower comfort levels, received interventions valued between €16.16 and €64.64 more than those not experiencing drafts. Interestingly, households with dry indoor air conditions did not report lower comfort but still received interventions worth a substantial €110.15 more than those without such conditions.

These findings indicate that the energy intervention program primarily assisted those most in need. Energy-poor households and individuals with low housing quality, especially those dealing with drafts, received more substantial interventions. However, not all households with lower comfort levels, such as social renters and those with limited control over their indoor environment, received larger interventions.

Comfort improvement

The previous passage revealed who received the largest energy interventions, which was expected to improve living comfort. Did those who experienced the lowest comfort and were thus most in need of the intervention – among which the energy-poor – also experience the largest comfort improvement?

The situation before the intervention

Comfort improvement was measured on a five-step 'comfort improvement ladder', ranging from *not less at all* to *very much less* cold in the dwelling. The average improvement was 1: *slightly less* cold in the dwelling. Regardless of their initial comfort levels or the size of the intervention, comfort improvement was experienced rather equally among all participants. The target group, energy-poor, did not experience a greater improvement despite their low comfort levels and larger interventions.

> *Sub-question (3): What is the relationship of a resident's socioeconomic characteristics, poor housing conditions, the energy measures applied to a dwelling, improved housing conditions, and adjusted energy-saving or comfort-enhancement behavior with the thermal living comfort improvement in their dwelling after a minor energy intervention?*

The housing quality and socioeconomic characteristics before the intervention only slightly explain the size of the intervention received by a household. Primarily anti-draft measures were associated with greater comfort improvement. Improved housing quality and behavior adjustments after the energy intervention are the strongest indicators of comfort improvement.

The situation before the intervention

While several socioeconomic groups experienced lower comfort, column 3 of Table 46 shows that only the young experienced an above-average comfort improvement. Social renters, who lived in inferior comfort, did not receive a larger intervention nor experienced a larger improvement.

Furthermore, it was found that pre-intervention housing quality poorly explained the comfort improvement post-intervention. Only a lack of control over the indoor environment before the intervention was related to a larger comfort improvement afterward. Interestingly, those experiencing drafts had inferior comfort but did not experience a larger comfort improvement. Additionally, households with dry indoor air conditions received substantially larger interventions despite not reporting lower comfort yet did not report greater comfort improvements. Moreover, individuals living in apartments did not report a smaller improvement, despite receiving a smaller intervention.

Energy measures

The prior socioeconomic and housing situation mentioned above only slightly explains the comfort improvement observed. The energy intervention – apart from weather and other possible effects – is the main cause of this improvement.

Two types of energy measures were applied.

1. Measures that reduce draft: draft strip at door and window, door brush, mailbox brush, and door draft seal tape.
2. Measures that improve energy and water efficiency: radiator foil, LED light, water-saving showerhead, timer switch, and low-flow aerators.

Table 47A relates the energy measures to the improvement of comfort. It shows that anti-draft measures were associated with greater comfort improvement. Specifically, door draft seal tape, draft strips at doors, and mailbox brushes demonstrated comparable positive relationships with comfort improvement. Conversely, water-saving showerheads were negatively related to comfort improvement. That indicates that the most commonly applied measures – radiator foil and LED lights – are not the most effective in terms of improving comfort.

Table 47A and 47B. The relationships between thermal comfort improvement and energy measures, improved housing quality, and adjusted behavior.

What is linked to the largest improvement?

Table 47A. Energy measures Benchmark: 0.641	Table 47B. Situation after intervention Benchmark: 0.231
Energy measures	*Improved housing quality*
Door draft seal tape (+0.333)	Less drafts (+0.538 to +2.152)
Draft strip door (+0.326)	*Adjusted behavior*
Mailbox brush (+0.333)	Heat less (+0.455)
Water-saving showerhead (-0.327)	Less (thick) clothes (0.191)

Note: The benchmark is the average comfort, intervention, or comfort improvement for a person without any of the listed characteristics in this table. Each characteristic indicates a lower or higher value compared to the benchmark.

The situation after the intervention

The interventions led to enhancements in housing quality and behavior adjustments, likely contributing to the increased experience of comfort. The extent to which the improved housing quality and adjusted behavior are related to comfort improvement is examined.

After the energy intervention, participants experienced fewer drafts, greater control over the indoor climate, less mold, and more fresh air. Table 47B links improved housing quality and adjusted behavior to comfort improvement. The improved housing quality was found to be the strongest indicator of improved comfort, with reduced drafts being the dominant factor.

Moreover, after the intervention, some participants heated less (while some heated more), wore lighter clothes, turned off or dimmed unnecessary lights less often, took more or longer showers, and ventilated their homes more (or less). The table indicates that heating less and wearing lighter clothes were both associated with greater comfort improvement.

Both improved housing quality and behavior adjustment were found to be stronger indicators of improved comfort than the energy intervention itself. The mechanism appears to be that the energy intervention enhances housing quality, which in turn prompts behavior adjustments, collectively influencing comfort improvement.

No interaction effects of energy poverty with comfort, the energy intervention, and comfort improvement after the intervention were found. That implies that the relationship of energy poverty with comfort, the energy intervention, and comfort improvement is consistent regardless of the levels of the other determinants.

The characteristics of the energy-poor

Finally, the characteristics of the energy-poor were compared to those of non-energy-poor to address the last sub-question. This comparison, facilitated by t-tests in section 6.4, revealed insightful patterns.

> Sub-question (4): *Do energy-poor households differ in socioeconomic characteristics, live in poorer housing conditions, behave differently, receive a larger energy intervention in an anti-energy poverty program, experience a larger improvement in housing quality, and adjust their behavior more compared to non-energy-poor households?*

The results indicated that the energy-poor indeed differed in socioeconomic characteristics, experienced lower comfort levels, lived in poorer housing conditions, and engaged in more energy-consuming behavior compared to their non-energy-poor counterparts. Moreover, they received a larger intervention. However, the energy-poor did not report a larger comfort improvement, but did report a larger improvement in housing quality, and adjusted their behavior more after the energy intervention than non-energy-poor households.

The analysis unveiled a prevalence of energy poverty among low-educated individuals, households with high energy costs, those not working full time (classified as 'work other'), and social renters. Conversely, couples without children were notably underrepresented among the energy-poor. Moreover, no significant difference in energy consciousness was observed between energy-poor and non-energy-poor households. This indicates that the higher energy consumption among the energy-poor in the sample is not due to a lack of environmental awareness.

Secondly, energy-poor households experienced lower thermal comfort compared to their non-energy-poor counterparts, likely attributable to inferior housing conditions. The energy-poor reported more complaints about cold, drafts, a lack of fresh air, limited control over the indoor environment, and dissatisfaction with their dwelling in general. However, energy-poor households exhibited slightly better indoor humidity levels compared to non-energy-poor households.

Additionally, behavioral differences were found for the energy-poor compared to non-energy-poor individuals. Despite facing higher heating costs, energy-poor households heated and ventilated their homes more than non-energy-poor households to attain an acceptable comfort level. Interestingly, even though energy-poor households already consumed more energy for heating, they demonstrated a greater willingness to adjust their behavior compared to non-energy-poor households if financial restrictions were lifted. They indicated that, if they were financially able, the energy-poor would heat more, ventilate more, shower more frequently and for longer periods, wear lighter clothing, and turn up the thermostat more than non-energy-poor households. This implies that the energy-poor compromised on their behavior more than non-EP.

The analysis highlighted that energy-poor households received a larger intervention both in terms of monetary value (€419.03 vs. €338.33) and number of measures (11.5 vs. 10.2). Particular measures that were applied more among the energy-poor were radiator foil, door drafts strips, door brushes, door draft seal tape, and water-saving showerheads Most of these measures were aimed at reducing drafts.

After the Klusbus, improvements in comfort and housing quality were observed across the sample. On average, the participants experienced *slightly less* cold in their dwelling. However, energy-poor households did not report a larger comfort improvement than non-energy-poor households. They did, however, experience a larger improvement in housing quality, particularly through a larger reduction in mold and a larger increase in fresh air.

Post-intervention, a minority adjusted their behavior after the energy intervention, with the Energy-poor showing the most substantial changes. To enhance their living comfort, energy-poor individuals started wearing lighter clothing, showering more, and turning off unnecessary lights more often than non-energy-poor individuals.

Main research question

Energy-poor households live in lower comfort than their non-energy-poor counterparts. This is likely due to their poorer housing quality, which was strongly linked to lower comfort, especially drafts. A policy program aimed at assisting the energy-poor by applying energy-saving measures in dwellings reached their target group, as the energy-poor received greater energy interventions. The energy-poor reported a greater improvement in housing quality and larger behavior adjustments. These housing quality improvements and behavior adjustments contributed to the comfort improvement. However, after the intervention, the energy-poor did not report a greater comfort improvement than non-energy-poor households.

7.2 Discussion

This section relates the results to previous studies. First, the groups that were related to greater thermal comfort, larger energy interventions, and greater comfort improvement after the intervention are evaluated. This is followed by evaluating the observed characteristics of the energy-poor.

Thermal living comfort

This section compares the findings to the literature regarding groups that experienced lower thermal comfort before the intervention.

Socioeconomic factors

Certain socioeconomic groups, specifically social renters, young respondents, and residents of single-family dwellings, experienced lower thermal comfort. Literature indicates that comfort experiences vary significantly among different socioeconomic groups, such as women, young people, and older individuals (Clancy, Daskalova, Feenstra, Franceschelli, & Sanz, 2017). However, this study did not observe lower comfort among older individuals and women. The lower comfort reported by social renters aligns with existing literature, which attributes this to poorer housing conditions. Conversely, respondents living in apartments reported higher comfort, likely due to reduced heat loss surface areas, consistent with the literature.

Housing quality

Regarding housing quality, drafts and a lack of control over the indoor environment were strongly associated with lower comfort. These findings are consistent with literature that highlighted the significant impact of controllability on comfort (Frontczak & Wargocki, 2011). Drafts were noted as one of the critical factors affecting comfort (ISO, 2005)). This low quality of housing presumably leads individuals to adjust their behaviors to cope with discomfort.

Behavior

In terms of behavior, airing the bedroom(s) was related to higher comfort, while wearing thick clothes was linked to lower comfort. The relationship of behavior may seem contradictory. Behaviors were namely expected to be performed to increase comfort. However, on one hand, certain behaviors, such as ventilating, are performed to enhance comfort, leading to a positive relationship with comfort. On the other hand, behaviors like wearing thicker clothes are performed to save energy, often resulting in a negative relationship with comfort as a side effect. Initially, one might expect a positive relationship between wearing thick clothes and comfort, because wearing fewer clothes at the same indoor temperature leads to lower comfort. However, the alternative, wearing lighter clothes, requires turning up the thermostat, making thick clothes primarily associated with saving energy rather than increasing comfort.

Energy poverty is found to be one of the strongest indicators of low comfort. This finding aligns with the literature, that suggested lower comfort for the energy-poor as they were found to have less control over the indoor environment due to limited financial capabilities and often reside in less energy-efficient dwellings (Frontczak & Wargocki, 2011). Moreover, lower income levels are associated with a higher tolerance for discomfort (Langevin, Gurian, & Wen, 2013).

The energy intervention

The groups that received more substantial energy interventions were evaluated in line with the literature. Energy-poor households, residents of single-family dwellings, and individuals experiencing drafts or dry indoor air received larger energy interventions. These findings align with expectations that the target group – the energy-poor – and those with lower housing quality would receive more extensive interventions. However, the strong relationship with dry indoor air was unexpected and remains unexplained.

Comfort improvement

The groups that experienced a larger comfort improvement after the intervention are compared to findings in the literature.

Socioeconomic

A larger comfort improvement was observed among younger individuals (under 35) and those with limited control over their indoor environment. Surprisingly, despite their initial low comfort levels and larger intervention, the energy-poor did not experience a larger improvement than the non-energy-poor.

The literature suggests that socioeconomic groups with limited (financially) capacity to improve their house themselves were expected to receive larger interventions and consequently experience greater comfort improvements. This aligns with the observed larger improvement among the young demographic, but the lack of larger improvements among the energy-poor contradicts this hypothesis.

Housing quality

The existing literature primarily focuses on the overall improvement in housing quality and comfort post-intervention, rather than examining specific groups that experienced greater improvement. However, the results are not entirely in line with expectations. Groups with lower comfort levels before the intervention or those who received larger interventions (such as individuals experiencing drafts) were anticipated to experience a large comfort improvement. However, this was not observed in the study, indicating a disconnect between the expected and actual outcomes.

Energy measures

Three anti-draft measures were positively related to an improvement in comfort: door draft strips, mailbox brushes, and door draft seal tape. Surprisingly, one efficiency measure, the water-saving showerhead, was negatively associated with comfort improvement. Most existing studies have focused on the benefits of large-scale renovations, but research has also demonstrated positive outcomes for small renovations in comfort, housing quality, and well-being (2013; Hernandez & Phillips, 2015). Van der Wal, van Ooij, & Straver (2023) highlighted the enhanced effectiveness of energy fixes when the measures were applied by the fixers. Therefore, the observed improvement in comfort after implementing these energy measures aligns with the existing literature. The effectiveness of individual measures had not been previously explored, underscoring the novelty of these findings. The negative relationship associated with water-saving showerheads remains unexplained. One possible reason could be that households receiving these showerheads received fewer anti-draft measures due to a cap on the total number of interventions a household could receive. A possible lower number of anti-draft measures may have resulted in a relatively smaller improvement in comfort.

