IASS WORKING PAPER

Institute for Advanced Sustainability Studies (IASS)
Potsdam, May 2016

Technological Options for the Future European Grid

Michele Ferrari, Dr. Adela Marian, Dr. Heiko Thomas

IASS POTSDAM

Abstract

* This publication is informed by research findings presented and discussed at the workshop "Technological Options for the Future European Grid", held at the IASS in Potsdam on 6 July 2015.

Technological innovations are crucial for addressing the challenges of expanding and operating the electricity grid posed by the ongoing transformation of the energy system and the integration of renewable energy sources in particular. A multitude of technologies are already available, however reshaping the grid goes beyond technological development and is strongly interlinked with broader economic, social, environmental, and political aspects. From this perspective, an integrated energy policy and the coordination of efforts both at the national and European level will be of key importance for the future grid.

Contents

1. Introduction: drivers and challenges of future grid planning

Across Europe, the modernisation and expansion of the electric grid has become an important objective, with ambitious grid development plans being drawn up for the next decades at national and European level. The growing renewable energy infeed and its intermittent character, the nuclear phase-out in Germany, and increasingly decentralised power generation all pose specific challenges for the grid, making it necessary to upgrade the local distribution grid and/or construct new transmission corridors to connect remotely located renewable sources. Overall, the European Network of Transmission System Operators for Electricity (ENTSO-E) estimates that up to 50 000 km of electric lines will have to be built by 2030 [1]. This figure includes 20 000 km of planned subsea cables, 23 000 km of new overhead lines and 4 000 km of upgraded infrastructure. More than half of these electric lines will be operated in direct-current (DC) mode. An interconnection target of 10% by 2020 and 15% by 2030 is envisaged, which will result on average in a doubling of the interconnection capacity throughout Europe. Beyond purely technological challenges, the interplay of ecological, social and economic dimensions adds to the complexity of the system. For instance, grid extension plans can raise environmental issues and sometimes face opposition from affected local communities.

In this context, the IASS organised a workshop on *"Technological Options for the Future European Grid"* on 6 July 2015 with the goal of assessing existing and emerging technologies and identifying steps for their development and implementation. The main actors in this field were represented at the workshop: transmission system operators (ENTSO-E, RTE, 50Hertz), regulatory agencies (German Federal Network Agency – Bundesnetzagentur), industry/development (ABB, Siemens), as well as various research institutes and associations (RWTH Aachen, Friends of the Supergrid, TU Darmstadt).

Longer-term scenarios that emphasise the drivers and challenges for future grid development were the focus of the RTE presentation of the e-Highway2050 project, which was supported by the European Union 7th Framework Programme. The aim of this project was to develop a methodology to strengthen the planning of the Pan-European Transmission Network, focusing on the period from 2020 to 2050. It is expected that this will ensure the reliable delivery of renewable electricity and pan-European market integration [2]. One major deliverable was the identification of the 'electricity highways' required in 2050 in order to facilitate investment decisions in the coming years. Five scenarios were selected to encompass a wide range of possibilities in 2050 with regard to relevant criteria (projected demand, renewable energy sources, cross-border power exchanges, fossil sources, decentralised generation, and nuclear power). They were based on the common target of reducing CO_2 emissions by 95%, and relied on general assumptions such as gross domestic product, population growth, new uses of electricity, and energy efficiency. As a result, several additional power transmission corridors with capacities from 5 to 20 GW were identified for the European grid, some of which are necessary across all scenarios. In particular, major North-South corridors and connections of peninsulas and islands to continental Europe are critical. Similarly, the Supergrid Consortium advocates the development of a pan-continental interconnected electricity grid in parallel to the harmonisation of relevant European energy policies [3].

