Optimization of the refurbishment of German single family homes based on construction era

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Abstract

This publication devises a method which formulates a national strategy for the renovation of single family houses by treating each era of initial construction independent of all the others, and applies a universally adoptable procedure to evaluate the cost efficiency of carbon emission reduction. A multi-objective optimization was conducted which varied the building envelope and energy systems while optimizing for annual cost and carbon emissions. The optimization was carried out in oemof.solph and PyGMO on typical German building stocks from 11 different construction eras between 1860 and 2020. The buildings were modelled in TEASER using TABULA building stock data. The results indicate that post-war era construction has the greatest improvement potential by saving over 16 tons of CO_2/yr with respect to its business as usual case. The recommended solutions for each construction era have an investment cost to emission reduction ratio which is 25% better than those of the current efficiency subsidies.

Keywords

Refurbishment, Renovation, Multi-objective optimization, Building modeling, Construction era, TABULA

1. Introduction

To address climate change, the German government has set the goal of at least 30% reduction in primary energy usage by 2030 from their 2008 levels, which equates to about 240 MToe [1]. Moreover, through the Climate Protection Act Germany has set a goal to decrease carbon emissions by 65% in 2030 from their 1990 levels [2]. Residential households in Germany are the largest consumer of final energy comprising nearly 30% of the total [3], and thus they have a major part to play in the country reaching its climate goals. Reductions in energy use and emissions will be spearheaded by the energetic refurbishment of existing buildings, which have been incentivized by the German government in recent years [4]. From 2010 to 2020 a total of 431 billion euros were invested in the refurbishment of the residential sector, which led to a total drop in emissions of 16 million tons of carbon dioxide equivalents [1, 5, 6, 7, 8]. While, in the same time, 13 billion euros were spent on energy efficiency subsidies through the federal funding for efficient buildings (BEG) program[4]. These subsidies saved around 0.7 million tons of carbon dioxide equivalents per year[9]. It is clear that these subsidies and goals are helping, but continually spending federal finances is not sustainable. Instead a strategy needs to be developed which identifies the paths of least resistance for energetic refurbishment of the residential sector without relying on subsidies. This study presents a new strategy that considers construction eras independent from one another and uses a multi-objective approach to optimize the refurbishment of the residential building stock.

In recent years the optimization of the energetic refurbishment of buildings has been highly researched. Some articles such as those by Lidberg [10] and Galimshina [11] considered optimizing around a single parameter such as energy consumption or cost of the retrofit. These were often paired with retrofit packages that combined different energy systems or envelope improvements in discrete ways, that would be practical in nature. Others such as those by Ascione [12, 13] and Haneef [14] look at a multi-objective approach with many key performance indicators (KPIs) such as cost, emissions, thermal comfort, and more. These used detailed energy modeling programs such as City Sim or EnergyPlus [15]. The models are simulated with different retrofit packages which examine building envelope improvements such as wall and roof insulation or new windows, but only test one or two different energy systems. Researchers such as Yu [16], Penna [17], and Asadi [18] took the optimization a step further by using genetic algorithms, which mimic evolutionary behaviors to solve complex problems [19, 20, 21]. With the use of genetic algorithms they were able to integrate even more insulation and building parameter possibilities to a single building. These parameters were given specific ranges of possibility and the algorithms identified the optimal operating point for each parameter, based on the objective functions. The nature of these optimizations goes further than discrete limits, such as retrofit packages, and toward a more complete approach in which all possibilities are considered within the bounds. The results from these multi-optimization procedures are generally not straightforward, in part due to the nature of considering multiple criteria. Multi-objective optimization will often not have one unique solution, but rather a set of solutions valid for the given problem. This set of solutions is called the Pareto front [22].

The study of the building envelope has been integral in the optimization of building refurbishment within the literature. There are often three main components which are adjusted; the exterior walls, roof, and windows [10, 13, 14]. Occasionally the ground floor is also considered [11, 17], but in practice this is very difficult to insulate without a basement. Roofs are often insulated with two main approaches; glass-fiber batt insulation within the rafters or blown-in insulation along the entire attic space [23]. Windows are often removed and replaced with an upgraded model [13, 17]. These replacements consist of double or triple pane options with argon, krypton or air-filled spaces. The material properties such as solar heat gain coefficient (SHGC) are occasionally adjusted. Exterior walls have the same insulation options as rooftops [24], but in Germany due to the frequency of brick/block construction over wood-framed construction, the insulation must be added to the exterior opposed to the interior of the house [25]. This makes blown-in and batt-type insulation less feasible as they need to be behind the moisture barrier in construction to prevent mold growth [23]. Extruded polystyrene (EPS) is the most common exterior insulation material due to its dense, water-proofing nature. A few optimizations have examined the optimal insulation thickness of exterior walls and found it to range between 6 and 12 cm depending on the constraints of the study [13, 26]. In recent years prefabricated exterior wall insulation has been studied [27, 28] which can greatly improve the labor costs associated with these installations. The German government has even included these so-called ”Serielle Sanierung” (German for ”serial renovation”) in the latest energy efficiency subsidies with an additional offer of 15% off the total cost [4].

Energy systems have also been researched in the context of building refurbishment, but often to a lesser extent than the envelope. For example in Galimshina three different systems are studied; a condensing boiler, pellet boiler, and an air-to-water heat pump [11]. In Ascione there are also three systems studied; photovoltaics (PV), air-source heat pump (AHP), and a condensing boiler [13]. Some considered mechanical ventilation systems but kept the primary heating system intact [17, 10]. While others considered only combined heat and power (CHP) as their basis technology [26, 29]. Most focus on a switch from a boiler to AHP, and occasionally include PV or another method of self-production. Very few, if any studies, look at the impact of thermal or electrical storage, power to heat (P2H), solar thermal (ST), or ground-source heat pumps (GHP) which are all viable as residential technologies.

The building with which to optimize around is also important as it should represent the larger building stock. Issermann [30] and Beagon [31] take an approach using the TABULA database [32] which has compiled building stocks by construction era for different countries within the European Union. Furthermore, it breaks the building stocks down by single family houses (SFH), multi-family houses, and apartment blocks, and offers building characteristics for the existing state of the construction era, a basic retrofit, and an advanced retrofit. All of the aforementioned optimization studies only focus on one building design within a single construction era and deem the solutions valid for all existing buildings within that location. But design standards [33, 34, 35], building materials [25], and building architecture have changed significantly in the last 150 years, and it is imperative to consider those differences in the context of energetic refurbishment.

To address this gap in the state of the art, this paper seeks to identify how the construction era of a home impacts its energetic refurbishment, specifically with regards to the building envelope and energy systems. Then apply the era-specific solutions to refurbishment strategies that can improve the cost and rate of refurbishment throughout Germany. Section 3 of this paper will focus on the methodology behind the optimization and will detail the meta-model used for the simulation, the design optimization and operation optimization, and the boundary conditions. Section 4 of this paper will focus on the results and analysis of the simulation by looking first at the Pareto fronts of the KPIs, then at the sizes and trends of the degrees of freedom, and lastly a validation case in another German location. Section 5 contains the conclusions of this paper and outlook for future scientific research.

2. Methodology

In this publication single family houses (SFH) can be represented by a meta-model composed of the various energy systems and building envelope used to meet the energy demands of the household. This meta-model is then used in a simulation comprised of two parts; a design optimization and an operation optimization. Both optimizations rely on specific boundary conditions such as meteorological data, demands for domestic hot water and electricity, and socio-economic factors surrounding the energy markets and technologies.

2.1. Meta-Model

In order to properly optimize the refurbishment of an SFH, a meta-model needed to be developed which would accurately replicate the energy infrastructure. The meta-model developed by Schmeling et al [36] was adapted for this research by adding in a building envelope compontent and removing some energy systems that are less applicable for SFH. In Figure 1 a representation of the meta-model is shown depicting the interaction of the energy systems with the overall energy flows and sinks of the household. Here one sees the possible residential energy systems which comprise: a condensing gas boiler, combined heat and power (CHP), power to heat (P2H), air-source heat pump (AHP), brine-source heat pump (BHP), geothermal wells, solar thermal (ST), photovoltaics (PV), electric batteries, and thermal storage. On the bottom of the figure are the three main demands of electric, domestic hot water (DHW), and space heating. And here one sees that the space heating demand is being manipulated by the building envelope. The arrows represent the flow of energy, often from the energy system towards the demand. In a few cases such as PV and CHP the energy produced can flow back into the grid, and in the case of battery and thermal storage the energy flows are bi-directional.

