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Summary

RS1c of the NEEDS project has provided an assessment of the external costs of the following upstream and/or downstream stages of energy production:
the externalities due to extraction and transport of oil and of gas;
the externalities due to import/transport of electricity and of H_2.
The present report concerns the uncertainty of the results in the EU; it also examines additional uncertainties introduced when these results are transferred to other regions.

This involves a detailed examination of the uncertainties of each of the steps of the impact pathway analysis (e.g. for transport of oil by tanker: transport distance, emission rates of pollutants per km, dispersion, dose-response functions, monetary valuation). The available input data are examined to estimate standard deviation and shape of the probability distribution of their uncertainties. The component uncertainties are then combined to obtain to uncertainty of the damage cost. A crucial observation is that only data with relatively large uncertainties need to be taken into account; data with relatively low uncertainty make a negligible contribution to the overall uncertainty. In this context "relatively low" means uncertainties that correspond to relative errors of less than about 20%; this feature that greatly simplifies the work.

The methodology uses the framework developed by Rabl and Spadaro [1999] and Spadaro and Rabl [2008]; it is based on lognormal distributions and geometric standard deviations (i.e. multiplicative confidence intervals). It has the advantage of being simple and transparent, by contrast to the opaque output of the traditional Monte Carlo calculations. The simplicity of the framework of Spadaro and Rabl [2008] makes it well suited for the communication with policy makers. It is based on the observation that the damage cost can be calculated as a product of a few factors, and the uncertainty of each of these factors can be estimated.

Geometric standard deviations have a simple interpretation in terms of multiplicative confidence intervals: if a quantity with a lognormal distribution has a geometric mean μ_g and a σ_g, the probability is approximately 68% for the true value to be in the interval $[\mu_g/\sigma_g, \mu_g\ \sigma_g,]$ and 95% for it to be in the interval $[\mu_g/\sigma_g^2, \mu_g\ \sigma_g^2]$.

An important overall conclusion is that for external costs based on LCA inventories the uncertainties are significantly larger than those of the external cost per kg of pollutant because of the uncertainties of LCA databases (especially when applied to scenarios of the future).

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1. Introduction

RS1c of the NEEDS project has provided an assessment of the external costs of the following upstream and/or downstream stages of energy production:
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The methodology uses the framework developed by Rabl and Spadaro [1999] and Spadaro and Rabl [2008]; it is based on lognormal distributions and geometric standard deviations (i.e. multiplicative confidence intervals). It has the advantage of being simple and transparent, by contrast to the opaque output of the traditional Monte Carlo calculations. The simplicity of the framework of Spadaro and Rabl [2008] makes it well suited for the communication with policy makers. It is based on the observation that the damage cost can be calculated as a product of a few factors, and the uncertainty of each of these factors can be estimated.

Since for the cases considered here one can assume statistical independence of the uncertainty distributions of the factors (e.g. cost per ton of pollutant and emitted quantity), one finds that the geometric standard deviation σ_{gz} of a product $z = x_1 x_2 \ldots x_n$ is given by

$$[\ln(\sigma_{gz})]^2 = [\ln(\sigma_{gx1})]^2 + [\ln(\sigma_{gx2})]^2 + \ldots + [\ln(\sigma_{gxn})]^2 \qquad (1)$$

where σ_{gxi} is the geometric standard deviations of the factor x_i.

