D2.2: Technical report on Balmorel scenario analysis
REALISE

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1. Introduction

This document gives an overview of the Balmorel energy system scenarios created for the REALISE project, with focus on the electricity price development towards 2050. A highly electrified main scenario towards 2050 is considered, with investment optimisation carried out for scenario years 2025, 2035 and 2045. In addition to the main scenario, a number of sub-scenarios, where some of the key inputs are varied, are created. Two example sub-scenarios are presented, with focus on how they differ from the main scenario in terms of electricity price projections and VRE installations. The full set of 30+ sub-scenarios is used to create a surrogate model for future electricity price time series in the REALISE project.

2. Methodology and scope

The methodology used to create the main energy system scenario toward 2050 is described in REALISE deliverable D2.1. However, a quick recap is given below. The scope in terms of countries and included sectors is then presented.

2.1 The Balmorel energy system model

The Balmorel energy system model [1] is used to study how the European energy system develops towards 2050. The model is open source (http://www.balmorel.com/), can model multiple energy sectors and their couplings [2], can be linked to the CorRES tool for modelling multiple VRE technologies [3], and manages the European-level geographical scale required in the REALISE project. Balmorel optimises investments in the included sectors, to obtain socio-economically optimal (lowest total cost) [1] energy system scenarios, while satisfying the energy demands. Generation, storage, transmission expansion, district heating, synthetic gas units, and more compete to satisfy the electricity, heat and hydrogen demands in the system.

The scenarios are differentiated by the inputs, e.g., investment costs, assumed CO_2 tax development and technology data (such as VRE capacity factors and storage technology limits). The inputs are described in more detail in REALISE D2.1. Scenario outputs are invested GW of each technology for each analysed region and for connections between the regions. A scenario includes multiple scenario years, e.g., 2025, 2035 and 2045, to model the pathway towards 2050.

Newest Balmorel model developments are utilised, considering linkages between the different energy sectors, heat demand requirements per temperature level, and intertemporal optimisation (considering future years when making investment decisions for a specific scenario year). Due to computational complexity, a reduced number of weeks and hours of the day are used in the investment optimisation [2].

In addition to having scenarios with installed GWs for different scenario years, Balmorel supports running day-ahead market simulation for each scenario year [4]. The day-ahead operation is based on optimisation of the energy markets, with storage levels (e.g., for hydro power and long-term heat storage) optimised over the year, and a final hourly resolution day-ahead run giving the hourly prices for the full year. The prices can be used to analyse revenues for the different technologies in different European countries [3].

2.2 VRE time series from CorRES

The VRE time series used in Balmorel are simulated with the CorRES model (https://corres.windenergy.dtu.dk/) [5], [6]. The runs are based on ERA5 reanalysis data (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5), with Global Wind Atlas (https://globalwindatlas.info/) wind speed information used to provide more details for the onshore wind modelling. Hourly resolution time series are simulated. The CorRES runs specify the capacity factors and hourly profiles for each VRE technology in Balmorel for each analysed region.

2.3 The analysed countries

The regions included in the Balmorel investment optimisation are shown in Figure 1. The investments in the analysed sectors are optimised for each region, with both electric transmission line and hydrogen pipeline investments optimised between the regions.

Figure 1. Countries included in the Balmorel energy system optimisation. Sweden, Norway, and Denmark are in regions based on Nord Pool bidding zones. Germany is analysed regionally to consider transmission bottlenecks.

2.4 The analysed sectors

The sectors analysed in Balmorel are shown in Figure 2. The couplings between the sectors allow, e.g., heat storage to be used to manage variability in VRE generation [2]. The electric power sector and heat sector investments are optimised in Balmorel (heat demand is given as an exogenous input). The transport sector modelling is based on exogenously set projections:

growth in electric vehicle (EV) penetration and annual need for hydrogen for the transport sector (including aviation and maritime). These exogenous assumptions drive the transport sector to be fully decarbonised by 2050 [2]. However, the operation of EVs and the time when hydrogen is produced (and stored) is optimised in Balmorel.

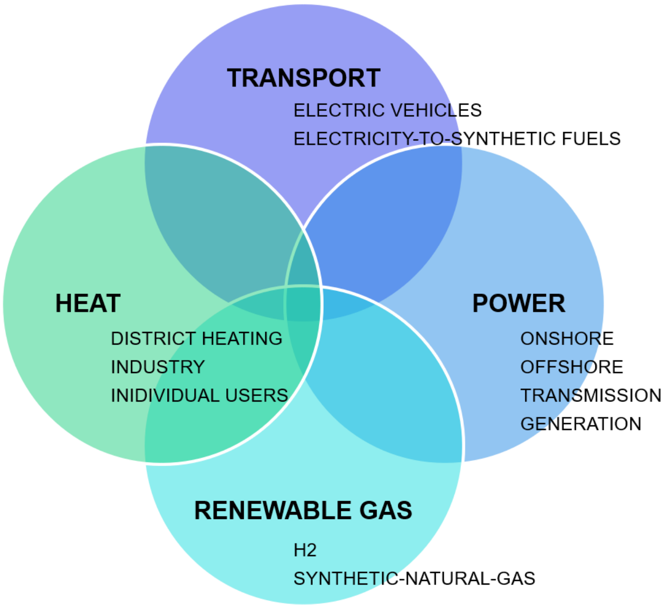

Figure 2. The sectors analysed in Balmorel.

2.5 The main scenario and sub-scenarios

The main scenario uses the fuel costs, CO_2 tax, mean cost projections and other inputs described in REALISE D2.1, including the updates to the mean inputs towards 2050 agreed with the project partners. As discussed in the previous sections, the demand side is assumed to be highly electrified towards 2050. The sub-scenarios are variations around the main scenario, where most inputs remain unchanged, but one or more of the inputs are modified to see the impacts on the scenario results. Table 1 describes all the analysed scenarios. The scenarios are defined as variations, given as a scale (1 = 100 %, i.e., no change), around the main scenario. The first row (scenario ID 1) is the main scenario, with all variations set to 1 (i.e., no variation). The scenario IDs 2 to 14 are sub-scenarios where one or many of the varied parameters are set to the most extreme value studied (the min and max variations are discussed more in REALISE D2.1). IDs 15 to 34 add coverage between the main scenario and the extreme-value sub-scenarios.

