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Energy security and renewable electricity trade—Will Desertec make Europe vulnerable to the ''energy weapon''?

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ABSTRACT

Solar power imports to Europe from the deserts of North Africa, as foreseen in the Desertec concept, is one possible way to help decarbonising the European power sector by 2050. However, this approach raises questions of threats to European energy security in such an import scenario, particularly in the light of increasing import dependency and Russia's use of the ''energy weapon'' in recent years. In this paper we investigate the threat of North African countries using the Desertec electricity exports as an ''energy weapon''. We develop and use a new model to assess the interdependence – the bargaining power symmetry, operationalised as costs – of a disruption in a future renewable electricity trade between North Africa and Europe. If Europe maintains current capacity buffers, some demand-response capability and does not import much more than what is described in the Desertec scenario, it is susceptible to extortion and political pressure only if all five exporter countries unite in using the energy weapon. Europe is not vulnerable to extortion by an export cut from only one country, as the European capacity buffers are sufficient to restore the power supply: no single exporter country would have sustained bargaining power over Europe.

1. Introduction

In its fourth assessment report, the Intergovernmental Panel on Climate Change suggested that global greenhouse gas emissions are reduced by at least 50%, and the emissions in the industrialised countries by at least 80%, by 2050 compared to 1990 (IPCC, 2007). The European Council, following the IPCC recommendation, has given a long-term – but still non-binding – commitment for a 80–95% greenhouse gas emission reduction by 2050 (European Commission, 2010). Due to technological or natural constraints and lack of carbon-neutral substitutes, some sectors may have difficulties to reduce their carbon emissions by 80% or more, which creates a need for other sectors where 80% reduction or more is possible to compensate for this shortfall. The power sector is one such sector which can – and must – be completely decarbonised in order to meet the long-term emission target (ECF, 2010).

There are many possible ways to decarbonise the European power sector and we will not discuss the advantages and disadvantages of different concepts and technologies. Instead, we will focus our considerations on one option that has gained a lot of media attention in the last years: imports of solar electricity from the Sahara, such as proposed by researchers from the German Aerospace Centre in the *Trans-CSP scenario* (DLR, 2006) and conceptualised by the Club of Rome as the *Desertec concept* (Club of Rome, 2008). The Desertec concept was the base for the creation of Desertec Industrial Initiative in 2009, a consortium of companies like E.on, Siemens and Deutsche Bank (DII, 2009). Desertec is a project of huge proportions: the plan foresees 100 GW of concentrating solar power plants in North Africa for export to Europe, satisfying 15% of Europe's electricity demand, in the coming 40 years, at a projected investment cost of 400 billion €.

In recent years, a number of technical studies have shown that a geographically very large power system design, such as Desertec, leading to 100% renewable electricity by 2050 is technically possible and economically feasible, but politically very challenging (e.g. Czisch, 2005; SRU, 2010). Despite some largely ideological criticism from the decentralised renewable energy community (see Hollain, 2009), the feasibility of Desertec is questioned by surprisingly few, although there are numerous questions that indeed require thorough investigation. Among these are questions that may be severe enough to make the implementation of the entire idea unfeasible.

One such critical question is the question of European security of electricity supply in a Desertec environment. Concerns about the European energy import dependency and the political reliability of the suppliers are frequently heard in both the academic discussion and the public media. One author writes about Desertec and asks ''*Why create a new hostage to fortune*?'' and

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states that "*the stage is set to recreate an uncomfortable parallel with western dependency on oil from Saudi Arabia, Iran and Iraq*" (Pearce, 2009). Indeed, the deliberate and one-sided cancellation of energy exports can have severe impacts on a country's economy. Russia's conflicts with its post-communist neighbours, and the oil crisis of 1973 are typical examples of governments using their energy exports as an *energy weapon* to extort its opponents and to achieve certain economic or political goals (Larsson, 2006, 2008). The fear of supply disruptions is increasing rapidly in Europe, especially after the recent series of gas delivery disruptions from Russia (e.g. European Commission, 2006, 2009). In this context, a proposal such as Desertec raises justified questions of security of supply. We will in this paper investigate the question whether the European fears of political extortion by the exporter countries are well-founded: *should Desertec become reality, is Europe susceptible to extortion by the exporters' use of the energy weapon*?

The risk of a deliberate energy supply disruption is difficult to assess, especially since most energy scenarios, including Desertec, focus on events taking place 20–40 years from today. We do not know how the world looks in 2050: perhaps some North African countries are EU members, or perhaps the EU does not exist at all. Still, we already today need to make reasonable estimates of whether a particular energy path is secure or not.

To our knowledge, no study quantitatively addresses the future political security of electricity supply. Instead, the extensive energy security literature focuses on security of gas and oil supply. Generally, such approaches circumnavigate the problem of not knowing how the future by either creating dimensionless indices with subjective weights, or they by declare the future a state of *ignorance* in which it is impossible to know both the probability and the impact of events (Stirling, 1994, 2010). Most approaches see supply diversification as the only available tool to ensure energy security. The method to assess this is typically a dual-concept diversity index, often coupled with a measurement of the current general political stability of the exporter (e.g. Frondel et al., 2009; Jansen et al., 2004; Lefèvre, 2010).

However, a diversity index measures only the supplier diversity, not whether a particular system is more secure than another. Furthermore, the diversity indices generally penalise energy imports, although it is not clear why imports are necessarily less secure than domestic energy. In such an approach, Desertec will always be more insecure than today's system, as Europe currently does not import any mentionable amounts of electricity. In addition, and for our purposes most significant, the assumption that current political stability in the exporter countries will be valid in 2030 or 2050 is directly misleading. Exporter stability is not the same as exporter reliability, but even the usage of country risk indicators are misleading: indicators of current general risk say nothing about a country's future reliability as an energy exporter.

Moreover, we can expect the risks of electricity and oil/gas imports to be very different, as these energy carriers differ significantly with respect to two important characteristics:

- First, oil and, to some extent, LNG are traded on a liquid and flexible world market. This increases the possibilities to substitute failed imports by rerouting supplies from other external sources to the European import terminals. Electricity imports, on contrast, will be grid-bound, and suppliers can only be substituted to an extent that the existing grid allows.
- Second, oil and gas can be stored. Many countries have storages large enough to bridge several months in the event of an import disruption. The storability of gas and oil also means that an exporter can store failed exports and deliver them at a later point. Electricity is a perishable good and cannot be stored in any significant amounts over significant times: a supply disruption would mean that the non-delivered amount of electricity is immediately missing.

Considering this combined with the weak price-responsiveness of the customers (Lijesen, 2007), it becomes clear that an electricity import disruption can, if the disruption is sudden and large enough, cause immediate blackouts and economic damages in the importing country. On the other hand, electricity has to be sold and consumed in the instant it is produced or it will not be sold at all: in the disruption case, the export revenues for this electricity would cease immediately. The effects of an electricity disruption are thus different – stronger – than those of an oil disruption, and the environment for causing a disruption is different, too.

To address this, we will develop a new method to assess the actors' vulnerability and susceptibility to political extortion by the use of the energy weapon in a Desertec future. This assessment will be based on the balance in bargaining power – conceptualised as the relative impacts, or the *costs* – of a supply disruption to both exporter and importer, recognising the special characteristics of electricity.

