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Expert opinion on the final report "continuation or restart?" and on related questions from mayors

With focus on technological aspects

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1 Assignment and basis of the expert opinion

The Ventilus Regional Spatial Plan (GRUP Ventilus) is intended to provide the necessary planning basis for the Ventilus project, which envisages a new transmission line to ensure 6 GW of additional transmission capacity in West Flanders from Bruges to the existing 380-kV-network around Izegem/Avelgem, as well as a new substation to provide infeed capacity for connections across the coast. Due to the scale of the Ventilus project and the nature of the process, there are many questions and contradictions in the region. A report was prepared by experts to clarify these issues. This expert opinion, entitled "Weitermachen oder Neustart?" and completed on February 28, 2022, touches various aspects of the VENTILUS project.

The Flemish government approached me as an expert in electrical power networks and High Voltage Direct Current (HVDC)-Technology and asked me to review the technological part of this report. This is section 5.1 of the report entitled "Results of the research on technology" and conclusions derived from it. This includes the conclusions presented in the related sections of Chapter 6. As I am not an expert on magnetic fields the comments will focus on the contents of section 5.1 and 6.2.1.

My expertise is based on 25 years of professional experience (after PhD) in the field of operation and design of electrical power systems with special focus on modern network control systems, HVDC and FACTS. Before I was appointed as a university professor, I worked for a manufacturer of power system technologies with an international focus in research, development and application. As a university professor, I have been working continuously on research projects with transmission system operators, distribution system operators and manufacturers for more than 15 years now. This allows me not only to know the current status in research, but also to be able to assess the state of the art and industry-specific and practical issues.

My understanding of the assignment is that I will comment on the related statements in the report with respect to completeness and accuracy of content, and comment on whether the conclusions derived from them are, in my opinion, valid and correct.

In the second part of the document, I will provide answers to the mayors' questions. The questions are available to me in a PowerPoint presentation entitled "Doublecheck Gleichstrom–vorschlag, Verfahren und erforderliche Informationen". In total there are 6 questions formulated.

Both the final report mentioned above and the PowerPoint file with the questions are available to me in a German translation. Furthermore, I was provided with a German translation of the report from Filip Vanaeken, dated August 30, 2022, entitled "GRUP VENTILUS, UMSETZ–UNGS-MÖGLICHKEITEN". I interpret this document as additional information. It is neither my task nor the objective of this expert opinion to analyze or comment on the contents of the report written by Filip Vanaeken.

In the following, I refer to the *state of the art* in several paragraphs. My understanding of the *state of the art* is based on §49(1) of the German Energy Law (Energiewirtschaftsgesetz, EnWG) in the current version, which regulates the requirements for power systems with respect to applied technology and methods. There, in free translation, a technology (or method) is referred to as state of the art if there are *generally accepted rules of technology* for it. Compliance of applied technology or methods with the generally accepted rules of technology is assumed if the technical rules of the VDE (German Electrical Engineering Association) have been complied with. The state of the art is therefore given when the majority of experts from manufacturers, users and academia are of the opinion that it is the state of the art and there are application rules in the above-mentioned sense for it.

My expert opinion is divided into two main chapters. Chapter 2 contains the results of the review of the technical part of the report in German language "Weitermachen oder Neustart?" dated 28.02.2022. In chapter 3 answers to the six questions of the mayors are given.

2 Review of the technical part of “Weitermachen oder Neustart?”

The technical part in terms of technology for the transmission network is essentially section 5.1 of the aforementioned report. In the following the report "Weitermachen oder Neustart?" dated 28.02.2022 will be referred to as the “report”.

2.1 Technical background, methods and system aspects

The technical part in the sense of technology for the transport network is essentially section 5.1 of the above report. Here, a rough outline of the VENTILUS CONNECTION and the current developments with regard to the need for adaptation of transmission networks due to the energy transition is given (section 5.1.2).

