Estimation of Investment Model Cost Parameters for VSC HVDC Transmission Infrastructure

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Abstract

Investment model cost parameters for VSC HVDC transmission infrastructure continue to be associated with high uncertainty and their validity remains a crucial challenge. Thus, it is the key objective of this analysis to identify a new cost parameter set providing better investment cost estimates than currently available cost parameter sets. This parameter estimation is based on a previously conducted review of investment model cost parameters including its collection of existing cost parameter sets and project cost reference data. By using a particle swarm optimisation, the overall error function of the review's evaluation methodology is minimised to obtain an optimal parameter set. The results show, however, that the optimised parameter sets are far from being realistic and useful, which is why an improved overall error function is developed. Effectively penalising negative and near-zero cost parameter coefficients, this new overall error function delivers a realistic and well-performing cost parameter set when being minimised. In fact, the new parameter set produces better cost estimates for back-to-back, interconnector, and offshore wind connection projects than any of the existing cost parameter sets. Therefore, it is a valuable contribution and shall be considered in future grid investment analyses involving VSC HVDC technology.

Keywords: Offshore grids, Transmission expansion planning, Cost model, HVDC, VSC, Parameter estimation, Particle swarm optimisation

1. Introduction

Voltage Source Converter (VSC) High Voltage Direct Current (HVDC) is the most suitable technology for future super grids and offshore grids in Europe [1] [2]. While multiple investment analyses of future offshore grid topologies have already been conducted (e.g. [3]), the subject of implementing integrated power grids continues to be an important research topic. As the optimisation algorithms used for assessing investment decisions in offshore grid infrastructure rely on a cost model and corresponding parameter sets, the validity of those parameter sets plays a crucial role.

However, it has been established in [4] that the cost parameter sets which have been widely used by academia and policymakers show significant variations from study to study. They indicate a high level of uncertainty both when comparing them against each other and when evaluating them against reference cost data from realised VSC HVDC projects. Acknowledging the fact that there are multiple and valid reasons for diverging cost estimates obtained with those parameter sets, a new parameter set based on the reference cost data for realised projects is needed to improve the validity of future grid investment and evaluation studies. Therefore, by drawing on the collected parameter sets and reference project cost data in [4], a new parameter estimation approach will be explored in this context to determine a new investment cost parameter set for VSC HVDC projects which can be used in transmission expansion studies.

In the remaining part of this article, Section 2 summarises the cost model and parameter information for the following parameter estimation. Section 3 introduces the particle swarm optimisation methodology which is used to compute the new parameter sets through error minimisation. Two optimised cost parameter sets based on the error function from [4] are presented in Section 4. Section 5 develops an extended overall error function including the new realness category. In Section 6, the final cost parameter set obtained from minimising the new overall error function is presented. Section 7 discusses the obtained comparison and evaluation results and Section 8 concludes the study.

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Nomenclature

Abbreviations

B2B	Back-to-Back
ITC	Interconnector
OWC	Offshore Wind Connection
PSO	Particle Swarm Optimisation
QEF	Quadruple Error Function
R	Realness
TEF	Triple Error Function

General

$\lceil real \rceil$	Ceiling of *real* ($\lceil real \rceil = \min\{n \in \mathbb{N}_0 \mid n \geq real\}$)
$\lvert set \rvert$	Cardinality of *set*

Indices and sets

$f \in F_i$	Set of branches within project i
$g \in G_i$	Set of nodes within project i
$h \in H_i$	Set of offshore nodes within project i
$i \in I_j$	Set of projects within category j
$j \in J$	Set of project categories ($J = \{\text{B2B}, \text{ITC}, \text{OWC}\}$)
$k \in K$	Set of cost parameter sets
$q \in Q^k$	Set of cost parameters of parameter set k
$z \in Z$	Set of categories including realness ($Z = J \cup \{\text{R}\}$)

Cost parameters and variables

B_0^k	Fixed cost for building a branch with cost parameter set k (M€)
B_{lp}^k	Length- and power-dependent cost for building a branch with cost parameter set k (M€/GW·km)
B_l^k	Length-dependent cost for building a branch with cost parameter set k (M€/km)
$C_{\text{est},i}^k$	Estimated investment cost for project i (M€)
$C_{\text{ref},i}$	Reference investment cost for project i (M€)
$C_{\text{ref},i}^{\text{con}}$	Reference contracted cost for project i (M€)
N_0^k	Fixed cost for building a node with cost parameter set k (M€)
N_p^k	Power-dependent cost for building a node with cost parameter set k (M€/GW)
S_0^k	Fixed additional cost for building an offshore node with cost parameter set k (M€)
S_p^k	Power-dependent additional cost for building an offshore node with cost parameter set k (M€/GW)

Technical parameters and variables

$\hat{P}_j$	Maximum power rating for a single installation within category j (GW). In case of a back-to-back system, this is twice the system rating (two fully rated converters at one node).
$l_{\text{OHL},f}$	Overhead line section length of branch f (km)
$l_{\text{SMC},f}$	Submarine cable section length of branch f (km)
$l_{\text{UGC},f}$	Underground cable section length of branch f (km)
l_f	Total equivalent line length of branch f (km)
p_f	Installed power rating of branch f (GW)
$p_{g/h}$	Installed power rating at node g/h (GW). In case of a back-to-back system, this is twice the system rating (two fully rated converters at one node).