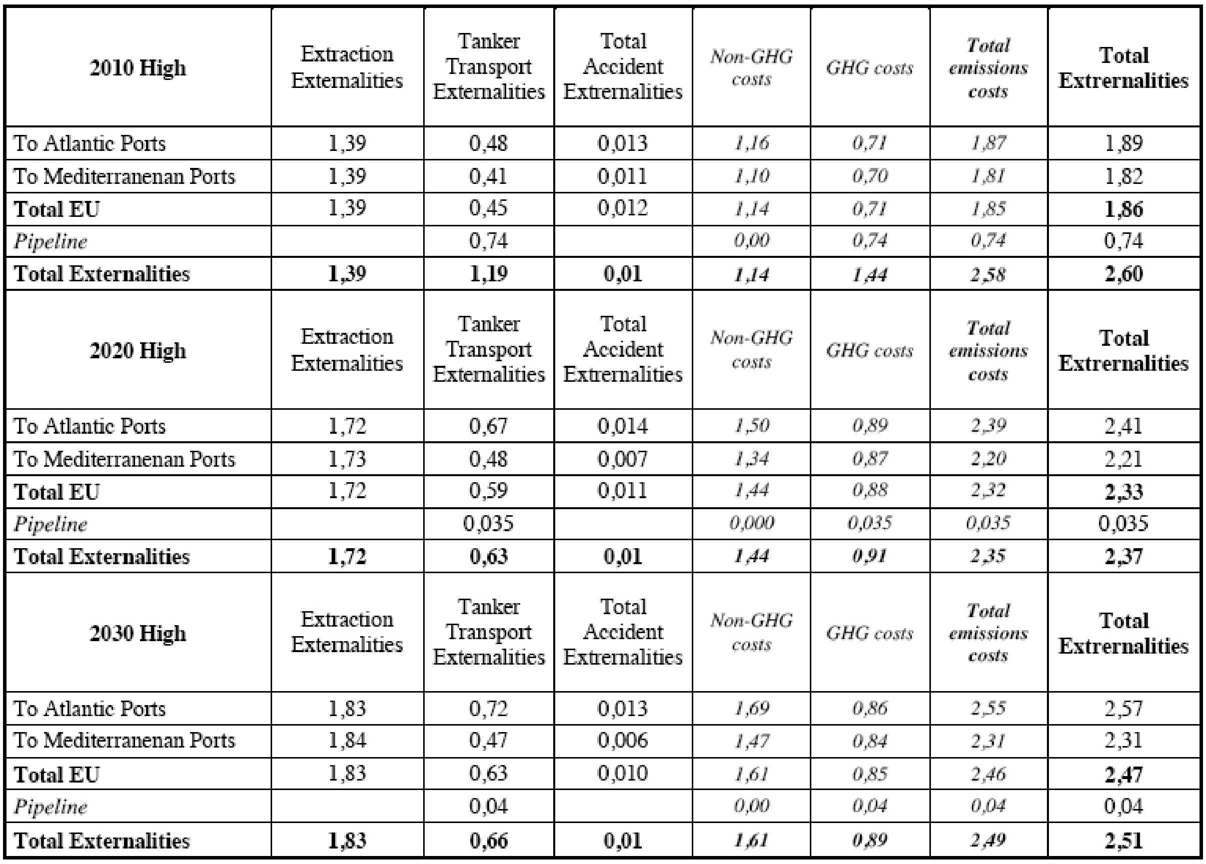
Geometric standard deviations have a simple interpretation in terms of multiplicative confidence intervals: if a quantity with a lognormal distribution has a geometric mean μ_g and a σ_g, the probability is approximately 68% for the true value to be in the interval $[\mu_g/\sigma_g, \mu_g \sigma_g,]$ and 95% for it to be in the interval $[\mu_g/\sigma_g^2, \mu_g \sigma_g^2]$.

Extraction and transport of oil and natural gas are discussed in Sections 2 and 3, respectively. Section 4 addresses the transport of H2, and Section 5 the transmission of electricity. Finally Section 6 presents a simple method for estimating additional uncertainties that arise if these results are transferred to other countries or regions.

2. Uncertainty of externalities due to extraction and transport of oil

It is appropriate to begin by looking at Table 7 of Deliverable Task 1.8 - RS 1c WP 1, "Report on the economic evaluation of externalities due to extraction and transport of oil" by SWECO [2007]; it is reproduced here as Table 1. It is for the high demand scenario, but the analogous table for the low demand scenario presents very similar numbers: the item with the largest difference in total externalities is the low demand scenario in 2030 for which the total externality is 2.32 €/ton instead of 2.51 €/ton for the high demand.

Table 1. External costs, in €/ton, of oil extraction and transport Projections to 2010, 2020 and 2030 in the high demand scenario.



