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ABSTRACT

The following report is aimed at quantifying and valuing the externalities due to transportation of hydrogen, based on the most diffused and technologically viable solutions for the present and the near future.

The transportation schemes selected were assessed from a technological point of view, highlighting advantages and drawbacks, in TP4.1; their contribution to the market penetration of the energy vector was assessed in TP4.2 and the environmental burdens carried by each scheme were eventually assessed in TP4.3. An additional, yet indispensable, contribution to the evaluation of externalities can be brought by the risk associated with the transportation of hydrogen as an energy vector. TP4.5 contains a full probabilistic risk analysis of all the main hydrogen transportation schemes.

This final report, which combines TP4.4 and TP4.6 ("*Assessment of impacts*" and "*Economic evaluation*" in short) provides the final values of Euro per unit of energy of hydrogen transported. This value can be readily included in any energy modelling tool as an additional marginal cost to be paid for transporting the energy carrier.

STRUCTURE

The report consists of two main parts:

- the first parts is dedicated to the description of the methodology used to evaluate externalities, starting from the previously estimated burdens on the environment and from the risk analysis
- the second part presents the results of the analysis in the form of commented tables.

SUMMARY

INDEX OF TABLES

1. Introduction

This report presents the results of the final step of the Impact Pathway Methodology. Once the burdens of the transportation of hydrogen activity have been evaluated in the previous works, their impact and their monetary evaluation are here assessed and results are reported.

This final step strongly depends on the reliability and availability of data from RS1b on “New and improved methods to estimate the external costs of energy conversion“.

As of the present date, not all of the final parameters and coefficients needed for a proper and complete analysis are available, although some reliable estimates already exist and these have been used here.

Results are reported in terms of euro per unit of energy transported in the form of hydrogen. This estimates represent the additional costs to be paid for externalities caused by the transport of this promising innovative energy vector, and these values are ready to be included in the work of Research Stream 2a on “Modelling internalisation strategies, including scenario building”.

2. Methodology

2.1 Environmental burdens

Within TP4.3, burdens related to transportation of hydrogen via:

- truck for gaseous hydrogen
- truck for liquid hydrogen
- ship for liquid hydrogen

were evaluated. Additionally, the liquefaction of hydrogen was also assessed as it was considered as part of the transportation phase. We then considered the operation of a combined cycle gas turbine, which is usually adopted in existing liquefaction plants to produce the necessary power.

2.1.1 Trucks

Concerning trucks, four kinds of vehicles were considered: these are real, existing trucks manufactured by Volvo and causing emissions which are reported in Table 2.1. It can be seen that the trucks are representative of the technology which obey to four different European emission standards. Choosing four kinds of vehicles was due to the interest in evaluating burdens associated to the technology most diffused today and to the technology that will be used tomorrow by law.

Table 2.1- Environmental performances of reference trucks [1]

		NO_x	PM	HC	CO
	Law from	g/litre	g/litre	g/litre	g/litre
EURO 1	1993	28-32	0.2-0.6	0.5-1.2	2-8
EURO 3	2001	17	0.25	0.8	2.7
EURO 4	2006	13	0.1	0.04	1.0
EURO 5	2009	7	0.1	0	1.2

In addition to the data on emissions, data on fuel consumption of the average truck was considered, as reported in Table 2.2. The kind of truck chosen is composed by a tractor and semi-trailer, the configuration that is most suitable so that the pressure cylinders for compressed hydrogen or the single cryogenic cylinder for liquid hydrogen can be installed.

Table 2.2– Energy performances of reference trucks [1]

	Payload	Total weight	Fuel consumption Empty	Fuel consumption Full load
	tons	tons	Litre/100km	Litre/100km
Tractor and semi-trailer, long haul traffic	26	40	21-26	29-35

The case of hydrogen differs from all of the other fuel transportation schemes: the payload of compressed gaseous hydrogen is considered to be about 450 kg. This means that the truck round-trip is composed by two full load one-way trips, as most of the weight of the truck is represented by the (empty) cylinders.

It should be argued that the tractor, in fact, transports only the tare of the truck: this is not true for the hydrogen case as the cylinders are heavier than normal vehicles due to the increased thickness of the walls. This is even truer for liquid hydrogen transportation which needs a cryogenic vessel to maintain its inner temperature below 20K. The payload for the cryogenic truck is 4000 kg.

The range of consumption values given in Table 2.2 was maintained for calculations so that a minimum and a maximum value of emissions per case were obtained.

TP4.3 reports the full results of the evaluations made in order to obtain the grams of the main greenhouse gases and other air pollutants per km run and per trip.