Deviations and errors

ϵ_R^k	Unscaled root-mean-square realness error for cost parameter set k (-)
$\epsilon_{q,\text{EXP}}^k$	Relative exponential deviation of parameter q for cost parameter set k (-)
$\epsilon_{q,\text{LOG}}^k$	Relative logarithmic realness deviation of parameter q for cost parameter set k (-)
$\epsilon_{q,\text{REL}}^k$	Relative realness deviation of parameter q for cost parameter set k (-)
A	Constant scalar realness error scaling factor (-)
D_i^k	Project investment cost estimation deviation of project i for cost parameter set k (-)
D_j^k	Category investment cost estimation deviation of category j for cost parameter set k (-)
E_{QEF}^k	Overall root-mean-square error of four category errors (Quadruple Error Function) for cost parameter set k (-)
E_{TEF}^k	Overall root-mean-square error of three category errors (Triple Error Function) for cost parameter set k (-)
E_{R}^k	Root-mean-square realness error for cost parameter set k (-)
E_q^k	Realness error of cost parameter q for cost parameter set k (-)
$E_{j/z}^k$	Category root-mean-square error of category j/z for cost parameter set k (-)

2. Fundamentals

This section contains a summary of the most important information, equations, and tables from [4], which are essential for the optimisation approach of this article. In addition, a new parameter set notation is introduced as it is convenient for all subsequent considerations.

2.1. Cost model

A linear uniform cost model has been defined in [4]. It provides an approximation of the investment cost associated with offshore grid HVDC infrastructure and yields a reasonable accuracy regarding long-term large-scale transmission expansion studies (e.g. [45]). The cost model is based on [46], [47] and [48].

Bear in mind that a mixed-integer linear cost model yields significant benefits for long-term large-scale transmission expansion planning problems and the optimisation algorithms solving them, as computation time and convergence face severe challenges when more complex cost models are applied.

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Since the main equations explained in [4] are inevitable for the subsequent calculations, they are repeated in this subsection. The linear uniform cost model for VSC HVDC transmission investments is defined by Equations (1) to (6):

$$C^k_{\mathrm{est},i} = \sum_g^{G_i} N^k_g(p_g) + \sum_f^{F_i} B^k_f(l_f, p_f) + \sum_h^{H_i} S^k_h(p_h) \quad (1)$$

$$N^k_g(p_g) = N^k_p \cdot p_g + \left\lceil \frac{p_g}{\hat{P}_j} \right\rceil N^k_0 \quad (2)$$

$$B^k_f(l_f, p_f) = B^k_{lp} \cdot l_f \cdot p_f + \left\lceil \frac{p_f}{\hat{P}_j} \right\rceil \left(B^k_l \cdot l_f + B^k_0 \right) \quad (3)$$

$$S^k_h(p_h) = S^k_p \cdot p_h + \left\lceil \frac{p_h}{\hat{P}_j} \right\rceil S^k_0 \quad (4)$$

$$\hat{P}_{\mathrm{B2B}} = 4\,\mathrm{GW} \quad \hat{P}_{\mathrm{ITC}} = 2\,\mathrm{GW} \quad \hat{P}_{\mathrm{OWC}} = 2\,\mathrm{GW} \quad (5)$$

$$l_f = l_{\mathrm{SMC},f} + \frac{5}{4} l_{\mathrm{UGC},f} + \frac{2}{3} l_{\mathrm{OHL},f} \quad (6)$$

It is important to stress that the installed power rating (p_g, p_h) corresponds to the total power rating of all converters at a node, which is twice the system rating for a back-to-back system (contains two fully-rated converters). This is the reason why $\hat{P}_{\mathrm{B2B}}$ is twice the size of $\hat{P}_{\mathrm{ITC}}$ and $\hat{P}_{\mathrm{OWC}}$.

In Equations (2) to (4), the ceiling operators are needed to enforce the necessary integer investment decisions which have to be made as part of the optimisation problem.

2.2. Parameter set notation

It is helpful to combine the seven parameters of a cost parameter set in a mathematical set, as denoted in Equation (7):

$$Q^k = \left\{ B^k_{lp}, B^k_l, B^k_0, N^k_p, N^k_0, S^k_p, S^k_0 \right\} \qquad \forall k \quad (7)$$

With that in mind, it is the primary goal of this article to identify a new parameter set Q^k constituting an optimal fit for estimating investment costs of VSC HVDC infrastructure.

2.3. Reference project data

All the collected and processed reference project cost data is summarised in Table 1.

Based on the collected data on contracted cost for the reference projects, the reference investment cost for the individual projects is calculated according to Equation (8).

Table 1: Techno-economic figures of realised and contracted VSC HVDC projects

Project category	Project name	Power: Rated	Power: Param.	Line length: SMC	Line length: UGC	Line length: OHL	Line length: equiv.	Cost: Contracted	Cost: Total	Source(s)
			$p_{f/g/h}$	l_{SMC}	l_{UGC}	l_{OHL}	l	$C^{\mathrm{con}}_{\mathrm{ref},i}$	$C_{\mathrm{ref},i}$	
		MW	MW	km	km	km	km	M€	M€	
B2B	TresAmigas	750	1,500	-	-	-	-	150.0	165.0	[5], [4]
	Mackinac	350	700	-	-	-	-	68.0	74.8	[6], [4]
	KriegersFlak	500	1,000	-	-	-	-	125.7	138.3	[7], [4]
ITC	EstLink1	350	350	74	31	-	113	84.8	106.0	[8], [4]
	EWIC	500	500	186	76	-	281	421.7	527.2	[9], [10], [4]
	NordBalt	700	700	400	13	40	443	438.6	548.3	[11], [12], [4]
	Åland	100	100	158	-	-	158	99.1	123.9	[13], [4]
	Skagerrak4	700	700	138	92	12	261	258.9	323.6	[14], [15], [16], [4]
	NordLink	1,400	1,400	516	54	53	619	1,332.3	1665.4	[17], [18], [4]
	NorthSeaLink	1,400	1,400	720	7	-	729	1,298.9	1623.6	[19], [20], [21], [4]
	COBRA	700	700	299	26	-	332	420.0	525.0	[22], [23], [4]
	IFA2	1,000	1,000	208	27	-	242	590.2	737.7	[24], [25], [4]
OWC	BorWin1	400	400	125	75	-	219	422.8	528.5	[26], [4]
	BorWin2	800	800	125	75	-	219	745.3	931.6	[27], [28], [4]
	HelWin1	576	576	85	45	-	141	745.3	931.6	[28], [29], [4]
	DolWin1	800	800	75	90	-	188	682.4	853.0	[30], [31], [4]
	SylWin1	864	864	160	45	-	216	745.3	931.6	[32], [33], [34], [4]
	DolWin2	916	916	45	92	-	160	832.6	1040.8	[35], [36], [4]
	HelWin2	690	690	85	45	-	141	845.3	1056.6	[37], [38], [4]
	DolWin3	900	900	83	79	-	182	1,150.0	1437.5	[39], [40], [41], [4]
	BorWin3	900	900	132	29	-	168	1,250.0	1562.5	[42], [43], [44], [4]