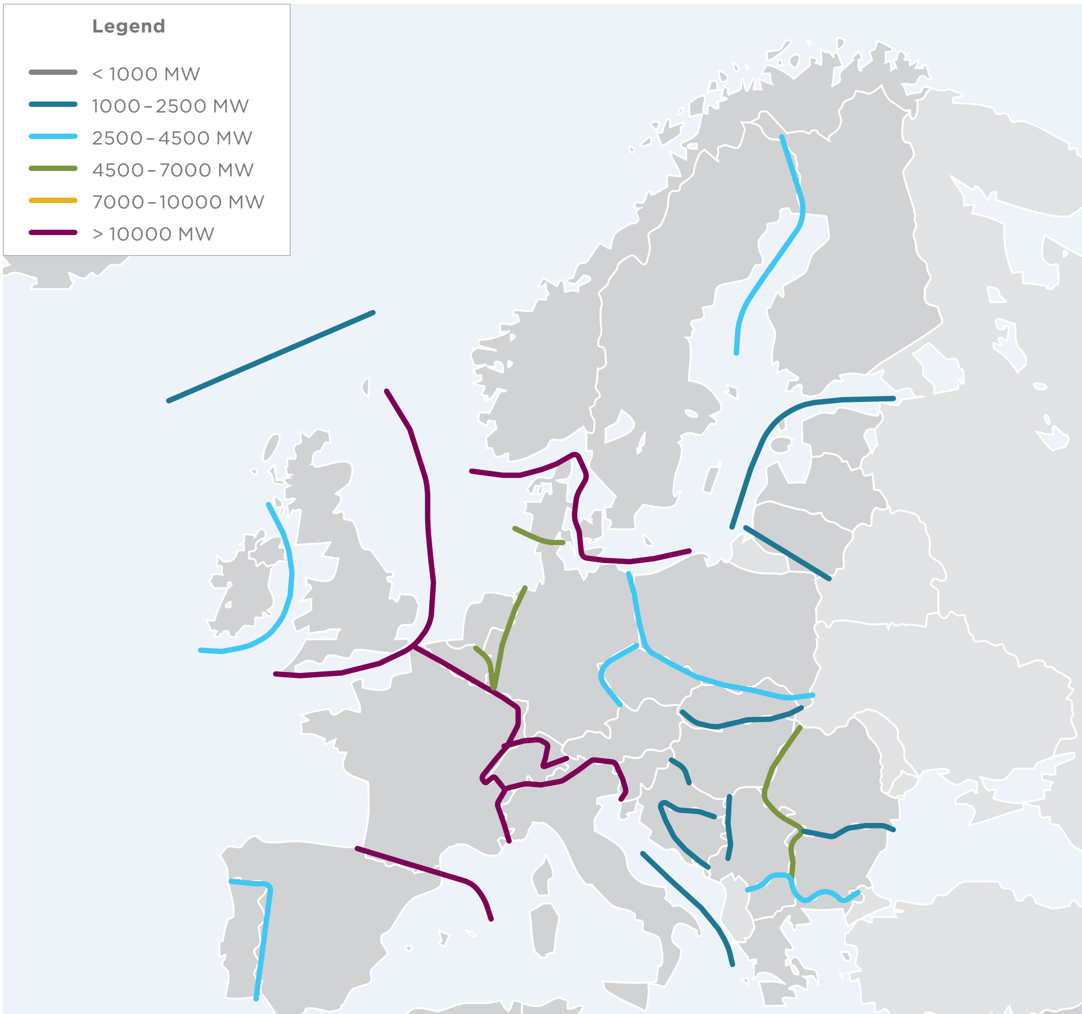

Figure 1: 2030 target transmission capacities connecting with existing infrastructure in Europe as planned by the ENTSO-E. This is one of four visions developed by the organisation and is entitled "Green revolution".

Source: IASS based on ENTSO-E

The complexity involved in forecasting trends and evolutions and adjusting grid planning accordingly was clearly illustrated during the workshop. For instance, the impressive growth of renewable energy sources in the last 10 to 15 years has vastly exceeded what had previously been forecasted. In future, similar unforeseen trends, driven for instance by changes in consumption patterns, could further impact the requirements and flexibility of a modernised electric grid. Moreover, new climate policy goals, and in particular the targets for renewable energy sources, will also help to set the pace of grid planning. The effects of a possible mismatch between grid planning and reality should not be underestimated and highlight the need to look into innovative technologies.

2. Technologies for the future grid and their maturity level

Rising shares of renewable energy generation and the phasing out of nuclear (and fossil) power plants are creating a demand for new, innovative technological options. In the modernisation and expansion of the electricity grid, the deployment of new technologies can bring benefits ranging from energy and cost efficiency to higher public acceptance and enhanced grid resilience. Recent years have seen a number of important technological advances that could play a role in shaping the future grid. As noted by the participants in the IASS workshop, grid development will not fail for lack of adequate technology.