2. Interdependence

The energy sector of today is highly international with vast amounts of energy traded across the globe. Most industrialised countries have a large and growing energy import dependency: in 2006, the EU imported 84% of its oil and 61% of its gas (Eurostat, 2009). Since the oil crises, if not before, governments of importing countries perceive a threat to their *security of supply*, with the formation of the IEA oil stocks, or the large-scale shift from oil to nuclear in the power sector as examples of security-increasing measures (López-Bassols, 2007). Equally, the energy exporting governments see *security of demand* as something vital to their economies, with the formation of the OPEC as an example of exporters trying to manage the oil export revenues (Yergin, 2006). Whereas a reliable energy supply is the motor of modern societies, the economies of energy exporting countries often relies heavily on the revenues of their energy exports: Algeria and Libya gain 30% of their GDP and at least 95% of their hard currency export earnings from oil and gas exports (CIA, 2010). The relationship of energy exporting and energy importing countries should thus not be described as simple dependence, or even as interconnectedness, but rather as a relationship of *interdependence* (cp. Keohane and Nye, 2001).

This interdependence can induce win–win situations, in which both parties benefit from a given common and reciprocal issue, but interdependence can also be a mutual threat of imposing costs on both parties. An example is the gas trade between the USSR and western Europe during the cold war: on the one hand the Soviets were highly dependent on the hard currency income from the trade and had large investment locked down in gas infrastructure, and at the same time the western Europeans were dependent on the Soviets as a main supplier of gas. As a consequence, there were no significant, politically motivated disruptions in gas trade between the USSR and Europe, despite the strong political tensions between the two blocks (Adamson, 1985). Both types of positive and negative symmetric interdependences are characterised by evenly distributed costs or benefits in non-compliance and compliance, respectively. Such a relationship can be considered to be a Nash equilibrium and as such, it is likely to be stable as no actor has *bargaining power*[1] over the other (Keohane and Nye, 2001).

[1] In the following, we will refer to bargaining power only as "power".

2.1. Power: asymmetric interdependence

On contrast to stable, symmetric interdependence, asymmetric interdependence may be a source of power: "It is asymmetries in dependence that are most likely to provide sources of influence for actors in their dealings with one another. Less dependent actors can often use the interdependent relationship as a source of power" (Keohane and Nye, 2001:10f). Considerations about the use of the energy weapon are thus strongly influenced by rational expectations and calculations about the future development and the cost symmetry of breaking the trading relationship (Keohane and Nye, 2001). Or put differently: "The future can [...] cast a shadow back upon the present and thereby affect the current strategic situation" (Axelrod, 1984:12).

The relevant measure is the opportunity costs of non-compliance. These, in turn, depend on the characteristics of the product and the alternative options of exporting or importing the product: the relationship can be a source of power for exporter B if a broken deal causes large damages for importer A, without damaging the deal-breaking actor B much. If A can substitute the shortage or if A can live completely without the embargoed product, the dependence does not constitute a source of power for B. And vice versa: if exporter B can do without or easily substitute the losses from the non-exports to importer A, an import embargo could not be a source of power (Caporaso, 1978).

The threat of an energy embargo due to political considerations is thus a function of the symmetry of the impacts of an one-sided cancellation of the deal on both actors. The less dependent actor can exercise her power on the more dependent partner and get her to do things she otherwise would not have done. The more dependent actor, on the other side, does not have power over the other actor: as her costs are higher, she will not be able to sustain pressure for a sufficiently long time. The less dependent actor will in this case be able to withstand the pressure and simply wait it out. However, an asymmetric relationship is a source of power, but this only means that this power *can* be used, not that it *will* be used (Keohane and Nye, 2001).

2.2. Power: time dependency

An interdependent trading relationship is not static, but can be highly dynamic. Already the threat of a disruption may be reason enough for one or both parties to prepare for future conflicts. The dependent actor will be especially sensitive to changes in perceived threat level and may take measures to reduce this dependence (Keohane and Nye, 2001). A typical example of this are the strategic oil reserves of the IEA countries, which have been "*both a deterrent to deliberate, politically motivated reductions in normal oil supplies and a powerful instrument to respond to such reductions*" (Bielecki, 2002:239f). The effects during a disruption are also not static: both sides will try to minimise their damages. Typically, the importer may try to substitute the embargoed good or find other suppliers, and may try to minimise the demand (López-Bassols, 2007). Equally, the exporter may aim at rerouting the exports to other markets, or use them by herself. Thus, the initial asymmetries of the interdependence as well as the development of the asymmetry over time, including possible counter-measures, must be taken into account when assessing the possibility of an energy weapon as a source of power.

3. Interdependence and Desertec

In the following, scenarios in which the North African exporters make use of the energy weapon and break the export deal are considered. The importer, Europe, is very unlikely to suddenly stop importing electricity and such scenarios are not considered here, for two main reasons. First, Europe is unlikely to start importing renewable electricity if it can produce it cheaper and better domestically. In the Desertec scenario, imports are cheaper than domestic renewable baseload generation; this is the main reason why Europe would import electricity at all. Second, by cutting imports, Europe would risk shortages in the short term, and these are very costly.

Exporter governments can have different reasons to use the energy weapon. These reasons can be either economical (e.g. higher prices) or political (e.g. achieving certain foreign policy goals) or personal (e.g. the arrest of a leaders son). We cannot know what reasons might trigger such events in the future, and due to the large number of imaginable reasons for conflict and the qualitative–subjective nature of political and personal reasons, it is not possible to quantify or assess these in a meaningful way. Essentially, the reason could be conceptualised as expected benefits for the exporter and expected costs of accepting the demands for the importer. The stronger the reason, the larger are the exporter's willingness to risk conflict and accept damages, and the higher is her stamina. However, it will not necessarily determine her chances of winning a conflict: here, the power balance – the threat, or the leverage to force the importer to accept the demands – is the more important determinant. The importance of the reason for the outcome of the event is further discussed in Section 5.

For these reasons, we here assume that a strong reason to deliberately break a trading deal is present. For this aim, the energy weapon can be a tool for a government only if they are in the power position and are able to extort other states by cutting the energy exports.

In the following, we will operationalise the interdependence concept and apply it to different scenarios by determining the symmetry and intensity of the interdependence in a dynamic perspective, conceived as the direct costs of a deliberate, one-sided electricity trade disruption. We only include the direct costs of a disruption, namely the costs of blackouts and counter-measures on the importer side and the lost income for the exporter side. Other effects of non-compliance, like lost credibility from breaking international treaties or very long-term effects, are not considered, although these could essentially also be seen as costs. These other costs – which are largely impossible to quantify *ex-ante* – will mainly apply to the actor breaking the deal, and make the use of the energy weapon less attractive.

3.1. Damage functions

Following Keohane and Nye (2001), the bargaining power symmetry is determined by the difference between exporter (c_{exp}) and importer (c_{imp}) costs. The actor with the higher costs is the more dependent actor and may be subject to power from the other actor. If both costs are equally high, the relationship is stable and no actor has power over the other. Due to the unequal economic strength of Europe and North Africa, we will express the results both in absolute (billion €) and in relative costs (% of GDP per time unit).

