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Integrating residential energy efficiency measures into optimizing urban energy system models

Kai Mainzer, Russell McKenna, Wolf Fichtner

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INSTITUTE FOR INDUSTRIAL PRODUCTION (IIP), CHAIR OF ENERGY ECONOMICS

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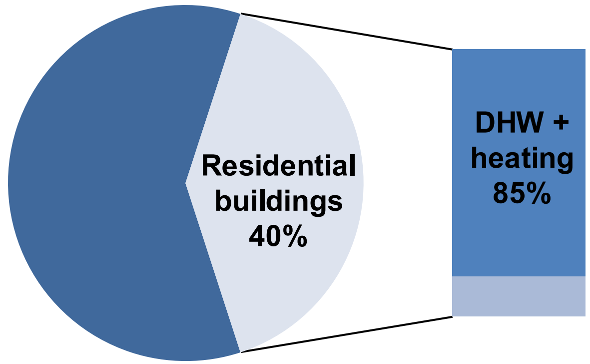
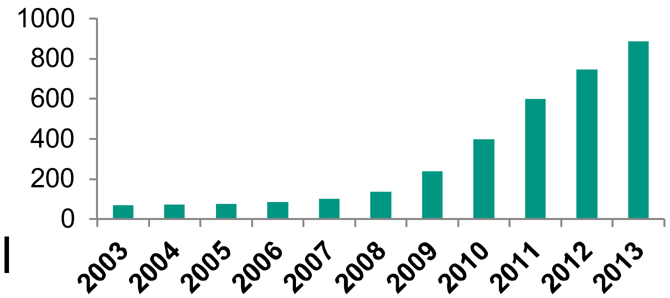
Background and motivation

- Residential building sector accounts for almost 40% of German energy consumption; 85% of this due to domestic hot water and space heating
- Political objective: 80% primary energy demand reduction until 2050
- Trend: local stakeholders get involved
  - organized in local energy cooperatives
  - formulation of energy schemes and objectives for municipalities
- How can cities be enabled to determine optimal pathways to reach their objectives?

➢ Complexity of interdependencies between technologies, energy carriers and stakeholders in urban energy systems calls for optimization methods





sources: [BMWi 2014], [AEE 2014], commons.wikimedia.org

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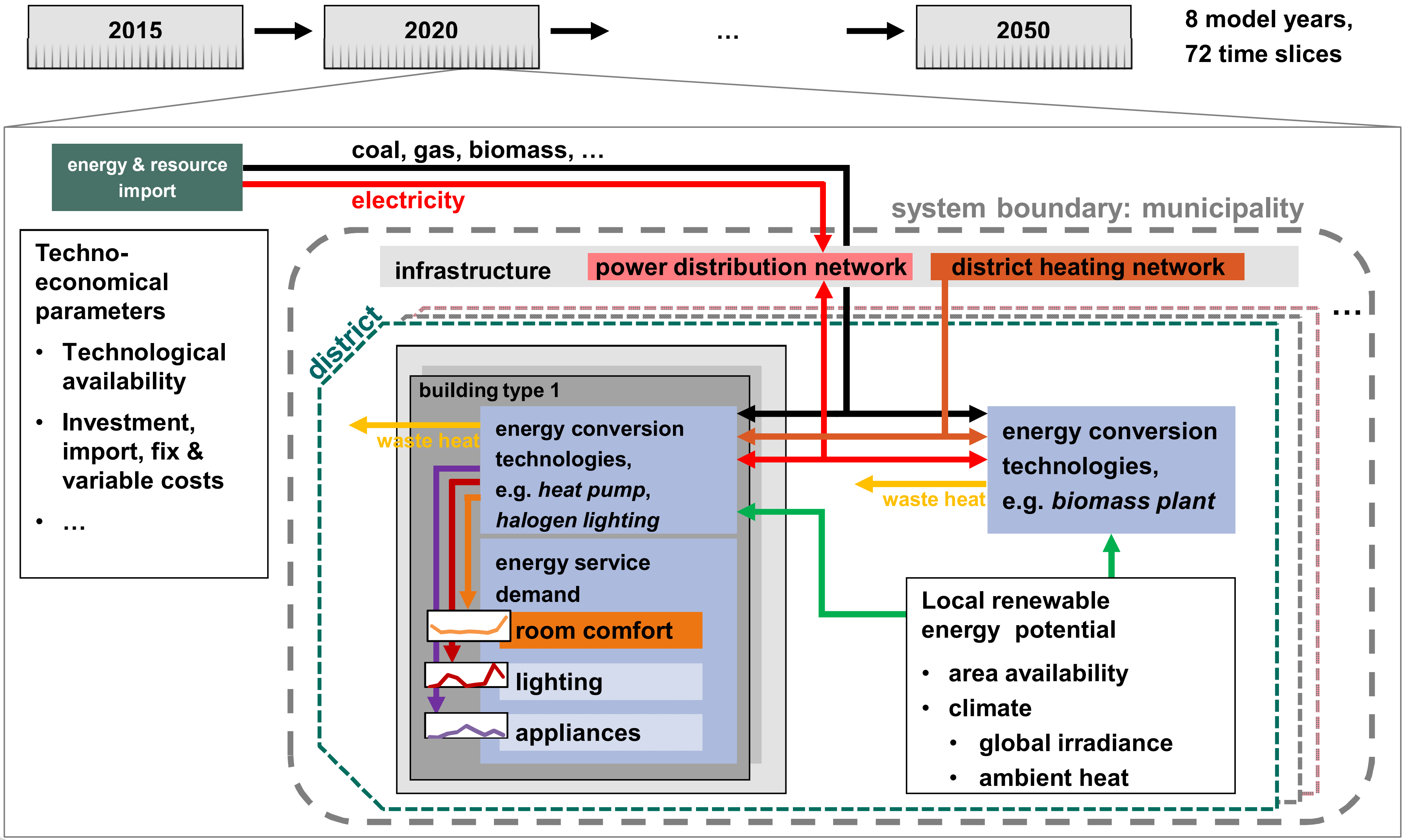
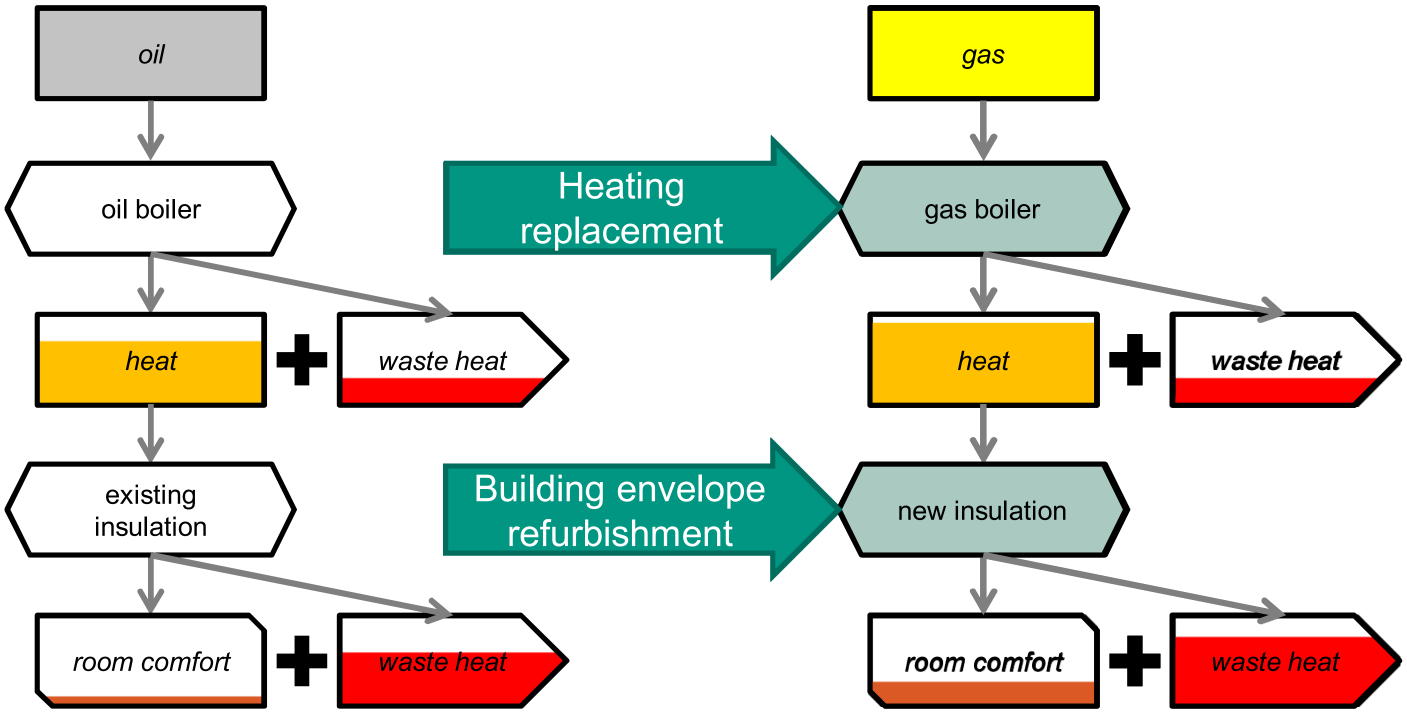
Methodological approach: optimizing energy and material flow model



Methodological approach: Representation of energy efficiency measures



Configuration	Overall efficiency
Original	11%
Heating replacement	14%
Retrofitting	21%
Both measures	27%

- Other relevant parameters:
  - investment and fuel costs
  - Emissions
  - Technical lifetime
  - Dimensioning

