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International Transport of Captured CO_2: Who Can Gain and How Much?

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Abstract If carbon capture and storage (CCS) is to become a viable option for low-carbon power generation, its deployment will require the construction of dedicated CO_2 transport infrastructure. In a scenario of large-scale deployment of CCS in Europe by 2050, the optimal (cost-minimising) CO_2 transport network would consist of large international bulk pipelines from the main CO_2 source regions to the CO_2 sinks in hydrocarbon fields and saline aquifers, which are mostly located in the North Sea. In this paper, we use a Shapley value approach to analyse the multilateral negotiation process that would be required to develop such jointly optimised CO_2 infrastructure. First, we find that countries with excess storage capacity capture 38–45 % of the benefits of multilateral coordination, implying that the resource rent of a depleted hydrocarbon field (when used for CO_2 storage) is roughly $1 per barrel of original recoverable oil reserves, or $2 per boe (barrel of oil equivalent) of original recoverable gas reserves. This adds 25–600 % to current estimates of CO_2 storage cost. Second, countries with a strategic transit location capture 19 % of the rent in the case of national pipeline monopolies. Liberalisation of CO_2 pipeline construction at EU level could eliminate the transit rent and is shown to reduce by two-thirds the differences between countries in terms of cost per tonne of CO_2 exported. Reaching agreement on such liberalisation may be politically challenging, since the payoffs are shown to be strongly divergent across countries.

Keywords Carbon capture and storage · International negotiations · Network optimisation · Pipelines · Resource rent · Shapley value · Transit fee

"This paper has not been submitted elsewhere in identical or similar form, nor will it be during the first three months after its submission to the Publisher".

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1 Introduction

In order to keep climate change below 2°C, the European Council reconfirmed in February 2011 the EU objective of reducing EU greenhouse gas emissions by 80–95 % by 2050 compared to 1990, in the context of necessary reductions according to the IPCC[1] by developed countries as a group. Reaching this target would require near-complete 'decarbonisation' of the European power sector: based on the PRIMES EU energy system model, the EU Climate Roadmap 2050 projects 93–99 % reduction of CO_2 emissions in the power sector by 2050 compared to 1990 (European Commission 2011a).

Carbon capture and storage (CCS) is one of the technological options for reducing CO_2 emissions from the power generation sector, as well as from other heavy industries. CCS is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location (such as a depleted hydrocarbon field or a saline aquifer) and long-term isolation from the atmosphere (see e.g. IPCC 2005). CCS could offer a bridge between the fossil fuels dependent economy and the carbon-free future, and figures quite prominently in EU energy and climate policies. The EU's Energy Roadmap 2050 contains 7 scenarios up to 2050, and on average these scenarios project 133 GW of installed CCS power generation capacity by 2050 (European Commission 2011b). Such large-scale deployment of CCS in Europe would require the development of an extensive international pipeline network to transport around 1 Gt/y of captured CO_2 from power plants to the appropriate CO_2 storage sites.

This paper studies the multilateral strategic game between countries in their negotiations to develop such an international CO_2 pipeline network. First we estimate the magnitude of the benefits associated with international cooperation in the development of this pipeline network, compared to a situation in which countries take individual action. The main focus of the paper, however, is to apply cooperative game theory to describe the strategic behaviour of countries in the multilateral negotiations. Since the benefits from international cooperation turn out to be large and positive, the analysis is focused on how the gains from such cooperation could be distributed among participating countries. Equivalently, the paper answers the question how the investment burden of an international CO_2 pipeline network would be allocated to the participating countries. In particular, we study how that allocation depends on EU legislation for CO_2 pipelines, by considering two possible policy scenarios: national pipeline monopolies on the one hand, and full liberalisation of pipeline construction on the other hand. It should be noted that despite the prominence of CCS in EU energy system projections, the acceptance of CCS is still low in many countries, hence large-scale cooperation still seems challenging. The policy relevance of this paper is first of all that it points out which monetary transfers may be needed in order to achieve cooperation. Secondly, the paper assesses the effect of EU CO_2 pipeline regulation options on the cooperation game between European countries.

International coordination in the construction of CO_2 transport infrastructure can be very beneficial. Indeed, since the costs of a pipeline do not scale proportionally with its transport capacity, substantial cost savings can be achieved by building a backbone of large bulk pipelines that collect CO_2 from multiple sources and transport it to the main clusters of CO_2 sinks. For that reason, a communication from the European Commission (2010) emphasises the need for a timely start of coordinated infrastructure planning and development at European level. The question then arises what such a European CO_2 transport infrastructure would look like. Recent research has produced a number of models that are capable

[1] Intergovernmental Panel on Climate Change.

of determining the optimal (i.e. cost-minimising) CO_2 transport network that can transport CO_2 from sources to sinks, such as Middleton and Bielicki (2009), Broek et al. (2010a,b), Mendelevitch et al. (2010) and Morbee et al. (2010, 2012). These studies, however, do not describe how the necessary coordination to achieve such optimal infrastructure would be realised. The case studies investigated by e.g. Middleton and Bielicki (2009) and Broek et al. (2010a) are focused on single countries or states, where coordination may be relatively feasible. However, the trans-European networks described by e.g. Mendelevitch et al. (2010) and Morbee et al. (2010, 2012) require coordination and joint pipeline infrastructure investment by a large number of countries. The question we study in this paper is how such international cooperation could be structured in order to achieve the benefits of joint infrastructure optimisation.

In particular, our paper aims to study how the gains from coordination can be allocated between countries in order to ensure participation in the joint coordination. We analyse the allocation by means of the *Shapley value* concept from cooperative game theory. Game theory has already been applied to energy networks by e.g. Hobbs and Kelly (1992), who apply cooperative models to short-run electricity transmission games and a dynamic non-cooperative Stackelberg game to long-run electricity transmission capacity decision games. Our model, by contrast, applies cooperative game theory to the capacity decision. Kleindorfer et al. (2001) provide an overview of strategic gaming in power markets, but do not focus on transmission infrastructure. Csercsik and Koczy (2011) study transmission networks—including expansion games—using cooperative game theory in a load flow model of the electricity system, and apply it to a stylised 5-node network. Our analysis is less detailed on the technical side (CO_2 transmission is treated here as a simple transport model) but the methodology is applied to an extensive European case study. As mentioned before, the focus of our study is on allocation of the benefits of cooperation, or equivalently, allocation of the network investment cost. Again for the case of electricity, cost allocation has been studied by e.g. Contreras and Wu (2000) and Evans et al. (2003), who use a Kernel approach from cooperative game theory. Gately (1974) provides a game-theoretic analysis of the distribution of the benefits of cooperation in electrical power investments between three regions in the Southern Electricity Region of India. The study considers 5 possible partitions of players, comprising 7 possible coalitions, and compares several game-theoretic methods for distributing the gains from cooperation, with Shapley value and Kernel as some of the possible options. Our model, by contrast, needs to consider a more complex game with 18 players, hence 262,143 possible coalitions and 682 billion possible partitions. As a result, our analysis of the strategic game is less extensive, and considers only the Shapley value as a possible allocation. As is well-known, the Shapley value is an approach for 'fair' allocation of gains from cooperation among participating actors. It has been applied to natural gas by e.g. Hubert and Ikonnikova (2009) and Ikonnikova and Zwart (2010), and to CO_2 emissions by e.g. Albrecht et al. (2002). In the context of CO_2 pipeline networks, the Shapley value can determine the bargaining power of individual countries in the international negotiation on CO_2 infrastructure investment, and hence the allocation of the cost burden. The bargaining power of each country, and hence its share of the benefits from cooperation, depends on how easily the country can be circumvented. As can be intuitively expected, countries with large storage potential or a strategic transit position are likely to receive large net benefits from the negotiation, while countries with large excess CO_2 quantities (i.e. CO_2 captured which cannot be stored domestically) make a net contribution.

The results of the analysis are twofold. First, we find that countries with excess storage capacity capture 38–45 % of the benefits of multilateral coordination, implying that the resource rent of a depleted hydrocarbon field (when used for CO_2 storage) is roughly $1 per barrel of original recoverable oil reserves, or \$2 per boe (barrel of oil equivalent) of original recoverable gas reserves. This adds 25–600 % to current estimates of CO_2 storage cost. Second, countries with a strategic transit location capture 19 % of the rent in the case of national pipeline monopolies. Liberalisation of CO_2 pipeline construction at EU level could eliminate the transit rent and is shown to reduce by two-thirds the differences between countries in terms of cost per tonne of CO_2 exported. Reaching agreement on such liberalisation may be politically challenging, since the payoffs are shown to be strongly divergent across countries.

The paper is structured as follows. First, Sect. 2 describes the potential structure and extent of a trans-European CO_2 transport network, and the benefits obtained from international coordination. Section 3 describes our game-theoretic solution concept. Section 4 applies this solution concept to CO_2 infrastructure negotiations, under two scenarios: one scenario with national CO_2 transport monopolies, and one scenario with liberalised pipeline construction. Section 5 contains an extensive set of sensitivity analyses. Section 6 summarises our conclusions.

