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The HOME-Health (HOusing, environMEnt, and Health) Study; Description of a Danish natural experiment, designed as a longitudinal study with repeated measurements, providing internal- and external validity of the study

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ABSTRACT

BACKGROUND: The ambient and indoor environment are pivotal to our health. We spend most of our time indoors within our home, why our home is where we are most exposed to indoor pollutants and indoor air quality (IAQ). Populations within social housing areas are more vulnerable due to advanced age, co-morbidity and social economic status. Commonly, studies within social housing are cross-sectional, few Nordic longitudinal studies exist, and fewer studies combine quantitative and qualitative measurements in a mixed method approach.

METHOD: This research proposal provides an extensive detailed description of the design and methodology of the HOME-Health study. The study is a longitudinal study and is a natural experiment employing structured surveys, objective measurements of indoor air parameters, lung function test and qualitative semi-structured interviews. Data collection are conducted seasonally (winter and summer), before and after building energy renovation (BER).

GENERALISABILITY: The study population before BER (n = 432) was explored and found similar to the Danish social housing population in terms of age, gender, persons per apartment and migration status. Future analyses should be stratified by multi-family apartments and terraced houses.

RESEARCH AIM: The aim of the HOME-Health study is to provide knowledge about residents' seasonal state of health, perception of indoor enviromental quality (IEQ), IEQ-related behaviours and practices, and objective measurements of IAQ before and after BER. By applying a design with repeated measurement before and after BER, and combining both objective and subjective quantitative as well as qualitative data the study is expected to create in-depth knowledge. Future results will provide evidence of both energy-savings and non-energy savings from different BER projects. Knowledge which are expected to benefit future renovation projects within social housing areas.

KEYWORDS: Energy renovation, buildings, repeated measurements, general health symptoms, comfort

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Introduction

In the western world, we spend most of our time indoors that being inside buildings or during transportation, which is why the quality of the indoor environment is critical for our health and comfort. Previous research attributes 2 million disability-adjusted life years (DALYs) to poor indoor air quality.[1] Poor quality of indoor air is also associated with a higher risk of allergy,[2] ocular, nasal, throat and dermal symptoms, headache and fatique,[3] cancer[1,4,5] as well as lung function decline[6] and sleep disturbance.[7] A better quality of indoor air is associated with a better quality of life,[8] lower health care costs,[9,10] less absence due to sickness and improved concentration,[11,12] improved performance,[13,14] as well as less hay fever, respiratory allergy, headaches, angina, and sinusitis.[15]

The European Union (EU) recommends the construction of zero-energy buildings and major renovations of the existing building stock to reduce energy consumption.[16,17] Buildings alone account for 40 to 50% of the European energy consumption, and Denmark is making a major effort to reduce energy consumption, aiming for a carbon dioxide (CO_2) neutral society by 2050.[17] Therefore, a great number of buildings must undergo extensive energy renovation to meet that goal.[18] The financial savings from building energy renovation (BER) can be optimised by including both energy and non-energy savings

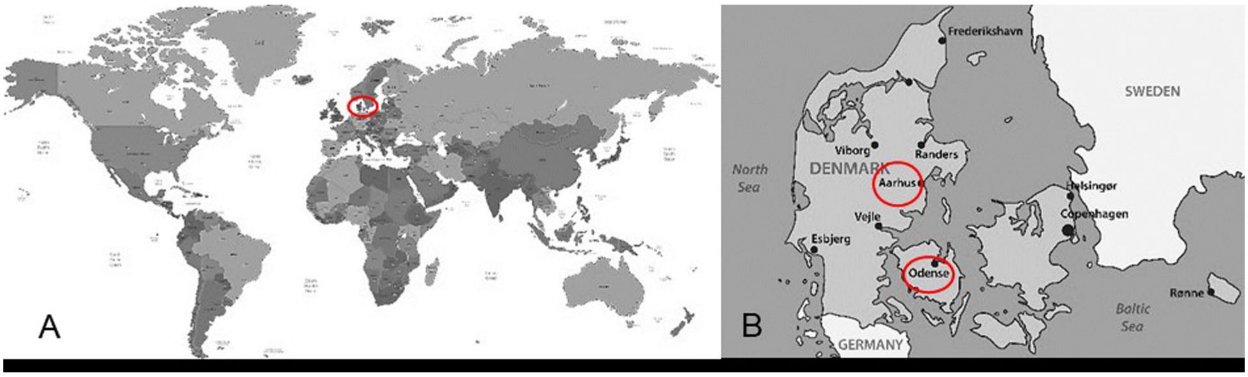

Figure 1. Map showing the location of Denmark (A). Map of Denmark where sites are located within the circled cities (B).

instead of energy savings alone.[19,20] To meet the goal of a CO_2 neutral society, health and comfort co-benefits from BER can therefore act as added value and add to justification of extensive BER.[15,21] The evidence associating housing improvements with positive health outcomes is not conclusive.[22] A French study previously reported adverse health effects due to reduced air dilution elevating the levels of indoor pollutants as a consequence of building renovations.[23] However, other studies, mainly in the US, link building renovations to improved indoor climate and health.[16,24–26] Therefore, monitoring the impact of BERs on indoor environmental quality (IEQ) and the impact of IEQ on human health is crucial to ensure a healthy indoor climate in the future.

In Denmark, the government has allocated DKK30.2 billion to renovation of the social housing sector by 2026, which is why a vast number of buildings are going to be renovated.[27] According to the review by Patino and Siegel, residents living in social housing areas are likely to be more susceptible to poor IEQ due to advanced age, lower socio-economic status and co-morbidity.[28] Another review by Adamkiewicz et al. found that areas where residents had a lower income experienced a higher level of indoor pollutants.[29] Moreover, there is a shortcoming of studies conducted in the social housing setting. Most available studies are cross-sectional partially due to the demanding nature of longitudinal studies. Finally, to our knowledge, only a limited number of Nordic studies exist on this topic[3,30–32] and none in a Danish setting warranting the HOME-Health (HOusing, environMEnt and Health) study.