Housing quality improvement

After the energy intervention, participants experienced less drafts, more control over the indoor climate, less mold, and more fresh air. This improved housing quality, particularly the reduction of drafts, is strongly related to comfort improvement. The improvement in housing quality aligns with existing literature on energy interventions, although previous research has predominantly focused on large-scale renovations. Fisk, Singer, & Chan (2020) observed a consistent reduction in dampness and mold across various studies. As previously mentioned, literature and this study's results positively relate housing quality to comfort, indicating that the strong correlation between improved housing quality and comfort improvement in this study is consistent with existing research.

Behavior adjustment

Heating less after the intervention was found to be positively associated with comfort improvement. This relationship between adjusted behavior and comfort improvement aligns with existing literature. As mentioned earlier, behavior is closely linked to comfort, so adjustments in behavior contribute to a change in comfort levels. Studies, such as Galassi & Madlener (2018), have shown that participants value increased ventilation and wearing lighter clothing as they correlate with improved comfort. However, the observed link between heating less and improved comfort contradicts some literature, which often associates increased temperature with comfort improvement (Fisk, Singer, & Chan, 2020). This discrepancy may be attributed to the survey being conducted during warmer weather, impacting participants' heating habits.

Both improved housing quality and behavior adjustment emerged as stronger predictors of comfort improvement compared to the energy intervention itself. This suggests an apparent mechanism where the energy intervention indirectly enhances comfort by improving housing quality, which likely influences behavior adjustment,

The characteristics of the energy-poor.

The observed characteristics of the energy-poor are related to the expectations from the literature.

Socioeconomic

The socioeconomic characteristics of the energy-poor observed in this study align with the literature. High rates of energy poverty were found among low-educated individuals, households with high energy costs, those not working full time, and social renters. Conversely, couples without children were underrepresented. Previous studies also identified energy poverty among the lower educated in France, Greece, and the Netherlands (Legendre & Ricci, 2015; Boemi, Samarentzi, & Dimoudi, 2020; Straver & Mulder, 2020). High energy costs and unemployment were noted problems among the energy-poor in Switzerland and the Netherlands (Brunner, Spitzer, & Christanell, 2012; Straver & Mulder, 2020). Social renters were often energy-poor in the Netherlands and France (Legendre & Ricci, 2015; Mulder, Batenburg, & Dalla Longa, 2023). Single-person households and single-parent households are strongly overrepresented among the energy-poor in the Netherlands (Mulder, Batenburg, & Dalla Longa, 2023). The underrepresentation of childless couples does not contradict the literature.

Housing quality

Poor housing conditions were anticipated among the energy-poor, as the selection criteria for the studied neighborhoods combined low energy quality and high energy costs. This expectation was confirmed by the results, which showed that energy-poor households experienced lower thermal comfort than their non-energy-poor counterparts, likely due to poorer housing conditions. The energy-poor reported more complaints about cold, drafts, lack of fresh air, limited control over the indoor environment, and general dissatisfaction with their dwellings.

Limited research exists on the relationship between energy poverty and comfort. However, the observed lower comfort does align with expectations based on literature, which also found more instances of cold and drafts among the energy-poor (van der Wal, van Ooij, & Straver, 2023). The lack of fresh air and limited control over the indoor environment was expected, as air quality (Andargie, Touchie, & O'Brien, 2019; ISO, 2005) and controllability (Frontczak & Wargocki, 2011) are key determinants of comfort. Better humidity levels were therefore unexpected. Contrary to expectations from the literature, the sample did not show a higher incidence of mold among the energy-poor.

The intervention

Energy-poor households received a more valuable intervention and more individual measures. They received particularly more radiator foil, door draft strips, door brushes, and door draft seal tape. This is in line with the hypotheses that the energy-poor, as the target group of the Klusbus program, would receive more extensive interventions. After the Klusbus, improvements in comfort and housing quality were observed across the sample. Energy-poor households were expected to experience a larger comfort improvement than non-energy-poor households, but this was not found. They did, however, experience a larger improvement in housing quality, particularly through a larger reduction in mold and a larger increase in fresh air.

Behavior

Energy-poor households exhibited distinct behaviors compared to non-energy-poor households. They tended to heat their bedrooms more throughout the day, heat their living rooms more at night, and ventilate their living rooms more frequently. However, they did not ventilate their living rooms more often, take longer or more frequent showers, turn off unnecessary lights, or wear thicker clothing more often than non-energy-poor households. Prior literature on the behavioral reactions of energy-poor households is limited. A prebound effect was expected, where these households would consume less energy than anticipated based on the energetic quality of their dwellings (Sunikka-Blank & Galvin, 2012). Studies from Greece and Austria observed reduced energy expenditures (Boemi, Samarentzi, & Dimoudi, 2020) and heating only one room among the energy-poor (Brunner, Spitzer, & Christanell, 2012). Contrary to these findings, this study found that energy-poor households heated their bedrooms even more than non-energy-poor households. Additionally, literature suggested behaviors such as less heating, less ventilation, less frequent showers, wearing thicker clothes, and dimming lights (Langevin, Gurian, & Wen, 2013), which were not observed in this sample.

Despite using more energy for heating, the energy-poor in this sample compromised their behavior more than non-energy-poor households. They indicated that, with better financial means, they would heat more, ventilate more, shower more frequently and for longer periods, wear lighter clothing, and turn up the thermostat more than non-energy-poor households. After the energy intervention, some households adjusted their behaviors, with energy-poor households showing the most significant changes. To enhance their living comfort, energy-poor individuals began wearing lighter clothing, showering more, and turning off unnecessary lights more often than their non-energy-poor counterparts.

These observed behavior adjustments align with existing literature, which suggests that energy-poor households tend to make larger behavior adjustments following efficiency upgrades (Roberdel, Ossokina, Karamychev, & Arentze, 2023; Milne & Boardman, 2000). This rebound behavior was expected as energy-poor households reinvest a larger portion of the energy savings from efficiency upgrades to enhance comfort. Common rebound behaviors in the literature include increased ventilation, higher internal temperatures (Hediger, Farsi, & Weber, 2018), wearing lighter clothing (Galassi & Madlener, 2018), less frequent turning off of lights, and less frequent showering (van der Wal, van Ooij, & Straver, 2023).

The combination of observed behaviors, preferred behaviors, and reported comfort indicates that the higher energy consumption among energy-poor households in this sample does not contradict the literature. The literature namely suggested that energy-poor households exhibit greater behavioral reactions. In absolute terms, the energy-poor in this sample consumed more energy, but in relation to their comfort levels, they likely restricted their consumption behavior more than non-energy-poor households.

7.3 Limitations

The limitations of the study are discussed, including the small sample size, geographic constraints, limited time frame, restricted range of energy measures, issues with establishing causality, limitations in analysis, absence of a control group, and discrepancies between the before and after measurements. The study's reliability and validity of the study are evaluated. Recommendations for future research are proposed to address these issues.

Limited sample size

The study's sample size was relatively small, with 155 respondents, including 35 energy-poor and 88 non-energy-poor respondents. This small sample size limited the statistical power and reliability of the findings, particularly when comparing different groups.

Increase the sample size in future research to enhance the reliability and validity of the results. A larger sample in future research size would provide more robust evidence of relationships and effects, potentially revealing statistically significant findings that were not detectable in the smaller sample.

Geographic limitation

The study's external validity is limited due to its narrow geographic focus. The research concentrated on four specific neighborhoods in Eindhoven with high rates of energy poverty. This lack of geographic diversity restricts the generalizability of the findings to the entire country. Populations in other cities or regions may have different characteristics, making it challenging to replicate the results elsewhere. The findings should be interpreted within the context of the specific location and may not be applicable on a broader scale.

Future research could encompass a diverse range of geographic locations, expanding to multiple municipalities, regions, or nationwide. This broader approach will capture a wider variety of contexts and demographic profiles, enhancing the generalizability of the findings. Additionally, comparing results from energy intervention projects in different locations can provide more general insights into energy intervention projects.

Limited time scope

The research was constrained by a limited time scope. The Klusbus project, which is the focus of this study, began in December 2022, and the survey was conducted in April 2024. As a result, only a limited number of households experienced the energy interventions, and there was limited time to compare pre and post-intervention conditions comprehensively. Furthermore, the study was conducted during a period of fluctuating energy prices. The constant news about energy price fluctuations could have influenced the participants' awareness of energy-saving behaviors.

Future studies could adopt a longitudinal approach, allowing participants to report their comfort and housing conditions across multiple winters. This would involve collecting data in the winter before the intervention and again a year later, in the winter after the intervention. This extended timeframe would provide a more accurate comparison and a clearer understanding of the intervention's impact.

Limited energy measures

The research focused on energy efficiency improvements specific to the Klusbus program in Eindhoven, limiting the generalizability of the findings. Other municipalities could have different programs or approaches to addressing energy poverty and implementing energy-saving measures. This limitation affects the external validity of the study and should be considered when interpreting the findings. Additionally, some energy measures, such as pipe insulation, door closers, and gap sealing, were implemented too sparingly to measure their effects accurately.

Expand the scope of energy measures studied by including a broader range of interventions from different municipalities. Collect more extensive data on the specific impacts of various energy-saving measures to provide a comprehensive understanding of their effectiveness. This could involve collaborating with other programs or conducting multi-site studies.

Causality

The conceptual models indicated that certain clusters, such as energy measures and improved housing quality, are causally related. This correlation prevented these variables from being entered into the same regression model.

Utilize advanced statistical techniques, such as path analysis or structural equation modeling, to explore the relationships between different clusters. These methods can accommodate complex relationships and provide a more nuanced understanding of the causal pathways in the model.

Limitations in analysis

The analysis was limited by the measurement level of variables. Most variables were measured on a five-point Likert scale, which is ordinal. OLS regression assumes interval or ratio-level measurement. However, the ordinal variables in the study were treated as continuous, assuming equal intervals between the levels. This way parametric models were not needed, and stronger regression models could be used.

For future research, it is advised to take measurement levels into account better when incorporating them into a linear regression model.

No control group

The study did not include a control group, limiting the ability to attribute observed changes in comfort solely to the intervention.

Include a control group in future studies to provide a baseline for comparison. A control group would allow for a comparison between those who received the intervention and those who did not, establishing a baseline for measuring the effects of the intervention on comfort. This would provide a better understanding of the impact of the intervention and help attribute observed changes in comfort more accurately. In this way, the influence of the time trend can be considered.

Before and after measurement

The before and after measurements in this study were not fully objective, which could limit the accuracy of the analysis. Most questions regarding the pre-intervention situation, except for those measured directly by Klusbus servicemen (i.e., drafts, mold, humidity, temperature), were asked retrospectively in the survey. Respondents had to recall conditions from months earlier, introducing the risk of recall bias, where participants might over- or underestimate the differences between the pre and post-intervention states.

Additionally, there was a discrepancy in how the before and after situations were assessed. Questions about the pre-intervention state were framed on a scale of frequency (e.g., "How often did you experience cold before?"), whereas post-intervention questions were comparative (e.g., "Did you experience less cold after the intervention?"). This inconsistency complicates direct comparisons and introduces potential bias, especially if a control group is used that did not receive an intervention, as asking them if they experienced less cold would be inappropriate.

Future studies should ensure consistency in question framing for both pre and post-intervention conditions. Both sets of questions should be either objectively framed or comparatively framed, but not a mix of both. For example, use objective questions like "How often do you experience cold?" at both time points.

Addressing the considerations mentioned in this section can enhance the study's internal validity, strengthen the argument for the assumed causality, and yield more robust and generalizable findings.

7.4 Final conclusion

This study employed a survey and statistical and econometric models to examine the relationship between energy poverty and thermal living comfort, using the Eindhoven Klusbus as a case study.

Which households had lower comfort before the Klusbus intervention?

The study reveals that households experiencing energy poverty (i.e., frequently struggling to pay energy bills) also suffer from significantly lower-than-average thermal comfort in their homes. In addition to lower comfort levels, energy-poor households reside in poorer quality homes, adjust their behavior more to enhance their comfort or to save energy, and are overrepresented in various socioeconomic groups (more often live in social housing, lower education levels, higher energy costs, less frequently employed full-time, and fewer couples without children). This suggests that energy poverty is intertwined with other factors affecting comfort, indicating that the relationship between energy poverty and comfort is not only direct but also part of an underlying mechanism.

Furthermore, lower-than-average home comfort is associated with housing complaints (drafts and a lack of control over the indoor climate), as well as certain behavioral adjustments (minimal bedroom ventilation and wearing heavy clothing at home). Finally, low living comfort is relatively more common among the following socioeconomic groups: social housing tenants, young people, and residents of single-family dwellings.

Which households received a larger intervention from the Klusbus?

Energy-poor households received a 27% larger energy intervention (measured in terms of the total cost of measures). Certain housing characteristics (complaints about drafts, dry indoor air, and the single-family dwelling type) were also associated with larger interventions.

Which households experienced a greater comfort improvement after the Klusbus intervention and why?

All households experienced a significant increase in living comfort and a reduction in complaints after the Klusbus intervention. Contrary to expectations, however, no relationship was found between energy poverty and a greater comfort improvement post-intervention, despite the energy-poor receiving generally larger interventions.