2 International Coordination of CO_2 Pipeline Networks

The starting point of our investigation is a projection of the optimal CO_2 pipeline network in Europe in 2050. We assume that the European power system evolves according to the *Power Choices* scenario (Eurelectric 2010).[2] The *Power Choices* scenario, which is based on the PRIMES model, is chosen for this purpose because it is in line with the EU's 80–95 % greenhouse gas emissions reductions targets by 2050 (implying near-complete decarbonisation of the power sector), and hence provides a view on large-scale pan-European deployment of CCS in the power sector. The scenario implies a reduction of CO_2 emissions from the power sector to 150 Mt/y by 2050, compared to 1,423 Mt/y in 2005. This is achieved through more than 40 % electricity production from renewable energy sources, close to 30 % of nuclear power, and the remaining 30 % from fossil fuels. The latter entails the construction of 63 GW of CCS-equipped coal and gas power stations by 2030 and an additional 128 GW between 2030 and 2050.

Since the *Power Choices* report by Eurelectric (2010) provides the amount of CCS only at aggregate European level, we need to make an assumption on how this breaks down to individual countries. First, we assume that CO_2 capture deployment is limited to the 18 countries in which CCS takes places in the EU's *Baseline 2009* scenario (Capros et al. 2010). Second, we assume that the aggregate European level of CCS (as obtained from the *Power Choices* scenarios) is distributed between countries in proportion to current CO_2 emissions from the power sector, as obtained from E-PRTR (2010). Third, within each country, the amount of CCS is distributed between various industrial 'clusters'. Further details about the clustering approach can be found in Morbee et al. (2012). Size and location of potential CO_2 storage sites (depleted hydrocarbon fields and saline aquifers) is obtained from the EU GeoCapacity project (Vangkilde-Pedersen et al. 2009). Due to technical uncertainty and public acceptance issues, onshore saline aquifers are excluded as potential CO_2 storage

[2] Ideally, the amount of CCS-based electricity production per country should be determined simultaneously with the optimisation of the CO_2 network, as in the least cost theory of industrial location (see e.g. Weber 1909). In such a model the location of CCS-based power plants would depend on the spatial distribution of electricity demand, coal transport costs, and the CO_2 pipeline network construction costs. This, however, would lead to severe computational challenges. As discussed later in Sect. 4 the problem is already very challenging from a computational complexity point of view, even when an exogenous scenario for CCS deployment is taken.

Table 1 CO_2 capture rates and storage potential assumed in this study

Country	Annual CO_2 captured Mt/y (2050)	Annual CO_2 storage potential Mt/y (2050)
Austria	8	
Belgium	30	
Bulgaria	25	
Czech Republic	62	
Denmark	15	14
France	27	17
Germany	337	111
Hungary	17	9
Italy	89	61
Netherlands	52	40
Norway		636
Poland	147	17
Portugal	17	
Romania	43	88
Slovakia	16	
Slovenia	6	
Spain	80	108
United Kingdom	173	315
Total	1,145	1,416

sites.[3] Details about the assumptions can be found in Morbee et al. (2012). Table 1 provides an overview of the assumed annual amounts of CO_2 captured in each of the countries, as well as the annual CO_2 storage capacity. CCS activities in Finland have been left out of this picture: since they are geographically far away from the CO_2 network in the rest of Europe, they do not contribute to the negotiation game described in the remainder of the paper. Leaving out Finland from the start reduces computational complexity of the Shapley value approach by an order of magnitude.

[3] Furthermore, Bentham and Kirby (2005) mention that *"In many European Union countries for example France and Germany, saline aquifers are used for natural gas storage. This may be in direct conflict of interest with* CO_2 *storage, especially for onshore closures."* This further supports the assumption of this paper to exclude CO_2 storage in onshore saline aquifers. With this assumption, the conflict of interest mentioned by Bentham and Kirby (2005) does not arise. More generally, the total capacity of saline aquifers and hydrocarbon fields in the EU may significantly exceed the amount needed for natural gas storage. Indeed, unlike natural gas storage, the permanent storage of CO_2 does not require the possibility of withdrawal at a later stage, which expands the range of suitable reservoirs. For example, for France and Germany, the above-mentioned EU GeoCapacity project estimates storage potentials of 8.7 and 17.1 Gt respectively. Using a very approximative rule of thumb that the volume required to store 2 tonnes of CO_2 corresponds roughly to the volume required to store a thousand cubic meters (tcm) of natural gas, the equivalent natural gas storage potential is 4,300 and 8,500 bcm (billion cubic meters) for France and Germany, respectively. The total volume of current natural gas storage sites, on the other hand, is 12.7 and 20.4 bcm, respectively, according to GIE (2012). Hence, the CO_2 storage potential seems to exceed the needs for natural gas storage by multiple orders of magnitude. Obviously, both the EU GeoCapacity estimates and the rough calculations here are subject to large uncertainties, but it seems safe to assume for the purposes of this paper that CO_2 storage does not interfere with natural gas storage. Nevertheless, the sensitivity analyses in Sect. 5 also address the issue of competition for storage sites from the natural gas industry.

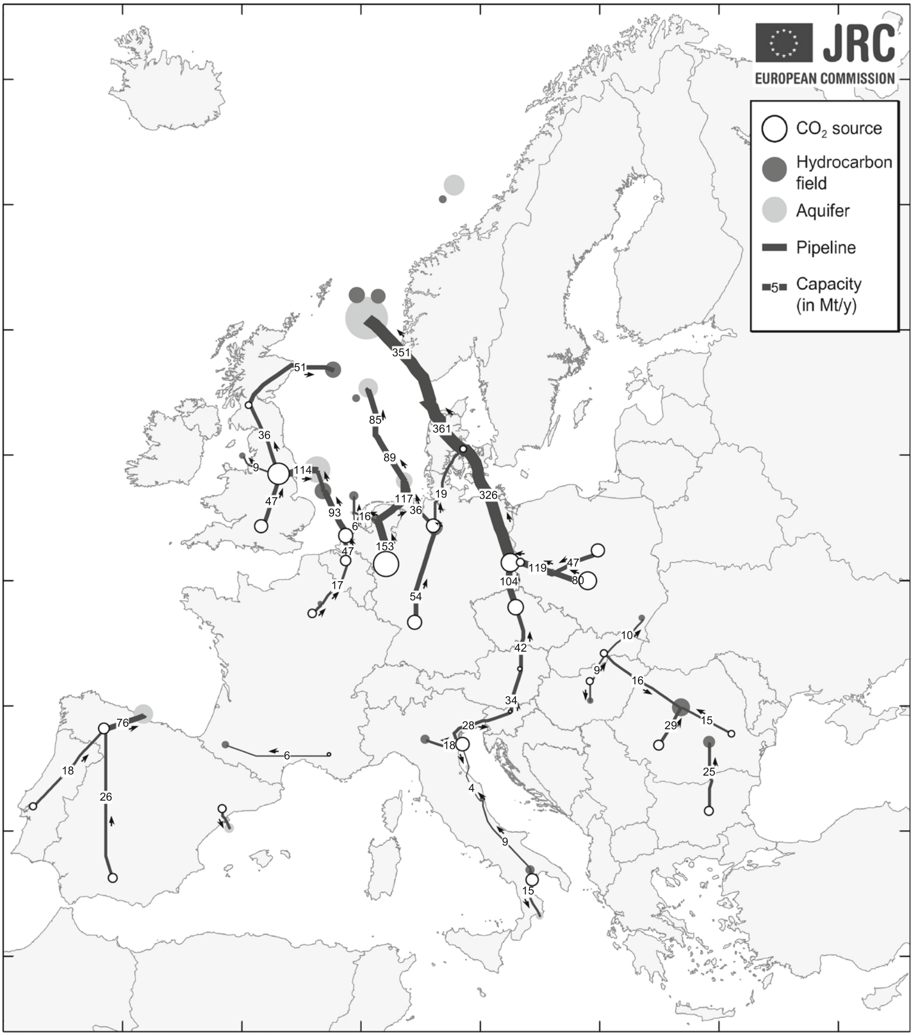

Fig. 1 CO_2 pipeline network in 2050, assuming joint international optimisation. Total amount of CO_2 captured and stored: 1,145 Mt/y

We use the *InfraCCS* model to compute the optimal CO_2 pipeline network in 2050 for the given configuration of sources and sinks. *InfraCCS* is a cost-minimising mixed-integer linear programming model, which takes into account the scale effects of pipelines (see Morbee et al. 2012 for more details[4]). The resulting optimal network is shown in Fig. 1. The network consists of 11,001 km of pipelines, which transport 1,145 Mt/y of captured CO_2 from sources to sinks. The total investment required is 28.0 billion euro. The network in Fig. 1 assumes joint international optimisation. If, by contrast, countries develop networks individually, the resulting pipeline construction would be as in Fig. 2. Since not all countries have sufficient

[4] In particular, the cost function used in the *InfraCCS* model takes into account the full costs of pipeline ownership, including e.g. obtaining the right-of-way, permitting, labour, materials, pumping stations, and costs due to pipeline ruptures or other accidental releases during temporary storage.