In section 5.1.3, the basic technological options for the expansion of transmission networks are presented. In AC technology, the author concludes that cabling at rated voltages up to 150 kV in Belgium (for comparison 110 kV in Germany) can be considered state of the art and is common. AC cables of higher voltages are limited in length to a few km due to their electrotechnical characteristics. These statements can be confirmed as comprehensive and correct. In addition to the remarks in the report, it should be mentioned that theoretically several such cable sections could be built one after the other with intermediate stations and compensation equipment. Practically, it is not known today how such a construction can be operated due to the large number of resonance points and is therefore not state of the art.

The following is a description of the HVDC technology. For the application in context of the Ventilus project only so called VSC-HVDC technology can be applied. Currently the voltage rating is limited to +/- 525 kV and the maximum power rating is roughly 2.5 GW per system. In my opinion, the explanations are comprehensive and correct. Regarding the possible ratings, it should be noted that a system rating of around 3 GW would certainly be possible even with a slight increase in the voltages and currents. The report does not explicitly state that VSC

HVDC with long cable paths and a nominal voltage of 525 kV are currently being built (e.g. in Germany), but that there is no experience in Europe in the commercial operation of such systems with land cables. It can be assumed that such a technology can be built and operated.

With regard to DC networks, I share the author's statements. There are currently many research projects in this direction and when setting up backbones for the transmission network, it would make the most sense to strategically build a new network level in DC technology. However, the technologies required for this in terms of equipment technology are not yet fully developed and the control software for the operation of such DC networks is also still far from the state of the art. In my estimate, this will only be available in the decade after 2030. An acceleration of this development could take place by defining something like this as a strategic expansion objective for the entire transmission grid in Europe - and indeed internationally.

The only real installation of a VSC-HVDC-grid is the Zhangbei[1] demonstration project in China, where a multiterminal network has been built on a 1:1 scale and it includes one mesh. In Europe, work is currently underway on multiterminal VSC-HVDC (without meshing). One example is the German Ultranet[2] project.

Section 5.1.4 describes the basics for the operation and planning of electrical networks, the influence of market behavior on power flows in the network and the importance of meshed networks as well as the treatment of network bottlenecks. The facts presented are comprehensively described and correct.

An important aspect also discussed here is the distribution of power flows in a meshed network according to the electrical impedances of the lines and the fact that parallel lines with different internal resistances can also carry different power flows unless special network controllers are used. These could, for example, influence the power flow and thus the load on lines when installed in a network mesh. With DC technology, this controllability is inherently available. In this respect, a DC line can also be used for AC network controllability, depending on the network configuration.

The following sections in 5.1.4 include remarks on the task of the transmission system operator in general and in particular in the structure of society, regulator and legislation. The statements are correct and there is nothing to add to them.

Section 5.1.5 deals with grid security aspects - in particular the (N-1) principle, which is the basis for secure grid operation and mandatory due to ENTSO-E regulations. In the design with 4 x 1 GW cable on the Stevin/Horta line and a parallel 2 x 3 GW design (Ventilus), the parallel lines can be operated with a maximum of 7 GW. The assumptions made are valid and the conclusions are correct. In that case the limiting factor is the parallel cable. A partial cabling of Ventilus would not change this. If the cable routes were designed with 6 cables, the maximum

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1 https://www.hitachienergy.com/about-us/case-studies/zhangbei, accessed Oct. 26th 2022

2 Network development plan Germany: Netzentwicklungsplan Strom 2035, Version 2021, zweiter Entwurf Aktualisierung Februar 2022

capacity in the (N-1) case would be 9 GW of secured power in the best case. This is only the case if the impedance ratios in the branches of the meshes are equal and there are no power flows (as mentioned in the report) from e.g. Avelgem to Horta. It is also correct, not to include here the concept of curative network operation. There is no profound operational experience in the European transmission network for this concept. In this respect, it cannot be regarded as state of the art here. The assumption that today preventive redispatch can be considered as standard in grid operation is correct.

In the following, relevant operating limits are listed, especially against the background of dynamic phenomena. In addition to the points specified by the operating rules of ENTSO-E, I share the conclusion that, especially in the case of (multiple) power electronic systems in the transmission grid, effects can occur in extreme situations that endanger stability and cannot be analyzed beforehand. Furthermore, it can be confirmed that the (N-1) principle is fundamental for secure grid operation and should also be the first objective in expansion planning. However, effects that go beyond this must also be considered.