The exporter's costs for a broken electricity delivery deal are mainly determined by the amount of non-delivered electricity (m_{exp}) and the price for this at the target market (p_{exp}). Following DLR (2006), we assume that no grid infrastructure to other significant export markets exists, due to the isolated geographical situation of the North African countries. If the export country is also a transit country for electricity (m_t) for which it receives a transit fee (p_t) from another country, the costs of an embargo will increase by the product of these two terms. We do not consider penalty payments, which may apply if deliveries are disrupted. Such clauses may be included in an electricity trade deal, but the magnitude of these is difficult to predict, as is the willingness of the exporter to actually pay these in case of an energy conflict. As such penalty payments will be ≥ 0, this may lead to an underestimation of the exporter costs. The damage function for the exporter is written as:

$$c_{\exp}(t) = m_{\exp}(t)p_{\exp}(t) + m_t(t)p_t(t). \tag{1}$$

The importer's costs are mainly determined by the size of the blackout and the blackout costs per non-delivered kWh (p_{bl}), minus the value of the non-delivered electricity ($p_{\exp}m_{\exp}$). The importer is prepared for technical contingencies and other disturbances and has access to different emergency response mechanisms to replace failed capacities. The reserve and control capacities are denoted by m_r and can produce at the price p_r. This includes primary, secondary and tertiary control, which are ordinarily used to balance fluctuations and handle technical contingencies in the grid but can also be used to make up failed imports, as well as spare capacities. The importer can also reduce its demand, both rapidly through pre-defined emergency measures and in a longer-term perspective through behavioural changes among the consumers. This load reduction is denoted by m_{red} and is assumed to imply only negligible direct costs, as these are already covered by lower prices for interruptible/reducible customers during normal operation. We do not consider disturbances long enough to make new-built capacity a factor to address: building new power plants typically takes years, and if a blackout lasts that long, the importer will succumb to the exporter long before new capacity is in place. As we assess the power balance of electricity trade as described by DLR (2006), we do not consider electricity imports from other regions, although these would be technically possible (Czisch, 2005).[2] The importer damage function is written as

$$\begin{aligned} c_{\text{imp}}(t) = {} & (m_{\exp}(t) + m_t(t) - m_r(t) - m_{\text{red}}(t))(p_{bl}(t) - p_{\exp}(t)) \\ & + m_r(t)(p_r(t) - p_{\exp}(t)). \end{aligned} \tag{2}$$

The equation is constrained by $m_{\exp}(t) + m_t(t) \geq m_r(t) + m_{\text{red}}(t)$.

3.2. Economic assumptions

The costs of a blackout (p_{bl}), which can be both direct (such as lost production) and indirect (such as looting during blackouts), are hard to quantify, but can be estimated by the concept of Value of Lost Load (VOLL) (Willis and Garrod, 1997). The VOLL depends on many factors: when the blackout occurs (day/night/summer/winter, etc.), how long the blackout lasts (computer processes may break down immediately, frozen food will stay frozen for hours), and the degree of preparedness influence the VOLL significantly. Still, the VOLL is always much higher than the price of the non-delivered power, as electricity is a catalyst to most economic processes. Due to difficulties with data availability, we will, based on recent research for Europe, in this paper assume a fixed VOLL of 8 €/kWh (Bliem, 2005; de Nooij et al., 2007).

The price of the exported/imported electricity, $p_{\exp}$, in 2050 is assumed to be 5 €c/kWh, based on both Trans-CSP and more recent research (DLR, 2006; Williges et al., 2010). We consider this as avoided costs for the importer – Europe will not pay for non-delivered electricity – and the lost income for the exporter. We assume that a transit country receives 1 €c/kWh passing through its territory. Furthermore, we assume that the costs and price for continuously operating the reserve and spare capacities (p_r) is 6.5 €c/kWh.[3]

Table 1
GDP 2009 (billion €) for the North African countries and the EU27 (official exchange rate), and projected GDP in 2050 assuming constant growth of 4.5% in North Africa and 2% in EU27.
Data: CIA, 2010; USDA, 2010

	GDP 2009, billion €	GDP 2050, billion €
Morocco	66	380
Algeria	97	570
Tunisia	29	170
Libya	44	260
Egypt	136	790
North Africa	372	2170
EU27	11,557	25,520

Both the cost symmetry in absolute numbers and the relative impact of these costs on the national economies are relevant measures, especially considering two economically differently strong regions such as the EU and North Africa. Thus, we present the cost and power symmetry results both in € and in % of GDP per time unit. The GDP figures (see Table 1) are based on data for 2009 and are extrapolated to 2050 with average growth rates of 4.5% (North Africa) and 2% (Europe); these are the average growth rates for Europe and North Africa in USDA (2010) for 2010–2030.

3.3. Importer response mechanisms

We base all capacity assumptions on an European peakload of 600 GW in 2050 as described in DLR (2006), which is about 20% higher than the current EU27 peakload of 500 GW (BALTSO, 2009; Eirgrid, 2009; National grid, 2009; Nordel, 2009; UCTE, 2008). All calculations assume that the disruption happens at peak times, which is when Europe would be the most vulnerable. This is an overestimation of the importer costs, especially if the disruption is long and stretches into the evening and night, which have lower loads than the day. Further, it is assumed that the import line connection points and response mechanisms are homogenously distributed across the entire system; thus, Europe is viewed as a copper-plate system. This could lead to an overestimation of Europe's capability to react to disturbances, as transmission bottlenecks cannot be ruled out in a real-world system. However, to facilitate a large-scale expansion of renewables, massive grid expansions will be required (ECF, 2010; SRU, 2010). These grid reinforcements and the creation of an overlay HVDC grid, such as suggested both by the DLR and others (see Battaglini et al., 2009), will significantly relieve bottlenecks and Europeanise the emergency response capabilities, strongly reducing the overestimation error resulting from this assumption.

Within all ENTSO-E grid areas, the core principles to maintain system stability during disturbances are the *n*-1 *principle* and the *no cascading principle*: the system must be able to maintain stability even if the largest unit fails and disturbances must be contained to the affected control area to avoid cascading effects (UCTE, 2009). We assume that these principles will remain intact

[2] The security of the importer and the rationale for the exporters to cut deliveries would change significantly in such a scenario: In principle, the diversification would increase the security for the importer and reduce the power situation for the exporter. However, such a scenario could also lead to higher import dependencies, thus reducing the European security of supply if the exporters pursue a joint embargo. Such scenarios, although interesting, are not investigated here but are the task for future assessments.

[3] Levelised electricity costs for a gas power station with 700 €/kW investment costs, 1.7 €c/kWh O&M costs, 70% efficiency, 30 years lifetime (see Garz et al., 2009), 7300 €/TJ_{th} fuel costs (33% higher than the 2010 price for natural gas in Germany, see BAFA, 2010), interest and discount rates of 8%, and a load factor of 85% following the disruption (all available capacities are in operation following the disruption, due to the strained capacity situation). Gas power stations are likely to make up the largest share of the reserves, as these are highly flexible and have low capital costs, making them the best suited for back-up and control operation with low load factors during normal operations.

until 2050. The importer spare capacities, m_r, are – as is currently the case – split into primary, secondary and tertiary control, and other spare capacity.

Currently, the continental primary control has a total capacity of 3 GW, or 0.8% of the continental ENTSO-E peakload, proportionally distributed among all control areas. This is also the maximum size of the largest unit. The primary control can reach full capacity within 30 s and sustain this for up to 15 min (Büchner et al., 2006; ENTSO-E, 2009b; TenneT, 2009; UCTE, 2008). We assume that the primary control capacity remains constant at 0.8% of the peakload, and that the operating time interval remains as it is today.

There are no numbers for the cumulated ENTSO-E secondary and tertiary control capacities, and these may vary slightly between control areas. The German control block currently has secondary and tertiary control capacities of around 4% and 4.2%, respectively. Assuming that this ratio is more or less constant across the synchronous and interconnected ENTSO-E area, this would mean around 20–21 GW secondary and tertiary control, distributed across the entire area (Büchner et al., 2006; Regelleistung.net, 2009). The secondary control is activated automatically within 5 min to free primary control and is foreseen to remain operational for up to 30 min, but parts of the secondary capacity can operate indefinitely during extraordinary events. The tertiary control is activated manually and has to be fully operational within 15 min and can operate for as long as is required (ENTSO-E, 2009a, b; Regelleistung.net, 2009; Swedish national grid, 2010a). We assume that the control capacities remain constant in relation to the peakload. Furthermore, we assume that the reaction times remain as they are today, and that half the secondary control and 2/3 of the tertiary control capacity can operate indefinitely. Operating the control capacities continuously would reduce the normal operation security in the entire ENTSO-E area, and thus the control capacities will be freed and returned to idle as fast as possible as spare capacities come online.