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Case study: Landau, Germany

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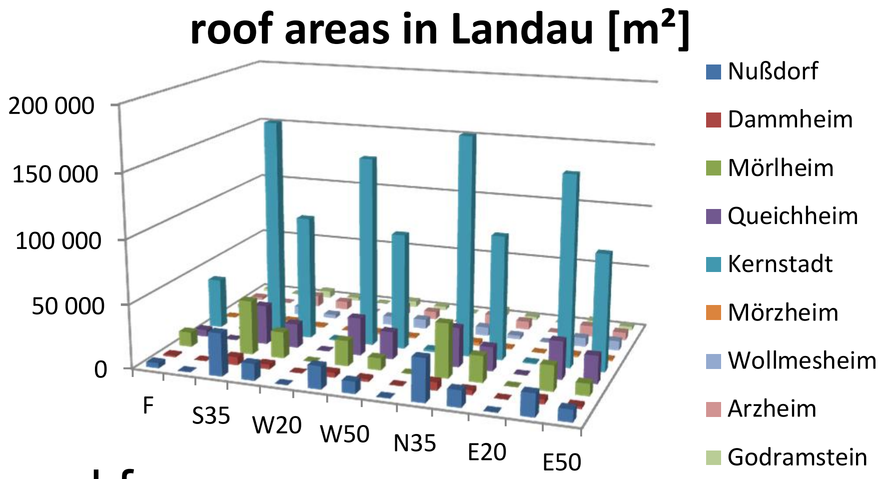
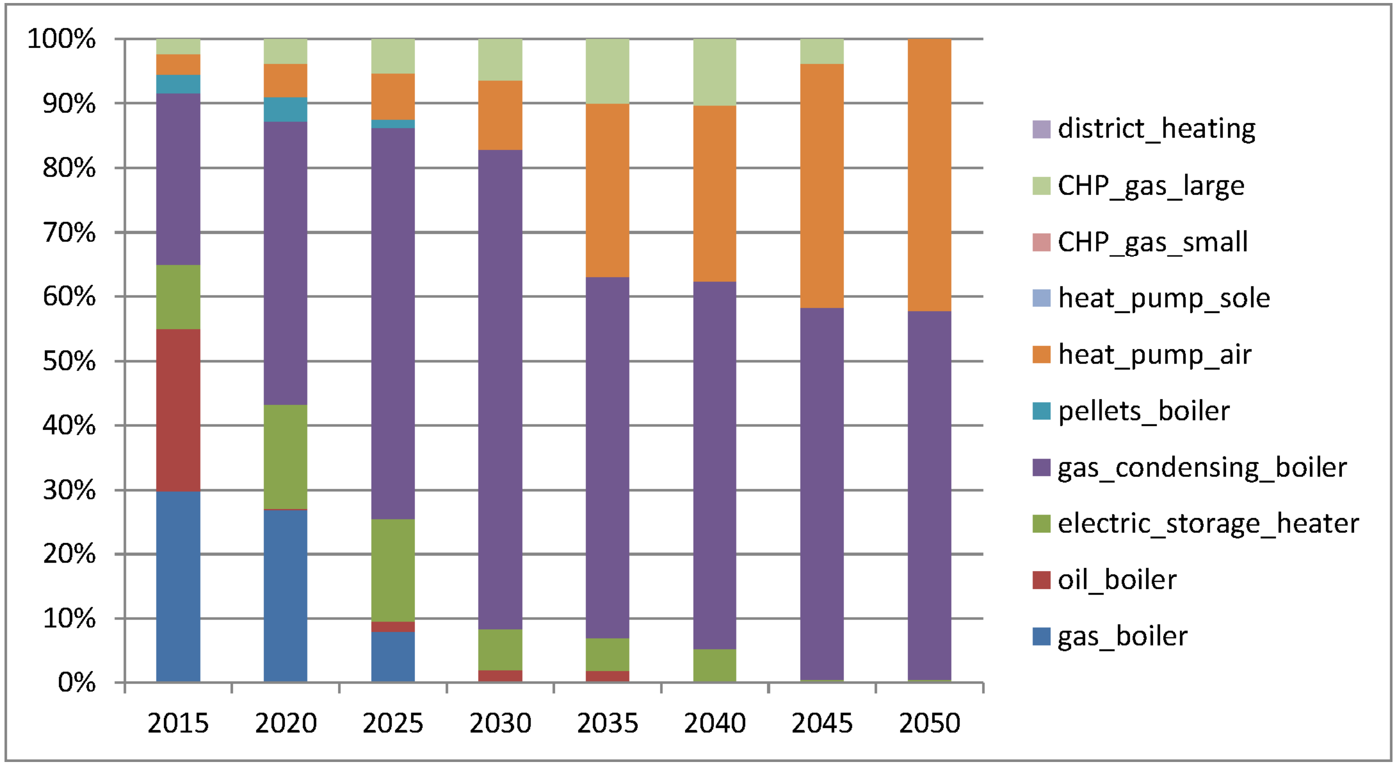
- 43,000 inhabitants, 83 km² in 9 districts
- Local stakeholders strongly encourage renewable energies and energy efficiency: formulation of an energy scheme [AES 2013]

vineyard farmland forest meadow building



- Data for case study has been gathered from
  - OpenStreetMap (geographical extent, buildings footprints, area availability)
  - Federal statistics office (heating technologies in stock, building info)
  - several other sources for climate, irradiation, technological parameters, …
- PV potential analysis, considering roof areas' irradiance profiles

Results – Business As Usual scenario



- Gas boiler and heat pumps are favored

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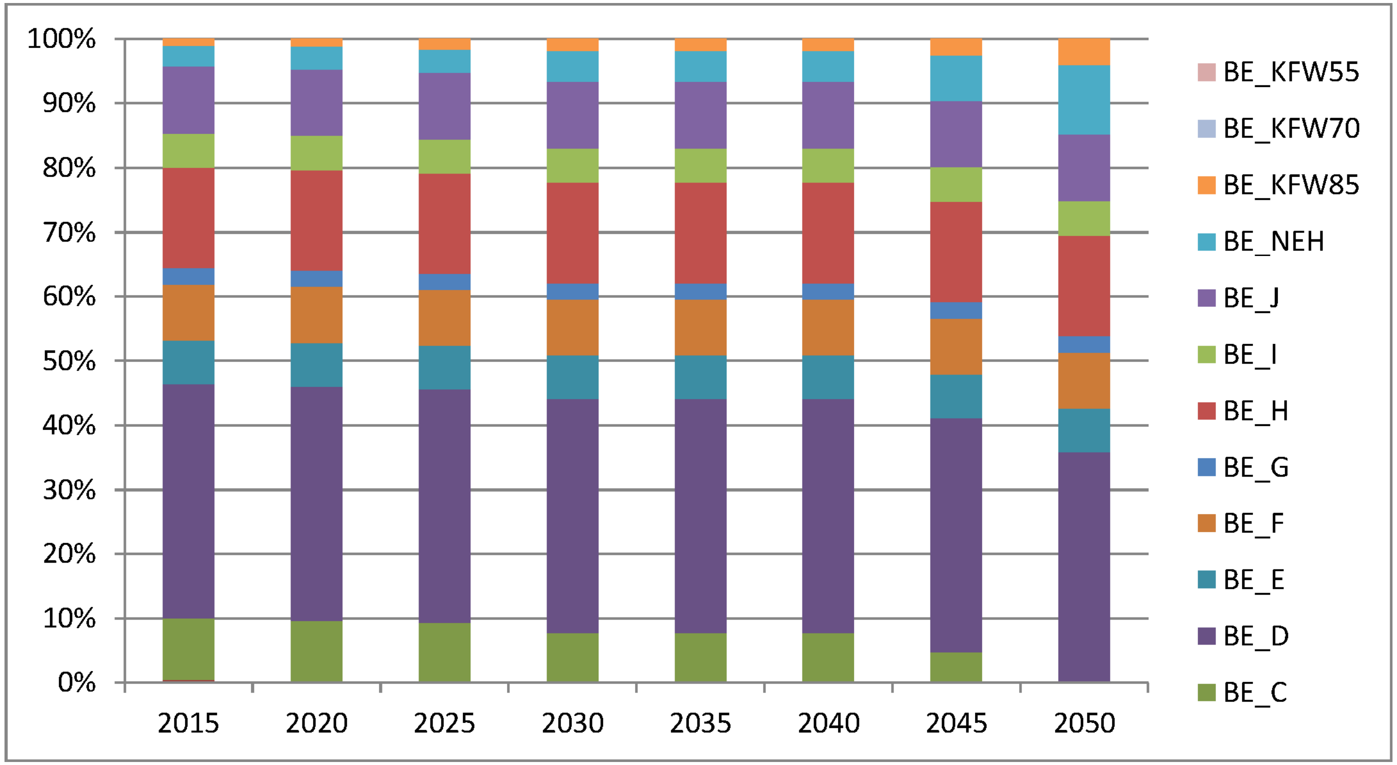
Results – Business As Usual scenario