Among all the measures implemented, anti-draft measures (draft strips and draft seal tape for doors and mailbox brushes) led to the most significant comfort improvements.

The primary driving factor in the improvement of comfort after the intervention is the enhanced housing quality, particularly the reduction of drafts. This is followed by changes in behavior after the intervention: heating less and wearing lighter clothing. This implies a mechanism whereby energy measures lead to improved housing quality and behavioral adjustments, collectively contributing to increased comfort.

In summary, addressing energy poverty requires a multifaceted approach that focuses not only on energy efficiency but also on housing quality, behavior, and socioeconomic factors. By understanding the interconnectedness of these factors and implementing targeted interventions, policymakers, housing associations, and other stakeholders can effectively reduce energy poverty and improve the comfort and well-being of vulnerable households.

7.5 Recommendations

Based on the study findings, several recommendations can be proposed for municipalities, housing associations, and other stakeholders involved in addressing energy poverty.

Firstly, the study confirms that energy-poor households experience lower comfort levels. It was particularly evident that issues such as drafts and a lack of control over the indoor environment significantly relate to comfort. Addressing these issues should be prioritized during dwelling renovations, as improving these housing conditions has been linked to substantial comfort improvements.

Additionally, the effectiveness of the existing policy program, 'De Eindhovense Klusbus', in targeting energy-poor households and enhancing their comfort has been demonstrated. It is advisable to focus on measures with proven effectiveness. Specifically, door draft seal tape, door draft strips, and mailbox brushes have shown strong associations with improved comfort. Conversely, water-saving showerheads were found to have a negative impact on comfort. No relationship was established between other energy-saving measures and comfort improvement.

The study also reveals that energy-poor individuals tend to adjust their behavior by wearing lighter clothing and reducing heating, ventilation, and showering when financially constrained. Therefore, it is essential to consider that improvements in housing conditions may lead to greater behavior adjustments among the energy-poor. These behavior adjustments, which were also observed after the Klusbus intervention, can enhance comfort but may potentially result in smaller energy savings among the energy-poor.

These recommendations aim to optimize the effectiveness of interventions targeting energy poverty by prioritizing key housing improvements and understanding the behavioral responses of energy-poor households.

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Appendices

A. Key information selected neighborhoods

Table A1. Distribution of ownerships, housing conditions, and temperature for all households that received an energy intervention in the first months of the Klusbus program.

Tenure	Percentage	Freq.
Homeowner	23.6%	358
Commercial rent	3.2%	48
'thuis	*0.3%*	*5*
Trudo	*2.2%*	*34*
Woonbedrijf	*63.6%*	*965*
Wooninc	*6.1%*	*93*
Unknown	1.0%	15
Total	100.0%	1518

Drafts	Percentage	Freq.
Never	6.2%	94
Rarely	27.5%	418
Regularly	41.2%	625
Often	15.1%	229
Always	10.0%	152
Total	100.0%	1518

Mold	Percentage	Freq.
Never	45.4%	689
Rarely	35.3%	536
Regularly	13.0%	198
Often	3.6%	55
Always	2.6%	40
Total	100.0%	1518

Humidity	Percentage	Freq.
<30%	14.0%	213
30%-60%	84.5%	1282
>60%	1.5%	23
	0.0%	

Measured temperature	Percentage	Freq.
10 °C	0.1%	2
11 °C	0.1%	1
12 °C	0.1%	2
13 °C	0.4%	6
14 °C	0.5%	8
15 °C	4.2%	64
16 °C	6.1%	93
17 °C	10.5%	160
18 °C	22.4%	340
19 °C	37.5%	570
20 °C	12.3%	187
21 °C	4.0%	60
22 °C	1.4%	22
23 °C	0.1%	2
24 °C	0.1%	1
Total	100.0%	1518

Desired temperature	Percentage	Freq.
13 °C	0.1%	1
14 °C	0.0%	0
15 °C	0.9%	13
16 °C	0.7%	11
17 °C	2.2%	33
18 °C	10.3%	157
19 °C	40.3%	611
20 °C	32.6%	495
21 °C	8.4%	127
22 °C	3.9%	59
23 °C	0.7%	11
Total	100.0%	1518

Table A2. Mean measured and preferred living room temperatures for all households that received an energy intervention.

Temperature	Mean	Range	Std Dev
Measured temperature	18.39 °C	10 - 24 °C	1.562 °C
Desired temperature	19.43 °C	13 - 23 °C	1.165 °C

Table A3. Descriptive information socioeconomic situation of the studied neighborhoods (Gemeente Eindhoven, 2023a)

Theme	Tivoli	Doornakkers-West	Kerstroosplein	Doornakkers-Oost	Eindhoven
EP rate	28%	11%	16%	24%	
Household type					
Households	815	1925	1050	1515	1093
Single-person	50%	51%	52%	53%	49%
Hh without children	20%	25%	19%	18%	25%
Hh with children	29%	24%	29%	28%	26%
Household size	1.9	1.9	1.8	1.9	1.9
Income					
Disposable hh income (€)	29,500	38,700	35,800	33,100	45,800
High income (upper 20%)	3.0%	9.7%	8.8%	6.1%	16.5%
Max 120% social minimum	35.8%	16.6%	19.2%	25.7%	13.6%
Low income (<€9250)	12.4%	7.7%	9.8%	10.6%	5.4%
Worries about money	20%	18%	18%	18%	9%
Has debts	19%	25%	30%	25%	21%
WW allowance	1%	2%	2%	2%	1%
UWV registered job seeker	4%	3%	4%	4%	6%
Energy consumption					
Electricity use (kWh)	2430	2490	2350	2380	2580
Gas use (m^3)	840	990	1070	850	910
Age					
0-14	17.0%	13.3%	14.3%	14.5%	13.6%
15-64	65.4%	72.8%	74.8%	67.7%	70.0%
>64	17.6%	13.9%	11.0%	17.8%	16.4%
Migration background					
Dutch	59.1%	55.1%	53.4%	50.9%	57.8%
Western	12.4%	16.4%	17.6%	13.8%	16.8%
Non-western	28.4%	28.5%	29.0%	35.2%	25.4%
Tenure					
Commercial rent	2%	16%	15%	6%	20%
Homeowners	6%	42%	33%	22%	43%
Social housing	92%	41%	51%	72%	37%
Dwelling type					
Multi-family	23%	26%	14%	31%	41%
Single-family	77%	74%	86%	69%	59%
Health					
Mediocre/bad health	17%	15%	13%	15%	12%
At home through illness	7%	7%	6%	7%	5%
(very) unhappy	9%	4%	8%	4%	6%
Limited social network	7%	15%	11%	15%	11%
Education					
Low	43.5%	26.7%	35.0%	39.6%	24.1%

Medium	41.7%	37.2%	33.1%	39.2%	35.0%
Highly	14.8%	36.1%	31.8%	21.2%	40.9%
Neighborhood					
Urbanization level (2023)	Strongly urban	Strongly urban	Very strongly urban	Strongly urban	Vergy strongly urban
Sometimes feels unsafe in the neighborhood	22%	30%	19%	30%	20%
Social nuisance	17%	17%	23%	17%	18%

B. Survey setup

Survey

<first screen>

Dear resident,

Last winter the Eindhoven Klusbus visited your home. It did home improvements that saved energy and improved comfort. To know how this worked out, TU Eindhoven developed a small survey. Would you please fill it in? This is important, to make the Klusbus better.

In the survey, we will ask you about the living comfort in your home before and after the Klusbus. We will also ask some questions about yourself. All answers will be processed anonymously and treated confidentially. The survey takes only 10 minutes.

Please take the time to read the questions and explanations carefully. Thank you for your participation!

If you have any questions or comments about this research, please send an email to: l.snoeren@student.tue.nl, the master student at TU Eindhoven responsible for the survey.

Next

<second screen>

Consent

First of all, thank you for participating. But before you start, we need your consent. Please read the following statements and the Information sheet <LINK > thoroughly. If you understand and agree with them, please give your consent. Please notice: if you do not consent, you will leave this questionnaire. The questionnaire takes about 10 minutes to complete.

- I agree with participation in this research
- I read the Information sheet. I was able to ask questions. I had enough time to decide whether I wanted to participate.
- I know that participation is voluntary. I also know that I can decide to quit at any moment.
- I give permission to collect and use my data to answer the research question
- I give permission for the storage of aggregated anonymized information from this research in data archives, to be used for replication purposes and future research.

Choose one of the following answers

- o I agree and wish to participate
- o I do not agree and leave the survey

Thank you for your cooperation!

<clickable pdf>

Information sheet. How much does living comfort depend on the energy efficiency of a home?

Dear Sir/Madam,

The Klusbus visited your home last winter. It made improvements to save energy and improve comfort. To know how this worked out, TU Eindhoven developed a 10-minute survey.

We ask you to fill in the survey. For this, we need your consent. Before you decide if you want to participate, we explain what the survey involves.

1. Research

This survey is a scientific research created by Luc Snoeren. Luc is a master's student at the Eindhoven University of Technology (TU/e). Luc will write his master's thesis using the survey data. He will study how much the living comfort depends on the energy efficiency of a house and the Klusbus. This is important to improve the Klusbus for other residents of Eindhoven.

2. What is expected of you

We ask you to complete a survey. This will take 10 minutes. The questions are about how comfortable your house was in the winter before and after the Klusbus, and how you heated your house. We will also ask some questions about yourself.

3. If you do not want to participate or want to stop

You decide whether to participate in the study. Participation is voluntary. If you do take part, you can always change your mind and stop anyway, even during the study. You do not have to say why you are stopping.

4. Use and storage of your data

Your data will be used for this study. It involves the following data:

• The comfort you experienced in your home in the winter before and after the Klusbus.

• How you heated your home.

• Your age group, gender, type of household, education level, address and energy costs.

The data collected are needed to answer the research questions of the survey. Eindhoven University is responsible for processing your data. None of your answers will be shared with others. None of your answers can be traced back to you in reports and publications. Your address will only be used to know which Klusbus improvements were made to your home and then removed. To protect privacy, all data will be encrypted and safely stored. The anonymized data will be stored for 10 years for replication purposes and further research about energy renovations in homes.

5. Do you have any questions?

If you have any questions, please contact the researcher Luc Snoeren via l.snoeren@student.tue.nl. If you have any complaints about the study, you can discuss them with the researcher. If you prefer not to, please contact the Data Protection Officer at Eindhoven University of Technology: dataprotectionofficer@tue.nl

For information about your rights when processing your personal data, you can consult the website of the Dutch Data Protection Authority (www.autoriteitpersoonsgegevens.nl/) or the privacy webpage of Eindhoven University of Technology (www.tue.nl/en/storage/privacy/).

Thank you for your cooperation!

Next

<third screen>

Q0.1 For how long have you been living in this dwelling?

- 0 to 2 years
- 2 or more years

Next

<fourth screen>

For the next questions, think about the winters BEFORE the Klusbus

COMFORT Q1.1: Did you suffer from cold in the living room in the winters BEFORE the Klusbus?

- Never
- Rarely
- Sometimes
- Often
- Always

SATISFACTION Q1.2: How satisfied were you with your home in the winters BEFORE the Klusbus?

- Very unsatisfied
- Unsatisfied
- Neutral
- Satisfied
- Very satisfied

QUALITY Q1.3: Did you experience shortness of breath in your home in the winters BEFORE the Klusbus?

- Never
- Rarely
- Sometimes
- Often

- Always

Next

<fifth screen>

The next questions are about how you heated your house in the winters BEFORE the Klusbus

BEHAVIOR Q1.4: Did you have the heating on in the LIVING room?

Part of the day	Yes	Partly	No
In the morning			
In the afternoon			
In the evening			
In the night			

BEHAVIOR Q1.5: Did you have the heating on in the BEDroom?

Part of the day	Yes	Partly	No
In the morning			
In the afternoon			
In the evening			
In the night			

B Q1.5a Would you prefer to heat the house more if you could?

BEHAVIOR Q1.6: Did you open the windows to ventilate the LIVING room?

- Multiple times per day
- Daily
- 5-6 times a week
- 3-4 times a week
- Twice or less per week

BEHAVIOR Q1.7: Did you open the windows to ventilate the BEDroom?

- Multiple times per day
- Daily
- 5-6 times a week
- 3-4 times a week
- Twice or less per week

B Q1.7a Would you prefer to ventilate more often if you could?

BEHAVIOR Q1.8: How many times per week did you take a shower?

- 7 or more
- 5-6
- 3-4

- 2 or less

BEHAVIOR Q1.9: What was the average length of a shower?

- Less than 5 minutes
- 5-9 minutes
- 10-14 minutes
- 15 or more minutes

B Q1.9a Would you prefer to shower longer / more often if you could?

BEHAVIOR Q1.10: Which clothes did you wear in your living room?

- ☐ Top
- ☐ Shirt
- ☐ Long-sleeved shirt
- ☐ Sweater/blazer
- ☐ Dress
- ☐ Trousers
- ☐ Skirt
- ☐ Jacket
- ☐ Open shoes
- ☐ Shoes
- ☐ Boots
- ☐ Scarf

BEHAVIOR Q1.10a: Would you prefer to wear lighter clothes if you could?

- Extremely less thick / less layers
- Much less thick / less layers
- Moderately less thick / less layers
- Slightly less thick / less layers
- Not at all

BEHAVIOR Q1.10: How often did you turn off/down ‘unnecessary’ lighting?

