The potential supply risk of vanadium for the renewable energy transition in Germany

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A B S T R A C T

Vanadium-based Redox Flow Batteries (VRFBs) seem to be a promising solution for medium and large storage systems required to smooth the fluctuating provision of solar and wind energy. Beside technological considerations, the challenge for VRFBs is the availability of vanadium, influenced by the high demand by the steel and chemical sectors and the small number of mines operating worldwide. Given vanadium's toxicity, the health, safety, and environmental (HSE) implications might, too, affect vanadium's availability.

This study assesses the risks of supply disruptions associated with vanadium for VRFBs for the German market through the Holistic Risk Analysis and Modelling (HoRAM) method. The analysis includes not only technological parameters but also HSE and societal ones. In total, 242 variables were selected to characterize vanadium's supply chain. Considering a successful energy transformation in 2050, four logic-stochastic models were created to assess the supply risks associated with four different market shares of VRFBs at the storage market, i.e. 10%, 25%, 50%, and 100%.

The most crucial factor influencing the overall risk of supply turned out to be mining activities. These are driven by a lack of qualified personnel, but the HSE and societal aspects can also hamper the supply chain. Therefore, both the Government and companies should consider these aspects to better orientate their future strategies.

Of the four analysed market shares, surprisingly the 50% one has shown the lowest risk. Further, the mitigation strategy of opening the domestic market could reduce the risk of vanadium supply disruption, i.e. high impacts for VRFBs.

1. Introduction

In Germany, in 2019, wind and solar plants provided roughly 30% of primary electricity consumption [1]. By 2050 the increase of renewables is expected to significantly grow and, depending on the realized climate and energy policies, approximately 80% of the 715 TWh is likely to come from wind and solar plants [2]. With the increasing relevance of the electrical fluctuating generation, mainly coming from wind and solar plants, the need for storage systems will grow to ensure grid stability.

In this context, Vanadium Redox Flow Batteries (VRFBs) are seen as the most promising solution for medium and large energy storage systems [3–5]. VRFBs have three main advantages, namely: 1) allow for sizing power and capacity independently, 2) do not suffer from permanent self-discharge and cross-contamination problems, and 3) has a long-life cycle [6]. However, the cost of the electrolyte, which increases the energy content of the battery, combined with the lower energy density, make VRFBs unsuitable for small-scale applications [7–10].

Besides the technological considerations, which were not part of this study, supply chain disruptions, which can be caused by competing sectors, oligopolistic market structures, as well as health, safety and environmental (HSE) implications, can hamper the market penetration of VRFBs.

Vanadium is an important feedstock for both the steel and the chemical industries worldwide [11]. In Germany, the steel industry alone absorbs about 90% of the total vanadium imported [11]. Since vanadium for batteries is not recyclable yet [12], the entry of the energy sector in the vanadium market would significantly intensify the competition and put a significant risk on the reliability of the vanadium

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availability. Assuming a need of vanadium of 5,500 t/GWh, in 2050 Germany would demand to the vanadium market something between 65 kt (in case of a market share of 10% of VRFBs at the energy storage market) and 650 kt (100% market share) depending on the realized policy, the market share of VRFBs and the installed capacity [12,13]. Currently, annual vanadium's worldwide production is about 92 kt [12], thus in 2050 Germany would need from 2/3 to more than 6 times as much today's worldwide production.

Just four countries share vanadium's world resources: China with its 47%, followed by Russia at 26%, South Africa at 18%, and, finally, Australia at 9% [12,14,15]. Currently, due to strong environmental constraints affecting its production [16–18], only few mines of vanadium are in operation in China, Russia, and South Africa. This increases the risk of supply disruption. Opening new mines in Australia will not change the share of resources. China and Russia dominate the market with mainly state-controlled companies [17]. Considering the significant financial commitment needed to run mines also in the future the market will stay oligopolistic.

The potentially increasing relevance of vanadium for the energy transformation gives the respective governments a strong leverage for acting [17]. Taking into account the risks outlined above, including vanadium in the list of critical metals by the European Commission (EC) was inevitable [19].

VRFBs require high-purity vanadium pentoxide (V_2O_5) in the electrolyte to operate [20], which is a highly toxic material. It is suspected to cause cancer if inhaled during the extraction refining processes [21,22] and, should it be dispersed in the atmosphere as micro-powder, its interaction with organic and inorganic matter in sediments can impact flora and fauna [16]. Thus, vanadium's extraction and refining processes would require a mature HSE culture [23–25] to keep operations sustainable.

A few studies have discussed the risk of supply disruption of critical metals [26–32]. Viebahn et al. [26] and Weber et al. [32] considered VRFBs in their assessment studies. Their common approach is to define indicators, which address different risk components. For the risk assessment, the indicators are aggregated to a risk matrix. Frenzel et al. [27] conclude that all these methods do not adhere to the risk principle, the weakness being in the heuristic aggregation of the indexes that fail to account for the interrelations amongst the different aspects mapped by each index. In other words, they fail to consider the inter-functional risks and to make them explicit and, as such, not explicitly checkable. The selected method, i.e. the Holistic Risk Analysis and Modelling (HoRAM) method [33], fills, by construct, this methodological gap.

HoRAM is a simulation-based risk engineering method that allow performing dynamic logic-stochastic simulations and not just numerical ones that generate scenarios under the form of readable stories, each with their probability value. This way it is possible to check the goodness of both the stochastic and the logic assumptions made in the model even through the semantic of the generated scenarios (white box approach) and not just by interpreting the risk curves produced as a result of the simulations as it happens with the purely numerical approaches – i.e. the black box approach. HoRAM leverages on the Artificial Logic Bayesian Algorithm [33] that allows to consider the reciprocal interrelations amongst the considered variables, thus making the calculation of the risk and the identification of the criticalities much more realistic, i.e. reflecting the complexity of the reality. Another important characteristic of the HoRAM method is the possibility to consider variables of both qualitative and quantitative nature, thus allowing to quantify the risk even considering variables stemming from different areas of knowledge that would be difficult to merge quantitatively.

The aim of the study is to support the German energy transition by analysing the risks associated with obtaining vanadium for VRFBs. Further, the study intends to provide transboundary knowledge to researchers, industries, and policymakers. It highlights common challenges that countries and companies will have to face if they want to enhance or restrain the development and implementation of VRFBs as energy storage. Moreover, the results should foster the interaction between researchers and policymakers, grounded on the risks involved in the sustainability of emerging technologies, especially after the signalling effects, nationally and internationally, of the German Energy Transition (Energiewende) [34].

The remainder of this paper is organized as follows. Section 2 introduces the modelling approach, data, and assumptions relevant to develop this study. The modelling results and interpretation of the risk analysis is presented in Section 3. The discussion and conclusions are presented in Sections 4 and 5.

2. Model creation for the risk assessment of the vanadium supply chain

2.1. Background of the HoRAM method

A supply chain disruption of vanadium can generate complex impacts on national energy systems in particular on the reliability of electricity provision, potentially demanding a reconsideration of the chosen strategy for the energy transformation process. To characterize the risk associated with obtaining vanadium it is necessary to tackle the problem from a multi-dimensional, systemic view and the HoRAM method in that respect revealed to be suited for the purpose as it allowed characterizing systemically and systematically the entire supply chain process of vanadium. The HoRAM method, which is in line with ISO 31000 scheme [33], requires three phases to be accomplished, namely:

1) Systemic analysis: characterization of the system or the phenomenon under review.
2) Simulation analysis: characterization of the risk level and identification of the criticalities associated with the phenomenon.
3) Sensitivity analysis: identification of the solution to mitigate the risk, i.e. risk treatment and engineering, and verification their goodness by means of simulations results.

The three steps are accomplished through the creation of a simulation model, in its logic-stochastic and phenomenological components, that feeds a simulation process, performed by means of the KlaRisk® platform, a cloud-based application, allowing to analyse the risk in all its facets and treat as well as engineer it.