One such advance is the development of HVDC transmission techniques for long-distance energy transfer. Up to a decade ago, this technique could only be used for point-to-point connections, in particular to access remote renewable energy sources. The development of the voltage source converter technology (VSC) now makes it feasible to realise meshed HVDC grids. In this respect, great efforts were put into developing HVDC circuit breakers in order to prevent power outages by isolating faults in a meshed grid [4]. These devices can quickly interrupt power lines with GW power transmission capacity in the case of fault currents. Furthermore, industrial innovators have been striving to develop ultra-high capacity underground HVDC XLPE cables as an alternative to overhead lines, notably to alleviate public acceptance issues. By matching the voltage level to that of long-distance HVDC overhead lines, it is now possible to use underground HVDC cables for substantial parts of transmission corridors [5].

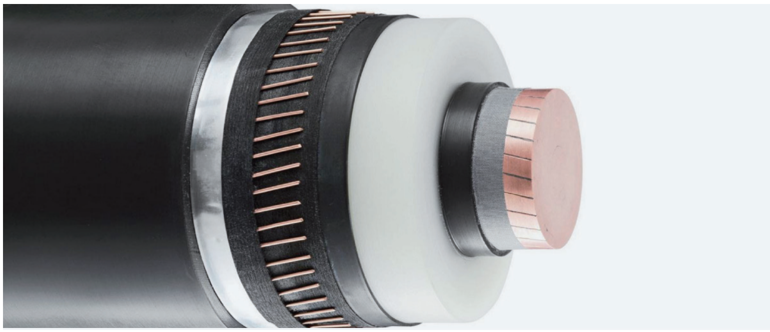

Figure 2: 525 kV HVDC XLPE underground cable developed by ABB

Photo: ABB

Gas Insulated Lines (GILs) represent another recent innovative development for high-capacity underground transmission with minimal right-of-way requirements [6]. GILs use the gas SF_6 to electrically insulate the conductor. This is a critical issue because SF_6 is an extremely potent greenhouse gas with a global warming potential 23 900 times higher than that of CO_2. It also has a much longer atmospheric lifetime: 3 200 years [7]. This discourages TSOs from employing GILs and other devices based on SF_6, since even small leaks could drastically increase the network's carbon footprint.

Looking further ahead, superconducting electric lines might also join the portfolio of available and mature technologies. Their specific advantages are potentially lower power losses and a small size, which would reduce right-of-way requirements [8][9]. Different cable designs that rely on different superconducting materials and coolants are currently at the R&D stage and a there is a growing number of projects that operate superconducting lines in real conditions.

A pure DC transmission and distribution grid might also be an option for the future grid, as supported by developments in DC-DC converter technology. These converters are important because they permit power taps along HVDC transmission lines, as well as the connection and interconnection of MVDC distribution grids. The local grid is likely to see more plug-and-play devices installed by private users, which can communicate in a smart fashion. For instance, consumers (e-cars) and additional small energy generators (PV) will further change the requirements of the local grid. Smart communication between energy devices can have a positive impact on the local distribution grids when it comes to reducing peak loads, and thereby decrease the need for grid reinforcements.

In addition to the above technological innovations that might profoundly affect the grid in the coming decades, efforts are also being directed at improving existing technologies and infrastructure. For instance, High-Temperature-Low-Sag (HTLS) conductors can be used to retrofit overhead lines with increased capacity, and could therefore help to bridge the gap between growing demand and the limited capability of the existing grid. Another example are superconducting fault current limiters (SCFL), which can protect the grid from short circuits arising under certain conditions from the increasing renewable energy generation (triggered for instance by simultaneous strong winds and sun irradiance). Distribution grids are especially sensitive to changes in the amount of decentralised generation from renewable energy sources, and retrofitting the grid using SCFL can mitigate grid stability problems and thus support the installation of additional renewable energy capacity. These grid reinforcement measures could gain us some time, but they will not solve the problem of a congested electric grid in the long term.

However, despite the increasing availability of new technological options, ground-breaking grid technologies remain scarce. This is partly due to the much longer investment cycles in the grid sector. And there was no great need for new grid technologies until the changes brought about by the strong increase in renewable energy generation. For instance, the connection of offshore wind farms to the existing AC grid necessitated new developments, since AC cables are not suitable for underwater operation. Furthermore, line commutated converters (LCC) have distinct disadvantages in offshore environments due to their massive size, and are unable to cope with weak AC networks in terms of voltage and frequency stability.