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$$
\begin{aligned}
C_{\mathrm{ref},i} &= \frac{11}{10} C^{\mathrm{con}}_{\mathrm{ref},i} && \forall i \in I_{\mathrm{B2B}} \\
C_{\mathrm{ref},i} &= \frac{5}{4} C^{\mathrm{con}}_{\mathrm{ref},i} && \forall i \in I_{\mathrm{ITC}} \qquad (8) \\
C_{\mathrm{ref},i} &= \frac{5}{4} C^{\mathrm{con}}_{\mathrm{ref},i} && \forall i \in I_{\mathrm{OWC}}
\end{aligned}
$$

These estimated markups are accounting for the difference between reference contractual cost $C^{\mathrm{con}}_{\mathrm{ref},i}$ and total project reference investment cost $C_{\mathrm{ref},i}$. These differences are caused by many different factors, including, but not limited to, internal efforts, risk budget, engineering and concession costs, land purchase, construction etc. The markup values are based on [53], [34], [59] and unquotable personal communication with relevant industry stakeholders.

2.4. Cost parameter sets

The cost parameter sets considered in this article are given in Table 2. Compared to the cost parameter sets considered in [4], four parameter sets are neglected here.

The parameter sets *Imperial College* and *Torbaghan* are only meant for long distance transmission systems, and not for back-to-back systems. They do not contain nodal cost parameters; all cost are proportional to transmission length. They do therefore not produce viable results for all of the three project categories, as cost for back-to-back stations (with zero transmission length) become zero. This has been shown in [4]. *Imperial College* and *Torbaghan* have therefore not been included in this study.

The parameter sets *ENTSO-E* and *Madariaga* contain data which lead to negative cost parameters when the given data is converted (extrapolated) to the here-used format of the linear uniform cost model. This indicates that the data sets in question are not complete enough to allow for meaningful conversion to the linear uniform cost model. Negative cost parameters are unrealistic and lead to mathematical problems in the parameter estimation process. *ENTSO-E* and *Madariaga* have therefore been disregarded in this study.

2.5. Average cost parameter set

Based on this reduced selection of cost parameter sets, the average parameter set is calculated (displayed in Table 3). Naturally, it differs from the average parameter set presented in [4] which also accounted for the four parameter sets that are ignored here.

Table 3: Average cost parameter set

Parameter	Unit	Q^{AVG}
N_p^{AVG}	M€/GW	92.84
N_0^{AVG}	M€	34.90
B_{lp}^{AVG}	M€/GW·km	0.96
B_l^{AVG}	M€/km	0.70
B_0^{AVG}	M€	5.00
S_p^{AVG}	M€/GW	116.26
S_0^{AVG}	M€	65.48

While six of the seven parameters are calculated as the arithmetic mean, B_0^{AVG} is treated differently. Since only one of the existing parameter sets actually considers B_0^k (*WindSpeed*), while the others have the parameter set to zero, calculating the mean would result in a very low value, giving a poor representation of the associated cost. Instead of calculating the mean, it was therefore decided to set B_0^{AVG} to the value provided by *WindSpeed*.

Table 2: Collected cost parameter sets

Name	Year	N_p^k M€/GW	N_0^k M€	B_{lp}^k M€/GW·km	B_l^k M€/km	B_0^k M€	S_p^k M€/GW	S_0^k M€	Source(s)
RealiseGrid	2011	83.00	0.00	2.58	0.07	0.00	0.00	28.00	[49], [4]
WindSpeed	2011	216.00	6.50	0.67	0.36	5.00	23.00	17.30	[50], [4]
Ergun et al.	2012	90.00	18.00	2.05	0.11	0.00	0.00	24.00	[51], [4]
ETYS13	2013	60.80	63.17	0.29	1.06	0.00	216.60	143.66	[52], [4]
NSTG	2013	58.90	54.90	1.23	0.00	0.00	130.83	0.00	[53], [54], [4]
NSOG	2014	58.90	54.90	0.50	0,45	0.00	0.00	111.30	[55], [4]
NorthSeaGrid	2015	65.00	54.00	0.35	1.85	0.00	125.00	218.95	[56], [4]
OffshoreDC	2015	100.00	0.00	1.30	0.00	0.00	75.00	0.00	[57], [4]
ETYS15	2015	103.00	62.60	0.63	1.45	0.00	475.90	46.07	[58], [4]

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2.6. *Project assessment*

The evaluation of a cost parameter set is carried out by first calculating cost estimations for each individual reference project. These cost estimations are then compared to the reference investment cost and the relative deviation is expressed on a logarithmic scale, as shown in Equation (9).

$$D_i^k = \log_2 \left(\frac{C_{\text{est},i}^k}{C_{\text{ref},i}} \right) \qquad \forall i, k \qquad (9)$$

Relative deviations guarantee an adequate assessment of both small and big projects. Using absolute cost figures would undervalue the correct estimation of smaller projects.

Logarithmic deviations account for the ratio between estimate and reality. It is important to use a logarithmic measure of the deviation to ensure a correct evaluation of both under- and overestimation.

