Appendix A Supporting Information

A.1 Retrofitting options for the Residential sector

Retrofitting processes are implemented to improve the insulation (R) values of the existing dwellings' building elements. Three retrofitting packages were defined, which provide shallow, medium or deep retrofitting of the roof, wall and window building elements. The improvements resulting from the retrofitting processes / measures are summarized in Table A.1. The data used in the definition of the packages was obtained from the ENTRANZE summary report [35].

Table A.1 Retrofitting measures available in TIMES-Europe. The top listed measures for each of the building elements correspond to the deep retrofitting package, followed by the measures which compose, respectively, the medium and shallow packages.

Building Element	Retrofitting Measures	R-Value Improvement	Average Cost (Euro / m^2)
Roof / Ceiling	Remove roof and refit adding a layer of insulation (15 cm)	3.75	100
	Add on a thermal insulation layer (15 cm) over the last slab in contact with unconditioned space (attic)	3.75	38
	Isolate below the last concrete slab (10 cm)	2.5	27
Walls	Ventilated facade (10 cm insulation)	2.5	155
	External insulation (10 cm - EIFS System)	2.5	52
	Internal insulation (5 cm)	1.25	44
Windows	Triple glass with argon cavity (18 mm)	1.54	410
	Triple glass with argon cavity (16 mm)	0.59	308
	Double glass with air cavity (16 mm)	0.37	252

A.2 Battery electric vehicle cost analysis

In order to project the cost development of battery electric vehicles (BEV), a simple model calculation is used. The main inputs to this model calculation are: i) the cost development of lithium-ion batteries, which was obtained from several recent publications [42-44], ii) 2019 – 2020 prices of BEV sales, iii) average battery size and drive range for current BEV models, iv) an assumed efficiency improvement of 0.5% per year, and v) allocation of the reduction in Li-ion battery cost to BEV sales price and battery size (drive range). The cost development of Li-ion batteries used in our study is summarized in Figure A.1. In our BEV cost projections, we distinguish between 3 BEV categories: small, medium and large, which correspond to EURO car segment classes A, C and D respectively. Table A.2 summarizes the fractions of battery cost reductions, which were allocated to either drive range extension or BEV cost decrease for the different vehicle classes as function of the already realized drive range. The final projections for BEV cost, battery pack size and drive range are included in Table A.3.

Table A.2 Overview of the assumed distribution of the benefit from battery cost reductions over drive range and BEV cost.

Category / Range [km]	Small		Medium		Large	
	Range	Cost	Range	Cost	Range	Cost
> 200	100%	0%	100%	0%	100%	0%
200 – 600 km	30%	70%	50%	50%	50%	50%
> 600 km	0%	100%	0%	100%	0%	100%

Table A.3 The final projections for BEV cost and the corresponding drive range resulting from the calculation outlined in the text.

	2020		2030		2040		2050	
BEV category	Investment [k€]	Range [km]	Investment [k€]	Range [km]	Investment [k€]	Range [km]	Investment [k€]	Range [km]
Small (Cat A)	23.2	208	21.2	245	20.4	268	19.9	287
Medium (Cat C)	39.9	289	37.6	382	36.5	444	35.8	498
Large (Cat D)	54.6	428	51.1	567	49.0	600	47.4	600

