Implications from WACC differentiation across technologies for energy system modelling

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Appendix

1 Introduction

Discounting of the future benefits and costs of energy production to earlier dates needs to be performed in order to conduct meaningful analyses of investments in energy technologies. Energy models at TNO Energy Transition Studies (ETS), such as COMPETES-TNO and TIAM-ECN, use a weighted average cost of capital (WACC) as the discount rate, already for many years.[1] The level of the WACC affects the absolute and relative costs of technologies. If the WACC increases (decreases), technologies that require high capital investments with low operating expenditures become more (less) expensive relative to technologies that require low capital investment with higher operating expenditures. In sustainable energy systems the share of renewable energy production assets that require high capital investments is high compared to fossil-fueled energy systems. Hence, with the ongoing energy transition the sensitivity of energy systems for the WACC increases strongly.

A realistic representation of the cost of capital is thus important for producing meaningful quantitative modelling results. However, current WACC assumptions used in the TNO-ETS models are inadequate for 3 main reasons:

1. In some energy models the level of the WACC does not reflect the current financial conditions e.g. the COMPETES-TNO model uses a WACC of 10% for all technologies, whereas current WACCs for investments in these technologies are typically much lower.
2. A uniform WACC is used which does not account for differences in country risks. Risks differ between countries due to variations in macro-economic circumstances, regulatory conditions, support schemes, etc.
3. A uniform WACC does not account for differences in risks between technologies. Technology risks include reliability, development/learning, as well as the familiarity of lenders with technologies. There is also a time dimension - as technologies mature, learning is possible and familiarity grows, thus (perceived) risks decline and as a result the WACC is lower.

It is worth noting that the TNO-ETS models, and notably the COMPETES-TNO model, are not an exception. Several organisations (IEA, OECD, Fraunhofer) simply apply one WACC level across all countries and technologies, and over time.

This study provides insights into the effects of varying the WACC across different technologies and (groups of) EU member states. Section 2 explains the different methods to estimating the WACC, and the decision to adopt a bottom-up method in this study. Section 3 shows the WACC calculations applying this method for different technologies. Section 4 discusses the results and their limitations, and section 5 discusses the effects of differentiating the WACC compared to applying a uniform WACC in the COMPETES-TNO model. Section 6 concludes.

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[1] Another TNO-ETS energy model is the OPERA model. Rather than the WACC, the OPERA model applies the national social discount rate of 2.25% (Rijksoverheid, 2020). The social discount rate is every 5 years reassessed by the Dutch central government.

2 Methodology

The cost of capital can be determined from different perspectives. For system cost analyses from a public or societal perspective, the cost of capital applied is typically the social discount rate which is the social cost of time preference and is technology indifferent. For system cost analyses focusing on modelling of decisions about technology choices as well as end-user cost analyses, a WACC is commonly applied. The latter reflects the actual financing costs for investments made by private actors and is the focus of this report.

The WACC of technologies typically cannot be directly and easily observed since project developers consider the WACC as confidential information, and thus the data is not available in the public domain. This means there is an problem of asymmetry of information.

Four main methods are available to overcome this information asymmetry between researchers/analysts and project developers, and thus obtain information about the WACC and its underlying gearing ratio (i.e. the debt share of total investment), cost of debt, and cost of equity parameters (Steffen, 2020);

1. Expert estimates
2. Elicitation of project finance data
3. Replication of auction results
4. Financial market data.

Expert estimates depend on the experts interviewed, either in person or by questionnaire, and their level of agreement. As such, these estimates often result in bandwidths, reflecting the different views of the experts and their inherent subjectivity. Hence, they are less appropriate for obtaining one WACC value for each technology. Expert estimates are invaluable though in estimating WACC values for innovative technologies for which other methods do not yield sufficient information.

Elicitation of project finance data is not simple. Term sheets are often confidential, while financial statements are often only available at the corporate and not individual project level, which are not held on corporate balance sheets and often set up as Special Purpose Vehicles (SPVs). An exception is that some projects issue prospectuses for obtaining crowdfunding, and in that context need to provide relevant financial information to potential financiers. However, currently only a small proportion of energy projects are financed by crowdfunding and a database with an overview of their financing parameters is currently lacking.

Replication of auction results is mainly used in the context of solar and wind energy. Given publicly available information on the winning bids about the remuneration per MWh generated and cost data, such as the capital expenditures, the cost of capital is the only missing piece of information. By constructing a levelized cost of electricity (LCOE) model, the cost of capital can be derived for a specific auction. This estimation method is not preferred for three reasons. First, for the purpose of this study the general country-specific situation is relevant rather than auction specific results. Second, the study covers the cost of capital irrespective of the subsidy mechanism available, while auctions are just one of the subsidy mechanisms for renewable energy. Third, as noted by Dobrotkova *et al.*

(2018) ‘winning bid prices cannot be explained by the LCOE calculations alone. Winning bids can be distinctly different from the sum of incurred costs and required margins as they reflect conditions, benefits, incentives, or strategies beyond the main LCOE parameters.’ In other words, the main limitation of the LCOE metric is that it does not include a representation of the value provided to the system. Hence, it ignores the implications of the variability and dispatchability of technologies for the system, and thus the consequences of simultaneous generation for both electricity prices and the need for generation curtailment (IEA, 2020).

Finally, financial market data can be used to calculate the cost of capital for stock exchange listed companies i.e. both the cost of debt and the cost of equity. The method is focused on finding comparable firms that are listed on stock exchanges. Both the cost of debt and cost of equity are calculated bottom-up. The cost of equity is calculated based upon the Capital Asset Pricing Model (CAPM), the most widely accepted and applied model in the financial sector to estimate the expected return of assets, in particular of shares. At the same time, as with any model, some of the assumptions taken are not in line with reality, e.g. transaction costs are assumed to be zero, all investors have the same rational expectations, and risk and return are linearly related.

Nevertheless, the financial market data method is considered to be the most appropriate for this project to yield unbiased estimates for different countries and technologies. Note that this method assumes balance sheet financing, while in practice often project finance is applied for investments in renewable generation technologies. Given that the resulting WACC values for balance sheet and project finance are often comparable, this does not have a major impact on the results (Lensink & Schoots, 2023).

For those technologies that are not yet fully commercialised (e.g. green hydrogen, hydrogen storage) or for which deployment is relatively limited (e.g. solar thermal, geothermal), insufficient listed companies that perform a majority of their activities using these technologies are available for adequate WACC calculations. For these technologies, other information from the public domain was used in this study, and usually expert estimates. The WACC has been calculated or estimated for a selection of technologies that is deemed important for energy modelling i.e. solar-pv, wind (onshore and offshore as one category),[2] nuclear, and hydrogen production. WACC calculations have not been performed for electricity, gas and hydrogen grids, since there was no opportunity to test these in the COMPETES-TNO model (see Section 5) and national regulators already calculate a WACC for regulated electricity and gas grids. For hydrogen storage, relevant information to estimate the WACC could not be found in due time.

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[2] There are insufficient listed companies available to allow for WACC calculations for wind offshore and wind onshore separately.

3 WACC calculations

The WACC combines the two main types of finance that are used for investments, debt and equity. The WACC formula is commonly presented as:

$$WACC_{post-tax} = \mathrm{g} \cdot CoD \cdot (1 - T) + (1 - \mathrm{g}) \cdot CoE$$

with g = gearing or the debt share of total assets, CoD = cost of debt before tax, T = tax rate, and CoE = cost of equity.

This is a nominal, post-tax WACC i.e. the WACC compensates for inflation and takes into account the advantage of a tax shield for the cost of debt. This means that both inflation and the tax shield are not included in the cash flows generated by the investment, otherwise there would be double counting.

In the following sections, the different components of the WACC are discussed in more detail and results are calculated with help of the S&P Capital IQ financial database for different energy technologies. All calculations are performed by 31 December 2022.