Note the length of the trip from the production site to the distribution or final use site. TP4.3 reports a full specification of the reasons for choosing the specific length. Remember that for gaseous hydrogen, the average trip is considered to be 50 km (one-way trip), while for liquid hydrogen two cases were considered: 300 and 500 km.

Table 2.4 and Table 2.5 summarize the results obtained in TP4.3 which are useful for the following valuation of externalities .

It should be remembered that while the emissions listed in Table 2.3 have limits determined by the standards and depend on the engine performances, sulphur and CO_2 depend on the fuel. Carbon dioxide is formed by combustion, and the carbon content of the fuel determines the amount. One litre of standard diesel fuel (EN590) creates about 2.7 kg carbon dioxide.

As the tool used for evaluating externalities requires the amount of the gas SO_2 ,as input data, a proper scaling was performed on the amount of sulphur emitted in order to take into account the different mass weight of the gas molecule.

Table 2.3 – Typical emissions according to Euro 1 -3 - 4 - 5 standards (Volvo truck example)

	CH_4		CO		NO_X		PM		CO_2		S		N_2O	NMVOC
	g/l		g/l		g/l		g/l		g/l		g/l			
EURO 1	0,85		5		30		0,4		2700		0,1			
	g/km		g/km		g/km		g/km		g/km		g/km		g/km	g/km
	min	max	min	max	min	max	min	max	min	max	min	max	0,025	0,82
EMPTY	0,1785	0,221	1,05	1,3	6,3	7,8	0,084	0,104	567	702	0,021	0,026		
FULL	0,2465	0,2975	1,45	1,75	8,7	10,5	0,116	0,14	783	945	0,029	0,035		
	g/l		g/l		g/l		g/l		g/l		g/l			
EURO 3	0,8		2,7		17		0,25		2700		0,1			
	g/km		g/km		g/km		g/km		g/km		g/km		g/km	g/km
	min	max	min	max	min	max	min	max	min	max	min	max	0,025	0,82
EMPTY	0,168	0,208	0,567	0,702	3,57	4,42	0,0525	0,065	567	702	0,021	0,026		
FULL	0,232	0,28	0,783	0,945	4,93	5,95	0,0725	0,0875	783	945	0,029	0,035		
	g/l		g/l		g/l		g/l		g/l		g/l			
EURO 4	0,04		1		13		0,1		2700		0,1			
	g/km		g/km		g/km		g/km		g/km		g/km		g/km	g/km
	min	max	min	max	min	max	min	max	min	max	min	max	0,025	0,82
EMPTY	0,0084	0,0104	0,21	0,26	2,73	3,38	0,021	0,026	567	702	0,021	0,026		
FULL	0,0116	0,014	0,29	0,35	3,77	4,55	0,029	0,035	783	945	0,029	0,035		
	g/l		g/l		g/l		g/l		g/l		g/l			
EURO 5	0		1,2		7		0,1		2700		0,1			
	g/km		g/km		g/km		g/km		g/km		g/km		g/km	g/km
	min	max	min	max	min	max	min	max	min	max	min	max	0,025	0,82
EMPTY	0	0	0,252	0,312	1,47	1,82	0,021	0,026	567	702	0,021	0,026		
FULL	0	0	0,348	0,42	2,03	2,45	0,029	0,035	783	945	0,029	0,035		

Table 2.4 – Emissions per round-trip of a truck, according to different standards – Gaseous hydrogen – in grams/round-trip

	CH_4		CO		NO_X		PM		CO_2		S		N_2O	NMVOC
	min	max	min	max	min	max	min	max	min	max	min	max		
EURO 1	24,65	29,75	145	175	870	1050	11,6	14	78300	94500	2,9	3,5	2,5	82
EURO 3	23,2	28	78,3	94,5	493	595	7,25	8,75	78300	94500	2,9	3,5	2,5	82
EURO 4	1,16	1,4	29	35	377	455	2,9	3,5	78300	94500	2,9	3,5	2,5	82
EURO 5	0	0	34,8	42	203	245	2,9	3,5	78300	94500	2,9	3,5	2,5	82

Table 2.5 – Emissions per round-trip of a truck, according to different standards – Liquid hydrogen - in grams/round-trip

