NORTH SEA OFFSHORE GRID – EFFECTS OF INTEGRATION TOWARDS 2050

Juan Gea-Bermúdez[1,2,*]
Lise-Lotte Pade[1]
Athanasios Papakonstantinou[1]
Department of Management Engineering
Technical University of Denmark
Kgs. Lyngby, Denmark
*jgeab@dtu.dk

Matti Juhani Koivisto[1,2]
Department of Wind Energy
Technical University of Denmark
Risø Campus, Roskilde, Denmark

***Abstract*— The purpose of the EU energy policy is to provide "secure, affordable and sustainable energy supplies", relying on an integrated electricity market, security of supply, and clean energy. In practice this means ambitious long term renewable energy targets in EU for 2030 and 2050 and ambitions to improve the energy grid across Europe. A significant share of the renewable energy development in EU is expected to take place in the North Sea. Coping with large shares of variable renewable energy in the North Sea calls for ambitious development of transmission capacity and interconnections between North Sea countries. We analyse what kind of grid infrastructure supports the renewable generation development in most efficiently: the integrated approach, or the conventional individual solution. We find that an early development of the transmission grid in an integrated configuration offers the most cost-efficient solution leading to decreasing electricity prices in most countries except Norway.**

***Index Terms*-- Grid, Interconnectors, Modelling, North Sea, Transmission**

I. INTRODUCTION

The EU energy policy is striving to assure an energy supply throughout Europe which is characterised by sustainability, competitiveness and security of supply [1]. This has resulted in ambitious long term renewable energy targets in EU for 2030 and 2050 and recently an ambition to improve the energy grid across Europe. A large share of the renewable energy push is expected to take place in the North Sea with its substantial offshore wind potential. Consequently, the offshore transmission capacity in the North Sea has to be further developed over the coming decades and the question arises: Which grid architecture supports the renewable generation development most efficiently: the integrated approach (i.e. meshed grid), or the conventional individual solution (i.e. radial grid)?

Considering coordination and integration with respect to electricity investment is nothing new [2]. Recently, the interest in grid expansion in the North Sea and the benefits have gained more attention and the European Commission considers the development of the North Sea offshore meshed grid as a top priority [3]. Furthermore, it is concluded in [4], [5] that a North Sea meshed grid can contribute to reductions in investment costs. Based on a system modelling approach, a number of cases were analysed and it was found that a meshed solution is the most beneficial [6]. Similar to our study they find that the costs and benefits from a meshed solution are unevenly distributed among the participating countries. Furthermore, analyse a similar case was analysed to a larger extent focusing on the policy implications [7]. Despite their significant contribution, in [6], [7] it was assumed that investments in production were fixed exogenous parameters.

The present paper contributes to the existing literature by changing the aforementioned assumption and endogenise investment decisions in generation as well as transmission. In doing so, we contribute in a wider discussion which calls for such variables to be decided by the proposed models instead of being exogenously set [8].

Against this background, we compare the effect of two potential transmission grid developments in the North Sea: a purely individual solution, i.e. radial vs an integrated approach, in this case a mix between meshed and radial. Initially we identify the grid architecture that minimises electricity system costs in the North Sea area, i.e. which grid architecture, which generation investments and which transmission line investments results in the lowest system costs of electricity by 2030 and 2050.

The proposed analysis extends the state of the art by allowing endogenous investments in renewable and conventional energy generation and also in transmission capacity between the North Sea countries, i.e. Belgium (BE), Denmark (DK), Germany (DE), Norway (NO), the Netherlands (NL) and Great Britain (GB). For this purpose, we use the Balmorel energy system model [9] to optimise the energy dispatch taking also into consideration the countries neighbouring the North Sea ones (up to 7 countries) for the electricity dispatch.

In order to assess which of the grid architectures is the most efficient we evaluate the overall system costs. Furthermore, we

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evaluate the impact on the individual countries with respect to producer surplus and consumer surplus and electricity prices.

We find that on the overall level an early development of the transmission grid in an integrated configuration minimises the system costs. Compared to the radial grid the meshed grid offers savings of 135 M€2012/year. On the individual scale, the early expansion of the transmission grid makes the average electricity prices slightly lower in most countries, except NO, which experiences a considerable rise. This indicates that the consumers in most countries except NO will benefit from the studied early grid expansion solution whereas the producers in NO will experience higher revenues.