2010 High	Extraction Externalities	Tanker Transport Externalities	Total Accident Extrernalities	*Non-GHG costs*	*GHG costs*	***Total emissions costs***	**Total Extrernalities**
To Atlantic Ports	1,39	0,48	0,013	*1,16*	*0,71*	*1,87*	1,89
To Mediterranenan Ports	1,39	0,41	0,011	*1,10*	*0,70*	*1,81*	1,82
Total EU	1,39	0,45	0,012	*1,14*	*0,71*	*1,85*	**1,86**
Pipeline		0,74		*0,00*	*0,74*	*0,74*	0,74
Total Externalities	**1,39**	**1,19**	**0,01**	***1,14***	***1,44***	***2,58***	**2,60**
2020 High	Extraction Externalities	Tanker Transport Externalities	Total Accident Extrernalities	*Non-GHG costs*	*GHG costs*	***Total emissions costs***	**Total Extrernalities**
To Atlantic Ports	1,72	0,67	0,014	*1,50*	*0,89*	*2,39*	2,41
To Mediterranenan Ports	1,73	0,48	0,007	*1,34*	*0,87*	*2,20*	2,21
Total EU	1,72	0,59	0,011	*1,44*	*0,88*	*2,32*	**2,33**
Pipeline		0,035		*0,000*	*0,035*	*0,035*	0,035
Total Externalities	**1,72**	**0,63**	**0,01**	***1,44***	***0,91***	*2,35*	**2,37**
2030 High	Extraction Externalities	Tanker Transport Externalities	Total Accident Extrernalities	*Non-GHG costs*	*GHG costs*	***Total emissions costs***	**Total Extrernalities**
To Atlantic Ports	1,83	0,72	0,013	*1,69*	*0,86*	*2,55*	2,57
To Mediterranenan Ports	1,84	0,47	0,006	*1,47*	*0,84*	*2,31*	2,31
Total EU	1,83	0,63	0,010	*1,61*	*0,85*	*2,46*	**2,47**
Pipeline		0,04		*0,00*	*0,04*	*0,04*	0,04
Total Externalities	**1,83**	**0,66**	**0,01**	***1,61***	***0,89***	***2,49***	**2,51**

The methodology for calculating the externalities of oil extraction is easy to summarize: one obtains the inventory of pollutant emissions from an LCA data base and multiplies the emissions by the damage costs calculated by EcoSense, see Deliverable 1.6b of RS 1c WP 1, "Impacts from oil transportation phase of oil by pipeline and from oil extraction" [FEEM 2007a]. Here the emissions were obtained from the EcoInvent data base, one of the most current and complete that are available for this purpose. [1]

For routine operation of tankers and oil pipelines the approach is the same, although the choice of the LCA data base was less clear. For transport by tankers FEEM [2007a] decided, correctly, that the EcoInvent data for oil transport are based on older tanker fleets and not at all relevant for the tankers that will be operating in the 2010 – 2030 time frame whose

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[1] We do not include the additional uncertainty (scenario dependent) due to uncertainties in tanker trajectories and flow distributions in different pipelines; however, such uncertainties are certainly smaller than 20% and can be neglected.

emissions will be far lower thanks to stricter environmental regulations. Therefore they also consulted the data base of TEAMS 1.3, developed by the Center for Economic Analysis and Policy, Rochester University, New York. The corresponding emissions are far lower, except for NO_x, and they are used to estimate the externalities.

For oil pipelines FEEM [2007a] also encountered a problem with EcoInvent, as explained in this passage from their report: *"Oil pipelines are listed in the Ecoinvent database but the fields for air emissions are empty. The only unit emissions record present in the database are heat emissions and oil spilled in the soil. Alternative LCI data for oil pipelines could not be found. However, gas pipelines work in a similar fashion, but more energy is necessary to displace gas rather than oil, since gas must be compressed first. Therefore gas pipelines' operational externalities can be considered as first approximation, an upper bound for oil pipeline externalities. In particular, according to the database used by the TEAMS model, which computes well-to-hull LCI data for marine transportation3, on average, one ton of natural gas requires 336 Btu/mile to be moved along a pipeline; crude oil requires about 240 Btu/mile. Therefore, assuming a linear relationship between energy intensity and emissions, gas pipelines' emissions should be multiplied by a factor of 0.714 to yield approximate values for analogous emissions from oil pipelines."* Needless to say, that increases the uncertainty.

To estimate the uncertainty of LCA inventories, one should compare different inventories. Unfortunately that is not possible in the present case, the FEEM report having found/considered only two inventories (EcoInvent and TEAMS), one of which is not appropriate for tanker transport and pipelines. The problem of outdated data for pollutant emissions is pervasive in LCA since most LCA data bases are derived from past or current technologies, without any attempt to indicate their evolution. The emissions of most pollutants other than CO_2 have been declining by typically a factor of two to ten per decade and any mismatch between the time frames of emissions data and application can introduce extreme errors. The only major exception is CO_2 because the dominant source, combustion of fossil fuels, is already carried out with almost as high an efficiency as is practical and the only significant reduction can come from CO_2 capture and sequestration, which will not play a significant role in the near future and whose contribution in 2030 is difficult to predict.