This paper presents a detailed research proposal describing the study design, methodology and recruitment strategy in the HOME-Health study. Further, this paper explores the generalisability of future baseline results. The study combines the data from 2 parallel BER studies called BE-READY and ReVALUE. The overall aim of the HOME-Health study is to explore residents' seasonal state of health, perception of IEQ, IEQ-related behaviours and measured indoor air quality (IAQ) before and after BER. One outcome is to describe and analyse residents' state of health, perception of IEQ, and IAQ before building renovation. The following outcome is to describe and analyse the change of residents' state of health, perception of IEQ, and measured IAQ after building renovation. In addition, the ReVALUE study also aims to identify co-benefits from BER in terms of architectural transformation, wellbeing and improved construction management and productivity. The HOME-Health study has adopted the ambition from ReVALUE to provide evidence for the development of a decision-support tool[33] for the building industry and emphasise the potential of co-benefits from BER.[21]

Material and Methods

Buildings and locations

Denmark is located in the Northern hemisphere and is a part of the Nordic countries (Figure 1A). In Denmark, any citizen can apply for an apartment in a social housing development. All social housing is organised by local non-profit social housing associations, where rental costs often are lower than the general market rate.[34] There are currently approximately 550 000 social housing households in Denmark. The social housing estates featured in the HOME-Health study are located in 4 different sites in 2 major cities (Figure 1B). The included buildings within the 4 sites were constructed during the 1950s, 1970s and 1980 (Table 1). All included buildings primarily face West and East except for the single-floored terraced houses. The buildings are either 3, 4 or 7 stories high, and all apartments have a private balcony varying in size. At site 3, the housing estate comprised of 2 different types of buildings: Site 3 (houses) is single-floor terraced houses while site 3 (apartments) is multi-family buildings. The tenants have the expense burden for both their heating, water, and electricity consumption.

Building renovation actions and energy consumption

The 3 sites included in the HOME-Health study were social housing areas with extensive renovations planned in the near future. We, as a research group, had no influence on the energy renovation plans. Table 2 provides an overview of the planned renovation actions. The renovation plans for all sites included the installation of balanced mechanical ventilation systems with heat recovery, and cooker hoods which only site 4 had

Table 1. Building characteristics of the 4 sites and time of renovation.

	SITE 1	SITE 2	SITE 3 APARTMENTS	SITE 3 HOUSES	SITE 4
Construction year	1980	1968-1972	1952-1957	1952-1957	1950
No. of dwellings	192	195	444	444[a]	605
Primary material	Concrete	Concrete	Yellow brick	Yellow brick	Red brick
Expense burden					
Heating	Tenant	Tenant	Tenant	Tenant	Tenant
Water	Tenant	Tenant	Tenant	Tenant	Tenant
Electricity	Tenant	Tenant	Tenant	Tenant	Tenant
No. of floors	Three	Four or eight	Three or four	Single-floor	Three or four
Year of renovation	2017-2018	2018-2019	2023	2023	2020-2023

[a]Same number of households as site 3 (apartments).

Table 2. Renovation actions at 3 social housing sites.

RENOVATION ACTION	SITE 1	SITE 2	SITE 4
New mechanical ventilation system with heat recovery	×	×	×
New cooker hood	×	×	×
New building enclosure (outer walls, floor, roof, windows)	×	×	×
New plumbing	×	×	×
New electrical wiring	×	×	×
New bathroom/kitchen interior	×	×	×
Open balconies instead of closed balconies	×		
Bigger or new balconies			×
New solar panel on the roof	×		

Information about renovation actions were provided by the individual social housing associations.

Table 3. Energy consumption separated by social housing site.

	SITE 1	SITE 2	SITE 3	SITE 4
Reference year	2016	2018	2018	2018
No. of dwellings	192	195	444	605
Energy consumption				
Heat (MWh)	1952	2320	4428	
Heat (m³)				130047
Electricity (KWh)	5911120	692306		
Water (m³)	14158	32488		

Reference year is based on year of baseline data collection. All measures are applied by the individual social housing associations.

prior to the renovation. The entire building enclosure (outer walls, roof, ground deck and windows) are planned to be updated to current standards for new buildings which is expected to reduce energy consumption by at least 50%. Plumbing and electrical wiring will also be renewed together with new bathroom and kitchen interior. Site 1 is part of an EU project called READY[34] and will undergo a more ambitious energy renovation including a Photovoltaic (PV) and Photovoltaic Thermal (PVT) systems mounted on the roof including a Battery Energy Storage System (BESS) for self-consumption of the PV production. The renovation of sites 1 and 4 also include a reconfiguration of balconies. The renovation plan for site 3 is currently unavailable.

Reference year for energy consumption in each area is based on the year of data collection (Table 3). It was not possible to obtain information on electricity or water consumption for site 3 and 4.

Study design and participants

The concept of the HOME-Health study is visualised in Figure 2. The concept was to design a longitudinal study with repeated measurements before and after BER within social housing areas. Each participant acts as their own control, as data on each participant is collected during the heating season (February-April) and the non-heating season (August-September) before the renovations, and again approximately 1 year after the participant returns to the renovated apartment. Participants are identified by a study ID and their Danish social security number (CPR). Loss to follow-up is expected, as some participants might move to another area and others might decide they no longer wish to participate in the study.