II. METHODOLOGY

A. *Definition of the problem*

In order to assess and compare the costs and benefits of different grid architectures in the North Sea we need to solve the energy dispatch problem. Optimizing this problem implies to satisfy the energy demand at the minimum cost for the system. The main costs of the energy system, which form the objective function of the problem, are related to: fuel consumption, investments in generation and transmission capacity, O&M and fixed costs of generation plants, energy distribution, taxes and subsidies, etc.

The energy dispatch problem is subject to several constraints that influence the optimal solution. The energy balance constraints assure that, for each geographical location and temporal dimension, the sum of the energy production, and net imports is equal to the energy demand plus the transmission losses. Furthermore, generation technology operation constraints are used to represent the limitations and capabilities of the generation units. For example, the maximum production constraints establishes that the generation in a given time step of a given producer located in a given region has to be lower or equal to the maximum capacity times the availability factor in that time step of that generation unit. Other type of constraints, including those establishing fuel potentials or the minimum level of hydro reservoir in a given geographical location and temporal dimension, contribute significantly towards a realistic solution.

B. *Balmorel*

To solve the aforementioned problem we have selected the tool Balmorel, a linear optimisation model covering the electricity and district heat sectors, and that optimises simultaneously transmission, generation and consumption of electricity under perfect competition conditions [9]. It is a deterministic model with a bottom-up approach, which provides flexible spatial and temporal resolutions adequate for the needs of the problem. Further information about Balmorel can be found in [9].

The main advantage of Linear Programming (LP) is that it is capable to solve large problems in reasonable time and without expensive computers [10]. However, in order to better represent the importance of economies of scales of the DC lines and hubs, key elements of the problem, a Mixed Integer Programming (MIP) approach was selected at the expense of increasing the complexity of the model. For this purpose, SOS of type 2 (SOS2) variables were introduced in Balmorel. These variables were selected as they are generally found to make the branch and bound optimisation process faster [11], [12] and are commonly used for modelling piecewise approximation functions of a unique variable [10], which improves the modelling of economies of scale. Further detailed information about SOS2 variables can be found in [11] and [12].

Among the different modes of Balmorel, BB4 has been used in this paper, since this mode is capable of optimizing several years simultaneously at the expense of increasing computational time [9]. However, this approach is desirable as this paper is focused on the planning the North Sea Grid, and the fact that certain technologies are expected to become cheaper in the future can have an important impact in the results of the optimisation for all scenario years.

As we take the society perspective, the only tax included in the model has been the carbon emission tax.

III. SCENARIOS

The scenarios used in this paper have as starting point Nordic Energy Technology Perspectives (NETP) 2016 [13], which shows the pathway towards a near carbon-neutral energy system in 2050 in the Nordic Region.

However, certain updates have been made to the assumptions used in NETP 2016. Firstly, the rapidly decreasing costs related to renewable energy investments have been updated. Wind and solar photovoltaic (PV) costs have been revised using the data from [14] as they were updated in June 2017. Especially solar PV and offshore wind investment costs are assumed to decrease significantly going towards 2050.

The costs related to DC connections are taken from the average cost parameter set presented in [15]. These numbers are used to model the costs of the offshore transmission lines in the radial and meshed cases, and the components related to offshore grid in the meshed case. DC breaker costs are not considered. These costs are assumed to decrease in the future following the annual cost reduction for offshore wind grid connection [14]. The fixed costs of the DC components are important especially in MIP modelling, as small lines or hubs can have very high costs in terms of €/MW.

The geographical distribution of future renewable generation investments is modelled in more detail compared to NETP. Specifically, limits on the capacity of the generation that is expected to be developed are introduced based on their location. For example, given that in northern Germany the best locations for onshore wind already saturate, offshore wind can become more attractive due to its large amounts of investable capacity with high capacity factors. The overall investable onshore wind limits are taken based on the 2050 wind potentials from NETP [13]. These limits are divided to three resources grades following [16]. It is assumed that current investments are placed in the most optimal locations, so in countries with already significant amounts of onshore wind, the future investments need to be placed in less favourable locations. Such modelling is important as it can take into account that not all investable onshore wind (or solar PV) capacity has the same capacity factor.