3.1 Cost of equity calculation

The cost of equity is calculated based upon the Capital Asset Pricing Model (CAPM). The idea behind the CAPM is that one can calculate the remuneration for the unavoidable or systemic market risk that is incurred by a company. The investor can eliminate risks that are not related to market risks, so-called idiosyncratic or firm specific risks, by maintaining an investment portfolio that is sufficient in size and well diversified. As a result, the cost of equity is equal to the cost of a risk-free investment plus a remuneration for the systematic, or market, risk of investment in shares. The CAPM is the most widely used model in the financial world to calculate the cost of equity (Van Horne, 1998; ACM, 2021).

The cost of equity can be expressed as formula:

$$CoE = r_f + \beta_e \cdot (r_m - r_f)$$

with r_f = risk free rate, β_e= equity bèta en $r_m - r_f$ = ERP = equity risk premium.

3.1.1 Risk free rate

The risk free rate is the rate of return that investors can earn from investing in a risk-free assets. Since any investment carriers risk, this is commonly approximated by the interest rate on 10-year government debt. This reflects the lower default risks on government bonds than company bonds in developed countries. For the calculations in this study, the average interest rate of the last quarter of 2022 on 10-year German government debt is used, which is 2.14% (S&P Capital IQ, 2023). Subsequently, the risk free rate is varied to obtain country-specific WACC estimates (see Section 3.3).

Given the current high volatility in interest rates, an average interest rate is calculated over the last quarter on a rolling basis. It would also be possible to calculate an average over half of a year on a rolling basis. However, given the steep increase of interest rates in 2022, it does not make sense to calculate an average interest rate over a longer time period such as the last year.

3.1.2 Equity risk premium

The equity risk premium (ERP) is defined as the difference between the expected market return and the risk free rate, which is the compensation that investors require to invest in more risky assets than government bonds. Following ACM (2021), the ERP is estimated to be 5.0%. This is mainly based upon the yearly study of Dimson, Marsh and Staunton of the historical ERP level during the period 1900-2019 (Dimson *et al.* 2020). Furthermore, ACM (2021) carried out an international WACC comparison in which 8 out of 14 European countries an ERP of 5% or lower is applied.

Alternatively, a total market return approach can be used to infer the ERP from the average difference between observed market returns and risk-free interest rates. According to ACM, this approach lacks both a robust economic-theoretical and empirical substantiation, with only a few examples of its application. Moreover, given the current high volatility of the stock market, this approach also leads to highly volatile ERP values in the S&P financial database.

Historical ERP values can be supplemented by a forecast of future ERP values, e.g. by including estimates for the risk premium levels from forward looking dividend growth models (DGM-models). ACM discusses this possibility, but did not include the results from this approach for two reasons. First, the results of the DGM-models are rather volatile from year-to-year, which is a disadvantage in a regulatory context that sets the WACC for a regulatory period of 3-5 years. Second, the results of this approach depend on the assessment of financial analysts which often suffer from excessive optimism or pessimism and sensitivity to market sentiments. For both reasons, the results of DGM models are not directly processed in the ERP estimations of ACM, but are taken into account when considering whether the historical ERP needs to be adjusted. Both reasons are also valid considerations in this study, which aims to provide more realistic but stable i.e. non-volatile WACC estimates for energy system models that include investments in both non-regulated energy generation and regulated energy networks.

3.1.3 Equity betas

3.1.3.1 Peer group selection

The beta is the sensitivity of an individual asset to price changes of the portfolio of financial assets such as traded in the stock market. A beta coefficient of 1 indicates that an asset price moves exactly in line with the market. A beta lower than 1 indicates that the asset volatility is lower than the market volatility, making the asset less risky. Once a beta is higher than 1 means, asset volatility is relatively high compared to market volatility, implying that the asset is riskier and providers of equity will require a higher return.

To estimate the beta, we need to find publicly traded firms (i.e. firms whose stock is traded on financial markets) with main activities in the selected technology. These firms are called ‘comparators’, ‘peers’ or ‘peer group’.

Three criteria are applied to determine the peer group for beta calculation (based upon ACM, 2021):

1. The risk profile of companies in the peer group should be representative for companies of the selected technology;
2. The bid-ask spread of the shares of companies in the peer group is 1% at maximum;
3. The peer group consist of a sufficient number of companies to allow for adequate beta estimation.

The compliance of companies with the first criterion is assessed with a number of indicators:

- A revenue indicator that shows the share of technology revenues (e.g. solar-pv) in total revenues. In principle, companies are only selected if the share is at least 50%.[3]
- The installed solar-pv capacity as a fraction of total installed capacity provides an indication of the installed capacities of the companies selected. Generally, this should result in the same selection of companies.
- The credit rating of the companies should be at least investment grade, this means a credit rating of BBB- or above in the rating terminology of credit agencies Standard & Poors (S&P) and Fitch. Stock prices of firms with lower credit ratings tend to be more reactive to company-specific news, as a result the measured beta will tend to underestimate the true beta. Consequently, companies with a lower credit rating are not representative for the industry-wide risk profile.

Concerning the second criterion, a bid-ask spread of the shares of a company exceeding 1% indicates insufficient stock trading (liquidity) in their stocks, and thus share prices that possibly do not accurately reflect the latest information, resulting in downward-biased beta estimates (Frontier Economics, 2020).

With regards to the third criterion, the number of companies in the peer group, there is a trade-off between on the one hand including more companies to limit the influence of outliers and therefore the statistical error of beta estimation, and on the other hand to add companies that are less comparable. According to Brattle (2021) and ACM (2021), when the peer group consists of six or seven companies, the size of the statistical error will be reduced only to a limited extent with an additional company.

In the following sub-sections, the peer group selection for solar-pv, wind, nuclear, and hydrogen production according to these criteria is elaborated.

Solar-pv

According to the financial database S&P Capital IQ Pro, for solar-pv there are 8 firms listed on stock exchanges with a share of solar-pv revenues in total revenues of about 50% or more. The installed solar-pv capacity as fraction of total installed capacity is sometimes slightly lower (e.g. for Neoen S.A.) since it disregards activities in other sectors than power generation. The scores for potential peers on the indicators are shown in table 3.1.

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[3] This is assessed with the Trucost revenues as reported by S&P.

Table 3.1: Overview of potential peers for solar-pv

Company name including exchange ticker	Country	Technology generation revenues ($M)	Technology/ total revenues (%)	Installed tech capacity (MW)[a]	Installed tech capacity/ total installed capacity (%)	Bid-ask spread (1 year average)	Credit rating (S&P)
Edisun Power Europe AG (SWX:ESUN)	Switzerland	12.51	100%	72.0	100%	1.37%	?
Etrion Corporation (OTCPK:ETRX.F)	Switzerland	21.88	100%	45.2	100%	121.67%	?
Solaria Energía y Medio Ambiente, S.A. (BME:SLR)	Spain	73.52	100%	121.6	100%	0.09%	?
7C Solarparken AG (XTRA:HRPK)	Germany	56.31	98%	47.0	100%	0.80%	?
Encavis AG (XTRA:ECV)	Germany	226.19	68%	1496.3	64%	0.37%	?
Atlantica Sustainable Infrastructure plc (NASDAQGS:AY)	United Kingdom	698.44	66%	973.0	59%	0.09%	BB+
Scatec ASA (OB:SCATC)	Norway	172.35	59%	1095.2	59%	0.14%	?
Neoen S.A. (ENXTPA:NEOEN)	France	163.67	48%	1643.9	59%	0.24%	?

[a] Generation capacity operating and under construction

? No S&P credit rating, but company may dispose of credit rating of another rating agency.