The energy system investments are optimized for three scenario years, 2025, 2035 and 2045, to see the model progression towards 2050. The scenario years relate to making investment decisions, so, e.g., 2025 means the existing installations up to that year (considering also decommissioning) plus the investment decisions in 2025. The realisation of those investments can take some time, so the 2025 scenario year can be seen to reflect the energy system by 2030.

Table 1: Input variations for the different scenarios.

ID	Onshore wind cost	Offshore wind cost	Solar PV cost	Natural gas price	CO_2 tax	Heat pump cost	Electrolyser cost
1	1	1	1	1	1	1	1
2	0.8	0.7	1.2	1	1	1	1
3	1.2	1.3	0.8	1	1	1	1
4	1	1	1	10	1	1	1
5	0.8	0.7	1.2	10	0.8	1.2	0.8
6	0.8	0.7	1.2	10	0.8	1.2	1.2
7	0.8	1.3	1.2	10	0.8	0.8	0.8
8	1.2	0.7	0.8	1	0.8	0.8	0.8
9	0.8	1.3	1.2	10	0.8	1.2	1.2
10	1.2	1.3	1.2	1	1.2	0.8	0.8
11	0.8	1.3	0.8	1	1.2	0.8	0.8
12	1.2	0.7	0.8	10	1.2	0.8	1.2
13	1.2	1.3	0.8	1	1.2	1.2	1.2
14	1.2	0.7	0.8	1	1.2	1.2	1.2
15	1.10	1.21	0.87	2.17	0.81	0.85	0.97
16	1.03	1.26	0.80	1.63	1.02	1.12	0.82
17	1.20	0.85	1.06	9.27	1.00	1.02	0.88
18	1.18	1.11	0.98	4.03	1.16	0.95	1.12
19	1.14	0.80	1.11	5.44	1.09	1.10	1.03
20	0.95	1.29	0.89	7.77	0.83	0.82	0.96
21	1.12	0.89	1.14	8.28	1.00	0.94	1.15
22	0.83	0.78	1.08	3.40	1.13	0.83	0.89
23	1.07	1.23	0.84	9.54	0.90	1.18	0.98
24	0.85	1.13	0.87	7.39	1.08	0.99	1.19
25	0.94	0.82	0.85	5.82	0.95	1.01	1.10
26	1.15	0.91	0.96	1.23	0.88	0.86	0.93
27	0.89	1.05	1.13	8.15	0.85	1.16	1.04
28	1.06	1.06	0.92	6.27	0.98	1.05	1.06
29	0.99	1.03	1.15	4.53	0.82	1.07	1.03
30	0.96	0.96	0.93	2.36	0.94	1.17	1.08
31	0.87	1.16	1.05	8.58	1.14	0.92	1.12
32	0.91	1.02	1.19	3.73	1.04	1.11	1.16
33	1.02	0.93	1.03	6.61	1.06	0.90	0.84
34	1.17	1.18	1.18	6.81	0.96	1.09	1.19

3. Results: the main scenario

3.1 Electricity demand development

Overview of the annual electricity demand is shown in Figure 3. The inflexible demand (INFLEX) and overall heat demand are expected to decrease towards 2050, driven by efficiency gains [7]. But the overall electricity demand still increases drastically towards 2050, driven by electrification of the transport sector and hydrogen production. The heat sector (where investments are optimised in Balmorel) is electrified significantly already in 2025, but the sector's electrification grows towards 2050, as can be seen in Figure 4 (the overall heat demand decreases due to the assumed efficiency gains). Hydrogen production in 2025 is mainly by natural gas, but from the 2030s onwards it is fully electrified.

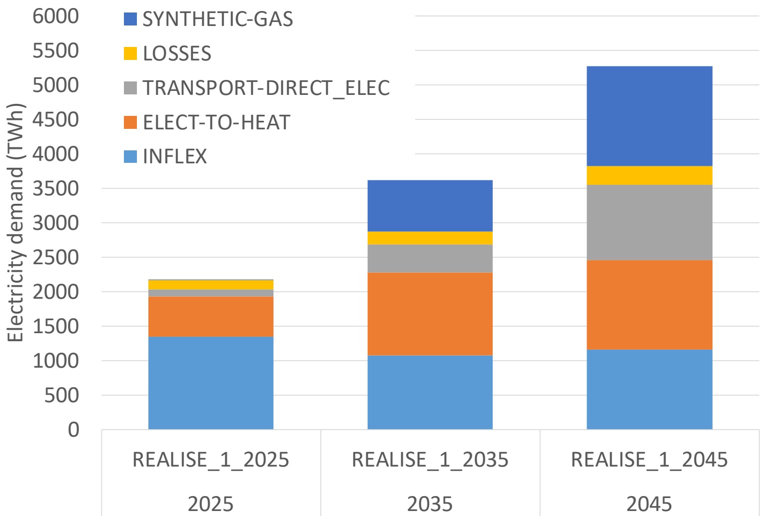

Figure 3. Annual electricity demand (main scenario); aggregate of all analysed countries.