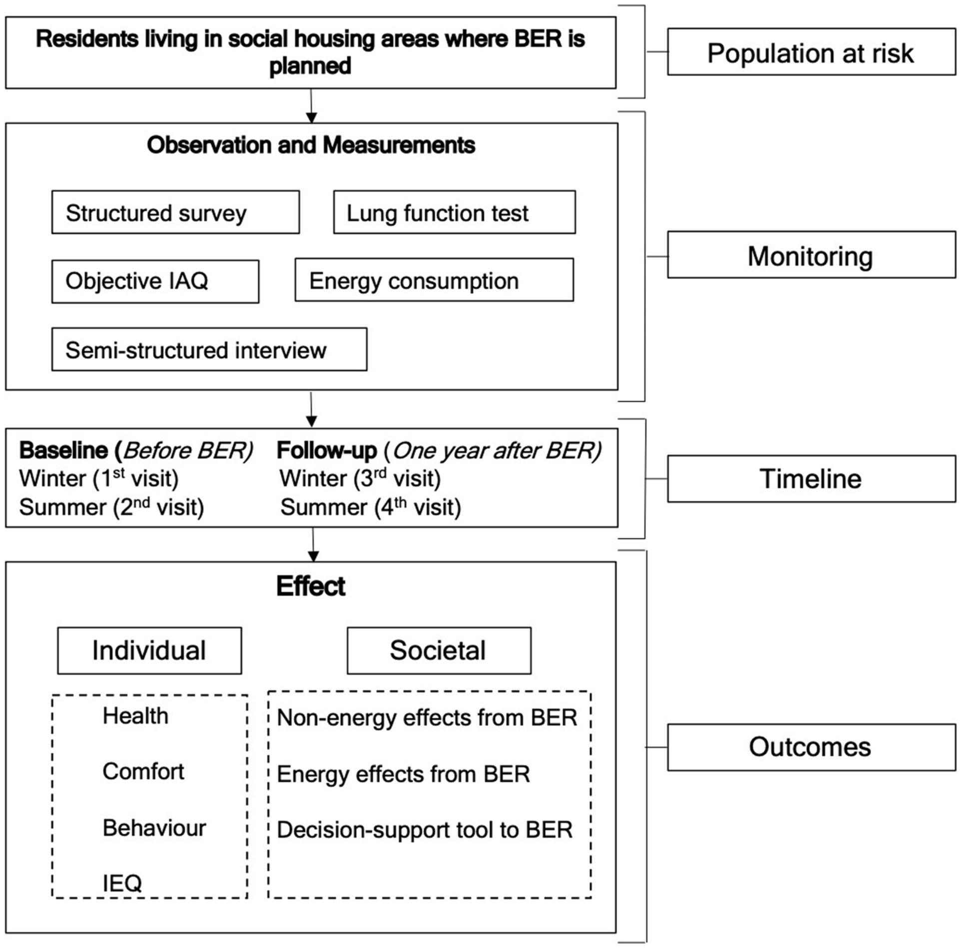

Figure 2. Conceptual framework of the HOME-health study.

Only 1 tenant per apartment is included as a participant. A mixed-method design is adopted including the following methods: *structured surveys; objective measurements of IAQ; lung function test (LFT); and semi-structured anthropological interviews*. The different data collection methods are conducted concurrently due to pragmatic and logistic reasons.

Recruitment strategy and inclusion

The HOME-Health study relies on voluntary participation without any form of compensation. The initial recruitment strategy included promotion campaigns at the housing association residential meetings and residents' board meetings. Along with, distribution of posters in hallways and flyers in mailboxes to increase awareness of the study and to provide information on how to enter the study. However, these efforts were not adequate to achieve a sufficient participation rate. Researchers were by the residents' board members advised to knock on every eligible door to get in personal contact with the tenants with a maximum of 3 attempts to avoid excessive intrusion of the residents' privacy.

All tenants above the age of 18 speaking either Danish, English, Arabic or Somali were eligible for inclusion. Recruitment of participants during the heating season was prioritised over non-heating season participation. Reasons for this were that residents were expected to spend more time indoors in the heating season, thus being more exposed to the indoor conditions. Also, they were expected to be ventilating less in the heating season than in the non-heating season and thereby minimise the effects of ambient air pollution through the opening of windows.[35]

In the study areas there were 1526 eligible apartments/houses. In total, 432 tenants were included in the study. The included tenants lived mainly in apartments (93%) and less so in houses (7%). There were 7 tenants more than the number of included apartments and houses due to the change of tenants in the included apartment the following season. The new tenant were included in the interest of interviewing them after renovation of the building (Figure 3).

Aim and outcome

The overall aim of the HOME-Health study is to provide knowledge about tenants' seasonal state of health, perception of IEQ, IEQ-related behaviours and practices, and objective measurements of IAQ before and after BER. There are 2 main outcome in the HOME-Health study. The first main outcome is to describe and analyse tenants' state of health, perception of IEQ, behaviours related to IEQ, and measured IAQ before building renovation. The second main outcome is to