Table 3.2: Overview of potential peers for wind

Company name including exchange ticker	Country	Technology generation revenues ($M)	Technology/ total revenues (%)	Installed tech capacity (MW) [a]	Installed tech capacity/ total installed capacity (%)	Bid-ask spread (1 year average)	Credit rating (S&P)
Alerion Clean Power S.p.A. (BIT:ARN)	Italy	148.41	100%	66.6	96%	0.51%	?
EDP Renováveis, S.A. (ENXTLS:EDPR)	Spain	1476.46	93%	3,279.2	93%	0.14%	?
Boralex Inc. (TSX:BLX)	Canada	379.14	81%	3,039.9	86%	0.75%	?
NextEra Energy Partners, LP (NYSE:NEP)	USA	522.46	65%	6,559.4	73%	0.05%	BB
Northland Power Inc. (TSX:NPI)	Canada	915.49	65%	2,577.5	56%	0.63%	BBB
Arise AB (publ) (OM:ARISE)	Sweden	17.06	62%	136.1	100%	0.58%	?
Terna Energy Societe Anonyme Commercial Technical Company (ATSE:TENERGY)	Greece	216.59	53%	1,090.5	99%	0.17%	?
Innergex Renewable Energy Inc. (TSX:INE)	Canada	235.97	47%	3,549.3	56%	0.88%	NR
Voltalia SA (ENXTPA:VLTSA)	France	211.77	46%	426.1	54%	0.61%	?

[a] Generation capacity operating and under construction

? No S&P credit rating, but company may dispose of credit rating of another rating agency.

NR No rating.

Table 3.3: Overview of potential peers for nuclear

Company name including exchange ticker	Country	Technology generation revenues ($M)	Technology/total revenues (%)	Installed tech capacity (MW) [a]	Installed tech capacity/ total installed capacity (%)	Bid-ask spread (1 year average)	Credit rating (S&P)
Electricité de France S.A. (ENXTPA:EDF)	France	48,471.47	62%	66,660.0	66%	0.05%	BBB
Constellation Energy Corporation (NASDAQGS:CEG)	USA	11,593.96	70%	21,644.4	62%	0.05%	?
Entergy Corporation (NYSE:ETR)	USA	4,449.43	44%	5,376.7	18%	0.03%	BBB+
Endesa, S.A. (BME:ELE)	Spain	6,265.77	33%	1,005.3	16%	0.06%	BBB+
Duke Energy Corporation (NYSE:DUK)	USA	6,825.00	29%	9,293.8	15%	0.01%	BBB+
Dominion Energy, Inc. (NYSE:D)	USA	4,056.03	29%	6,194.9	20%	0.02%	BBB+
Pinnacle West Capital Corporation (NYSE:PNW)	USA	978.17	27%	1,225.0	17%	0.02%	BBB+

[a] Generation capacity operating and under construction

? No S&P credit rating, but company may dispose of credit rating of another rating agency.

Table 3.4: Overview of potential peers for hydrogen production

Company name including exchange ticker	Country	Technology generation revenues ($M)	Technology/ total revenues (%)	Bid-ask spread (1 year average)	Credit rating (S&P)
Foosung Co., Ltd. (KOSE:A093370)	South Korea	281.63	100.00	0.28%	?
Linde plc (NYSE:LIN)	United Kingdom	23,895.67	100.00	0.03%	A
Nel ASA (OB:NEL)	Norway	74.09	100.00	0.28%	?
WONIK Materials Co.,Ltd. (KOSDAQ:A104830)	South Korea	229.54	100.00	0.27%	?
Air Products and Chemicals, Inc. (NYSE:APD)	USA	8,210.26	95.05	0.03%	A
L'Air Liquide S.A. (ENXTPA:AI)	France	22,106.95	94.70	0.09%	A
Kanto Denka Kogyo Co., Ltd. (TSE:4047)	Japan	326.46	77.68	0.27%	?
Koatsu Gas Kogyo Co., Ltd. (TSE:4097)	Japan	463.02	74.39	0.40%	?
Nippon Sanso Holdings Corporation (TSE:4091)	Japan	4,848.78	73.22	0.27%	NR
Toho Acetylene Co., Ltd. (TSE:4093)	Japan	140.42	58.17	0.38%	?
SOL S.p.A. (BIT:SOL)	Italy	438.06	47.32	0.95%	?
Air Water Inc. (TSE:4088)	Japan	3,010.83	46.12	0.27%	NR

? No S&P credit rating, but company may dispose of credit rating of another rating agency.
NR No Rating.

Concerning solar-pv, the credit rating of one potential peer (Atlantica Sustainable Infrastructure plc) is below investment grade and hence is not representative for the risks that the industry as a whole is facing. Hence, this company is removed from the peer group.

For having a sufficient number of companies in the peer group it was checked whether there exist north American firms from developed countries (i.e. US and Canada) with a comparable risk profile. This is not the case as the north American company with the largest share of revenues from solar-pv obtains only 24% of its total revenues from solar-pv. Hence, the peer group does not contain north American firms.

Furthermore, one initially selected company (Etrion Corporation) shows a bid-ask spread which is much larger than 1%. Therefore there is insufficient trading in the stocks of this company, implying that it is not suited for beta calculation. Hence, the company is removed from the peer group. Also the bid-ask spread of Edisun Power Europe AG is larger than 1%, but not significantly. Since excluding this company would imply that the minimum number of peer companies is not reached (cf. third criterion outlined above), the company is not exempted. This is in line with Frontier Economics (2020) which points to the “grey area” above the 1% bid-ask spread as well as to the need to balance the risk of including an illiquid peer in the sample versus the benefits of including the peer, for instance when increasing the sample size is considered valuable.

Wind

Based upon the financial database S&P Capital IQ Pro, for wind there are 9 firms listed on stock exchanges with a share of wind revenues in total revenues of about 50% or more. All initially selected firms are shown in table 3.2.

The table also confirms that for all selected firms more than half of total installed generation capacity concerns wind capacity generation. Some companies such as Arise AB seem to be involved to a limited extent in wind generation since it owns only 136 MW of installed wind power capacity, but at the same time according to earnings information of July 2022 they operate a portfolio of 2,600 MW. Unfortunately, the installed generation capacity that is not owned but only operated is not available in the S&P database.

Concerning the bid-ask spread criterion, no peer shows a bid-ask spread larger than 1%, hence trading of the shares of all companies is sufficiently liquid, and all potential peers are suited for beta calculation.

For having enough peer companies for adequate beta estimation, four North American firms with comparable risk profile were included. One initially selected US company (NextEra Energy Partners) shows a S&P credit rating that is below investment grade credit rating. Since there are sufficient other peer companies available, this company is removed from the peer list.

Nuclear

Based upon financial database S&P Capital IQ Pro, for nuclear there are only 2 firms listed on stock exchanges with a share of nuclear revenues in total revenues of about 50% or more. For having at least 6-7 peer companies, the list is complemented with listed firms that have substantial revenues from nuclear generation. See table 3.3.

All selected firms are traded frequently enough since they show a bid-ask spread that is well below 1%. In case they dispose of a S&P credit rating, the rating is investment grade.

Hydrogen production

Since hydrogen production is not classified as an industry, it is checked in which sector companies involved in grey hydrogen production such as Linde, Air Liquide and Air Products are included. In the S&P financial database these companies are part of the industrial gas manufacturing industry. Peer companies are identified from this industry. Since the number of firms in Europe and North America is too limited, also companies in developed countries in Asia-Pacific (i.e. Japan and South-Korea) are included in the peer group. Developing countries in Asia-Pacific (i.e. China, India, and Indonesia) are excluded from the table since they show a different risk profile. See table 3.4.[4]

3.1.3.2 Asset beta calculation

For each of the selected peer companies, first the equity beta is calculated by regressing the monthly returns of an individual stock on market returns of the last 5 years in a dedicated S&P WACC template. For companies that are based in Europe, the market returns of the STOXX 600 market index are used. According to Brattle (2021) this is 'the most commonly followed stock market indices for the Eurozone'. It is a broad equity index considered to be representative of the Eurozone stock markets, although it also includes stocks from countries outside of the Eurozone, namely Denmark, Norway, Sweden, and the UK. The idea behind taking a European rather than national market indices is that an investor would likely diversify its portfolio within a single currency zone in order to prevent exchange rate risk.[5] Instead, for US firms the S&P 500 market index is applied. Hydrogen production is an exception in this respect. Since the peer group for hydrogen production also contains companies from developed Asia, for this technology the MSCI world index is applied for all peers.