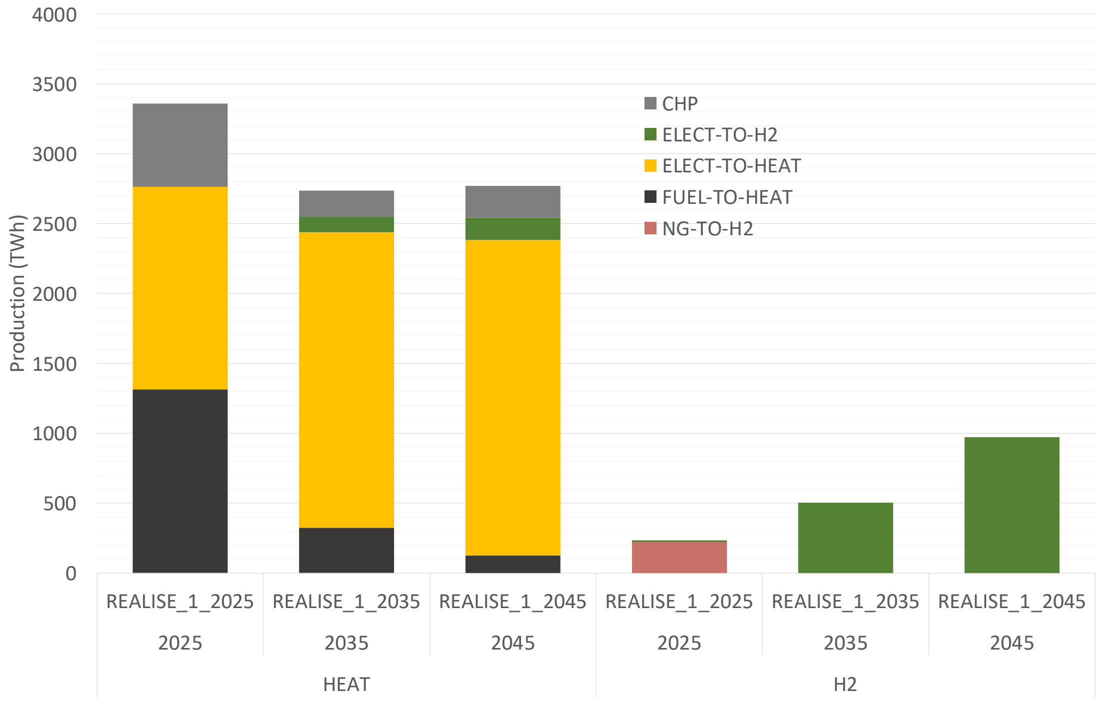

Figure 4. Annual heat and hydrogen production (main scenario); aggregate of all analysed countries. ELECT-TO-H2 in the heat production is excess heat from the electrolysers.

3.2 Electricity generation development

The share of wind generation is significant already in 2025, with the combined share of wind and solar PV reaching around 90 % of annual electricity generation by 2050 (see Figure 5). In all scenario years, solar PV generates roughly 1/3 of the annual VRE generation, with wind generating the rest (run-of-river hydro could also be counted as VRE, changing the VRE shares only slightly). Offshore wind generation share starts quite small in 2025, but by 2045 onshore and offshore wind generate around the same annually. Some thermal generation remains in the system, coming mainly from French nuclear and to a lesser degree from gas generation.

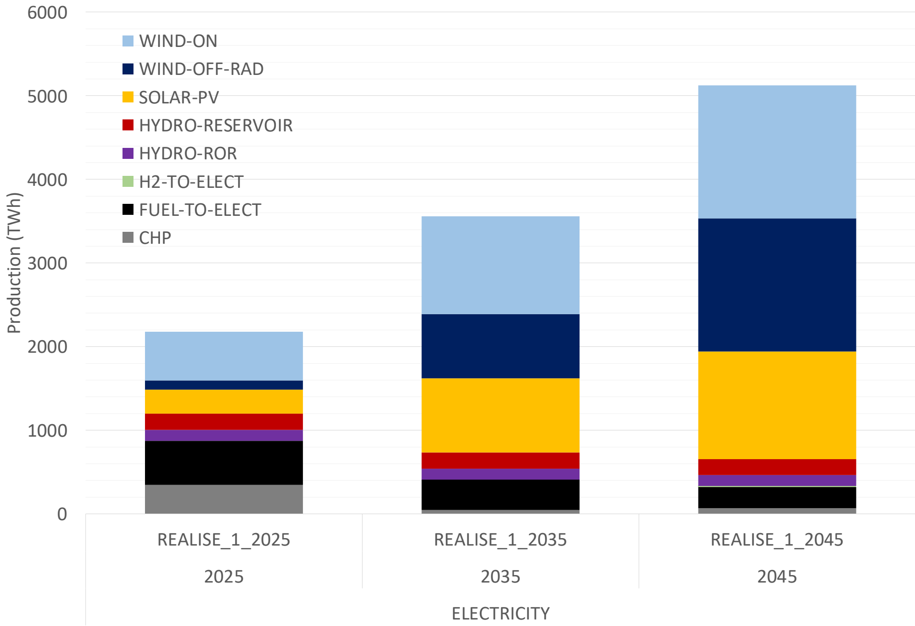

Figure 5. Annual electricity generation (main scenario); aggregate of all analysed countries.

3.3 Transmission expansion

Electric transmission lines for 2025 and 2045 are shown in Figure 6 and Figure 7, respectively. Transmission expansion is significant, with Scandinavian countries increasing their intra-country transmission lines, Germany, France and Poland seeing very significant cross-border transmission capacity increases, and the UK getting highly interconnected with both continental Europe and Norway. The very large interconnection between the UK and Norway by 2045 may be preferred by Balmorel optimisation to provide connection of Norwegian hydro power also to France and Belgium (transiting the power through UK); this can be unfeasible if one would consider intra-country transmission expansion in more detail (which is omitted in Balmorel) or due to political reasons. However, the tendency of seeing very significant overall transmission expansion is very clear in the results.

Figure 6. Electric transmission lines in the main scenario, year 2025 (GW).

Figure 7. Electric transmission lines in the main scenario, year 2045 (GW).

3.4 Electricity price development

An overview of electricity price (hourly spot market) statistics towards 2050 is shown in Figure 8 for the main scenario (for some example regions). The increasing VRE share drives the mean price down towards 2050, with the mean prices of the different regions getting more similar in 2045 compared to 2025. The price variability within a year (both standard deviation and the maximum price) increases especially from 2025 to 2035. From 2035 to 2045, the price variability stays similar or even decreases. There was limited time to analyse the drivers for the changes towards 2050 in detail, but it can be expected that by 2035, increasing CO_2 tax makes the hours requiring gas generation to have high prices (driving the price variability up). By 2045, sector coupling increases, which allows heat and hydrogen storage to be used to manage the supply side variability with lower cost, thus reducing the need to use gas generation (which can drive the price variability down).

Table 2 and Table 3 show that correlation in prices between the regions increases significantly towards 2050, driven by increasing transmission capacity and VRE becoming the dominant generation technology (as high or low wind conditions tend to occur simultaneously in nearby regions, and similarly for solar generation).