For offshore wind, the locations of possible future offshore wind power plants (OWPPs) are taken from a database at DTU Wind Energy based on [17]. This gives investable offshore wind capacity in the radial case for each region. In the meshed case, OWPPs can be connected also to hubs. Based on distance, each possible future OWPP is assigned either to be radially connectable (to shore) or connectable to the closest offshore hub. The results are then aggregated to reach investable capacity for each hub. From these investable capacities, Balmorel optimises the actual installed capacities.

Wind and solar PV generation profiles were generated using the DTU Wind Energy's CorRES tool. Its capabilities to model spatiotemporal dependencies in variable renewable generation has been shown, e.g., in [18]. Expected future capacity factor development is calibrated so that it is in line with [14].

In this context, we introduce three progressive scenarios in order to analyse the effects of integration towards 2050 of the North Sea Offshore Grid: restricted transmission (RT), radial case (RC) and meshed case (MC). The endogenous countries, i.e. countries where investments in transmission and generation are optimised, are Denmark, Norway, Germany, Great Britain, Netherlands and Belgium. For these countries, the exogenous base transmission line development assumption for 2030 and 2050 is directly taken from the year 2030 of the NETP 2016 scenario, which is based on Ten Year Network Development Plan (TYNDP) 2014 of the European Network of Transmission System Operators (ENTSOE) [19] (Figure 1).

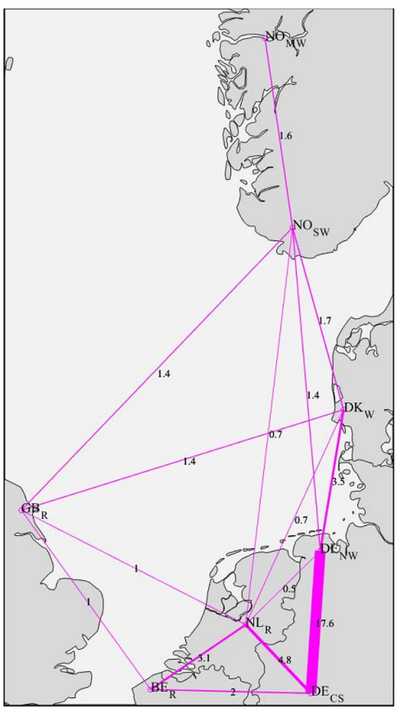

Figure 1. Exogenous transmission capacities (GW between regions most relevant to the North Sea area (connection points to the onshore power systems are not the actual locations)). DK_W to DE_NW is an onshore line

Moreover, the generation capacity scenario (Figure 2) has been built based on NETP 2016. The district heat-linked part of the system is provided as exogenous from NETP 2016, which is the reason why there are still gas CHP plants in the system. However, the not district heat-linked part of the system is built differently. Condensing power plants have been linearly decommissioned with time based on the base year capacities of NETP 2016, which was 2014. The exogenous wind and solar capacities are based on what it is expected to be in place by 2020. Nuclear power is based on lifetimes of existing and planned plants. Finally, hydro power is also taken directly from NETP 2016. The rest of the countries, which participate in the electricity dispatch optimisation and are provided as exogenous based on NETP 2016 scenario, are Estonia, Lithuania, Latvia, Poland, Finland, France and Sweden.

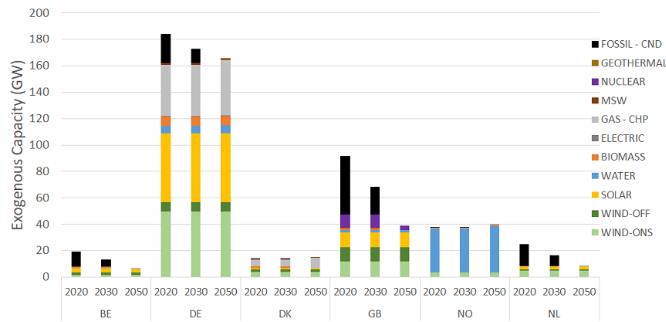

Figure 2. Exogenous generation capacity development

C. *Restricted Transmission scenario*

This scenario assumes that the transmission network development between the North Sea countries by 2030 is fixed to the one shown in Figure 1. However, in 2050 all lines are open for investments. The countries can however invest in reinforcing their national grids and in generation investments in any year. This scenario will be used as base for costs comparison.