Cost estimations range between the two worst possible estimates $\{0, \infty\}$, which are both equally evaluated on a logarithmic scale $\{-\infty, +\infty\}$. A non-logarithmic (linear) measure would inadequately evaluate them $\{-1, +\infty\}$, creating the wrong impression that zero cost would be a much better estimate than infinite cost.

The non-logarithmic measure would equally evaluate $\{0, 2\}$, yielding $\{-1, +1\}$. $\{2\}$ is by all means not a good estimation, but it still represents a valid result. On the contrary, $\{0\}$ implies that the infrastructure can be deployed at zero cost, which is obviously wrong, leading to over-investments in 'free' assets when a transmission expansion planning optimisation is conducted. The logarithmic measure returns $\{-\infty, +1\}$ for this example, correctly reflecting the practical implications of the two estimates.

As a consequence, the following evaluation of parameter sets employs the relative logarithmic measure, as denoted in Equation (9).

2.7. *Project category assessment*

Based on the individual project deviations, the category mean deviations are calculated according to Equation (10):

$$D_j^k = \frac{1}{|I_j|} \sum_i^{I_j} D_i^k \qquad \forall j, k \qquad (10)$$

Based on the individual project deviations, the category root-mean-square errors are calculated according to Equation (11):

$$E_j^k = \sqrt{\frac{1}{|I_j|} \sum_i^{I_j} (D_i^k)^2} \qquad \forall j, k \qquad (11)$$

2.8. *The TEF-based evaluation methodology*

The abbreviation 'TEF' stands for the term *Triple Error Function* because the overall error function Equation (12) is based on the three project categories (B2B, ITC, OWC). This overall error function is identical to E^k in [4], but since an improved error function is introduced later in this article, a slightly amended notation (E_{TEF}^k) is more convenient here.

An overall assessment is achieved by calculating the overall root-mean-square error of the category root-mean-square errors, as expressed in Equation (12).

$$E_{\text{TEF}}^k = \sqrt{\frac{1}{|J|} \sum_j^{J} \left(E_j^k\right)^2} \qquad \forall k \qquad (12)$$

3. Optimisation methodology

In order to determine a new parameter set based on the information summarised in Section 2, error functions have to be optimised, i.e. minimised. However, the overall error functions used here are non-linear and difficult to minimise by using standard optimisation algorithms. Instead, to minimise these functions, it is convenient to employ a heuristic algorithm which is not mathematically guaranteed to find a solution but can often be successfully applied to many problems. For the purpose of this study, a Particle Swarm Optimisation (PSO) is used as it can efficiently and reliably solve problems [60] of this type.

PSO was first introduced by [61] as a concept for the optimisation of non-linear functions using particle swarm methodology. It is based on a population, referred to as a swarm, of particles simulating the social behaviour patterns of organisms that live and interact within large groups. In essence, these particles explore the search space to minimise the objective function, or *landscape*, of a problem. A detailed description of the underlying principles, as well as a recent review of studies analysing and modifying PSO algorithms, can be found in [62].

Moreover, all PSO parameter estimation results were validated against a rather unsophisticated grid search approach. This computationally far more expensive approach yielded very similar solutions for the parameter estimation, hence confirming the validity of all results obtained from the PSO estimation.

4. The TEF-optimal cost parameter sets

The PSO algorithm is used to find the cost parameter set (seven variables) minimising the overall error function given by E_{TEF}^k in Equation (12).

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4.1. The TEF-optimal cost parameter set

Based on the overall error function in Equation (12), the new cost parameter set is determined by solving Equation (13):

$$Q^{TEF} = \underset{Q^k}{\operatorname{argmin}} \left(E^k_{\text{TEF}} \right), \qquad Q^k \in \mathbf{R}^k \qquad (13)$$

The estimation result for the cost parameter coefficients is shown in Table 4.

Table 4: E^k_{TEF}-optimal cost parameter set

Parameter	Unit	Q^{TEF}
N_p^{TEF}	M€/GW	90.52
N_0^{TEF}	M€	43.91
B_{lp}^{TEF}	M€/GW·km	0.72
B_l^{TEF}	M€/km	1.02
B_0^{TEF}	M€	-169.07
S_p^{TEF}	M€/GW	982.40
S_0^{TEF}	M€	-65.84

Although this E^k_{TEF}-optimal parameter set yields the lowest overall error, as defined by Equation (12), it is unrealistic and therefore rather useless. This is because the cost parameter set contains two negative coefficients, which on the one hand are a logical result of the optimisation algorithm, but, on the other hand, do not correspond at all to the cost components of a real HVDC project.

The reason behind these negative numbers is the poor data base on which the optimisation relies upon. More specifically, a lack of a sufficient number of representative low-power offshore VSC HVDC links results in the negative S_0^{TEF}. A similar lack of a sufficient number of representative high-power VSC HVDC projects causes the negative B_0^{TEF}.

Applying such an unrealistic cost parameter set in a transmission expansion planning problem could trigger the construction of an infinite number of short low-power HVDC links as their construction cost are negative, potentially resulting in an infinite profit.

4.2. The TEF0-optimal cost parameter set

The straight-forward approach to tackle the problem of negative cost parameters is to constrain the optimisation by only allowing non-negative coefficients for the seven parameters. Thus, based on the error function in Equation (12), the new cost parameter set is determined by solving Equation (14):

$$Q^{TEF0} = \underset{Q^k}{\operatorname{argmin}} \left(E^k_{\text{TEF}} \right), \qquad Q^k \geq 0, \quad Q^k \in \mathbf{R}^k \quad (14)$$

The estimation result for the cost parameter coefficients is shown in Table 5.