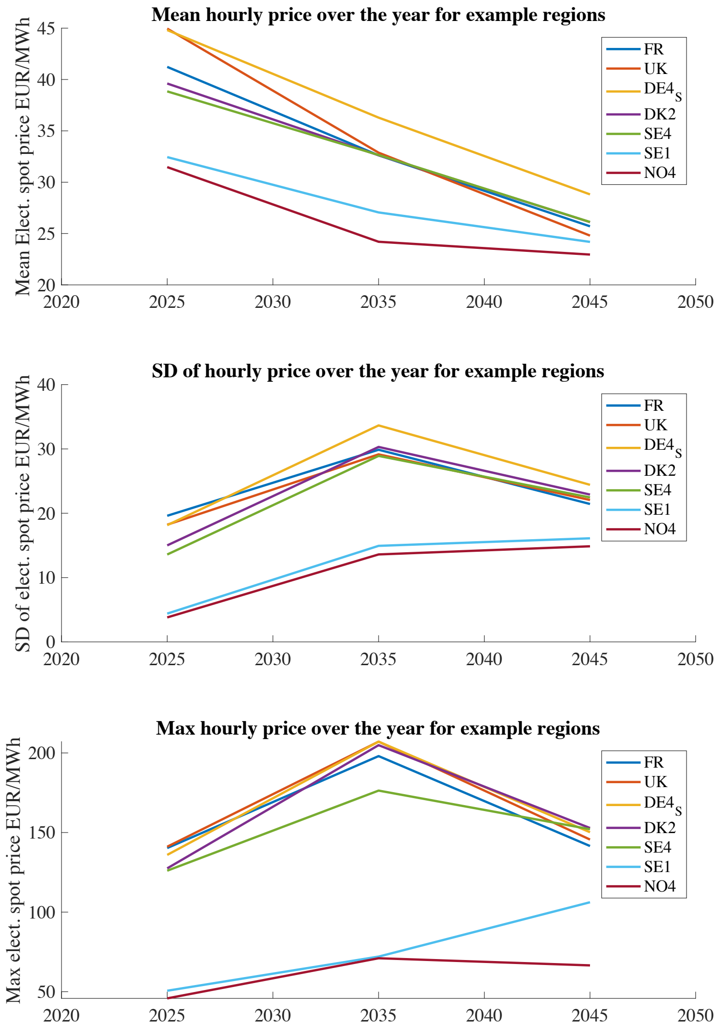

Figure 8. Main scenario electricity price statistics towards 2050 in example regions. SD = standard deviation.

Table 2. Correlations between hourly electricity prices in 2025 in the main scenario.

2025	BE	DE4_E	DE4_N	DE4_S	DE4_W	DK1	DK2	EE	FIN	FR	LT	LV	NL	NO1	NO2	NO3	NO4	NO5	PL	SE1	SE2	SE3	SE4	UK
BE		0.93	0.95	0.97	0.97	0.92	0.88	0.78	0.79	0.95	0.78	0.78	0.99	0.85	0.86	0.59	0.53	0.85	0.74	0.59	0.60	0.83	0.87	0.94
DE4_E	0.93		0.99	0.96	0.98	0.95	0.92	0.82	0.78	0.90	0.83	0.82	0.95	0.84	0.86	0.53	0.47	0.84	0.85	0.55	0.57	0.84	0.89	0.87
DE4_N	0.95	0.99		0.97	0.99	0.95	0.92	0.82	0.79	0.92	0.83	0.82	0.97	0.85	0.87	0.55	0.49	0.85	0.83	0.57	0.58	0.85	0.90	0.88
DE4_S	0.97	0.96	0.97		0.99	0.93	0.90	0.79	0.78	0.96	0.79	0.79	0.98	0.84	0.86	0.57	0.52	0.84	0.79	0.58	0.60	0.83	0.87	0.91
DE4_W	0.97	0.98	0.99	0.99		0.94	0.91	0.80	0.78	0.94	0.81	0.80	0.98	0.85	0.86	0.56	0.50	0.85	0.81	0.58	0.59	0.84	0.89	0.90
DK1	0.92	0.95	0.95	0.93	0.94		0.96	0.82	0.83	0.89	0.83	0.82	0.92	0.89	0.91	0.60	0.54	0.89	0.82	0.62	0.63	0.89	0.94	0.87
DK2	0.88	0.92	0.92	0.90	0.91	0.96		0.85	0.85	0.86	0.86	0.85	0.89	0.89	0.90	0.59	0.53	0.89	0.85	0.61	0.62	0.90	0.96	0.83
EE	0.78	0.82	0.82	0.79	0.80	0.82	0.85		0.85	0.75	1.00	1.00	0.78	0.82	0.82	0.46	0.39	0.82	0.89	0.50	0.50	0.85	0.90	0.71
FIN	0.79	0.78	0.79	0.78	0.78	0.83	0.85	0.85		0.78	0.84	0.84	0.78	0.95	0.92	0.61	0.53	0.95	0.73	0.64	0.64	0.97	0.91	0.75
FR	0.95	0.90	0.92	0.96	0.94	0.89	0.86	0.75	0.78		0.75	0.75	0.94	0.84	0.85	0.60	0.55	0.84	0.71	0.60	0.61	0.82	0.85	0.91
LT	0.78	0.83	0.83	0.79	0.81	0.83	0.86	1.00	0.84	0.75		1.00	0.79	0.82	0.82	0.45	0.38	0.82	0.91	0.49	0.50	0.85	0.90	0.71
LV	0.78	0.82	0.82	0.79	0.80	0.82	0.85	1.00	0.84	0.75	1.00		0.78	0.82	0.82	0.45	0.38	0.82	0.90	0.49	0.49	0.85	0.89	0.71
NL	0.99	0.95	0.97	0.98	0.98	0.92	0.89	0.78	0.78	0.94	0.79	0.78		0.84	0.86	0.58	0.52	0.84	0.77	0.58	0.60	0.83	0.87	0.93
NO1	0.85	0.84	0.85	0.84	0.85	0.89	0.89	0.82	0.95	0.84	0.82	0.82	0.84		0.99	0.66	0.59	1.00	0.74	0.67	0.68	0.99	0.94	0.83
NO2	0.86	0.86	0.87	0.86	0.86	0.91	0.90	0.82	0.92	0.85	0.82	0.82	0.86	0.99		0.65	0.58	0.99	0.76	0.66	0.67	0.97	0.93	0.85
NO3	0.59	0.53	0.55	0.57	0.56	0.60	0.59	0.46	0.61	0.60	0.45	0.45	0.58	0.66	0.65		0.96	0.66	0.39	0.98	0.98	0.64	0.60	0.64
NO4	0.53	0.47	0.49	0.52	0.50	0.54	0.53	0.39	0.53	0.55	0.38	0.38	0.52	0.59	0.58	0.96		0.59	0.32	0.95	0.95	0.57	0.54	0.58
NO5	0.85	0.84	0.85	0.84	0.85	0.89	0.89	0.82	0.95	0.84	0.82	0.82	0.84	1.00	0.99	0.66	0.59		0.74	0.67	0.67	0.99	0.94	0.83
PL	0.74	0.85	0.83	0.79	0.81	0.82	0.85	0.89	0.73	0.71	0.91	0.90	0.77	0.74	0.76	0.39	0.32	0.74		0.43	0.44	0.78	0.85	0.65
SE1	0.59	0.55	0.57	0.58	0.58	0.62	0.61	0.50	0.64	0.60	0.49	0.49	0.58	0.67	0.66	0.98	0.95	0.67	0.43		0.99	0.66	0.62	0.63
SE2	0.60	0.57	0.58	0.60	0.59	0.63	0.62	0.50	0.64	0.61	0.50	0.49	0.60	0.68	0.67	0.98	0.95	0.67	0.44	0.99		0.66	0.63	0.64
SE3	0.83	0.84	0.85	0.83	0.84	0.89	0.90	0.85	0.97	0.82	0.85	0.85	0.83	0.99	0.97	0.64	0.57	0.99	0.78	0.66	0.66		0.95	0.80
SE4	0.87	0.89	0.90	0.87	0.89	0.94	0.96	0.90	0.91	0.85	0.90	0.89	0.87	0.94	0.93	0.60	0.54	0.94	0.85	0.62	0.63	0.95		0.82
UK	0.94	0.87	0.88	0.91	0.90	0.87	0.83	0.71	0.75	0.91	0.71	0.71	0.93	0.83	0.85	0.64	0.58	0.83	0.65	0.63	0.64	0.80	0.82	