Fig. 2 CO_2 pipeline network in 2050, assuming individual optimisation per country, without international cooperation. Total amount of CO_2 captured and stored: 565 Mt/y

storage potential, not all captured CO_2 projected in the *Power Choices* scenario can be stored. In total, in the network in Fig. 2, only 565 Mt/y of CO_2 is transported and stored, i.e. less than half of the amount stored under joint international optimisation (Fig. 1). Non-stored CO_2 can be recognised in the figure as white circles that are not connected with any pipeline. The network in Fig. 2 is 5,097 km in length and costs 6.4 billion euro.

Thus, the benefits of international cooperation are that an additional 580 Mt/y of CO_2 can be captured and stored compared to individual country action, albeit at the cost of a more expensive network. In order to translate the benefits of international cooperation into a single total quantity, we need to make an assumption about the cost of the outside option for the 580 Mt/y of CO_2 that cannot be stored in the non-cooperative case. Clearly, this cost should be lower than the assumed CO_2 emissions allowance price in the EU Emissions Trading System

(EU ETS), since the fact that the CO_2 cannot be stored also saves the cost of capturing it in the first place. The description of the PRIMES model in Eurelectric (2010) states that the assumed CO_2 transport and storage cost ranges from 6 to 25 euro per tonne of CO_2. Assuming that (i) the lower bound of the range refers to a situation with only storage costs and no transport costs (i.e. storage very close to the capture site) and (ii) CO_2 storage costs are constant and geographically uniform, we infer that the transport cost in the *Power Choices* scenario ranges from 0 to 19 euro per tonne of CO_2. Hence, if transport costs exceed 19 euros per tonne of CO_2, the PRIMES model will switch technologies and the required emissions reduction will be realised through other means (e.g. wind energy). We therefore assume in our analysis the availability of an 'outside option' that costs 19 euros per tonne of CO_2.[5]

For the sake of simplicity we apply this value uniformly across all countries.[6] Assuming a 7.5 % discount rate[7] and a 10-year horizon, the cost of not being able to capture and store 580 Mt/y is 75.7 billion euro. Combined with the investment of 6.4 billion euro, the total cost of the non-cooperative case is therefore 82.1 billion euro, compared with 28.0 billion euro in the cooperative case. In this setting, the benefits of international cooperation are therefore 54.1 billion euro.

The question addressed in this paper is how these benefits can be allocated between participating countries in order to ensure cooperation. Equivalently, the question is how to allocate the cost burden of the 28.0 billion euro investment.

3 Bargaining Power in Multilateral Cooperation: The Shapley Value

The allocation of benefits between participating countries depends on each country's bargaining power. In the context of this analysis, bargaining power is mainly associated with two types of rents:

Storage rent. Countries with excess CO_2 storage (i.e. more storage capacity than what is required to store the amounts of CO_2 captured within the country) can offer this capacity to other countries who are short of CO_2 storage capacity. Since the availability of additional storage capacity reduces the need for recurrence to the outside option (i.e. switching to an alternative technology at a cost of 19 euro per tonne), it brings about a cost reduction

[5] Note that this value is *lower* than the full CO_2 emissions allowance price, which is projected to be 103.2 euro per tonne by 2050 in the scenario under consideration (Eurelectric 2010). Indeed, if a country decides to pursue the outside option (hence no CCS) it does not need to pay for any other CCS-related costs, such as the CO_2 capture costs, or the residual allowances for non-captured CO_2. These cost savings, together with the 19 euros, pay for the outside option of 103.2 euro per tonne. Since the negotiation takes place about the long term, it should be emphasised that the outside option does *not* mean that CO_2 would be captured and subsequently released into the atmosphere. If that were the case, the outside option would cost the full 103.2 euro per tonne, since an emission allowance would have to be bought for each tonne of CO_2 released, *plus* the capture costs—including the energy consumption penalty of the capture process—*plus* any additional costs such as the costs of pipeline leakages due to changes in pressure. The cost of the outside option would be much higher than the 19 euro per tonne considered here. Put otherwise: in 2050 the value of CO_2 emissions reduction will be 103.2 euro per tonne. Of this amount, only 19 euro per tonne is available for CCS transport, because enough 'budget' needs to be available for capture and other CCS costs. If the transport cost is higher than 19 euro per tonne, then CCS becomes uncompetitive and society switches to alternative ways of reducing CO_2 emissions such as wind energy.

[6] Section 5 contains extensive sensitivity analysis regarding this assumption.

[7] This value is the same as the value used for previous *InfraCCS* simulations (see Morbee et al. 2012). The value is midway between the rate of around 5 % suggested for cost-benefit analysis of European regional investment projects (Florio 2008) and typical industrial discount rates for this type of investments (around 10 %).

for the coalition partners of a country with excess storage. This increases the bargaining power of countries with excess storage, and allows them to obtain a 'storage rent'.

Transit rent. Some countries have a strategic location, which allows for shortcuts between CO_2 sources and storage sites. For example, in Fig. 1, the participation of Denmark allows for a near-straight pipeline from Poland to Norway. Non-participation of Denmark would require a detour of the pipeline and hence a higher construction cost. This translates into bargaining power for transit countries, allowing them to obtain a 'transit rent'. This is in fact the reverse of the well-known *Jepma-effect* in international transport networks. The Jepma-effect, first described by Jepma (2001) in the context of liberalisation of the Dutch natural gas transport network, is the observation that gas transport tariff differences between neighbouring countries may incentivise gas shippers to reroute gas flows in order to take advantage of a cheaper neighbouring network, even if the new route is inefficient from a technical perspective. The CO_2 pipeline transit rent described in this paper is essentially the same effect but in the opposite direction: a country with an advantageous transit location may be incentivised to increase CO_2 transport tariffs because it would be even more costly for foreign CO_2 shippers to reroute CO_2 flows in order to circumvent the country.

To assess these storage and transit rents in an integrated way, we apply the *Shapley value* approach, introduced by Shapley (1953). The Shapley value defines a 'fair' allocation of the benefits of cooperation, taking into account the contributions of each of the players. It defines the only allocation that satisfies a set of desirable properties (individual fairness, efficiency, symmetry, additivity and zero-player property). Starting from a set N of n players (in this case: countries), we define the function $v : \mathcal{P}(N) \to \mathbb{R}$, such that, for every subset S of N, $v(S)$ is the payoff of a cooperation among the countries in S. According to the Shapley value, the amount of benefit received by player $i \in N$ is:

$$\phi_i = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(n - |S| - 1)!}{n!} (v(S \cup \{i\}) - v(S)) \tag{1}$$

The sum is computed over all possible coalitions of players. For each coalition, Eq. (1) computes the difference $(v(S \cup \{i\}) - v(S))$ between the payoff of the coalition with and without player i. The Shapley value ϕ_i is then a weighted average of those values. Intuitively, the formula computes the contribution added by player i to the 'grand coalition' (the coalition of all players) averaged over all possible sequences in which this grand coalition can be formed. As an example, we compute $(v(S \cup \{i\}) - v(S))$ for the subset S that includes all countries except Denmark. i is Denmark. For this case we have $S \cup \{i\} = N$, hence the payoff $v(S \cup \{i\})$ is the cost of the fully cooperative CO_2 network from Fig. 1, i.e. 28.0 billion euro. The payoff $v(S)$ can be determined by running the *InfraCCS* tool without Denmark. This is shown in Fig. 3. The cost of this network is 32.1 billion euro. Hence, by including Denmark in the coalition, there is a cost saving of 4.1 billion euro, because the participation Denmark permits more efficient routing of pipelines from central Europe to Norway. Furthermore, the inclusion of Denmark in the coalition offers cost savings in Denmark itself, because by participating, Denmark does not have to build its own small network, which would cost 0.6 billion euro. In addition, the inclusion of Denmark offers a solution for the 1.6 Mt/y that Denmark would not be able to store domestically (which would cost 0.2 billion euro in order to pay for the NPV of the outside option of 19 euros per tonne). In total, the contribution $(v(S \cup \{i\}) - v(S))$ of Denmark to the coalition S is therefore 4.9 billion euro. This computation is done for all possible subsets S of N and all players i. Equation (1) requires a total of 262,143 runs of the above-mentioned *InfraCCS* model.