The following section 5.1.5.4 highlights the reliability of the technology commercially available today for grid expansion. The assessment of the reliability of overhead lines, cables and HVDC converters is accurate. As an addition, it could be noted that for long cable links, the joints between cable segments (length e.g. 1km) are a weak point. The longer the cable connection, the less available it will be. In the absence of real installations of the rating of 3 GW and more with a land cable, there are no reliable figures here on the availability of long (HVDC) cable links. However, it can certainly be assumed that the overall availability is significantly lower than that of overhead lines.

Two more paragraphs follow regarding the use of high temperature cables and congestion of the grid. There is nothing to add to the correct comments.

Section 5.1.6 derives the average load on the Ventilus line and estimates the corresponding 0.4-Microtesla-corridor. Unfortunately, I do not have the exact calculations from Appendix 2 of the report (not included in the provided material). Simple estimation of 3.5 GW wind feed-in at 40 % full load hours and 1.4 GW at 50 % full load hours towards Belgium and 50 % towards UK gives 0.7 GW contribution from import/export from/to UK. In total, this results in 2.1 GW, which is distributed over both parallel paths. In this respect, the estimation with 30 % (40 %) is conservative and refers to the load of Ventilus. In this respect, the results here (even without knowing Appendix 2) are plausible.

Preliminary conclusion: The information and facts given in sections 5.1.1 to 5.1.6 are comprehensive and correct. The conclusions drawn are reasonable and plausible. The scope of the facts and study results presented here is appropriate.

2.2 Discussion of planning objectives and characteristics

Section 5.1.7 addresses the key issues of the citizen petition and a discussion of Ventilus' plan objectives. In the following, I give my assessments of the interpretation of the planning objectives and the statement of the Citizen Platform questions. I will focus only on those about which questions have been asked.

Planning objective 2: creating a robust grid by a high-voltage connection of 6 GW between the Stevin axis and the high-voltage substation in Avelgem.

In my opinion, this planning objective is the most controversial planning objective. Since it is assumed here that it was formulated in such a way to exclude possible technologies for Ventilus in advance. Like the author of the report, I do not see it that way. That a connection with at least 6 GW is needed between Stevin and Avelgem is in my opinion unquestionable, because otherwise the planned feed-in from offshore plants and an interconnector to the UK cannot be transported. The question is rather how to translate the requirement "robust grid" into technical characteristics. If one interprets robust solely against the background of an (N-1) secure connection, it would be sufficient to build an additional 3 GW connection, which would have to be spatially separated from the current line between Stevin and Horta in order to obtain (N-1) security even in case of common mode failures. This line is then particularly robust if it is itself designed to be (N-1) secure as well. In this respect, the design as 2x3 GW is reasonable and correct. The Stevin - Avelgem connection closes a mesh in the transmission network, which makes a positive contribution to the robustness of the network.

I share the author's opinion that the difference of impact between a 3 GW line and 2x3 GW lines does not make a big difference in the practical implementation (also visual impact). Another aspect not addressed in the report is the difference in impedance ratios in the case of a design with only one 3 GW line, which could lead to an unfavorable distribution of power flows.

An underground connection at that power level and of such a length is only possible in HVDC technology. As mentioned above, in this power range, there is no operational experience for HVDC and thus no reliability or availability figures. It is foreseeable that an HVDC cable route will have a significantly lower availability than an AC overhead line. For this reason, 2x3 GW systems with metallic return conductors would have to be built in a Ventilus and HVDC design, which means at least a total of 6 underground cables. A metallic return is a conductor that is not current carrying during normal operation but current carrying if on pole of the bipole of an HVDC scheme is for what reason ever out of service. In this case the HVDC scheme could be operated as half the rated power. However, the copper cost for the cables would increase by a factor of 1.5.