The spare generation capacities are significant, as parts of the generation fleet are not permanently used. These capacities can be used during extreme peaks or contingency times, or they can be used to replace capacity that is down. In 2006, the EU27 generation capacity was 762 GW, of which 570 GW was fossil and nuclear thermal and 130 GW is hydro power (Eurostat, 2009). Assuming that 10% of the capacity is not available (e.g. due to repairs, refuelling, etc., see NERC, 2009) and that only half of the hydro capacities are fully dispatchable, we get an 80 GW buffer between peakload and available, dispatchable capacity. Subtracting the control capacities leaves about 36 GW, or some 7% of the current EU27 peakload, of dispatchable capacities which can be made operational within hours and operate for as long as needed. We assume that this spare capacity remains constant relative to the peakload, and that it can be started within 12–24 h and operate indefinitely.

The control and spare capacities as described above may be an underestimation of these capacities in 2050. As the power system in the investigated scenario consists largely of renewable capacity, of which parts are intermittent, the system is likely to have larger back-up capacities compared to the peakload than the current system. For example, a recent study projects more than twice as large back-up capacities in 2050 (in an 80% renewables scenario, with more than 50% intermittent generation) as in 2020; the primary driver for this back-up increase is the intermittent generation (ECF, 2010). In the Desertec scenario, the share of intermittent renewable power (about 25%) is much lower than in the ECF scenario, and therefore it will not require such high back-up capacities, but this need may still be higher than today. Overall, the assumptions made here, including some 10% of capacity that is typically down for maintenance, lead to control and spare capacities are around 25% of peakload, which is the same as the capacity margin in DLR (2006).

The reaction speed of the importer response mechanisms as described above refers to the start-up times of the different capacities under optimal circumstances. If a disturbance leads to a blackout, the system operation must be restored, a process that takes longer than the simple start-up of control and reserve capacities. How long this takes depends on the circumstances of the blackout, but historical data shows that very few blackouts in the industrialised countries last longer than a few hours (<8 h): even the very large blackout in western Europe in November 2006 lasted less than 2 h (Eaton, 2010; UCTE, 2007). The overwhelming majority of past blackouts were caused by technical failures and cascading. It is thus not possible to, based on historical data, foresee how long time it would take to restore the grid after an export cut – this may be different from a blackout caused by technical failures – nor is it possible to predict cascading. Here, we assume that the secondary and tertiary control capacities will increase linearly to their maximum available capacity with an 8 h lag, to simulate for delays in reigniting the grid and a short-term magnification of the blackout size due to cascading.

During an emergency, demand can be reduced both within pre-defined demand-response programs and through additional measures to mobilise other saving potentials. The demand-response programs typically encompass a few percent of total demand, and utilities which can reduce demand by up to 5% on very short notice are not seldom (Meier, 2005). Often, these are considered part of the control capacities and are able to operate in the same time frames as these (Swedish national grid, 2010b). Other measures mainly include requests to the public to reduce their demand or shift it in time, and – if consumers sees the price in real time – responses to increased electricity prices. These additional measures may be significant if a shortage warning is issued a long time in advance,[4] but may be very limited if preparation time is short[5] (see Meier, 2005). In the case of energy weapon events, the exact timing is unknown and a long-term advance warning is unlikely. Therefore, we assume a conservative 5% demand reduction potential, which can react as fast the secondary control and can be maintained for as long as needed. As the demand response schemes are part of normal operation (and are typically "paid" for by lower prices to interruptible customers) and public electricity saving of this magnitude can be expected to have no immediate costs, the cost for the demand reduction is assumed to be zero. Despite this, the demand reductions are only triggered during emergencies, and not during normal operation. All response mechanisms and their timing, as well as the model input data are summarised in Table 2.

3.4. Disruption magnitudes

The base for the scenarios is the Med-CSP and Trans-CSP scenarios (DLR, 2005, 2006), or *Desertec*, which include and European imports of 100 GW baseload solar power from North Africa. Desertec foresees imports from the entire Middle East and North African region, not just North Africa, so we will modify the geographical distribution of the export capacities to apply only to

[4] Brazil, for example, reduced its demand by up to 20% in 2001 as a response to a drought-induced hydro power shortage and maintained this reduction for 10 months. In this case, the warning was issued 5 months in advance, and there was much time to prepare.

[5] During the heatwave of 2003, France used all interruptible contracts and there was a large media campaign to save electricity. Due to the short preparation time –only one day – and weaknesses in the demand-response contracts, savings were a mere 0.5% of normal demand.

Table 2
Summary of the magnitudes of the European current control capacities and the spare capacity and the current operating time interval of these following a disruption, as well as the corresponding model input data. The model works with 30-minute steps.

	Current capacity (% of peakload)	Current scheduled time interval	Model input capacity (% of peakload)	Model input time interval
Primary control	3 GW (0.8)	0–15 min	5 GW (0.8)	0–30 min, then back to idle
Secondary control	20 GW (4)	5–30 min	24 GW (4)	0–30 min (half cap.), then back to idle 0 min—∞ (half cap.)
Tertiary control	21 GW (4.2)	15 min – hours/∞	25 GW (4.2)	30 min—24 h (1/3 cap.)→ linear decrease 36 h (back to idle) 30 min–∞ (2/3 cap.)
Spare capacity	36 GW (7)	Hours, days—∞	42 GW (7)	12 h (start)→ linear increase to 36 h (full cap.)—∞
Demand response	25 GW (5)	~As secondary/ tertiary controls	30 GW (5)	0–30 min (1/3 cap.), then back to idle 0 min—∞ (2/3 cap.) Only used in addition to control and spare capacity if these are not enough to prevent capacity shortage

Table 3
Share of North African installed CSP capacity in 2050 according to DLR (2005), and the corresponding capacities assuming that all Desertec export capacities (100 GW) are located in North Africa proportional to DLR (2005).

	Share of North African CSP capacity in DLR (2005) (%)	Assumed c_{exp} (and c_t for scenario 7) (GW)
North Africa (scenario 1)	100	100
Morocco (scenario 2)	19	19
Algeria (scenario 3)	21	21
Tunisia (scenario 4)	6	6
Libya (scenario 5)	3	3
Egypt (scenario 6)	51	51
Transit Tunisia (scenario 7)	19.5	c_{exp}=6, c_t=13.5

the five North African countries, relative to the CSP capacity as given by DLR (2005), see Table 3. We assume 7 different scenarios: the total electricity embargo of all five North African countries in a coordinated manner ($c_{exp,1}$=100 GW), and the cut-off of all exports from each single country individually ($c_{exp,2-6}$= 3–51 GW), and the total embargo of all CSP electricity deliveries from and through Tunisia to Europe, assuming that half of the Algerian and all Libyan exports transit through Tunisia ($c_{exp,7}$=6 GW export, 13.5 GW transit).

For simplicity, we will not show the results of all scenarios in Section 4, as some results will be almost identical.