As a next step, for obtaining betas at an equal footing betas the unlevered asset beta needs to be calculated. To that aim, the levered equity betas are corrected for different debt/equity ratios and tax rates between companies with the Hamada formula (sometimes called Modigliani & Miller formula):

$$\beta_a = \beta_e / \left[1 + (1 - tax\ rate)\frac{D}{E}\right]$$

with β_a= *asset bèta*, β_e= *equity bèta*, D/E = debt/equity ratio, and tax rate = effective corporate tax rate of peer companies.

Asset betas by technology

For solar-pv, wind, nuclear, and hydrogen production the unlevered betas of the ultimately selected peer companies are shown in table 3.5, table 3.6, table 3.7, and table 3.8 respectively. Also the resulting average asset betas are shown.

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[4] Revenue figures are from 2020, since figures for 2021 are missing for Linde plc, WONIK Materials Co. Ltd, Toho Acetylene Co. and SOL S.p.A.

[5] Additional autocorrelation and heteroskedasticity tests to assess if the beta estimates satisfy the standard conditions underlying Ordinary Least Squares (OLS) regression have not been performed.

Table 3.5: Asset betas of peers for solar-pv

Company name including exchange ticker	Country	Unlevered beta
Edisun Power Europe AG (SWX:ESUN)	Switzerland	0.102
Solaria Energía y Medio Ambiente, S.A. (BME:SLR)	Spain	1.359
7C Solarparken AG (XTRA:HRPK)	Germany	0.368
Encavis AG (XTRA:ECV)	Germany	0.671
Scatec ASA (OB:SCATC)	Norway	0.683
Neoen S.A. (ENXTPA:NEOEN)	France	0.626
Average		*0.635*

Table 3.6: Asset betas of peers for wind

Company name including exchange ticker	Country	Unlevered beta
Alerion Clean Power S.p.A. (BIT:ARN)	Italy	0.812
EDP Renováveis, S.A. (ENXTLS:EDPR)	Spain	0.558
Boralex Inc. (TSX:BLX)	Canada	0.238
Northland Power Inc. (TSX:NPI)	Canada	0.337
Arise AB (publ) (OM:ARISE)	Sweden	1.264
Terna Energy Societe Anonyme Commercial Technical Company (ATSE:TENERGY)	Greece	0.511
Innergex Renewable Energy Inc. (TSX:INE)	Canada	0.413
Voltalia SA (ENXTPA:VLTSA)	France	0.799
Average		*0.616*

Table 3.7: Asset betas of peers for nuclear

Company name including exchange ticker	Country	Unlevered beta
Electricité de France S.A. (ENXTPA:EDF)	France	0.271
Constellation Energy Corporation (NASDAQGS:CEG)	USA	1.143
Entergy Corporation (NYSE:ETR)	USA	0.144
Endesa, S.A. (BME:ELE)	Spain	0.478
Duke Energy Corporation (NYSE:DUK)	USA	0.152
Dominion Energy, Inc. (NYSE:D)	USA	0.201
Pinnacle West Capital Corporation (NYSE:PNW)	USA	0.148
Average		*0.362*

Table 3.8: Asset betas of peers for hydrogen production

Company name including exchange ticker	Country	Unlevered beta
Linde plc (NYSE:LIN)	United Kingdom	0.697
Foosung Co., Ltd. (KOSE:A093370)	South Korea	0.994
Nel ASA (OB:NEL)	Norway	1.518
WONIK Materials Co.,Ltd. (KOSDAQ:A104830)	South Korea	0.861
Air Products and Chemicals, Inc. (NYSE:APD)	USA	0.855
L'Air Liquide S.A. (ENXTPA:AI)	France	0.664
Kanto Denka Kogyo Co., Ltd. (TSE:4047)	Japan	0.499
Koatsu Gas Kogyo Co., Ltd. (TSE:4097)	Japan	0.478
Nippon Sanso Holdings Corporation (TSE:4091)	Japan	0.177
Toho Acetylene Co., Ltd. (TSE:4093)	Japan	0.295
SOL S.p.A. (BIT:SOL)	Italy	0.325
Air Water Inc. (TSE:4088)	Japan	0.225
Average		*0.704*

3.1.3.3 Equity beta and resulting cost of equity

In order to obtain the equity beta of the peer group, the asset beta is relevered with the average debt/equity ratio and average tax rate of the peers. To this aim, the earlier shown Hamada formula is applied. As an example, given an asset beta of 0.635, a debt/equity ratio of 105% and an average tax rate of 25% this results for solar-pv in an equity beta of 1.14.

Given the cost of equity formula shown above, the cost of equity for solar-pv is equal to the risk free rate of 2.1% plus the product of the equity risk premium of 5.0% and the equity beta of 1.14. This results in a cost of equity for solar-pv of 7.8% for Germany. The cost of equity is varied among countries by using the country-specific risk free rate for other countries than Germany. For other technologies the same approach is applied.

3.2 Cost of debt calculation

The cost of debt is the sum of the risk free rate and the debt risk premium. The risk free rate has been discussed in Section 3.1.1. The debt risk premium is estimated by credit default swap rates of the peer companies, if available. A credit default swap (CDS) is a privately negotiated credit derivative contract designed to transfer credit exposure of fixed income products between two counterparties. The Protection Buyer (the one seeking to shed the risk), pays a fee or premium to the Protection Seller (the one taking on the risk) for protection against a loss that may be incurred on exposure to a loan or bond as a result of a credit event. A credit event is an unforeseen development indicating that the borrower (the reference entity) on which the CDS contract is written is unable to pay its debts. If such an event occurs, the Protection Seller will make a payment to the Protection Buyer of the contract. The CDS thus represents a market driven view of the creditworthiness of companies issuing bonds. The mid-price for a company's CDS can be taken to approximate the credit risk rate or risk premium (S&P Global, 2022).

For the selected solar-pv, wind, and hydrogen production firms, S&P does not provide (enough) CDS pricing information. Therefore, the cost of debt is based upon the corporate yield curve for energy sector debt in euros with a tenor of 10 years and an investment grade credit rating. This results in a cost of debt of 3.0%.

For nuclear, the mid-price for the 5-year CDS amounts to 87, representing 87 basis points above the German 10-year government bond rate of 2.14%. This also results in a cost of debt of 3.0%.

Since interest paid is tax deductible, it is common to calculate the after-tax cost of debt. The average effective tax rate differs per peer group of technologies. As an example, for solar-pv the average effective tax rate of the peer group amounts to 25% over the last 5 years.[6] The after-tax cost of debt is then equal to 2.3% (3.0% times (1-0.25)). Since the average effective corporate tax rate differs significantly across technologies (e.g. for nuclear 19%), which reflects the country practices of the peer companies rather than the actual tax conditions for firms investing in new power plants, instead the company-independent corporate tax rate by country could be used. This is likely to provide more uniform tax rates across technologies.

3.3 WACC results by technology and country

The formula to calculate the post-tax nominal WACC is shown at the beginning of Section 3.

The debt share of total assets, also called the gearing, can be calculated from the debt/equity ratio. The gearing is equal to (D/E)/((D/E)+1). For example, for solar-pv the gearing is 1.05/2.05 = 51% (rounded).

Table 3.9 shows the resulting WACC figures per technology, assuming the risk free rate of Germany.

Table 3.9: WACCs per technology for Germany

	Solar-pv	Wind	Nuclear	Grey hydrogen production
Risk free rate	2.1%	2.1%	2.1%	2.1%
Debt risk premium [a]	0.9%	0.9%	0.9%	0.9%
Return on debt before tax	3.0%	3.0%	3.0%	3.0%
Average effective corporate tax rate	25%	29%	19%	27%
Return on debt after tax	**2.3%**	**2.1%**	**2.4%**	**2.2%**
Risk free rate	2.1%	2.1%	2.1%	2.1%
Asset beta	0.635	0.616	0.362	0.704
Equity beta	1.14	0.91	0.61	0.89

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[6] Outliers have been removed from this tax rate.