- Never

- Rarely
- Sometimes
- Often
- Always

CONTROL Q1.12: Did you have control over the indoor environment?

- Extremely
- Very
- Moderately
- Slightly
- Not at all

EP Q1.13: Think about last winters. Did your household have difficulty paying the energy bills?

- Never
- Rarely
- Sometimes
- Often
- Always

Next

<sixth screen>

For the next questions, think about the Klusbus visit. Do you agree with the statements below?

COMFORT Q2.1: After the Klusbus, I suffer less from cold in the living room.

- o Extremely
- o Very
- o Moderately
- o Slightly
- o Not at all

QUALITY Q2.2: After the Klusbus, I suffer less from drafts in my home.

- o Extremely
- o Very
- o Moderately
- o Slightly
- o Not at all

QUALITY Q2.3: After the Klusbus, I suffer less from mold in my home.

- o Extremely
- o Very
- o Moderately
- o Slightly
- o Not at all

QUALITY Q2.4: After the Klusbus, I suffer less from shortness of breath in my home. The air quality in my home improved.

- o Extremely
- o Very
- o Moderately
- o Slightly
- o Not at all

BEHAVIOR Q2.5: After the Klusbus, I have the heating on more often (in the living room and/or bedroom(s)).

- o Extremely
- o Very
- o Moderately
- o Slightly
- o Not at all

BEHAVIOR Q2.6: After the Klusbus, I ventilate my home more often (the living and/or bedroom(s)).

- o Extremely
- o Very
- o Moderately
- o Slightly

- Not at all

BEHAVIOR Q2.7: After the Klusbus, I take more or longer showers.

- Extremely
- Very
- Moderately
- Slightly
- Not at all

BEHAVIOR Q2.8: After the Klusbus, I wear less thick clothes in the living room.

- Extremely less thick / less layers
- Much less thick / less layers
- Moderately less thick / less layers
- Slightly less thick / less layers
- Not at all

BEHAVIOR Q2.9: After the Klusbus, I turn off / down the lighting less often.

- Extremely
- Very
- Moderately
- Slightly
- Not at all

BEHAVIOR Q2.10: After the Klusbus, I have more control over the indoor environment.

- Extremely
- Very
- Moderately
- Slightly
- Not at all

BEHAVIOR Q2.11 What was the average temperature in the living room after the Klusbus?

Next

<seventh page>

Could you tell us a bit about yourself

SOCIO Q3.1: To what age group do you belong?

- o <25
- o 25-34
- o 35-44
- o 45-54
- o 55-64
- o 65-74
- o 75 or older

SOCIO Q3.2: What is your highest completed education level?

- o Primary school
- o VMBO, lower half HAVO/VWO, MBO level 1 or 2
- o MBO, HAVO, VWO completed
- o HBO, WO Bachelor
- o WO Master, PhD
- o Other

SOCIO Q3.3: What is your household composition?

- o Single
- o Couple without child(ren) living at home
- o Single parent with child(ren) living at home
- o Couple with child(ren) living at home
- o Other

SOCIO Q3.4: What do you pay for ENERGY (GAS+ELECTRICITY+WATER) per month (do NOT include any governmental subsidies such as energy refunds and energy allowance)?

- o Less than 60eu per month
- o 61 to 120eu per month
- o 121 to 180eu per month
- o 181 to 240eu per month
- o 241 to 300eu per month
- o More than 300eu per month
- o I do not know

SOCIO Q3.5: What is your gender?

- o Male
- o Female
- o Prefer not to say / other

SOCIO Q3.6: What is the employment status of your household?

- o All adults work full-time (32 hours a week or more)
- o One adult works full-time (32 hours a week or more)

- All adults are retired
- Other

SOCIO Q3.7: In what type of house do you live?

- Multi-family house (apartment)
- Terraced house
- Corner house
- Semi-detached house
- Detached house

SOCIO Q3.8: What is your living sit

- Owner-occupier
- Social rent
- Other rent

SOCIO Q3.10: Are you an energy-conscious person

- Extremely
- Very
- Moderately
- Slightly
- Not at all

Next

<eighth screen>

This is the end of the survey. Thank you!

Q4.1: If you like to share any questions or comments, please use the space below.

C. Data Preparation

Table C1. Replacement of missing values by the mean

Variable	Missing cases	Replaced by mean
Temperature	1	18˚C
Desired temperature	1	19˚C
Drafts	2	2. Sometimes
Mold	4	1. Rarely
Humidity	2	0. 30%<->60%

Table C2. Transformation and computation of some of the variables for the regression analyses.

Variable	Old variable	Old values	Recode	New values
Energy-poor	Difficulty paying the energy bills	-2= Never -1= Rarely 0= Sometimes 1= Often 2= Always	-2= 0 -1= 0 0= 0 1= 0 2 = 1	0 = no 1= yes
Socioeconomic				
Social rent	Tenure	1= Homeowner 2= Social rent 3= Other rent	1= 0 2= 1 3= 0	0 = no 1= yes
Younger than 35	Age	-3= Younger than 25 -2= 25-34 -1= 35-44 0= 45-54 1= 55-64 2= 65-74 3= 75 or older	-3= 1 -2= 1 -1= 0 0= 0 1= 0 2= 0 3= 0	0 = no 1= yes
Older than 64	Age	-3= Younger than 25 -2= 25-34 -1= 35-44 0= 45-54 1= 55-64 2= 65-74 3= 75 or older	-3= 0 -2= 0 -1= 0 0= 0 1= 0 2= 1 3= 1	0 = no 1= yes
Is single	Household composition	1= Single 2= Couple without child(ren) 3= Single parent with child(ren) 4= Couple with child(ren) 5= Other	1= 1 2= 0 3= 0 4= 0 5= 0	0 = no 1= yes
Household with children	Household composition	1= Single 2= Couple without child(ren)	1= 0 2= 0 3= 1 4= 1	0 = no 1= yes

		3= Single parent with child(ren) 4= Couple with child(ren) 5= Other	5= 0	
Work not full-time / not retired	Work	1= All adults work full-time (32 hours or more) 2= One adult works full-time 3= All adults are retired 4= Other	1= 0 2= 0 3=0 4=1	0 = no 1= yes
Female	Gender	1= Male 2= Female 3= Prefer not to say / other	1=0 2=1 3=0	0 = no 1= yes
Low educated	Education	1= Primary school 2= vmbo, lower half havo/vwo, mbo level 1 or 2 3= mbo, havo, or vwo completed 4= hbo/wo bachelor 5= wo master, PhD	1=1 2=1 3=0 4=0 5=0	0 = no 1= yes
Medium educated	Education	1= Primary school 2= vmbo, lower half havo/vwo, mbo level 1 or 2 3= mbo, havo, or vwo completed 4= hbo/wo bachelor 5= wo master, PhD	1=0 2=0 3=1 4=0 5=0	0 = no 1= yes
Highly educated	Education	1= Primary school 2= vmbo, lower half havo/vwo, mbo level 1 or 2 3= mbo, havo, or vwo completed 4= hbo/wo bachelor 5= wo master, PhD	1=0 2=0 3=0 4=1 5=1	0 = no 1= yes
Energy conscious		-2= Extremely -1= Very 0= Moderately 1= Slightly 2= Not at all	-2= 0 -1= 0 0= 0 1= 1 2= 2	0 = no 1= yes
Housing (quality)				
Apartment	Dwelling type	1= Multi-family house 2= In-between house 3= Corner house	1=1 2=0 3=0	0 = no 1= yes

		4= Semi-detached house 5= Detached house	4=0 5=0	
Dry	Humidity	-1= <30% 0= 30%<->60% 1= >60%	-1= 1 0= 0 1= 0	0 = no 1= yes
Humid	Humidity	-1= <30% 0= 30%<->60% 1= >60%	-1= 0 0= 0 1= 1	0 = no 1= yes
Behavior				
Temperature Centered	Temperature	Continuous	Temperature – mean(temperature)	Continuous
Heating liv morning	Heating living room	1= Morning 2= Afternoon 3= Evening 4= Night A= Yes B= Partly C= No	1A = 1 1B = 1 1C = 0	0 = no 1= yes
Heating liv afternoon	Heating living room	1= Morning 2= Afternoon 3= Evening 4= Night A= Yes B= Partly C= No	2A = 1 2B = 1 2C = 0	0 = no 1= yes
Heating liv evening	Heating living room	1= Morning 2= Afternoon 3= Evening 4= Night A= Yes B= Partly C= No	3A = 1 3B = 1 3C = 0	0 = no 1= yes
Heating liv night	Heating living room	1= Morning 2= Afternoon 3= Evening 4= Night A= Yes B= Partly C= No	4A = 1 4B = 1 4C = 0	0 = no 1= yes
Heating bed morning	Heating bedroom(s)	1= Morning 2= Afternoon 3= Evening 4= Night A= Yes B= Partly C= No	1A = 1 1B = 1 1C = 0	0 = no 1= yes
Heating bed afternoon	Heating bedroom(s)	1= Morning 2= Afternoon 3= Evening	2A = 1 2B = 1 2C = 0	0 = no 1= yes

		4= Night A= Yes B= Partly C= No		
Heating bed evening	Heating bedroom(s)	1= Morning 2= Afternoon 3= Evening 4= Night A= Yes B= Partly C= No	3A = 1 3B = 1 3C = 0	0 = no 1= yes
Heating bed night	Heating bedroom(s)	1= Morning 2= Afternoon 3= Evening 4= Night A= Yes B= Partly C= No	4A = 1 4B = 1 4C = 0	0 = no 1= yes
Light clothes	Clothes	Multiple options possible 1= Top 2= T-shirt 3= Long-sleeved shirt 4= Sweater-blazer 5= Dress 6= Trousers 7= Skirt 8= Jacket 9= Open shoes 10= Shoes 11= Boots 12= Scarf	If 4, 8, AND 12 = 0, then 1, else 0	0 = no 1= yes
Medium clothes	Clothes	Multiple options possible 1= Top 2= T-shirt 3= Long-sleeved shirt 4= Sweater-blazer 5= Dress 6= Trousers 7= Skirt 8= Jacket 9= Open shoes 10= Shoes 11= Boots 12= Scarf	If 4 OR 8 = 1, AND 12 = 0 then, 1, else 0	0 = no 1= yes
Thick clothes	Clothes	Multiple options possible 1= Top 2= T-shirt	If 12=1, then 1, else 0	0 = no 1= yes

		3= Long-sleeved shirt 4= Sweater-blazer 5= Dress 6= Trousers 7= Skirt 8= Jacket 9= Open shoes 10= Shoes 11= Boots 12= Scarf		
Measures				
Anti-draft measures	Draft strip door Door brush Mailbox brush Door draft seal tape Window draft strip	Continuous	= draft strip door + door brush + mailbox brush + door draft seal tape + window draft strip	Continuous
Efficiency measures	Radiator foil LED light Water-saving showerhead Timer switch Low-flow aerators	Continuous	= Radiator foil + LED light + Water-saving showerhead + Timer switch + Low-flow aerators	Continuous
Behavior adjustment				
Heat less	Heating duration after	-2= Much less -2= Less 0= Not less / not more 1= More 2= Much more	-2= 1 -1= 1 0= 0 1= 0 2= 0	0 = no 1= yes
Heat more	Heating duration after	-2= Much less -2= Less 0= Not less / not more 1= More 2= Much more	-2= 0 -1= 0 0= 0 1= 1 2= 1	0 = no 1= yes
Ventilate less	Ventilating frequency after	-2= Much less -2= Less 0= Not less / not more 1= More 2= Much more	-2= 1 -1= 1 0= 0 1= 0 2= 0	0 = no 1= yes
Ventilate more	Ventilating frequency after	-2= Much less -2= Less 0= Not less / not more 1= More 2= Much more	-2= 0 -1= 0 0= 0 1= 1 2= 1	0 = no 1= yes

D. Correlation matrices

Before the Klusbus

Table D1. Pearson correlation matrix of the housing quality cluster. Red: correlation greater than 0.5.

	Drafts	Mold	Dry air (<30% humidity)	Humid	Lack of fresh air	Lack of control indoor environment	Energy-poor
Drafts	1	0.19	-0.015	0.067	-0.105	0.047	0.183
Mold	0.19	1	-0.003	0.015	-0.18	0.027	0.128
Dry air (<30% humidity)	-0.015	-0.003	1	-0.091	0.004	0.06	-0.116
Humid	0.067	0.015	-0.091	1	0.06	0.133	0.076
Lack of fresh air	-0.105	-0.18	0.004	0.06	1	-0.154	-0.206
Lack of control indoor environment	0.047	0.027	0.06	0.133	-0.154	1	0.162
Energy-poor	0.183	0.128	-0.116	0.076	-0.206	0.162	1

Table D2. Pearson correlation matrix of the socioeconomic cluster. Red: correlation greater than 0.5.