3.5. Scenario variations

The input data builds largely on assumptions which are justifiable and reasonable, but are still assumptions. The results should therefore be interpreted as indicative results, showing a pattern in the balance of power. The uncertainties, however, also call for investigations of how the cost balance changes when modifying key input data. We will therefore, based on the data and assumptions described in Sections 3.3 and 3.4, perform the following variations:

- (A) *Baseline*: All assumptions as described in Section 3.3.
- (B) The power stations in North Africa are owned and operated by non-North Africans, and the electricity payments do not go to the exporter country's government. The North African countries receive royalties of 1 €c/kWh (and 1 €c/kWh transit fee, in scenario 7b). The price paid by Europe in this variation is thus 5+1 €c/kWh (cost+royalty)=6 €c/kWh.
- (C) The demand reduction of the European consumers is stronger (2 times the baseline demand response, for example due to crisis preparations during periods of political tension with North Africa) and weaker (no demand response).
- (D) All import and transit capacities are doubled, whereas the response mechanisms remain as in the baseline.

For simplicity, and as some scenarios will show a similar cost balance behaviour, we will not graphically represent all scenarios in the variations.

4. Results

In the baseline scenarios, no single North African country will have the power to put Europe under political pressure and sustain this over time, but all five exporters together will if they coordinate their activities (see Figs. 1 and 2). All interesting events regarding responses happen within the first 36 h following the disruption: both the importer and exporter costs per time unit are stable at the level of the end of the second day until the deliveries are resumed.

In scenario 1a – all 5 exporters participate in the export cut – Europe will not be able to restore the normal power system functionality, as the lost capacity is too large. In this case, uncontrolled blackouts will prevail unless further measures are taken (like rolling blackouts). The European costs increase rapidly, whereas the exporter costs are modest in comparison. In this case, the North African countries will have bargaining power over Europe and they are likely to win the conflict; a Desertec future may make Europe vulnerable to extortion and the coordinated North African use of the energy weapon. As there is a perspective of winning such a dispute, the exporters may be tempted to try it, if they are given a strong reason to challenge Europe.

In all single country scenarios, except 4a and 5a (which do not cause mentionable blackouts), the costs for Europe are initially high, as the export cut causes blackouts. As the system is restored within 8 h, only the exporter experiences significant costs over time. The importer sees slightly increased costs from the operation of the more expensive back-up capacity. If it withstands the initial shock, Europe can wait the exporter out in all single-country scenarios, as the single exporting country has no temporally sustained power over the importer. Thus, Europe is not very susceptible to extortion by one single country. In scenario 6a, the exporter may have a greater incentive to cut supplies, as it in this case has more leverage and may inflict considerable – possibly unacceptable – damage on Europe.

The costs in absolute terms (billion €) are different for importer and exporter: due to the higher GDP of Europe, the European costs at times when Europe has blackouts are much

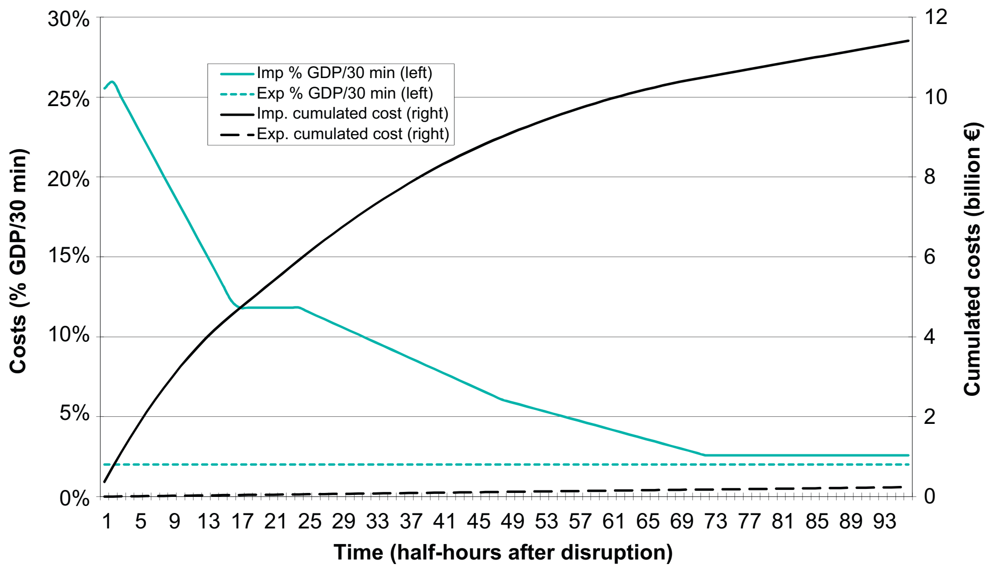

Fig. 1. Result summary for scenario 1a for the first 2 days (96 half-hour steps): costs for exporter and importer as % of GDP per 30 min (left scale) and cumulated costs in billion € (right scale). The dashed lines are the exporter costs, the solid lines are the importer costs.

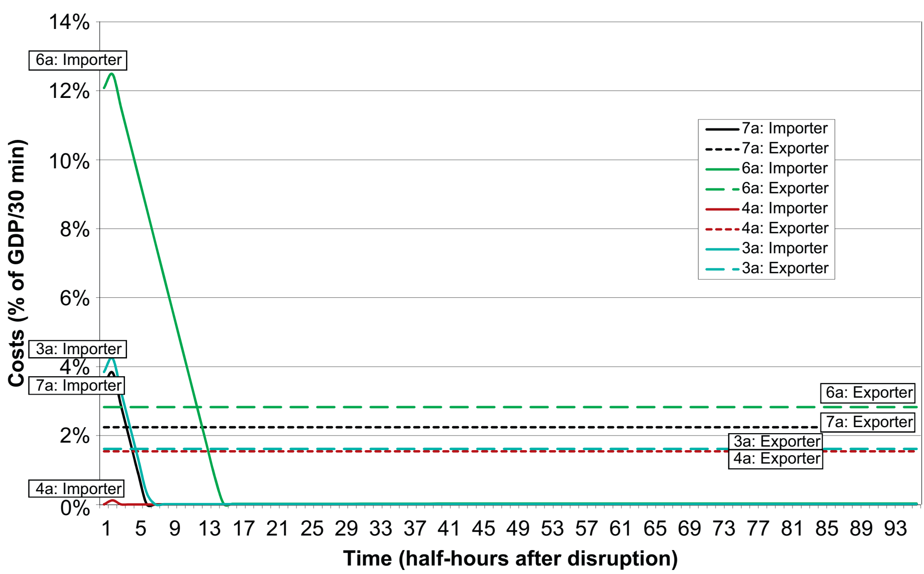

Fig. 2. Result summary for the single country scenarios (scenarios 3a, 4a, 6a, and 7a shown): costs as % of GDP per half-hour for the first 2 days (96 half-hour steps) following a disruption. The dashed, flat lines are the exporter costs, the solid lines are the importer costs. The importer costs in scenario 5a are constantly almost 0, whereas the exporter costs are low; the importer and exporter costs in scenario 2a are very similar to scenario 3a. Scenarios 2a and 5a are thus not shown here.

higher than the exporter costs (see Fig. 3). However, also in this respect, the single exporter cannot sustain pressure on Europe over time: in the long run (weeks–months), also the absolute costs are higher for the exporter in all single-country scenarios. Thus, the exporters will have permanent bargaining power over Europe through the use of the energy weapon only in the case where all exporters join forces.

In scenario variation B, the effect is an exporter cost shift downward while the importer costs are almost the same as in the baseline (Fig. 4). Thus, in scenario 1b, the exporter has an even stronger power situation than in scenario 1a, as her costs are lower whereas the importer's costs are essentially the same. The single-country scenarios behave in a similar way, and the impact of the reduced exporter costs can be seen in Fig. 5: the break-even point in cumulated costs is delayed by up to a factor 7 compared to scenarios A. Still, in the single-country variation B scenarios, the European damages are temporally limited, and Europe is thus only slightly more susceptible to extortion than in the baseline. Nonetheless, it shows the importance of the ownership issue: if the revenue for the exporter is lower and it only receives royalties for power plants that someone else (who may be European[6] or non-European) owns, the exporter's energy weapon power situation improves.