Within the meta-model the energy systems and building envelope are

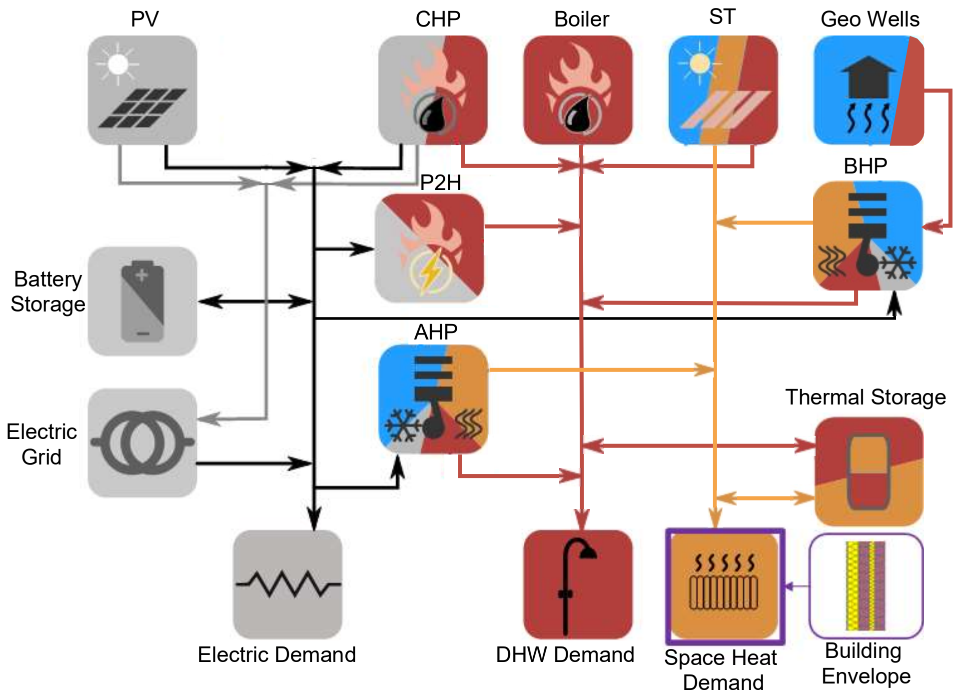

Figure 1: A flowchart representing the different energy streams, energy systems, and energy demands in the household simulation, edited from Schönfeldt et al. [37]

all variable but the electric and DHW demands remain constant. The space heat demand is dependent on the building envelope and is calculated using the heat demand function explained in detail below.

2.2. Heat Demand Function

The heat demand function is a Python workflow that uses TEASER [38], a building modeling tool developed by the University of Aachen, to import construction era-specific TABULA data for German SFH building stocks [32]. The existing envelope data is manipulated to match the building envelope sizing parameter and exported as an AixLib model [39]. Using OMPython the model is simulated in a virtual Open Modelica environment and the space heat demand time series is attained [40, 41]. A flowchart of this workflow can be seen on the left side of Figure 2.

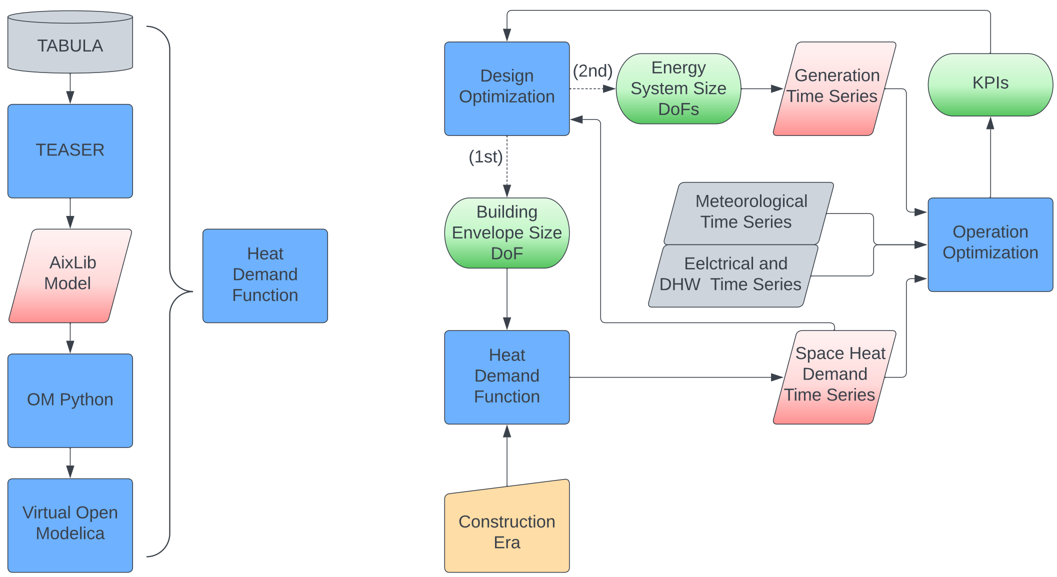

Figure 2: On the left is a flowchart depicting the workflow of the heat demand function. On the right is a flowchart depicting the overall simulation with the heat demand function integrated. The blue boxes represent functions or algorithms, the solid gray shapes represent constant inputs or databases, the solid yellow shape represents a constant input for one simulation but can change in parallel simulations, the red gradient angled shapes represent models or time series that change within the simulation, and the green gradient round shapes represent the degrees of freedom (DoFs) and key performance indicators (KPIs) which are the primary characteristics used to evaluate the simulations.

The TABULA database for Germany contains building stock information starting from before 1860 and going to the present day. In Table 1 the existing and advanced building U-values, as well as the existing energy systems are presented for each construction era studied. In Table 2 the envelope areas are presented for each construction era studied and standardized off a reference conditioned floor area in TEASER of $200m^2$. Also the usable areas as defined by the Energy Saving Ordinance of 2009 (EnEV) are presented for each era [42, 43].

Table 1: The construction eras in TABULA [42] with their associated wall, roof, and window existing and advanced U-values (W/m^2K), and existing energy system

Constr.	*Wall*		*Roof*		*Window*		Energy
Era	Ex	Adv	Ex	Adv	Ex	Adv	System
1860-1918	1.715	0.129	1.349	0.142	2.801	0.800	Boiler
1919-1948	1.715	0.129	1.441	0.138	2.801	0.800	Boiler
1949-1957	1.379	0.104	1.466	0.142	2.801	0.800	Boiler
1958-1968	1.211	0.125	0.846	0.142	2.801	0.800	Boiler
1969-1978	1.011	0.123	0.490	0.131	2.801	0.800	Boiler
1979-1983	0.783	0.119	0.355	0.142	3.201	0.800	Boiler
1984-1994	0.483	0.109	0.355	0.142	3.201	0.800	Boiler
1995-2001	0.320	0.097	0.275	0.142	1.900	0.800	Boiler
2002-2009	0.320	0.097	0.275	0.142	1.400	0.800	Boiler
2010-2015	0.244	0.112	0.203	0.120	1.300	0.700	AHP
2016-Now	0.150	0.122	0.150	0.120	1.100	0.700	AHP

Table 2: The construction eras in TABULA and their associated wall, roof, window, and usable areas as defined by EnEV (m^2) [42]. These areas are all based on a conditioned floor area in TEASER of $200m^2$

Era	Wall	Roof	Window	Usable
1860-1918	273	117	31	269
1919-1948	155	141	35	223
1949-1957	212	226	33	219
1958-1968	248	279	45	266
1969-1978	205	212	40	224
1979-1983	148	93	25	192
1984-1994	282	164	40	219
1995-2001	208	189	53	224
2002-2009	257	117	39	209
2010-2015	243	141	45	283
2016-Now	243	141	45	283

2.3. Simulation

The simulation uses the aforementioned meta-model within its two optimization procedures. *The design optimization* proposes sizes for the building envelope and various energy system technologies, which together equate to the degrees of freedom (DoFs) in the simulation. And *the operation optimization* takes the given DoF sizes and uses them to meet the demand profiles in a way that minimizes the key performance indicators (KPIs) of annual cost and emissions. A visualization of this process can be seen on the right side of Figure 2. Here the simulation is consistently gaining knowledge and adapting from the iteration of each optimization and will run until it has been deemed to converge on a Pareto front of optimal KPIs.

2.4. Design Optimization

The design optimization relies upon a genetic algorithm to find an optimal system construction with limited constraints. Each DoF has a sizing parameter which is linearly interpolated between a minimum value, 0, and a maximum value that is often determined from physical parameters or by the demand. In Table 3 the maximum values of the energy systems are summarized.

Table 3: The maximum value of each energy system investigated, thermal demand considers both space heat and domestic hot water demands

Gas Boiler	CHP	AHP	BHP	Geo Wells	P2H	ST	PV	Heat Stor.	Battery Stor.
Therm Dem.	10 kW	Therm Dem.	Therm Dem.	10 Wells	Therm Dem.	South A_{Roof}	South A_{Roof}	5 m^3	50 kWh

As noted in Figure 2, the building envelope DoF must always be calculated first. This is because it determines the heat demand time series upon which many of the thermal systems rely for sizing. Unlike the energy systems, the building envelope is comprised of multiple components and will be discussed in detail further.