Coming up with a reliable estimate for the uncertainty of the emissions is therefore problematic, unless one carries out a very detailed examination of the TEAMS database – beyond the scope of the current WP. Fortunately a precise determination of the emission uncertainties does not have a strong effect on the overall uncertainties. The reason lies again the role of contributions that are relatively less uncertain. Specifically, for the external cost due to CO_2 emissions Spadaro and Rabl [2008] have estimated that the cost per ton of CO_2 has a geometric standard deviation of about 5; compared to that the uncertainty of the emissions is entirely negligible. Even for the classical air pollutants the uncertainty of the cost per ton of pollutant is sufficiently large to dominate the result, the geometric standard deviation being about 3. For the corresponding emissions we estimate, very roughly, a geometric standard deviation of about 2 to 2.5. The resulting overall uncertainty of the contribution of the classical air pollutants to the external cost per ton of oil is about 4, as the reader can readily verify by using Eq.1.

For total external cost per ton of oil Table 1 indicates that the contributions of GHG (greenhouse gas) and non-GHG emissions have the same order of magnitude. In such a situation the uncertainty of the total external cost per ton of oil can be characterized by a geometric standard deviation in the range of 4 to 5. The absolute error of two uncertain terms is always larger than that of each summand, but as explained in Spadaro and Rabl [2008], in many cases of interest to external costs the relative error of the sum is smaller than the relative error of each of the summands. Specifically that is indeed the case here as the reader can verify by using Eqs.21-23 and Fig.2 of Spadaro and Rabl [2008] with $\sigma_{g1} = 5$ and σ_{g2} = Both the quantities $a = (\sigma_{g1}/\mu_1)/(\sigma_{g2}/\mu_2)$ and $x = \mu_2/\mu_1$ of Fig.2 are close to unity, implying that the overall uncertainty corresponds to a geometric standard deviation of $0.8\ \sigma_{g1} = 4$. Thus we conclude that the **total external cost per ton of oil has an uncertainty characterized by a geometric standard deviation of 4.**

The external cost of oils spills in Table 1 is two orders of magnitude smaller than the external costs due to extraction and routine operation of transport of oil. Its contribution to the overall uncertainty is therefore negligible, unless there is an appreciable probability of the cost of oil spills being much more than ten times larger than the estimate in Table 1. We argue that such a possibility is not plausible because in Spadaro and Rabl [2008] we have estimated the uncertainty due to transfer of WTP (willingness-to-pay) studies corresponds to a geometric standard deviation of at most 2, and significantly less for a transfer between countries of similar GDP/capita. Since that type of transfer is the dominant source of uncertainty in the case of oil spill damage cost estimates, the contribution to the total external cost per ton of oil is negligible. Of course, the **cost due to oil spills** by itself is also of interest for some policy decisions. Here the probability of an accident is also contributes to the uncertainty and we estimate its geometric standard deviation to be about 1.5, including further risk reductions due to tightened safety regulations [CEDRE 2007]. So we suggest that the total **uncertainty of oil spill costs be characterized in terms of a geometric standard deviation of about 2**.

3. Uncertainty of externalities due to extraction and transport of gas

The quantification of the external costs due to extraction and transport of natural gas is very similar to that of oil, and so is the uncertainty. Results for the external costs have been provided by FEEM [2007b]. The dominant contributions to external costs come from extraction and from transport (by pipelines or LNG tankers). Like for oil, the methodology involves LCA data for emissions and EcoSense data for the damage cost of the pollutants. For emissions from LNG transport FEEM used the same data as for oil tankers. For pipeline emissions they used EcoInvent data, noting that they are based on existing pipelines and that the CH_4 emissions from Russian pipelines have been one to two orders of magnitude higher than corresponding emissions from pipelines in Italy. Since even for Russian pipelines the CH_4 emissions will probably be reduced to EU standards during the coming decades, FEEM also evaluates the external cost under the assumption of improved pipelines in Russia. Results are reproduced here in Tables 2 (for existing pipelines) and 3 (for improved pipelines in Russia).

Like for oil, the expectation value of the costs of an accident is very small. Because of insufficient data FEEM [2007b] does not provide an explicit estimate of the cost of an accident, but indicates the rate of deaths if the number of fatalities at the Skikda liquifaction plant in Algeria in 2004 (by far the largest LNG accident in the world) is prorated over the total world production of LNG up to that time. That rate of deaths is about 0.01 deaths/Bcm or 1.5E-8 deaths/ton. Taking the value of a prevented fatality (also known under the unfortunate name ”value of statistical life”) as 4 million €, the corresponding cost would be 0.06 €/t. That is probably an upper limit because safety procedures tend to be improved over time. In any case, it is small compared to the external costs from extraction and transportation, which is 1.48 €/ton for the reference scenario in 2010 and will remain above 0.30 €/ton even if one assumes that the Russian pipelines will reach EU standards by 2020. Therefore the uncertainty of accidents can be neglected in the analysis, like for oil – quite apart form the question to what extent accidents are already internalized in labor contracts.