As a result of the simulation process, three decision-making tools are achieved, namely:

1. Critical Function List (CFL)
2. Complementary Cumulative Distribution Function (CCDF)
3. Risk Distribution Function (RDF)

The CFL identifies which variables considered in the model contribute to producing the overall risk. To put it differently, the CFL clarifies whether the overall risk is generated by a small set of variables or by a larger one. A critical function can consist of one or "n" variables. The former is a critical function of the first order, while the latter of the n^{th} order. Given the same probability value, the higher the order of the critical function, the greater the reliability of the condition considered. If different alternatives or conditions are compared, the CFL helps to understand the reliability of each alternative or condition in relation to the number of variables producing the overall risk and their order (see section 1.2 of the Supplementary Material).

Together, CCDF and RDF reveal the risk profile. The CCDF is well known in the risk engineering community as the "risk curve". It reveals the probability to exceed a chosen impact value. In cases of comparison of different alternatives or conditions, the CCDF helps to visualize which of them holds a higher risk, and in which position along the consequences range (see section 1.2 of the Supplementary Material).

The newly defined RDF shows how the risk, in terms of calculated scenarios, is distributed along the consequences range, thus clarifying how the risk profile looks like, i.e. how the imaginary line linking the peak of the classes shapes. More specifically, for each of the 100 defined classes the consequences range is divided into, the RDF reveals the risk value, and how many and what are the scenarios contributing to it, i.e. those giving the risk value of the considered class. In cases of comparison of different alternatives or conditions, the RDF helps to visualize, along the entire consequences range, where, i.e. for which classes, and how much the risk level of one alternative/condition differs from that of the other(s) (see section 1.2 of the Supplementary Material).

2.2. *Multi-dimensional systemic analysis*

The main decision-making dilemma identified during the system understanding is whether Germany should produce VRFBs by importing vanadium resources, or by importing the manufactured technology, i.e. the batteries, directly. In this regard, it is worth highlighting that Germany is Europe's leading country in the production of VRFBs, while China is the world's largest producer [15,35,36]. Germany has trade agreements with the majority of countries that have vanadium reserves [37]. On the basis of EC data [19], Europe imports firstly from Russia (71% of the overall demand share), secondly from South Africa (13% of the overall demand share) and thirdly from China (13% of the overall demand share). This study has applied the same German import priority list, yet without considering China as a further supplier of vanadium ore in the future. In recent years, the Chinese government has become more careful in managing its raw materials through the implementation of export quotas [38]. For this reason, Australia has been assumed as the third exporting country. This assumption is justified by the Australian plan of initiating vanadium mining in the next few years [12,15,39]. On a 2050-time horizon perspective, China has been then considered as a supplier of VRFBs, i.e. a back-up plan in case of vanadium ore shortage.

The production of VRFBs would raise the German consumption of vanadium. Consequently, the German energy sector would become dependent on the vanadium supplier countries as Germany has neither reserves nor stocks of the metal [19,40]. In this context, the political system of the supplier countries becomes relevant as it could determine the reliability of trade agreements. In addition, a reliable, safe, and secure logistic system would be required. This would include an adequate packaging of vanadium pentoxide to prevent possible dispersion in the environment during the logistic process and the securing of the transportation along the entire providers' value chain to prevent attacks by terrorists and pirates.

Should the production of VRFBs not be possible in Germany, either partly or completely, then importing the technology would become an additional, and perhaps the only, solution. In this situation, the technical aspects, such as the construction quality of VRFBs, add to the aforementioned variables that need to be accounted for. Fig. 1 summarizes the narrative scheme.

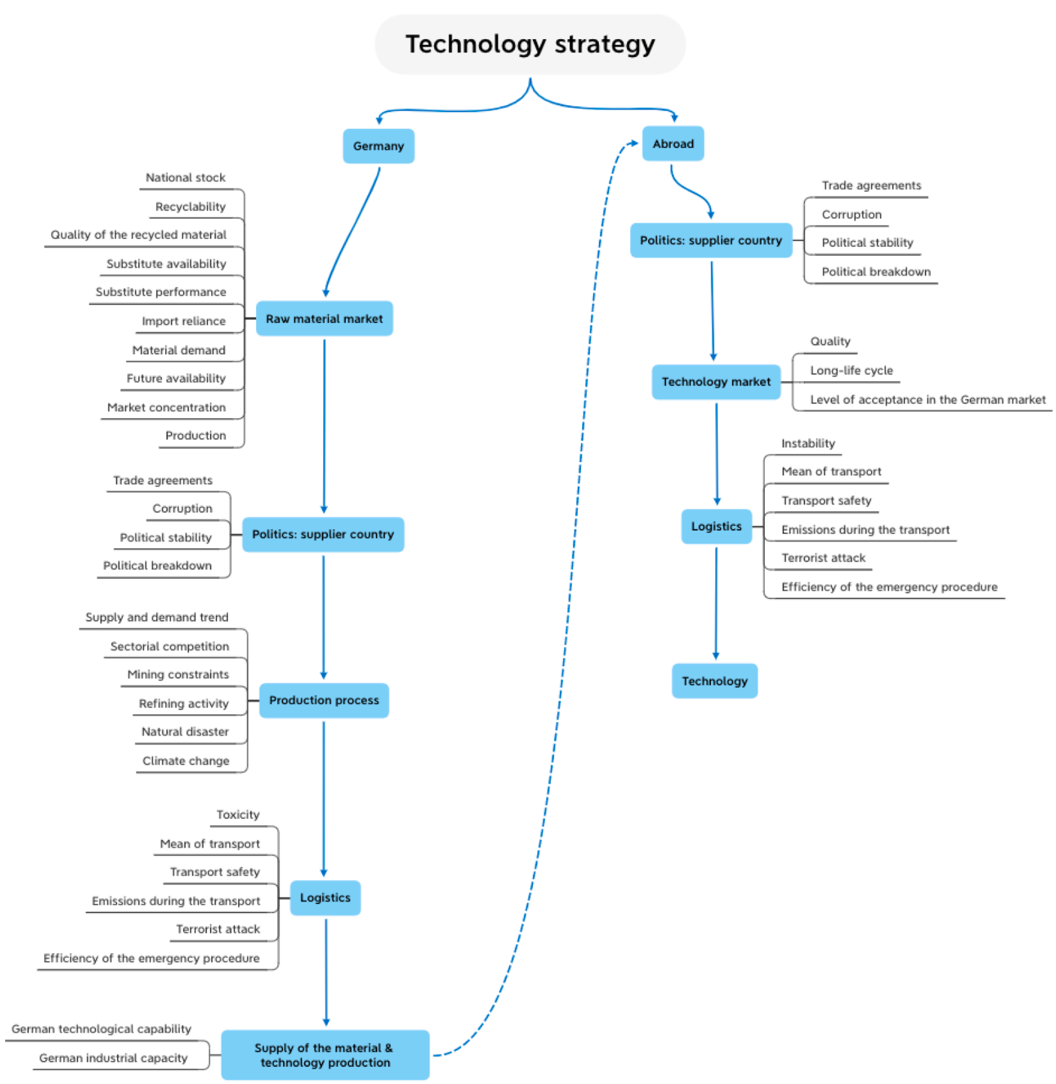

Fig. 1. Systemic analysis for the VRFBs strategies in Germany.

The identification of the relevant variables to use in the model is the first step to accomplish. To that end, a functional analysis was performed (details are in the Supplementary Material). Seven macro-areas of knowledge were identified: 1) the raw material market, 2) the production process, 3) the technology market, 4) the Health, Safety and Environment implications (HSE), 5) the logistics, 6) the community impact, and 7) the politics.

For each area, quantitative variables were defined, summing up to 242 variables. To identify the 242 variables, a review of scientific papers and reports, as well as online research, was carried out and assumptions were verified through interviews with experts in system analysis, technology assessment, supply chain, and risk assessment analysis. To reflect the phenomenon described, i.e. the acquisition of vanadium ore and/or batteries by Germany, these variables have been logically and stochastically interconnected as well as temporally ordered. The system developed gave rise to the searched logic-stochastic model. Fig. 2 shows the organization of the variables in the model according to the logical classification.