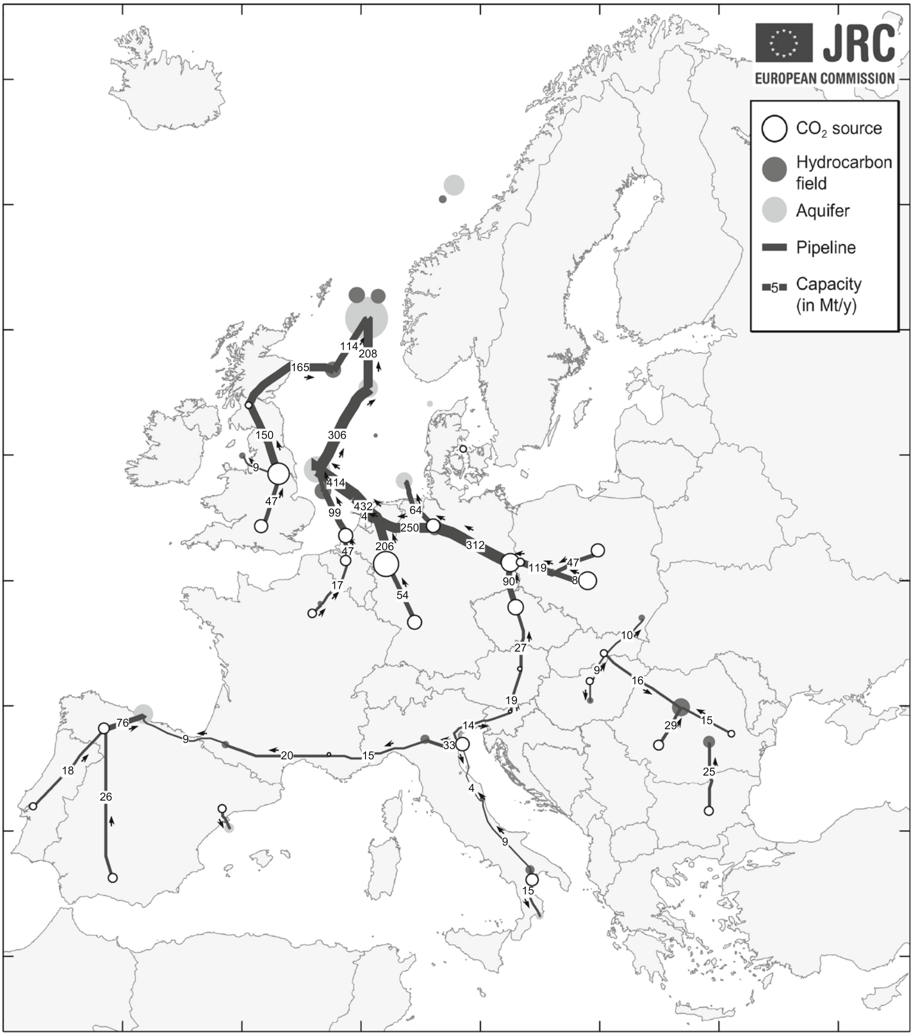

Fig. 3 CO_2 pipeline network in 2050, assuming joint international optimisation without participation of Denmark

In addition to the computational complexity—which will be discussed in Sect. 4—the Shapley value has a number of other disadvantages. Intuitively, since the Shapley value is an average over all possible sequences, it implicitly assumes that all sequences are equally likely, which is unappealing. Futhermore, the Shapley value assumes that all players have the same perfect information about the benefits of forming the grand coalition, which may not necessarily be the case. However, from the perspective of cooperative game theory, one of the most important drawbacks of the Shapley value is that the solution is not necessarily part of the 'core', the set of allocations for which no coalition has a value greater than the sum of its members' payoffs. Shapley (1971) proves that the Shapley value is part of the core for convex games. However, in this paper the mixed-integer model required for accurate pipeline network optimisation may lead to some non-convexities. Nevertheless, as mentioned in the introduction the Shapley value is a proven concept for network cost allocation, hence the application to the case of CO_2 pipeline networks seems justified.

In the introduction, it was mentioned that CCS currently suffers from lack of public acceptance. For instance, a project funded by the UK Department of Trade and Industry (Wright et al. 2007) found that the general public in Europe has a very negative opinion about the risks and safety issues arising from CCS programmes. This may affect countries' bargaining position. Negative public perception of CCS has the effect of increasing the political cost of implementing CCS. In the set-up of the current paper, this is mathematically equivalent to a *decrease* in the cost of the outside option. Indeed, as public perception of CCS becomes more negative, the relative willingness to pay for alternatives (e.g. wind energy) increases, hence their cost decreases. Therefore, in order to assess the effect of public acceptance issues on the negotiations, Sect. 5 contains a number of sensitivity analyses that examine the impact of changes in the cost of the outside option.

Likewise, it could be argued that the multilateral negotiation may be affected by a potential conflict of interest in the subsurface, where CO_2 storage could interfere with oil and gas production (see e.g. Bentham and Kirby 2005). As will be argued at the end of Sect. 4, the resource rents that are obtained from hydrocarbon production are far larger than the rents that can be obtained from CO_2 storage. It is therefore very likely that oil and gas production always gets preference over CO_2 storage. Therefore the EU GeoCapacity project, from which the CO_2 storage capacity estimates are used in this paper, focuses on *depleted* hydrocarbon fields. Indeed, the storage sites identified in the project are mostly located in mature oil and gas provinces, or provinces that will certainly be depleted at the time horizon required for the implementation of CCS. One exception to this is the North Sea area. However, this province is so large that CO_2 storage could start in the many fields that are already depleted and later expand to other fields as and when they too become depleted. In addition to a potential conflict of interest, there are also potential *synergies* between CO_2 storage and the oil and gas industry, since CO_2 injection can be used for Enhanced Oil Recovery (EOR) or Enhanced Gas Recovery (EGR) from mature fields. The conflict of interest between CO_2 storage and the oil and gas industry can be modelled in this multilateral negotiation game through a higher CO_2 storage cost, since the opportunity cost of using the field for CO_2 storage (and hence affecting its use for oil and gas extraction) is higher. The potential synergies between CO_2 storage and the oil and gas industry can be modelled through a lower CO_2 storage cost, since the additional revenues from enhanced hydrocarbon production may create a willingness to pay for the CO_2, which offsets part of the storage costs. Sensitivity analyses using both higher and lower storage costs are therefore performed in Sect. 5.

4 Simulations

4.1 Set-up

In this section, we apply the Shapley value to the issue of European multilateral CO_2 pipeline infrastructure negotiations. The realisation of the network of Fig. 1 requires cooperation among $n = 18$ countries: 17 source countries within the EU,[8] plus Norway. When applying Eq. (1), we distinguish two cases:

[8] As mentioned before, Finland has been omitted from the set of 18 countries active in CCS according to the simulations by Capros et al. (2010).

> **Case 1: National CO_2 pipeline monopolies**. In this case, we assume that every country has a monopoly on CO_2 pipeline construction within its territory. As a result, a pipeline through a given country cannot be built by a coalition that does not include this country.
> **Case 2: Liberalised CO_2 pipeline construction**. In this case, any country is free to build pipelines in the entire EU and Norway. This does not mean however, that the land on which these pipelines are constructed is free: a cost to cover the right-of-way is included in the pipeline costing approach embedded in the *InfraCCS* model.

Note that in both cases, CO_2 cannot be stored in a given country by a coalition that does not include that country.

We compute the Shapley value for both cases, which, as mentioned above, requires the computation of the pay-offs of 262,143 coalitions in each case. This is a computational challenge, because each pipeline optimisation problem is a mixed-integer problem (MIP), which is NP-hard to solve, i.e. no efficient algorithms for such problems exist today. In Case 1, due to national pipeline monopolies, many coalitions can be broken down into independent contiguous subsets. As a result, Case 1 requires the computation of the pay-offs of only 26,922 contiguous coalitions, which can then be combined to obtain the results for all 262,143 coalitions. Hence, in Case 1 the number of runs of the *InfraCCS* model can be reduced by almost a factor 10. In Case 2 however, all coalitions need to be run with the *InfraCCS* model.[9]

4.2 Results: Shapley Value

Table 2 shows the resulting Shapley values in both cases. The Shapley value is shown both in absolute terms and as a percentage of the total. These Shapley values show how the 54.1 billion euro benefit from international cooperation can be allocated between countries. In Case 1, large rents are allocated to Norway and the UK, which are the main net storage providers in this analysis (see Table 1). In total, the net storage providers capture 38 % of the benefits. A large rent is also allocated to Denmark, which plays a crucial role as transit country in Fig. 1. The large Shapley value for Germany is related to the fact that it contributes the most CO_2 , which allows for avoiding a large 'outside option' cost.

In Case 2, the rents shift more towards the largest storage provider, i.e. Norway. In total, net storage providers capture 45 % of the benefits in this case. Due to the liberalisation of pipeline construction, Denmark loses most of its Shapley value, which demonstrates indeed that its bargaining power in Case 1 can be attributed to its transit position. Likewise, one notes that Germany's bargaining power decreases between Case 1 and Case 2, which points to the fact that a portion of its bargaining power in Case 1 is due to its central location in Europe, which allows it to serve as a hub for CO_2 transport. Finally, note that Poland gains significantly in the transition from Case 1 to Case 2: indeed, since Poland is at the end of the pipeline network, it does not have an advantageous transit position and therefore stands to gain from pipeline liberalisation.