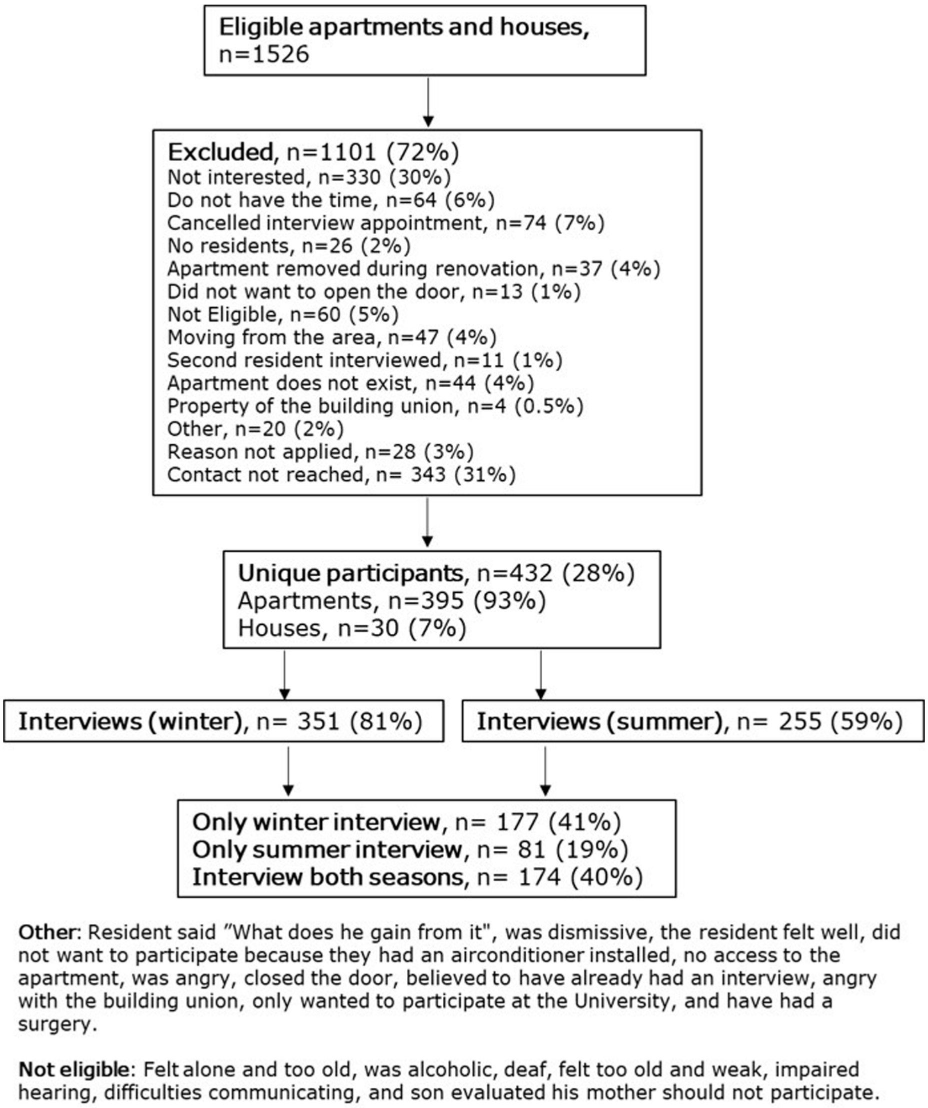

Figure 3. Flowchart of the HOME-health study population before building renovation.

describe and analyse the same parameters after building renovation. Moreover, the HOME-Health study is expected to explore seasonal differences of health, perception of IEQ, behaviours related to IEQ, and measured IAQ. Further, how residents' perception of IAQ (thermal comfort and comfort related to air humidity, circulation and quality) is distributed across measured IAQ (ie, level of temperature, relative humidity, carbon dioxide and air change rate), and how measured IAQ, building characteristics, crowding, behaviour related to IAQ, and perception of IAQ are associated with residents' general health symptoms. Alongside, if more extensive BER is associated with improved health, perception of IEQ, and measured IAQ.

Survey and IEQ measurements

A panel of experts within environmental exposure research constructed the survey (Supplemental Material S1, Appendix A). Before the main data collection, a pilot study was conducted among tenants living at site 1 (n = 12) to test the understanding of the questions among relevant participants. Survey and measurements are conducted by 2 interviewers, who visits the tenants in the tenants' homes. All interviewers are students from a health-related university educational program, and speaking Danish fluently with either English, Somali, or Arabic as their second language. They were carefully trained in conducting the survey, setting up IAQ measuring equipment, and instructing LFT. The survey material was in Danish and addressed different domains. Table 4 lists the domains investigated, and the equipment used, including an English translation of the scale. The domains and their method for data collection are briefly elaborated in the following sections to support the information in Table 4.

Health domains. Participants were asked to recall their health status the past 12 months and additionally asked; *if anyone in the household was coughing without having a common cold; general health, and general physical ability*. The SF-12 health survey[36] was adopted for general health and physical ability questions. Exercise was defined as elevated pulse, that being,

Table 4. Description of domains and sub-domains, the method used for data collection, and scaling.