		CH_4		CO		NO_X		PM		CO_2		S		N_2O	NMVOC
	km run	min	max	min	max	min	max	min	max	min	max	min	max		
EURO 1	300	147,9	178,5	870	1050	5220	6300	69,6	84	469800	567000	17,4	21	15	492
	500	246,5	297,5	1450	1750	8700	10500	116	140	783000	945000	29	35	25	820
EURO 3	300	139,2	168	469,8	567	2958	3570	43,5	52,5	469800	567000	17,4	21	15	492
	500	232	280	783	945	4930	5950	72,5	87,5	783000	945000	29	35	25	820
EURO 4	300	6,96	8,4	174	210	2262	2730	17,4	21	469800	567000	17,4	21	15	492
	500	11,6	14	290	350	3770	4550	29	35	783000	945000	29	35	25	820
EURO 5	300	0	0	208,8	252	1218	1470	17,4	21	469800	567000	17,4	21	15	492
	500	0	0	348	420	2030	2450	29	35	783000	945000	29	35	25	820

2.1.2 Ship and liquefaction plant

Concerning transportation via ship, in TP4.3 we stated that while this transportation scheme is still far from becoming the preferred way of transporting liquid hydrogen, due to technical and economic reasons, the internal combustion engine of the ship would be fuelled directly with hydrogen. Other ICE applications of hydrogen has shown that the only relevant emission is nitrous oxide; a greenhouse gas.

The liquefaction plant was characterised using the emissions caused by its combined cycle gas turbine plant. These are reported in Table 2.6.

Table 2.6 – Emissions due to normal operation of a natural gas fuelled Combined Cycle Gas Turbine [2]

	CH_4	CO	NO_x	PM	CO_2	SO_2	N_2O	NMVOC
Emissions per MJ produced	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ
CCGT	7	138	138	0.7	90400	0.7	4	7

2.2 Evaluation of impacts and externalities due to emissions

The valuation of externalities derived from the burdens quantified according to the previously described procedure was performed by applying the EcosenseLE code [*http://ecoweb.ier.uni-stuttgart.de/ecosense_web/ecosensele_web/ frame.php*].

EcoSenseLE is an online tool for estimating costs due to emissions of a typical source (e.g. power plant, industry, transport) or all sources of a sector in an EU country or group of EU countries. It is a parameterised version of EcoSense, based on European data for receptor (population, crops, building materials) distribution, background emissions (amount and spatial distribution), and meteorology. The input required is annual emissions of NO_x, SO_2, PM10, NMVOC, CO_2, N_2O, CH_4; the pollutants considered are O_3, SO_2, PM10, sulphates, nitrates and greenhouse gases. The cost calculation is based on ExternE exposure-response function and monetary values. User defined values for mortality and greenhouse gas emissions are possible.

Thus, EcosenseLE input data were:

- the country where the emissions are produced
- the quantity of emissions in terms of mass per year (for pollutants at low or high height release)

- the characterisation of local environment for the emission source (agglomeration, urban city, rural)
- the type of emission source for low release emission values (ground-level, domestic heating, industry)

2.2.1 Data on emissions

The final relevant values reported in Table 2.4 and Table 2.5 of this report were in terms of grams per round-trip of the truck. To obtain the data necessary to meet the requirements of EcosenseLE, it was necessary to make some assumptions:

1) gaseous hydrogen tube trailers run 400 trips each year (two round trips a day, 50 km each run)

2) liquid hydrogen tank trucks run 50 round trips a year (300 or 500 km each run).

During the year, the truck considered was transporting a total payload that was evaluated as the payload of the single round-trip multiplied by the number of trips, thus obtaining the energy embedded in hydrogen transported by a single truck in one year.

Concerning the liquefaction plant, it was possible to calculate the total emissions from one year of operation using the following assumptions:

- size of the plant: 12500 $kg_{LH2\ produced}$/h
- hours of operation/year: 5000
- energy content of the produced hydrogen: 120 MJ/kg
- efficiency of the plant (MJ of LH_2 obtained per MJ of energy spent: 0.3)

Ships emit only N_2O and the evaluation of externalities due to this transportation scheme doesn't need the application of EcoSense. In fact, EcoSense is very useful for evaluating impacts and externalities due to polluting emissions (NO_x, SO_2, PM10, NMVOC), while for greenhouse gases a simpler approach can be used (see Paragraph 2.2.3).

2.2.2 Location of the emissions

Impacts and externalities were evaluated choosing the EU whole territory as the location for the source of emissions. This choice can be particularly suitable for transportation activities, which are meant to be links between different countries (especially true for transportation of liquid hydrogen).

Concerning trucks transporting gaseous hydrogen, pollutants are emitted as low release at ground level, in urban areas. This choice was due to the need for taking into account the most sensitive parts of the full run of the truck. While it is true that most of the trip from the production site to the usage area occurs in rural areas, the development of a hydrogen economy would lead to a massive increase in demand for hydrogen in city centres, where numerous receptors are present.