These would have to be arranged in such a way that in the event of a cable fault, neighboring cables (especially the metallic return conductor) would not be disturbed, which could result in the area in which the magnetic DC field affects the surroundings being larger than in a pure bipolar design of metallic return conductors.

In addition, there is an operational issue. If a common mode failure occurs on the line between Stevin and Horta, for example because a tower breakdown due to a thunderstorm, the entire AC network between Stevin and the fault location will be supplied only by the feed from the NEMO link and the Ventilus line. To maintain the supply, there would have to be a switchover of the inverter control to so-called grid-forming operation to prevent a total breakdown resp. blackout of the energy supply the region of Flanders, not to speak of the impact on the European interconnected system if, in the worst case, more than 3 GW of power are missing. which is the worst-case failure scenario in the entire European interconnected system. This type of control, including fault detection and switching over, is not state of the art today and would need to be developed which would take several years with all the corresponding technological risks before it would become commercially available. The development of this technology prior to the construction of an HVDC line equipped with it, including its erection, cannot, from today's perspective, be done in the current decade.

This HVDC solution for Ventilus is qualitatively judged to be less robust (in the above sense) than the proposed AC technology solution. However, the comments above show that there are already technological alternatives and that one can be made according to the criteria of robustness. In this respect, I can confirm the author's conclusion on this planning objective that says, that the specific planning objective is to increase transmission capacity from the coast (Stevin node) to the inland from the current 3 GW to 7 GW in a most robust manner and does not include a specific technology selection.

Planning objective 3: creating connection capacity for new onshore energy generation in West Flanders.

It is correct that wind farms feed mainly into the 150 kV grid due to their installed capacity. Since the 150 kV grid and the 400 kV grid are connected at certain points and the long-distance transmission will happen via the 400 kV level, this objective is reasonably formulated, and the analysis remarks are permissible conclusions.

Planning objective 6: reinforcing the security of supply in the Izegem region.

I also see it that the Izegem connection can also be made more robust with other network technological means. Using Ventilus for this purpose would be a reasonable but not the only possibility.

Sections 5.1.7.3 through 5.1.7.6 address the discussion in the characteristics of planning objectives to be bundled or partially bundled in the planning process.

Characteristic 1 includes the requirement for 6 GW of transmission capacity. The definition of one single transmission capacity on one particular line in the interconnected system can indeed be misunderstood. The conclusion in the report that the order of magnitude is justified but the formulation of the characteristic should better take place at system level can be confirmed.

For **characteristic 2**, it is critically noted that the (N-1) secure 3 GW design philosophy was not consistently applied. This is also a language formulation problem. In the design with

2 x 3 GW and partial cabling with 4 cables, Stevin / Horta is (N-1) secure with regard to the power of 3 GW.

Characteristic 3 includes the length requirement of 50 km to 100 km. In my eyes, this is not a limitation of technology but a requirement from the distance to be bridged.

Characteristic 4 requires the possibility to create branches from the interconnection in the future. I agree that this feature is not a constraint and can contribute to the robustness of the network. It is also not a constraint in terms of technology. In the case of an HVDC option, intermediate tapping would also be possible (see also comments above).

Conclusion on the planning objectives and characteristics: It can be confirmed that the objections and questions from the citizens' platform are justified and partly result from the not quite precisely formulated objectives. The fundamental problem, namely to be able to transport a certain power between Stevin and Avelgem and to make the overall system more reliable (robust) through the grid expansion, remains unaffected. In this respect, it is reasonable to conclude that even if the planning objectives were changed, no fundamentally different solution would result.

2.3 Alternatives to Ventilus and impact of future developments

Section 5.1.8 is dedicated to the question of alternatives to Ventilus. First of all, other expansion projects and other expansion options are discussed. Last but not least, taking into account the aspects mentioned above, the author correctly concludes that none of the alternative options presented is suitable for making Ventilus unnecessary.