Table 3. Correlations between hourly electricity prices in 2045 in the main scenario.

2045	BE	DE4_E	DE4_N	DE4_S	DE4_W	DK1	DK2	EE	FIN	FR	LT	LV	NL	NO1	NO2	NO3	NO4	NO5	PL	SE1	SE2	SE3	SE4	UK
BE		0.97	0.98	0.98	0.98	0.94	0.95	0.89	0.86	0.94	0.91	0.90	0.98	0.90	0.91	0.84	0.77	0.90	0.92	0.83	0.85	0.93	0.94	0.93
DE4_E	0.97		0.99	0.99	0.99	0.94	0.97	0.92	0.87	0.93	0.95	0.94	0.97	0.87	0.88	0.81	0.77	0.87	0.96	0.84	0.86	0.94	0.97	0.89
DE4_N	0.98	0.99		0.98	0.99	0.96	0.97	0.92	0.88	0.91	0.94	0.93	0.98	0.89	0.90	0.83	0.79	0.89	0.95	0.85	0.87	0.95	0.97	0.90
DE4_S	0.98	0.99	0.98		0.98	0.93	0.96	0.90	0.86	0.95	0.93	0.92	0.97	0.87	0.88	0.81	0.77	0.87	0.94	0.83	0.85	0.92	0.95	0.89
DE4_W	0.98	0.99	0.99	0.98		0.95	0.96	0.91	0.87	0.92	0.93	0.93	0.99	0.88	0.89	0.82	0.77	0.88	0.94	0.83	0.86	0.94	0.96	0.90
DK1	0.94	0.94	0.96	0.93	0.95		0.97	0.92	0.89	0.88	0.91	0.91	0.96	0.92	0.92	0.87	0.80	0.93	0.91	0.87	0.90	0.97	0.96	0.90
DK2	0.95	0.97	0.97	0.96	0.96	0.97		0.93	0.88	0.89	0.95	0.95	0.95	0.89	0.88	0.83	0.79	0.89	0.95	0.85	0.88	0.96	0.99	0.88
EE	0.89	0.92	0.92	0.90	0.91	0.92	0.93		0.90	0.84	0.97	0.98	0.90	0.85	0.83	0.80	0.77	0.85	0.96	0.84	0.87	0.94	0.94	0.82
FIN	0.86	0.87	0.88	0.86	0.87	0.89	0.88	0.90		0.82	0.86	0.87	0.86	0.86	0.83	0.85	0.88	0.85	0.85	0.93	0.92	0.94	0.89	0.82
FR	0.94	0.93	0.91	0.95	0.92	0.88	0.89	0.84	0.82		0.85	0.85	0.91	0.87	0.88	0.81	0.76	0.87	0.87	0.80	0.82	0.87	0.89	0.90
LT	0.91	0.95	0.94	0.93	0.93	0.91	0.95	0.97	0.86	0.85		1.00	0.91	0.83	0.82	0.77	0.74	0.83	0.99	0.81	0.84	0.92	0.96	0.81
LV	0.90	0.94	0.93	0.92	0.93	0.91	0.95	0.98	0.87	0.85	1.00		0.91	0.84	0.82	0.78	0.75	0.84	0.98	0.82	0.85	0.93	0.95	0.81
NL	0.98	0.97	0.98	0.97	0.99	0.96	0.95	0.90	0.86	0.91	0.91	0.91		0.89	0.90	0.83	0.77	0.89	0.92	0.83	0.86	0.93	0.94	0.91
NO1	0.90	0.87	0.89	0.87	0.88	0.92	0.89	0.85	0.86	0.87	0.83	0.84	0.89		0.98	0.95	0.82	1.00	0.83	0.86	0.89	0.92	0.89	0.96
NO2	0.91	0.88	0.90	0.88	0.89	0.92	0.88	0.83	0.83	0.88	0.82	0.82	0.90	0.98		0.93	0.80	0.98	0.82	0.83	0.86	0.90	0.87	0.98
NO3	0.84	0.81	0.83	0.81	0.82	0.87	0.83	0.80	0.85	0.81	0.77	0.78	0.83	0.95	0.93		0.88	0.95	0.76	0.90	0.93	0.87	0.83	0.91
NO4	0.77	0.77	0.79	0.77	0.77	0.80	0.79	0.77	0.88	0.76	0.74	0.75	0.77	0.82	0.80	0.88		0.82	0.73	0.96	0.92	0.84	0.79	0.78
NO5	0.90	0.87	0.89	0.87	0.88	0.93	0.89	0.85	0.85	0.87	0.83	0.84	0.89	1.00	0.98	0.95	0.82		0.83	0.86	0.89	0.92	0.89	0.97
PL	0.92	0.96	0.95	0.94	0.94	0.91	0.95	0.96	0.85	0.87	0.99	0.98	0.92	0.83	0.82	0.76	0.73	0.83		0.80	0.83	0.92	0.96	0.82
SE1	0.83	0.84	0.85	0.83	0.83	0.87	0.85	0.84	0.93	0.80	0.81	0.82	0.83	0.86	0.83	0.90	0.96	0.86	0.80		0.97	0.90	0.86	0.82
SE2	0.85	0.86	0.87	0.85	0.86	0.90	0.88	0.87	0.92	0.82	0.84	0.85	0.86	0.89	0.86	0.93	0.92	0.89	0.83	0.97		0.93	0.89	0.85
SE3	0.93	0.94	0.95	0.92	0.94	0.97	0.96	0.94	0.94	0.87	0.92	0.93	0.93	0.92	0.90	0.87	0.84	0.92	0.92	0.90	0.93		0.96	0.88
SE4	0.94	0.97	0.97	0.95	0.96	0.96	0.99	0.94	0.89	0.89	0.96	0.95	0.94	0.89	0.87	0.83	0.79	0.89	0.96	0.86	0.89	0.96		0.87
UK	0.93	0.89	0.90	0.89	0.90	0.90	0.88	0.82	0.82	0.90	0.81	0.81	0.91	0.96	0.98	0.91	0.78	0.97	0.82	0.82	0.85	0.88	0.87	