Table 2. Overall external costs (Euro per ton) from natural gas extraction and transport. Base year and projections to 2010, 2020 and 2030 under reference, low demand and high demand scenarios, assuming no improvement in technical standards. Ref: Table 18 of FEEM [2007b].

	Base year	*Low Scenario*			*Reference Scenario*			*High Scenario*		
	2004	*2010*	*2020*	*2030*	*2010*	*2020*	*2030*	*2010*	*2020*	*2030*
NMVOC	3,37E-03	3,27E-03	1,65E-03	1,66E-03	3,10E-03	1,65E-03	1,64E-03	3,13E-03	1,64E-03	1,64E-03
NO_X	4,10E-02	6,64E-02	1,70E-01	1,83E-01	8,43E-02	2,00E-01	2,24E-01	9,11E-02	2,18E-01	2,52E-01
PPM^{co}	4,36E-04	4,30E-04	6,63E-04	6,85E-04	4,20E-04	7,11E-04	7,50E-04	4,20E-04	7,41E-04	7,97E-04
PPM^{25}	7,51E-03	7,41E-03	1,14E-02	1,17E-02	7,24E-03	1,22E-02	1,28E-02	7,26E-03	1,26E-02	1,35E-02
SO_2	3,42E-02	3,41E-02	3,63E-02	3,63E-02	3,43E-02	3,62E-02	3,61E-02	3,45E-02	3,62E-02	3,61E-02
CO2	2,77E-02	3,21E-02	4,01E-02	3,95E-02	3,51E-02	4,33E-02	4,37E-02	3,63E-02	4,50E-02	4,64E-02
CH_4	1,59E+00	1,47E+00	1,13E+00	9,99E-01	1,31E+00	1,08E+00	9,34E-01	1,28E+00	1,03E+00	8,84E-01
N_20	5,40E-03	5,54E-03	5,77E-03	4,96E-03	5,65E-03	5,88E-03	5,12E-03	5,75E-03	5,97E-03	5,26E-03
TOTAL	**1,71**	**1,62**	**1,39**	**1,28**	**1,48**	**1,38**	**1,26**	**1,46**	**1,35**	**1,24**

Table 3. Overall external costs (Euro per ton) from natural gas extraction and transport. Base year and projections to 2010, 2020 and 2030 under reference, low demand and high demand scenarios. Ref: Table 16 of FEEM [2007b].

	Base year	*Low Scenario*			*Reference Scenario*			*High Scenario*		
	2004	*2010*	*2020*	*2030*	*2010*	*2020*	*2030*	*2010*	*2020*	*2030*
NMVOC	3,37E-03	3,27E-03	9,67E-04	9,79E-04	3,10E-03	9,88E-04	1,01E-03	3,13E-03	1,01E-03	1,04E-03
NO_X	4,10E-02	6,64E-02	1,70E-01	1,83E-01	8,43E-02	2,00E-01	2,24E-01	9,11E-02	2,18E-01	2,52E-01
PPM^{co}	4,36E-04	4,30E-04	6,63E-04	6,85E-04	4,20E-04	7,11E-04	7,50E-04	4,20E-04	7,41E-04	7,97E-04
PPM^{25}	7,51E-03	7,41E-03	1,14E-02	1,17E-02	7,24E-03	1,22E-02	1,28E-02	7,26E-03	1,26E-02	1,35E-02
SO_2	3,42E-02	3,41E-02	3,63E-02	3,63E-02	3,43E-02	3,62E-02	3,61E-02	3,45E-02	3,62E-02	3,61E-02
CO2	2,77E-02	3,21E-02	4,01E-02	3,95E-02	3,51E-02	4,32E-02	4,36E-02	3,63E-02	4,50E-02	4,64E-02
CH_4	1,59E+00	1,47E+00	5,40E-02	4,80E-02	1,31E+00	5,20E-02	4,52E-02	1,28E+00	4,99E-02	4,30E-02
N_20	5,40E-03	5,54E-03	5,77E-03	4,96E-03	5,65E-03	5,88E-03	5,12E-03	5,75E-03	5,97E-03	5,26E-03
TOTAL	**1,71**	**1,62**	**0,32**	**0,32**	**1,48**	**0,35**	**0,37**	**1,46**	**0,37**	**0,40**

Assuming no improvement in Russian pipelines Table 2 shows that the CH_4 emissions make the dominant contribution to the external costs. Thus the **geometric standard deviation is about 5 for current conditions**. If/when Russian pipelines attain EU standards, the contribution of greenhouse gas emissions will become so small that the classical air pollutants remain as the largest item; in that case the geometric standard deviation will be about 4.