2.4.1. Building Envelope Degree of Freedom

The building envelope is an integral parameter when considering refurbishment and in this research its variable components include the exterior walls, roof, and windows. The improvement of the walls and roof will be represented by an additional layer of insulation. The walls will gain a layer of exterior extruded polystyrene so as to not affect the living space [44]. While the roof will gain an additional layer of glass fiber batt between the rafters in the attic space. The windows will be assumed to be completely replaced with an upgraded window of the associated U-value.

All three of the envelope components scale in accordance with the envelope sizing parameter where, the existing U-values from Table 1 represent the minimum envelope sizing criteria, and the advanced U-values represent the maximum sizing criteria for the design optimization. With the minimum and maximum values set, the parameter to interpolate around had to be identified. In Figure 3 one can see the results of interpolating with respect to U-value and thus overall heat transfer, or interpolating with respect to insulation thickness.

In order to keep consistency across all the DoFs we selected to interpolate around insulation thickness because that will mean that all of the DoFs scale proportionally with the cost KPI. This choice means that more heat transfer is mitigated in the first 20-40% of the envelope improvement than the latter 60%, which may impact the size of the optimal building

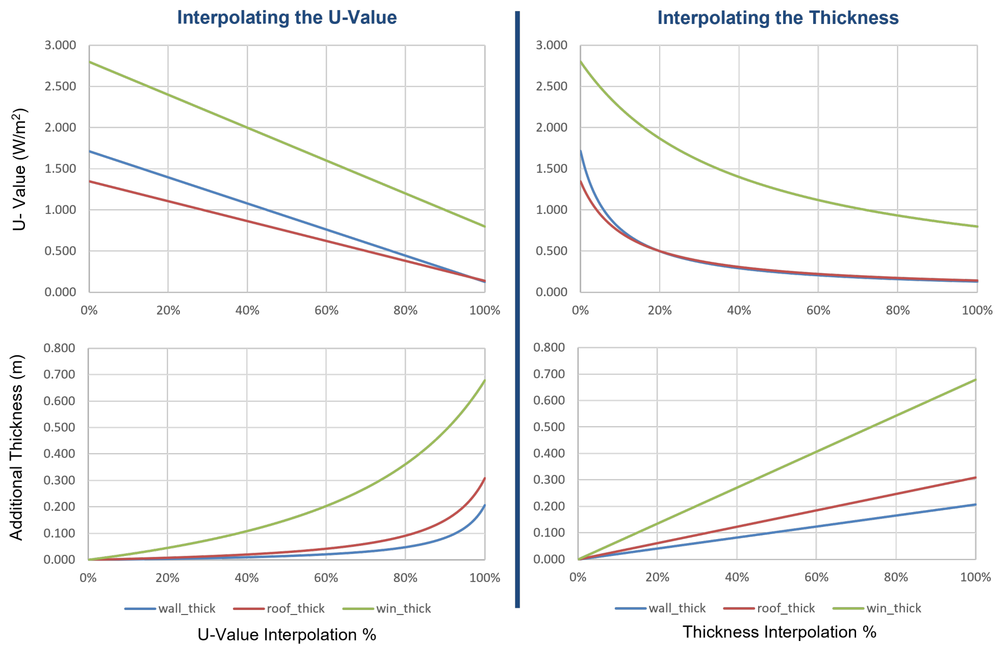

Figure 3: Building envelope interpolation possibilities for the 1860-1918 construction era. On the left are plots if the envelope was interpolated via the U-value, and on the right is if it were interpolated via the insulation thickness. The top graphs represent the U-values of the envelope surfaces, and the bottom graphs represent the respective thicknesses.

envelope DoF.

2.5. Operation Optimization

The operation optimization is built around a mixed-integer linear programming algorithm which simulates the first year of the SFH's operation, given the DoF sizes calculated in the design optimization. It allocates energy systems to meet the demand profiles by trying to minimize cost and emissions for every point in time. If there is the ability to sell back to the grid or store excess energy created, this will also be accounted for. The entire run is iterated until the optimizer converges on the best possible KPI outputs for that sizing configuration. The open energy modeling framework (oemof.solph) along with the model template for residential energy supply systems (MTRESS) are the forces behind this optimization [45, 37]. The cost and emission objective functions used in the genetic algorithm are described below.

2.5.1. Cost Objective Function

The cost objective function accounts for both the capital expenditures (CAPEX), and operational expenditures (OPEX). This relationship is depicted in Equation 1.

$$Cost_{year1} = CAPEX + OPEX \tag{1}$$

The CAPEX take the investment, replacement, and leftover costs of a system and amortizes it over a specified number of payment years as seen in Equation 2 [46]. The system investment costs were interpolated from actual pricing data obtained by a third party. It should be noted, that subsidies or other incentive programs are not considered in the cost KPIs of the optimization.

$$CAPEX = \sum_i (P_i + R_i - L_i) * \frac{r(1+r)^{n_i}}{(1+r)^{n_i} - 1} \quad (2)$$

Where:

i		system
P_i	(€)	principle investment cost of the system
R_i	(€)	replacement costs of the system within the payment period
L_i	(€)	leftover system value at end of payment period
n_i	(yrs)	payment period
r	(%)	interest rate

The OPEX relies on energy market factors such as electricity price and natural gas price which can fluctuate throughout the day. Thus, for each time step of the simulation the electric and natural gas demands along with the electric supply, if applicable, are multiplied by their respective market prices [47, 48]. The sum of these is added to the average annual maintenance cost, and the entire process is completed for each DoF. The OPEX calculation can be found in Equation 3. Note that most DoFs will only have natural gas or electric demand. Only PV and CHP will have electric feed-in.

$$OPEX = \sum_i (M_i + \sum_t (D_{NG} * P_{NG} + D_{El} * P_{El} - S_{El} * P_{Feed-in})) \quad (3)$$

Where:

i		degree of freedom
M	(€)	annual maintenance cost
t	(hr)	time step
D_{NG}	(kWh)	demand for natural gas by the system
P_{NG}	(€/kWh)	price of natural gas
D_{El}	(kWh)	demand for grid electricity by the system
P_{El}	(€/kWh)	price of grid electricity
S_{El}	(kWh)	supply of electricity fed into the grid by the system
$P_{Feed-in}$	(€/kWh)	price of electricity fed into the grid

2.5.2. Emission Objective Function

The emission objective function calculates all possible CO_2 equivalent emissions in the first year of operation. For the energy systems investigated, this only considers the emissions released during the energy production phase. Gray emissions, while relevant, will not be considered for the energy systems, because life cycle analysis data was found for some but not all of the systems and it is often a parallel field of research [49, 50]. However, for the building envelope calculations, gray emissions can, and will, be considered because a simplified approach is available and all data could be extracted from the same source [51]. The total annual emissions are calculated using Equation 4.

$$Emissions_{Ann} = Gray_{Ann} + Prod_{Ann} \quad (4)$$

The gray emissions, like investment cost, occur in year 0 but can be spread across the lifetime of the system for accounting purposes. But emissions unlike cost, do not have a time value, meaning that emissions in the present day, or emissions twenty years from now have the same value [52]. Thus, using Equation 5 one can discount the total gray emissions, $Gray_{Envelope}$ over the lifetime of the house, $n_{Envelope}$.

$$Gray_{Ann} = \frac{Gray_{Envelope}}{n_{Envelope}} \tag{5}$$

The production emissions, similar to the OPEX, are based on the demand and supply of the energy types from their respective systems. These demand and supplies are multiplied by an equivalent CO_2 emission factor. For natural gas this is constant and based on its chemical makeup, but for the electric grid this is based on data pertaining to the different primary fuels used for grid production at that point in time. This is expressed in Equation 6.

$$Prod_{Ann} = \sum_i [\sum_t [D_{NG} * E_{NG} + D_{El} * E_{El} - S_{El} * E_{El}]] \tag{6}$$

Where:

$Prod_{Ann}$	(t/yr)	Annual emissions due to energy production
i		energy system
t	(hr)	time step
D_{NG}	(kWh)	demand for natural gas by the system
E_{NG}	$(\frac{t}{kWh})$	natural gas emission factor
D_{El}	(kWh)	demand for grid electricity by the system
E_{El}	$(\frac{t}{kWh})$	electric grid emission factor
S_{El}	(kWh)	supply of electricity to the grid by the system

2.6. Boundary Conditions

The boundary conditions of this paper include the present price and regulatory framework, the meteorological data, and the domestic hot water and electricity demands. The optimization takes place in the year 2020 and uses meteorological data from the Deutscher Wetterdienst (German Weather Service, DWD) station 691 located at the Bremen airport. [53]. Additional data was taken from the Würzburg weather station 5705, as a validation case for the model. This location was chosen because it is much warmer on average than Bremen and should have some different climatic impacts. While all eras were studied in Bremen, only a few were studied in Würzburg.

For the DHW and electricity demands of the household the Load Profile Generator developed by Pflugradt [54] was utilized. Using this program an SFH was selected with an average family consisting of two parents and two children, and using standard appliances. The results were output as an hourly time series.