Table 5: E^k_{TEF}-optimal non-negative cost parameter set

Parameter	Unit	Q^{TEF0}
N_p^{TEF0}	M€/GW	98.82
N_0^{TEF0}	M€	35.31
B_{lp}^{TEF0}	M€/GW·km	1.30
B_l^{TEF0}	M€/km	0.00
B_0^{TEF0}	M€	0.00
S_p^{TEF0}	M€/GW	811.50
S_0^{TEF0}	M€	0.00

Due to the non-negativity constraints, the Q^{TEF0} parameter set only contains coefficients greater than zero and is therefore not as unrealistic and problematic when using it in e.g. transmission expansion planning problems. However, three out of seven parameters become zero, implying a significant simplification of the cost model. In fact, the irrelevant parameters result in unrealistically low cost estimates for low-power installations as purchasing and installing 1 km of 1 kW cable costs 1.3 €.

This simplification of the cost model is not desired because all seven cost parameters were initially introduced for a good reason. In other words, the cost model features comprehensive components and de facto removing almost half of the parameters undermines the cost model's purpose and reasoning behind it.

4.3. Evaluation

An interim conclusion is that neither the Q^{TEF} nor the Q^{TEF0} cost parameter set shows satisfactory results. This means that the overall error function E^k_{TEF}, as developed in [4], is not entirely sufficient for identifying a new optimal parameter set.

E^k_{TEF} had originally been designed to evaluate the collected parameter sets, while the identification of an optimal cost parameter set was not the objective. Since the focus was on evaluating the existing cost parameter sets, the information contained in these parameter sets was not included in the overall error function. Otherwise, the parameter sets would have been evaluated against themselves.

However, when pursuing the estimation of an optimal cost parameter set, all available information should be used and accounted for. This means that not only the reference project data but also the existing cost parameter sets need to be somehow included in the overall error

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function. It is therefore sensible to develop an extended overall error function by incorporating the information of existing cost parameter sets.

5. The QEF-based evaluation methodology

'QEF' abbreviates the term *Quadruple Error Function* because the improved overall error function in Equation (24) is based on four components: the three project categories and the new 'realness' category. Essentially, the realness measure is based on the deviations from the Q^{AVG} cost parameter set. The extended overall error function is called E^k_{QEF} and it has to be distinguished from E^k_{TEF}, which is identical to E^k in [4]. Hence, the new E^k_{QEF} takes into account all the information gathered from reference projects and existing cost parameter sets.

It is important that the improved error function E^k_{QEF} is backward compatible and does not distort the results of the error function E^k_{TEF} because it should still be useful for assessing existing parameter sets. Otherwise, E^k_{QEF} could not replace the existing error function E^k_{TEF}.

5.1. Definition of realness

As discussed in Subsection 4.1 and Subsection 4.2, both E^k_{TEF}-optimal parameter sets gave unsatisfactory results because the resulting coefficients are not realistic. In order to implement the improved error function, this subjective assessment of realness must be expressed in mathematical terms so that the optimisation algorithm can factor it in. As mentioned before, it was decided to base the realness measure on the deviations from the Q^{AVG} cost parameter set.

A natural first approach is using a relative logarithmic deviation, similar to Equation (9), resulting in Equation (15):

$$\epsilon^k_{q,\text{LOG}} = \log_2\left(\frac{q^k}{q^{\text{AVG}}}\right) \qquad \forall q \in Q^k, \quad \forall k \tag{15}$$

However, this approach turns out to be not feasible. A parameter set of which at least one parameter is disappearing, i.e. equal to zero, would produce a deviation of minus infinity. This implies that all parameter sets except *WindSpeed* would be assessed with an infinite error. Therefore, such a deviation function is not particularly useful for assessing the existing cost parameter sets.

Another trivial approach is to rely on relative deviation without logarithmic consideration, resulting in Equation (16):

$$\epsilon^k_{q,\text{REL}} = \frac{q^k - q^{\text{AVG}}}{q^{\text{AVG}}} \qquad \forall q \in Q^k, \quad \forall k \tag{16}$$

This deviation definition solves the issue of the disappearing parameters because they are assessed with a deviation of one instead of infinity. Despite that, it does not adequately penalise negative coefficients, and, as a consequence, still permits the optimal parameter set to contain negative parameters.

To capture the intended realness of parameter coefficients, the corresponding mathematical term needs to:

- return a finite number if zero is the input
- have a highly negative slope (first derivative) for inputs close to zero
- have an almost flat slope for inputs around the average parameter value

In this context, an inverse exponential function was chosen as the most suitable mathematical function to fulfil the expressed requirements.

Based on Equation (7), the unscaled realness deviation for a single parameter k of a parameter set q can be expressed by Equation (17):

$$\epsilon^k_{q,\text{EXP}} = \exp -\left(\frac{q^k}{{}^1\!/\!_4\, q^{\text{AVG}}}\right) \qquad \forall q \in Q^k, \quad \forall k \tag{17}$$

Here, the factor $^1\!/\!_4$ is important since it determines the shape of the exponential function.

Basically, a small factor results in a steep slope at zero and a gentle slope around the average parameter. Conversely, a larger factor reduces the function's slope at zero but widens the steep slope area around zero. This implies a systematic overestimation of the investment cost because a larger factor favours high parameters. It has to be stated that there is no scientific means to set this factor to a correct value. The factor $^1\!/\!_4$, which was finally selected and applied, has been determined by trial and error yielding the best compromise to deliver an adequate error function.