- No “active” renewal of building insulation

Results – Business As Usual scenario

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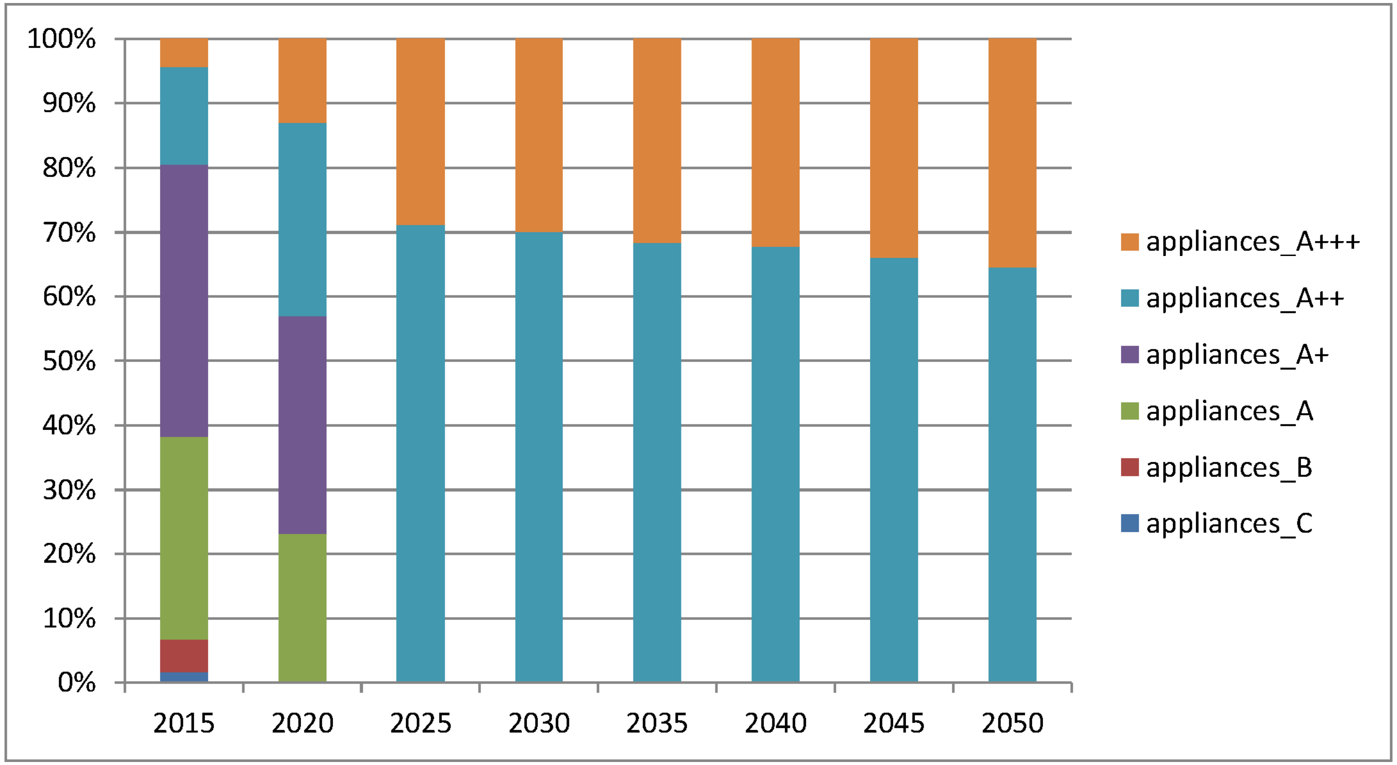
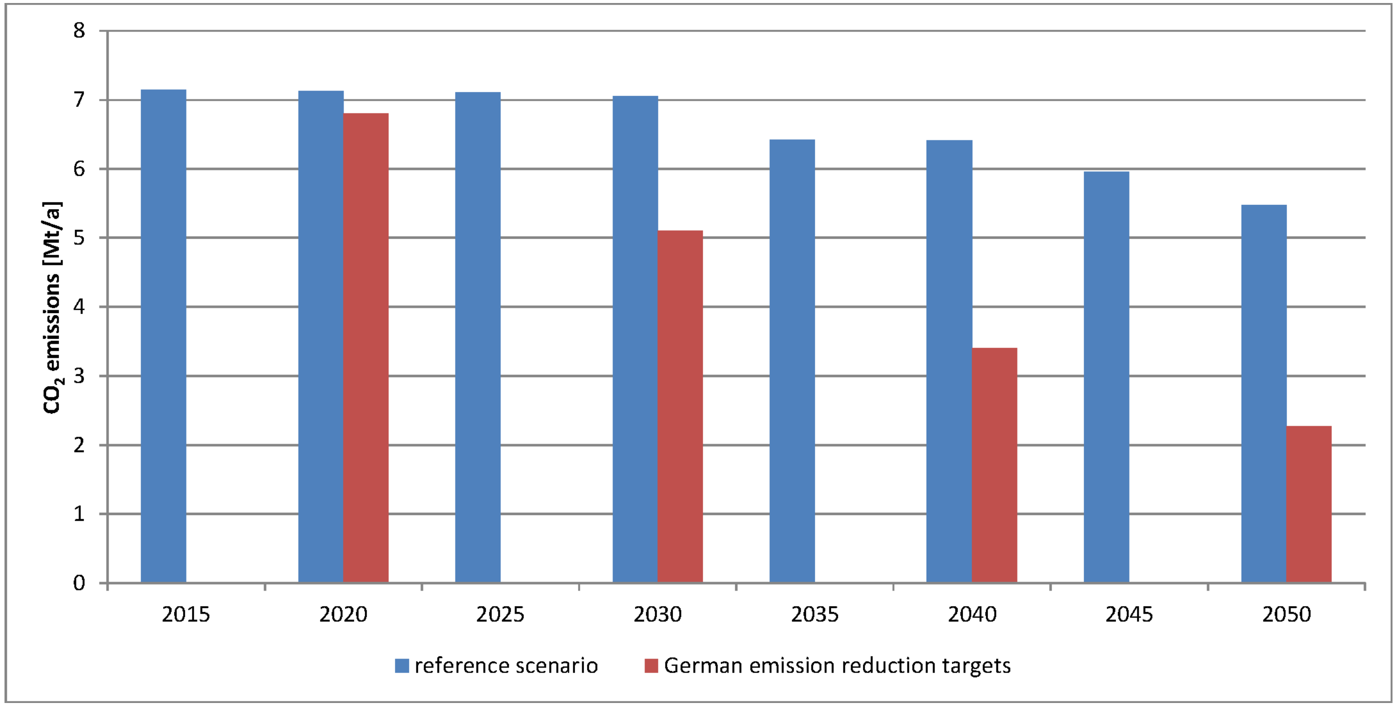


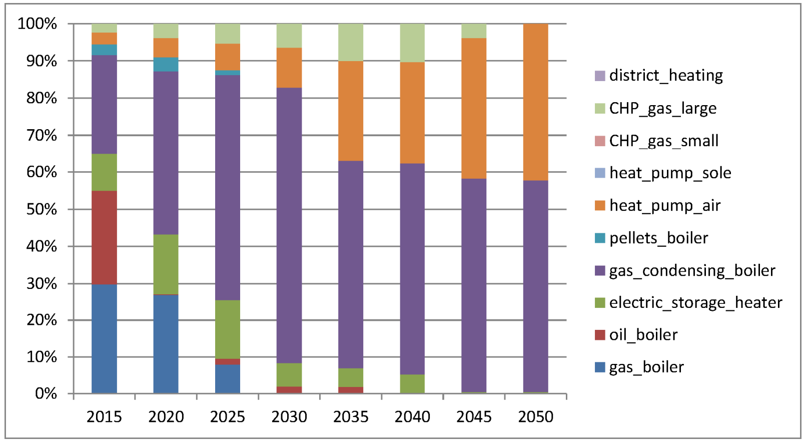
- adoption of A++ efficiency standard

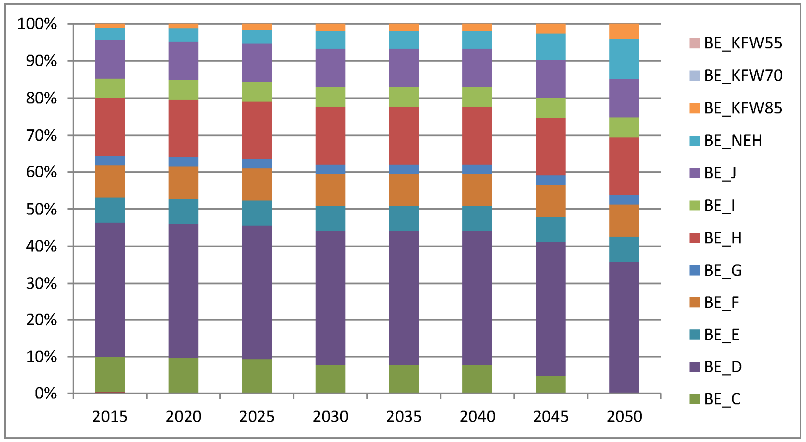
Results – Business As Usual scenario



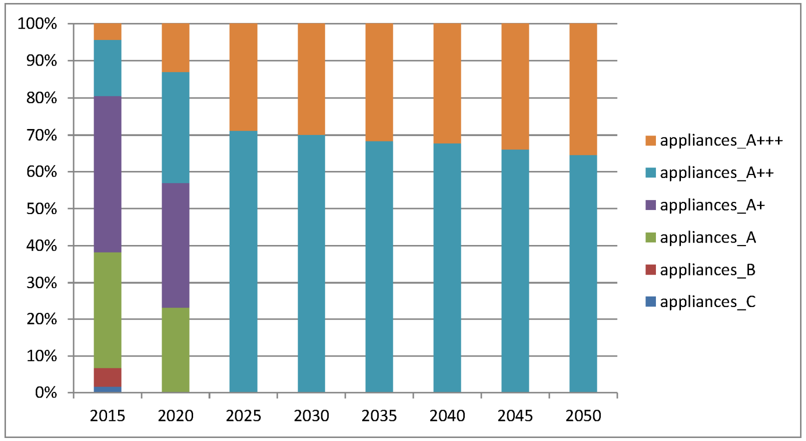
- GHG reductions not sufficient to meet targets

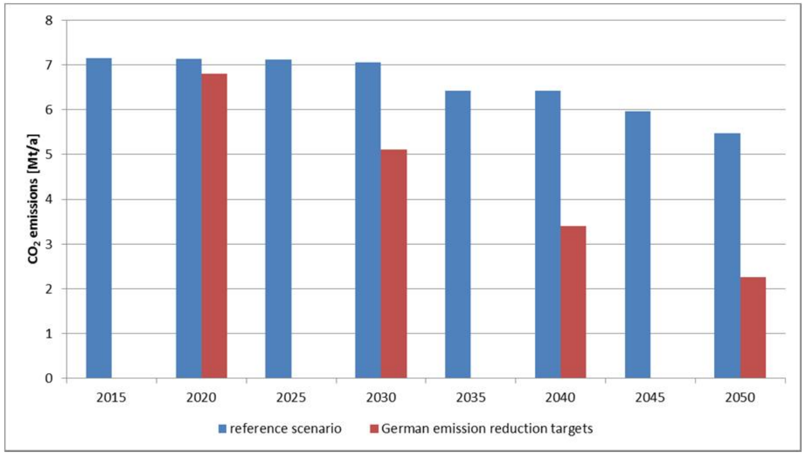
Results – Business As Usual scenario





- Gas boiler and heat pumps are favored
- No "active" renewal of insulation





- adoption of A++ efficiency standard
- GHG reductions not sufficient to meet targets
- No significant incentives for EE/RE investments => targets not reached