3.5 Electricity prices in the Swedish regions

Electricity price duration curves, and mean and standard deviations (SDs) are shown for the Swedish regions in Figure 9. From 2025 to 2045, the mean price decreases, similar to the overall European trend described above. For the Northern regions (SE1 and SE2), SD increases towards 2045, whereas for SE3 and SE4, the highest SD is seen in 2035. Overall, the SD in the Northern regions remains lower than in SE3 and SE4, indicating that the availability of hydro power can be used to mitigate price variability around the year. The Norther regions show also slightly lower mean electricity price compared to the South.

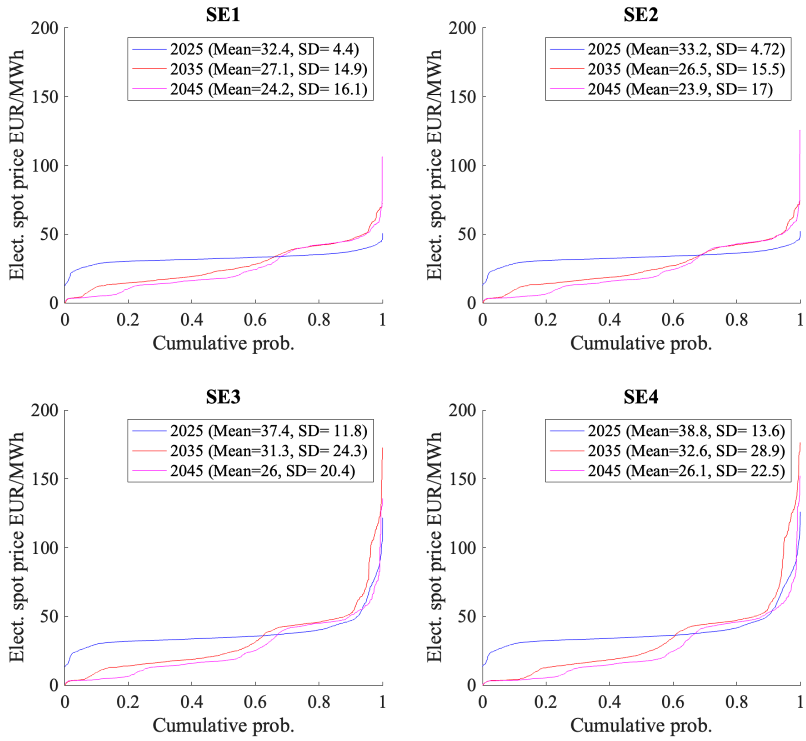

Figure 9. Electricity price durations curves for the Swedish regions in the main scenario. SD = standard deviation.

3.6 Comparison to historical prices for the Swedish regions

Historical electricity price duration curves for the Swedish regions are shown in Figure 10 for some example years (time before the 2022 high gas prices). There is significant variation between the different years both in the mean price and price variability. The same-year statistics for the different regions are very similar, but the Norther regions (SE1 and SE2) show consistently slightly lower mean price and lower price variability. Although the historical years cannot be directly compared to the scenario year 2025, the Swedish regions' 2025 simulated prices in the main scenario (Figure 9) are reasonable similar to the historical data, indicating that the simulated prices are at least not completely unrealistic. A notable difference is seen in the price SD of the Norther regions: both SE1 and SE2 show lower SD in the 2025 scenario year than is seen in any historical year. This may indicate that the dispatch of hydro power is not simulated in a fully realistic way in Balmorel (hydro power is expected to be the main driver to dampen price variability in northern Scandinavia).