DOMAIN	SUBDOMAINS	DATA COLLECTION METHOD	SCALE
Demographics			
	CPR, age Sex Current educational level Current occupation Own and parental ethnicity	Survey	Numerical Female/male Grade (>7th, 7th, 8th, 9th, 10th); college; years of higher education (1-2, 3-4 or >5); or other Paid employment; work beside paid employment; student; spare time job; unemployed; stay-at-home; early retirement; disability retirement; retired; not relevant Country
Health			
Objective	PEF FVC FEV1 FEV1/FVC ratio	MicroDL spirometry	Litres/minute Litres Litres Percentage
Symptoms	Eye irritation, watery eyes, sneezing, nose irritation, smell, hoarseness, throat irritation, cough, shortness of breath, chest tightness, nausea, stomach pain, headache, dizziness, trouble sleeping, abnormal tiredness, and skin irritation	Survey	No; less than twice a month; at least twice a month; at least twice a week; daily; daily during the season
Diagnoses	Cardiovascular, chronic bronchitis, asthma, other lung diseases, hay fever, allergy, migraine, mental illnesses, epilepsy, metabolic disease, diabetes, kidney disease, liver disease, cancer, and skin disease	Survey	Yes; no; currently ill; diagnosed by a physician
Other	Anybody in the household coughing without having a cold, and if so whom Frequency of the common cold, pneumonia, tonsilitis, sinusitis the past 12 months	Survey	Yes; no None; 1-2 times; 3-5 times; >5; don't know
Lifestyle	Smoking status Smoking consumption Type of smoking Number of alcohol units per week General health General physical ability Hours of exercise per week	Survey SF-12 survey SF-12 survey	Currently; previously; never; age of initiation/ cessation Numerical E-cigarettes; pipe; cigarettes; water pipe; cheroots; cigars; drugs None; 1-4; >5; >10; >15; >20 Excellent; very good; good; less good; poor Excellent; very good; good; less good; poor Never; >1; 1-2; 3-4; 5-6; <6
Perception			
IEQ	A need of more ventilation Visible moisture spots on flooring/walls/ sealing Loose/discoloured flooring Suspect invisible mould/damp Flooding/water damage Presence of silverfish Condensation on windows Daylight intensity Daylight satisfaction Temperature Air humidity Air circulation Air quality Acoustic Bothered by noise from neighbours Bothered by stuffy/mouldy/earthy/tobacco odour More sensitive to IEQ than others	Survey	Yes; yes a little; no Yes; no Yes; no; don't know No; <5 cm; >5 cm Too bright; dim; comfortable; dim; very Very satisfactory; satisfactory; neither; unsatisfactory; very unsatisfactory Too warm; warm; comfortable; cold; too cold Too dry; dry; comfortable; humid; too humid A lot of draught; a little draught; comfortable; a little stale; very stale Very good; good; neutral; bad; very bad Annoyingly noisy; noisy; comfortable; dead; annoyingly dead Yes; no; sometimes Weekly; sometimes; never Yes; no; don't know

(Continued)

Table 4. (Continued)

DOMAIN	SUBDOMAINS	DATA COLLECTION METHOD	SCALE
Additional themes related to perception of the built environment	Privacy Acoustic, materials used, possibility to arrange the apartment, access to private outside areas, ability to change IEQ/privacy, ability to get in touch with neighbours Feeling safe in the area Aesthetics of the building	Survey	Too public; public; neither; private; too private Very satisfactory; satisfactory; neither; unsatisfactory; very unsatisfactory Very safe; safe; neither; unsafe; very unsafe Very appealing; appealing; neither; unappealing; very unappealing
Behaviour			
	Hours indoors (week/weekend) Year of move-in House animals Number of times being in the kitchen per week while frying Usage of cooker hood while frying Drying of clothes Vacuuming/sweeping/washing the floor Cleaning the home with spray/air freshener Usage of candle light Place of smoking	Survey	Numerical Cat; dog; other >1; 1-2; 3-4; >4 Never; seldom; often; all ways Dryer with an exhaust to the outdoors; dryer without an exhaust to the outdoors; inside the home; another building/basement; winter garden; outside Every day; twice a week; once a week; every other week; once a month; seldom Yes; no Every day; several times a week; seldom; never Room
Energy consumption			
	Domestic water (m^3), electricity (KWh) and Heat (MWh district heating)	Main energy meter	Numerical
Environmental quality parameters			
Indoor	Temperature (degrees Celsius) Relative humidity (%) Absolute humidity (%) Carbon dioxide (ppm) Air change rate (h^{-1}) Dust	Tinytag Ultra Tinytag Ultra Modelled Tinytag CO_2 Modelled EDC	Numerical Counts
Ambient	Temperature (degrees Celsius) Relative humidity (%)	Nearest weather station	Numerical
Characteristics of the housing			
Housing	Flooring Walls Presence of cooker hood Home painted the previous year	Survey	Wood; linoleum; tiles; concrete; wall-to-wall carpeting; carpets Wallpaper; painted wallpaper; glass fibre; painted concrete; wood panels; other Yes; no Yes; no; don't know

Abbreviations: CPR, Danish social security number; EDC, electrostatic dust collector; FEV1, forced expired volume in the first second; FVC, forced volume capacity; PEF, peak flow; IEQ, indoor environmental quality; KWh, kilo watt per hour; MWh, Mega watt per hour; m^3, cubic meter.

cleaning, biking to work, walking fast or exercise. A unit of alcohol was defined as 4 cl spirits, 33 cl beer or 12 cl wine.

LFT was expressed as; *forced Expired Volume in 1 second* (*FEV_1*); *Forced Volume Capacity (FVC); Peak Flow (PEF) and FEV_1/FVC ratio* were obtained with a transportable medical device (Micro DL),[37] using a disposable tube for each participant. Every device was calibrated with a three-litre syringe before data collection and validated using Spida 5[38] and a spirometry checklist.[39]

Perception and behaviour domains. The tenants expressed their perception and behaviour according to the season in which the interview was carried out. Spatial variation was included (kitchen, bedroom, spare room, living room, hallway and bathroom) for several items such as: *temperature; daylight; flooring; added ventilation; visible moisture spots; loose or discoloured flooring; condensation on windows; privacy; acoustic; materials used in the home; the arrangement of furniture and access to private outdoor areas*.

Energy consumption. Energy consumption during 2014 to 2018 was obtained from the respective social housing building associations. The main meters measuring electricity, water and heat consumption were located in each staircase at site 2 and 1 for the

Table 5. Expected movement of participants from symptoms to no-symptoms before (insufficient ventilation) and after (improved ventilation), that being, 12% is expected to move from symptoms to no symptoms going from insufficient ventilation to improved ventilation.

AFTER (IMPROVED VENTILATION) / BEFORE (INSUFFICIENT VENTILATION)	SYMPTOMS (%)	NO-SYMPTOMS (%)	TOTAL (%)
Symptoms	30 (15)	23 (12)	53 (27)
No-symptoms	4 (2)	138 (71)	142 (73)
Total	34 (17)	161 (83)	195 (100)

entire area site 3, site 1, and site 4. Average energy consumption in terms of heat (MWh), electricity (KWh) and water (m^3) are calculated to enable comparison and benchmarking of the buildings involved. An energy meter is installed in each apartment or house as a part of the renovation.