	Solar-pv	Wind	Nuclear	Grey hydrogen production
Equity risk premium	5.0%	5.0%	5.0%	5.0%
Return on equity	**7.8%**	**6.7%**	**5.2%**	**6.6%**
Debt/equity ratio	105%	66%	85%	35%
% debt (gearing)	51%	40%	46%	26%
% equity	49%	60%	54%	74%
Nominal WACC after tax	**5.0%**	**4.9%**	**3.9%**	**5.4%**
Inflation rate	2.0%	2.0%	2.0%	2.0%
Real WACC after tax	**2.9%**	**2.8%**	**1.9%**	**3.4%**

[a] For solar-pv and wind generation, the implicit debt risk premium is shown. This premium is inferred from the difference between the return on debt before tax and the risk free rate.

As an example, the WACC for solar-pv for a German-based company is calculated as (51%*2.3)+(49%*7.8) = 5.0%.

Similarly, WACCs for other countries can be calculated, taking into account their different risk free rate of return levels for both cost of debt and cost of equity. The debt risk premium of Germany i.e. the difference between the cost of debt and the German risk-free rate of return, is assumed to hold for other countries as well. The country-differentiated WACCs by technology are shown in Table 3.10. Unsurprisingly, the lowest technology-dependent WACCs hold for Switzerland, while the highest WACCs are calculated for the Eastern European countries Hungary, Poland, Bulgaria, and Czech Republic.

Table 3.10: WACC (rounded)* differentiated to technology and country

	AT	BE	BG[a]	CH	CZ	DE	DK	ES	FI	FR	GR	HU[b]	IE	IT	NL	NO	PL[a]	PT	SE	UK
Solar-pv	5.5%	5.5%	7.5%	4.0%	7.5%	5.0%	5.0%	6.0%	5.5%	5.5%	7.0%	11.0%	5.5%	7.0%	5.0%	6.0%	9.5%	6.0%	5.0%	6.0%
Wind	5.5%	5.5%	7.5%	4.0%	7.5%	5.0%	5.0%	6.0%	5.5%	5.5%	7.0%	11.0%	5.5%	6.5%	5.0%	6.0%	9.5%	5.5%	5.0%	6.0%
Nuclear	4.5%	4.5%	6.5%	3.0%	7.0%	4.0%	4.0%	5.0%	4.5%	4.5%	6.0%	10.0%	4.5%	6.0%	4.0%	5.0%	8.5%	5.0%	4.0%	5.0%
Grey hydrogen production	6.0%	6.0%	8.0%	4.5%	8.5%	5.5%	5.5%	6.5%	6.0%	6.0%	7.5%	11.5%	6.0%	7.5%	5.5%	6.5%	10.0%	6.5%	5.5%	6.5%
Green hydrogen production[c]	8.0%	8.0%	10.0%	6.5%	10.0%	7.5%	7.5%	8.5%	8.0%	8.0%	9.5%	13.5%	8.0%	9.5%	7.5%	8.5%	12.0%	8.0%	7.0%	8.5%

* For preventing mock accuracy due to WACC sensitivity for amongst others interest rate volatility, WACC is rounded to closest 0.5%.

[a] Based upon risk free rate of 7-year government bonds, since interest rates of 10-year government bonds are not available in the S&P database.

[b] Based upon risk free rate of 15-year government bonds, since interest rates of 10-year government bonds are not available in the S&P database.

[c] This is explained in Section 4.

4 Discussion of the WACC results

This section discusses the WACC results, and shows that the WACC results based on listed companies are not the best indicators for costs of capital for nuclear generation and green hydrogen production. Differences between investments in mainstream and innovative technologies are highlighted. Furthermore, the impact of subsidies on the WACC is elaborated upon.

Nuclear technology

It is striking that results show that the WACC for nuclear power generation is lower than the WACCs for wind and solar-pv generation. At first sight, this appears to be counterintuitive since nuclear generation is commonly understood as a more risky generation technology than wind and solar-pv given its high upfront investment costs (including for required safety measures), long development and construction times, and the cost involved with nuclear waste treatment. It is likely that this result reflects the government backing of the selected peer companies for existing assets through grants or other forms of governmental support, reducing their risks and therefore the WACC. For instance, a company such as EDF disposes of a large portfolio of existing nuclear power plants for which construction risks and nuclear waste treatment are secured with existing agreements with governments, reducing the company's risk profile. Moreover, in July 2022 the French government announced to increase their stake in EDF from 84% to 100% (Baringa, 2022). Hence, EDF is now fully owned by the French state, limiting default risks and making its company risk profile more comparable to public entities.

The calculated WACC also mainly reflects the financing of existing investments and thus is not necessarily representative for the WACC of new investments in third plus generation nuclear power plants. These are Pressurised Water Reactors (PWR) or Boiling Water Reactors (BWR) that dispose of passive safety systems, and are designed to operated more flexible than the second generation while meeting additional safety requirements following the Fukushima accident (Witteveen + Bos, 2022). Notably a first-of-a-kind (FOAK) design of a third plus generation nuclear power plant is characterised by higher technology and construction risks cumulating in cost overruns and lengthy construction periods. Such plants require a higher cost of capital than existing nuclear power plants. Government support is deemed indispensable to achieve realisation of all types of new nuclear power plants (either FOAK or n-th-of-a-kind (NOAK)), since experience from case studies shows that these plants are unlikely to be realised without government support (Witteveen + Bos, 2022). A classic private developer or merchant operation model does not work due to the size and complexity of nuclear power plants (Baringa, 2022).

Without government support, the high risks will translate into significantly higher required costs of equity and cost of debt, and therefore a significantly higher WACC, as reported in table 3.9.

Green hydrogen production

The bottom-up calculated WACC is about 5.5-6.5% in most Western European countries. This result reflects the cost of capital of companies that produce chemical gasses including hydrogen. This hydrogen is mainly produced from fossil fuels using either Steam-Methane Reforming (SMR) or methane splitting i.e. 'grey' hydrogen, while our main interest is in 'green' hydrogen production through electrolysis based upon Alkaline or PEM technologies.

To gain insight into the extent to which the WACCs differ for grey hydrogen and green (and blue) hydrogen, a short literature review was performed. IEA (2019) mentions a WACC of 8% for both green and blue (natural gas and coal with CCUS) hydrogen production. Deloitte *et al.* (2021) assume the same average WACC for EU-27 for a range of green, blue and grey hydrogen technologies. They differentiate the WACC by country with the Ease of Doing Business scores from the World Bank. Country-specific WACCs are determined by the relative ratio of the indicator scores of each country against the EU average. IRENA (2020) indicates WACCs for green hydrogen ranging from 10% for the current situation to 6% for the future situation.[7] Quintel (n.d.) mentions a real WACC of 7% for mature technologies such as electrolysis, which given a long-term inflation rate of 2% can be translated to a nominal WACC of 9%. The publication of Lazard (2021) is the only study found that provides a bottom-up estimate of the WACC.

Based upon a levelized cost of hydrogen analysis of the current unsubsidized cost to produce green hydrogen through electrolysis, in the Lazard study the nominal WACC after tax amounts to 9.7%. To arrive at this percentage they assume a cost of debt of 8%, a cost of equity of 12%, and debt and equity shares in total investment of 40% and 60% respectively. Notably the cost of debt percentage is high compared to other studies that assume that some type of government support is in place. If this is the case, green hydrogen is less risky and cost of debt will be significantly lower. For instance, for the Dutch SDE subsidy scheme for CO_2 emission reduction technologies, including green hydrogen, it is assumed that the debt risk premium for green hydrogen is only about 1.5% higher than for low risk technologies such as wind and solar-pv generation. Besides, it is assumed that with subsidies a debt share of 70% in total investment is possible (Lensink and Schoots, 2023), to be prudent a debt share of 60% is assumed here. Given the same risk free interest rate and debt risk premium for wind and solar-pv as assumed in table 3.9, this would result in a cost of debt of 4.5% and a nominal WACC after tax of 6.9%. Hence, green hydrogen adds 1.5 to 4.3 percentage points to the estimated bottom-up WACC for existing SMR hydrogen production of 5.4% in table 3.9.