A control case where no refurbishment takes place, called the Business as Usual (BAU) scenario, was identified for each era as a reference point. The BAU case is calculated in a very similar manner to the optimization, except the sizing parameters are known and CAPEX will be ignored. Every sizing parameter was 0, except for the existing energy system, found in Table 1, which was at its maximum because it represents the entire building demand. The CAPEX is ignored because no investment is made on the system. The annual costs, emissions, and German federal reconstruction loan company (KfW) efficiency level of each era's BAU scenario can be found in Table 4. This table refers to each era as a single representative year. This simplification will be used in the paper going forward. The KfW efficiency levels were calculated using Equations 7 & 8. Here the usable areas are taken from IWU data and found in Table 2 [42], the primary energy factors are taken from GEG Appendix 4 [55], and the KfW100 building was calculated using the steps laid out in GEG Appendix 1 [56].

$$PE = PEF_{gas} * G_{im} + PEF_{el_im} * El_{im} - PEF_{el_ex} * El_{ex} \tag{7}$$

Where:

PE	$(\frac{kWh}{yr})$	Annual primary energy
PEF_i		Primary energy factor from GEG Annex 4
G_{im}	$(\frac{kWh}{yr})$	Imports of natural gas
El_{im}	$(\frac{kWh}{yr})$	Imports of electricity from the grid
El_{ex}	$(\frac{kWh}{yr})$	Exports of electricity to the grid

$$KfW_{eff} = \frac{PE}{Area_{usable}} \tag{8}$$

Table 4: Presents the Business as Usual annual cost, emissions, and KfW efficiency level for a representative year studied in each construction era

Year	1860	1920	1950	1960	1970	1980	1990	2000	2008	2012	2020
Cost (€/yr)	5043	4486	4854	4909	4103	3176	3859	3736	3156	1690	1704
CO_2 (ton/yr)	7.6	6.8	7.3	7.4	6.2	4.8	5.8	5.6	4.8	2.7	2.7
KfW Eff.	206	168	190	180	152	132	115	107	102	45	43

3. Results and Discussion

The optimizations were run in parallel with each era going through about 10,000 iterations. Any solutions that were not physically realizable were omitted. The results were then broken down into the main components of the optimization; the KPI Pareto fronts from the operation optimization, and the degrees of freedom from the design optimization. These results will be presented and discussed below.

3.1. Operation Optimization - Pareto Fronts

The Pareto fronts represent the set of solutions that are most optimal for the construction era. Since some Pareto sets contain 60 or more solutions, we identified three characteristic points to compare across the eras. These would be the most economic, most ecologic and recommended solutions. The *most economic solution* is the one with the lowest annual cost and the *most ecologic solution* is the one with the lowest annual emissions. The *recommended solution* is found by identifying the location on the Pareto front which matches the BAU annual cost. Thus, this solution represents a break-even point where an investment can be made with significant emission savings, but no net economic change for the homeowner.

In Figure 4 one can see all of the KPI solutions for the 1990 construction era with the optimality plotted on the z-axis, and the Pareto front, BAU case, and most economic, ecologic, and recommended solutions demarcated. From a first glance it is clear that almost every solution represents a significant improvement from the BAU case with regards to the emissions KPI. Many of the solutions are net-zero carbon or better, which means that the refurbished home is selling back to the grid enough PV and CHP energy to offset both the production and gray emissions. One also sees that the cost KPIs for most of the solutions are within the same factor of spending as the BAU case, showing that these refurbishments are feasible from an economic level.

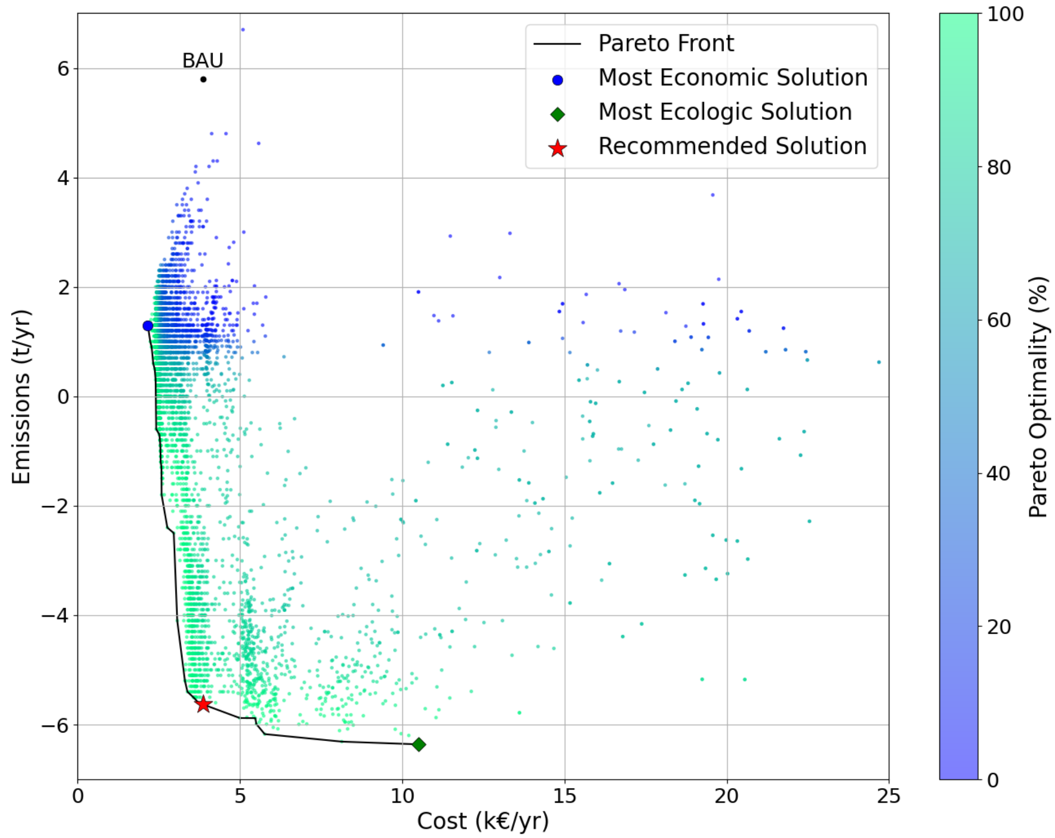

Figure 4: KPI results for the optimization of the 1990 construction era. The colormap depicts the optimality of the simulation with the Pareto optimal front being represented by a black line. Three points are called out on the Pareto front representing the most economic, ecologic, and recommended solutions. The Business as Usual case is represented by a black dot and labeled BAU.

What is interesting about Figure 4 is that it has two very distinct regions along the Pareto front. These can be identified as the *cost optimal front*, represented by the low costs and decreasing emissions, and the *emission optimal front*, represented by the low emissions and increasing costs. The cost optimal front is important because it shows that for only minor increases in annual cost, significant gains in emission reduction can be achieved. The ecologic point is essentially the opposite, where to get more emission reduction significant economic investment must be made. Unlike some Pareto fronts which are more round and arcing in shape, this is much more elbow shaped, with the cost and emission optimal fronts being very linear in nature. While all of the Pareto points are optimal solutions for the genetic algorithm, the elbow is intriguing because it is seemingly the place where the range of low cost and low emissions meet. Thus if bothKPIs have an equal weight, then the elbow would represent the most optimal of the Pareto solutions. One can also see that the elbow closely aligns with the recommended solution. So not only is the recommended solution the break even point for the homeowner, but it is also close to the marginal cost optimum.

3.1.1. Construction Era Comparison

A comparison of the Pareto fronts of all the years can be found in Figure 5. The Pareto fronts are color-mapped from the earliest construction era (1860) in dark blue, to the newest construction era (2020) in light green. The recommended solutions are connoted with red stars where applicable.

Here one can see dense cost optimal fronts for every construction year, but limited emission optimal fronts. The cost optimal fronts appear to sort into 2 distinct sections based on construction era . The least expensive of those sections would be modern construction beginning from 1980 where the costs seem to increase with age. The second is a chronological path from 1860 to 1970, identified as early eras, where the costs appear to decrease with age.