For the identification of the risk level associated with the phenomenon, each variable was assigned the respective probability value. The probability values were calculated based on both the available indexes and the phenomenological aspects associated to the variables. More specifically, amongst the 242 variables considered, 32 of them capitalize both “known and widely used” indexes, and “known but never used” for the purpose ones. “Known and widely used” indexes are, for example, the World Bank index for political stability [41], and the index provided by Transparency International for the corruption level of a country [42]. Amongst the “known but never used” for the purpose indexes, there is the one provided by Institute for Economics and Peace [43] that accounts for the terrorism aspect. The remainder of the variables are specific for this study, such as material demand as the ratio between the German vanadium demand for VRFBs and the global vanadium demand for VRFBs. Further details on the variables and references used to determine the probabilities, as well as the choices made in the calculations, are available in section 3 of the Supplementary Material.

2.3. The consequence modelling for the simulation analysis

To calculate the risk, it is necessary to value possible consequences associated with any of the 242 variables considered in the model.

The possible consequences related to a variable were valued with a number ranging from 0 to 100. The value 0 means that the variable has no impact on the supply of the raw material or the acquisition of the VRFB technology, whereas the value 100 means the impossibility of obtaining the material or the technology. The risk of a hampered access to the material or the technology is influenced by a set of factors like severe environmental problems (s. Table 1).

A total failure of accessing the material or the technology is assumed to happen when 1) the technology or material is no more at hand, e.g., due to its loss during the transportation, 2) an environmental accident occurs, e.g., vanadium getting in touch with water as it is aqueous and dilutes instantly with water, and 3) social aversion against VRFBs is fostered due to its potential environmental impacts.

2.4. Cases

The overall risk of disruption of the supply chain of VRFBs for the

Table 1
Classification of the possible impacts assigned.

Groups of factors influencing the access to the material or technology	Score
Not having the technology + Environmental problems + Social problems	100
Not having the technology	90
Not having the material + Natural disaster/ Terrorist attack + Social problems	80
Not having the material + Environmental problems + Social problems	70
Not having the material	60
Environmental with mine (social + environment + additional investment)	30
Environmental impact accident	20
Environmental problems with transport	10
Additional investment/delay/ accident with limited impact	5

Note: A score of 100 indicates the highest risk; a score of 0 would indicate no risk.

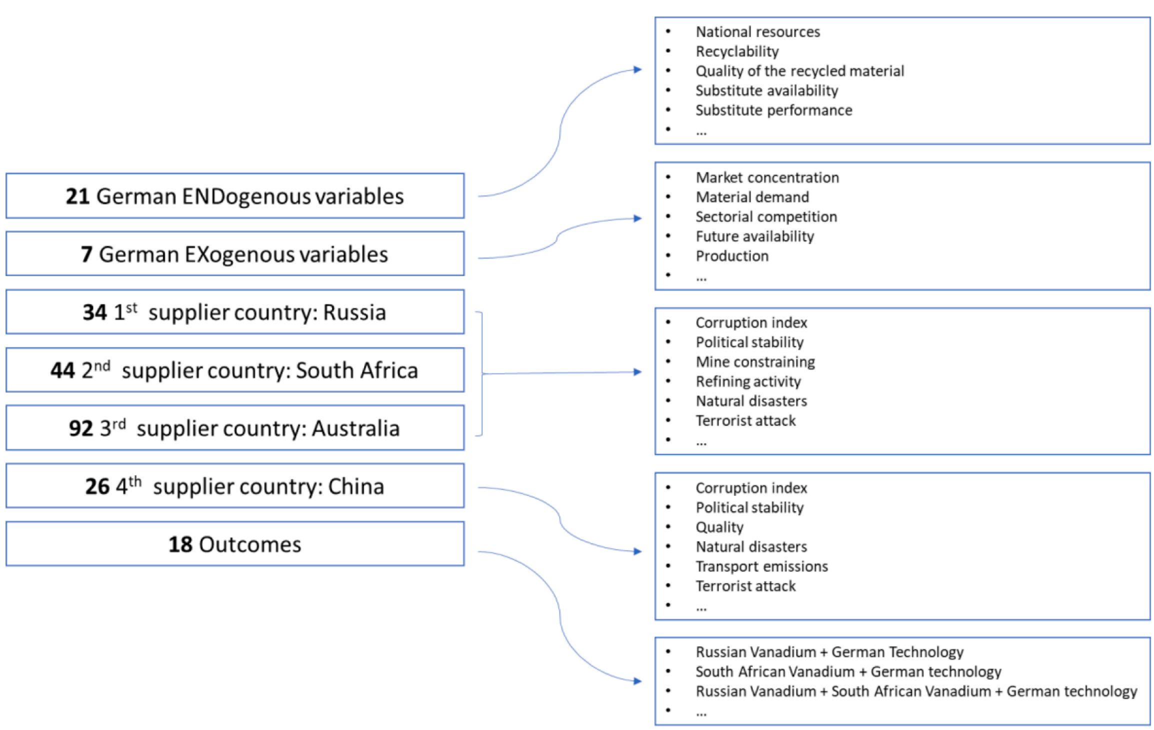

Fig. 2. Structure of the variables in the logic-stochastic model.

energy system heavily depends on the adoption relevance of VRFBs on the storage market, i.e. the higher the adoption, the higher the risk associated with a disruption. Focusing on this risk, four cases were analysed, which represent different market shares of VRFB in the storage market.

- Case 1: installed energy storage capacity of VRFBs reaches 100% of total energy storage capacity, demanding roughly 650 kt vanadium;
- Case 2: installed energy storage capacity of VRFBs reaches 50% of total energy storage capacity, demanding roughly 325 kt vanadium;
- Case 3: installed energy storage capacity of VRFBs reaches 25% of total energy storage capacity, demanding roughly 163 kt vanadium;
- Case 4: installed energy storage capacity of VRFBs reaches 10% of total energy storage capacity, demanding roughly 65 kt vanadium.

Using the energy scenario KAS-ZS-EE, which was developed within the project ENavi – Energy Transition Navigation System (www.kopernikus-projekte.de) –, representing a rather fast coal phase-out with no nuclear power, the total energy storage capacity for Germany is assumed to be approximately 20,018 MW in 2050 [13].

2.5. *Simulation model and sensitivity analysis*

The simulation is performed by means of the KlaRisk® platform. By feeding the software with the created logic-stochastic model, it generates all the possible scenarios that correspond to all possible ways in which the acquisition of the vanadium can manifest; ways that depend on the variables included in the model and their reciprocal logical constraints and stochastic influences. For the purpose of the study, a probability cut of 5E-8, i.e. 5 occurrences in 100 million, was applied. Thus, only the constituents, i.e. the stories, with a probability of occurrence equal or higher than the cut value were analysed during the simulation. The stories below that cut are ignored, thus implying that they are not meaningful from a decision-making point of view [33].

The decision on the cut to apply was made based on two aspects, namely: 1) the variable with the lowest probability value, and 2) the simulation time, which was around six hours for each case. The lowest probability value in the model is that of an aircraft accident, which is equal to 1E-6 (one in a million). It is good practice to position the probability cut from 2 to 3 orders of magnitude below the lowest probability value. To limit the simulation time the probability cut was kept between one and two orders of magnitude lower than the lowest probability value.

Once the model was built in its logic-stochastic and phenomenological components and the simulations performed, the risks calculated as the product of probability time the magnitude were calculated for each scenario and for the entire universe of possible scenarios, thus allowing to derive the risk profile, i.e. CCDF and RDF, and the criticalities. This done, a sensitivity analysis was performed by changing the assumptions, probabilities or modifying the consequence values to analyse the change in the risk profile both for the CCDF and the RDF, as well as in the CFL, i.e. to check whether the criticalities were the same and with which relative contribution to the overall risk. This step was useful to examine whether the proposed changes would have brought an improvement of the overall risk, and to verify the system's sensitivity to some modification of the "boundaries".

3. Risk analysis results

3.1. *Critical functions*

To identify the relevant CFL, which lists the critical variables considered in the model prioritized by their contribution to the overall risk, the universe, i.e. the number of scenarios generated by the simulation, for each case was calculated. The universe ranges between 1.623 million (Case 3) and 1.654 million scenarios (Case 2; s. Table 2). The residual probability, i.e. the number of scenarios not analyzed reflecting the cut applied to the simulation spans between 2.76E-01 (Case 1) and 9.57E-02 (Case 2).