	Social rent	Younger than 35	Older than 64	Single-person household	Household with children	Work not full-time / not retired	Female	Highly educated	apartment	Very energy conscious	Energy-poor
Social rent	1	-0.225	0.122	0.193	0.018	0.265	0.077	-0.393	0.214	-0.175	0.176
Younger than 35	-0.225	1	-0.269	-0.17	-0.012	0.026	0.021	0.067	0.073	0.129	0.012
Older than 64	0.122	-0.269	1	0.164	-0.394	-0.177	-0.059	-0.292	0.069	-0.018	-0.002
Single-person household	0.193	-0.17	0.164	1	-0.526	0.05	0.012	0.012	0.192	-0.11	0.068
Household with children	0.018	-0.012	-0.394	-0.526	1	0.038	0.117	0.02	-0.134	0.071	0.078
Work not full-time / not retired	0.265	0.026	-0.177	0.05	0.038	1	0.032	-0.273	-0.003	0.094	0.214
Female	0.077	0.021	-0.059	0.012	0.117	0.032	1	-0.059	-0.073	-0.087	-0.024
Highly educated	-0.393	0.067	-0.292	0.012	0.02	-0.273	-0.059	1	-0.034	0.114	-0.182
Apartment	0.214	0.073	0.069	0.192	-0.134	-0.003	-0.073	-0.034	1	-0.079	-0.024
Very energy conscious	-0.175	0.129	-0.018	-0.11	0.071	0.094	-0.087	0.114	-0.079	1	0.043
Energy-poor	0.176	0.012	-0.002	0.068	0.078	0.214	-0.024	-0.182	-0.024	0.043	1

Table D3. Pearson correlation matrix of the behavior cluster. Red: correlation greater than 0.5.

		Heating liv morning	Heating liv afternoon	Heating liv evening	Heating liv night	Heating bed morning	Heating bed afternoon	Heating bed evening	Heating bed night	Shower freq.	Shower length	Ventilate liv	Ventilate bed	Thick clothes	Light clothes	Turn off lights
Heating liv morning	1.000	0.276	0.223	0.179	0.179	0.022	0.077	0.056	-0.053	0.048	0.023	-0.088	-0.068	0.093	-0.097	-0.025
Heating liv afternoon	0.276	1.000	0.102	0.181	-0.016	0.199	0.048	0.017	0.059	0.029	0.065	0.041	0.081	0.021	-0.051	0.077
Heating liv evening	0.223	0.102	1.000	0.121	0.050	0.037	0.166	0.107	0.077	0.051	0.069	0.123	-0.097	0.082	-0.109	-0.013
Heating liv night	0.179	0.181	0.121	1.000	0.423	0.316	0.331	0.551	-0.046	0.232	0.235	-0.026	0.107	0.120	-0.125	0.134
Heating bed morning	0.179	-0.016	0.050	0.423	1.000	0.599	0.632	0.634	-0.075	0.091	0.030	-0.225	0.057	0.070	0.058	0.209
Heating bed afternoon	0.022	0.199	0.037	0.316	0.599	1.000	0.570	0.478	0.003	0.142	0.158	-0.126	0.033	-0.010	-0.011	0.295
Heating bed evening	0.077	0.048	0.166	0.331	0.632	0.570	1.000	0.538	0.051	0.221	0.108	-0.225	0.084	0.100	-0.006	0.237
Heating bed night	0.056	0.017	0.107	0.551	0.634	0.478	0.538	1.000	0.022	0.061	0.151	-0.097	-0.007	0.057	-0.021	0.240
Shower freq.	-0.053	0.059	0.077	-0.046	-0.075	0.003	0.051	0.022	1.000	0.005	-0.094	-0.035	0.018	-0.027	-0.024	-0.077
Shower length	0.048	0.029	0.051	0.232	0.091	0.142	0.221	0.061	0.005	1.000	0.074	-0.096	0.108	0.059	-0.081	0.028
Ventilate liv	0.023	0.065	0.069	0.235	0.030	0.158	0.108	0.151	-0.094	0.074	1.000	0.449	0.023	0.124	-0.179	0.210
Ventilate bed	-0.088	0.041	0.123	-0.026	-0.225	-0.126	-0.225	-0.097	-0.035	-0.096	0.449	1.000	0.032	-0.034	-0.172	-0.001
Thick clothes	-0.068	0.081	-0.097	0.107	0.057	0.033	0.084	-0.007	0.018	0.108	0.023	0.032	1.000	-0.127	-0.105	0.093
Light clothes	0.093	0.021	0.082	0.120	0.070	-0.010	0.100	0.057	-0.027	0.059	0.124	-0.034	-0.127	1.000	-0.131	0.008
Turn off lights	-0.097	-0.051	-0.109	-0.125	0.058	-0.011	-0.006	-0.021	-0.024	-0.081	-0.179	-0.172	-0.105	-0.131	1.000	-0.050
Energy-poor	-0.025	0.077	-0.013	0.134	0.209	0.295	0.237	0.240	-0.077	0.028	0.210	-0.001	0.093	0.008	-0.050	1.000

Energy interventions

Table D4. Pearson correlation matrix of the energy measures. Red: correlation greater than 0.5.

	Radiator foil	LED light	Water-saving showerhead	Draft strip door	Timer switch	Door brush	Mailbox brush	Door draft seal tape	Low-flow aerator	d Window draft strip	Pipe insulation	Door closer	Gap sealing	Tot points	Points corrected	Energy-poor
Radiator foil	1.000	-0.226	-0.084	-0.102	-0.126	-0.027	-0.067	-0.064	-0.184	-0.001	0.127	0.030	0.030	0.559	0.270	0.260
LED light	-0.226	1.000	0.156	-0.067	0.242	-0.064	0.103	0.208	0.311	-0.039	-0.087	-0.055	0.024	0.375	-0.243	-0.084
Water-saving showerhead	-0.084	0.156	1.000	0.058	0.181	-0.019	0.111	0.064	0.334	-0.053	-0.090	-0.111	0.050	0.328	-0.012	0.026
Draft strip door	-0.102	-0.067	0.058	1.000	0.022	0.377	0.262	-0.005	0.155	0.211	-0.061	-0.075	-0.075	0.340	-0.117	0.137
Timer switch	-0.126	0.242	0.181	0.022	1.000	0.058	0.233	0.143	0.366	-0.030	0.079	0.201	-0.065	0.314	-0.075	-0.106
Door brush	-0.027	-0.064	-0.019	0.377	0.058	1.000	0.151	-0.054	0.031	0.106	-0.005	0.081	-0.058	0.190	0.110	0.222
Mailbox brush	-0.067	0.103	0.111	0.262	0.233	0.151	1.000	-0.002	0.151	0.115	-0.090	-0.052	-0.052	0.274	-0.071	-0.073
Door draft seal tape	-0.064	0.208	0.064	-0.005	0.143	-0.054	-0.002	1.000	0.169	0.158	-0.069	-0.040	-0.040	0.176	-0.078	-0.161
Low-flow aerator	-0.184	0.311	0.334	0.155	0.366	0.031	0.151	0.169	1.000	0.147	-0.061	-0.038	-0.038	0.300	-0.235	-0.010
Window draft strip	-0.001	-0.039	-0.053	0.211	-0.030	0.106	0.115	0.158	0.147	1.000	-0.035	-0.020	-0.020	0.177	0.008	-0.035
Pipe insulation	0.127	-0.087	-0.090	-0.061	0.079	-0.005	-0.090	-0.069	-0.061	-0.035	1.000	-0.011	-0.011	0.119	0.080	0.174
Door closer	0.030	-0.055	-0.111	-0.075	0.201	0.081	-0.052	-0.040	-0.038	-0.020	-0.011	1.000	-0.006	-0.005	0.116	-0.044
Gap sealing	0.030	0.024	0.050	-0.075	-0.065	-0.058	-0.052	-0.040	-0.038	-0.020	-0.011	-0.006	1.000	0.033	-0.047	0.149
Tot points	0.559	0.375	0.328	0.340	0.314	0.190	0.274	0.176	0.300	0.177	0.119	-0.005	0.033	1.000	0.025	0.240
Points corrected	0.270	-0.243	-0.012	-0.117	-0.075	0.110	-0.071	-0.078	-0.235	0.008	0.080	0.116	-0.047	0.025	1.000	0.156
Energy-poor	0.260	-0.084	0.026	0.137	-0.106	0.222	-0.073	-0.161	-0.010	-0.035	0.174	-0.044	0.149	0.240	0.156	1.000

After the Klusbus

Table D5. Pearson correlation matrix of the housing improvement cluster. Red: correlation greater than 0.5.

	Less drafts	More fresh air	Less mold	More control	EP
Less drafts	1	0.341	0.28	0.586	-0.017
More fresh air	0.341	1	0.576	0.43	0.149
Less mold	0.28	0.576	1	0.325	0.219
More control	0.586	0.43	0.325	1	0.055
EP	-0.017	0.149	0.219	0.055	1

Table D6. Pearson correlation matrix of the behavior adjustment cluster. Red: correlation greater than 0.5.

	Heat more	Heat less	Heat less	Ventilate less	Shower more/longer	Lighter clothes	Turn off unnecessary lights less	Energy-poor
Heat more	1.000	-0.093	0.101	-0.037	0.169	0.268	0.138	-0.011
Heat less	-0.093	1.000	0.126	0.228	-0.047	0.218	0.021	-0.009
Ventilate more	0.101	0.126	1.000	-0.053	0.131	0.045	0.090	0.047
Ventilate less	-0.037	0.228	-0.053	1.000	0.143	0.109	0.254	0.052
Shower more/longer	0.169	-0.047	0.131	0.143	1.000	0.246	0.238	0.203
Lighter clothes	0.268	0.218	0.045	0.109	0.246	1.000	0.345	0.222
Turn off unnecessary lights less	0.138	0.021	0.090	0.254	0.238	0.345	1.000	0.132
Energy-poor	-0.011	-0.009	0.047	0.052	0.203	0.222	0.132	1.000

E. Temperature

Table E1. Mean measured temperatures (and count of responses) per month among the sub-samples.

Month (average outside temperature (KNMI, 2023))	All	Non-EP	EP 1	EP 2
December (3.9 ˚C)	18.40 ˚C (15)	18.29 ˚C (7)	18.50 ˚C (8)	18.86 ˚C (7)
January (5.8 ˚C)	18.43 ˚C (30)	18.38 ˚C (16)	18.50 ˚C (14)	18.33 ˚C (6)
February (5.7 ˚C)	18.43 ˚C (37)	18.60 ˚C (25)	18.08 ˚C (12)	18.33 ˚C (9)
March (7.5 ˚C)	18.16 ˚C (69)	18.47 ˚C (38)	17.77 ˚C (31)	17.33 ˚C (12)
April (8.7 ˚C)	17.50 ˚C (4)	18.00 ˚C (2)	17.00 ˚C (2)	18.00 ˚C (1)
Average	18.28 ˚C (155)	18.47 ˚C	18.04 ˚C (67)	18.09 ˚C (35)
Range	13 - 22 ˚C	15 - 22 ˚C	13 - 22 ˚C	13 - 22 ˚C
Std Dev	1.666 ˚C	1.508 ˚C	1.838 ˚C	1.961 ˚C

F. Bivariate Analysis: Characteristics of the Energy-poor

In this section, a detailed analysis is conducted to study the differences between the energy-poor and non-energy-poor. Statistical tests are performed to check whether the characteristics of the energy-poor are also statistically different from those of non-energy-poor. This way, insight and understanding of the data is gained. Furthermore, it can be verified whether the Klusbus program accurately its intended target group: those experiencing energy poverty.

F.1 Socioeconomic characteristics of the energy-poor

This section explores whether energy-poor households have different socioeconomic characteristics than non-energy-poor households. Table F1 outlines the average socioeconomic characteristics for each energy poverty group as collected in the survey: age, education level, household type, energy costs, gender, employment status, tenure, and energy consciousness. The socioeconomic characteristics were measured in binary (no-yes) or on an ordinal Likert scale. For the ordinal variables, the distribution across each category is listed below the average value. The second-to-last and last columns indicate if EP1 or EP2, respectively, have a socioeconomic characteristic significantly different from non-energy-poor. The differences found are discussed below. Figure F1 provides a detailed explanation of how to read the table.

No significant differences are found in the age distribution between energy-poor and non-energy-poor households. However, the energy-poor are less highly educated than non-energy-poor. The more severe the energy poverty, the lower the education: both EP1 and EP2 groups (in descending order) have lower education levels than non-energy-poor. This is particularly evident in the group with higher education, where significantly fewer energy-poor individuals (both EP1 and EP2) are present compared to non-energy-poor individuals. Additionally, EP2 households are less likely to be without children living at home. No other differences in household type were found for the energy-poor.

The most critical factors influencing energy poverty are energy costs and income. Energy-poor households have relatively higher energy costs than non-EP households, with EP1 and EP2 groups having increasingly higher energy costs compared to non-energy-poor households. No significant differences were found in the gender distribution among the subgroups.

Reading instructions Table F1-F4, F6-F7, F9-F11

The tables in this chapter can be interpreted as follows:

- Column 1 lists the relevant variables. Some variables consist of several categories or levels. These levels are given below the variable to which they belong.
- Column 2 to 4 display the mean value of the continuous and ordinal variables for each energy poverty subgroups first. The distribution across each level of the variables is presented as a percentage below the variable's average. For categorical variables, only the percentage distribution is given.
- Column 5 to 6 give the results (the one-tail p-value) of the t-tests of difference. Column 5 tests whether there is a statistically significant difference in average between EP1 and non-EP, while column 6 assesses the difference between EP2 and non-EP. A p-value below 0.10 indicates a significant difference in average between the two tested groups.

Figure F1. Explanation how to read the tables in this chapter.