As with nuclear generation, the WACC for green (and blue) hydrogen heavily depends upon the extent of government support. At the same time, given its technology development cycle and its importance for decarbonisation, it is likely that green hydrogen is stimulated in all developed EU countries and it can be assumed that risk-mitigating effects of government support hold for the green hydrogen WACC of all EU-27+ countries. As such, the WACC for green hydrogen is to the lower end of the mentioned range i.e. 4.9% plus 1.9%, resulting in almost 7% in total.

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[7] None of these studies specifies whether it concerns a vanilla WACC without tax treatment, a pre-tax WACC, or a post-tax WACC.

Wind and solar-pv generation

The WACC for wind generation is slightly lower than for solar-pv generation, although the difference is not visible for most countries. In practice the resource risks for wind generation are usually estimated to be higher than for solar-pv generation, because the latter does not have rotating equipment with accompanying higher wear-and-tear. Although Steffen (2020) suggests that the WACCs for both technologies are often the same, as typically the same proxies are used for solar and wind projects, this does not hold for our study since we use different peer companies for solar and wind projects. Calculated WACC results are sensitive though to the peer group selection, hence further analysis can be useful to establish more robust peer groups by technology. For instance, additional autocorrelation and heteroskedasticity tests can be performed to assess if the beta estimates satisfy the standard conditions underlying Ordinary Least Squares (OLS) regression. This may indicate additional outliers, and removing these may reduce the variation of asset betas calculated and thus improve the robustness of beta calculations. At the same time, this may result in peer groups becoming too small.

Other technologies such as solar thermal and geothermal energy are not analysed

For less mature, more innovative technologies such as solar thermal and geothermal energy, the number of firms is too small to establish statistically representative peer groups and thus to apply the bottom-up WACC approach. Interaction with sector experts could reveal which companies are mainly active in the implementation of these technologies, their accompanying risk profiles, and thus help to establish a representative peer group.

5 Effects of WACC differentiation in COMPETES-TNO

The effects of technology and country-differentiated WACCs for electricity generation as mentioned in Table 3.10 are tested in the COMPETES-TNO EU-27+ electricity market model up to 2050. A short model description can be found in Appendix A. To this aim, the project alternative with technology and country-differentiated WACCs is compared against a base case with a WACC of 10% across all technologies and EU Member States. Based upon a comparison of the model results for both cases, relative or incremental differences are calculated for several key variables including generation capacities, production levels, generation investments, and electricity prices.

A higher or lower WACC for one or more technologies implies a decrease or increase of the future net benefits of investments in generation technologies. Hence, investors will favour some technologies more than others. Higher or lower installed generation capacities also mean higher or lower technology-specific production levels i.e. the generation mix changes. This means that during some time periods demand is met by a different supply mix, and as a result average hourly electricity market prices will change. These variables are discussed in more detail in the sections below.

5.1 Generation investments

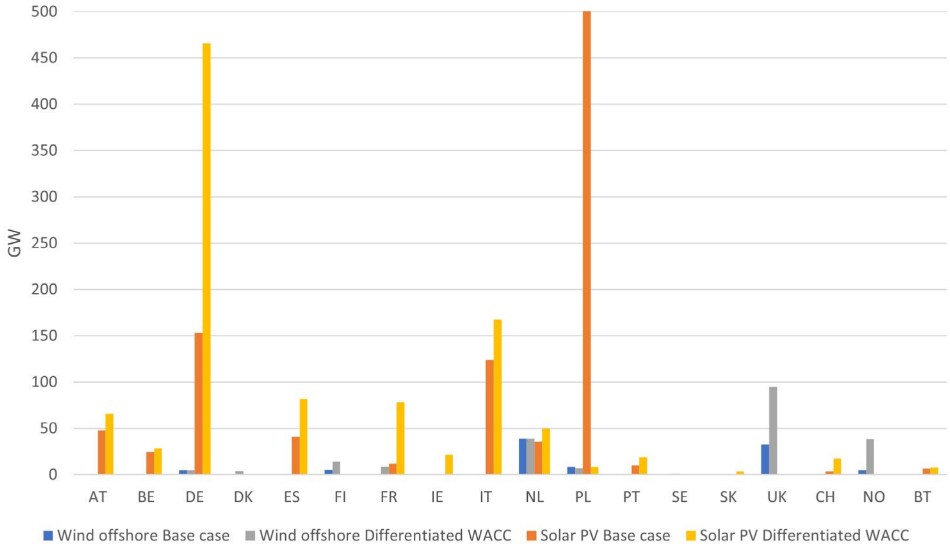

Figure 5.1: Wind offshore and solar-PV investments in 2050[a n]

[a] Solar PV investments in Poland in the base case of 884 GW are an outlier and capped to increase visibility of generation investments in other countries.

[b] All country codes are ISO 3166-1 alpha 2 codes, except for BT and BK which stand for the Baltic and Balkan region respectively. See in Appendix A for the country composition of these regions.

Figure 5.1 shows that the lower WACCs for wind and solar-pv generation result in higher investments in offshore wind (+117 GW, mainly in the United Kingdom, Norway, Finland, France, and Denmark), but unexpectedly also in lower investments in solar-PV (-328 GW in total, of which 876 GW less in Poland). In Germany, solar-pv generation capacity triples from 153 GW in the base case to 466 GW in the differentiated WACC case.

Installed wind onshore capacity is increasing only in Switzerland, which is the only country with some wind onshore potential not yet deployed in the base case (+3.6 GW).

A remarkable result is that the decrease of the WACC for nuclear generation did not result in higher installed nuclear generation capacity. On the contrary, nuclear investments in Germany (which were allowed in the COMPETES-TNO model for illustrative purposes despite the nuclear phase-out), are 33 GW lower in the differentiated WACC case compared to base case. This might relate to shifts in the generation merit order, since the WACC decreases not only for nuclear but also for wind and solar-pv in the differentiated WACC case. Additional model analyses are required to prove or disprove this conjecture.

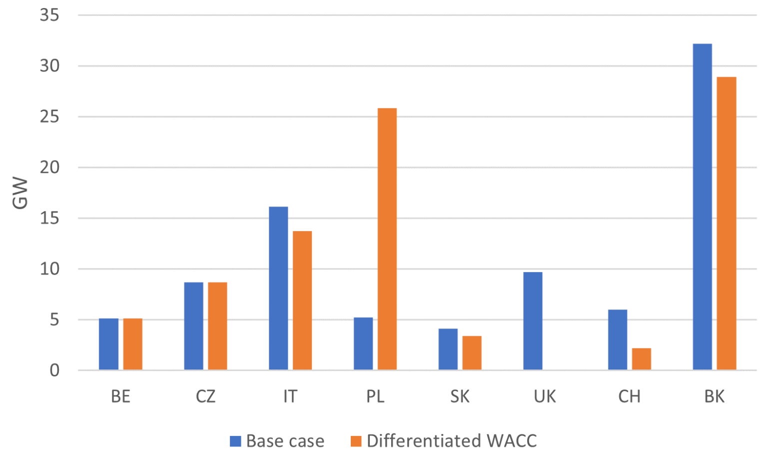

Figure 5.2 : Biomass CCS investments in 2050*

* BK stands for Balkan countries

Although the WACC for biomass CCS is the same in both the project alternative with technology and country differentiated WACCs and the base case i.e. 10%, biomass CCS investments (figure 5.2) change considerably. This result can be explained by the changes in installed capacity of solar-pv. For example in Poland solar-pv decreases significantly, resulting in an higher need for alternative energy sources such as biomass CCS. Because of its negative CO_2 emissions, and the CO_2 price in place, biomass CCS seems to be the preferred technology to replace solar-pv. As a consequence, in Poland biomass CCS capacity increases by 20.6 GW. At the same time, capacity decreases are visible in the UK (-9.7 GW), Switzerland (-3.8 GW), Balkan (-3.3 GW), Italy (-2.4 GW), and Slovakia (-0.8 GW). Total decreases in generation capacity amount to 19.9 GW, resulting in a net European wide increase of biomass CCS generation capacity of 0.7 GW.