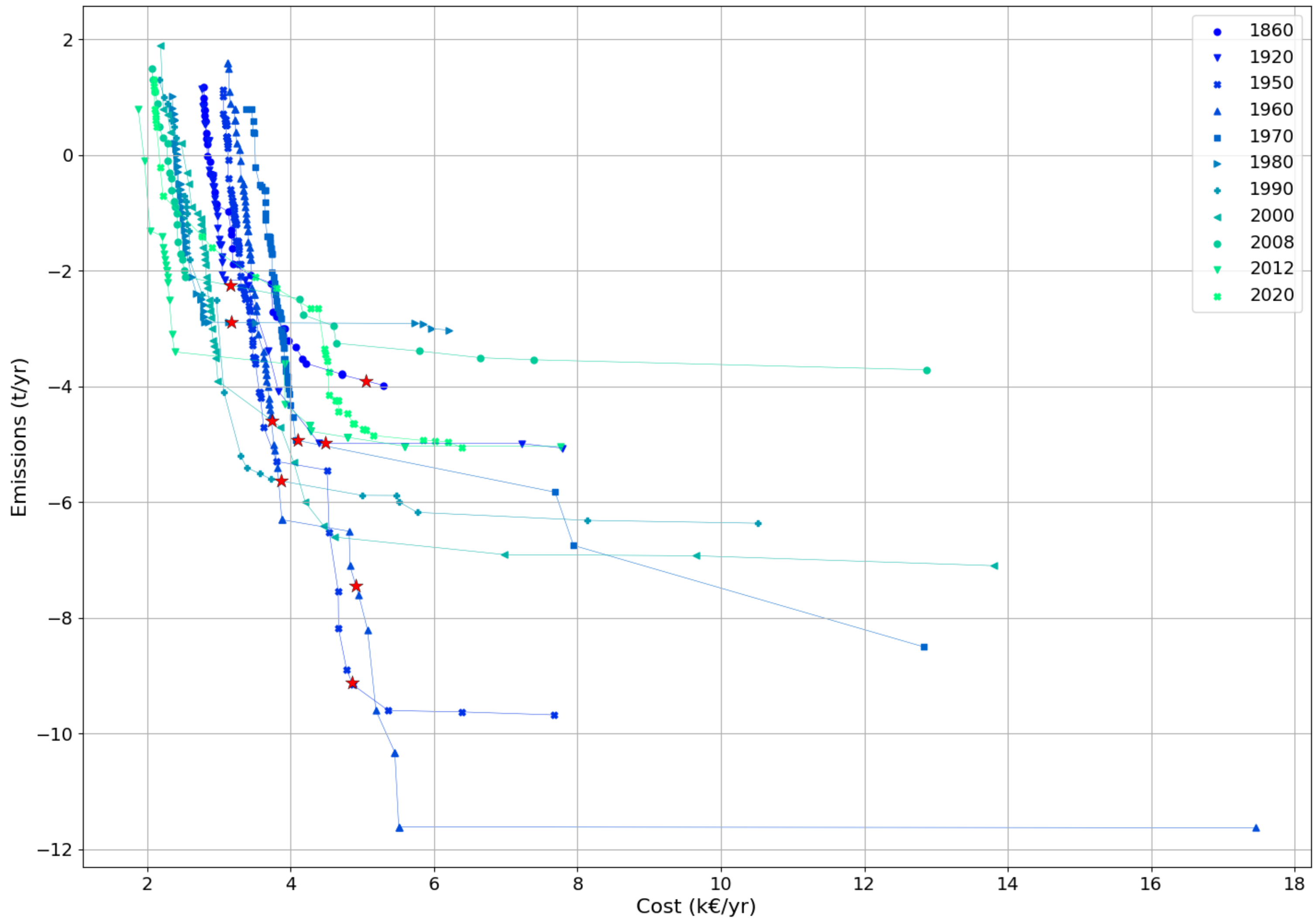

Figure 5: KPI results for the Pareto fronts of each construction era studied, and their associated recommended solutions

The modern era being most cost optimal tends to make sense as it is already rather energy efficient, and thus does not require much improvement. Early construction being less expensive than post-war era construction seems to break a trend that the newest buildings should be cheaper. But if one looks at the overall size of buildings for the same conditioned area, Table 2, then one sees a clear increase in building size as each envelope component reaches a local maximum during the 1960 era. This could be from a number of factors including increases in ceiling heights, the addition of unconditioned spaces such as a garage, or the use of single-story homes with expansive floor plans etc. And since the envelope cost calculations are based on surface area, and early era buildings would benefit much more from envelope improvement than modern era ones, then it makes sense that buildings with the smaller envelope areas would have lower costs.

As one moves down the economic front closer to the elbow, these distinctive era groupings begin to blur a bit. 1980 appears to reach its emission optimal front first, followed by 2008 and then 1860. The lowest emission values come from 1950 and 60 which seem to lack an emission optimal front altogether. Thus, unlike with cost, it seems that emission reduction does not have a strong correlation with the construction era.

3.1.2. Most Optimal Era for Renovation

Looking at all of the eras together it is clear that the construction era a residence was built in has an impact on the effect of its refurbishment, but how should the optimal era to focus refurbishment be identified? If one takes cross-sections of Figure 5, a procedure can be developed for identifying the optimal eras to focus renovation. For example, if the goal is net-zero emissions as is commonly discussed [57], based on these results, it would be wise to focus on homes in the modern eras starting with 2012, 2008, 1990 and so forth. But if the goal is to spend a set amount of money per household, say 4000€/yr, then it would be better to focus on 1950, followed by 1990, and then 2000. But these approaches have the same fallacy and that is treating every era identically when they have vastly different physical characteristics from one another that affect their energy demand.

Instead we suggest a strategy which compares each construction era against a reference criteria unique to its era; its BAU case. The optimal era can thus be identified by comparing the recommended solutions of each era. The recommended solutions as shown by the red stars in Figure 5 quantify the amount of CO_2 a homeowner can save while spending the same amount of money annually as they do today. The recommended solutions for each era and their corresponding emission improvement values are given in Table 5. It is important to note that there is not a recommended solution for the 2012 and 2020 eras and this is because no refurbishment could equal the costs of the BAU case. This is also the same time that the EnEV legislation came out and building standards became stricter. This standard appears to be a direct cause of why it is not recommended to renovate residences built after the 2008 era.

The improvement table in Figure 5 shows that the most benefit per home can be gained from refurbishing 1950 era single family homes, with an improvement rate of 16.4 tonnes per year. When comparing against the entire building stock, the largest gains can be found in the 1960 era with

18 Mton per year. This value is largely due to the prevalence of homes constructed in the 1960 era. Thus, it is clear that post-war era construction of 1950 and 1960 represent the rates with the highest improvement gains from renovation. So if Germany wants to decrease its emissions as fast as possible, then it is recommended to start with these construction eras first.

On the right side of the improvement table are values that can put these recommended solutions in perspective with existing strategies. The first would be energy improvement without subsidies which has a net invested money per CO_2 savings of approximately 7.7 k€/t when considering emission savings due to household fossil fuel consumption and the percentage of energy supply associated with households [5, 6, 7, 8, 3]. Similarly considering energy refurbishment in Germany that uses KfW subsidies a metric of 5.4 k€/t is achieved [58]. It is clear that all of the recommended savings are below these existing metrics, highlighting their improvement in the gains of the refurbishment. Additionally the KfW efficiency values for every era except 1960 are lower than the best subsidy values today of KfW 40 houses. So it is clear that the recommended solutions can not only save a lot of emissions, but can also do so better than the current strategy employed by Germany.

3.2. Design Optimization - Degrees of Freedom

As with the KPIs, a deeper dive into the DoFs across the span of construction eras is required. So Figure 6 was developed which identifies the range of each DoF found to be Pareto optimal, as well as explicitly showing the most economic, most ecologic, and recommended solutions. The y-axis is scaled to present the maximum DoF values as laid out in Table 3.