Energy-poor households (EP2) are less likely to have full-time employment compared to non-energy-poor households. For EP1, energy-poor individuals are also less likely to be retired. Instead, the 'other' employment category is overrepresented among both EP groups compared to non-energy-poor households. Among energy-poor households, the proportion of social rent is much higher for both EP groups.

Almost all respondents indicated that they are at least somewhat energy-conscious. However, energy-poor households were not found to be more energy-conscious compared to non-energy-poor households.

Table F1. Average socioeconomic characteristics for each energy poverty group. The p-value in the last two columns shows whether the socioeconomic characters were significantly more or less prevalent compared to non-EP among EP1 and EP2, respectively. Source: survey.

Variable (range)	Mean / frequency distribution EP1	Mean / frequency distribution EP2	Mean / frequency distribution non-EP	P-value EP1 vs non-EP	p-value EP2 vs non-EP
Age (-3,3)	0.42	0.43	0.48	0.409	0.437
-3. Younger than 25	0%	0%	3%		
-2. 25 - 34	18%	14%	7%		
-1. 35 - 44	15%	17%	17%		
0. 45 - 54	15%	17%	24%		
1. 55 - 64	22%	20%	16%		
2. 65 - 74	19%	26%	26%		
3. 75 or older	10%	6%	8%		
Education (1,5)	2.93	2.71	3.28	0.028 **	0.008 ***
Low educated	31%	37%	27%	0.293	0.153
Medium educated	10%	11%	7%	0.217	0.226
Highly	30%	23%	47%	0.016 **	0.005 ***
Household type					
Single	48%	51%	43%	0.287	0.208
Couple without children	22%	11%	28%	0.197	0.011 **
Single parent with children	10%	11%	7%	0.217	0.226
Couple with children	15%	20%	18%	0.295	0.411
Other	4%	6%	3%	0.370	0.303
Energy costs (1,7)	3.72	3.83	3.40	0.080 *	0.063 *
1. Less than 60 per month	4%	3%	2%		
2. 61 to 120 per month	12%	9%	27%		
3. 121 to 180 per month	33%	37%	32%		
4. 181 to 240 per month	24%	26%	21%		
5. 241 to 300 per month	13%	9%	7%		
6. More than 300 per month	12%	14%	8%		
7. I don't know	1%	3%	3%		
Female	0.54	0.57	0.64	0.109	0.258
Employment status					
All adults work full-time	19%	11%	26%	0.161	0.022 **
One adult works full-time	19%	20%	21%	0.436	0.478
All adults are retired	21%	20%	31%	0.083 *	0.105
Other	40%	49%	23%	0.011 **	0.005 ***
Tenure					
Homeowner	27%	23%	48%	0.004 ***	0.004 ***
Social rent	63%	69%	44%	0.011 **	0.007 ***
Other rent	10%	9%	8%	0.300	0.456

Energy consciousness (0,4)	2.51	2.57	2.39	0.163	0.125
0. Not at all	0%	0%	1%		
1. Slightly	9%	9%	10%		
2. Moderately	39%	37%	40%		
3. Very	45%	43%	10%		
4. Extremely	8%	11%	2%		

*Note: ***,**,*: Statistical significance level 1%, 5%, 10%.*
Note: See Figure F1 for table reading instructions.

Conclusion

What are the most notable socioeconomic characteristics of sample and the energy-poor households in this study? The sample does not reflect the demographics of the Netherlands, as certain socioeconomic characteristics are more prevalent in the studied neighborhoods compared to the national average. Specifically, the sample comprises relative few young individuals and homeowners, but a higher proportion of single-person households, females, persons living in terraced houses, and social renters.

The results of the statistical tests indicate that the energy-poor tend to have lower levels of education, are substantially less likely to be couples without children, incur higher energy costs, have lower rates of full-time employment but are overrepresented in the ‘other’ employment category, are far fewer in homeownership, and more commonly reside in social rental housing. There is no clear tendency towards a higher or lower energy consciousness among energy-poor households compared to others.

F.2 Before the Klusbus

The situation studied before the Klusbus renovations considers factors regarding comfort level, housing quality, and behavior to conserve energy. These factors are compared between the energy-poor and non-energy-poor to determine whether energy-poor households compromise on comfort, reside in inferior housing conditions, and exhibit different energy conservation behaviors compared to non-energy-poor households. Statistical tests are conducted to ascertain the differences between the energy-poor and non-energy-poor.

Comfort

The energy-poor are expected to compromise on comfort. Table F2 presents, for each subgroup, the average thermal living comfort before the Klusbus intervention. Comfort was assessed in the survey and is measured as the frequency of experiencing cold in the living room. The distribution across each category of comfort is provided below the average. The last two columns indicate whether the average comfort level of EP1 and EP2, respectively, were significantly lower or higher than that of non-EP.

Column 1 reveals that, on average, respondents in the sample *sometimes* experienced cold. However, energy-poor households, both EP groups, experienced significantly lower comfort levels compared to non-energy-poor households. The broad energy-poor group experienced cold *sometimes*, while the narrow group experienced cold *often.* In contrast, non-energy-poor households experienced cold *rarely* to *sometimes*, on average.

Table F2. Average comfort for each energy poverty group. The p-value in the last two columns shows whether EP1 or EP2, respectively, reported significantly more or fewer complaints about housing quality than non-EP. Source: survey.

Variable (range)	Mean / frequency distribution EP1	Mean / frequency distribution EP2	Mean / frequency distribution non-EP	P-value EP1 vs non-EP	p-value EP2 vs non-EP
Cold in living room (**comfort**) (-2,2)	-0.28	-0.8	0.30	0.001 ***	0.000 ***
-2 Always (0/1)	21%	31%	8%		
-1 Often (0/1)	22%	29%	17%		
0 Sometimes (0/1)	25%	29%	25%		
1 Rarely (0/1)	27%	11%	38%		
2 Never (0/1)	5%	0%	13%		

*Note: ***,**,*: Statistical significance level 1%, 5%, 10%.*
Note: See Figure F1 for table reading instructions.

Housing and housing quality

This section aims to understand the extent to which the Klusbus participants experienced issues with housing quality and whether energy-poor households reported more complaints about housing quality compared to non-energy-poor households. Several complaints (i.e., about drafts, mold, and humidity) were asked or measured by the Klusbus servicemen during the intervention. The other complaints (i.e., about a lack of fresh air, lack of control over the indoor environment, and overall satisfaction with the dwelling) and dwelling type were surveyed after the intervention.

Tables F3A and F3B give, for each subgroup, the dwelling type and average complaints about housing quality. These complaints were measured on a (five-point) Likert scale, mostly ranging from '*never*' to '*always*' experiencing the issue. The distribution across each category of the complaint is listed below the average. The penultimate column indicates if the first energy-poor group (EP1) reported significantly more or fewer complaints compared to non-energy-poor, and the final column does the same for the second energy-poor group (EP2) and non-energy-poor. The differences found are discussed below.

First, the distribution of different dwelling types is relatively equal between energy-poor and non-EP households, with too few respondents living in (semi)-detached dwellings to test for differences in these categories. Moving on to housing quality, one particular housing complaint that led to discomfort was drafts. On average, the participants *sometimes* experienced drafts. EP 2 experienced significantly more drafts than non-energy-poor households, while no significant difference was found between EP 1 and non-energy-poor households.

Draft-related discomfort may be linked to air quality in the dwellings. Energy-poor households *rarely* to *sometimes* lacked fresh air, which was significantly more than non-energy-poor, who reported *never* to *rarely* lacking fresh air. EP1 did not report lacking fresh air more often than non-energy-poor households.

Related to fresh air is the humidity level. Less than 30% is considered dry, 30%-60% is considered neutral, and more than 60% is considered humid, which can lead to the mold formation (Clean Air Optima, 2023). EP 2 exhibited fewer issues with excessively dry or humid indoor air levels than non-energy-poor. For EP1, no significant difference was found compared to non-EP.

As mentioned, humid air conditions could lead to mold formation. Mold was a less prevalent issue, with the average respondent experiencing it *never* to *rarely*. However, mold occurred slightly more often among EP 2 than among non-EP. No difference was found between EP 1 and non-energy-poor households.

Moreover, on average, the respondents had a *slight* to *moderate* lack of control over the indoor environment. Energy-poor households experienced a larger lack of control. The EP2 reported a *moderate* lack of control, which was significantly more than non-EP.

The assessments of indoor environmental quality discussed above undoubtedly influence individuals' overall satisfaction with their dwelling. The stronger the energy poverty, the more dissatisfied with the dwelling, with EP2 reporting *slightly unsatisfied* to *neutral*, EP1 reporting *neutral*, and non-EP reporting *neutral* to *satisfied*.

Table F3A and F3B. Average housing quality for each energy poverty group. The p-value in the last two columns shows whether EP1 or EP2, respectively, reported significantly more or fewer complaints about housing quality than non-EP. Source 3A: (Gemeente Eindhoven, 2023). Source 3B: survey.

F3A. Klusbus data

Variable (range)	Mean / frequency distribution EP1	Mean / frequency distribution EP2	Mean / frequency distribution non-EP	P-value EP1 vs non-EP	p-value EP2 vs non-EP
Dwelling type					
Apartment	15%	11%	11%	0.261	0.496
In-between house	67%	71%	66%	0.435	0.277
Corner house	16%	17%	19%	0.321	0.390
Semi-detached house	0%	0%	3%	-	-
Detached house	2%	0%	0%	-	-
Drafts (0,4)	2.01	2.37	1.99	0.442	0.048 **
0. Never	8%	3%	3%		
1. Rarely	28%	23%	35%		
2. Sometimes	34%	31%	31%		
3. Often	15%	20%	21%		
4. Always	15%	23%	10%		
Humidity (-1,1)	-0.16	-0.06	-0.17	0.466	0.095 *
-1. <30%	19%	11%	21%		
0. 30%<->60%	78%	83%	76%		
1. >60%	3%	6%	3%		
Mold (0,4)	0.52	0.74	0.52	0.499	0.138
0. Never	72%	57%	66%		
1. Rarely	13%	20%	23%		
2. Sometimes	9%	17%	7%		
3. Often	3%	3%	2%		
4. Always	3%	3%	2%		

F3B. Survey data

Variable (range)	Mean / frequency distribution EP1	Mean / frequency distribution EP2	Mean / frequency distribution non-EP	P-value EP1 vs non-EP	p-value EP2 vs non-EP
Lack of fresh air (0,4)	1.70	1.91	1.48	0.004	0.038 **
0. Never	25%	23%	44%		
1. Rarely	49%	46%	44%		
2. Sometimes	16%	20%	7%		
3. Often	9%	11%	5%		

4. Always	0%	0%	0%		
Lack of control indoor environment (0,4)	1.70	1.91	1.48	0.115	0.038 **
0. Not at all	18%	17%	23%		
1. Slightly	27%	17%	31%		
2. Moderately	30%	34%	24%		
3. Very	18%	20%	22%		
4. Totally	7%	11%	1%		
Satisfaction (-2,2)	-0.01	-0.26	0.42	0.003 ***	0.001 ***
-2. Very unsatisfied	9%	17%	3%		
-1. Unsatisfied	22%	23%	10%		
0. Neutral	33%	31%	33%		
1. Satisfied	33%	26%	48%		
2. Very satisfied	3%	3%	6%		

*Note: ***, **, *: Statistical significance level 1%, 5%, 10%.*
Note: See Figure F1 for table reading instructions.

Behavior

This section aims to find whether energy-poor households adjusted their behavior differently to reduce energy consumption or enhance comfort. Table F4 outlines, for each energy poverty group, the average behavior: heating and ventilating the living room and bedroom(s), shower frequency and length, turning off unnecessary lights, clothing, and room temperature. Behaviors were asked in the survey and measured binary (no-yes) or on an ordinal Likert scale. Indoor temperature was measured by the Klusbus servicemen. For the ordinal variables, the distribution across each category is listed below the average value. The last two columns indicate whether EP1 and EP2 engaged statistically significantly more or less in each behavior compared to non-EP.

Most households only heat their living room (or partly), and only throughout the day. Heating of bedrooms is much less common, but both EP groups heat their bedroom(s) significantly more than non-EP households throughout all parts of the day. During the *afternoon* and *night*, energy-poor households heat their bedrooms two and a half times more frequently compared to non-energy-poor households, with EP2 showing this difference increase to three and a half times. The energy-poor also heat their living room more than non-EP throughout the night.

Does this suggest that energy-poor households are less conscious about their energy consumption? Connecting the relative 'overconsumption' of heating with the lower thermal comfort experience by the energy-poor compared to non-energy-poor households supports the hypothesis made in the previous section. It seems that the energy-poor need to heat their home more (often) to reach a somewhat acceptable comfort level, which is still lower than that of non-energy-poor households. This suggests that the energy-poor in this study's sample indeed live in dwellings of lower quality.

Secondly, ventilation behavior was inquired. EP2 households ventilated the living room significantly more often than non-energy-poor households. EP2 ventilated their living room about 5 to 6 times per week, while non-EP only ventilated about 4 times per week. The fact that energy-poor households ventilate more often could be linked to their greater lack of fresh air, as stated in the previous section.

While the frequency of ventilation in *bedrooms* is higher than in living rooms, no statistical difference was found in the ventilation behavior of the bedrooms for energy-poor compared to non-energy-poor. Similarly, no statistical differences were found in shower frequency, shower length, turning off unnecessary lights, or clothing between EP and non-EP.