In some cases, the increasingly urgent need for a better technology has led to developments that were more or less commissioned by TSOs in their discussions with the industry – 525 kV XLPE cables are one such example. These cables can have a capacity of 2 600 MW per link, which is close to the limit that current ENTSO-E regulations impose to preserve stability in case of an outage. In terms of comparative voltage levels, it should be noted that overhead HVDC lines operating at voltages of up to 1100 kV already exist. However, it is very unlikely that such high voltages would be employed in Germany given the acceptance and approval hurdles. In light of this, the ability of XLPE cables to match the voltage level of overhead lines in Germany is an asset, allowing for a combination of underground cables and overhead lines for the planned HVDC corridors.

Maturity status of innovative and recently developed technologies			
Technologies	ENTSO-E classification	EC TRL	
±500 kV HVDC XLPE underground cables	Large-scale testing phase	TRL 6	This technology has been successfully demonstrated in relevant environments and will soon be demonstrated in an operational environment.
Gas Insulated Line (GIL)	Mature	TRL 8–9	GILs have been reliably used within the existing meshed grid for many years and have proved their general applicability.
HVDC circuit breaker	Large-scale testing phase	TRL 4	HVDC circuit breakers have not been employed in HVDC transmission line applications so far, but have been validated at component and system levels.
High-power DC – DC converter	Development phase	TRL 3	High-power DC-DC converters have passed proof-of-concept tests but are still under ongoing development.
Superconducting lines – High-Temperature Superconductors (HTS)	Large-scale testing phase	TRL 6–7	Several HTS power lines have been or are operating in the existing meshed grid, but they are still undergoing reliability tests and are usually backed by standard cables installed in parallel.
Superconducting lines – MgB_2	Development phase	TRL 3	The technology passed an experimental proof-of-concept test and will soon be validated in the lab under operational conditions. There is still a need to engineer missing elements such as an appropriate cryogenic system for longer distances.

Table 1: The table presents the maturity and readiness status of selected innovative grid technologies, using the maturity classification scheme of ENTSO-E and for comparison the Technology Readiness Level (TRL) scheme as employed by the European Commission for the Horizon 2020 programme.

The question of how innovative technologies can best facilitate grid development has become crucial, and it encompasses issues like technology choice and timing of implementation. In this context, determining the maturity and level of readiness of a given technology is an important and necessary requirement for large-scale deployment. Among the various stakeholders (TSOs, grid agencies, industry, etc.) the criteria and methodology used to assess readiness and maturity often vary greatly (see Table 1). Typically, cable manufacturers consider a technology to be ready once it has been tested according to internationally recognised standards, whereas grid operators often require a long period of in-grid operation (e.g. 15–20 years).

In addition to the different views on technological maturity, grid operators are sometimes reluctant to make use of these new technologies, preferring to rely on established technologies that have operated for decades at known costs. The reasons behind this attitude are diverse, and can include higher costs, security of supply, and difficulties with introducing DC technologies in predominantly AC systems. Moreover, identifying the best technology for a given application is a complex task, since different kinds of advantages and disadvantages (costs, efficiency, public acceptance, environmental impact, etc.) all need to be weighted. With respect to costs, it has been pointed out that there might be an opportunity cost in delaying the implementation of a new technology until it has become cheaper, since new lines may bring economic benefits that should also be taken into account.

The reluctance to adopt new technologies also poses a latent risk for developers, who may not be able to achieve a return on their investment in the research and development of new innovative technologies, and it influences related decisions about research investments and overall strategies.

Beyond the mere funding of research, stronger backing by funding bodies and energy policy with the goal of achieving more widespread implementation of innovative but mature grid technologies could be considered if appropriate for the system. A built-in incentive scheme for grid operators and developers might be a way of overcoming economic barriers when first employing new technologies.

KEY MESSAGES

- Grid expansion will not fail for lack of technology.
- Demand will lead to faster technological development.
- Assessments of readiness levels are stakeholder dependent.
- A preference for conventional technologies can result in missed opportunities.

3. Beyond technology: further dimensions of grid development

Grid development raises a number of questions that go beyond technological aspects, and concern wider economic, social, environmental and political dimensions. The ambitious plans of European countries to expand their national grids and increase cross-border interconnections represent not only a technical challenge but also a financial one. According to ENTSO-E's projections, around 100 'bottlenecks' need to be addressed by 2030 if the EU is to meet its interconnectivity targets, and the investment required to achieve this is estimated at 150 billion euro [1]. The financial burden for developing these "projects of pan-European significance" still rests mostly with national TSOs – the share for Germany, for instance, is estimated to be around 30–50 billion euro. And these projects are only a subset of all the transmission investments needed in Europe, which have to include purely national plans as well, and especially investments in the distribution grid.