Table 2 reveals the critical functions associated with the four cases analyzed, yet limited to the four most important one resulting in a contribution of these ranging from 69% (Case 2) to 83% (Case 1) of the overall risk. The complete table can be found in the Supplementary Material. The four critical functions are dominated by a small set of variables: ten variables (Case 1), eleven variables (Cases 2 and 3), and seven variables (Case 4), respectively, out of 242 variables. That means that the overall risk is highly concentrated.

The constraining of the Russian and Australian mines is highly relevant and common to all cases, whereby the supply disturbances from Russian mines shows the highest risk. The corruption level in Russia and a potential Russian breakdown are also relevant, but the importance differs amongst the cases. Vanadium co-production shows an interesting

Table 2
Most important critical function of the four cases.

	Case 1 – 100% VRFBs	Case 2 – 50% VRFBs	Case 3 – 25% VRFBs	Case 4 – 10% VRFBs
Universe	1,648,685	1,654,742	1,623,592	1,631,451
Residual Probability	2.76E-01	9.57E-02	6.21E-02	2.73E-02
Critical Function 1	Vanadium co-production + Constraining of Russian mines (2nd order)	Constraining of Russian mines + Constraining of Australian mines (2nd order)	Constraining of Russian mines + Constraining of Australian mines (2nd order)	Constraining of Russian mines (1st order)
Cumulative Risk	41.71%	33.41%	33.16%	47.25%
Critical Function 2	Vanadium co-production + Russian corruption + Russian breakdown (3rd order)	Russian corruption + Russian breakdown + Constraining of Australian mines (3rd order)	Russian corruption + Russian breakdown + Constraining of Australian mines (3rd order)	Vanadium co-production + Constraining of South African mines (2nd order)
Cumulative Risk (CF 1+2)	72.32%	49.83%	49.46%	63.10%
Critical Function 3	Vanadium co-production + Russian instability+ Russian breakdown (3rd order)	Russian corruption + Russian breakdown + Constraining of South African mines (3rd order)	Russian corruption + Russian breakdown + Constraining of South African mines (3rd order)	Russian corruption + Russian breakdown + Constraining of Australian mines (3rd order)
Cumulative Risk (CF 1+2+3)	79.89%	62.72%	62.22%	73.19%
Critical Function 4	Vanadium co-production + Constraining of Australian mines (2nd order)	Russian instability + Russian breakdown + Constraining of Australian mines (3rd order)	Vanadium co-production + Russian corruption + Constraining of Russian mines (3rd order)	Vanadium co-production + South African terroristic attack (2nd order)
Cumulative Risk (CF 1+2+3+4)	82.97%	69.04%	70.81%	78.57%

Note: CF: Critical Function.

pattern, with a noteworthy divergence between the cases regarding its relevance. Whereas vanadium co-production is highly relevant in Cases 1 and 4, its contribution is quite low in Case 3 and is not included in the six most important variables in Case 2.

The relevance of Russia, as well as of Australia and South Africa, is due to the assumed import structure that sees Germany importing primarily from Russia, then from South Africa and, finally, from Australia. China is treated as a back-up for the reasons stated earlier in case of the impossibility to import the ore [15,35,36].

Comparing the four cases, one can easily notice that Case 4 differs from Cases 1-3. In Case 4, the first critical function, which is of the first order as it is composed of just one variable, contributes nearly half to the overall risk, i.e. 47.25%. In all other cases, two variables are required to reach even a lower risk contribution, ranging from 33.16% to 41.71% (Table 2), thus indicating a higher vulnerability of Case 4 compared to the other cases. The most relevant variable in Case 4 is the “Constraining of Russian mines”. For Cases 2 and 3 to reach a comparable risk level to Case 4, i.e. around 49%, it is necessary that two functions fail. This means that three other variables need to be added to the “Constraining of Russian mines”, namely: 1) “Constraining the Australian mines” for critical function 1, and 2) “Russian corruption” jointly with 3) “Russian breakdown” for critical function 2. Case 1 presents a different situation, as “Vanadium co-production” and “Constraining Russian mines” together (critical function 1) are sufficient to reach 41.71% of the risk, which is comparable to that of Case 4. In this study, mining activities include refining processes.

The demand volume of the German energy market mainly drives the different relevance. In Case 4, the demand of VRFBs is quite low and, thus, it can be satisfied by the available extraction technologies. As Russian mines have the highest market share (71%), in this case they dominate the risk portfolio. With higher demands for VRFBs, i.e. Cases 2 and 3, the possible supply disruption by Australian mines needs to be added to those of Russia to create a critical situation. In Case 1, the demand for VRFBs is so challenging that it requires a switch of extraction technologies. Whereas, currently, co-production dominates the extraction of vanadium, a high demand for VRFBs, as Case 1 assumes, imposes a revaluation of the production scheme, i.e. the reason for extraction should be primarily to satisfy vanadium’s demand by VRFB producer.

3.2. Risk curves

The risk profile, as it is set by both CCDF and RDF, depends on the strategy adopted by Germany in acquiring VRFBs. The two strategies considered in the study were as follows:

- Strategy A: the domestic demand for VRFBs is completely satisfied by German companies, which assign the production either to German or Chinese production sites,
- Strategy B: only a part of the German demand for VRFBs is satisfied by German production; the rest is imported.

The risk curve, as it is shown by CCDF, of the strategy A is visualized in Fig. 3. Up to an impact value of 300, the slope is quite smooth, but from that value onwards, it gets steeper. This trend is similar for all cases. This means that up to the value 300 the percentage of adoption of VRFBs has no or little influence on the risk. Beyond that threshold, the risk associated with the different shares starts making the difference although that difference is not graphically so marked. Further, from an impact value of 400 the difference between the cases remains constant.

Beyond the impact value of 300, Case 1 (blue line), i.e. a market share of 100%, shows the highest risk, i.e. the probability of exceeding the chosen impact values, while Cases 2 and 3 (green and red respectively) hold the lowest risks; the difference between Cases 2 and 3 is subtle. Counterintuitively, Case 4, as the market adoption for VRFBs is the lowest, i.e. 10% market share, is in between. These results are coherent with the explanation given above on the critical functions. The lowest risk brought by Case 2 is explained by the fact that 50% market share, on the one hand, would impose a move from co-production to primary production; but, on the other hand, would not imply a critical German demand in terms of quantity as for Case 1.

A slightly different risk behaviour can be observed for strategy B (Fig. 4). Overall, the market share differences are slightly more marked than in strategy A. The overall risk is lower as the risk curve has, for the same magnitude values, a lower probability of exceeding the chosen value.

The reason why the four risk curves are flattened for most of their length is reasonably ascribable to the fact that the installed capacity for the decarbonized scenario (20,018 MW) is extremely demanding in terms of vanadium needs for all the four assumed market shares. Thus,

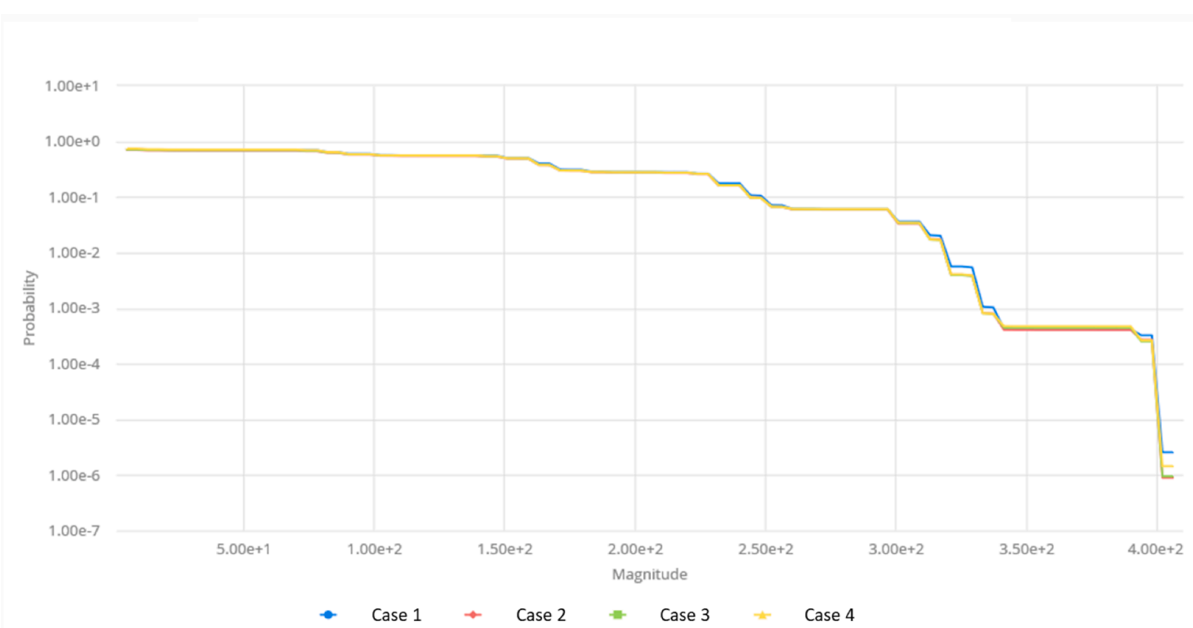

Fig. 3. CCDF for the market shares for the strategy A.