Results – Emission Reduction scenario

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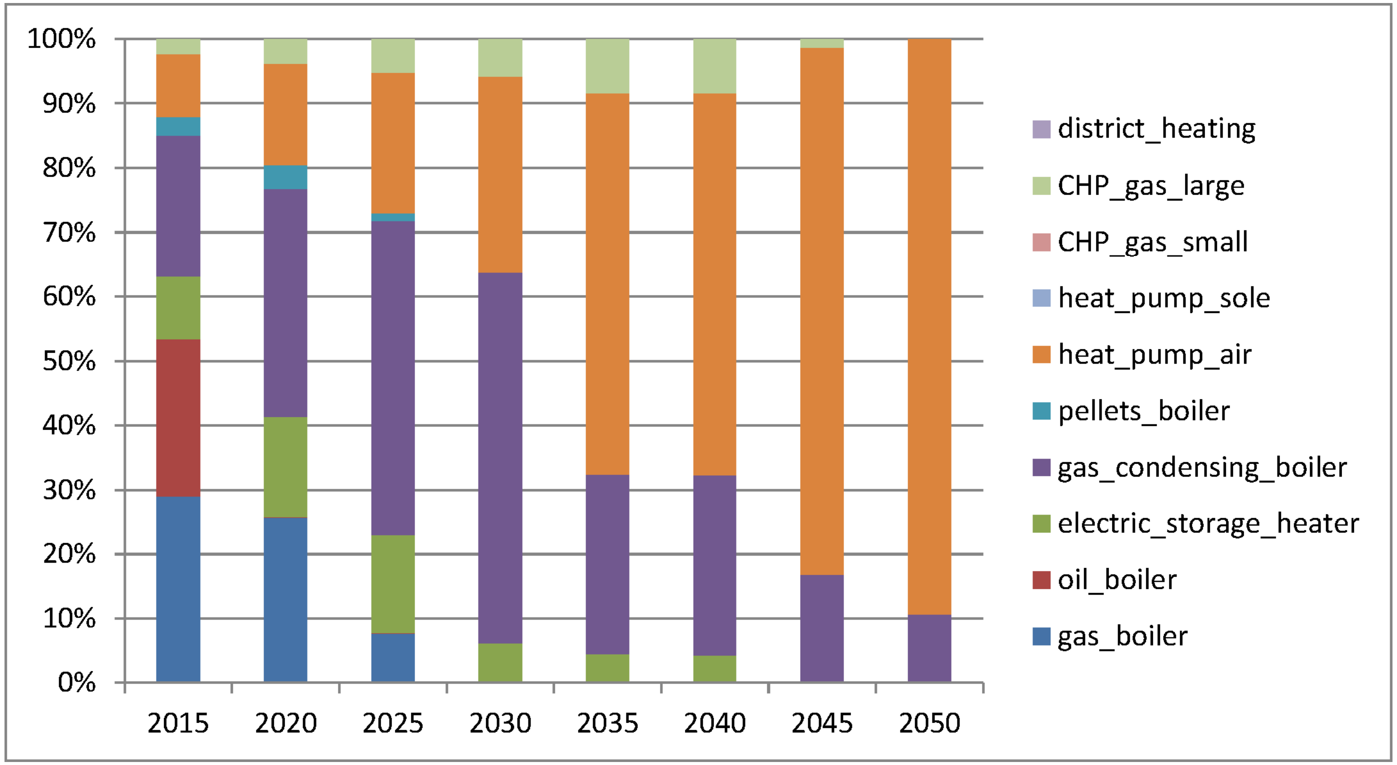
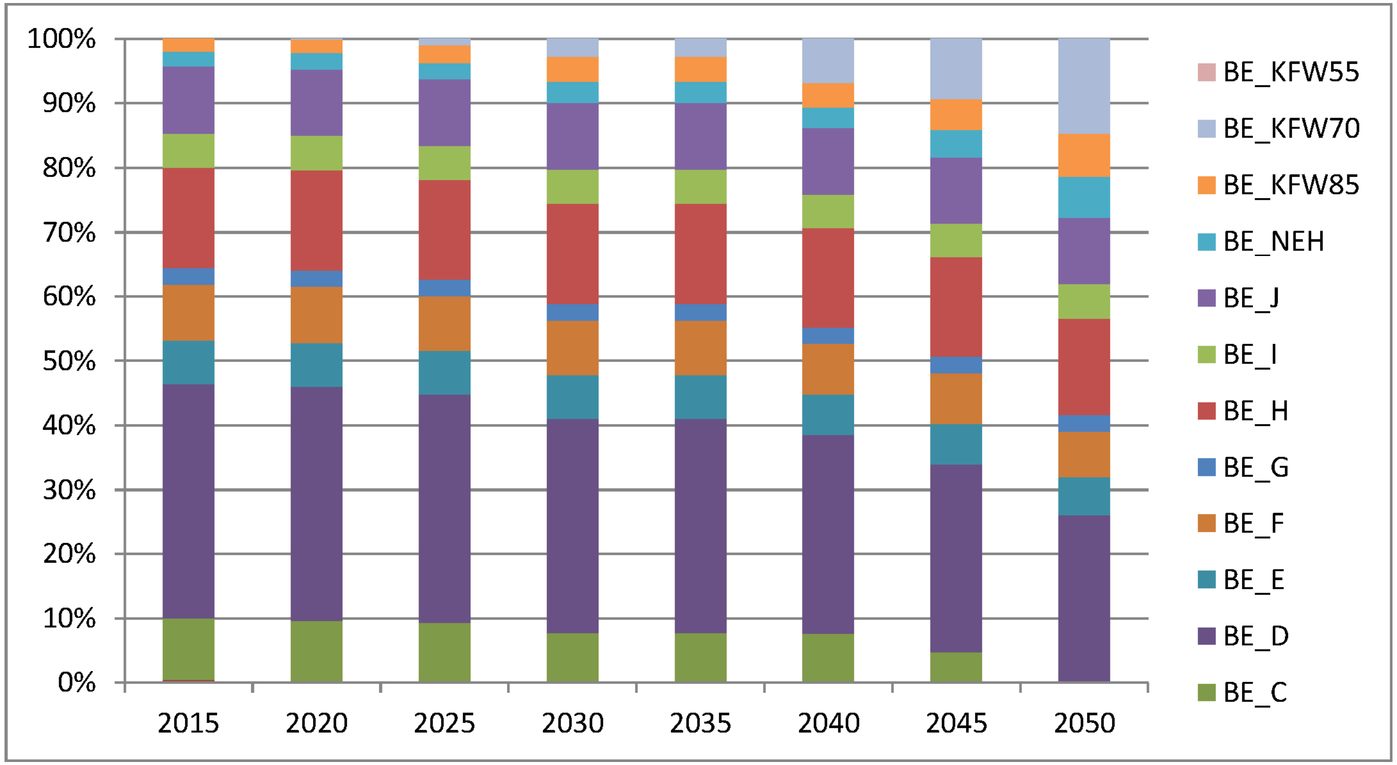


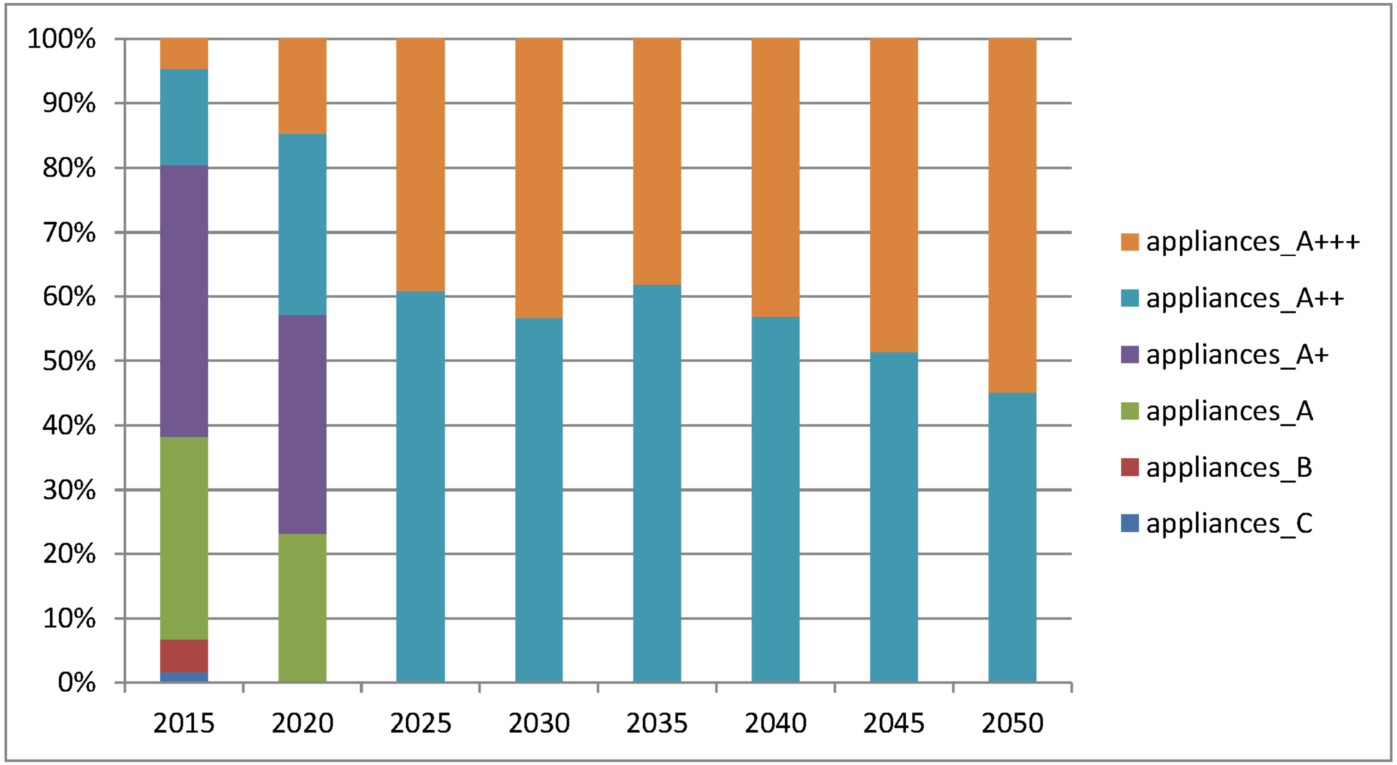
- Increased use of more efficient heat pumps