Of course, economic benefits can also be expected: increased interconnectivity can lead to lower electricity prices as the market grows bigger and price differences between countries are at least partially levelled. Still, there are many questions to be addressed with respect to which financial instruments are best suited to grid expansion projects, and what regulatory frameworks are appropriate to these types of investment. Technological choices are another important factor in determining costs; the technologies that can be implemented the fastest might not be the cheapest, and, as already mentioned, possible opportunity costs also need to be taken into account.

Grid development is also tied up with several environmental and climate-related issues. Put simply, the expansion and modernisation of the grid is a prerequisite for the continued deployment of renewable energy sources, and as such contributes indirectly to making power generation cleaner and reducing CO_2 emissions. It follows that delays in grid development might hinder the realisation of our energy and climate policy goals. At the same time, the installation of new power lines, especially high-voltage overhead lines, can have negative consequences for natural habitats and wildlife, land use, electromagnetic fields, soil disturbance and heating, etc. [10]. These environmental impacts vary depending on the selected technology, the location and the installation procedures. While measures can be implemented to reduce impacts, it is clear that no technological choice is environmentally neutral. Every technology has implications, which often entail difficult trade-offs between environmental risks and costs. And it seems that of all the changes that the energy transition will bring about, grid development is likely to be one of the most technology-intensive.

Since planned grid expansion projects entail major infrastructure changes that affect almost everyone, they have become topics of heated public debate. There are many reasons why local communities might oppose power line projects, including their ecological footprint, health concerns, the alteration of landscapes, visual impact, and possible effects on property values. Overhead lines in particular are most likely to elicit popular resistance. TSOs increasingly have to contend with public opposition, with the result that projects can be delayed or even cancelled. In the case of the France-Spain link *Inelfe* for instance, plans for a new overhead line were met with strong opposition. After many years of delays, they were cancelled and replaced by a project to build an underground cable [11]. In Germany, the approval process for the HVDC corridor C (Südlink) faced similar opposition, ultimately leading to a modification of the Energy Line Extension Act that stipulated the priority use of underground cables for this link [12]. Clearly, public acceptance has become a major factor in grid development, with the potential to support the process or slow it down.

In addition to switching to underground transmission whenever possible, TSOs can make new power lines less invasive by utilising existing corridors. Furthermore, in the future, innovative technological options (e.g. superconducting electric lines) could also greatly reduce the visual and environmental impact of power lines. In this sense, public opposition should not be seen only as an obstacle to be overcome, but also as a positive force that spurs efforts to find and implement new ideas.

Opposition to grid extension projects is often linked to a lack of engagement and participation in the process. In general, citizens have understood the implications of the Energiewende and the increasing renewable energy supply and are not opposed to grid development per se. Thus, effective communication with local communities could foster acceptance, especially if this takes place as early as possible in the process. However, communication alone might not be sufficient, and avenues for active participation could be explored. In this respect, some useful lessons could be drawn from our experience of developing renewable energy sources where citizen ownership (e.g. energy cooperatives) has supported the deployment of renewables and made it more socially acceptable. It might be worth considering similar opportunities for grid extension projects.

Figure 3: Organised public opposition to high-voltage overhead lines in Germany.

Source: Citizens' action group in Garbsen

The issue of public participation exemplifies how grid development straddles different dimensions and takes place within the wider framework of the energy transition processes under way at the national and European levels. In addition to the impact of an increasing share of renewables in the power supply, other transformations, such as changes in power consumption modes and behaviour ('smart homes', electric vehicles, etc.), could necessitate a review of how to operate and structure the grid. This means that grid development, its design and implementation, cannot be seen in isolation from other areas of energy policy. Furthermore, its intrinsically transnational aspects, like interconnectivity, indicate that at least some parts of it should be discussed and addressed at European level.

As a possible component of an integrated European energy policy, we need to ask how grid development efforts are to be coordinated and how they should complement overall strategic objectives. The EU Energy Union project provides the overall policy framework: integrating renewables and climate targets with security of supply [13]. But there is a need to identify the proper discussion fora for linking grid planning to demand response, storage options, and all other connected topics. The importance of defining institutional settings that can coordinate these efforts is therefore increasingly evident, although it is less clear who should assume the lead (and the responsibility). In this respect, the question of how to deal with different interests and paces of development in different EU countries is also likely to gain relevance.