4. Uncertainty of externalities due to import/transport of H_2

Unlike the reports on oil and gas, the report on H_2 addresses only transport, not production [POLITO 2007]. There are many different technologies for producing H_2, and for most of them the external costs are large because the production requires large inputs of energy, such as electricity or fuel. The externalities of H_2 production have been analyzed in RS1a, by carrying out an LCA of the production chain.

For transport of compressed H_2 the report evaluates the following modes:
- truck for gaseous hydrogen
- truck for liquid hydrogen

- ship for liquid hydrogen.

The methodology is similar to the one for oil and gas, the main steps being the determination of emissions from an LCA database or other source of information, and the multiplication by the cost per kg of pollutant. The emitted pollutants are, as usual, greenhouse gases and the classical air pollutants. In addition the report considers the cost of accidents from transport by truck, ship or pipeline.

For the emissions of trucks the report uses the limit values of the EURO regulations, EURO1, EURO3, EURO4 and EURO5, since trucks of all these vintages will be used; but the report makes no attempt to estimate the relative contributions of these truck types. That does not affect the costs due to CO_2, SO_2 and NMVOC because it is the same for all of these trucks, but the emissions of CH_4, CO, NO_x and PM are greatly reduced between EURO1 and EURO5 (by factors around 4 for CO, NO_x and PM and even more for CH_4). Using regulatory limit values for trucks is probably much better than LCA databases which tend to be outdated, but the uncertainties are nonetheless considerable. Real emissions for most pollutants tend to be significantly lower than regulatory limits, because the manufacturer must plan for a sufficient margin of safety to ensure that the limits are respected at all times, even under highly variable driving conditions. Thus the results in the report for truck emissions are probably upper bounds, except for CO_2 and SO_2 the emission of which is determined by the fuel consumption (SO_2 comes from the sulfur in the fuel which is the same for all trucks at a given time). The emissions are all the more uncertain because they can vary strongly with driving conditions and state of maintenance of the vehicle.

A geometric standard deviation around 1.5 seems plausible for transport emissions. Compared to the uncertainty of the damage costs, 3 for the classical air pollutants and 5 for greenhouse gases, that is sufficiently small not to cause an appreciable increase in the geometric standard deviation of the result, as can be seen by inserting these numbers into Eq.1.

For transport by ship the H_2 is liquefied and the external costs of pollution are negligible because the engines of the ship are fueled by H_2. For the liquefaction plant a natural gas fueled gas turbine is assumed, with emissions from an Italian LCA database. For the plant efficiency the report assumes current practice, i.e. an energy loss of about 30% of the energy content of the H_2. It is likely that losses can be greatly reduced with research and development, perhaps to about 10% [see e.g. http://www.hydrogen.energy.gov/pdfs/progress05/v_e_1_shimko.pdf]. Since large scale use of H_2 is decades into the future, so is the relevant time frame for the external costs. Hence the external costs of liquefaction in the report can be taken as upper bounds and the real cost will probably be much lower; of course the uncertainty of such efficiency improvements is high, perhaps a factor of two.

A variety of possibly accidents during liquefaction or transport have been considered in the report. The expectation value of the corresponding costs in the report is extremely small, on the order of 10^{-10} to 10^{-9} €/MJ, except for a catastrophic BLEVE (boiling liquid expanding vapour explosion) accident with a liquid H_2 tanker for which the cost is shown as 6.6E-6 €/MJ. The accident probabilities and consequences were modeled with the commercial software package DNV-PHAST [available from http://www.dnv.com]. This software does not include an analysis of uncertainties, but it can carry out sensitivity studies and Raffaella Gerboni [personal communication 30 May 2008] has kindly provided the results of several sensitivity studies. However, the main uncertainties arise from assumptions about the locations of potential accidents and the population densities. That is difficult to estimate, and the uncertainties could be an order of magnitude or more.

5. Uncertainty of externalities due to import/transport of electricity

The report on externalities due to import/transport of electricity [VITO 2007] presents a thorough and comprehensive examination of essentially all the possible impacts. The following external costs are addressed in the report but not all of them are quantified:

- Transmission losses (and external costs of these losses)
- Visual intrusion of overhead lines
- Impacts of electromagnetic fields of overhead lines and cables
- Impacts due to visual intrusion, noise and perceived risks
- Impacts due to emissions from production of materials for power lines
- Impacts on biodiversity from construction and infrastructure
- Security of supply issues
- Land use.