Air quality domains. The parameters used to evaluate IAQ, that is: *air temperature (°C); relative air humidity (%), absolute air humidity (%), carbon dioxide concentration (ppm), dust, and air change rate (h^{-1})* (Table 4), were either measured or derived from measurements for each apartment. Indoor air temperature (TP), relative humidity (RH) and CO_2 concentration were measured using calibrated Tinytags logging every 5 minutes.[40,41] Electrostatic dust collectors (EDC)[42] were applied to collect dust (ie, endotoxin, and moulds). Absolute humidity (AH) was estimated from measurements of TP and RH (Supplemental Material S2, Appendix B, equation (6)), and air change rate due to permanent infiltration (ie, without temporary venting) was derived using a decay analysis of the measured CO_2 level (Supplemental Material S2, Appendix B, equation (7)).

The measurements were conducted seasonally for at least 14 consecutive days in the living room of each apartment as the living room was expected to be the place where tenants spent most of their time awake while at home. The IAQ parameters were only evaluated for periods where data suggested occupancy in the living room. The method used for determining occupancy was based on probabilities ascribed to patterns in the measured data (Supplemental Material S2, Appendix B, equations(1)-(5)).

Local hourly outdoor air temperature and global solar radiation during the measurement periods were extracted from the database available at www.vejrdatafiler.dk.[43]

Semi-structured qualitative interview

The qualitative interviews provided in-depth situated knowledge[44,45] The Interview guide was semi-structured, covering the themes considered to have a particular impact on the indoor climate (ie, cooking, cleaning, laundry, and airing out), while also leaving a room for other themes to emerge, contingent on the flow of the conversation.[46] Each interview lasted 1.5 to 2 hours, including a home tour, moving around the house to see where different practices were carried out, which allowed for further contextualisation, and gave an opportunity to discuss specific practices in more detail. All interviews were carried out by a trained anthropologist. They were recorded with a recording device, transcribed and subsequently analysed, using qualitative thematic analysis.[47] Before each interview, written consent was obtained. A full interview guide is available in Supplemental Material S3, Appendix C.

Follow-up

Self-reported health was recalled the past 12 months. Therefore, follow-up was initiated 12 months after the participants moved back to a renovated apartment to avoid any risk of participants self-reporting health when they were not living in a renovated apartment. Further any risk of excessive or peaks of particle emission from building materials was expected to be substantially limited after 12 months. All measurements carried out before building renovation, are also employed after building renovation, to investigate changes of general health symptoms, perception of IEQ, and measured IAQ.

Statistical method, confounding, and power

All data will be tested for normal distribution. To analyse how IAQ, perception of IEQ, building characteristics and crowding are associated with general health symptoms data will be analysed by linear or logistic regression. Mean within individual changes will be tested with paired *T*-test and unpaired for group differences. In case of not normally distributed data we apply Wilcoxon Rank Sum test or McNemars test for ordinal data and Wilcoxon Sign Rank test for nominal data. The same approach is used for follow-up data and results compared to baseline results to investigate changes. The level of statistical significance is defined at $P < .05$. The statistical software program Stata (Release 17) is used for analyses.[48]

The covariates for data analyses are expected to be determined by either the use of Directed Acyclic Graphs (DAGs),[49] a priori, and from existing literature.

Estimated power was calculated from a two-sample paired – proportions test and Large-sample McNemar's test (Table 5). Power estimation was based on alpha (0.05), number (195), delta (0.1000), p12 (2%) and p21 (12%). The power was estimated to be 96.70. A 30% participation rate was expected (n = 431) before the data collection prior to the renovation, and a drop-out rate of 50% at follow-up after renovation (n = 216).

Ethical considerations

Oral informed consent was obtained from all included participants at the start of the interview and they were also informed that they could retract from the study at any time and all their data would be deleted. At the same time, approval from the Danish Data Protection Agency (2016-051-000001, 1475) was obtained. At site 2, 3 and 4, a lung function test was applied to the study design. For this purpose, ethical approval was required and obtained from the Ethical Council (1-10-72-267-19). Oral information was given to the participants at least 24 hours before the interview. Written informed consent was obtained at the interview. To comply with the General Data Protection Regulation (GDPR), all interviews were carried out and stored on encrypted platforms – property of Aarhus University.

Generalisability

Internal validity

Demographics and smoking habits in the HOME-Health study population are presented in Table 6 stratified by the included sites. Compared to the populations of site 1, site 2, site 3 (apartments) and site 4, tenants living in site 3 (houses) are substantially different. Residents are usually females (73 vs 54, 63, 57 and 51%, respectively), aged 65+ years (77 vs 15, 12, 28 and 9%, respectively), receive social welfare support (87 vs 55, 53, 49 and 38%, respectively) and only few are immigrants (3%) compared to site 2, site 3 (apartments) and site 4 (60, 17 and 20%, respectively). Compared to site 1, site 3 (houses), site 3 (apartments) and site 4, the population of site 2 substantially differs in terms of less residents with a completed higher education (2-6 years) (29 vs 60, 63, 76 and 56%, respectively), fewer with employment (20 vs 32, 41, 46 and 33%, respectively), and a higher number of never-smokers (61 vs. 28, 43 and 38%, respectively). At site 2 there were more immigrants from non-western countries (56%) compared to site 3 (apartments) (11%) and site 4 (18%). Age and gender were similar across multi-family social housing sites.