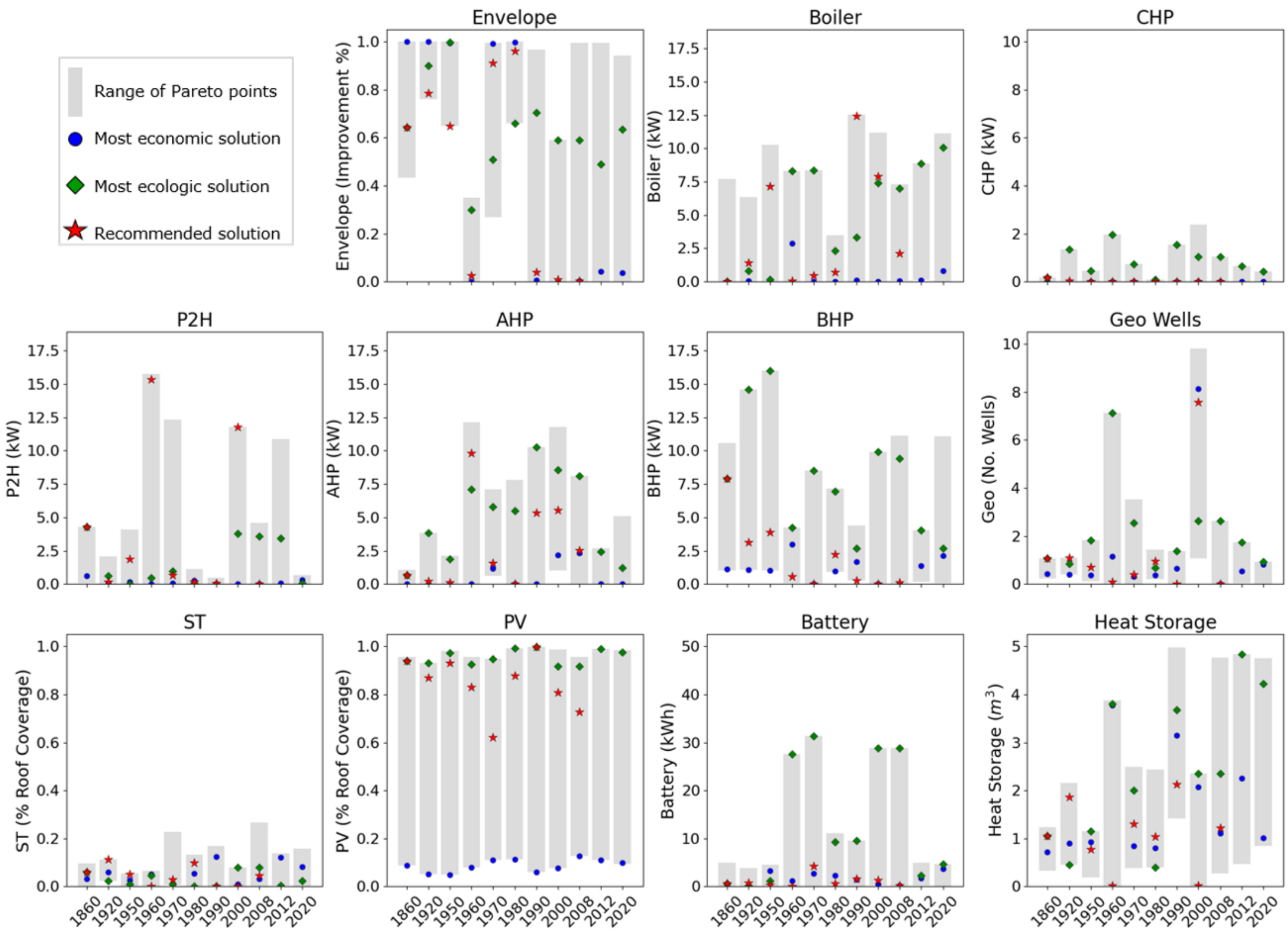

Figure 6: Pareto optimal comparison of the degrees of freedom sizing data across the eras. The bars represent the range of system sizes within all of the Pareto optimal points, the green diamond represents the most ecologic solution, the blue circle represents the most economic solution, and the red star represents the recommended solution where applicable.

Table 5: Presents on the left side the CO_2 improvement factors for each construction era based on its BAU case, and then the total amount of CO_2 that can be saved annually if the entire building stock is renovated. On the right is a metric of total invested euros per emissions saved to compare with current standards and the KfW efficiency value of the house. Note only eras which had costs lower than the BAU were considered.

Year	Improvement (t/yr)	Bldg Stock (Mm^2)	Saved CO_2 (Mton/yr)	Metric (k€/CO_2)	KfW Eff.
1860	11.5	171	9.8	4.7	30
1920	11.8	190	11.2	4.4	15
1950	16.4	140	11.5	3.9	16
1960	14.8	243	18.0	3.2	61
1970	11.1	234	13.0	4.5	23
1980	7.7	122	4.7	4.6	20
1990	11.4	163	9.3	3.3	35
2000	10.2	167	8.5	3.5	39
2008	7.1	125	4.4	3.1	34
Sum	102	1555	90.4		

3.2.1. Pareto Optimal Ranges

First one will consider the different ranges of the Pareto DoFs in relationship to the maximum possible size of the DoF. Here it is clear that large CHP and ST systems did not reach the Pareto front. The remaining thermal systems are rather variable across the construction eras but are generally present in some capacity. However, none reach the maximum size available, which points to the optimizer preferring a diversity of production options.

PV definitely stands out from the rest of the DoFs because it often spans the entire range from nearly minimum to nearly maximum. It also does this consistently across all of the construction eras in a way that no other DoF does. Additionally, PV and also thermal storage almost always exist, meaning their system size is greater than zero, in every Pareto optimal solution regardless of construction era, which point to their importance in the overall energy production system of households.

If one looks at the building envelope DoF they will see a similar segregation of eras with early vs. modern as was seen in Figure 5, the 1960 era not withstanding. It is clear that the early eras prefer relatively significant envelope improvement. Almost all of their ranges start at 30% envelope improvement or more. This of course was to be expected as they had the weakest existing envelopes but it is still good to see the results pan out in the design optimization. The modern eras however have a building envelope improvement that is a little less certain. The range spans all the way from 0% to nearly 100% in the case of 1990, 2008, and 2012. So clear conclusions cannot be drawn from the ranges alone with regards to modern era envelope improvement.

3.2.2. Most Economic Solution

For the majority of the energy systems, the most economic solutions (blue circles) are found at the minimum range of the Pareto front or at least near the bottom. PV would be the strongest example of this, followed by CHP, P2H, and batteries.

What is intriguing though, is those values which are not at the minimum. For example thermal storage is at least 1 m^3 for almost all of the most economic points. This leads one to believe that the cost of having a storage device for thermal energy to help with peak demands is better and more effective than increasing the capacity of the thermal systems. Whereas for batteries this same storage dichotomy does not seem to exist; most likely because the electric grid is bidirectional and there are economic benefits to selling back to the grid vis a vis the feed in tariff.

Geothermal wells and BHP are other systems where the most economic point is often above the minimum. It isn't quite as stark as the thermal storage, but this still represents a cost savings value on the part of these systems. Also these two systems follow almost the exact same trend across the eras, pointing to the optimizer recognizing them as a unit and installing them together at similar ratios. For 1920 it appears that BHP , geothermal wells, and ST along with thermal storage are able to manage the full heat demand of the system while still being very small overall. This finding is important because often geothermal is deemed too expensive for installation. But when considering the annuitized lifetime costs it is one of the better options for homeowners, given they have the capacity and space for it.

The building envelope shows the strongest dichotomy between the eras among its most economic points, 1960 notwithstanding. In the early eras it is clear that the costs of the envelope improvement are greatly outweighed by the benefits in energy saving and decreased system sizes. But once the 1990 construction era is reached, there is a flip and the existing building envelopes are efficient enough that it is less cost effective to renovate the envelope than it is to swap out systems. This finding is intriguing because in 1990 the U-value of the window is still very poor, see Table 1. But the gains in the wall U-value between 1980 and 1990 must have been enough for the optimizer to no longer find it cost beneficial to improve the entire envelope.

It is difficult to say with certainty why 1960 breaks the trends of its neighbors, but it most likely comes down to the fact that it has the largest envelope surface area and sometimes a few hundred euros can represent a new direction for the optimizer. In fact to test this hypothesis, the DoFs of the 1950 and 1970 Pareto points were input into the 1960 optimization and they did not reach the 1960 Pareto front. This proves it is not the convergence of the optimizer, but rather the makeup of the 1960 construction, era that differs it from its neighboring eras.

3.2.3. Most Ecologic Solution

Almost all of the most ecologic Pareto points (green diamonds) occur at or near the maximum of the DoFs. This phenomena is most prevalent for PV and CHP which makes sense because they are the only systems that can produce negative emissions by selling electricity back to the grid based on Equation 4. It then follows that renewable systems like BHP , geothermal wells, and ST would also have relatively large system sizes since they produce essentially zero emissions during production. For BHP and geothermal wells this is true for the most part, as their system sizes are considerably larger for the most ecologic points. ST however still has really small values, often times lower than the most economic point. But one has to consider that PV and ST share the same physical space, and because PV so strongly influences emissions, ST has to use whatever space remains. When looking at the roof as a whole though, in almost every construction era 100% of the roof area is used for energy production.

It doesn't just appear to be the renewable energy systems that are maximized however. In fact nearly all of the systems including the boiler, which should be the largest polluter of all the DoFs, have at least one construction era with the maximum Pareto system size being the most ecologic point. However system size does not equate to system usage, thus, Figure 7 shows the energy production in megawatt-hours of each energy system throughout the year for the most economic, ecologic, and recommended solutions. And from this one sees that for a large boiler size such as the 1970 era, the boiler is never actually used. Instead most of the energy comes from the AHP and ST systems.