Differences for other conventional generation technologies such as coal-fired plants with CCS, and gas CCGTs (with and without CCS) are negligible.

5.2 Generation mix

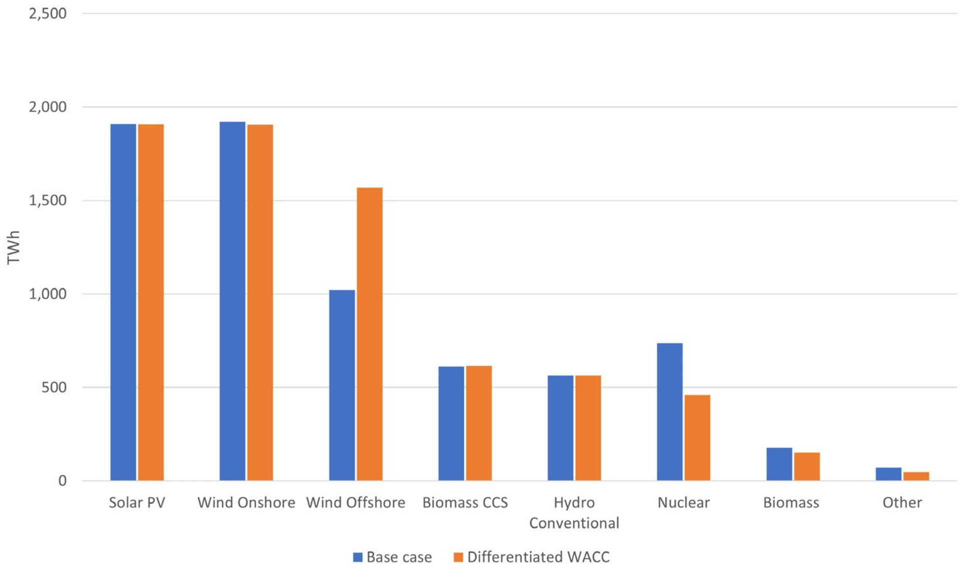

Figure 5.3 EU-27+ generation mix in 2050

figure 5.3 shows that electricity production from wind offshore increases significantly with differentiated WACCs (i.e. a lower WACC for wind offshore), and electricity production from nuclear, and to a lesser extent biomass and other technologies (all remaining technologies), falls with higher WACC levels.

Net electricity production increases significantly with about 450 TWh from 6,534 TWh (7,011 TWh minus 477 TWh curtailment of wind and solar-pv) for EU-27+ in 2050 in the base case to 6,986 TWh (7,220 TWh minus 234 TWh wind and solar-pv curtailment) in the differentiated WACC case. This increase is probably due to lower electricity prices which stimulates increases in flexible electricity demand. Lower electricity prices result from lower marginal costs of production due to lower WACCs for wind and solar-pv technologies. In COMPETES-TNO flexible electricity demand consists of power-to-hydrogen ($P2H_2$), electricity storages, power-to-heat, heat pumps, and electric vehicles. Although static electricity demand and H_2 demand are fixed, industrial heat demand changes since the model endogenously determines to which extent this demand is met by electricity.

The overall growth of net electricity production is hiding some of the differences across countries due to differentiated WACC values. The largest changes occur in Poland, the United Kingdom, and Norway. In Poland, total electricity production decreases by 408 TWh, which results from a decrease of solar-pv by 574 TWh (of which 368 TWh originally was solar-pv curtailment), and an increase of biomass CCS by 144 TWh. In the United Kingdom, overall electricity generation increases by 198 TWh, with an increase of 287 TWh of offshore wind and a decrease of 68 TWh of biomass CCS. In Norway, electricity production increases by 178 TWh, which is entirely explained by an increase of offshore wind generation.

5.3 Electricity prices

Given the prevailing energy-only market model, electricity prices reflect short-term marginal costs. Hence, changes in fixed capital costs due to WACC differentiation are not directly reflected in electricity prices. However, because of the change in the generation mix towards offshore wind with lower marginal costs, and the model assumption of perfect competition which means that prices are equal to marginal costs, electricity prices decrease (see figure 5.4). Given interconnections, cheap offshore wind power is also (more) regularly exported to countries either without the potential for offshore wind generation (e.g. Austria, Czech republic, Slovakia, and Switzerland) or that do not show an increase in installed offshore wind capacity.

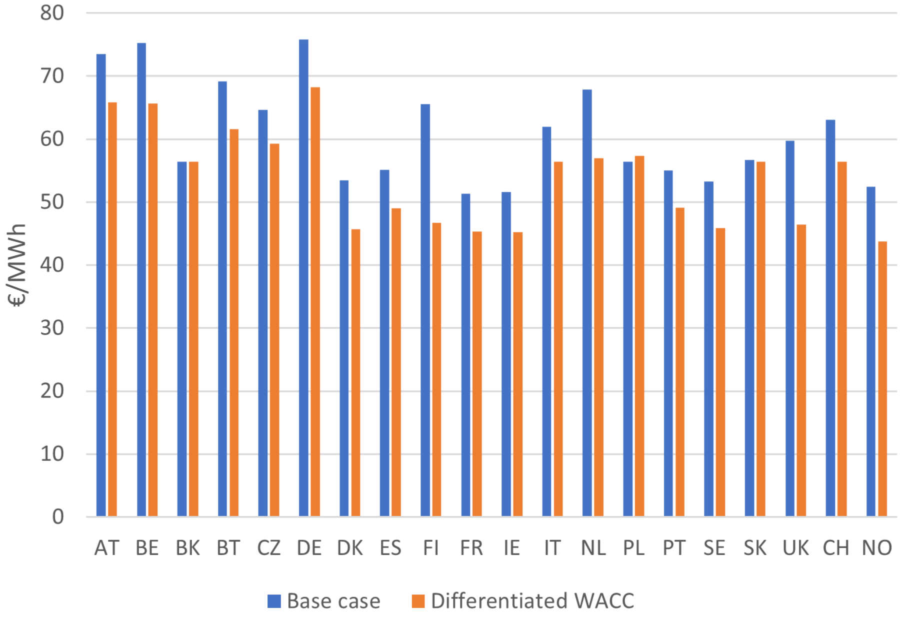

Figure 5.4 Average electricity prices in 2050

6 Conclusions

This study shows that application of technology-dependent WACCs has significant effects on the investments in generation technologies, the generation mix, and average electricity prices compared to the application of one fixed technology and country independent WACC. Several technologies that require high capital investments such as solar-pv, wind, nuclear, and green hydrogen production require a lower WACC than until recently was assumed in the COMPETES-TNO model. Applying technology-dependent WACCs is thus likely to deliver more realistic estimates of the financing costs of the energy transition during scenario modelling work.

System cost analyses based upon energy system models such as OPERA, TIAM and COMPETES-TNO can provide better insights into the real financing costs of investments once they are based upon a technology differentiated WACCs rather than just one social discount rate and uniform WACC value respectively. A social discount rate implicitly assumes that all investments will be publicly funded, while it is common in developed countries that are characterised by liberalised, market-based energy systems that the private sector has a strong financing role to play. With the increasing demand for funding for the energy transition, the role of private financiers is inevitably going to increase. This should also be reflected in the WACC values in energy system models.

The application of the bottom-up approach to estimate the WACC turned out to be more challenging than envisaged beforehand, especially the identification of a representative peer group for beta estimation. Another challenge is that the revenues and risk profiles of these listed companies reflect their main activities, which usually relate to fully commercialised mainstream technologies rather than innovative technologies with lower technology readiness levels. Therefore, this method is less suited to obtaining WACCs for innovative technologies that are prior to or just starting commercialisation. The bottom-up WACC method needs to be supplemented by forward looking technology and financial expert estimates in order to obtain WACC estimates for a larger set of (innovative) technologies. This was illustrated in the efforts to calculate the WACCs for third generation nuclear generation as well as green hydrogen production.