The second major option presented as an alternative to Ventilus is a meshed HVDC network: "Prepare for the future". As mentioned above, I think it is a very good option to establish a meshed HVDC grid as the new backbone of electrical power supply. The development of such a system will certainly take more than a decade and a technology with the necessary maturity is not available today. Therefore, if it is decided to do so, it must not only be seen in the context of a European HVDC network, but also a correct strategic decision must be made by the transmission system operators concerned. In the short term/mid term, i.e. in the period up to 2030, it cannot be expected that a significant contribution can be made to increasing the transmission capacity of the Belgian Transmission System.

Not least because of the time constraints, I share the author's view that such an HVDC grid should rather be seen as complementary to Ventilus but not as a substitute.

The last issue addressed in section 5.1 is the influence of the energy island (Princess-Elisabeth) and a possible interconnector with Denmark (Triton). Basically, three connections converge on the energy island. First, the feed-in from two wind farms arrives here; in a first wave of 2.1 GW and in a second wave of 1.4 GW.

Secondly, the interconnector with the UK (Nautilus) is to arrive here and thirdly, a connection with the mainland is to take place from this energy island. In a first step, 220 kV cables are to be used, and with the second phase of the wind connection, a coupling into the HVDC-Nautilus connection is to take place, which would then be designed as a multi-terminal HVDC.

To what extent a landing of the Triton link with Denmark is also to be made here does not yet seem to have been determined. Assuming that a large part of the wind energy is to be transported to the UK via the interconnector, the conclusion in the report that the energy island itself will not have a major impact on the basic requirements for Ventilus is correct. It appears that the Triton connection is not yet developed to the point where exactly the landing point is fixed. It is therefore not possible to assess the impact on Ventilus. The best that can be concluded, as stated in the report, is that when Ventilus is finally defined, Triton will be designed in such a way that it will not have a negative impact on Ventilus.

2.4 Conclusion on section 5.1

The content and scope of the section are appropriate in the context of the study objective. The representations are correct and have been reflected with respect to the current state of knowledge within the scope of this assessment document. It could not be determined at any point that essential matters have not been presented or that incorrect conclusions have been drawn.

2.5 Comments and conclusions on chapter 6

The conclusions in section 6.1 are consistent with the findings in section 5.1. This also applies to the technical entries in the table at the beginning of this section. I cannot judge the representations to the health aspects, since I lack the expertise here. However, I can note that the calculations of the magnitude of the magnetic fields (Fig. 14) are plausible in terms of their order of magnitude, without having done any calculations. In section 6.3 a summary of the findings already discussed above is given. The conclusions are comprehensible and correctly reflect the contents of the corresponding sections.

Regarding the question of a fundamentally fully underground solution, I agree with what is stated in the report. The technology for this is VSC-HVDC. In this case, however, one should not only consider the Ventilus problem but develop a dedicated network that can serve as a backbone of the Belgian transmission network.

A first step could be the connection from Stevin to Courcelles with an intermediate tap in Izegem. Furthermore, a mesh could be realized between Stevin and Horta to Avelgem or Izegem. This would also offer the possibility of a further connection to Doel and a connection to other interconnectors and wind farms.

Due to the lower availability of HVDC systems, this HVDC ring that would then be created would certainly have to be designed with double redundancy and operated by an appropriate operating concept through curative measures in interaction with the 400 kV grid that would then be subordinate. As correctly stated in the report from my point of view, the technology required for this is not available today and can rather be seen as a long-term goal.

Such an HVDC ring does not help to solve the rather short-term problems until 2030 but is to be seen in my opinion as a complementary solution to Ventilus.

3 Questions of the mayors

In this section, an answer is provided to 6 specific questions by the mayors as provided in the PowerPoint presentation entitled "Doublecheck Gleichstromvorschlag, Verfahren und erforderliche Informationen / Dubbelcheck gelijkstroomvoorstel – proces en nodige info".

In total there are 6 questions formulated, namely on Slide 9-14. A concise answer is requested on each of these questions.

This part has been developed by me (Prof. Dirk Westermann) and discussed in detail with the intendant Guy Vloebergh and Prof. Dirk Van Hertem.

3.1 Wind turbine connection

Question 1: Can an HVDC line be used to bring the energy from the wind turbines/connectors at sea/energy islands to shore for use in Flanders?