The average temperature in the living room was about 18.3 ˚C, with no significant difference between energy-poor and non-energy-poor households. When examining climate effects, it was noted that the average room temperature remained relatively consistent across different months, regardless of outside temperatures. Table F5 shows that the exception was in April, where room temperatures appeared slightly lower. However, this observation was based on a limited number of measurements (4 measurements from April 1 to 7) and therefore does not accurately depict the average room temperature for the entire month. The greater standard deviation indicates that the room temperatures for energy-poor households varied more especially on the lower side.

Table F4. Average behavior for each energy poverty group. The p-value in the last two columns shows whether EP1 or EP2, respectively, engaged significantly more or less in each behavior than non-EP. Source: survey and (Gemeente Eindhoven, 2023).

Variable (range)	Mean / frequency distribution EP1	Mean / frequency distribution EP2	Mean / frequency distribution non-EP	P-value EP1 vs non-EP	p-value EP2 vs non-EP
Heating					
Heating liv morning (0/1)	0.84	0.83	0.85	0.391	0.377
Heating liv afternoon (0/1)	0.85	0.86	0.76	0.080 *	0.104
Heating liv evening (0/1)	0.94	0.94	0.95	0.349	0.399
Heating liv night (0/1)	0.31	0.31	0.14	0.005 ***	0.024 **
Heating bed morning (0/1)	0.28	0.37	0.16	0.035 **	0.012 **
Heating bed afternoon (0/1)	0.28	0.40	0.11	0.005 ***	0.001 ***
Heating bed evening (0/1)	0.43	0.54	0.26	0.014 **	0.003 ***
Heating bed night (0/1)	0.27	0.34	0.10	0.005 ***	0.004 ***
Vent liv pre (0,4)	1.63	2.06	1.33	0.119	0.008 ***
0. 2 or less times per week	43%	29%	50%		
1. 3 - 4 times per week	6%	6%	11%		
2. 5 - 6 times per week	7%	9%	2%		
3. 1 time per day	31%	46%	28%		
4. More than 1 time per day	12%	11%	8%		
Vent bed pre (0,4)	2.25	2.37	2.47	0.183	0.374
0. 2 or less times per week	22%	23%	16%		
1. 3 - 4 times per week	9%	6%	10%		
2. 5 - 6 times per week	13%	6%	9%		
3. 1 time per day	31%	43%	41%		
4. More than 1 time per day	24%	23%	24%		
Shower freq. (0,3)	1.57	1.46	1.65	0.326	0.187
0. 2 or less per week	19%	20%	19%		
1. 3 - 4 per week	30%	34%	28%		
2. 5 - 6 per week	25%	26%	20%		
3. 7 or more per week	25%	20%	32%		
Shower length (0,3)	1.10	1.09	1.00	0.213	0.316
0. Less than 5 minutes	24%	29%	22%		
1. 5 - 9 minutes	51%	46%	60%		
2. 10 - 14 minutes	16%	14%	15%		
3. 15 minutes or more	9%	11%	3%		
Turn off lights (0,4)	2.52	2.57	2.81	0.076	0.170
0. Never	7%	9%	5%		
1. Rarely	16%	11%	8%		
2. Sometimes	18%	20%	28%		
3. Often	33%	34%	20%		
4. Always	25%	26%	39%		
Clothes					

Thick clothes (0/1)	0.13	0.17	0.10	0.273	0.172
Medium clothes (0/1)	0.76	0.71	0.78	0.369	0.218
Light clothes (0/1)	0.10	0.11	0.11	0.429	0.496
Temperature (˚C)	18.04	18.09	18.47	0.065	0.153

*Note: ***,**,*: Statistical significance level 1%, 5%, 10%.*
Note: See Figure F1 for table reading instructions.

Table F5. Mean measured indoor temperatures (and count of responses) per month among the sub-samples. Source: (Gemeente Eindhoven, 2023).

Month (average outside temperature (KNMI, 2023))	All	EP 1	EP 2	Non-EP
December (3.9 ˚C)	18.40 ˚C (15)	18.50 ˚C (8)	18.86 ˚C (7)	18.29 ˚C (7)
January (5.8 ˚C)	18.43 ˚C (30)	18.50 ˚C (14)	18.33 ˚C (6)	18.38 ˚C (16)
February (5.7 ˚C)	18.43 ˚C (37)	18.08 ˚C (12)	18.33 ˚C (9)	18.60 ˚C (25)
March (7.5 ˚C)	18.16 ˚C (69)	17.77 ˚C (31)	17.33 ˚C (12)	18.47 ˚C (38)
April (8.7 ˚C)	17.50 ˚C (4)	17.00 ˚C (2)	18.00 ˚C (1)	18.00 ˚C (2)
Average	18.28 ˚C (155)	18.04 ˚C (67)	18.09 ˚C (35)	18.47 ˚C
Range	13 - 22 ˚C	13 - 22 ˚C	13 - 22 ˚C	15 - 22 ˚C
Std Dev	1.666 ˚C	1.838 ˚C	1.961 ˚C	1.508 ˚C

Conclusion

Energy-poor households experienced more cold in their living rooms, and consequently lived in lower comfort than non-energy-poor households. Additionally, they lived in poorer housing conditions. The results indicate that the energy-poor (EP2) experienced more drafts, lacked fresh air more often, had less control over the indoor environment, and were less satisfied with their dwelling than non-EP. Even the broad group (EP1) were less satisfied with their dwelling than non-EP. However, EP2 households had less dry indoor air conditions and did not experience more mold.

Due to their poorer housing conditions, did the energy-poor drastically adjust their behavior to keep energy costs low? Not really. The study indicates that energy-poor actually heated their bedroom(s) much more often throughout the entire day than non-energy-poor households. They also heated their living rooms more during the night than non-EP. This indicates that the energy-poor need to heat more to reach an acceptable comfort level, likely due to living in lower-quality dwellings. Regarding ventilation, energy-poor households ventilated their living rooms slightly more often than non-EP. Apart from heating and ventilating, the energy-poor did not exhibit significantly different behaviors compared to non-energy-poor households.

F.3 Preferred behavior

This section aims to find out whether the respondents would adjust their behavior if they were financially able. Moreover, it seeks to find out if energy-poor households would prefer to adjust their behavior even more than non-energy-poor households. A desire to behave differently suggests that a household restricts its energy consumption behavior due to financial limitations. The survey posed five questions to gauge potential changes in behavior if participants had the financial capacity to do so. These questions addressed considerations about heating the home more frequently or for extended durations, adjusting ventilation habits, prolonging or increasing the frequency of showers, opting for lighter clothing, and turning up the thermostat. Statistical tests were conducted to identify any significant differences in behavior preferences between energy-poor and non-energy-poor households.

Table F6 outlines the preferred behavior of each subgroup if they were financially able. The preferred behaviors were measured on a five-point Likert scale ranging from '*much less*' to '*much more*' or '*never*' to '*always*'. The distribution across each category of the preferred behavior is listed below the average value. The penultimate column indicates if EP1 preferred significantly different behaviors compared to non-energy-poor households, and the final column does the same for EP2 compared to non-energy-poor. The differences found are discussed below.

On average, EP2 would heat their home *more* if they were financially able. Non-EP would *not* prefer to heat their home more, indicating a significant difference compared to the energy-poor. This is notable, as energy-poor households already heat their home much more than non-energy-poor households. EP1 would also prefer to heat their home significantly more than non-EP, albeit to a lesser extent than EP2.

Turning to ventilation preferences, a comparable pattern emerged, albeit a bit less radical. Non-EP would *not* ventilate their home more if financially able, while EP2 would prefer to ventilate their home *not more* to *more*. EP1 households also indicated a preference to ventilate significantly more than non-EP.

When it comes to showering, a larger difference in preference is seen. EP2 would *sometimes* shower more or longer, while non-EP would only *rarely* shower more or longer if financially able. EP1 would also adjust their behavior more than non-EP if financially able.

Additionally, the energy-poor would adjust their clothing significantly more than non-EP if financial constraints were lifted. EP2 would *sometimes* wear less (thick) clothes and EP1 would rarely to *sometimes* wear less (thick) clothes, while non-EP would *never* to *rarely* wear less (thick) clothes.

Finally, the desired temperature that the respondents indicated was 19.43˚C which is comparable for each subgroup. Delta temperature, the difference between this desired temperature and the actual temperature in the living room, did differ for the energy-poor. A negative delta indicates that one lives in suboptimal thermal conditions. EP1 compromised their temperature significantly more than non-EP.

Table F6. Average preferred behavior for each energy poverty group. The p-value in the last two columns shows whether EP1 or EP2, respectively, preferred to engage significantly more or less in each behavior than non-EP. Source: survey.

Variable (range)	Mean / frequency distribution EP1	Mean / frequency distribution EP2	Mean / frequency distribution non-EP	P-value EP1 vs non-EP	p-value EP2 vs non-EP
Heating less/more (-2,2)	0.66	0.94	0.27	0.000 ***	0.000 ***
-2. Much less	2%	0%	0%		
-1. Less	0%	0%	2%		
0. Not more / not less	39%	23%	72%		
1. More	51%	60%	23%		
2. Much more	9%	17%	3%		
Ventilating less/more (-2,2)	0.37	0.46	0.18	0.032 **	0.037 **
-2. Much less	0%	0%	1%		
-1. Less	5%	9%	1%		
0. Not more / not less	60%	49%	81%		
1. More	30%	31%	13%		
2. Much more	6%	11%	5%		
Shower more/longer (0,4)	1.64	2.06	0.77	0.000 ***	0.000 ***
0. Never	27%	17%	64%		

1. Rarely	24%	17%	15%		
2. Sometimes	21%	29%	8%		
3. Often	15%	17%	8%		
4. Always	13%	20%	6%		
Less (thick) clothes (0,4)	1.42	1.77	0.51	0.000 ***	0.000 ***
0. Never	24%	14%	68%		
1. Rarely	31%	26%	21%		
2. Sometimes	25%	31%	7%		
3. Often	18%	26%	1%		
4. Always	2%	3%	3%		
Desired temperature ˚C	19.43	19.46	19.43	0.498	0.469
Delta temperature ˚C	-1.39	-1.37	-0.97	0.049 **	0.107

*Note: ***,**,*: Statistical significance level 1%, 5%, 10%.*
Note: See Figure F1 for table reading instructions.

Conclusion

The behavior preferences outlined above indicate that, despite already heating their homes more frequently than non-energy-poor households—which leads to higher heating expenses—the desire to adjust their behavior remains substantially larger among the energy-poor. This underscores the likelihood that energy-poor individuals inhabit dwellings of lower energetic quality. The energy-poor expressed a greater desire to heat more, ventilate more, shower more/longer, and to wear less thick clothes. For each behavior, the desire to adjust it if financially able was stronger with the narrower definition of energy poverty. The heightened desire for behavior adjustment stresses the necessity for policies aimed at improving the living (dis)comfort of the energy-poor.

F.4 The Klusbus interventions

This section investigates whether energy-poor households received more energy measures and a larger overall energy intervention than non-energy-poor households. The municipality provided data on the energy measures applied by the Klusbus. Table F7 gives the average intervention size and the number of applications for each measure per dwelling across the different subgroups. The last two columns indicate whether EP1 and EP2 received significantly more or fewer energy measures compared to non-EP. The intervention size was measured in points, representing the monetary value of the intervention. Energy-poor households received significantly larger interventions than non-energy-poor households, with EP1 receiving an average intervention worth €384.04 and EP2 receiving €419.03, compared to €338.33 for non-EP.

Apart from value, the number of measures per dwelling also serves as a metric for the intervention size. Energy-poor households received significantly more measures, with EP1 receiving 11.3 measures, EP2 receiving 11.5 measures, and non-EP receiving 10.2 measures. This indicates that more and larger energy measures were implemented in households facing greater energy poverty challenges, demonstrating that the Klusbus project effectively targets households struggling with energy bills.

A total of thirteen distinct types of energy efficiency measures were implemented in the selected dwellings. They are categorized into anti-draft measures and other efficiency measures, with efficiency measures as the predominantly applied type of measures. The most applied were LED lights, radiator foil, door draft strips, and water-saving showerheads. Table F8 shows that a majority of the households received those measures. Less frequently implemented measures included gap sealing (only applied 1 time), door closers (1), pipe insulation (4), and draft strips at doors (10).

Statistical differences were found for certain measures. EP2 received significantly more draft strips and door brushes, but fewer door draft seal tape than non-EP. Those seem to cancel each other out, as energy-poor households seemed to have received more anti-draft measures, but no overall statistical difference in anti-draft measures was found.

For efficiency measures, both groups of energy-poor households received significantly more radiator foil, and EP1 received significantly more water-saving showerheads than non-energy-poor households. However, no overall statistical difference in the total number of efficiency measures was found between energy-poor and non-energy-poor households.

Table F7. Average number of applications of the energy measures per dwelling for each energy poverty group. The p-value in the last two columns shows whether EP1 or EP2, respectively, received more measures than non-EP. Source: (Gemeente Eindhoven, 2023).