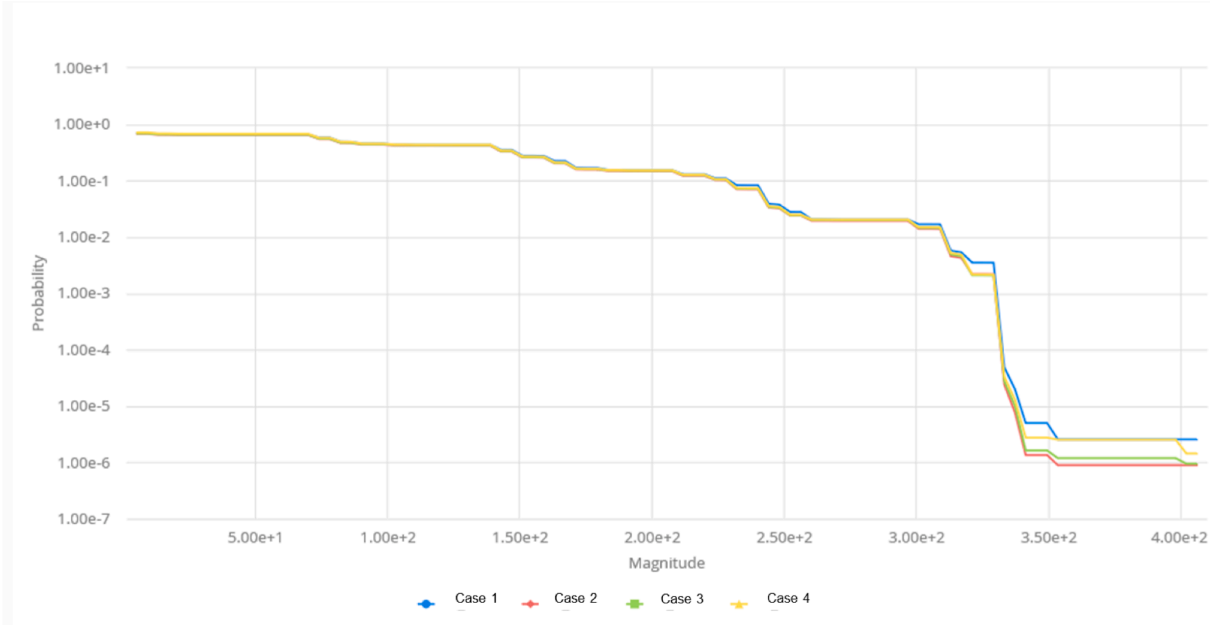

Fig. 4. CCDF for the market shares for the strategy B.

the differences can only be appreciated at the higher levels of risk, where even the minor effects are amplified. However, looking deeper at Figs. 3 and 4, one might notice that the differences amongst the percentages of adoption beyond the value 300 are more marked in Fig. 4. This means that, at higher impact values, a strategy aiming at allowing for more supplier of the material or the technology to satisfy the domestic demand would reduce the overall risk. Fig. 5 shows, for Case 2, how the different behaviour between the two strategies is particularly evident around the value 330, where the risk for strategy B (red line) drops significantly.

Tables 3 and 4 summarise the results for the four cases for strategies A and B respectively.

As it can be seen in Tables 3 and 4, the minimum impact value and the maximum one is identical for all cases and strategies, ranging from 5 to 410. The only difference can be found in the expected damage and the total probability, i.e. the probability of all scenarios contributing to producing the overall damage. This justifies the difference in the risk profile.

3.3. *Risk distribution*

Similar considerations can be made by analysing the Risk Distribution Function (RDF). The advantage of the risk spectrum is that it allows verifying both where and to what extent the risk increases or decreases, and whether it changes its profile or remains the same. In the RDF, the scenarios produced for each case are distributed in the 100 classes of the

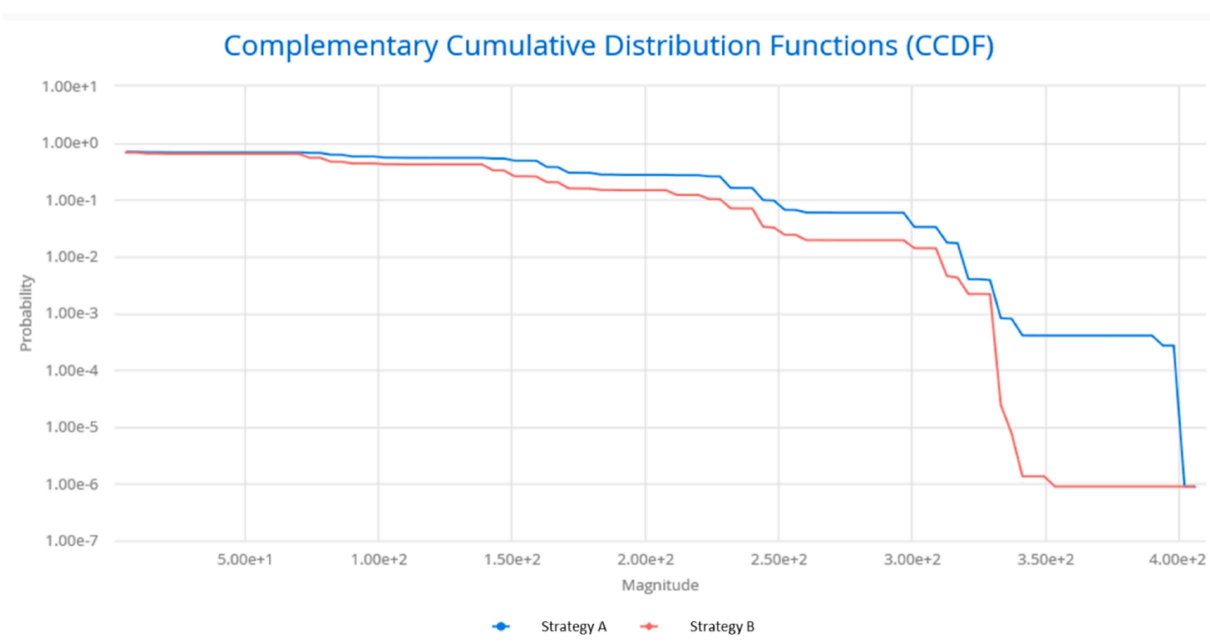

Fig. 5. Comparison of both strategies in Case 2.

Table 3
Risk values for the cases for the strategy A (refers to Fig. 3).

	Residual probability	Max conseq.	Min conseq.	Expected damage	Total risk	Total probability
Case 1 – 100% VRFBs	2.76E-01	410	5	178.91	129.32	72.28%
Case 2 – 50% VRFBs	9.57E-02	410	5	178.62	125.57	70.30%
Case 3 – 25% VRFBs	6.21E-02	410	5	178.30	127.16	71.31%
Case 4 – 10% VRFBs	2.73E-02	410	5	174.23	129.44	74.29%

Table 4
Risk values for the cases for the strategy B (refers to Fig. 4).