Results – Emission Reduction scenario



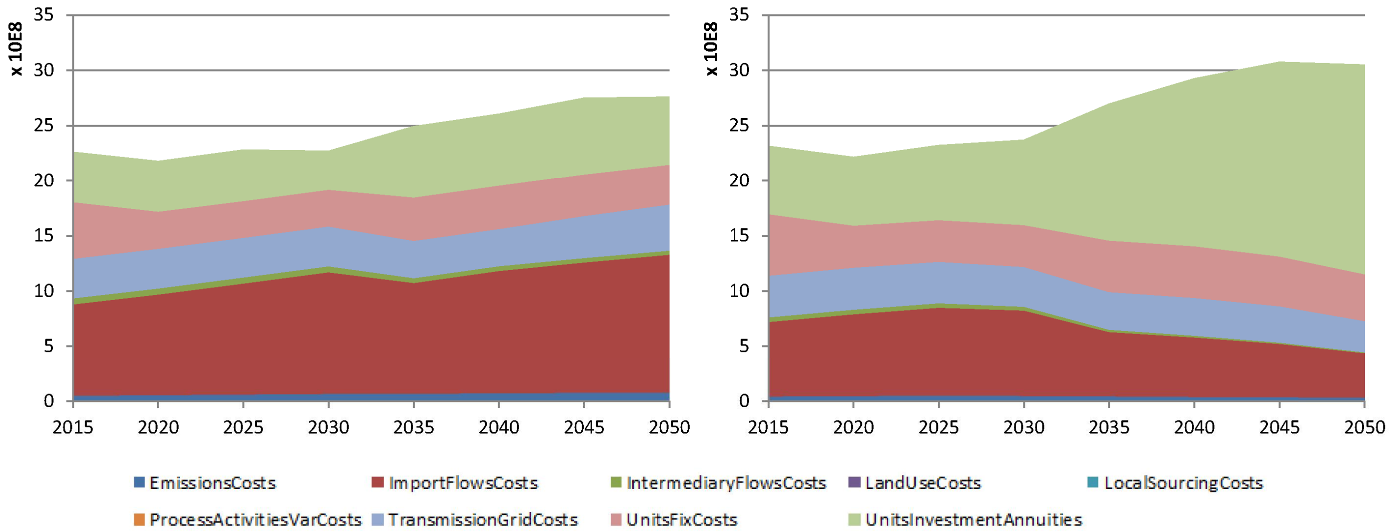
- Active renewal of building insulation before the end of its lifetime

Results – Emission Reduction scenario



- Increased share of most efficient appliance class A+++

Results – Emission Reduction scenario



- Larger investments are (partly) remedied by lower import costs. Total costs: +4.88%

Results – Emission Reduction scenario

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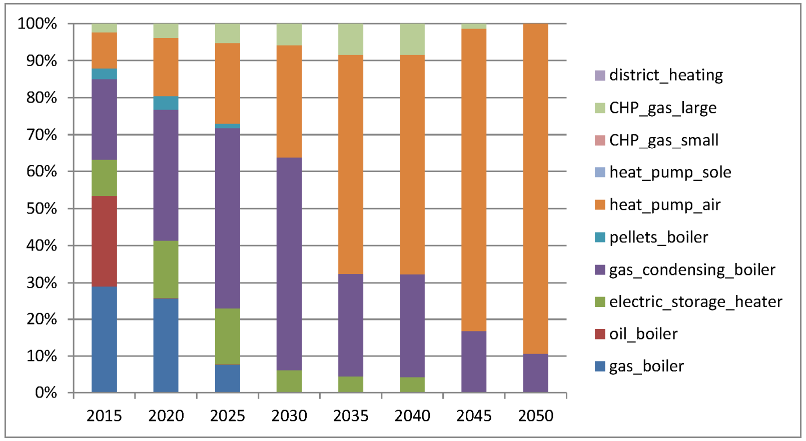
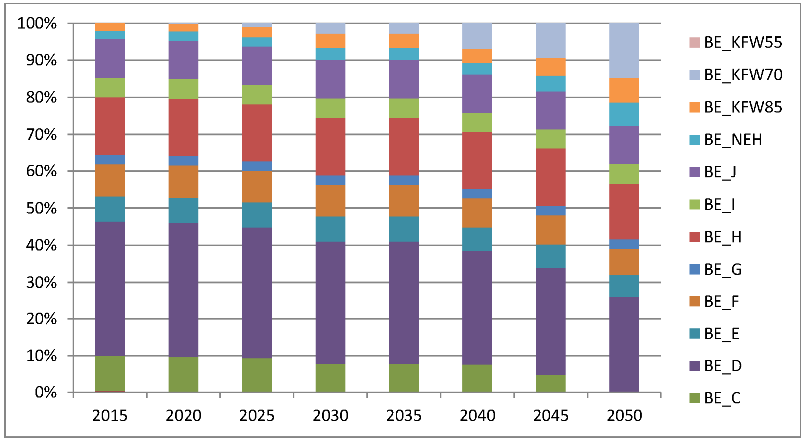
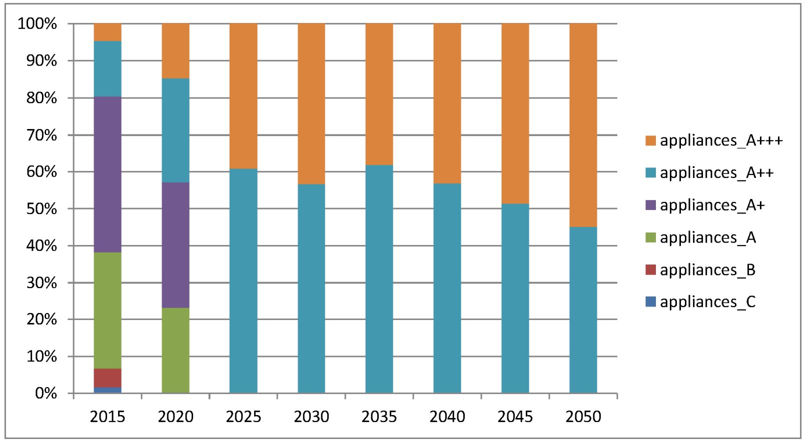
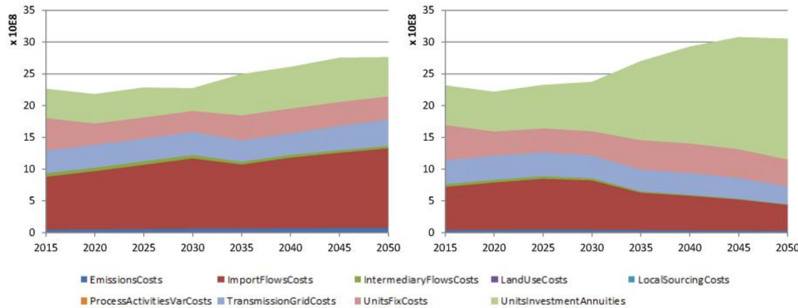




- Increased use of more efficient heat pumps
- Active renewal of insulation before the end of its lifetime





- Increased share of most efficient appliance class A+++
- Larger investments are (partly) remedied by lower import costs

➢ A pathway which meets the German Governments objectives can be achieved with only minor increases in system costs

Critical appraisal

- Perfect foresight: no uncertainties
- Macro-economic perspective: not necessarily coincident with local stakeholder's perspective(s)
- No statement how optimal pathway could be incentivized
- Not considered:
  - Subsidies and other political incentives
  - Non-economical incentives
  - user behaviour and demand side management
  - Emerging technologies
- Information on energy infrastructure very limited, no model-endogenous infrastructure extension
- Volatility to input parameters not quantified

Summary and outlook

- A new model for urban energy system modelling has been presented
- It enables policy makers to derive cost-optimal investment pathways for reaching their targets
- The technological (demand & supply side technologies) and spatial detail exceeds that of previous models

- Application to case study demonstrates its use and possible results:
  - targets will not be reached with “business as usual”
  - A target-compliant pathway can be achieved with only minor cost increases
  - Heat pumps, building retrofitting and more efficient appliances are the key elements for this strategy

- Further work:
  - Automation of data aggregation
  - More detailed renewables potential analysis (PV, biomass, wind)
  - Additional scenarios (especially price development)
  - implementation of sensitivity analysis
  - Application and validation with more case studies