5.2. Improved error function including realness

Based on the unscaled realness deviation for a single parameter in Equation (17), the unscaled root-mean

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square realness error of a parameter set k can be defined by Equation (18):

$$\epsilon_R^k = \sqrt{\frac{1}{|Q^k|}\sum_q^{Q^k}\left(\epsilon_{q,\text{EXP}}^k\right)^2} \qquad \forall k \tag{18}$$

The unscaled function in Equation (17) returns $\epsilon_{q,\text{EXP}}^k = 1$ for a disappearing parameter ($q^k = 0$). This amplitude is arbitrary and does not relate to the other error functions which are based on the project categories. To better align the realness error amplitude with the other error categories, the ratio between unscaled realness error and the E_{TEF}^k-based overall error is calculated as the mean for all existing cost parameter sets presented in Table 2, see Equation (19):

$$A = \frac{\frac{1}{|K|}\sum_k^K E_{\text{TEF}}^k}{\frac{1}{|K|}\sum_k^K \epsilon_R^k} \tag{19}$$

A is a constant scalar and can be used to scale the realness error, so that its amplitude relates to the other error amplitudes, as shown in Equation (20):

$$E_q^k = A\epsilon_{q,\text{EXP}}^k \qquad \forall q \in Q_k, \quad \forall k \tag{20}$$

The scaling factor also applies to the realness error for a parameter set from Equation (18), which is denoted as Equation (21):

$$E_{\text{R}}^k = A\epsilon_R^k = \sqrt{\frac{1}{|Q^k|}\sum_q^{Q^k}\left(E_q^k\right)^2} \qquad \forall k \tag{21}$$

Incorporating the scaled realness error from Equation (21) into the overall error function Equation (12) as a fourth category results in the improved *Quadruple Error Function*:

$$E_{\text{QEF}}^k = \sqrt{\frac{1}{1+|J|}\left(\left(E_{\text{R}}^k\right)^2 + \sum_j^J\left(E_j^k\right)^2\right)} \qquad \forall k \tag{22}$$

Formally, the realness error can be added as a further category which is denoted in Equation (23):

$$Z = J \cup \{\text{R}\} \tag{23}$$

By using the combined category set Z from Equation (23), Equation (22) can be simplified to Equation (24):

$$E_{\text{QEF}}^k = \sqrt{\frac{1}{|Z|}\sum_z^Z\left(E_z^k\right)^2} \qquad \forall k \tag{24}$$

5.3. Validation

An overall error value comparison of both the E_{TEF}^k and E_{QEF}^k for all previously collected parameter sets is shown in Figure 1.

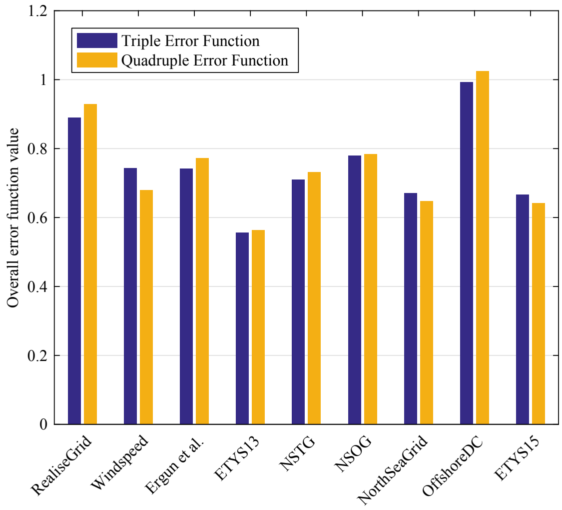

Figure 1: Comparison of E_{TEF}^k and E_{QEF}^k values (for the collected parameter sets from Table 2)

As can be seen from the resulting values, the E_{TEF}^k and E_{QEF}^k produce very similar results. The minor error differences between the two overall error function values are caused by the existing cost parameter set's deviations from the Q^{AVG} cost parameter set. For instance, *WindSpeed* reveals a slightly better E_{QEF}^k value because it has no parameter coefficient equalling zero (full rank), while most of the parameter sets experience a marginal E_{QEF}^k increase. In summary, this validation implies that the E_{QEF}^k does not distort the evaluation of the collected parameter sets which was earlier conducted in [4].

Additionally, Figure 1 also evokes the good performance of the *ETYS13* parameter set, documented in [4]. Since *ETYS13* provides a low overall error in comparison, it is going to be included in the remaining parameter evaluation analysis.

6. The QEF-optimal cost parameter set

Based on the improved error function in Equation (24), the new cost parameter set is determined by solving the following Equation (25) with PSO:

$$Q^{QEF} = \underset{Q^k}{\text{argmin}}\left(E_{\text{QEF}}^k\right), \qquad Q^k \in \mathbf{R}^k \tag{25}$$

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Table 6: E^k_{QEF}-optimal cost parameter set

Parameter	Unit	Value
N_p^{QEF}	M€/GW	112.99
N_0^{QEF}	M€	23.50
B_{lp}^{QEF}	M€/GW·km	0.98
B_l^{QEF}	M€/km	0.27
B_0^{QEF}	M€	3.63
S_p^{QEF}	M€/GW	723.42
S_0^{QEF}	M€	57.32

Table 6 shows the estimation result for the cost parameter coefficients.

The new realness error category ensures non-negative coefficients for all seven cost parameters of Q^k, particularly B_0^k, B_l^k, and S_0^k. As opposed to both Q^{TEF} and Q^{TEF0}, the Q^{QEF} cost parameter set uses all available parameters of the VSC HVDC cost model in a realistic manner.

7. Evaluation of the cost parameter sets

To evaluate the new Q^{QEF} parameter set, an assessment and comparison of its parameter coefficients, resulting deviations, and overall errors against the other parameter sets is presented in this section.

7.1. Comparison of cost parameter coefficients

The cost parameters N_p^k and N_0^k are presented in Figure 2, constituting the node cost part of the investment model in Equation (2).

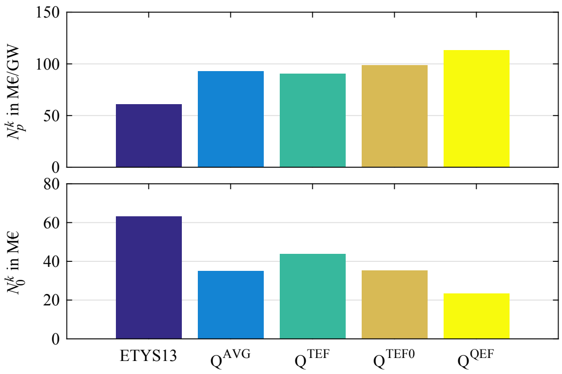

Figure 2: Comparison of node cost parameters N_p^k and N_0^k

While the mathematical, but unrealistic node cost parameter optimum is represented by Q^{TEF}, with Q^{TEF0} and Q^{AVG} lying quite close to it, the Q^{QEF} parameter set shows the highest N_p^k and lowest N_0 values.