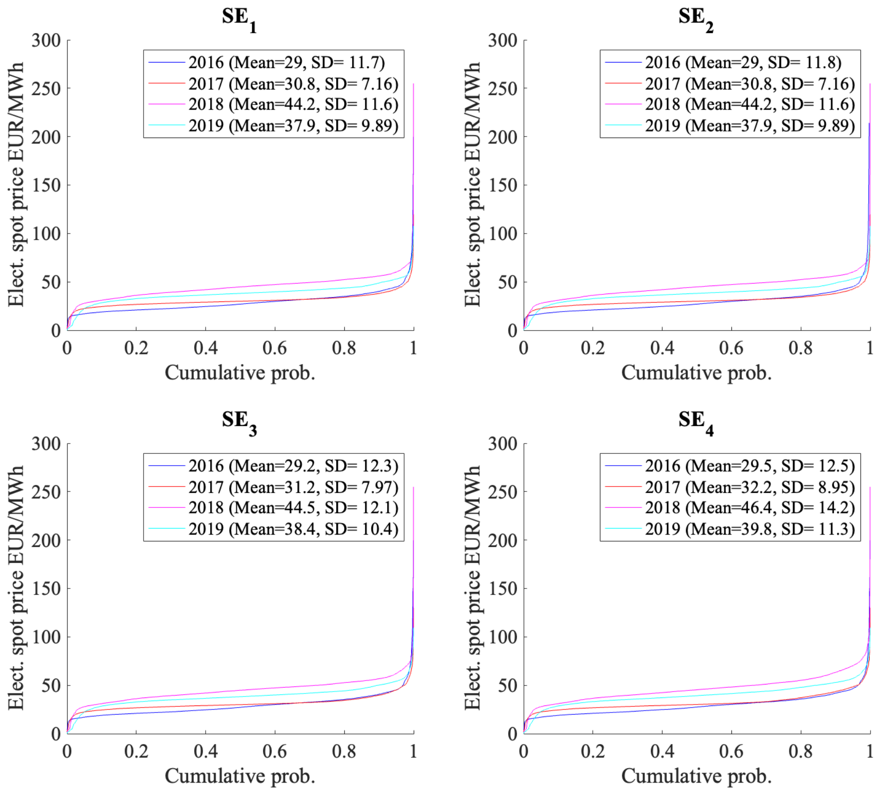

Figure 10. Historical electricity price durations curves for the Swedish regions for 2016, 2017, 2018 and 2019 [8]. SD = standard deviation.

4. Results: Sub-scenarios

This section presents two example sub-scenarios, focusing on scenarios which are significantly different compared to the main scenario. The sub-scenarios have otherwise the same inputs as the main scenario, but one or more of the inputs are varied to see how especially the electricity prices and VRE installations change towards 2050.

4.1 High gas price scenario: strong impact on electricity prices

In the high gas price scenario (scenario ID 4), the gas price is 10 times higher than in the main scenario (for all scenario years). Other inputs remain the same.

As a consequence of high gas price, mean electricity prices are much higher than in the main scenario, as can be seen when comparing Figure 11 to Figure 8. However, by 2045, when VRE generation share grows very high, the mean prices drop to a level similar to the main scenario (although remaining on average slightly higher). In 2025, the difference between areas with high share of hydro power (NO4 and SE1) and the other areas is even larger in the high gas price scenario compared to the main scenario.

The standard deviation (SD) of the prices is much higher in the high gas price scenario compared to the main scenario, driven by some hours dominated by low/near-zero marginal cost units (mainly wind and solar PV) whereas other hours require at least some gas power plants to be used, driving the electricity price very high for these hours (as they set the price for these hours, and the gas price is very high). The SD remains on an elevated level even in 2045, indicating that some gas generation is required even as flexibility from the heat and hydrogen sectors increase.

The maximum annual electricity prices in the high gas price scenario are much higher than in the main scenario, reaching levels of 800-1000 EUR/MWh in many regions in 2025. The maximum electricity price decreases towards 2050; however, all studied regions experience at least one hour per year with higher than 400 EUR/MWh price, indicating again that some gas generation remains in the system, setting the price for one or a few hours during the year.

The electricity price duration curves for the Swedish regions (Figure 12 vs. Figure 9) show similar differences between the high gas price and the main scenario as discussed above, with both the means and the SDs of the prices higher in the high gas price scenario. The regions in the north (SE1 and SE2) show lower prices with less variability compared to the regions in the south (SE3 and SE4), driven by reservoir hydro in the north. In all regions in the high gas price scenario the electricity prices are low or modest for more than 80 % of the hours, but a few hours in the year the prices peak at a level of around 600-900 EUR/MWh.

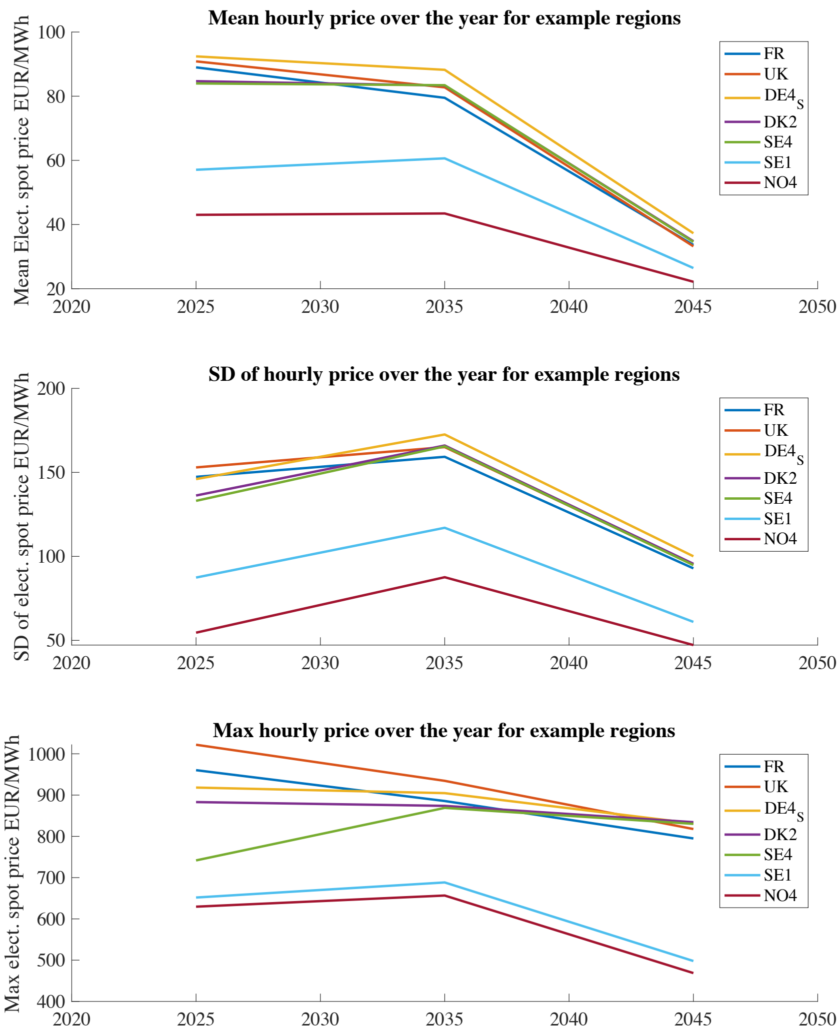

Figure 11. High gas price scenario electricity price statistics towards 2050 in example regions. SD = standard deviation.