Yes, this is possible in principle and has already been realized in many cases. Depending on the required installed capacity, several systems may have to be built in parallel. A capacity of approx. 3 GW per system should also be possible today with submarine cables. For redundancy reasons, several systems with smaller capacity would be recommended. However, HVDC has been used with an installed power of 1,2 GW (today under construction) so far for connection of offshore wind parks.

The use of HVDC as an option to connect offshore wind has been discussed in detail in the report of the intendant (e.g. section 5.1.3.2).

3.2 Connection to transmission grid without Stevin

Question 2: Is it technically/electrically feasible to bring 6 GW via HVDC underground to the 380 kV grid without Stevin (a)? Can the coastal cities and the inland continue to be supplied with electricity if Stevin is shut down, e.g. for maintenance work (b)?

Stevin is a line limited to 4 GW by an underground section. This "antenna" currently connects the renewables from the North Sea and Nemo Link to the backbone on the mainland.

We understand that under this question, the mayors propose to develop Ventilus in HVDC, at a rating of 6 GW. In the first part (a) of the question, they ask whether it is possible to transfer

6 GW underground using HVDC when Stevin is out of service. In part (b) they question whether it is possible to supply the coastal region when Stevin goes into shutdown.

(a) Yes, this is possible in principle. The HVDC line would have to be operated in grid forming mode. Such a system with a radial HVDC link with multiple variable offshore wind farms, HVDC connections, etc. has not been developed elsewhere before.

(b) The main issue here is the transition between operating states (connected in the mesh and operating radial HVDC). Furthermore, the question is whether the requirement is to transport 6 GW (N-1) secure or 3 GW (N-1) secure. It will not improve the reliability of the Stevin interconnection.

See also discussion on planning objective 2 on page 5/6 of this assessment report and in the report of the intendant in section 5.1.5.3).

3.3 Additional capacity for connecting offshore projects

Question 3: Can HVDC interconnection help create additional capacity for connecting onshore projects?

There are 600 MW wind turbines planned onshore in West Flanders.

In principle, this is possible. In this case, one would provide an HVDC line with intermediate taps. Here, however, the question of economic efficiency must be asked. At each connection point, a converter must be provided. Such an HVDC tapping would be of a smaller power rating compared to the main HVDC converter stations at the terminals of the line and would be comparatively large and expensive compared to comparable AC technology. Such tapping has not been realized so far in commercial installations in particular not in Europe.

3.4 Additional interconnection with UK

Question 4: Can the additional second connection of 1.4 GW with the UK be connected?

Nautilus is planned for 2028 and has a capacity of 1.4 GW. The HVDC cable is to be connected via an energy island.

Yes, the HVDC cable can be connected either via a power island or directly. The basic question is whether the capacity of the AC grid is sufficient to transport the power. This has also been mentioned in the report of the intendant and incorporated in the analysis carried out in the report of the intendant (Appendix 1, section 1.2).

3.5 Replacement of the 150 kV Ostend-Bruges line

Question 5: Can the current 150 kV line be placed underground?

The current capacity is X GW

Yes, 150 kV lines can be laid underground. This can be regarded as the state of the art. It is not clear from the question what power is to be transmitted here. Depending on the power multiple parallel cables might be necessary.

3.6 Additional energy supply Izegem

Question 6: Is it possible to double the capacity in Izegem without additional overhead lines? Izegem is an antenna connected to the 380 kV grid. Currently, 0.95 GW is connected to transformers. The current capacity is sufficient until 2030, but will need to be significantly increased thereafter.

In principle, yes, this should be possible (without knowing the exact technical parameters). This can be done in part (up to 50%) with modifications in the substation and transformer upgrades. Beyond that one will end up with a situation that has significant power supplied via a double circuit 380 kV line mounted on the same towers. This is not an ideal solution from an operational point of view. Like the Stevin antenna, this might be subjected to rare but large incidents that have a large impact on the region, including possible voltage stability issues (in case of outage) in the wider region. Completing the mesh with Ventilus would add significant robustness.