The last column in Table 2 shows how the Shapley value changes from Case 1 to Case 2 for each country. A negative value means that a country loses benefits in the event of pipeline liberalisation. A negative value is therefore a measure of the transit rent obtained by each country in Case 1. The abolute value of the sum of all negative values, i.e. the total transit rent in Case 1, is 10.1 billion euro, which represents 19 % of the total benefits.

[9] For that reason, the MIP computation time is deliberately capped at 3 min per coalition in Case 1, and 3 s in Case 2. In total, the computation takes about a week on a standard computer.

Table 2 Shapley value allocation for the coalitional game described in Sect. 2

Country	Shapley value				
	Case 1		Case 2		Difference Case 2–Case 1
	Bn EUR	Percent	Bn EUR	Percent	Bn EUR
Austria	0.4	1	0.4	1	0.0
Belgium	1.8	3	1.7	3	−0.1
Bulgaria	1.0	2	1.1	2	0.1
Czech Republic	1.8	3	3.3	6	1.5
Denmark	4.5	8	0.3	1	−4.2
France	1.4	3	0.6	1	−0.8
Germany	14.1	26	11.9	22	−2.2
Hungary	1.0	2	0.5	1	−0.6
Italy	0.9	2	1.0	2	0.1
Netherlands	1.4	3	0.7	1	−0.7
Norway	11.7	22	16.6	31	4.9
Poland	3.5	7	6.5	12	3.0
Portugal	0.6	1	0.7	1	0.1
Romania	2.2	4	2.4	4	0.2
Slovakia	0.6	1	0.8	2	0.2
Slovenia	0.5	1	0.2	0	−0.2
Spain	1.2	2	1.2	2	0.0
United Kingdom	5.4	10	4.0	7	−1.4
Total	54.1	100	54.1	100	

The last column can also be interpreted as each country's payoff from EU legislation that would liberalise CO_2 pipeline construction. For some countries this payoff is positive while for others it is negative, hence this column indicates which countries are likely to lobby for EU legislation that liberalises CO_2 pipeline construction and which countries are likely to oppose it. First, countries that have bargaining power mostly because of their storage capacity and not because of their transit location are likely to advocate pipeline liberalisation. For example, Norway and to some extent Romania are likely to be proponents of liberalisation: they can gain 4.9 and 0.2 billion euro respectively. Second, countries with difficult access to the main storage sites in the North Sea are also likely to be proponents of liberalisation. For example, liberalisation may bring Poland and the Czech Republic gains of 3.0 and 1.5 billion euro respectively, because liberalisation would reduce the transit rents that Denmark and Germany obtain for transporting CO_2 to the North Sea. Third, countries with advantageous transit locations are likely to oppose liberalisation of CO_2 pipeline construction. For example, Denmark and Germany would lose 4.2 and 2.2 billion euro, respectively. Fourth, for several countries such as Italy the difference between Case 1 and Case 2 is small or insignificant, which means that they are likely to have a neutral stance regarding liberalisation of CO_2 pipeline construction. Note that this does not mean that they would be indifferent between participating and not participating in the coalition. Indeed, for example Italy gains around 1 billion euro from participating in the coalition, both in Case 1 and in Case 2. Hence in both cases there is a strong incentive for Italy to participate in the coalition. The small difference between Case 1 and Case 2 merely illustrates that Italy would be likely to be neutral regarding the liberalisation question (with a slight preference in favour of liberalisation). All in all, the payoffs in the last column show that 10 countries would benefit to a smaller or larger extent from liberalisation, while 8 countries would lose. In such a divided landscape it will probably be challenging to reach a political compromise on liberalisation.

An interesting additional question is what would happen in the event another nearby country wants to join the coalition once the network is already in place. As in the game described in this paper, the entrant country would have to negotiate access to pipelines and storage sites in the coalition countries. Under the assumptions of this paper, the existing network is right-sized and does not have any spare capacity to accommodate new flows.[10] Hence, new pipelines will have to be built specifically for CO_2 flows of the entrant country. The result of the negotiation can be computed using the same methodology as used in this paper. The entrant country will negotiate with all existing countries, in order to form the grand coalition that brings CO_2 from the entrant country to a storage site in the most efficient way. The benefits will be divided among storage countries, transit countries and the entrant country in the same way as before, i.e. in proportion to the extent to which a country is indispensable in the CO_2 chain. The same two cases can be distinguished. In Case 1, large rents may go to the transit countries. In Case 2, a larger rent will be allocated to the storage country. In any case, a large part of the rent will be allocated to the entrant country, since without its participation there are no gains at all. Clearly, since the existing players will not accept to be worse off, the entrant country will have to pay at least for all new pipeline investments and storage costs. In addition the entrant country will pay a premium (rent) to the existing players. The rent will be such that the entrant country is still better off than when it acts alone. The size of the premium depends on the extent to which various alternatives routings of the entrant's CO_2 flow are available, which will have the effect of diluting the bargaining power of existing players. Besides the above-mentioned Cases 1 and 2, there is a potentially interesting Case 3: if existing players managed to form a cartel against the entrant, then the game would cease to be a multilateral game, and become a bilateral game between the entrant and the cartel. The Shapley value would then degenerate to the Nash bargaining solution, in which the benefits of cooperation would be split equally between the entrant and the cartel.

4.3 Results: Cost Allocation

Table 3 translates the Shapley values from Table 2 into the allocation of the cost burden of the network. As mentioned in Sect. 2, the total required investment in the CO_2 pipeline network is 28.0 billion euro. Table 3 shows how this cost of 28.0 billion euro is shared between individual countries. Note that some countries make a net payment, while others are net recipients from the cooperation. A large share of the cost is borne by countries with large volumes of excess CO_2, such as Germany and Poland. Due to reasons mentioned before, Germany contributes more in Case 2 than in Case 1, while Poland contributes less. Note that Denmark is a net recipient in Case 1, while it is a net contributor in Case 2.

4.4 Results: Export and Import Prices

Finally it is possible to translate the Shapley values into prices expressed per tonne of CO_2 stored. For this purpose, we first compute—for each country—the additional investment

[10] For a discussion on potential oversizing of a European CO_2 pipeline network in anticipation of future flows, see Morbee et al. (2012).

Table 3 Investment cost burden sharing for the CO_2 pipeline network shown in Fig. 1

Country	Shapley value				
	Case 1		Case 2		Difference Case 2–Case 1
	Bn EUR	Percent	Bn EUR	Percent	Bn EUR
Austria	0.6	2	0.6	2	0.0
Belgium	2.1	8	2.2	8	0.1
Bulgaria	2.2	8	2.1	7	−0.1
Czech Republic	6.3	22	4.8	17	−1.5
Denmark	−3.7	−13	0.5	2	4.2
France	0.5	2	1.3	5	0.8
Germany	16.3	58	18.5	66	2.2
Hungary	0.2	1	0.8	3	0.6
Italy	3.3	12	3.2	12	−0.1
Netherlands	0.5	2	1.2	4	0.7
Norway	−11.7	−42	−16.6	−59	−4.9
Poland	13.8	49	10.8	38	−3.0
Portugal	1.6	6	1.5	6	−0.1
Romania	−1.9	−7	−2.1	−8	−0.2
Slovakia	1.5	5	1.3	5	−0.2
Slovenia	0.3	1	0.5	2	0.2
Spain	−0.1	0	−0.1	0	0.0
United Kingdom	−3.8	−14	−2.4	−9	1.4
Total	28.0	100	28.0	100	

made when going from the non-cooperative case (Fig. 2) to the cooperative case (Fig. 1), i.e. the value from Table 3 minus the domestic pipeline investments made to realise the network of Fig. 2. Secondly, we divide this number by the additional amount of CO_2 captured in this country in the cooperative case compared to the non-cooperative case.[11] Obviously, this computation is meaningful only for net CO_2 exporters. The results of the countries with the highest cost per tonne of CO_2 exported are shown in Table 4. One immediately observes that the spread of costs is much smaller in Case 2 than in Case 1. Indeed, in Case 1 there is much more heterogeneity between countries, depending on their transit position. In Case 2, differentiation between counties is mostly due to their distance from the main storage sites. The range of costs is reduced from over 15 euro per tonne in Case 1, to less than 5 euro per tonne in Case 2. Note that e.g. Slovenia, although located far away from the North Sea, pays a rather low price in Case 1, due to its role as a transit country for Italy. In Case 2 however, this advantage disappears and it ranks as one of the higher-cost countries.

A similar analysis can be done for countries that are net importers of CO_2. As above, we divide the difference in cashflow (when going from the non-cooperative case to the cooperative case) by the amount of CO_2 imported, with discounting as above. The results are in Table 5. We observe that in Case 1, the revenue per tonne of CO_2 imported and stored ranges from 3.9 to 10.0 euro per tonne of CO_2, with a weighted average of 5.1 euro per

[11] As before, discounting at 7.5 % is performed and a 10-year time horizon is assumed.