	Residual probability	Max conseq.	Min conseq.	Expected damage	Total risk	Total probability
Case 1 – 100% VRFBs	2.76E-01	410	5	141.37	99.10	70.09%
Case 2 – 50% VRFBs	9.57E-02	410	5	140.46	95.41	67.93%
Case 3 – 25% VRFBs	6.21E-02	410	5	140.77	96.84	68.79%
Case 4 – 10% VRFBs	2.73E-02	410	5	138.96	99.75	71.79%

consequences range, according to their risk and consequence values. For each class, the contribution to the risk is then calculated.

Looking at the risk distribution of Cases 1, 2 and 3 for each strategy, no clear-cut trend can be revealed. That means, depending of the class investigated, either Case could contribute the most to the risk. Some classes occur only for one Case, e.g. at strategy B the class 400. Comparing the profile of the risk distribution of both strategies for Cases from 1 to 3, the profile are quite similar as long as the magnitude of consequences is below about 300 (Figs. 6 and 7). This pattern changes beyond that threshold. Additional classes are observable for Strategy A.

A more detailed analysis confirms this broad picture, as shown for the Case 2 in Fig. 8. However, as long as the magnitude of consequence is below 300 the contribution of each class to the risk is, with some exception, basically the same, i.e. a clear-cut trend not observable.

Beyond that threshold strategy B, i.e. German production supplemented by imports, is better as it brings less risk. Actually, strategy A shows five new classes at high values of magnitude with respect to the second strategy. This is exactly the phenomenon of the change in risk profile: the risk not only changes its overall quantity, i.e. it is lower or higher, but even its quality, i.e. there is more risk of higher classes than that of lower ones and vice versa. The risk curve cannot represent this phenomenon. The Supplementary Material shows the extraction of the class details available in KlaRisk® for one of the cases analysed.

3.4. Multilevel analysis of the mining processes

As shown in Table 2, the constraint of mines is the most critical variable common to all cases. This study uses a multilevel approach to investigate and highlight which are the variables that are critical for the mining activity. In practice, a variable at the macro scale, which was the aggregation level of the analyses presented above, becomes a subsystem at the meso scale, made up of variables that are visible only at that level of analysis. The usefulness of performing a multilevel analysis is provided by the insights that might emerge from a different level of analysis, and that can allow to envisage possible preventive measures by the German government or companies to reduce the risk. Further, the findings at the meso scale can be used to feed the macro model as was done in this study.

To create the generalized model for mines, the "Mokopane Vanadium project" in South Africa was selected [44]. It is worth noting that the general structure of the meso model could be used to analyse any other mine, as it would simply require to adjusting the probability

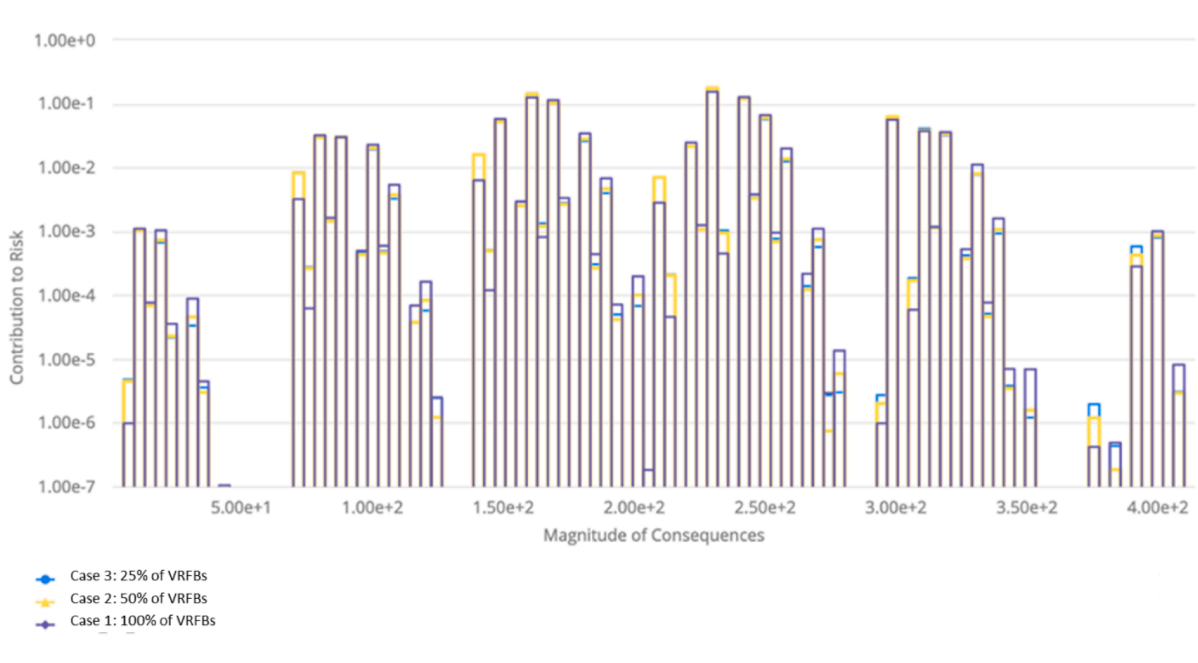

Fig. 6. RDF for Cases 1 to 3 for the strategy A – homologous of Fig. 3.

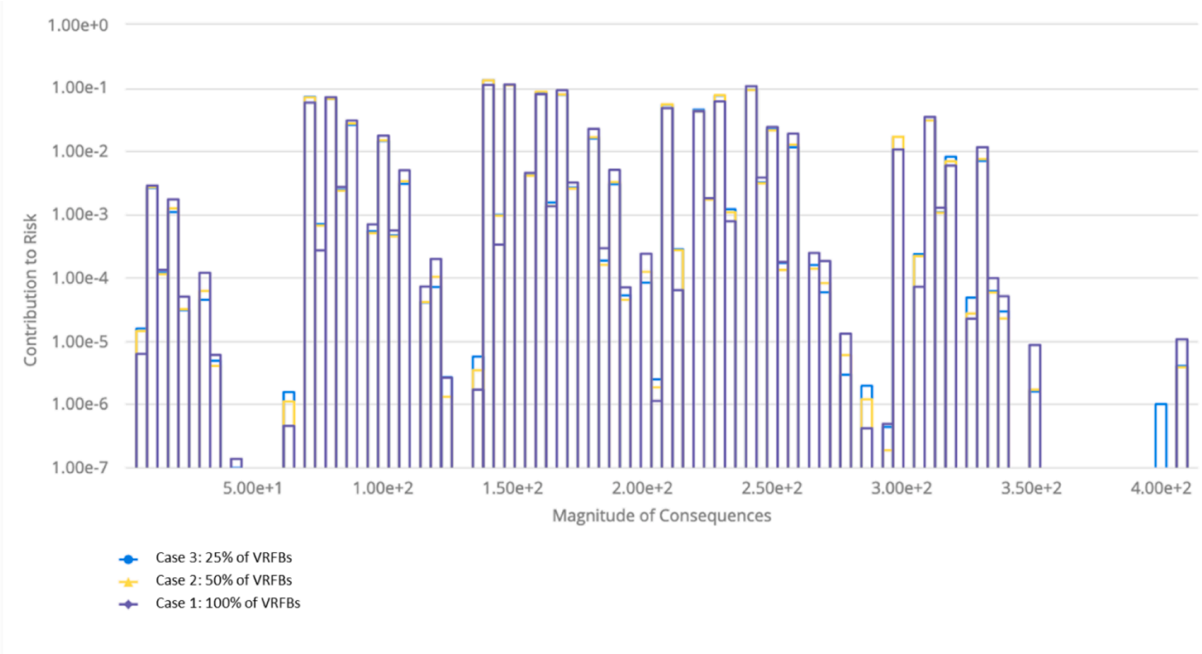

Fig. 7. RDF for Cases 1 to 3 for the strategy B – homologous of Fig. 4.