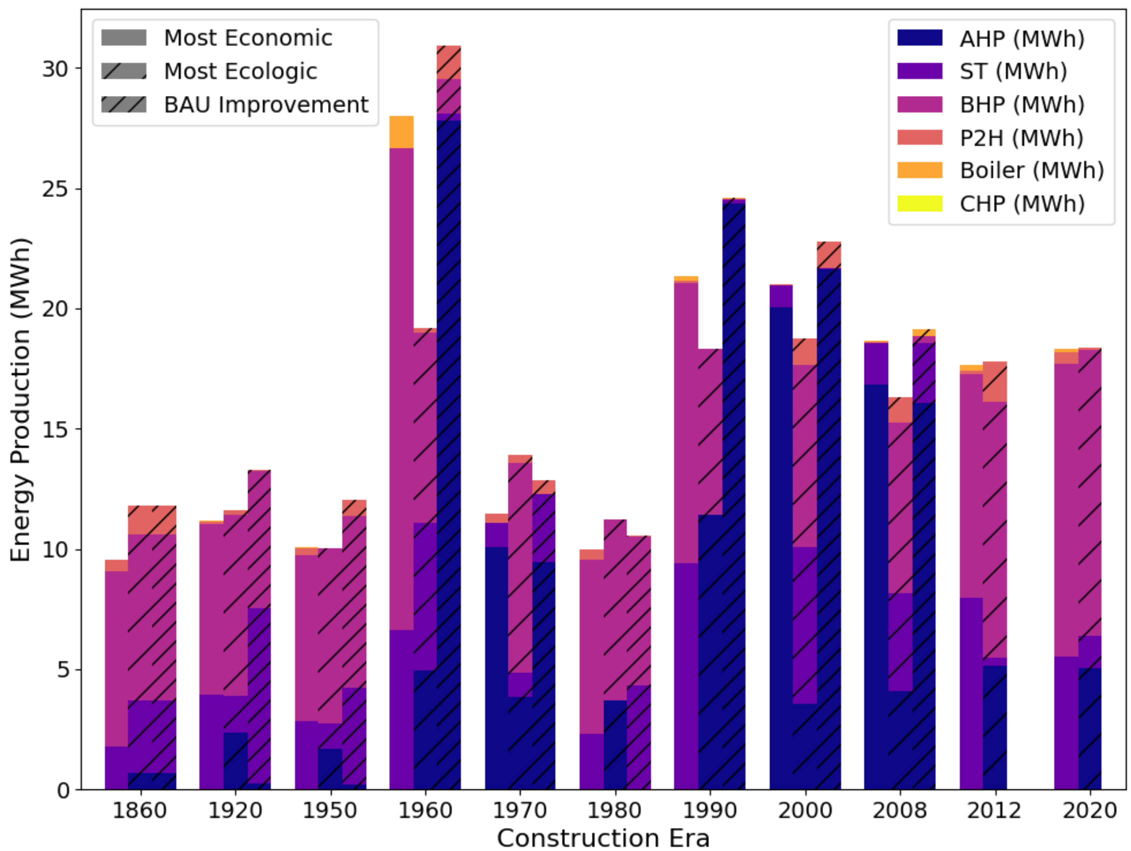

Figure 7: Stacked bar plot showing the energy usage in megawatt-hours of each thermal energy system for the most economic, ecologic, and recommended solutions across the construction eras.

Furthermore, one sees from Figure 7 that regardless of the system sizes, the energy systems that are preferred for use are either renewable, heat pumps, or backup electric resistance heat. Across the eras, the boiler is only marginally used in 1960 and the CHP is never used. Either AHP, or BHP in conjunction with the geothermal wells and ST, is used in almost every scenario. This outcome is really promising for ST because it shows that even with only a marginal roof space significant thermal demands can be met. It also shows that the ability to have some source of P2H can be much more effective to meeting the peak loads than increasing the size of the main thermal system. It is also relevant to point out that these results favor electrification of the heating system as almost no gas is consumed.

When looking at both Figure 6 and 7 the most economic points really only include energy systems that are used in the annual energy production, but the ecologic points often contain energy systems that are never used to meet the thermal energy demands of the house. This is probably the reason why the ecologic fronts in Figure 5 are almost always flat. They have varying, unused sizes of thermal systems while maintaining the same, maximum PV system. The PV system keeps the emissions at the low value while the varying thermal system sizes increase the cost while having minimal emission impact.

3.2.4. Recommended Solution

The recommended solutions (red stars) often fall between the most economic and ecologic points. They tend to still have relatively large PV systems, and renewable thermal systems sized somewhat appropriately for the demand. Like the most economic points, most of the recommended solutions have system sizes greater than zero only when they are used for energy production, but it isn't perfect. For example 1860 has an almost equal BHP energy use in MWh as the most economic point, but with a system size nearly 5 times larger. Likewise the boiler sizes are much larger than they need to be for 1950, '60, and '90. This would indicate that even more cost savings are available and the BAU improvement factors could conceivably increase.

For the building envelope DoF, the recommended solutions seem to temper those of the most economic points, especially for the early eras. This seems to suggest a breaking point in envelope improvement where the economic gains from adding more insulation, which results in smaller energy systems, no longer outweigh the ecologic benefits of say installing renewable energy such as PV. This phenomena comes in part from the nature of heat transfer. Insulation thickness is inversely related to U-value and thus the overall heat transfer. So the majority of energetic gains are made in the first 20-40% of additional insulation thickness. The remaining thickness up to the maximum is beneficial, but as one can see, greater benefits can be found by investing in renewable energy systems.

Applying these recommended solution DoFs in a strategic manner seems to suggest nearly full roof coverage with PV and some ST. Additionally, residences should have a thermal supply comprised of geothermal or AHP, but generally not both. And they should have P2H for backup situations as a way to decrease other system sizes, potentially in the form of a heating rod or other integrated system for the heat pumps. Thermal storage should also be considered for additional flexibility it offers. Gas-powered systems would not be installed, as they are not used over the course of a year, and batteries would be avoided, in part due to their high upfront costs. Lastly, the envelope would be improved in the early eras to around 60% but be untouched in the later eras and 1960. One could argue that if a home is being renovated and the envelope is included then it should be fully improved and not merely go halfway and need to be done again in the future. But, in nearly all cases 60% of the maximum insulation thickness results in meeting or exceeding the U-value for new construction. Additionally, given a homeowner has a fixed income to perform these retrofits, the avenue to save the most emissions is to invest in renewable energy over the final 40% or so of the envelope thickness, which is why it is recommended here.

3.3. Validation of Results

In order to make the case that the strategy presented here is valid for the whole of Germany, a second location was selected to run the simulation over a handful of the construction eras which has a vastly different meteorological profile to Bremen. The results comparing the KPIs of Würzburg and Bremen can be found in Figure 8 and the results comparing the DoFs of the locations can be found in Figure 9. The Pareto fronts of the 1860 and 1950 eras are nearly identical for the two locations, and the 1990 and 2020 eras are still quite close to each other. 1990 has the largest difference between the two locations, but even then it appears to be a phase shift up and to the right rather than a completely different structure of the Pareto front. A phase shift could be expected as the boundary conditions of the simulation are slightly modified but the overall results are of the same shape.

Looking at the DoFs between the two locations similar conclusions can be drawn. Most of the Pareto front ranges are similar between the two locations. The energy systems that weren't favored by the optimizer are still not favored, and those that had wider ranges, still have wide ranges. The values differ a little but the overall trends remain. Additionally the main strategies, of beneficial but not excessive envelope improvement, nearly complete rooftop use for energetic purposes, and installation of renewables with flexible thermal options are all still prevalent. For that reason it can be assumed that the results found for Bremen can be used through the whole of Germany.

4. Conclusion

The impact of the construction era of a German single family home was tested by optimizing the refurbishment of an average home in eleven different construction eras with the same conditioned area. The optimization consisted of 2 parts. The design optimization which manipulated the size of 10 different energy systems and the building envelope improvement percentage. And the operation optimization which took the given system sizes and simulated the first year of operation, outputting key performance indicators of annuitized cost and annual emissions. The key performance indicator (KPI)s and degrees of freedom (DoFs) were compared across the different eras in order to develop an ideal strategy for the renovation of German single family households.

A recommended solution was identified which takes the current annual costs of the homeowner given their business as usual situation and finds the Pareto optimal solution with the closest cost. In this respect,