Thank you very much for your attention

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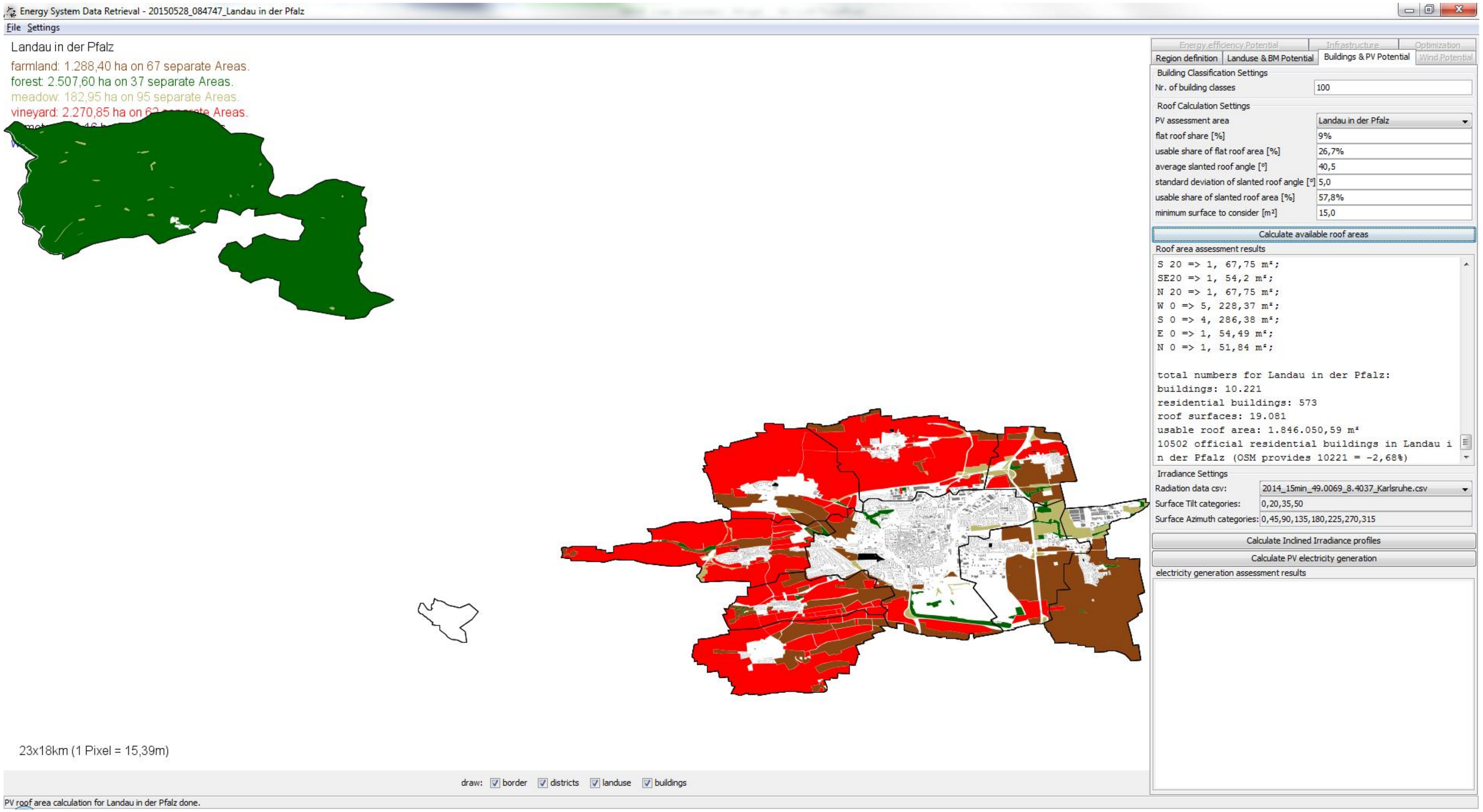
Backup: Common approaches to urban energy system modelling

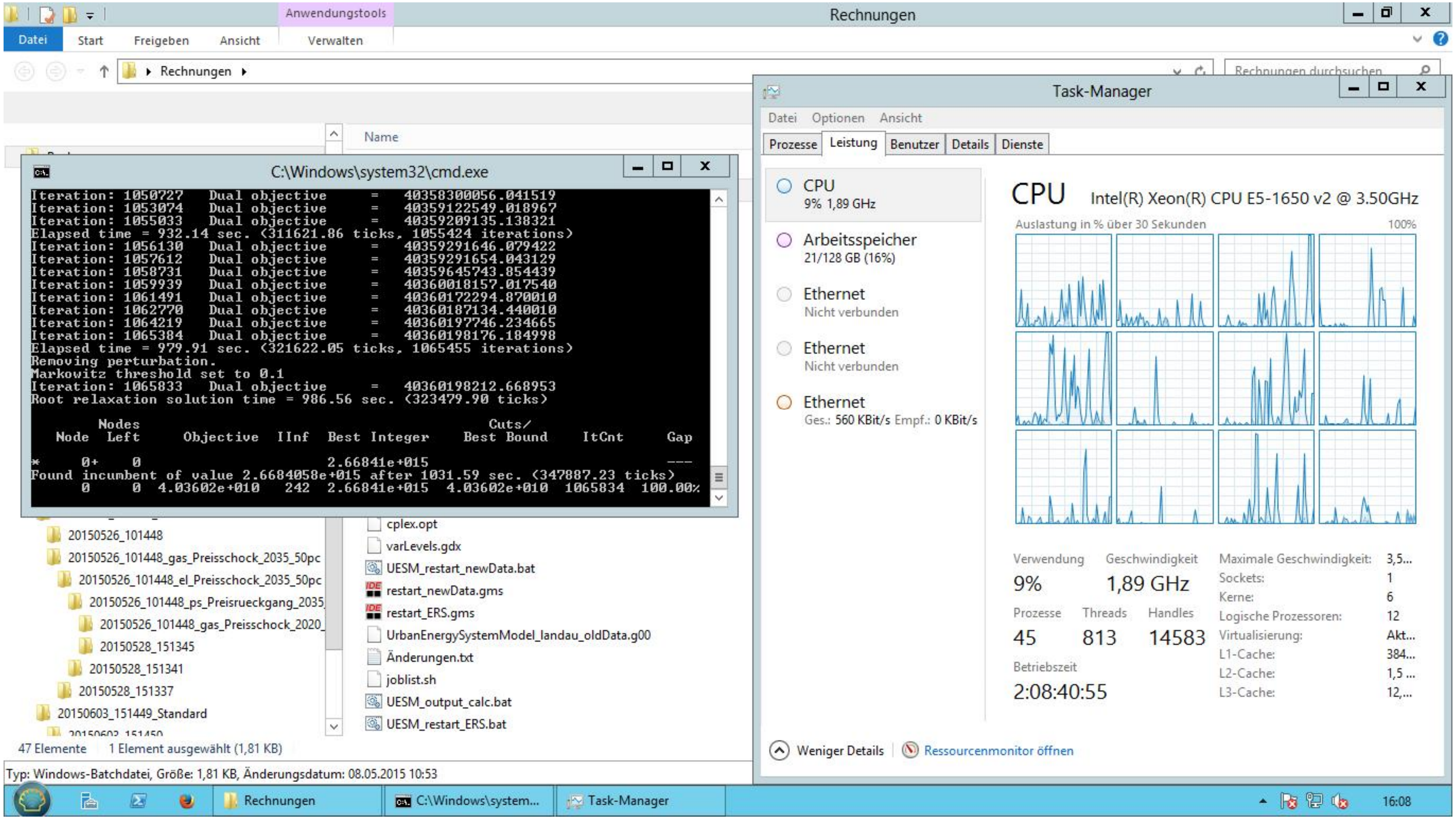
- National energy system models
  - Overview: [Jebaraj, Iniyan 2006]
  - Large scale power plants, no decentral technologies, heat mostly neglected
- Models which focus on heat on a national level
  - e.g. [Johnston et al. 2005], [Merkel et al. 2014]
  - No spatial resolution, no local renewable energy potentials
- Few models focus on regional/urban energy systems
  - Overview: [Keirstead et al. 2012]
  - Demand side efficiency measures usually not considered
- Few models consider (demand side) energy efficiency measures
  - e.g. [Jennings et al. 2014]
  - Only building retrofit measures, strongly simplified geographical structure and building stock

➢ No models which explicitly model regional energy systems, considering supply & demand side technologies with detailed geographical & technological resolution are currently available

Backup: Data aggregation screenshot



Backup: optimization model screenshot



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Backup: Technical details

- Implementation:
  - data aggregation and calculations: Java
  - optimization model: GAMS, solver: CPLEX, options:
    - MIP relaxation: dual simplex
    - Sub-problems: automatic (CPLEX)
- model size
  - 14,018,281 rows 7,251,113 columns 42,793,441 non-zeroes 20,136 discrete-columns
  - Reduced MIP:
    - 1,886,203 rows, 1,810,156 columns, and 7,173,948 nonzeros, 19,200 binaries
  - Model size: up to 70 GB
- Machine
  - 64 bit, Intel Xeon E5-1650 v2 @ 3.5 GHz, 12 Threads
  - 128 GB DDR3 RAM
  - Solving time: ~20 hours

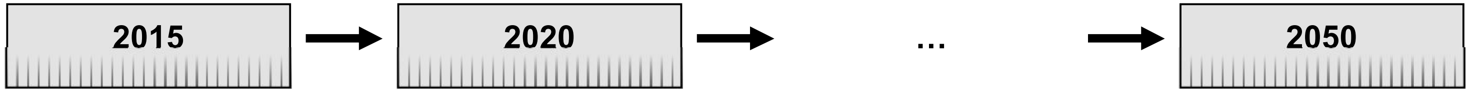
Backup: Objective function

- Minimization of all decision relevant system expenditures, discounted to base year (discount rate: 5%)
- The cost function is composed of several cost factors:
  - *Import flow costs* are associated with the import and export of energy carriers. These flows are valued by wholesale market prices.
  - *Transmission grid costs* represent the costs that arise from using the national transmission grid for these imports and exports.
  - *Intermediary flow costs* arise from the utilization of the local transport grids.
  - *Investment annuities* for installed units represent the share of investment costs that are allocated to each year the technology is in use.
  - *Fixed* and *variable costs* arise from the ownership and utilization of technologies.
  - *Emission costs* are caused by applying a CO_2-emission penalty on the utilization of technologies.

Backup: Constraints

- Several constraints provide technological as well as economical bounds to the problem. The most important constraints are:
  - *Energy balance* constraints:
    energy has to be balanced at all times and at all locations in the model.
  - *flow restrictions:*
    flow between districts can be restricted (in order to represent transportation bottlenecks) or completely forbidden (if districts are not connected).
  - *land use constraints:*
    The amount of available land, which is essential for some technologies such as PV modules which represents potential restrictions.
  - *emission restrictions:*
    constrain the amount of CO_2 as well as PM_{10} that is emitted through the city's energy system during each year.