KEY MESSAGES

- Grid development is an integral part of wider energy transition processes, and it entails challenging trade-offs with regard to costs, technical efficiency, environmental risks and societal impacts.
- Public acceptance is becoming a decisive factor, which necessitates greater efforts to ensure citizen engagement and participation.
- These dimensions of grid planning raise the question of how to organise coordination with other areas of European energy policy.

4. Conclusion

The transformation of the energy system, and the deployment of renewable energy sources in particular, are reshaping the way we plan, build, and operate the grid. Technological innovations play a key role in addressing these new challenges and have the potential to profoundly affect the future grid. The question of what will constitute the right mix of technologies is still open, but it seems that grid development will not fail due to a lack of technological options. However, expanding and modernising the grid is not only a technical challenge: it is tied up with wider economic, social, and political dimensions, and thus calls for a more integrated approach and the coordination of efforts at the national and European level.

5. References

[1] ENTSO-E (2014). *Ten Year Network Development Plan, 2014*. Available at: https://www.entsoe.eu/major-projects/ten-year-network-development-plan/tyndp-2014/Pages/default.aspx (last accessed on 09.05.2016)

[2] e-Highway2050 (2015). *e-Highway 2050: Europe's future secure and sustainable electricity infrastructure*. Available at: http://www.e-highway2050.eu/fileadmin/documents/e_highway2050_booklet.pdf (last accessed on 09.05.2016)

[3] Friends of the Supergrid, available at: http://www.friendsofthesupergrid.eu/ (last accessed on: 03.05.2016)

[4] ABB (2013). Focus on power products and power systems. – *FFWD Newsletter*, 1, pp. 8–9.

[5] Ohata, K., Tsuchiya, S., Shinagawa, N., Fukunaga, S., Osozawa, K., Yamanouchi, H. (1999). Construction of long distance 500 kV XLPE cable line. Paper presented at the Jicable'99 International Conference on Power Insulated Cables in Versailles.

[6] Koch, H. (2012). Gas Insulated Transmission Lines (GIL). Wiley, New York, pp. 33–36.

[7] IPCC (2007). IPCC Fourth Assessment Report. *Climate Change 2007: The Physical Science Basis*. Available at: http://ipcc.ch/publications_and_data/ar4/wg1/en/contents.html (last accessed on 03.05.2016)

[8] Thomas, H., Marian, A., Chervyakov, A., Stückrad, S., Salmieri, D., Rubbia, C. (2016). Superconducting Transmission Lines – Sustainable electric energy transfer with higher public acceptance? – *Renewable & Sustainable Energy Reviews*, 55, pp. 59–72.

[9] Chervyakov, A., Ferrari, M., Marian, A., Stückrad, S., Thomas, H. (2015). Superconducting Electric Lines, (IASS Fact Sheet 2/2015), Potsdam: Institute for Advanced Sustainability Studies (IASS).

[10] Knoepfel, I., Bernow, S., Lazarus, M. (1994). Environmental Impacts of Long Distance Energy Transport: Additional Benefits of Efficiency. Conference paper presented at the Summer Study on Energy Efficiency in Buildings of the American Council for an Energy-Efficient Economy in Pacific Grove, California.

[11] Inelfe (France-Spain Electric Connection), available at: http://www.inelfe.eu/?-rubrique25-&lang=en (last accessed on 03.05.2016)

[12] Deutscher Bundestag (2015). Erdverkabelung bekommt Vorrang. [Underground cables are given priority], Press release available at: https://www.bundestag.de/presse/hib/2015-12/-/398150 (last accessed on 03.05.2016)

[13] European Commission, Energy Union and Climate, available at: http://ec.europa.eu/priorities/energyunion/index_en.htm (last accessed on 03.05.2016)

IASS Working Paper
May 2016

Institute for Advanced Sustainability Studies Potsdam (IASS) e. V.

Contact:
Dr. Adela Marian: adela.marian@iass-potsdam.de
Dr. Heiko Thomas: heiko.thomas@iass-potsdam.de

Address:
Berliner Strasse 130
14467 Potsdam
Germany
Phone 0049 331-28822-340
www.iass-potsdam.de

email:
media@iass-potsdam.de

DOI: 10.2312/iass.2016.010

SPONSORED BY THE
Federal Ministry of Education and Research

FONA
Research for Sustainable Development
BMBF

LAND BRANDENBURG
Ministerium für Wissenschaft, Forschung und Kultur