Table 4 Costs per tonne of CO_2 exported (in EUR per tonne of CO_2)

Case 1		Case 2	
Country	Cost	Country	Cost
Poland	15.0	Italy	13.9
Czech Republic	14.7	Portugal	13.1
Italy	14.3	Slovenia	12.8
Portugal	13.7	Bulgaria	12.3
Slovakia	13.5	Poland	11.7
Bulgaria	13.1	Austria	11.6
Austria	11.3	Hungary	11.6
Belgium	10.2	Slovakia	11.6
Germany	9.9	Germany	11.3
Slovenia	7.4	Czech Republic	11.2
Hungary	2.3	France	11.0
Netherlands	1.1	Belgium	10.7
France	−0.3	Netherlands	9.4

Table 5 Revenue per tonne of CO_2 imported and stored (in EUR per tonne of CO_2)

Case 1		Case 2	
Country	Revenue	Country	Revenue
Spain	10.0	Spain	10.1
United Kingdom	8.5	Romania	8.6
Romania	7.9	United Kingdom	6.3
Norway	3.9	Norway	5.6
Weighted average	5.1	Weighted average	6.0

tonne. In Case 2, with liberalised pipeline construction, the average revenue increases to 6.0 euro per tonne. Revenues increase especially for countries with little transit role (Norway, Romania).

As a side-effect of the results of Table 5, we can compute an estimate of the resource rent associated with a depleted hydrocarbon field that is to be used for CO_2 storage. As a very approximative rule of thumb, a depleted oil field can store roughly 1 tonne of CO_2 per tonne of original recoverable oil reserves. The resource rent of 5–6 euro per tonne of CO_2 stored therefore corresponds to approximately $1 per barrel of original recoverable oil reserves. This is clearly far below the resource rent that was originally obtained from oil extraction. For gas fields, the results are more favourable. As a very approximative rule of thumb, a depleted gas field can store roughly 2 tonnes of CO_2 per thousand cubic meters (tcm) of gas in its original recoverable reserves. The resource rent of 5–6 euro per tonne of CO_2 stored therefore corresponds to approximately 1 euro per MWh of gas, i.e. around $2 per barrel of oil equivalent. This is roughly 5 % of the wholesale price of natural gas: e.g. the average German import border price was 20 euro per MWh in 2010 according to BAFA (2011). Overall, therefore, it seems that the rent is relatively small from the perspective of petroleum economics. However, it is relatively large from the perspective of CCS economics. Indeed, typical storage costs are estimated to be 1–20 euro per tonne of CO_2 stored depending on such factors as the type of storage site (hydrocarbon field or aquifer), the location (onshore/offshore) and the presence of re-usable legacy wells (see e.g. ZEP 2011). The rent of 5–6 euro per tonne of CO_2 needs to be added to this number, and represents an increase of 25–600 % of the costs.

5 Sensitivity Analyses

As described in Sect. 2 the analysis in this paper assumes that the both the cost of storage and the cost of the outside option are (i) constant, and (ii) uniform across all countries. In this section we perform a sensitivity analysis on those assumptions to check the robustness of the results.

5.1 Uniform Changes in Costs of Storage and Outside Option

Until now, we have assumed that all countries have an outside option that costs 19 euro per tonne of CO_2. Furthermore, since storage costs were assumed to be uniform across all countries, there was no mathematical need to include storage costs in the model. This does not mean that no storage cost is paid. As mentioned in Sect. 2, the PRIMES storage cost of 6 euro per tonne had already been subtracted from the outside option. So, another mathematically equivalent way of looking at the results of this paper, is that all countries producing CO_2 need to pay a fixed storage fee of 6 euro per tonne, while the cost of the outside option is increased from 19 to 25 euro per tonne. The results would be identical. Therefore, in the model in this paper the effect of a uniform *increase* in the storage cost is identical to the effect of a uniform *decrease* in the cost of the outside option. Intuitively, both have the same effect of reducing the available 'budget' for CO_2 transport, thereby affecting the negotiation margin of the CO_2 source countries and hence the rents of the transit and storage countries.

An increase in storage cost could be the result of more stringent regulation of safety and security of CO_2 storage reservoirs. It could also result from competition with natural gas storage, which typically makes use of the same types of reservoirs in depleted hydrocarbon fields or saline aquifers. In non-mature hydrocarbon provinces there could also be competition with ongoing oil and gas extraction activities. Competition with natural gas storage or with hydrocarbon extraction would increase the opportunity cost of using the reservoir for CO_2 storage as opposed to using it for other purposes. This would raise the storage cost. On the other hand, if CO_2 can be injected into hydrocarbon fields for the purpose of EOR or EGR, this would lead to additional oil or gas revenues, which would create a willingness-to-pay for CO_2 that would offset the storage costs. Synergies between CO_2 storage and EOR/EGR could therefore lead to a decrease in CO_2 storage costs. ZEP (2011) estimates CO_2 storage costs to be in the range of 1–20 euro per tonne. When excluding the most expensive types of storage (i.e. offshore reservoirs without legacy wells) the range is reduced from 1 to 12 euro per tonne. Therefore, in this sensitivity analysis we choose to use a $[-5, +5]$ range around the initially assumed storage cost of 6 euro per tonne.

Applying this sensitivity range to the storage cost is equivalent to applying an opposite $[+5, -5]$ sensitivity range to the cost of the outside option. A decrease in the cost of the outside option could be the result of technological advances in e.g. wind energy, which make CCS less competitive as an option to reduce CO_2 emissions. Lack of public acceptance of CCS would also result in higher political costs of CCS, which would have the same effect of reducing the cost of the outside option because the lack of support for CCS would increase the relative willingness-to-pay for other emission reduction options such as wind energy. Conversely, a lack of progress in e.g. costs of offshore wind, or a breakthrough in CO_2 capture technologies would have the effect of increasing the cost of the outside option.

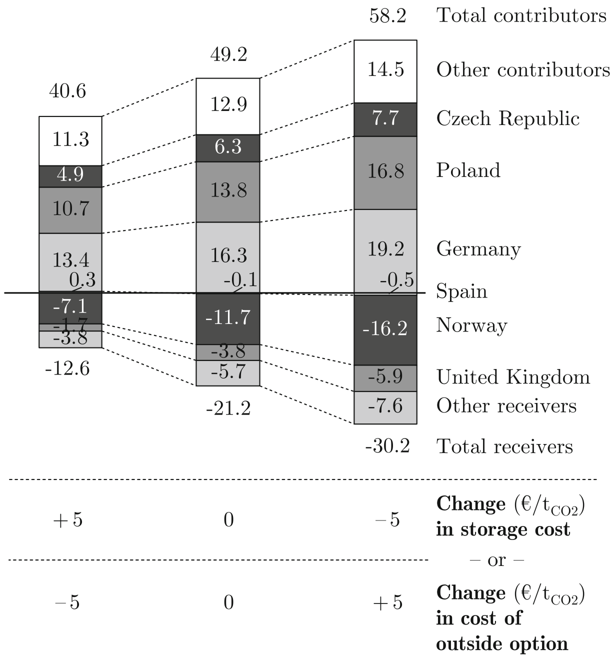

Fig. 4 Sensitivity analysis on investment cost burden sharing in Case 1. Net payments in billion euro

The effect of these sensitivities on the investment cost burden sharing of Table 3 is shown in Fig. 4. For the sake of conciseness the results are only shown for Case 1; the effects for Case 2 are similar. The middle column in the figure corresponds to the cost burden allocation of Table 3. The column on the left corresponds to the effect of a 5 euro per tonne increase in storage cost, or—equivalently—a 5 euro per tonne decrease of the cost of the outside option. Conversely, the column on the right corresponds to the effect of a 5 euro per tonne decrease in storage cost, or—equivalently—a 5 euro per tonne increase in the cost of the outside option. The part of the graph above the axis shows the net contributors to the investment, the part below the axis shows the countries who receive a net payment.

As can be expected, an increase in storage cost or decrease in the cost of the outside option makes CO_2 transport less attractive for the participating source countries, hence they have to pay less in the negotiation and the rents of the transit and storage countries decrease. Conversely, a decrease in storage costs or an increase in the cost of the outside option makes CO_2 transport more attractive for the source countries. Part of this value is extracted as a rent by the transit and storage countries, hence the payments increase. The effect is more pronounced for some countries than for others. E.g. both Poland and Germany need to pay around 3 billion euro more in the column on the right, but as a result the relative share of Poland in the cost burden increases. This is because the decrease in Poland's bargaining power (due to the cost change) is not offset by an increase in transit rent (as it is the case in Germany). Spain is the only country that switches between contributing and receiving: in the base case it receives a small net payment, while in the column on the left it needs to make a net contribution. All other countries are always net contributors or always net receivers. Overall, the relative contributions and main qualitative conclusions seem to remain fairly stable in this sensitivity analysis.