Backup: Temporal structure



8 model years,
72 time slices each

- Multi-periodic approach
- 72 time slices per year:
  - 4 seasons (spring, summer, fall, winter)
  - 2 day types (working day, weekend)
  - 9 continuous blocks of 5 hours (night) and 2 hours (day) length each
  - Preserves daily demand and supply (PV) variation
  - Minimizes number of time slices to a (computationally) manageable amount
- Investment decisions yearly
- Dispatch decisions for each time slice

Backup: Technologies

- 47 technologies in the categories:
  - Heating (11)
  - Lighting (4)
  - Appliances (6)
  - Insulation (14)
  - Decentral power generation (12)

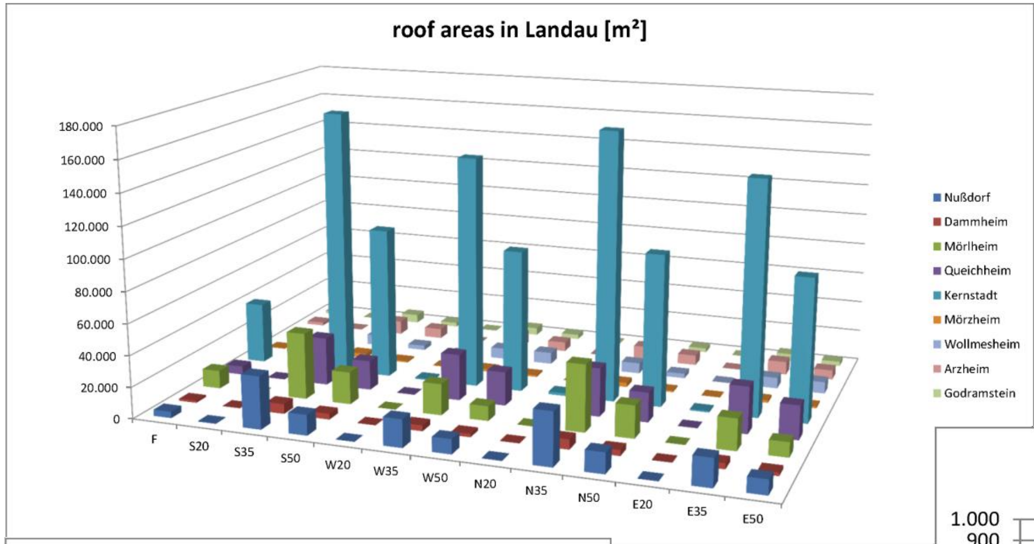
Kategorie	Bezeichnung	scale	process	efficiency	IO_el	IO_gs	IO_ol	IO_ps	IO_ah	IO_dh	IO_ht	IO_rh	IO_wh	IO_li	IO_as	EM_CO2	EM_PM10	Invest [€/kW]	Installation [€]	Invest [€]	FixCost [f_{inst}/a]	FixCost [€/a]	VarCost [€/kWh]	Lifetime
heating_main	gas_boiler	building	gas_boil	90%	0	-6,667	0	0	0	0	6	0	0,6667	0	0	1,60667	0,2266667	425	3600	2550	3,00%	76,5	0	20
heating_main	oil_boiler	building	oil_boile	70%	0	0	-8,633	0	0	0	6	0	2,6331	0	0	2,70216	0,7769784	600	3800	3600	12,00%	432	0	15
heating_main	electric_storage_heater	building	electric_	100%	-6	0	0	0	0	0	6	0	0	0	0	3,348	0	458,3333333	800	2750	3,00%	82,5	0	20
heating_main	gas_condensing_boiler	building	gas_con	97%	0	-6,186	0	0	0	0	6	0	0,1856	0	0	1,49072	0,2103093	483,3333333	3600	2900	3,00%	87	0	20
heating_main	pellets_boiler	building	pellets_	78%	0	0	0	-7,692	0	0	6	0	1,6923	0	0	0,13846	876,92308	1016,67	5000	6100,02	6,00%	366,0012	0	15
heating_main	heat_pump_air	building	heat_pu	350%	-1,714	0	0	0	-4,286	0	6	0	0	0	0	0,95657	0	1983,333333	3100	11900	2,50%	297,5	0	20
heating_main	heat_pump_sole	building	heat_pu	380%	-1,579	0	0	0	-4,421	0	6	0	0	0	0	0,88105	0	2750	3100	16500	2,50%	412,5	0	20
heating_main	CHP_gas_small	building	CHP_gas	25%	4	-16	0	0	0	0	10,4	0	1,6	0	0	3,856	0,544	4000	8828	9258	8,00%	740,64	0	15
heating_main	CHP_gas_large	building	CHP_gas	27%	8	-29,63	0	0	0	0	19,259	0	2,3704	0	0	7,14074	1,0074074	3000	8828	16015	8,00%	1281,2	0	15
heating_main	district_heating	building	district_	100%	0	0	0	0	0	-40	40	0	0	0	0	11,8	0		5077	351	3,00%	1519,85	0,0602	30
heating_support	solar_thermal	district	solar_th	82%	0	0	0	0	0	0	2,0709	0	0	0	0	0	0	3700	1000	7662,488	1,50%	114,937321	0	20
lighting	incandescent_light_bulb	building	incande:	10%	-0,05	0	0	0	0	0	0,0452	0	0	0,0048	0	0,0279	0		0	2		0	0	5
lighting	halogen	building	halogen	16%	-0,05	0	0	0	0	0	0,042	0	0	0,008	0	0,0279	0		0	3		0	0	5
lighting	CFL	building	CFL_pc	40%	-0,01	0	0	0	0	0	0,006	0	0	0,004	0	0,00558	0		0	2		0	0	10
lighting	LED	building	LED_pc	80%	-0,01	0	0	0	0	0	0,002	0	0	0,008	0	0,00558	0		0	5		0	0	10
appliances	appliances_G	building	applianc	135%	-1	0	0	0	0	0	0	0	0	0	0,7407	0,558	0			1,00E+10	0,00%	0	0	10
appliances	appliances_F	building	applianc	120%	-1	0	0	0	0	0	0	0	0	0	0,8333	0,558	0			1,00E+10	0,00%	0	0	10
appliances	appliances_E	building	applianc	108%	-1	0	0	0	0	0	0	0	0	0	0,9302	0,558	0			1,00E+10	0,00%	0	0	10
appliances	appliances_D	building	applianc	92%	-1	0	0	0	0	0	0	0	0	0	1,0899	0,558	0			1,00E+10	0,00%	0	0	10
appliances	appliances_C	building	applianc	83%	-1	0	0	0	0	0	0	0	0	0	1,2048	0,558	0		0	400	0,00%	0	0	10
appliances	appliances_B	building	applianc	61%	-1	0	0	0	0	0	0	0	0	0	1,6393	0,558	0		0	400	0,00%	0	0	10
appliances	appliances_A	building	applianc	56%	-1	0	0	0	0	0	0	0	0	0	1,7857	0,558	0		0	430	0,00%	0	0	10
appliances	appliances_A+	building	applianc	47%	-1	0	0	0	0	0	0	0	0	0	2,1164	0,558	0		0	520	0,00%	0	0	10
appliances	appliances_A++	building	applianc	39%	-1	0	0	0	0	0	0	0	0	0	2,5478	0,558	0		0	550	0,00%	0	0	10
appliances	appliances_A+++	building	applianc	32%	-1	0	0	0	0	0	0	0	0	0	3,125	0,558	0		0	810	0,00%	0	0	10
large_scale_power	biogas_plant	district	biogas_plant_pc			0	0	0	0	0	0	0	0	0		0	0							40
large_scale_power	wind_plant	district	wind_plant_pc			0	0	0	0	0	0	0	0	0		0	0							20
insulation	BE_A	building	BE_A_pc	6,01%	0	0	0	0	0	0	-0,048	0,0029	0,0453	0	0	0	0		1,00E+10	1,00E+10		1	0	100
insulation	BE_B	building	BE_B_pc	6,09%	0	0	0	0	0	0	-0,048	0,0029	0,0447	0	0	0	0		1,00E+10	1,00E+10		1	0	100
insulation	BE_C	building	BE_C_pc	6,67%	0	0	0	0	0	0	-0,043	0,0029	0,0405	0	0	0	0		1,00E+10	1,00E+10		1	0	100
insulation	BE_D	building	BE_D_pc	6,07%	0	0	0	0	0	0	-0,048	0,0029	0,0449	0	0	0	0		1,00E+10	1,00E+10		1	0	100
insulation	BE_E	building	BE_E_pc	7,51%	0	0	0	0	0	0	-0,039	0,0029	0,0357	0	0	0	0		1,00E+10	1,00E+10		1	0	100
insulation	BE_F	building	BE_F_pc	7,07%	0	0	0	0	0	0	-0,041	0,0029	0,0381	0	0	0	0		1,00E+10	1,00E+10		1	0	100
insulation	BE_G	building	BE_G_pc	9,29%	0	0	0	0	0	0	-0,031	0,0029	0,0283	0	0	0	0		1,00E+10	1,00E+10		1	0	100
insulation	BE_H	building	BE_H_pc	8,29%	0	0	0	0	0	0	-0,035	0,0029	0,0321	0	0	0	0		1,00E+10	1,00E+10		1	0	100
insulation	BE_I	building	BE_I_pc	12,16%	0	0	0	0	0	0	-0,024	0,0029	0,0209	0	0	0	0		1,00E+10	1,00E+10		1	0	100
insulation	BE_J	building	BE_J_pc	12,39%	0	0	0	0	0	0	-0,023	0,0029	0,0205	0	0	0	0		1,00E+10	1,00E+10		1	0	100
insulation	BE_NEH	building	BE_NEH_	14,29%	0	0	0	0	0	0	-0,02	0,0029	0,0174	0	0	0	0		22410	115		1	0	100
insulation	BE_KFW85	building	BE_KFW	18,18%	0	0	0	0	0	0	-0,016	0,0029	0,013	0	0	0	0		22410	135		1	0	100
insulation	BE_KFW70	building	BE_KFW	22,22%	0	0	0	0	0	0	-0,013	0,0029	0,0101	0	0	0	0		22410	180		1	0	100
insulation	BE_KFW55	building	BE_KFW	28,57%	0	0	0	0	0	0	-0,01	0,0029	0,0072	0	0	0	0		22410	250		1	0	100
insulation	BE_KFW40	building	BE_KFW	40,00%	0	0	0	0	0	0	-0,007	0,0029	0,0043	0	0	0	0			1,00E+10		1		100
insulation	BE_PH	building	BE_PH_p	66,67%	0	0	0	0	0	0	-0,004	0,0029	0,0014	0	0	0	0			1,00E+10		1		100
decentral_powergen	PV_S20	district	PV_S20_	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_S35	district	PV_S35_	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_S50	district	PV_S50_	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_W20	district	PV_W20	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_W35	district	PV_W35	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_W50	district	PV_W50	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_E20	district	PV_E20_	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_E35	district	PV_E35_	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_E50	district	PV_E50_	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_N20	district	PV_N20_	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_N35	district	PV_N35_	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20
decentral_powergen	PV_N50	district	PV_N50_	15%	0,26	0	0	0	0	0	0	0	0	0	0	0	0	1700	1000	442	1,50%	6,63	0	20