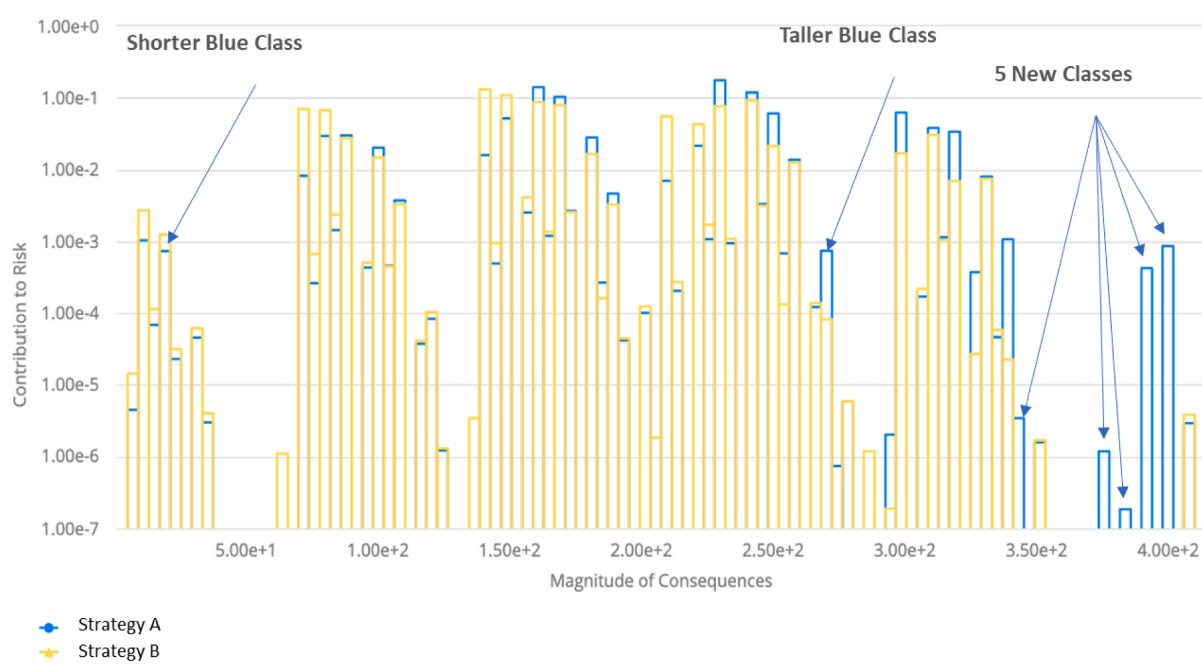

Fig. 8. Comparison of RDF of both strategies in Case 2 – homologous of Fig. 5.

values. The logical structure would remain the same.

Table 5 shows the critical functions contributing to generate 80% of the overall risk. More information and all the assumptions made can be found in the Supplementary Material.

The first thing that one might immediately notice is that, contrary to the analysis at macro level, there are only critical functions of the 1st order, i.e. each critical function is made up by one variable only. This means that the “vanadium supply system”, i.e. the macro system, is less vulnerable or more reliable than its most critical “mine subsystem”.

The absence of qualified personnel is the first criticality identified, with a weight of 34.56% to the overall risk. It is assumed that this variable increases the probabilities of failure for HSE influences and the uncertainty of having reliable data on soil condition and weather forecasts; thus, there will be a higher probability of floods with respect to the forecasted ones, and slope and tailings instability. The second critical function addresses the societal problem linked to the presence of communities that must be relocated, and that are abandoned by the company. The third critical function has to do with the HSE consequences during the excavation of the slope, and finally, the possibility of having high HSE implications after the collapse of the tailing, both for the magnetic and the calcine separator. The first four critical functions alone contribute to generate more than 75% of the overall risk, i.e. the risk is highly concentrated. Knowing these elements might turn out to be worthwhile for German politicians, as they can capitalise on this

Table 5
Major findings of the risk analysis for the mining activities.

	Mining activities - Mokopane Vanadium project
Universe	115.503
Residual Probability	3.60E-08
Critical Function 1	Absence of qualified personnel
Cumulative risk	34.56%
Critical Function 2	Local communities must be relocated
Cumulative risk (CF 1+2)	52.70%
Critical Function 3	Local communities are abandoned
Cumulative risk (CF 1+2+3)	65.44%
Critical Function 4	HSE consequences during the excavation activities
Cumulative risk (CF 1+2+3+4)	75.51%
Critical Function 5	Injury due to the Magnetic separator (Magsep) residue disposal facility collapse
Cumulative risk (CF 1+2+3+4+5)	77.95%
Critical Function 6	Injury due to the calcine residue disposal facility collapse
Cumulative risk (CF 1+2+3+4+5+6)	80.01%

Note: CF: Critical function.

information by deciding to invest more efforts in negotiating trade agreements with those countries that pay more attention to fostering the creation of qualified personnel and increasing their HSE maturity, which might not necessarily be those countries with higher vanadium reserves. To put it differently, analysing the problem from a different level of abstraction (upwards or downwards) can help identifying those leading indicators that might turn out to be useful to support the decision-making process.

3.5. Sensitivity analysis

The findings of the analysis at macro level indicate a high relevance of the Russian situation in term of both political stability and corruption level. These results are coherent with both the assumed import structure for Germany and the fact that Russia is the most important exporter of vanadium ore. Then the question arises: could a change in the German import strategy influence the risk profile? Put it differently: could a change of the import structure reduce the overall risk of a supply chain disruption?

To give an answer to that question, the macro model used to characterize the four cases with different shares of adoption of VRFBs and with the two production strategies was divided in four models to allow analysing the risks associated with each exporting country in a more precise way. The outcome of the analysis are summarized in the Figs. 9 and 10. It should be noted that only Australia, Russia, and South Africa were taken into account, since it was assumed that China would restrict its exports of vanadium.

Looking at the risk profiles, as revealed by the CCDF and RDF, focusing only the export countries, the maximum magnitude of consequences drops from 410 to around 250. The maximum value of Australia trails behind the one of Russia and South Africa (Fig. 9). As long as the magnitude of consequences is below around 70, the CCDF of Australia shows the highest probability. This changes in the region between 70 and 170, where South Africa shows the highest values, trailed by Russia and Australia equally. From a value of 170 onwards Australia shows the lowest risk, i.e. lower probability per magnitude of consequences, whereas Russia and South Africa alternate their ranking.

Considering the risk distribution in all classes, Australia's contribution to the risk is always the lowest one. Comparing Russia with South Africa, no clear-cut pattern can be observed (Fig. 10). This can be considered as an opportunity for Germany, and as advice for policy makers and investors, to continue with the trade agreements initiated with the Australian government [15].

4. Interpretation of the results and future possible improvements

4.1. Interpretation of the results

The macro scale analysis showed that the mining and refining processes are the most critical variables for the supply of vanadium (Table 2). The meso scale analysis showed that the availability of qualified personnel (process-related aspect), the community reallocation (societal-related aspect) and the Health, Safety and Environmental implications (HSE-related aspect) are the most relevant variables that supplier countries ought to address in order to make their vanadium production reliable. The possibility of an interruption, due to societal and environmental constraints, seems to be the most critical outcome. This might be reasonable considering the continuous and growing interest in climate change and supporting land cleaning and societal wellbeing.

Political aspects become a critical variable when considering the international trade of a good. At the current stage of development and with the current level of knowledge, the CCDF and the RDF showed that 50% market adoption of VRFBs presents the lowest risk compared to the other cases analysed (see Section 3.1). The change in the risk profile is then not only given by the amount of metal demand for VRFBs, but by political-related aspects. Thus, under the assumption that German

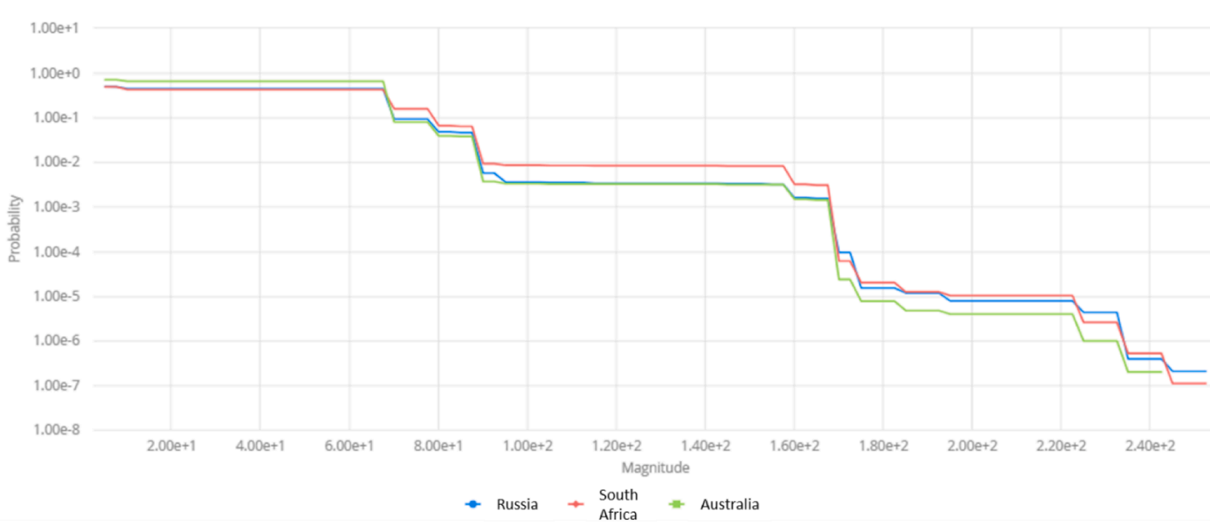

Fig. 9. Compared CCDFs for the sensitivity analysis on the separated supplier countries.