External validity

By 2018 social housing areas in Denmark[50] consisted predominantly of adult residents (82%) living alone (56%). They were less likely to have finished a higher education (−16% percent point) and more likely to receive social welfare support (+23% percent point) compared to the rest of the Danish population living in rental property. Moreover, more immigrants from non-western countries (+20% percent point) resided in Danish social housing areas (Table 7). The cohort of the HOME-Health study is intended to combine the study populations of site 1, site 2, site 3 (apartments), site 3 (houses) and site 4. Age, gender and immigration status in the HOME-Health study are similar to the rest of the Danish social housing population. The HOME-Health study population includes more residents with a completed higher education (+38% percent point) and fewer are living alone (−13% percent point) compared to the Danish social housing population.

Strengths and Limitations

The strength of the study is being a longitudinal as well as a natural experiment in a Danish social housing setting. It is an interdisciplinary project, adopting methods from Engineering, Architecture, Anthropology and Public Health as well as the private building sector. It enables us to look at IEQ from different perspectives, thereby gaining a deeper understanding of the effect of IEQ on human health and comfort. Assessment of an annual lung function is common within longitudinal studies[51] which is why it is chosen for the HOME-Health study. The lung function test included in the HOME-Health study should be representable for the tenant's annual real lung function before and after BER. Follow-up data collection is carried out 12 months after they have returned to their renovated apartment eliminating the risk of overlapping recall of health symptoms from time spent in another apartment. Further, the likelihood that the tenant has furnished, adapted to and established routines in the apartment is expected to be higher, when the tenant has lived there for at least 12 months. The HOME-Health study seeks to investigate if the tenants' general health symptoms (ie, sneezing, hoarseness, coughing) and IEQ within their home changes after building renovation. General health symptoms might not be obtained in any other way than by asking them. General health symptoms are most probably not obtained from national registers as people might not contact their general practitioner about these types of symptoms. Obtaining self-reported health symptoms might be prone to self-selection bias and misclassification, but previous studies have shown self-reported health to correlate with clinical health[52–54] and a similar study used the same method.[32] Further, The HOME-Health study uses IEQ measurements from time periods when a tenant is assumed to be at home. This assumption is based on the decay of CO_2 and is a common method.[55,56] Therefore, only measurements where a tenant is actually exposed are analysed and not the overall exposure limiting the risk of overestimation of a tenant's actual exposure to IEQ. Final, the tenants' Danish national identification number is obtained in the HOME-Health study, making it possible to link data to the Danish national registers, and include additional information on the study participants. This might unravel the number of absent days from work due to sickness, usage of medical prescription and so on. The HOME-Health study population is similar to that of the Danish social housing population comparing age, gender and migration status, but differ considerably between educational

Table 6. Demographics and smoking as prevalence (%) stratified by sites included in the study.

	SITE 1	SITE 2	SITE 3, APARTMENTS	SITE 3, HOUSES	SITE 4
	N = 82	N = 75	N = 70	N = 30	N = 175
Smoking					
Never	23 (28)	46 (61)	30 (43)	5 (17)	66 (38)
Previous	22 (27)	9 (12)	20 (29)	20 (67)	46 (26)
Smoker	35 (43)	24 (32)	17 (24)	7 (23)	61 (35)
Age					
18-24	3 (4)	5 (7)	5 (7)	-	32 (18)
25-34	20 (24)	15 (20)	13 (19)	-	50 (29)
35-49	23 (28)	28 (37)	17 (24)	2 (6)	48 (29)
50-64	21 (26)	16 (21)	15 (21)	3 (10)	21 (12)
65-79	8 (10)	8 (11)	17 (24)	15 (50)	12 (7)
80+	4 (5)	1 (1)	3 (4)	8 (27)	4 (2)
Gender					
Male	36 (44)	26 (35)	30 (43)	8 (27)	84 (48)
Female	44 (54)	47 (63)	40 (57)	22 (73)	89 (51)
Immigrants					
Non-western countries	N/A	42 (56)	8 (11)	0	28 (16)
Western countries	N/A	3 (4)	4 (6)	1 (3)	7 (4)
Person(s) per apartment					
1 person	27 (33)	17 (23)	36 (51)	14 (47)	91 (52)
2 persons	25 (31)	18 (24)	19 (27)	16 (53)	57 (33)
3 persons	12 (15)	11 (15)	9 (13)	-	11 (6)
4 persons	10 (12)	11 (15)	2 (3)	-	7 (4)
5+ persons	5 (6)	16 (21)	4 (6)	-	7 (4)
Occupation (ages 18-64)					
Social welfare support[a]	45 (55)	40 (53)	34 (49)	26 (87)	66 (38)
Student	8 (1)	17 (23)	5 (7)	-	49 (28)
Employment	26 (32)	14 (19)	29 (41)	3 (10)	58 (33)
Education					
Elementary	16 (20)	28 (37)	5 (7)	9 (30)	31 (18)
High school	11 (13)	18 (24)	10 (14)	1 (3)	38 (22)
Vocational education[b]	N/A	N/A	N/A	N/A	N/A
Higher education (2-6 y)[c]	49 (60)	22 (29)	53 (76)	19 (63)	98 (56)
Researcher	N/A	N/A	N/A	N/A	N/A

Percentages might not add up to 100% due to missing values or rounding.
[a]Unemployment/stay at home/sick leave/early retirement/retirement due to disability/retirement.
[b]Vocational education is defined as an education where you are trained within professional skills (ie, Carpenter, hairdresser, gardener, electrician, plumber).
[c]Both short, medium or long higher education (1 year to more than 5 years).

Table 7. Demographics of the study population, residents living in Danish social housing and the general population in Denmark by 2018.