D. *Radial Case scenario*

The scenario RC extends scenario RT by allowing for investments in country-to-country transmission lines for the North Sea countries already in 2030.

E. *Meshed Case scenario*

Relative to scenarios RT and RC, scenario MC offers the opportunity of offshore wind farms to be either hub connected or radially connected to onshore. Furthermore, there is also the possibility for meshing between the hubs.

VII. Numerical Analysis

Given the computational complexity of the problem, four representative full weeks were run for the years 2030 and 2050, and investments were allowed in transmission and generation in the endogenous countries. For scenario MC, which is considerably more computationally expensive to solve, a reduced scenario was first run to reduce the number of possibilities available in the four full week run.

The resulting transmission grid development by 2050 for scenarios RC and MC can be seen in Figure 3. Both scenarios show considerable investments in the corridors NO-GB and GB-DE, this latter through BE. In the MC scenario part of the transmission investments of the country-to-country interconnection goes through the hubs. This suggests that here is a non-negligible value in utilizing the hubs for both wind dispatch between different countries and country-to-country interconnections. It seems that when investments in hubs and meshing is allowed, GB, and specially DE, benefit as the optimal solution provided by the model involved the construction of several of their hubs.

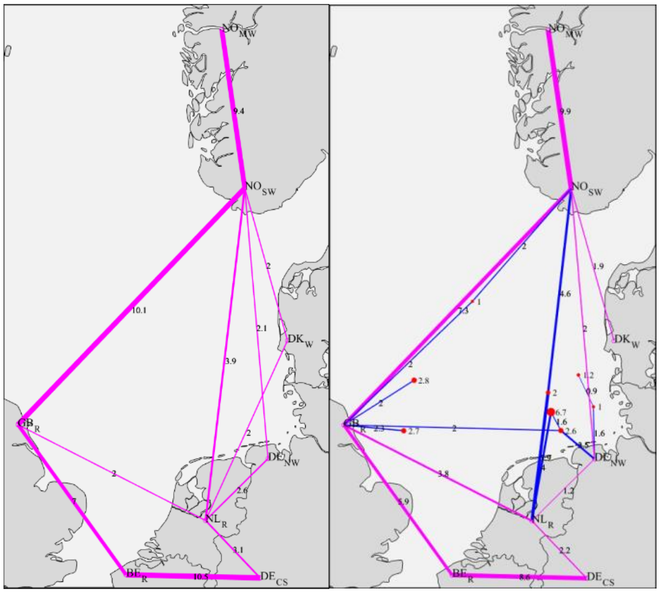

Figure 3. Accumulated transmission investments and hub investments by 2050. Radial Case (left) vs Meshed Case (right)

As depicted in Figure 4, which shows the accumulated investments in electricity generation by 2050 in the endogenous countries, in all the scenarios the optimal solution was found to invest basically in solar PV, wind offshore and wind onshore, ordered in terms of GW. The MC scenario provided overall around 7 GW more offshore wind, 9.5 GW less onshore wind and similar solar PV investments than the RC scenario. However some countries increased considerably their offshore wind (DE) whereas others, such as NL, decreased. NO seems to be key for the integration of wind and solar, providing cheap flexible hydro power for the other countries. It is worth mentioning that for the MC scenario there was almost no need for investments in gas turbines, whereas in the RC scenario a few GW were required. This suggests that the energy dispatch with the meshed configuration reduces the need for back-up capacity. Moreover, even though we have more solar PV in GW-terms, in TWh-terms wind generated overall 4 times more than solar, due to its 2-5 times higher capacity factor.

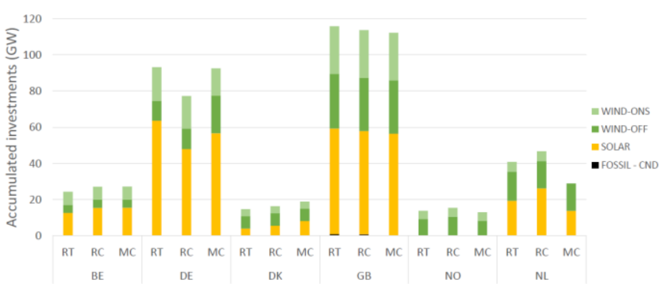

Figure 4. Accumulated investments by 2050

In terms of the energy system costs (Figure 5), results show that an early development of the transmission grid (RT vs RC) is considerably beneficial for the total North Sea region, by reducing the annual costs by 1900 M€2012/year. On the other hand, the meshed solution offers savings of 135 M€2012/year with respect to the radial solution. Although the total capital costs were found slightly more expensive in the MC scenario, the O&M, fuel, fixed and CO_2 costs were reduced, resulting in an overall cheaper scenario.