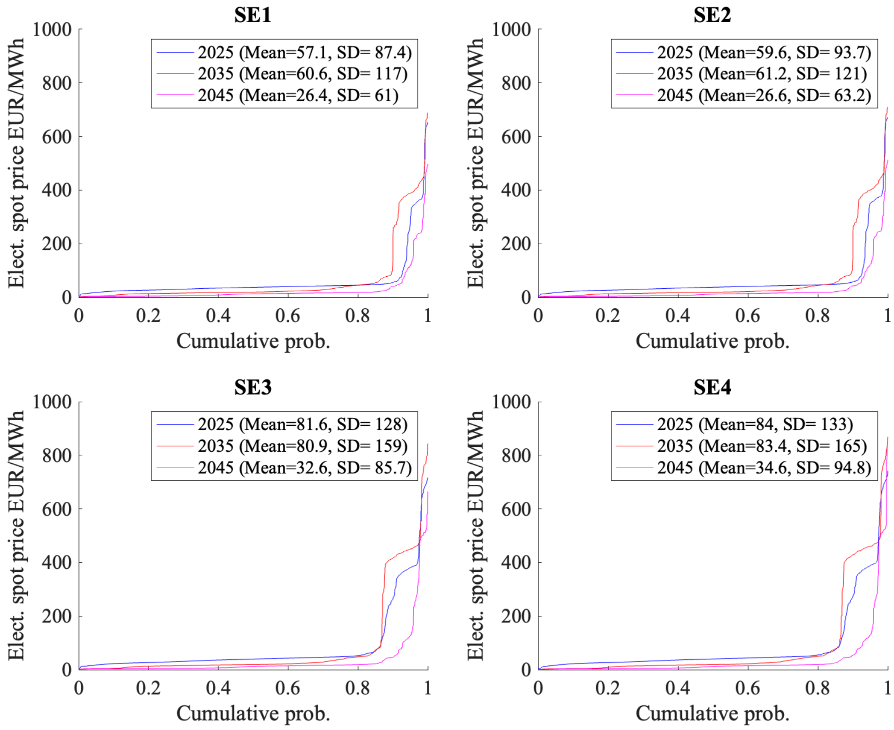

Figure 12. Electricity price durations curves for the Swedish regions in the high gas price scenario. SD = standard deviation.

4.2 High wind & low solar PV cost scenario: changes in VRE investments

In the high wind & low solar PV cost scenario (scenario ID 3), the wind CAPEX and OPEX are assumed to be 30 % higher for offshore wind and 20 % higher for onshore wind, and the solar PV CAPEX and OPEX 20 % lower compared to the main scenario (for all scenario years). Other inputs remain the same as in the main scenario.

As a consequence of more expensive wind and cheaper solar PV, the installed offshore wind decreases significantly towards 2050 and solar PV increases, as can be expected (see Figure 13). However, even with such large changes in the CAPEXs, both of these VRE technologies see significant investments. Onshore wind investments decrease compared to the main scenario, but only slightly, and by 2050 all the studied scenarios reach approximately the same installed onshore wind GW. This relates to assumed investment limits in the different countries [7]; these limits impact mainly onshore wind and not the other VRE technologies.

Figure 13 also includes the high gas price scenario (scenario ID 4). Compared to the main scenario, approximately similar VRE GW are installed by 2045 (slightly more), but the investments occur earlier, especially for wind power. High gas prices, and resulting higher electricity prices, should thus drive VRE investments; but it should be noted that in this sub-scenario the gas prices were assumed to remain on a very high level all the way to 2050, whereas in reality we may expect the gas prices to return to a lower level at some point.

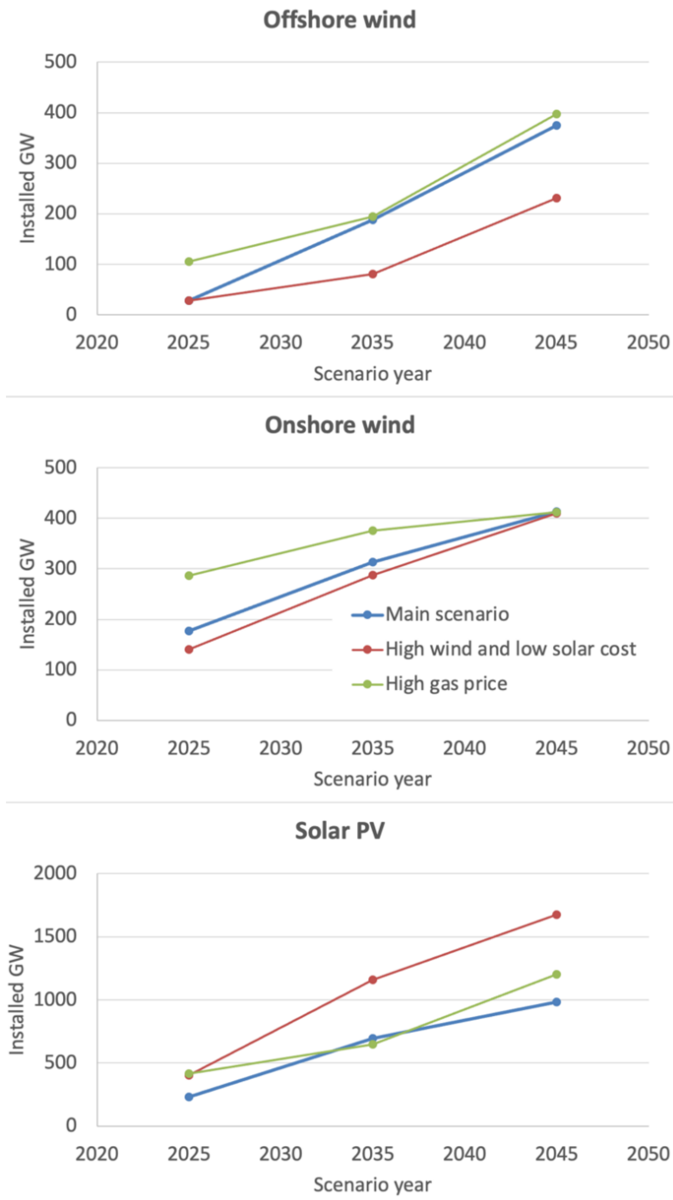

Figure 13. VRE installations in the main scenario and two studied sub-scenarios; aggregate of all analysed countries.

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