The private cost of transmissions losses is of course internalized in the electricity price, and therefore the external cost is simply the external cost of the average electricity that is produced and transmitted. The uncertainty of the latter can be characterized by a geometric standard deviation of about 3.

The possibility of health impacts caused by electromagnetic fields from transmission lines has been and continues to be controversial. Claims of effects have been contested mainly for two reasons. One is that the epidemiological studies have very large uncertainties and are not very conclusive. The other reason is the lack of any known mechanism that could explain an impact at the field strengths in question. Among the impacts that have been mentioned the most likely is childhood leukemia. The VITO report uses a dose-response function in a pooled analysis by RIVM of studies in the literature. In view of the intrinsic uncertainties of the studies and the lack of any plausible mechanism one must take the resulting damage cost estimate with extreme caution. Trying to provide an estimate of a geometric standard deviation does not seem meaningful. The best one can say is that the damage cost in the VITO report is most probably an upper bound and the true value could just as well be zero.

VITO provides an estimate for the amenity loss due to visual intrusion and perceived quality of life near a high voltage transmission line. It is based on hedonic studies of the values of houses near power lines. The two main sources of uncertainty of the resulting external cost are the % loss of property values and the number of houses that are affected. Based on the information in the VITO report we estimate a geometric standard deviation of 1.7 for the former and 2 for the latter. With those two inputs Eq.1 yields a geometric standard deviation of 2.5 for the uncertainty of amenity losses.

The external costs due to emissions from the production of materials for power lines are calculated as product of emission and damage cost per pollutant, like for the other applications of LCA inventories in RS1c. Thus the associated uncertainty is the same as for the corresponding impacts of the oil chain in Section 2 above, so the geometric standard deviation is about 4.

Security of supply is discussed in the report of VITO, but no results are presented. While there are studies that have estimated the cost of electric power failures for the consumer, one would need to identify the portion attributable to the transmission grid; the report of VITO cites a few numbers for the former but nothing for the latter. Quite apart from that, there is the question to what extent the cost of supply disruptions of electric power is an externality. After all, it is an issue entirely between supplier and consumer of electricity.

Among other possible externalities, accidents and land use are discussed, but without any numerical results; in any case, these impact categories are not expected to entail significant external costs.

6. Uncertainty due to the transfer of Results

Uncertainties due to the transfer of the results to other countries or regions has been discussed in the final report for WP3 of RS3a [Rabl 2008]. Here we only summarize the key findings. Uncertainties arise mainly from the transfer of dispersion calculations, exposure-response functions (ERF), of monetary values and of technologies (more correctly, the characteristics of the technologies used in other regions or countries, especially the use of pollution abatement). Recommended values for the associated geometric standard deviations are listed in Table 4. Some explanations and comments follow below.

Table 4. Geometric standard deviations associated with the transfer of components of the damage cost calculation. The ones that are relevant for a region of interest have to be combined with the geometric standard deviations of the damage costs for the EU15 to obtain the total uncertainty in the region.

Component of calculation	σ_g
Transfer of technologies	
Pollutant emissions	[a]
Atmospheric modeling	
If no data for effective deposition velocity v_{dep}	2
If no data for stack height	2
If no data for local population or no data for wind	3
Background Concentrations for sulfate and nitrate formation	1.2
Background Concentrations for O_3 formation due to NO_x	2
Background Concentrations for O_3 formation due to VOC	1.3
Modeling of ingestion dose	
Toxic Metals	2
Exposure-Response Functions	
PM, NO_x, SO_2, toxic metals	2
Monetary values, non-market goods	
WTP for goods other than health	2
WTP for health	[b]
$(GDP/cap)/(GDP/cap)_{ref} = 0.5$	1.3
$(GDP/cap)/(GDP/cap)_{ref} = 0.2$	1.7
$(GDP/cap)/(GDP/cap)_{ref} = 0.1$	2.1

[a] depends on site

[b] Eq.2 in Section 6.3

6.1. Uncertainties due to transfer of dispersion calculation

The laws of physics and chemistry are of course the same everywhere, and therefore the transfer of atmospheric models to other regions or times does not introduce any additional uncertainties in so far as the models involve only these laws. However, the modeling also involves boundary conditions and parameters that depend on regional or local conditions. Among such items the variability of the following is especially important:

- Background concentrations of air pollutants that affect nonlinear chemical reactions;
- Meteorology (precipitation, wind, solar radiation, temperature, …);
- Surface conditions and their effect on deposition velocities and wind speed.