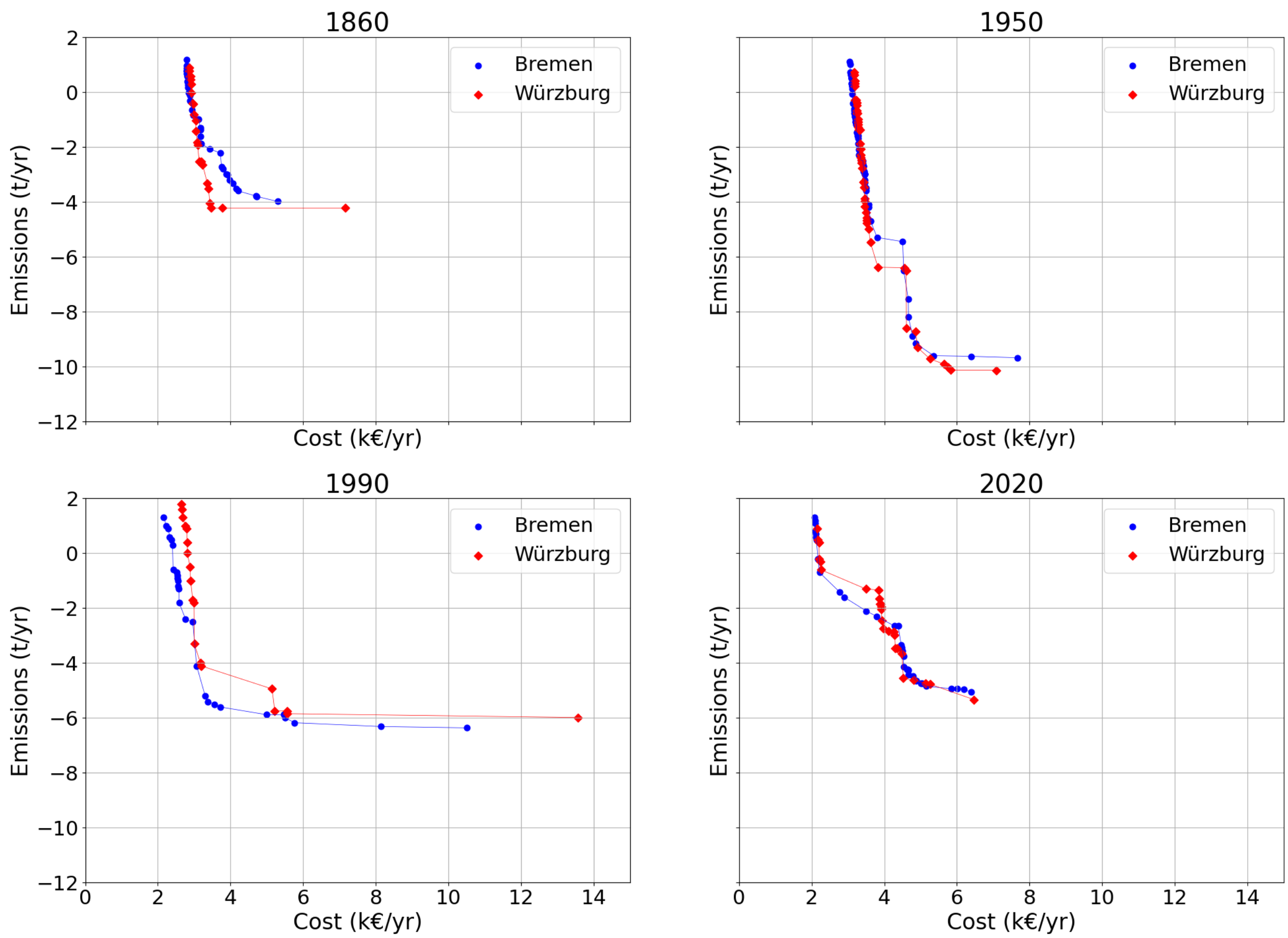

Figure 8: KPI results comparing Bremen (blue) and Würzburg (red) for the 1860 (top left), 1950 (top right), 1990 (bottom left), and 2020 (bottom right) construction eras

the homeowner has no additional annual cost difference, but has significant ecological savings in the form of decreased emissions. All of these recommended solutions had significant gains in the refurbishment metric of investment spending per carbon emissions saved with reference to the current refurbishment strategies. And nearly all had lower KfW efficiency values than the goals of the present subsidies.

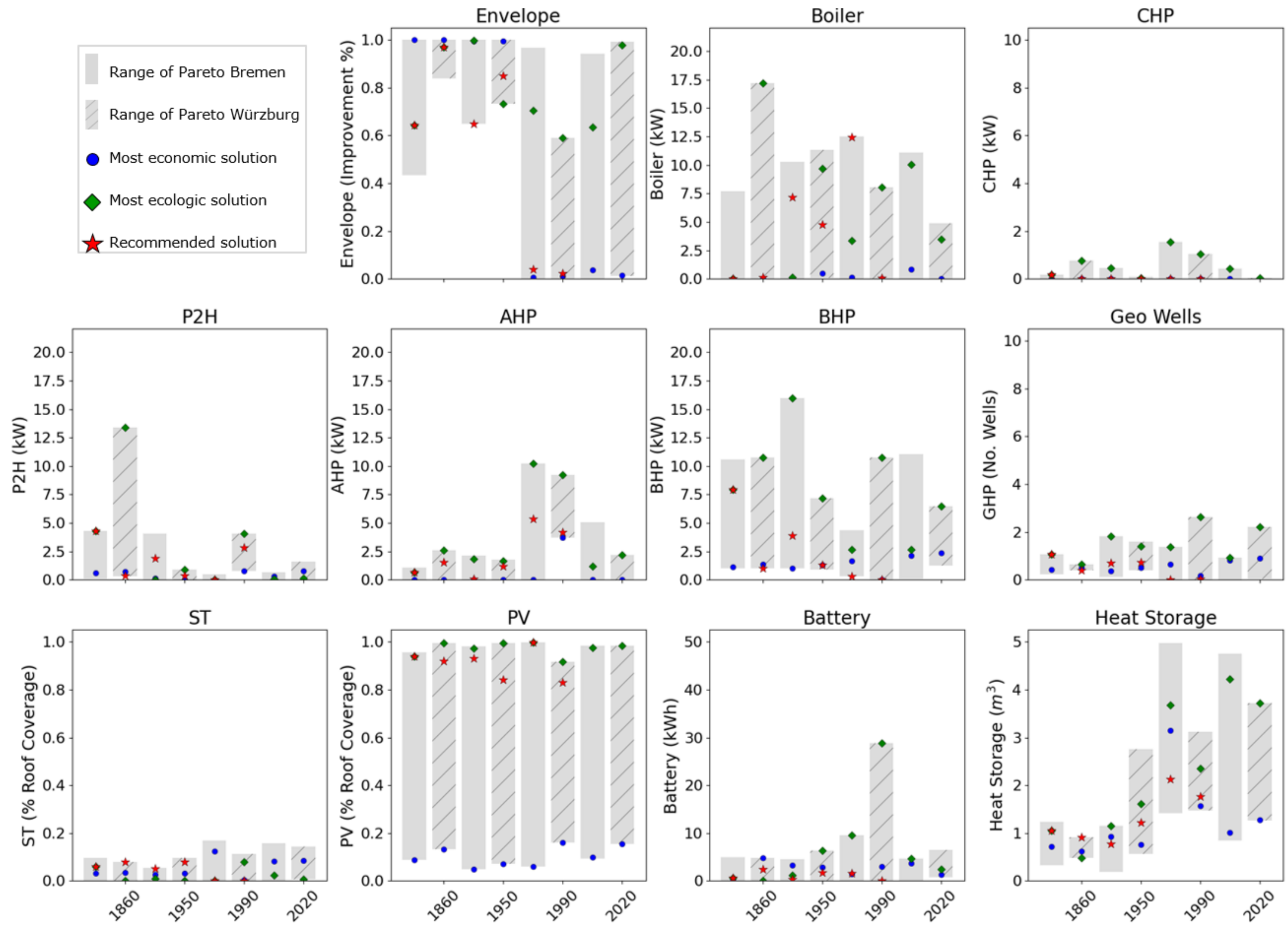

Figure 9: Pareto optimal comparison of the degrees of freedom sizing data across the eras. The bars represent the range of system sizes within all of the Pareto optimal points, the green diamond represents the most ecologic solution, the blue circle represents the most economic solution, and the red star represents the recommended solution where applicable. The solid bars represent data for Bremen, and the hatched bars for Würzburg.

We found that the construction era has a significant impact on the benefits gained from renovation due to the different building materials, architectural styles, and design standards of the era. The post-war era from 1949-1959 represented the largest emission savings from its business as usual case when considering the recommended solution. And if the recommended solution of each era is to take place across the whole of the building stock, Germany can save over 90 MTon of carbon dioxide emissions, which represents over 12% of the country's total emissions.

Additionally during renovation the building envelope should be improved if the residence was built before 1984 and even then should only be to around 60% of the maximum, as the majority of heat transfer gains occur within that first 60%. After 1984 or from 1958-68, adding additional insulation to the walls and roof or replacing the windows appears to be economically infeasible and the investment is put to better use by installing renewable energy systems.

The energy system trends were relatively consistent across the eras and point to a strategy which should focus on complete utilization of the rooftop for mostly PV but some solar thermal production. Plus, renewable thermal energy systems with flexibility in terms of backup power-to-heat and thermal storage sized around one cubic meter. Gas-fueled systems were not used in the heat production throughout the year of the recommended solutions and should thus, be avoided entirely.

While the majority of the results were carried out for Bremen, a validation case of a few eras was done for Würzburg as well. The Pareto fronts were nearly identical and the energy systems followed the same general trends pointing to the validity of this strategy across the entirety of Germany.

Future experiments will take this work a step further and look at a sensitivity analysis on how system prices, fuel prices, and building orientations affect the recommended solution. They will also examine the optimization in the future considering renovations take a while to enact over the entire building stock. These future considerations could be the impact of cooling as it becomes more prominent throughout Germany, or the impact of a more renewable grid on the recommended solutions.

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