Variable (range)	Mean / frequency distribution EP1	Mean / frequency distribution EP2	Mean / frequency distribution non-EP	P-value EP1 vs non-EP	p-value EP2 vs non-EP
Tot points (25,630)	384.04	419.03	338.33	0.019 **	0.001 ***
Tot measures (1,23)	11.31	11.51	10.20	0.091 *	0.098 *
Anti-draft measures (0,7)	1.87	2.00	1.78	0.373	0.237
Draft strips door (0,3)	0.79	0.94	0.70	0.249	0.080 *
Door brushes (0,2)	0.46	0.66	0.39	0.212	0.012 **
Mailbox brushes (0/1)	0.27	0.23	0.31	0.303	0.187
Door draft seal tape (0,3)	0.30	0.11	0.28	0.442	0.031 **
Draft strips window (0,2)	0.04	0.06	0.10	0.112	0.212
Door closers (0/1)	0.00	0.00	0.01	-	-
Gap sealing (0/1)	0.01	0.03	0.00	-	-
Efficiency measures (0,23)	8.93	8.74	8.40	0.238	0.341
Radiator foil (0,8)	2.64	3.20	2.11	0.038 **	0.004 ***
LED lights (0,23)	4.79	4.17	4.82	0.484	0.200
Water-saving showerheads (0,2)	0.76	0.71	0.64	0.066 *	0.240
Timer switches (0,2)	0.45	0.37	0.52	0.224	0.106
Low-flow aerators (0,3)	0.28	0.29	0.31	0.409	0.437
Pipe insulation (0,14)	0.51	0.74	0.01	-	-

*Note: ***, **, *: Statistical significance level 1%, 5%, 10%.*
Note: See Figure F1 for table reading instructions.

Table F8. The percentage of dwellings that received at least one measure for each energy poverty group. Source: (Gemeente Eindhoven, 2023).

Intervention	EP 1	EP 2	Non-EP	Range
Radiator foil	79.1%	82.9%	77.3%	1 – 8 pcs (per radiator)
LED lights	67.2%	62.9%	79.5%	1 – 23 lights
Water-saving showerheads	71.6%	65.7%	63.6%	1 – 2 showerheads
Draft strips door	61.2%	65.7%	50.0%	1 – 3 pcs (per door)
Timer switches	38.8%	31.4%	46.6%	1 – 2 switches
Door brushes	40.3%	60.0%	35.2%	1 – 2 doors
Mailbox brushes	26.9%	22.9%	30.7%	1 pc (per mailbox)
Door draft seal tape	20.9%	8.6%	23.9%	1 – 3 doors
Low-flow aerators	20.9%	17.1%	21.6%	1 - 3 aerators
Draft strips windows	4.5%	5.7%	8.0%	1 – 2 pcs (per window)
Pipe insulation	4.5%	5.7%	1.1%	1 - 14 meter
Door closers	0.0%	0.0%	1.1%	1 pc (per door)
Gap sealing	1.5%	2.9%	0.0%	1 frame

Conclusion

Did the households most in need of intervention – the energy-poor – receive the most and largest energy measures? The results indicate that the energy-poor indeed received significantly larger interventions than the non-energy-poor households, both in terms of the value of the intervention and the number of measures applied to their dwelling. Specifically, radiator foil, door draft strips, door brushes, and water-saving showerheads were installed significantly more often in energy-poor households. Contrarily, door draft seal tape was installed less among the energy-poor. The Klusbus project successfully achieves its goal to target households struggling to pay the energy bills, by applying more extensive energy measures.

F.5 After the Klusbus

The Klusbus renovations are expected to enhance living comfort, improve housing quality, and influence residents' energy-saving and comfort-enhancing behavior. This section elaborates on the observed changes.

Comfort

This section aims to determine the extent to which the Klusbus participants experienced an improvement in comfort after the intervention and whether this increase was larger for energy-poor households than for non-energy-poor households. Table F9 outlines the average comfort improvement following the intervention for each subgroup. Comfort improvement was asked in the survey and measured on a five-step comfort improvement ladder that indicates the extent to which the respondents experienced less cold in their dwelling after the Klusbus. The distribution across each of the five categories is provided below the average comfort improvement. The second-last and last columns indicate whether EP1 and EP2, respectively, experienced a significantly larger or smaller comfort improvement compared to non-EP.

Column 1 shows that 74% of the participants experienced a comfort improvement after the Klusbus, with an average reduction of *slightly* less cold in their dwelling. Overall, both groups of energy-poor households experienced a comparable comfort improvement to non-energy-poor households. So, the target group, the energy-poor, was reached by the program, as they made a comfort improvement, but were not reached more than the rest of the sample.

Table F9. Average comfort improvement after the Klusbus for each energy poverty group. The p-value in the last two columns shows whether EP1 or EP2, respectively, reported a significantly larger or smaller cold reduction than non-EP. Source: survey.

Variable (range)	Mean / frequency distribution EP1	Mean / frequency distribution EP2	Mean / frequency distribution non-EP	P-value EP1 vs non-EP	p-value EP2 vs non-EP
Less cold (**comfort**) (0,4)	1.09	1.09	0.93	0.163	0.196
0. Not less at all	30%	23%	40%		
1. Slightly less	43%	54%	38%		
2. Moderately less	16%	14%	15%		
3. Much less	9%	9%	6%		
4. Very much less	1%	0%	2%		

*Note: ***,**,*: Statistical significance level 1%, 5%, 10%.*
Note: See Figure F1 for table reading instructions.

Housing quality improvement

This section aims to ascertain whether the participants experienced an improvement in housing quality after the Klusbus intervention and whether these improvements were larger or smaller for energy-poor households compared to non-energy-poor. The survey included questions about the housing quality improvements: a reduction in drafts and mold, and an increase in fresh air and control over the indoor environment. Table F10 gives the average housing quality improvements for each subgroup, measured on a five-point Likert scale, ranging from '*no improvement at all*' to '*very much*'. The distribution across these 5 categories is given below the average for each improvement and subgroup. The penultimate and final column indicate if EP1 and EP2, respectively, reported significantly larger or smaller housing quality improvements compared to non-energy-poor households. The differences found are discussed below.

The most notable impact was observed on drafts, with 73% of the sample experiencing a reduction of drafts, resulting in *slightly fewer* drafts on average. No statistical difference in draft reduction was observed between the energy-poor and non-energy-poor.

The impact on mold was much smaller, but energy-poor households reported a significantly larger reduction than non-energy-poor households. 19% of EP1 and 31% of EP2 experienced less mold, with an average of *not less* to *slightly less* mold after the Klusbus. In contrast, only 6% of non-energy-poor experienced less mold, on average *not less mold at all*.

This difference between the subgroups is also evident concerning improvements in air quality. 27% of EP2 experienced more fresh air, resulting in *not more* to *slightly more* fresh air on average. This is significantly higher than the proportion of non-energy-poor households, of whom only 10% experienced more fresh air, with *not more fresh air at all* on average.

Furthermore, 27% of the respondents experienced more control over the indoor environment after the Klusbus, with an average of *not more* to *slightly more* control. No statistical difference was found between energy-poor and non-energy-poor households.

Table F10. Average housing quality improvement for each energy poverty group. The p-value in the last two columns shows whether EP1 or EP2, respectively, reported a significantly larger or smaller improvement in housing quality than non-EP. Source: survey.

Variable (range)	Mean / frequency distribution EP1	Mean / frequency distribution EP2	Mean / frequency distribution non-EP	P-value EP1 vs non-EP	p-value EP2 vs non-EP
Less drafts (0,4)	1.24	1.14	1.14	0.304	0.489
0. Not less at all	37%	37%	38%		
1. Slightly less	25%	29%	32%		
2. Moderately less	19%	23%	18%		
3. Much less	12%	6%	5%		
4. Very much less	6%	6%	8%		
Less mold (0,4)	0.40	0.60	0.16	0.041 **	0.014 **
0. Not less at all	81%	69%	94%		
1. Slightly less	7%	14%	1%		
2. Moderately less	6%	9%	1%		
3. Much less	3%	6%	1%		
4. Very much less	3%	3%	2%		
More fresh air (0,4)	0.34	0.46	0.22	0.119	0.039 **
0. Not more at all	73%	63%	90%		
1. Slightly more	19%	29%	3%		
2. Moderately more	7%	9%	3%		
3. Much more	0%	0%	2%		
4. Very much more	0%	0%	1%		
More control indoor environment (0,4)	0.46	0.49	0.36	0.220	0.207
0. Not more at all	69%	66%	76%		
1. Slightly more	21%	20%	14%		
2. Moderately more	7%	14%	9%		
3. Much more	1%	0%	0%		
4. Very much more	1%	0%	1%		

*Note: ***, **, *: Statistical significance level 1%, 5%, 10%.*
Note: See Figure F1 for table reading instructions.

Behavior after the Klusbus

The last section aims to determine if participants changed their behavior after the energy intervention and if the energy-poor adjusted their behavior more than non-energy-poor to optimize comfort. Participants were surveyed regarding six behavior adjustments post-intervention: a change in heating duration, ventilating, showering, clothing, turning off lights, and temperature. Table F11 presents the average extent of behavior adjustments for each subgroup, measured in five categories, ranging from '*much less*' to '*much more*' or '*not less/more*' to '*very much less/more*'. The distribution across these categories is provided below the average behavior adjustment. The second-last and last columns indicate whether EP1 and EP2, respectively, adjusted their behavior significantly more or less than non-EP. The differences found are discussed below.

Most respondents did not alter their heating or ventilation habits post-intervention. 22% started *heating* less, and only 4% started *heating* more, while 4% started *ventilating* less, and 7% started *ventilating* more. No significant differences were observed in heating and ventilation adjustments between the energy-poor and non-energy-poor. However, differences in behavior change between the energy poverty groups were found for the remaining behavior adjustments.

Table F11. Average behavior adjustment for each energy poverty group. The p-value in the last two columns shows whether EP1 or EP2, respectively, adjusted their behavior significantly more or less than non-EP. Source: survey.

Variable (range)	Mean / frequency distribution EP1	Mean / frequency distribution EP2	Mean / frequency distribution non-EP	P-value EP1 vs non-EP	p-value EP2 vs non-EP
Heating less/more (-2,2)	-0.18	-0.23	-0.19	0.436	0.380
-2. Much less	3%	6%	1%		
-1. Less	16%	14%	20%		
0. Not less / not more	76%	77%	76%		
1. More	4%	3%	1%		
2. Much More	0%	0%	1%		
Ventilating less/more (-2,2)	0.06	0.06	0.00	0.172	0.262
-2. Much less	0%	0%	1%		
-1. Less	4%	6%	2%		
0. Not less / not more	87%	86%	92%		
1. More	7%	6%	5%		
2. Much More	1%	3%	0%		
Shower more/longer (0,4)	0.27	0.34	0.09	0.012 **	0.017 **
0. Not more at all	78%	74%	93%		
1. Slightly more	18%	17%	6%		
2. Moderately more	4%	9%	0%		
3. Much more	0%	0%	1%		
4. Very much more	0%	0%	0%		
Less (thick) clothes (0,4)	0.28	0.43	0.15	0.064 *	0.014 **
0. Not at all	78%	66%	89%		
1. Slightly less thick / less layers	16%	26%	10%		
2. Moderately less thick / less layers	6%	9%	0%		
3. Much less thick / less layers	0%	0%	0%		
4. Very much less thick / less layers	0%	0%	1%		
Turn off unnecessary lights less (0,4)	0.34	0.43	0.18	0.090 *	0.059 *
0. Not less at all	81%	74%	90%		
1. Slightly less	9%	11%	7%		
2. Moderately less	6%	11%	1%		
3. Much less	4%	3%	0%		
4. Very much less	0%	0%	2%		
Temperature (°C)	18.24	18.11	18.52	0.172	0.165

*Note: ***, **, *: Statistical significance level 1%, 5%, 10%.*

Note: See Figure F1 for table reading instructions.

Energy-poor households adjusted their showering behavior significantly more than non-EP. 22% of EP1 and 26% of EP2, began taking longer or more frequent showers, although these adjustments were slight, compared to only 7% for non-EP.

A disparity was also observed in clothing adjustments, with 22% of EP1 and 34% of EP2 wearing less (thick) clothes, compared to only 11% of non-EP, primarily involving slight adjustments.

A small group indicated a decreased tendency to turn off unnecessary lights: 19.4% of EP 1 and 25% of EP 2, but significantly less non-EP with 10%.

The mean temperature in the living room did not increase significantly compared to pre-intervention levels, by 0.20 ˚C for EP1, 0.02 ˚C for EP2, and 0.05 ˚C for non-EP. The average post-intervention temperature was 18.4 ˚C, still below the desired temperature of 19.4 ˚C.

Conclusion

Did the improvement have a bigger effect on the comfort of the energy-poor than of the non-energy-poor? On average, the respondents experienced a slight reduction of cold in their dwelling (i.e., comfort improvement) after the Klusbus intervention. However, the energy-poor did not report a larger comfort improvement than the non-energy-poor.

Improvements in housing quality were observed across the entire sample, through a reduction of drafts and mold, an increase in fresh air, and enhanced control over the indoor environment. Notably, the energy-poor experienced a significantly greater reduction in mold and an increase in fresh air compared to the non-energy-poor.

The most substantial differences between the energy-poor and non-energy-poor were observed in behavior changes after the Klusbus. While the majority did not alter their behavior after the intervention, the energy-poor made slightly more adjustments. They began wearing less (thick) clothes, showering more, and turning off unnecessary lights less often. However, changes in ventilation frequency and living room temperature were not significantly different between the energy-poor and non-energy-poor.