The importer demand reduction capacity makes a significant difference for large disruptions (such as scenario 1c, see Fig. 6), but it does not make a large difference in the smaller-cut scenarios (such as scenario 3c, see Fig. 7). Doubling the demand reduction capacity in scenario 1c enables Europe to eliminate the

[6] If Europeans own the power plants, the costs of a disruption would be slightly higher as the avoided costs are 1 €c/kWh (the royalty) instead of 6 €c/kWh (the price in scenario 1b). This difference would hardly be visible in the graphs shown here, as the outage costs are 800 €c/kWh. The point of scenario B remains: the exporter's power situation improves compared to scenario A.

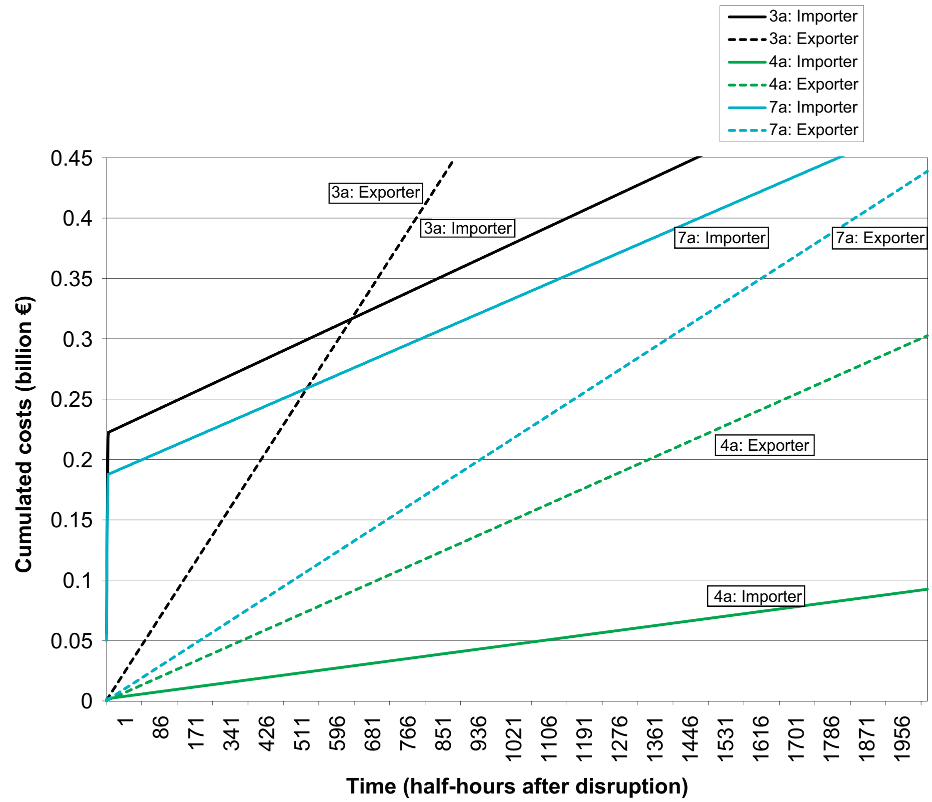

Fig. 3. Results for the scenarios 3a, 4a and 7a: cumulated costs in billion € for the first 6 weeks (2016 half-hour steps) following a disruption. The cumulated cost curves of exporter and importer intersect in scenario 3a after 12 days, in scenario 4a after 10 hours, and in scenario 7a after 54 days. Scenarios 2a and 6a (not graphically shown) follow the same pattern and have cost curve intersection after 11 and 33 days, respectively. In scenario 5a (also not shown), the exporter costs are always higher.

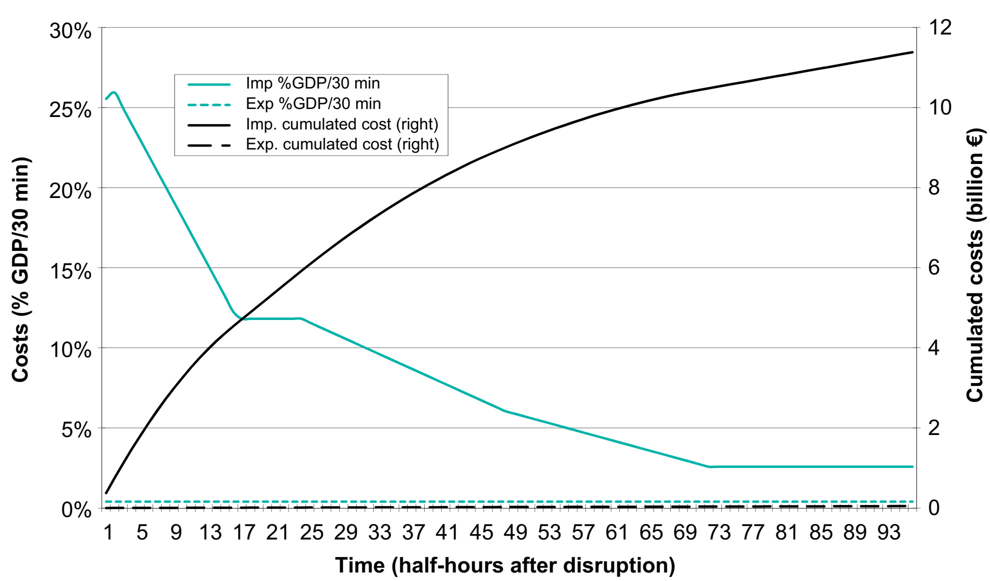

Fig. 4. Result summary for scenario 1b for the first 2 days (96 half-hour steps): costs for exporter and importer as % of GDP per 30 min (left scale) and cumulated costs in billion € (right scale). The dashed lines are the exporter costs, the solid lines are the importer costs.

blackouts – and thus most of its costs – whereas halving it compared to scenario 1a increases the long-term cost level from 2.5% to 8% of GDP per half-hour. In scenario 3c, doubling the demand response leads to elimination of blackouts after 2.5 h, whereas halving it leads to system restoration after 5 h. This shows the importance of demand-response capabilities as the cheapest way to reduce vulnerability to large-scale import disruptions. Europe would be well advised to prepare such measures if it wishes to import electricity in the future.

In scenario 1d (Fig. 8), the European damages are very high: this scenario is unlikely, but it shows the impact of a badly designed import scheme. In the single country scenarios D (Fig. 9), the importer damages are higher than in the baseline, but only scenario 6d shows permanent and significant costs to Europe: in the other scenarios, the blackouts can be eliminated even at this high import level. Scenarios D show the importance of the ratio export cut/importer response capacity: a higher ratio increases the European vulnerability to the energy weapon, whereas a