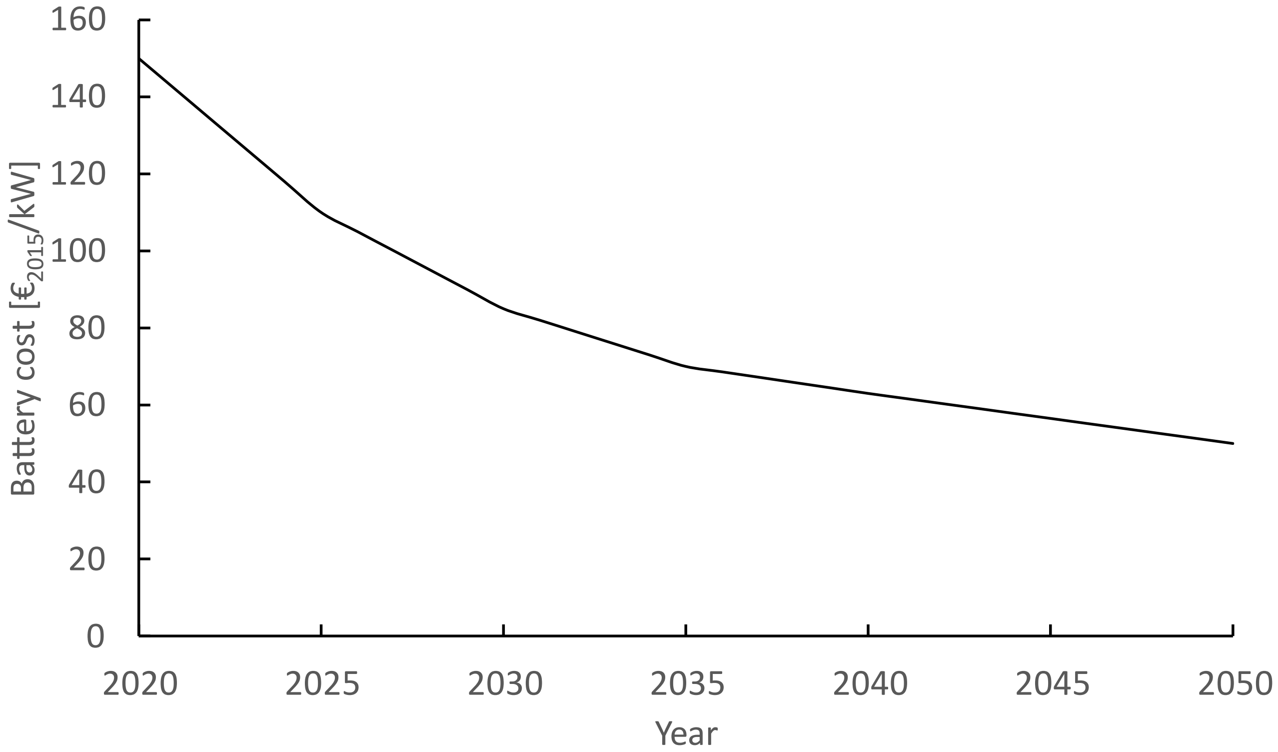

Figure A.1 Projection of the Li-ion battery investment costs on the basis of a number of recent publications [42-44]

In order to establish investment cost projections for battery electric vehicles in the other road transportation categories (Bus, LCV, HDV) the derived battery cost development was used once again. In addition, we defined a vehicle base cost as the vehicle investment cost excluding the battery pack. This we derived from the EU Reference Scenario 2020 investment cost data [46]. Subsequently, under the assumption of a drive range fitting the vehicle category, a cost projection of the total investment costs was made. The resulting cost projections and ranges used are summarized in Table A.4.

<u>A.3 Model parameters electricity storage options</u>

Table A.4 summarizes the parameters used to model electricity storage options in TIMES-Europe, the data used was obtained from Schmidt *et al.* [51] and Abdon *et al.* [53]. The total investment costs for the various storage technologies vary with both their nominal power and energy capacity. The former determines the power output of the technology, while the latter sets the total amount of electricity that can be stored. The investment cost for the various electricity storage options in TIMES-Europe were determined using equation A1:

$$Investment\ cost = I_P \cdot CAP_P + I_E \cdot CAP_{E,} \tag{A1}$$

in which CAP_P and CAP_E, respectively, refer to power and energy related capacity and I_p and I_E to the specific power and energy investment cost. The ratio between CAP_E and CAP_P sets the technology's E2P ratio.

Table A. 4 Projections for BEV cost for the Bus, LCV and HDV categories and the corresponding drive range.