The cost parameters B_{lp}^k, B_l^k and B_0^k are presented in Figure 3, representing the branch cost part of the investment model in Equation (3).

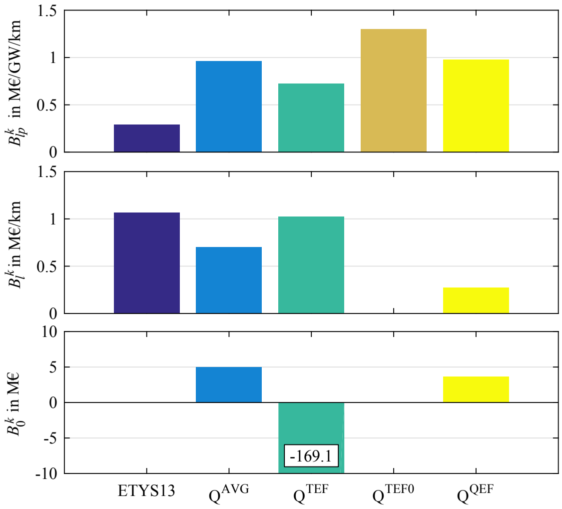

Figure 3: Comparison of branch cost parameters B_{lp}^k, B_l^k and B_0^k

From the figure, it becomes obvious that the realness category came into effect, particularly for B_l^k and B_0^k. With Q^{AVG} and Q^{QEF} being the only two cost parameter sets with reasonable, i.e. non-disappearing and non-negative, coefficients, the branch parameters of the Q^{QEF} cost parameter set lie between the Q^{TEF0} and the Q^{AVG} set. This effect was exactly intended by the realness component in the new overall error function.

The cost parameters S_p^k and S_0^k are presented in Figure 4, contributing the additional offshore cost part (deployment at sea) of the investment model in Equation (4).

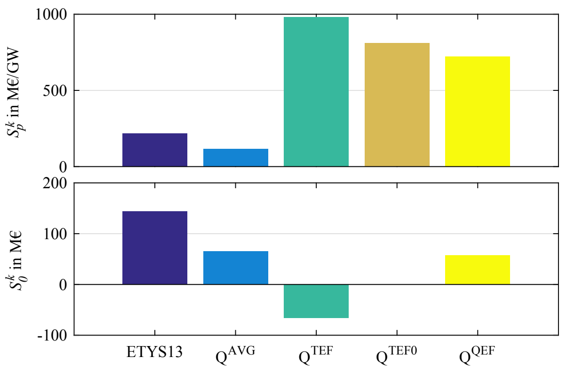

Figure 4: Comparison of offshore cost parameters S_p^k and S_0^k

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Importantly, all optimised sets show significantly higher offshore cost parameters, which is a logical consequence of the substantial investment cost underestimations of offshore wind connection projects reported in [4]. Similar to the branch cost parameters, the S_p^k and S_0^k parameters of Q^{QEF} result in a trade-off between the Q^{TEF0} and Q^{AVG} cost parameter set.

7.2. *Assessment of deviations*

The project deviations and category deviation of investment costs for back-to-back projects are illustrated in Figure 5.

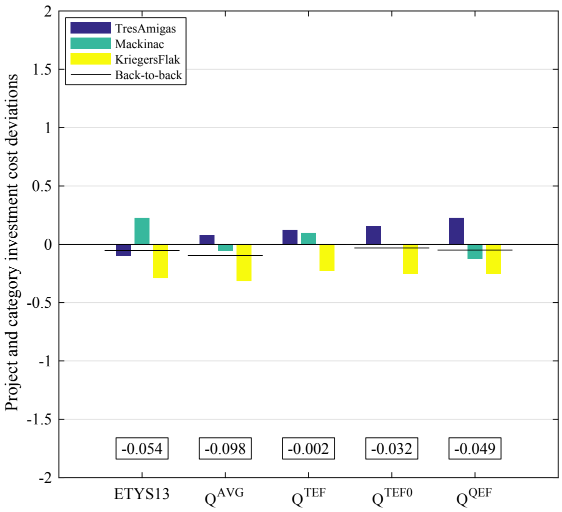

Figure 5: Deviations D_i^k for back-to-back projects (category deviation D_{B2B}^k shown in boxes)

In comparison, the results indicate only minor deviations among all considered parameter sets. As expected, the Q^{TEF} cost parameter set yields the smallest category deviation. That said, back-to-back project category deviations of Q^{QEF} are only slightly higher, but still very small.

The project deviations and category deviation of investment costs for interconnector projects are illustrated in Figure 6.

As can be seen from the resulting interconnector category deviations, all optimised parameter sets, i.e. Q^{TEF}, Q^{TEF0}, and Q^{QEF}, avoid the systematic overestimations becoming obvious for *ETYS13* and Q^{AVG}.

Figure 7 illustrates the project deviations and category deviation of investment costs for offshore wind connection projects.