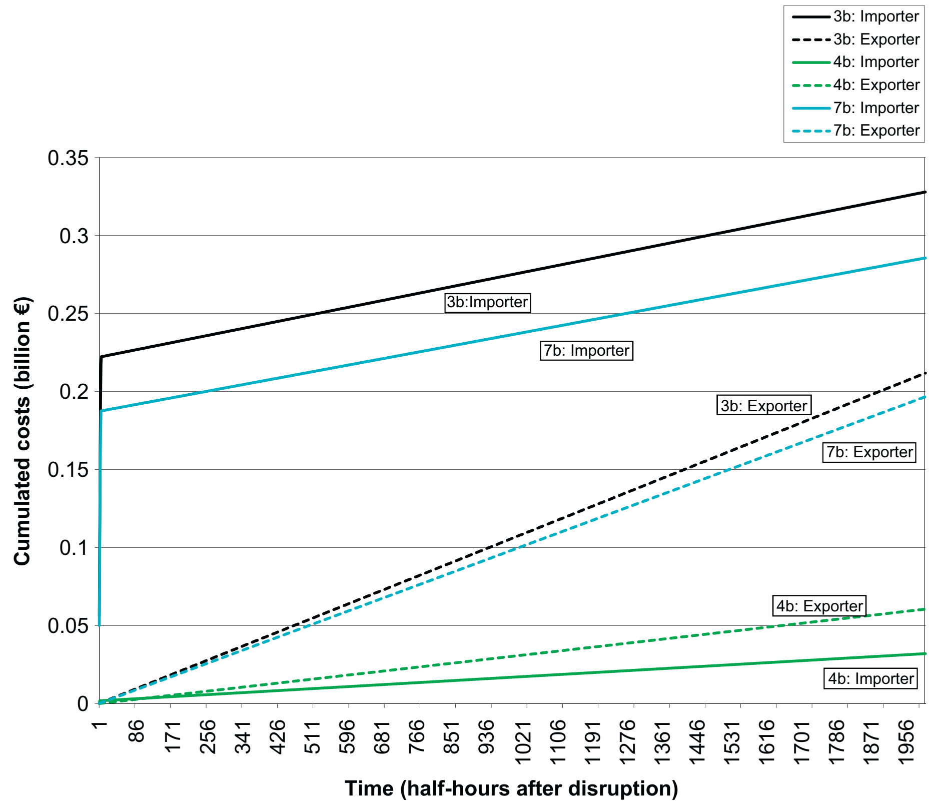

Fig. 5. Results for the scenarios 3b, 4b and 7b: cumulated costs in billion € for the first 6 weeks (2016 half-hour steps) following a disruption. The cumulated cost curves of exporter and importer intersect in scenario 3b after 88 days, in scenario 4b after 3 days, and in scenario 7b after 80 days. Scenarios 2b and 6b (not graphically shown) follow the same pattern and have cost curve intersection after 78 and 233 days, respectively. In scenario 5b (not shown), the exporter costs are always higher.

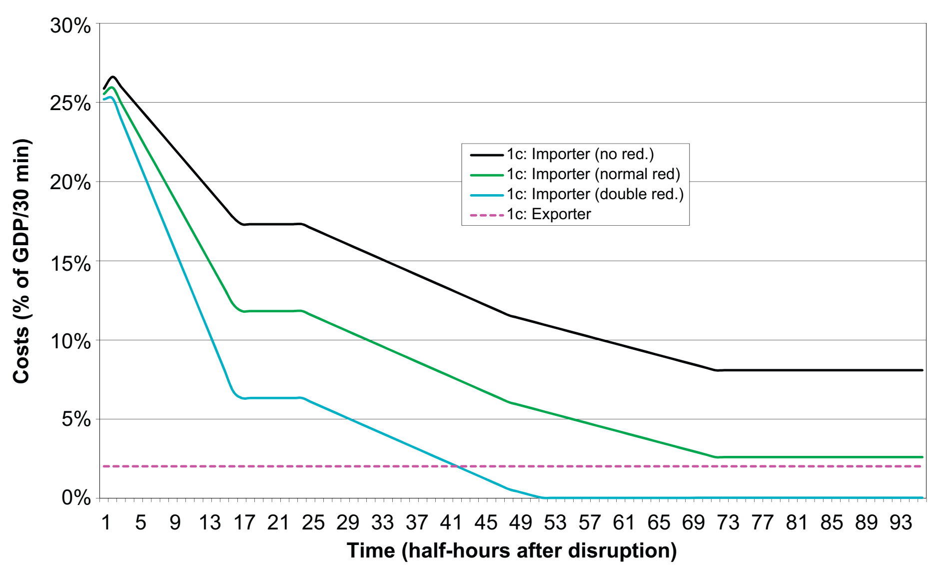

Fig. 6. Result summary for scenario 1c for the first 2 days (96 half-hour steps): costs for exporter and importer as % of GDP per 30 min. The dashed line is the exporter costs, and the solid lines are the importer costs for the cases that the demand reduction capacity is 0, 1, and 2 times the capacity described in Section 3.3.

lower ratio decreases it. Thus, if Europe wishes to import more electricity than in the Desertec scenario, it is well advised to increase its response capabilities as well.

5. Discussion

Desertec implies some political risks for Europe, but the overall extortion risks from the North Africans' use of the energy weapon are not likely to be high. If the deliveries are cut, Europe will suffer economic damage, but this damage is modest in most scenarios. No single country will have sustained power over Europe, as the European response mechanisms are likely to suffice to restore the system after initial blackouts. Thus, Europe is not very susceptible to extortion (political demands, price manipulations, etc.) through the use of the energy weapon by one single country, as long as it maintains proper capacity margins and the capability to reduce demand during emergencies. However, if the

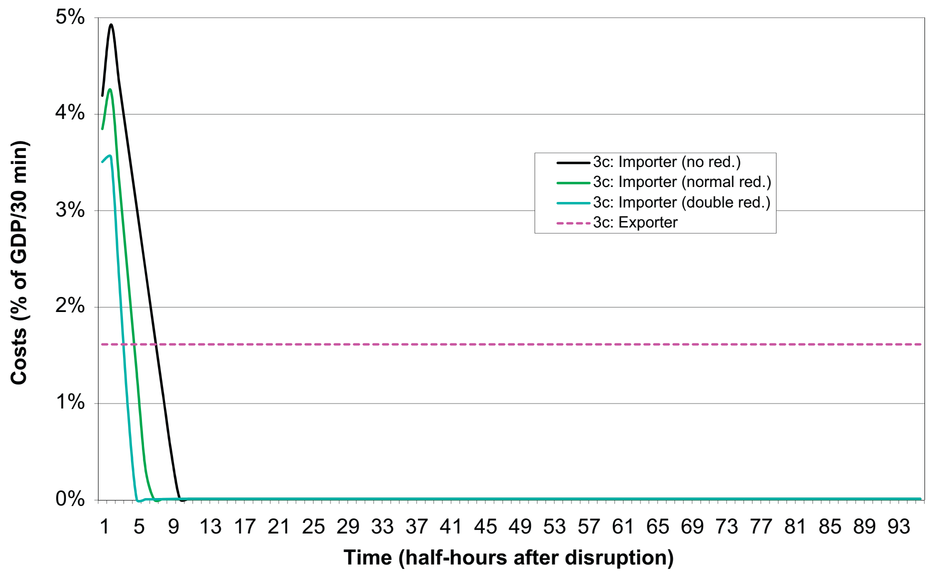

Fig. 7. Result summary for scenario 3c for the first 2 days (96 half-hour steps): costs for exporter and importer as % of GDP per 30 min. The dashed line is the exporter costs and the solid lines are the importer costs for the cases that the demand reduction capacity is 0, 1, and 2 times the capacity described in Section 3.3. Scenarios 2c and 4c–7c show similar cost balance behaviours; for simplicity, only scenario 3c is shown here.