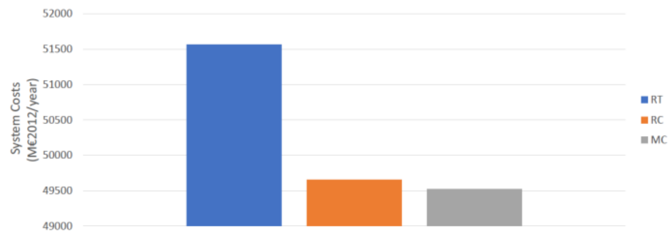

Figure 5. Average annual system costs

The average electricity prices are depicted in Figure 6. An early development of the transmission grid in the North Sea countries (scenario RT vs RC) by 2030 seems to decrease electricity prices in most countries except NO, which experiences a drastic increase (13.6 €2012/MWh), and DK, which experiences a slight increase. However, by 2050 the price levels are very similar as the optimal solution expanded the grid considerably in this year in the RT scenario. On the other hand, the meshed solution provides slightly cheaper prices than the RC, which is in line with the total system costs, although overall there is no significance difference between the MC and RC scenarios: some countries experience a minor price increase and others a slight decrease.

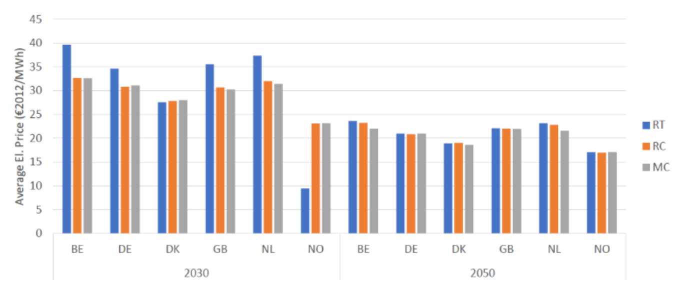

Figure 6. Average Electricity prices

The annual Net Electricity surplus in the endogenous countries and their net profit from electricity sales are shown in Figure 7 and Figure 8, respectively.

Figure 7. Net electricity surplus

Comparing scenarios RT and RC, it can be seen that in the RC, for the net exporting countries such as DK and NO, each unit of electricity surplus results in a higher income than in the RT, while for the net importing countries, each negative electricity surplus results in a lower cost. This fact benefits all the participants of the electricity markets. It is worth remarking the drastic change in net profit that NO experiences from an early development of the transmission grid. On the other hand, the meshed solution, compared to the RC scenario, has a considerable impact in DE, reducing its net electricity deficit and associated costs.

Figure 8. Net profit from electricity sales

It should be clarified that while the results provide a significant insight on the impact of the various scenarios there are also subjective to the modelling assumptions. For example, in terms of exogenous transmission grid development for DE, the assumption has been very optimistic, i.e. an additional 10 GW line solving the North to South bottle neck current problem was assumed. It would be worth testing what would happen if this line was not assumed. Related to this point, the fact that the internal grid of the countries was not model in full detail could have led to a too optimistic transmission line development, highlighting the major GB-DE line expansion via Belgium, and the modelling GB as a unique region.

As expected, utilizing a deterministic tool to optimise investments is an important limitation due to the uncertainty of the input parameters, although the results can be validated through a sensitivity analysis. Moreover the results obtained with the version of Balmorel used were sensible to the time steps due to scaling issues with the time series.

VIII. CONCLUSSIONS

An early development of the transmission grid in an integrated configuration is found optimal among the options studied in this paper. Compared to a radial configuration, a meshed one offers savings of 135 M€2012/year as it reduces the variable costs of the generation system more than it increases the investment costs. However, this development requires international cooperation between the North Sea countries. The results suggest that solar PV and wind will increase considerably their share in the total electricity production in the North Sea region, and in this context, NO seems to be key for this development, providing cheap flexible hydro power for the other countries. However, this grid expansion is expected to result in higher electricity prices in NO, a fact that would benefit the producers, but at the expense of the consumers. Elaborating further on the implications of that challenge is a possible line of future research.