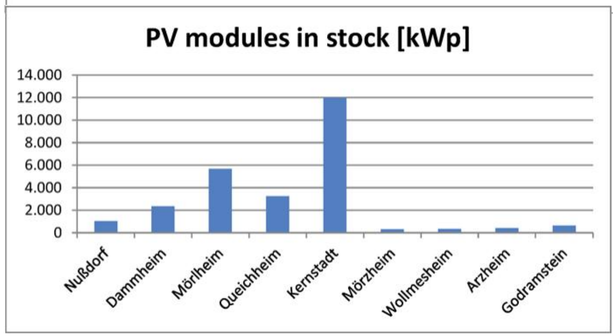
Backup: Data generation

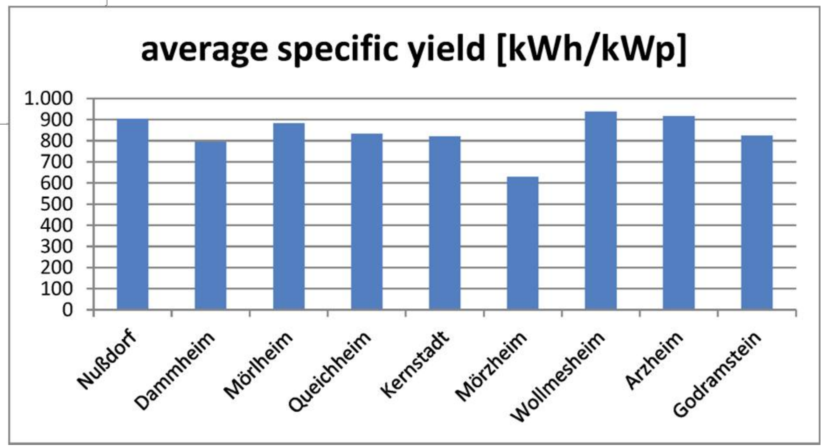
- Buildings
  - Number and sizes of each building (OpenStreetMap)
    + distributions of building ages and types (Federal statistics office)
    => sample of 100 buildings (building type classification, tailored to use case), each with a scale factor
  - For each building in the sample, the technologies in stock and their installation year have been determined (using data for technology frequency and age distributions)
- PV potentials
  - Building footprints (OpenStreetMap) => size and azimuth
    + Roof inclination estimated as normal distributed (μ=40.5°, σ=5°)
    => calculation of roof size and orientation
  - Irradiation profiles calculated using global irradiation data (MACC-RAD) and applying algorithms for calculation of inclined irradiance profiles for different roof orientations
- Demand
  - Measured household/building data not available, but demand fluctuations of single buildings are important and should be considered
  - Application of an activity-based electricity demand generation method [Richardson et al. 2010] => generation of demand curve for each household in each building
  - Heat: yearly specific demands per building type + heating degree days + hourly distribution

Backup: Landau roof area analysis

- Based on building footprints, roof areas calculated from building orientation and statistical assumptions on roof inclinations
- Total: 1.8 km², 9% already occupied. Mean yield: 838 kWh/kWp

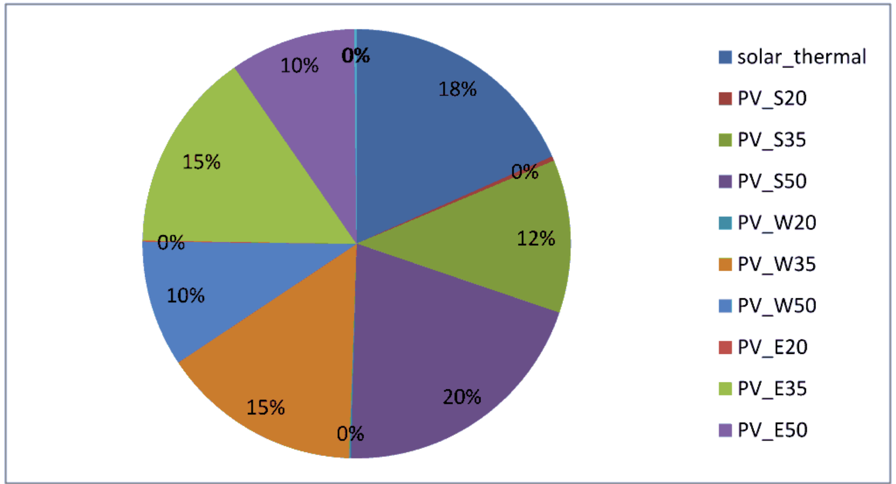


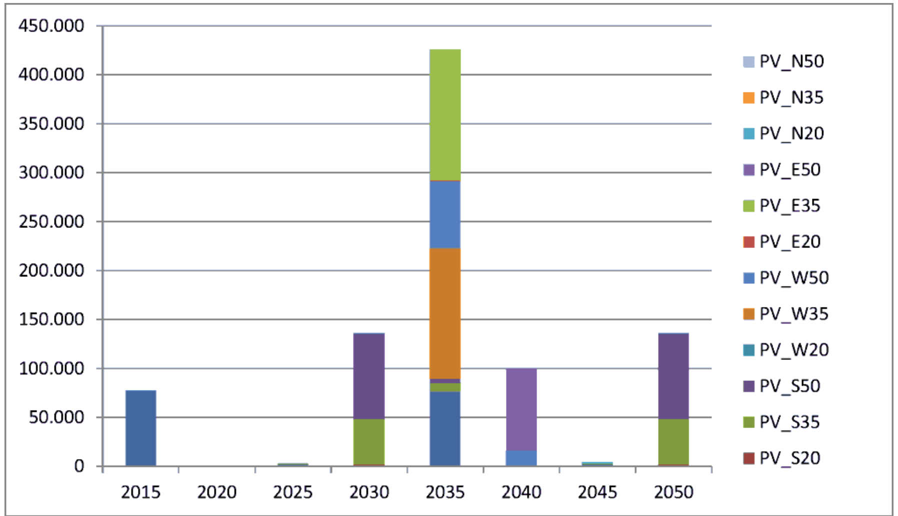




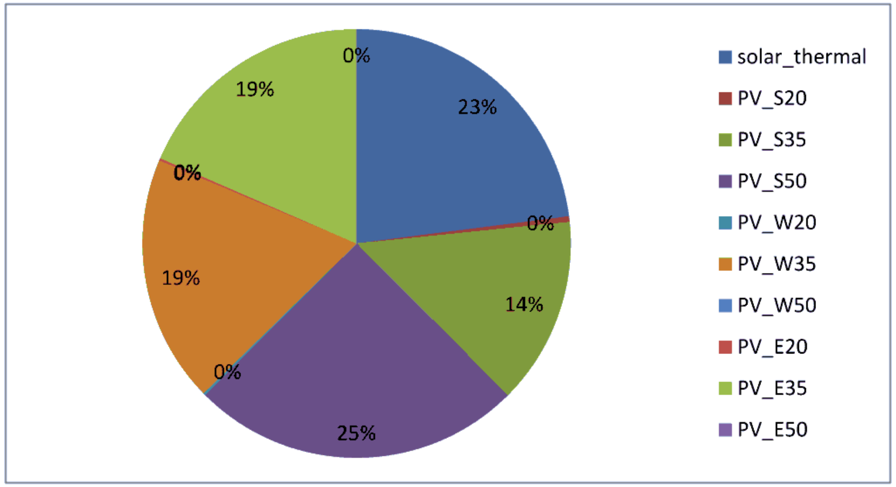
Backup: Results – PV & Solar Thermal installations

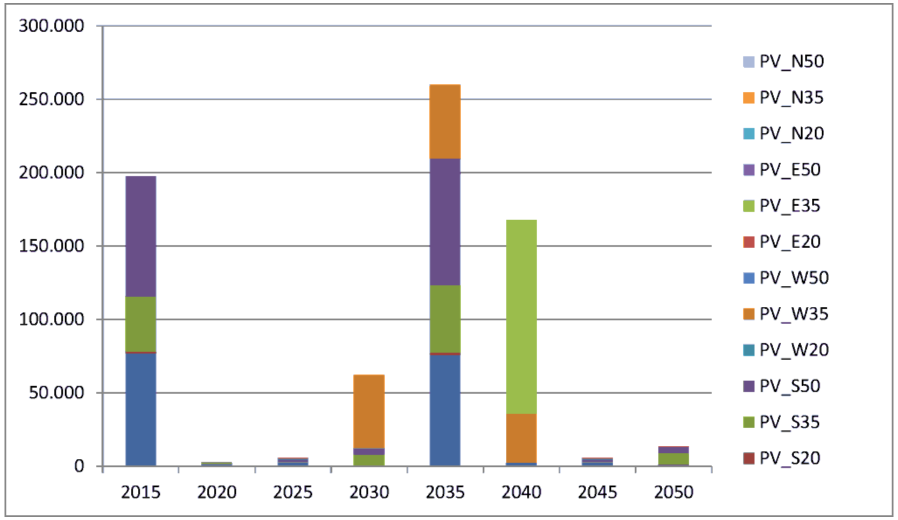
Business As Usual scenario





Emission Reduction scenario





Backup: Results – Scenario comparison

- Emission Reduction scenario vs. Business As Usual scenario:
  - Total costs: +4.88%
  - CO_2 emissions: -37.5%
  - PM_{10} emissions: -38.7%
  - Energy import: -23.4%
  - Specific CO_2-avoidance cost: 121 €/t_{CO2}