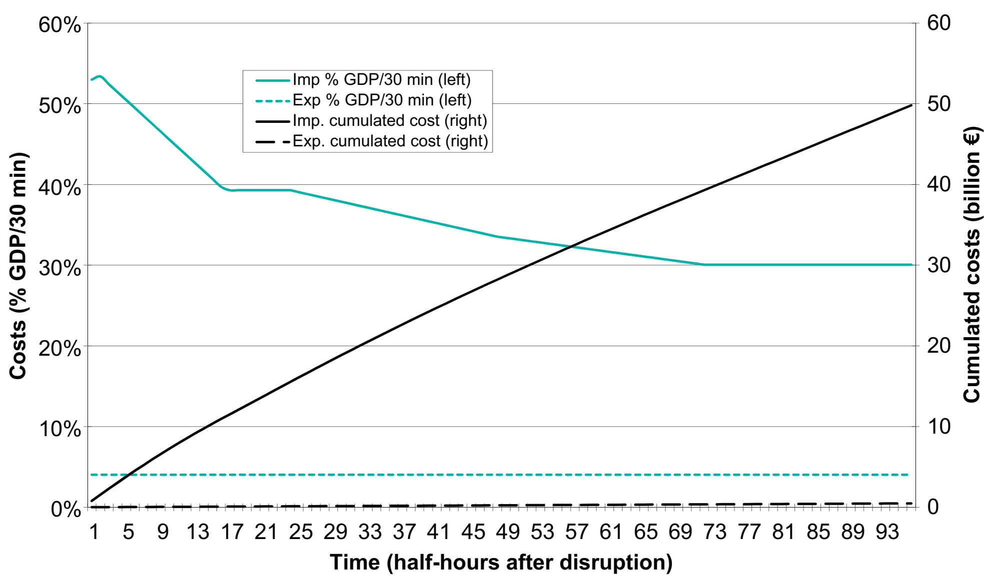

Fig. 8. Result summary for scenario 1d for the first 2 days (96 half-hour steps): costs for exporter and importer as % of GDP per 30 min (left scale) and cumulated costs in billion € (right scale). The dashed lines are the exporter costs, the solid lines are the importer costs.

North African exporters join in energy weapon action against Europe, or if the imports are significantly larger than in the Desertec scenario, the European vulnerability increases. Thus, substantial capacity reserves and good relations to the southern neighbours seem to be good measures to minimise the political risks of Desertec.

Some factors besides the magnitude of the trade would increase the North African exporters' power position. For example, we do not know how intra-North African relations will develop in the future, but this paper has made clear that coordinated energy weapon action from all North African exporters leads to European vulnerability. Thus, increased political cooperation among the North African states could make this threat more credible, increasing Europe's risks in a Desertec-style future. Furthermore, the ownership issue is important: if the export power stations are not owned by the North Africans themselves (but by Europeans or non-Europeans), the exporter's losses in a conflict are lower and its bargaining power higher. Conversely, North African ownership of this infrastructure thus implies lower political risks for Europe.

A number of factors may shift the power balance in favour of the importer. For example, the expansion of electricity storages – which may be needed in a largely renewable power system, with or without imports – would weaken the exporter's power situation, as storages will likely increase the European short-term response capacity without allowing the exporter to store non-delivered electricity over long times in an economically efficient way (see Leonhard, 2008). Similarly, if a strong European emergency preparedness is combined with a credible communication that Europe is willing to accept damages in the very short term and will not bend in a conflict, the case for a single country to cut exports is further weakened. Overall, as long as Europe can manage its short-term supply without the imports from one country, this exporter is unlikely to succeed in increasing prices to levels higher than the permanent operation cost of the

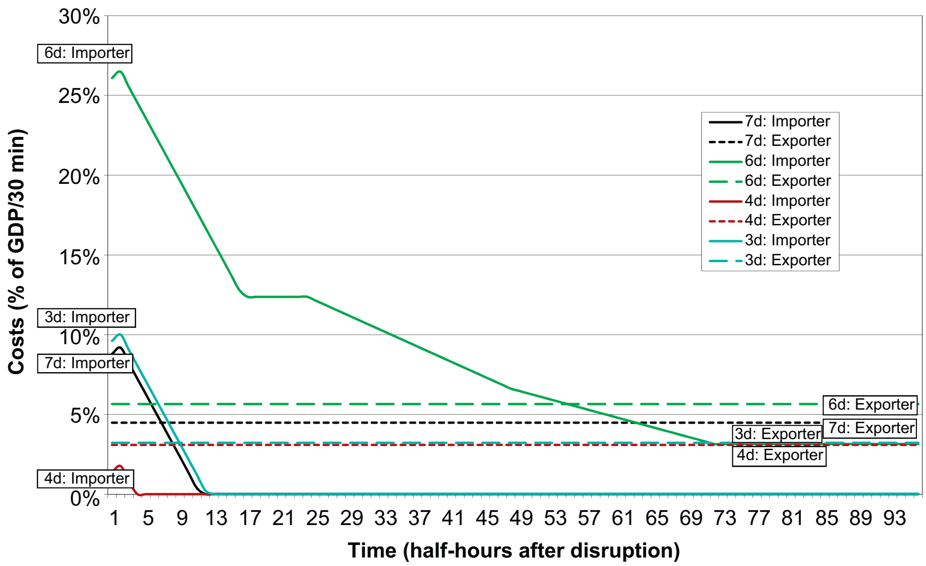

Fig. 9. Result summary for the single country scenarios (scenarios 3d, 4d, 6d, and 7d shown): costs as % of GDP per 30 min for the first 2 days (96 half-hour steps) following a disruption. The dashed, flat lines are the exporter costs, the solid lines are the importer costs. The importer costs in scenario 5d are constantly close to 0, whereas the exporter costs are low; the importer and exporter costs in scenario 2d are very similar to scenario 3d. Scenarios 2d and 5d are thus not shown here.

European reserves; this reduces European vulnerability not only to cut-offs but also to price manipulations.

In reality, the power symmetry is not only influenced by the direct economic impacts on both actors, but also by and the long-term reputational costs for the actor breaking the deal and by the reasons for the conflict.

The reputational costs, which are impossible to quantify, must be added to the costs of an actor contemplating to cut exports, and they may be high. An example is the first oil crisis: although the OPEC was initially successful—the political demands were at least partially met, and in the short term the oil price increase led to increasing total OPEC income. In the long term, the reputational loss of OPEC as an exporter led to efficiency increases and a massive fuel switch away from oil in the West: OPEC probably lost income in the long run. Thus, the reputational costs act as a deterrent to using the energy weapon.

The exporter's expected benefits – the reason for conflict – are important, but are impossible to include in the kind of assessment performed here. If the reason is economical ("price manipulations"), this could be quantified and included in the power calculations as long-term costs (importer) and benefits (exporter). If they are political, they are subjective and qualitative but nonetheless they are essentially costs. Especially political demands, which may be characterised by issues like emotions, national or personal pride, revenge, etc., may increase the exporter's willingness to accept damage, even beyond what a rational assessment of her actual power position would allow. The reason will affect the outcome, especially by influencing the "enough" point, where the importer accepts or the exporter abandons the demands, but it will not affect the power balance. Due to the large number of possible reasons and their qualitative–subjective nature, it is not possible to meaningfully assess them, and it is also not necessary for the assessment we have done: regardless of the reason for the conflict, an actor must have power over another to successfully use the energy weapon.

As last point, there is the possibility of economically "irrational" actors, using the energy weapon without chances of success. Further research is needed to understand such reasons, and the consequences of such decisions in the energy sector. Typical examples of "irrational" measures are the Iraqi oil delivery stop in 2001 and the Libyan three-day oil embargo against Switzerland in 2008 (López-Bassols, 2007; Tagesanzeiger, 2010). These measures had no noticeable effect on the supply and price situation, and in the long run the only effect were another proof of the untrustworthiness of the Iraqi (Hussein) and Libyan (Gaddafi) leaders. If such events happen in a Desertec future, they may have negative consequences for investment security and similar issues, but irrational energy weapon events will not make Europe vulnerable to the North Africans' use of the energy weapon.

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