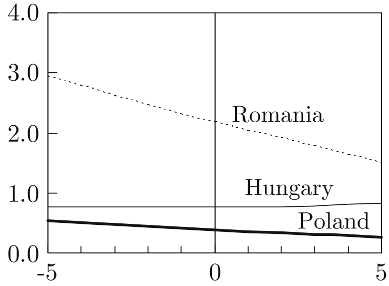

Fig. 5 Shapley value of each storage country (in billion euro, *vertical axis*) as a function of a ceteris-paribus change in its storage costs (in euro per tonne of CO_2, *horizontal axis*)

5.2 Non-uniform Changes in Costs of Storage and Outside Option

The sensitivity analyses in the previous section were applied uniformly to all countries. However, it may be the case that storage costs or costs of the outside option vary between countries. Storage cost differences could be caused by different levels of competition with natural gas storage or with the oil and gas industry, or different availability of EOR/EGR possibilities. Storage cost differences could also result from quality differences in reservoirs. Reservoirs of lower quality will require more investments and operating costs to store a given amount of CO_2, hence per-unit storage costs for lower-quality reservoirs should be expected to be higher. For example, ZEP (2011) differentiates its CO_2 storage cost estimates by type of storage site (hydrocarbon field or aquifer), location (onshore/offshore) and presence of re-usable legacy wells. Even when the location is the same, and no legacy wells are present, the range of storage costs for depleted hydrocarbon fields is slightly lower than for saline aquifers: for the former the range is 1–10 euro per tonne, while for the latter it is 2–12 euro per tonne.

Differences in the cost of the outside option could result from different availability of alternative emission reduction options. E.g. countries with large potential for wind and solar energy may have a lower outside option cost than others. Differences in the cost of the outside option could also result from different public perceptions of CCS. If CCS is publicly supported in one country but opposed in another country, this would result in different political costs of CCS, with would be equivalent to having different costs of the outside option.

In the previous section, a uniform change in storage costs was mathematically equivalent to an identical but opposite uniform change in the costs of the outside option. When a change is non-uniform, this is not the case anymore, hence sensitivity analyses for storage costs and for costs of the outside option need to be treated separately. To keep the sensitivity analysis simple and transparent, the analysis is performed on a reduced set of countries. For this purpose, we choose the set of five countries in the eastern part of Europe that happen to have a separate network in the grand coalition depicted in Fig. 1: Bulgaria, Romania, Hungary, Slovakia and Poland. For Poland, only the depleted hydrocarbon field in the southeast is considered, hence in this sensitivity analysis it will be negotiating purely as a storage provider. The aim of the analysis is to determine the effect of individual changes in costs of storage or the outside option, on the distribution of gains from cooperation according to the Shapley value. For the sake of simplicity, we consider only the case with national pipeline monopolies.

First, we study the effect of changes in storage costs. We assume a change in the storage cost of one country and recompute its Shapley value after the change. Figure 5 shows the evolution of the Shapley value of each of the three storage countries in the set (Hungary, Poland and Romania) as a function of a negative or positive individual change in its storage costs. Note that for each of the curves only the country itself is subjected to a change in

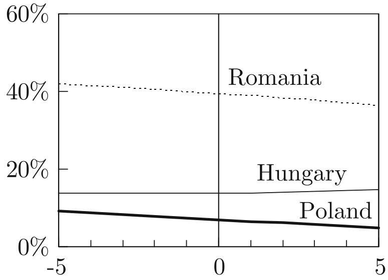

Fig. 6 Shapley value of each storage country (as % of total coalition gains, *vertical axis*) as a function of a ceteris-paribus change in its storage costs (in euro per tonne of CO_2, *horizontal axis*)

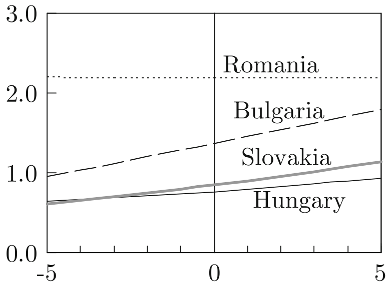

Fig. 7 Shapley value of each source country (in billion euro, *vertical axis*) as a function of a ceteris-paribus change in the cost of its outside option (in euro per tonne of CO_2, *horizontal axis*)

storage costs, while the storage costs of the others remain constant. As can be expected, an increase in storage cost for Romania and Poland leads to a decrease in their respective Shapley values, hence a decrease in bargaining power: as their storage becomes more expensive, they provide less marginal benefits to the grand coalition and hence get a smaller share of the gains from cooperation. The case of Hungary is counterintuitive, since its Shapley value increases slightly with increasing storage costs. However, this is mostly because its increased storage costs are mainly damaging for its own CO_2 production. As a result, its marginal contribution to the coalition increases because by joining the coalition it would not have to store its CO_2 in expensive domestic storages but rather contribute to economies of scale in the joint network. In addition, the value shown is only the Shapley value: an analysis of Hungary's net payment to the investment cost burden shows that its net payment does increase when storage costs in Hungary go up. It should be noted that the absolute numbers for the Shapley value in Fig. 5 and the following are different from the numbers appearing in Table 2 because the game considered here is only for the reduced set of countries.[12]

The decline in Shapley value for Romania as a function of changes in its storage costs in Fig. 5 seems quite steep. However, the decline is far less steep when considered in relative terms, i.e. as a percentage of the total gains from cooperation generated by the grand coalition (the sum of all Shapley values). Figure 6 shows the values from Fig. 5 in those terms. One can observe that the profiles are fairly flat, meaning that a country's share of total gains is relatively stable as a function of its storage cost level.

Next, we study the effects of changes in costs of the outside option. As before, we assume a change in the cost of the outside option for one country and recompute its Shapley value. Figure 7 shows the evolution of the Shapley value of each of the four source countries in the set (Bulgaria, Hungary, Romania and Slovakia) as a function of a negative or positive

[12] Nevertheless, one can observe that the Shapley values for Bulgaria, Hungary, Romania and Slovakia in Figs. 5 and 7 differ only by maximum 0.3 billion euro from those in Table 2, which illustrates the robustness of the results. The result for Poland is obviously very different since this reduced analyis considers only the hydrocarbon field in the southeast of Poland and not its CO_2 sources.

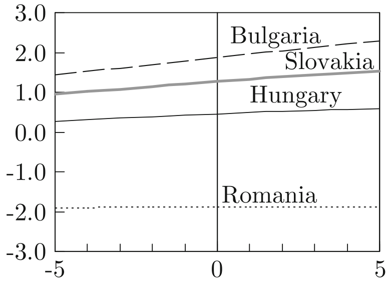

Fig. 8 Investment cost burden of each source country (in billion euro, *vertical axis*) as a function of a ceteris-paribus change in the cost of its outside option (in euro per tonne of CO_2, *horizontal axis*)

individual change in the cost of its outside option. Again, for each of the curves only the country itself is subjected to a change in costs, while the costs of the outside option of the others remain constant. For Romania, the curve is flat, meaning that the cost of its outside option does not affect its Shapley value. This is fairly obvious since Romania has excess storage capacity, hence it does not need to rely on its outside option. The results for the other countries are counterintuitive: their Shapley value increases when the cost of their outside option increases, while one would expect that their Shapley value would decrease. The reason is that the Shapley value only shows the distribution of gains from cooperation. A country's final result is the sum of what it can do on its own, plus its share of the gains from cooperation. An increase in the cost of the outside option leads to a sharp decline in the benefits a country can achieve on its own. This has the relative effect of enlarging the gains from cooperation, hence enlarging the 'pie' to be distributed. On the other hand, the country's relative bargaining power is weakened. The net effect is that in the negotiation the country gets a smaller share of a bigger pie, which turns out to be a net gain in this case. However, the final effect on the country is still negative, because the net gain in Shapley value does not offset the decrease in benefits it can achieve on its own. Another way of looking at this is by checking the net payments that each country makes to the investment cost burden of the network. This is shown in Fig. 8. Clearly, the net payments increase slightly as a function of the cost of the outside option.

Overall, it seems that the results of the analysis, especially the relative shares of countries in the gains from cooperation and the payments for investments, are fairly robust vis-à-vis uniform and non-uniform changes in storage costs or costs of the outside option.

6 Conclusions

In this paper, we have analysed bargaining power in the multilateral negotiation process that would be required to develop a cost-minimising trans-European CO_2 transport infrastructure if CO_2 carbon capture and storage is deployed on a large scale by 2050. We apply the Shapley value to the coalitional game between 18 European countries, in two different cases: one case with national pipeline monopolies and one case with liberalised pipeline construction. Using the *InfraCCS* pipeline optimisation model, we perform a numerical simulation, which computes each country's contribution to a 28 billion euro trans-European CO_2 pipeline network.

First, we find that countries with more storage capacity than capture activity obtain 38–45 % of the benefits of cooperation, with the higher number corresponding to the case with liberalised pipeline construction. This means that a depleted hydrocarbon field (when used for CO_2 storage) can earn a resource rent of roughly $1 per barrel of original recoverable oil reserves, or $2 per boe of original recoverable gas reserves. This number is small from the perspective of petroleum economics, but corresponds to 5–6 euro per tonne of CO_2 stored, which may increase CO_2 storage costs by 25–600 %.