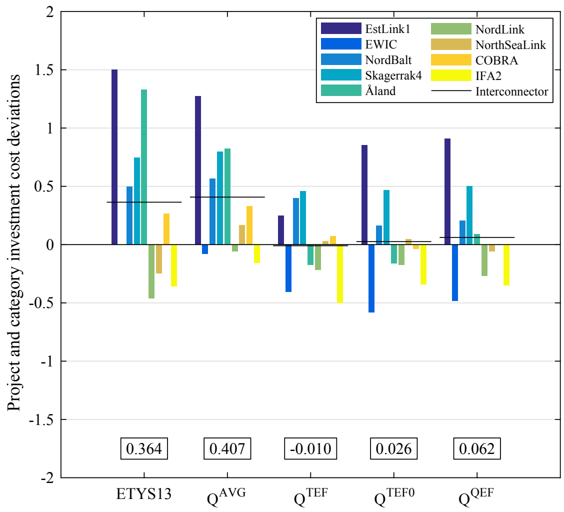

Figure 6: Deviations D_i^k for interconnector projects (category deviation D_{ITC}^k shown in boxes)

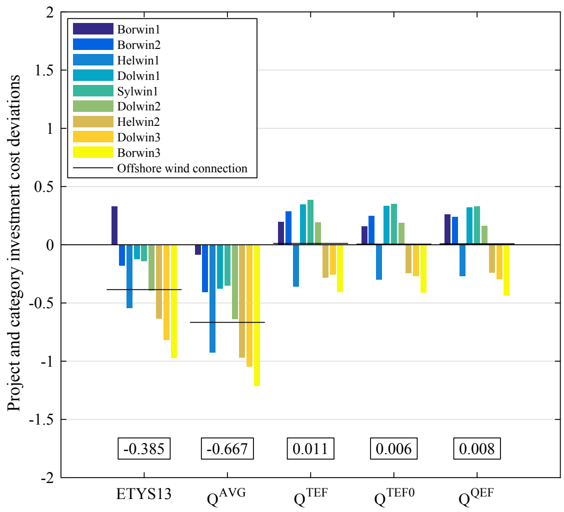

Figure 7: Deviations D_i^k for offshore wind connector projects (category deviation D_{OWC}^k shown in boxes)

By contrast to the interconnector deviations, the costs of offshore wind connection projects are systematically underestimated by *ETYS13* and Q^{AVG}, which is no longer the case for the E_{TEF}^k-optimal and E_{QEF}^k-optimal cost parameter sets.

Clearly, single projects are still over- or underestimated, but, when comparing them against the existing cost parameter sets and Q^{AVG}, the three project category deviations are significantly better for the three optimised cost parameter sets, i.e. Q^{TEF}, Q^{TEF0}, and Q^{QEF}.

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7.3. *Assessment of errors*

Finally, Figure 8 shows the category error E_z^k and the overall error E_{QEF}^k for all considered parameter sets.

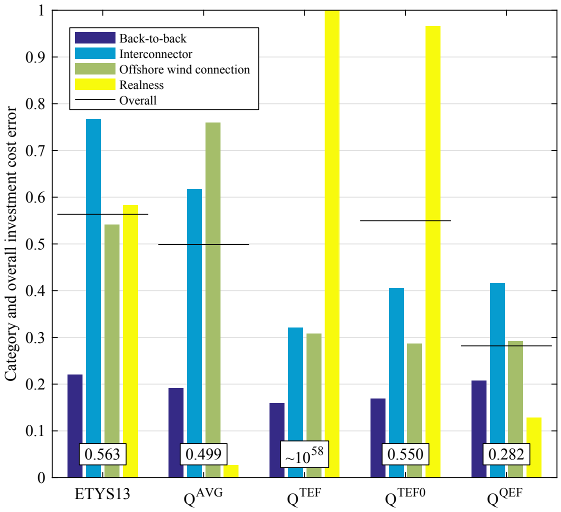

Figure 8: Evaluation of category errors E_z^k (overall error E_{QEF}^k shown in boxes)

Remember that *ETYS13* gave the best overall error results (E_{TEF}^k) among the collected parameter sets in [4]. While the additional realness category does not impose any significant distortions, as discussed in Subsection 5.3, *ETYS13* yields a high overall error $\left(E_{\text{QEF}}^k\right)$ in the figure above.

As for the Q^{AVG} cost parameter set, all project category errors exhibit elevated levels, also resulting in a high overall error. Notably, its realness category error is the lowest for all considered parameter sets since it is based on the deviation from itself. However, it is still greater than zero because the exponential function in Equation (17) only asymptotically approaches zero.

The Q^{TEF} cost parameter set achieves the lowest category errors for back-to-back, interconnector, and offshore wind connection projects. However, the negative parameter coefficients of the E_{TEF}^k-optimal Q^{TEF} result in an extreme overall error, thus causing the poorest performance when comparing it to all other parameter sets.

Similarly, the Q^{TEF0} cost parameter set produces good project category errors in comparison, but its realness category error remains high.

The key result is that the lowest overall error can be reported for the optimised Q^{QEF} cost parameter set. It exhibits the second smallest realness category error, only at the cost of slightly higher project category errors. Compared to the Q^{TEF} cost parameter set, category errors for back-to-back and interconnector projects tend to be a bit higher, while offshore wind connection project category errors turn out to be slightly smaller.

Therefore, Q^{QEF} fulfils all the requirements of a suitable cost parameter set including the realness category and still produces significantly better investment cost estimates than *ETYS13* and Q^{AVG}.

8. Conclusion

Based on the currently available reference project cost data and the collected cost parameter set information, the newly developed Q^{QEF} cost parameter set can essentially be seen as the optimal parameter set for estimating investment cost of VSC HVDC projects. Hence, it is the best parameter set available at the moment and embodies a valuable contribution for future grid investment analyses including VSC HVDC technology.

It has to be mentioned, however, that the validity of the Q^{QEF} cost parameter set is limited, as neither inflation nor cost reduction potentials are considered here. A common parameter set of the applied linear uniform cost model can also never account for the individual aspects of specific VSC HVDC projects. Nonetheless, common investment cost parameter sets are being used, no matter how valid they may be. Hence, the results of this analysis introduce a base line transparency and validity.

With the emergence of more realised VSC HVDC projects, new reference cost data will be obtained and should be included in future parameter estimations. For instance, older reference projects could be weighted less to better account for the more recent data to be dominant.

Moreover, the cost parameter evaluation and estimation methodology proposed in this context might also be helpful for cost models of other technologies and applications, especially with sparsely available reference data.

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