Uncertainties about local meteorological conditions have the same effect as lack of local population data: they affect the calculation of the impacts in the local zone, especially within about 50 km from the source.

6.2. Uncertainties due to transfer of exposure-response functions

As for the transfer of ERFs, the best approach in view of the epidemiological evidence is to use the same exposure-response functions everywhere. The resulting contribution to the total uncertainty of health damage costs is difficult to estimate, although comparison of ERFs for acute mortality due to PM_{10} suggests that it might amount to a factor of about two.

In addition to the ERFs, for many endpoints the calculations involve data for the background incidence or prevalence rates of the respective endpoints in the affected region(s). Since for many sites such data are not available, the uncertainty is increased, possibly by as much as 50%. However, the largest impact in terms of costs is mortality and for that the background rates are well known. Thus we conclude that the uncertainty due to background rates, even if relatively large for some particular endpoints, does not make an important contribution to the total external cost of a pollutant.

Further uncertainties can arise from the calculation of life expectancy (LE) loss from chronic mortality. Here we refer to a detailed analysis by Leksell & Rabl [2001] who have calculated the LE loss when the same ERF for chronic mortality is applied in different countries. Their results imply that the uncertainty fo this calculation (for the same ERF) is about +-30%, small compared to uncertainties of ERF itself.

6.3. Uncertainty due to the transfer of Monetary values

For market costs, e.g. the cost of lost agricultural production, the uncertainties are sufficiently small compared to the other uncertainties, so they can be neglected. But the largest contribution to external costs comes from non-market goods, and for these the WTP (willingness-to-pay) to avoid a loss is difficult to determine and the uncertainties are large even in countries where detailed WTP studies have been carried out. Economists have carried out much work to develop and test procedures for the transfer of monetary values from one country to another. Needless to say, transferring the results of WTP studies to other countries involves large uncertainties, especially if the standard of living is very different.

We suggest estimating the uncertainty due to value transfer by considering two estimates, one with an income elasticity of $\eta = 0.35$, the other with an income elasticity of $\eta = 1.0$, as upper and lower bounds. In order to fit such a range into the framework of geometric standard deviations, we treat the ratio of these two extremes as 68% confidence interval of a lognormal distribution. Thus we take the geometric standard deviation σ_g of the WTP transfer to be

$$\sigma_g = \sqrt{\frac{\left(Y/Y_{ref}\right)^{0.35}}{\left(Y/Y_{ref}\right)}} \quad . \tag{2}$$

where Y and Y_{ref} are the PPP adjusted GDP/capita, for the site in question and the reference site (i.e. the EU15).

6.4. Uncertainty due to the transfer of Technologies

Here the key question is: what are the emissions of pollutants for technologies used in different regions of the world and how will they evolve in the future? For technologies in current use the emissions should be easy to determine, although in practice the data may be difficult to obtain if the utility companies are not obliged by law to report such data. In this regard one has to distinguish the different pollutants.

CO_2 emissions depend only on the fuel used and on the conversion efficiency, except for future technologies when carbon capture and sequestration (CCS) will be implemented. Thus for current technologies the CO_2 emissions can be determined quite accurately from data for fuel input and electricity output. Lacking such data, one can still estimate the conversion efficiency from the power plant type. As for CCS, it does not seem feasible in the foreseeable future for the transport sector.

The emission of the classical air pollutants (NO_x, PM, SO_2, and COV) depends strongly on the abatement equipment that is used. In the EU the data of the European Pollutant Emission Register [http://eper.ec.europa.eu/eper/] can provide a good estimate of the emissions. In other countries the limit values of environmental regulations can be used as an estimate of the emissions if the pollutants are regulated and the regulations are enforced. But if no data are available, the uncertainties for these pollutants can be quite large. The uncertainties need to be estimated for each case.

7. Conclusion

We have provided estimates of the uncertainties associated with the externalities that have been reported in RS1c. An important overall conclusion is that for external costs based on LCA inventories the uncertainties are significantly larger than those of the external cost per kg of pollutant because of the uncertainties of LCA databases (especially when applied to scenarios of the future).

Needless to say, the estimation of uncertainties is difficult and full of its own uncertainties; it necessarily involves subjective judgment, and various readers might well come up with different assessments of the component uncertainties. However, unless the present report systematically over or underestimates all the component uncertainties (which we obviously do not believe to be the case), there will be compensation of errors: some may be higher, some lower, but the overall uncertainty of the results may not change all that much.

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