Second, countries with a strategic transit location capture 19 % of the rent in the case of national pipeline monopolies. EU legislation that liberalises pipeline construction eliminates this transit rent and reduces by two-thirds the differences between countries in terms of cost per tonne of CO_2 exported. For example, Denmark obtains a net benefit of over 4 billion euro in the case of national pipeline monopolies, but loses almost all of this if pipeline construction is liberalised. Since the payoffs from liberalisation are strongly divergent across countries, reaching a political compromise on such legislation may be challenging.

In a sensitivity analysis the results of this paper, especially the relative shares of countries in the gains from cooperation and the payments for investments, are shown to be fairly robust vis-à-vis uniform and non-uniform changes in storage costs or costs of the outside option.

The results are dependent on the assumptions made in the model developed in this paper. Considering the capture process, it is recognised that carbon allowance prices need to be set aside against not just storage and transport costs but also against capture costs in CCS participating countries that resist a power tariff rise. The ratio of capture costs to transport and storage costs depends on the typology of capture technology used. Regarding the bargaining process, it is clear that countries' bargaining position in negotiations is also conditioned by perceived risks of CO_2 transport and storage in certain national contexts. More generally, the results are obviously strongly dependent on the assumptions underlying the Shapley value. Other approaches exist, and the allocation shown in this paper is not necessarily the only possible allocation. Even more importantly, the cooperative game theory framework from which the Shapley value arises, assumes that the grand coalition is eventually formed. This is in stark contrast with current developments in Europe: unlike the US, there is no CO_2 pipeline network in Europe yet, and many countries would oppose such developments. As a further caveat, it should be mentioned that the rent computed here is only the rent arising from market power in CO_2 transport. In addition there may be a Hotelling (1931) rent for storage sites if storage becomes scarce. Furthermore, supranational regulation and enforcement may be required in order to avoid renegotiation once the network is in place.[13] More generally, there is a question about which market organisation would be suited for the operation of such a jointly optimal network. Finally, an important area for future work is a more thorough understanding of the 'outside option' through better integration with the economic equilibrium models that generate the scenarios of CO_2 capture rates.

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[13] Given that the CO_2 pipeline network requires a large upfront investment and relatively little operating costs afterwards, there is little incentive for CO_2 -producing countries to leave the coalition once the network has been constructed. However, countries with storage and transit rents could extract additional rents by demanding supplementary payments for access to their territories once the investment has been done and the network is in place. This is similar to the 'hold-up' problem in natural gas infrastructure (see e.g. Hubert and Ikonnikova 2009; Morbee and Proost 2010). For this type of non-compliance, supranational regulation and enforcement of contracts may be required.

References

Albrecht J, Francois D, Schoors K (2002) A Shapley decomposition of carbon emissions without residuals. Energy Policy 30(9):727–736

BAFA (2011) Monatliche Erdgasbilanz und Entwicklung der Grenzübergangspreise, ausgewählte Statistiken zur Entwicklung des deutschen Gasmarktes. Bundesministerium für Wirtschaft und Technologie—Bundesamt für Wirtschaft und Ausfuhrkontrolle, http://www.bmwi.de/BMWi/Navigation/Energie/Energiestatistiken/gasstatistiken.html, last consulted in February 2011

Bentham M, Kirby G (2005) CO_2 Storage in Saline Aquifers. Oil Gas Sci Technol Rev IFP 60(3):559–567

Broek Mvd, Ramirez A, Groenenberg H, Neele F, Viebahn P, Turkenburg W, Faaij A (2010a) Feasibility of storing CO_2 in the Utsira formation as part of a long term Dutch CCS strategy: an evaluation based on a GIS/MARKAL toolbox. Int J Greenh Gas Control 4:351–366

Broek Mvd, Brederode E, Ramirez A, Kramers L, van der Kuip M, Wildenborg T, Turkenburg W, Faaij A (2010b) Designing a cost-effective CO_2 storage infrastructure using a GIS based linear optimization energy model. Environ Modell Softw 25(12):1754–1768

Capros P, Mantzos L, Tasios N, De Vita A, Kouvaritakis N (2010) EU energy trends to 2030—Update 2009. Publications Office of the European Union, Luxembourg

Contreras J, Wu F (2000) A kernel-oriented algorithm for transmission expansion planning. IEEE Trans Power Syst 15(4):1434–1440

Csercsik D, Koczy L (2011) Externalities in the games over electrical power transmission networks. IEHAS Discussion Papers

E-PRTR (European Pollutant Release and Transfer Register) (2010) Database available from the European Environment Agency, Copenhagen. Update of 8 June 2010. www.eea.europa.eu

EURELECTRIC—Union of the Electricity Industry (2010) Power choices, pathways to carbon-neutral electricity in Europe by 2050. Eurelectric, Brussels

European Commission (2010) Energy infrastructure priorities for 2020 and beyond—a Blueprint for an integrated European energy network. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2010) 677 final, Brussels, 17.11.2010

European Commission (2011a) A Roadmap for moving to a competitive low carbon economy in 2050. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2011) 112 final, Brussels, 08.03.2011

European Commission (2011b) Energy Roadmap 2050. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2011) 885/2 final, Brussels, 19.12.2011

Evans F, Zolezzi J, Rudnick H (2003) Cost assignment model for electrical transmission system expansion: an approach through the Kernel theory. IEEE Trans Power Syst 18:625–632

Florio M (2008) Cost-benefit analysis of investment projects—structural funds. Cohesion Fund and Instrument for Pre-Accession,Brussels, Directorate General Regional Policy, European Commission

Gately D (1974) Sharing the gains from regional cooperation: a game theoretic application to planning investment in electric power. Int Econ Rev 15:195–208

Gas Infrastructure Europe, The European Association of the Natural Gas Industry (2012) Gas Storage Europe—Storage Map. GIE, Brussels. Available from www.gie.eu

Hobbs B, Kelly K (1992) Using game theory to analyze electric transmission pricing policies in the United States. Eur J Oper Res 56:154–171

Hotelling H (1931) The economics of exhaustible resources. J Polit Econ 39(2):137–175

Hubert, F, Ikonnikova S (2009) Investment options and bargaining power the Eurasian supply chain for Natural Gas. MPRA Paper No. 17854, September 2009

Ikonnikova S, Zwart G (2010) Reinforcing buyer power: Trade quotas and supply diversification in the EU natural gas market. TILEC discussion Paper No. 2010–018

IPCC (2005) Special report on carbon dioxide capture and storage. In: Metz B, Davidson O, de Coninck HC, Loos M, Meyer LA (eds) Prepared by working group III of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Jepma CJ (2001) Gaslevering onder druk: invloed van de Richtlijnen van de DTe op de Nederlandse gasstromen. Stichting JIN, Groningen/Paterswolde

Kleindorfer P, Wu D-J, Fernando C (2001) Strategic gaming in electric power markets. Eur J Oper Res 130:156–168

Mendelevitch R, Herold J, Oei P-Y, Tissen A (2010) CO_2 highways for Europe—modeling a carbon capture, transport and storage infrastructure for Europe. DIW discussion Paper, (1052) September 2010. Deutsches Institut für Wirtschaftsforschung, Berlin

Middleton R, Bielicki J (2009) A scalable infrastructure model for carbon capture and storage: SimCCS. Energy Policy 37:1052–1060

Morbee J, Proost S (2010) Russian gas imports in Europe: how does Gazprom reliability change the game? Energy J 31(4):79–110

Morbee, J, Serpa J, Tzimas E (2010) The Evolution of the extent and the investment requirements of a trans-European CO2 transport network. JRC Scientific and technical report series, EUR 24565 EN. Publications Office of the European Union, Luxembourg

Morbee J, Serpa J, Tzimas E (2012) Optimised deployment of a European CO_2 transport network. Int J Greenh Gas Control 7:48–61

Shapley LS (1953) A value for n-person games. In: Kuhn HW, Tucker AW (eds) Contributions to the theory of games, volume II, vol 28. Annals of Mathematical Studies, Princeton, pp 307–317

Shapley LS (1971) Cores of convex games. Int J Game Theory 1(1):11–26

Vangkilde-Pedersen T, Kirk K, Smith N, Maurand N, Wojcicki A, Neele F, Hendriks C, LeNindre Y-M, Antonsen KL (2009) D42 GeoCapacity Final Report. EU GeoCapacity project—assessing European capacity for geological storage of carbon dioxide. Available from www.geology.cz/geocapacity

Weber A (1909) Über den Standort der Industrie

Wright I, Ashworth P, Sun Xin, Li Di, Zhu Yizhong, Xi Liang, Anderson J, Shackley S, Itaoka K, Wade S, Asamoah J, Reiner D (2007) Public perception of Carbon Dioxide capture and storage: prioritised assessment of issues and concerns. Summary for policy-makers. CO_2 capture project, available from www.co2captureproject.org

ZEP (Zero Emissions Platform) (2011) The costs of CO_2 storage. European Technology Platform for Zero Emission Fossil Fuel Power Plants, Brussels