Further application of the combination of both methods – bottom-up and expert estimates - to estimate WACCs for technologies such as hydrogen grids and hydrogen storage, amongst others, would be required in future studies. When estimating technology-differentiated WACCs for energy system models with 2040 and 2050 as target years, it should be acknowledged that technologies develop over time. Commercialisation of technologies typically leads to risks associated with reliability, project construction and development decreasing over time, leading to lower technology-specific WACC levels. Consequently, depending on assumed technology learning rates as well as increasing familiarity of lenders with innovative technologies, technology-specific WACCs are likely to be lower in 2050 than in 2040 and earlier years.

Furthermore, country-differentiated WACCs may reduce over time as countries develop financially i.e. once their economy becomes more stable, and financial institutions, banking systems and financial markets develop. This could be the case for countries such as Bulgaria, Hungary and Poland which are still catching up and currently show relatively high WACC levels that exceed the WACC levels of other European member states.

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Appendix A

COMPETES-TNO model description[8]

COMPETES-TNO ('*Competition and Market Power in Electric Transmission and Energy Simulator*') is a power system optimisation and economic dispatch model that seeks to meet European power demand at minimum social costs (maximizing social welfare) within a set of techno-economic constraints – including policy targets/restrictions – of power generation units and transmission interconnections across European countries and regions.[9]

COMPETES-TNO consist of two major modules that can be used to perform hourly simulations for two types of purposes:

- *A transmission and generation capacity expansion module* in order to determine and analyse least-cost capacity expansion with perfect competition, formulated as a linear program to optimise generation capacity additions in the system;
- *A unit commitment and economic dispatch module* to determine and analyse least-cost unit commitment (UC) and economic dispatch with perfect competition, formulated as a relaxed mixed integer program considering flexibility and minimum load constraints and start-up costs of generation technologies.

The COMPETES-TNO model covers all EU Member States and some non-EU countries – i.e. Norway, Switzerland, the UK and the Balkan countries (grouped into a single Balkan region) – including a representation of the cross-border power transmission capacities interconnecting these European countries and regions (see figure a.1).[10] The model runs on an hourly basis, i.e. it optimises the European power system over all 8760 hours per annum.

Over the past two decades, COMPETES-TNO has been used for a large variety of assignments and studies on the Dutch and European electricity markets, e.g. about the effects of more interconnection capacity and bidding zones as well as on the role of flexibility options such as electricity trade, demand response, and storage in systems with higher shares of electricity from variable and less predictable renewable generation.

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[8] This Appendix is taken in modified form from Sijm et al. (2022).

[9] Over the past two decades, COMPETES was originally developed by ECN Policy Studies – with the support of Prof. B. Hobbs of the Johns Hopkins University in Baltimore (USA). The COMPETES-TNO model is the successor to the COMPETES model that currently is co-developed and used by PBL.

[10] Note that in Figure A.1 the Balkan region also includes several EU countries, i.e. Bulgaria, Croatia, Greece, Hungary, Romania, and Slovenia.

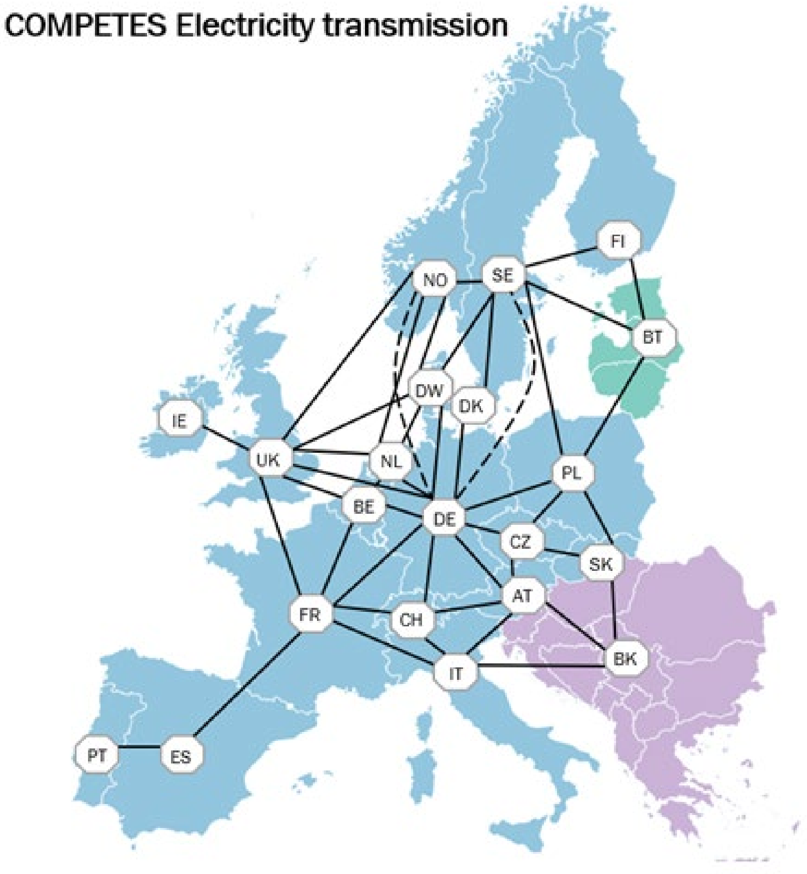

Figure A.1: The geographical coverage of the COMPETES-TNO model

For each scenario year, the major inputs of COMPETES-TNO include parameters regarding the following exogenous variables:

- Electricity demand across all European countries/regions, including conventional power demand and additional demand due to further sectoral electrification of the energy system by means of P2X technologies;
- Power generation technologies, transmission interconnections and flexibility options, including their techno-economic characteristics;
- Hourly profiles of various electricity demand categories and renewable energy (RE) technologies (notably sun, wind and hydro), including the full load hours of these technologies;
- Assumed (policy-driven) installed capacities of RE power generation technologies;
- Expected future fuel and CO2 prices;
- Policy targets/restrictions, such as meeting certain RE/GHG targets or forbidding the use of certain technologies (for instance, coal, nuclear or CCS).

As indicated above, COMPETES-TNO includes a variety of flexibility options. More specifically, these options include:

- Flexible power generation, including:
  - Conventional electricity production, notably by means of natural gas and, to some extent, coal/nuclear energy;
  - Curtailment of renewable electricity generation from solar-pv/wind;
- Cross-border power trade;

- Storage, in particular:
    - Pumped hydro (notably in other EU countries besides the Netherlands);
    - Compressed air energy storage (CAES), including both diabetic and advanced adiabatic CAES;
    - Batteries, including lead-acid (PB) batteries, vanadium redox (VR) batteries and, notably, lithium-ion (Li-ion) batteries, in particular for electric vehicles (EVs);
    - Underground storage of power-to-hydrogen ($P2H_2$);
- Demand response, notably by means of the following P2X technologies:
    - Power-to-hydrogen (P2H2);
    - Power-to-heat in industry (P2H-i), notably hybrid (electricity/gas) boilers to generate industrial heat;
    - Power-to-heat in households (P2H-h), in particular all-electric heat pumps for household space heating and hot water purposes;
    - Power-to-mobility (P2M), especially passenger electric vehicles (EVs).

On the other hand, for each scenario year and for each European country/region, the major outputs (‘results’) of COMPETES-TNO include:

- Investments and disinvestments (‘decommissioning’) in conventional power generation and interconnection capacities;
- Hourly allocation (‘dispatch’) of installed power generation and interconnection capacities, resulting in the hourly and annual power generation mix – including related CO_2 emissions and power trade flows – for each European country/region;
- Demand and supply of flexibility options;
- Hourly electricity prices;
- Annual power system costs for each European country/region.

For a more detailed description of the COMPETES-TNO model, see Sijm *et al.* (2017), notably Appendix A.

Energy & Materials Transition

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