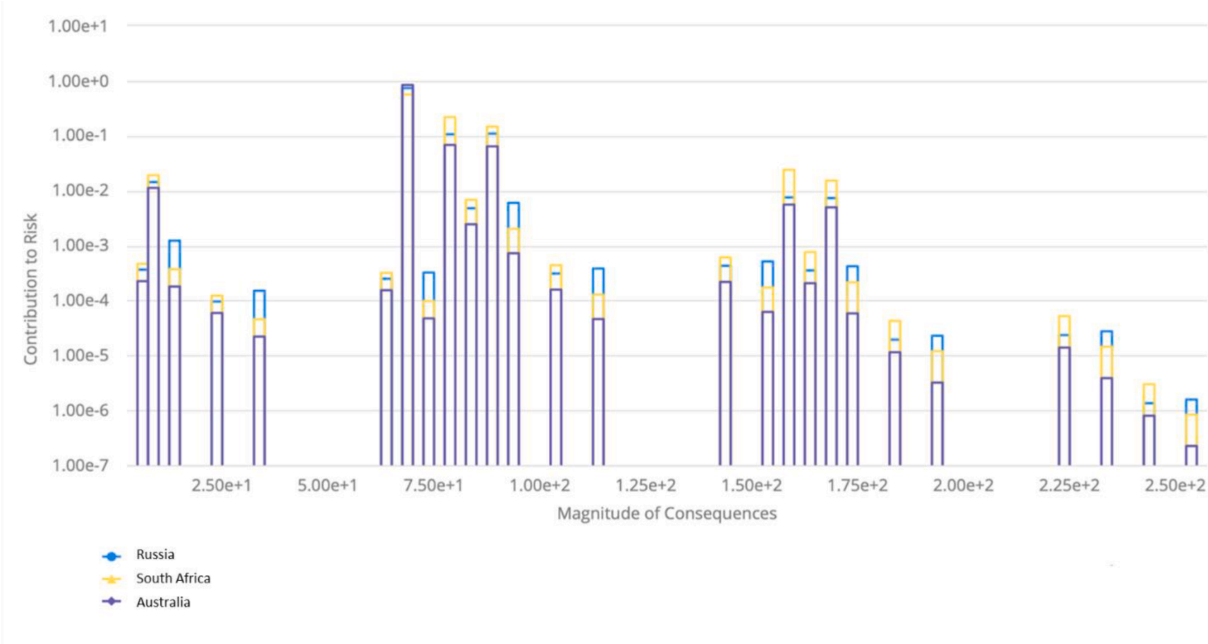

Fig. 10. Compared RDFs for the sensitivity analysis of the supplier countries.

companies in China have the same access to vanadium as Chinese companies, having German companies in China makes it possible to consider vanadium availability not to be a top priority. This would allow a focus of efforts on national and diplomatic aspects.

To improve the robustness of the supply chain of vanadium for VRFBs, the supplier countries were analysed separately, with the goal of ranking them. Amongst Australia, Russia, and South Africa, the results demonstrated that Australia, thanks to its expected long-term political stability, would be the most reliable country for the supply of vanadium.

Global security problems are increasingly more important, and it is not possible to perform a risk assessment on the availability of a critical good without considering this aspect as a possible variable contributing to the overall risk of supply. From the results of Case 4 (10% of adoption of VRFBs), "South African terrorist attack" appears as a contributing cause of the 4th critical function, which weights alone for more than 5% of the overall 80% shown in Table 2. It is worth noting that even for the other three cases, security aspects appear in the list of critical functions, yet as contributors to generate the remaining 20% of the overall risk (the full list of the critical functions is reported in the Supplementary Material). Thus, the second-best supplier country would be Russia for its assumed higher capability to face terrorism.

4.2. *Future modelling improvements*

The macro model in its current version accounts for the economic aspects only indirectly e.g. mining, refining, and transport economic activities as a weighting assignment. Investment potentials, prices, profits of available VRFBs and vanadium ore itself need to be further investigated and better modelled. Given the importance of these aspects in the supply of strategic goods, it is expected that the results of the analysis would change as result of their introduction into the model. For example, a high investment potential is expected to lead to a higher probability of supplying the material in a situation where high material demand and high sectoral competition is present. The supplier countries are not classified based on the price at which they sell the material after mining and refining to the required purity grade. Moreover, the fluctuation of the material's price can significantly modify the preference of buying the material with respect to importing the technology. Finally, this study assumed co-production as a global variable and not a national one. In the model, the vanadium is either co-produced or primarily produced. However, this assumption is probably too conservative as, in practice, it could be co-produced in one country and primarily produced in another, thus giving more flexibility to the overall supply system with a consequent lower risk.

5. Conclusions

This study has paved the way for quantitatively defining the risks associated with the supply of vanadium for VRFBs in a broad and complex way that can embrace all the topics surrounding it. Four different cases were analysed, differing between different market penetration rates of VRFBs, i.e. 10%, 25%, 50%, and 100%, with two different implementation strategies, i.e. German companies as producer both in Germany and in China with German companies, and Germany as producer in Germany only and importer of the technology at need.

The application of the HoRAM methodology allowed analysing quantitatively, and at different levels of abstractions (that benefited from one another), the complex system behind the supply of a raw material.

The study confirmed the high relevance of mining, including refining processes, for a secure supply of vanadium [30]. Beyond that, the study highlights that, amongst the four analysed cases, that bearing the lowest risk is 50% market adoption. This result is counterintuitive, as one might have expected the 10% of adoption be the lower. More deeply, the study revealed that the strategy selected to achieve 50% market adoption makes a substantial difference, and that there is no a clear, easy cut in the decision. There is not a condition for which the risk profile is lower along the entire consequences range. Of the two strategies analysed, the second, i.e. supplementing the German production of VRFBs with import, would be preferred by a decision-making strategy that privileges the effects at high impact values, while the first would be preferred by a decision-making strategy that privileges the effects at low impact values – probably less popular.

A further analysis was performed to unveil the impact of the supplier country on the overall supply of vanadium and Australia was identified as the country with the lowest risk. Thus, trade agreements with Australia could reduce the risks of disruption.

Given the importance of the mining activity, an in-depth analysis was performed to identify the criticalities associated with it. The results showed that the three major critical variables that can put mining production at risk are: 1) the lack of qualified personnel, 2) the societal problems linked to the presence of communities that must be relocated and that are abandoned by the company, and 3) the HSE consequences during excavation activities. Awareness of these aspects, which are at different levels of abstraction, can contribute to support the decision maker in directing efforts towards those countries that are more mature in paying attention to those aspects and not necessarily towards those having more metal reserves, thus allowing them to tackle risk prevention from a different perspective and at source.

Finally, it is worth highlighting that the models were created in a way that could be easy to adapt to analyse the risk associated with other potentially competing raw materials, such as lithium.

CRediT authorship contribution statement

Angela Ciotola: Data curation, Software, Methodology, Writing - original draft. **Maryegli Fuss:** Conceptualization, Visualization, Investigation, Writing - original draft. **Simone Colombo:** Methodology, Software, Supervision. **Witold-Roger Poganietz:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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