	THE HOME-HEALTH RESIDENTS (N = 432)	DANISH SOCIAL HOUSING RESIDENTS (N = 987.319)	GENERAL DANISH RESIDENTS[a] (N = 2.913.521)
Age			
18-24	10%	11%	9%
25-34	23%	14%	12%
35-49	27%	17%	20%
50-64	18%	18%	20%
65-79	14%	15%	15%
80+	5%	7%	4%
Gender			
Male	43%	47%	50%
Female	56%	53%	50%
Immigrants			
Non-western countries	20%	30%	10%
Western countries	3%	5%	5%
Person(s) per apartment			
1 person	43%	56%	34%
2 persons	31%	25%	36%
3 persons	10%	9%	13%
4 persons	7%	6%	12%
5+ persons	8%	4%	6%
Occupation (age 18-64)			
Social welfare support[b]	27%	33%	10%
Student	18%	N/A	N/A
Employment	30%	31%	N/A
Education (age 18-64)			
Elementary	20%	38%	20%
High school	18%	12%	11%
Vocational education[c]	N/A	26%	31%
Higher education (2-6 years)[d]	56%	18%	34%
Researcher	N/A	0.2%	0.9%

Prevalence is presented in percentages. Percentages might not add up to 100% because of missing data (not shown) and rounding.
[a]The general Danish residents living in rental property excluding Danish social housing residents.
[b]Unemployment/stay at home/sick leave/early retirement/retirement due to disability.
[c]Vocational education is defined as an education where you are trained within professional skills (ie, Carpenter, hairdresser, gardener, electrician, plumber).
[d]Both short, medium or long higher education (1 year to more than 5 years).

level. In the study population, 56% have obtained a higher education (2-6 years) as opposed to 18% in the Danish social housing population. The HOME-Health study treats vocational education as a higher education (2-6 years), where The Danish social housing population does not. If vocational education was treated as a higher education (2-6 years) the proportion of the group within the Danish social housing population (n = 987.319) would increase to 45%. With a cautious interpretation, this might decrease the educational differences between populations and increase the external validity of the HOME-Health study population.

The main weakness of the study is its nature of being a longitudinal study. This design makes it prone to censoring when either participants refuse follow-up contact or move to another area. This might leave results underestimated.[57] The study is also a natural experiment, as we have no influence on the renovation. The execution of the renovation projects has been postponed several times, increasing the risk of losing participants as they may have moved out of the area before the renovation is finalised. It will be key to evaluate the non-response population enabling description whether the non-response population is different from the response population.[58] The planned renovation schemes are similar across sites, but site 1 is different being part of the READY project and have Photovoltaic (PV) and Photovoltaic Thermal (PVT) systems mounted on the roof including a Battery Energy Storage System (BESS) for self-consumption of the PV produce. This might create a challenge treating the study population as one entity when analysing the impact of BER. The overall participation rate in the HOME-Health study is low (28%) compared to another recent Nordic study which was 72%[32] but similar compared to an American study.[24] It is worth mentioning that the Nordic study was among residents living in mainly owner-occupied households not limited to social housing areas.[35] Our study might include more people on social welfare support, as these tenants are potentially more at home and therefore more likely to be available for inclusion in the study, which in turn may lead to selection bias. As pointed out by Patino and Siegel, adding a control group to compare social housing with non-social housing can be challenging and costly.[28] Instead, each participant acts as their own control to overcome this difficulty as done by others.[32,59] Finally, the study is prone to recall bias as participants have to recall their symptoms from the past 12 months. This poses a risk of misclassification of health symptoms. To overcome this challenge, national registers or objective measurements can be used to validate health data.[57] The appropriateness using an EDC as a measure of personal inhaled dust can be argued. EDC's samples dust from the indoor environment, why particles encountered when commuting or at work are not detected. A personal sampler might have been appropriate when evaluating total personal inhaled dust and particles.[60,61]

Conclusion

This paper is relevant because there is a lack of longitudinal studies with repeated measurements before and after building energy renovation (BER). Further, there is no Danish study exploring the state of health, perception of IEQ and measured IAQ in social housing areas, where the population often is more vulnerable. This paper presents the study design, recruitment strategy and generalisability of the baseline study population in the HOME-Health study to allow for reproducibility of the project in a different setting. The study aims at adding a deeper understanding of the state of residents' health, perception of IEQ and IEQ-related behaviour and practice, and measured IAQ before and after BER. The results will add knowledge to the current epidemiologic scientific evidence on health in relation to IEQ and the built environment. The HOME-Health study combines quantitative and qualitative data to gain a deeper understanding of the complex interplay between residents and the built environment. This paper also describes how future results from the HOME-Health study can be extrapolated to the general Danish social housing population adding value to the study. Results from the HOME-Health study is expected to impact both on an individual and societal level. Individuals will gain insights into how IAQ and their own behaviour impact their health and comfort. On a societal level, the HOME-Health study can identify both energy and non-energy benefits from different BER scenarios and help justify extensive BER. Furthermore, the findings can provide important information for decision-support-tools for the building industry.

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Authorship

All authors have made substantial contributions to all of the following: The conception and design of the study (Torben Sigsgaard [TS], Grethe Elholm [GE], Steffen Petersen [SP], Charlotte Gabel [CG], Mia Kruse Rasmussen [MKR] and Stina Rask Jensen [SRJ]). Acquisition of data (GE, CG, MKR and SRJ). Analysis and interpretation of data (TS, GE, SP, CG, MKR and Thea Broholt Hauge [TBH]). Drafting the article (CG). Revising it critically for important intellectual content (TS, SP, GE, MKR, CG, SRJ and TBH) and final approval of the version to be submitted (TS, GE, SP, MKR, CG, SRJ and TBH).

Data Availability

Currently data cannot be shared for privacy and ethical reasons

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Supplemental Material

Supplemental material for this article is available online.

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