IX. ACKNOWLEDGMENT

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X. REFERENCES

[1] European commission (2018) https://ec.europa.eu/energy/en/topics/ energy-strategy-and-energy-union (assessed Apr 2018)

[2] D. Gately, (1974). "Sharing the Gains from Regional Cooperation: A Game Theoretic Application to Planning Investment in Electric Power." *International Economic Review*, vol. 15, no. 1, pp. 195–208.

[3] European Commission - DG for Energy, (2011). "Energy Infrastructure Priorities for 2020 and beyond – A Blueprint for an Integrated European Energy Network," Available: https://ec.europa.eu/energy /sites/ener/files/documents/2011_energy_infrastructure_en.pdf.

[4] J.D. Decker et al., (2011). "Offshore Electricity Grid Infrastructure in Europe", Available: https://ec.europa.eu/energy/intelligent/projects/ sites/iee-projects/files/projects/documents/offshoregrid_offshore_ electricity_grid_infrastructure_in_europe_en.pdf.

[5] NSCOGI, (2012). "Working Group 1 – Grid Configuration", Available: http://www.benelux.int/files/1414/0923/4478/North_Seas_Grid_Study. pdf.

[6] I. Konstantelos et al., (2017). "Integrated North Sea grids: The costs, the benefits and their distribution between countries." *Energy Policy*, vol 101, pp. 28-41.

[7] I. Konstantelos, R. Moreno and G. Strbac, (2017). "Coordination and uncertainty in strategic network investment: Case on the North Seas Grid." *Energy Economics*, vol. 64, pp. 131-148.

[8] J. G. Dedecca and R. A. Hakvoort, (2016). "A review of the North Seas offshore grid modeling: Current and future research." *Renewable and Sustainable Energy Reviews*, vol 60, pp. 129-143.

[9] F. Wiese et al., (2018). "Balmorel open source energy system model." *Energy Strategy Reviews*, vol 20, pp. 26-34

[10] C. Guéret, C. Prins and M. Sevaux, (2000). *Programmation linéaire*. Ed. Eyrolles.

[11] E. M. L. Beale and J. J. H. Forrest, (1976). "Global optimization using special ordered sets." *Mathematical Programming*, vol 10(1), pp. 52-69.

[12] E. M. L. Beale and J. A. Tomlin, (1970). "Special Facilities in a General Mathematical Programming System for Nonconvex Problems Using Ordered Sets of Variables." in *Proc. 5th IFORS Conference, Tavistock.*

[13] NORDEN and IEA, (2016), "Nordic Energy Technology Perspectives 2016":http://www.nordicenergy.org/project/nordic-energy-technology-perspectives/ (accessed April 2018)

[14] Danish Energy Agency's Technology Catalogue: https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger (accessed on July 2017)

[15] P. Härtel. T. K. Vrana, T. Hennig, M. von Bonin, E. J. Wiggelinkhuizen and F. D.J. Nieuwenhout, "Review of investment model cost parameters for VSC HVDC transmission infrastructure", *Electric Power Systems Research*, vol. 151, pp. 419-431, October 2017.

[16] P. Nahmmacher, E. Schmid and B. Knopf, "Documentation of LIMES-EU - A long-term electricity system model for Europe", Working Paper, Oct. 2014 https://www.pik-potsdam.de/research/sustainable-solutions/ models/limes/DocumentationLIMESEU_2014.pdf (accessed April 2018)

[17] 4 C offshore wind farm database: http://www.4coffshore.com/ windfarms/ (accessed June 2017)

[18] E. Nuño, P. Maule, A. Hahmann, N. Cutululis, P. Sørensen, I. Karagali, "Simulation of transcontinental wind and solar PV generation time series," *Renewable Energy*, vol. 118, pp. 425–436, April 2018.

[19] ENTSO-E (2014). Ten Year Network Development Plan 2014. https://www.entsoe.eu/publications/tyndp/tyndp-2014/ (accesed April 2018)