	2020		2030		2040		2050	
BEV category	Investment [k€]	Range [km]	Investment [k€]	Range [km]	Investment [k€]	Range [km]	Investment [k€]	Range [km]
BEV Bus	428	158	330	275	326	375	314	375
BEV LCV	22.8	250	21.2	300	20.6	350	19.8	350
BEV HDV	258.2	500	173.9	500	153.1	500	141.7	500

Table A.5 Overview of the electricity storage model parameters.

Storage technology	Investment costs (2020)		Round-trip efficiency [%]	E2P-range [h]	Lifetime [y]
	Power [$€_{2015}$/kW]	Energy [$€_{2015}$/kWh]			
Li-ion network battery	553	654	86	2-8	13
PHS	920	65	80	8 - 128	50
D-CAES	710	32	54[1]	16 - 128	30
AA-CAES	605	128	75	16 - 128	30

[1] For D-CAES the quoted efficiency corresponds to the energy efficiency, which is obtained by dividing the electrical energy output by the sum of the electrical input and the fuel (natural gas) consumed.

Out of the multiple storage technologies implemented only the investment cost of Li-ion battery technology is projected to reduce over time. The other technologies are either proven technologies or based on well-known processes and engineering, for which little cost reductions are expected. The projection of the Li-ion network battery cost used in TIMES-Europe is included in Table A.5.

Table A.6 Overview of the Li-ion network battery cost projection.

	Investment cost [$€_{2015}$/kW]			
E2P ratio	2020	2030	2040	2050
2h	1023	428	298	260
4h	1742	728	507	443
8h	3180	1330	925	809

A.4 Analysis of time-slice (dispatchable) capacity requirement

The average capacity requirement for the various dispatchable technologies during each time-slice is calculated from the corresponding electricity generation, the annual fraction of the time-slice and the technology capacity factor, according to:

$$\bar{C}_{TS,i} = \frac{ELC_{TS,i}}{YF_{TS} \cdot CF_i}, \quad \text{(A2)}$$

in which $\bar{C}_{TS,i}$ corresponds to average capacity requirement of technology *i* during time-slice *TS*, $ELC_{TS,i}$ to the electricity generated by *i* during *TS*, YF_{TS} refers to the year fraction of *TS* and CF_i to the capacity factor of technology *i*. From Figure A.2 it becomes clear that the average capacity requirement for natural gas plants during WP is approximately five times larger than during the other time-slices.

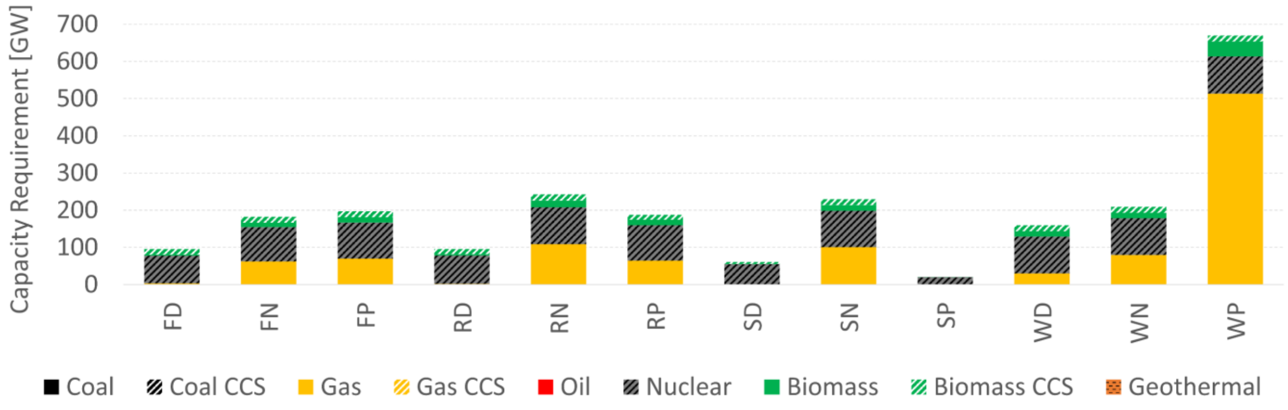

Figure A.2 Dispatchable capacity requirement per time-slice for the NZ-RES60 scenario