On the contrary, transportation of liquid hydrogen has more the character of an industrial activity, where liquid hydrogen is transported from the liquefaction plant or the discharge port to the regasification terminal or the chemical plant. For this reason pollution was considered to take place to be rural areas.

The liquefaction plant is in every aspect an industrial plant, and therefore the emissions produced are considered to be released from a high stack, in a rural area.

2.2.3 Economic evaluation of impacts

EcoSense's results depend on a variety of parameters but its simplified version EcoSenseLE allows the user to specify only two economic values:

- the Standard Value, which represents a value for acute mortality. The software provides as a default value the 75,000 Euro, which is the Value of a Life Year (VOLY) used by ExternE. It is possible to enter a User-defined value which has to be given on the same basis (i.e. in terms of VOLY). This value is adapted automatically for the valuation of mortality effects due to long-term exposure.
- the abatement cost of CO_2. This value is set by default as equal to €19 per tonne of CO_2. This value represents a central estimate of the range of values for meeting the Kyoto targets in 2010 in the EU based on estimates by Capros and Mantzos [3]. Fahl et. al. [4] estimate €19 per tonne of CO_2 for meeting a 25% emission reduction from 1990 to 2010 in Germany. It is assumed that measures to reduce CO_2 emissions are taken in a cost effective way. This implies that reduction targets are not set per sector, but that the cheapest measures are implemented, no matter in which sector.

  This value can also be user-defined.

For our evaluations, the work performed by Research Stream 1b of NEEDS was used. In particular: concerning the user defined value of the Value of a Life year

(VOLY; which is equivalent to the value of a YOLL (Year of Life Lost) we used YOLL = 40.000 euro, instead of the default 75,000 euro, adopting the results from NEEDS 1b study on mortality valuation [5]. The impacts from the exposure-response functions in EcoSense are based presented in terms of YOLL.

The value adopted for the marginal abatement cost of CO_2, instead, is kept equal to the default value of 19 Euro/tCO_{2eq}. The final value is not yet defined at this time since more FUND model runs have to be made within NEEDS RS1b. The 19 Euro/tCO_{2eq} value comes from Exiopol [*http://www.feem-project.net/exiopol/*] and it is a good estimate. The revised central estimate is not likely to differ much from this, but the final estimate is expected to be a central value *range* rather than a single central estimate.

The emitted amounts of the greenhouse gases CO_2, CH_4 and N_2O were aggregated in terms of CO_2 equivalents for each case study; taking into account the their different Global Warming Potential of the gases (1 for CO_2, 21 for methane and 296 for nitrous oxide). The number of tons of CO_2 equivalents was then multiplied by the marginal abatement cost (per tonne).

2.3 Evaluation of impacts and externalities due to risk

TP 4.5 reports a full risk analysis of the transportation of hydrogen by means of pipelines and trucks for gaseous hydrogen, and by means of trucks and ships for liquid hydrogen.

The results are reported in Table 2.7.

Values are given in terms of number of fatalities per year for each type of accident. In order to estimate the economic value of externalities due to accidents during hydrogen transport, the economic value of fatalities per MJ transported had to be estimated.

The analysis was performed assuming some parameters that might be useful to remember here:

- flow rate in the pipelines:
    - 10 bar 0.2 m diameter pipelines: 0.13 kg/s
    - 20 bar 0.3 m diameter pipelines: 0.3 kg/s
    - 50 bar 0.5 m diameter pipelines: 0.7 kg/s

- capacity of one single tube in tube trailer: 34.7 kg of hydrogen
- number of tubes in a tube trailer (with equal probability of a rupture): 10
- capacity of a cryogenic vessel: 2100 kg of liquid hydrogen
- number of round-trips per year of a tube trailer truck: 400
- number of round-trips per year of a tank trailer: 50
- capacity of a single cryogenic vessel in a ship: 200 tons
- number of vessels on a ship: 5
- number of trips of a ship per year: 10

Table 2.7 Results of risk analysis performed on several hydrogen transport schemes

System		**Frequency**	**Damage**	**Risk**
		event/year	fatalities/ event	fatalities/ year
Pipeline *10 bar* *0.2 m diameter*	Jet-fire	$5{,}00\ 10^{-6}$	0,13	$6{,}50\ 10^{-7}$
	Flash fire or explosion	$1{,}34\ 10^{-5}$	0,22	$2{,}95\ 10^{-6}$
Pipeline *20 bar* *0.3 m diameter*	Jet-fire	$5{,}00\ 10^{-6}$	0,19	$9{,}50\ 10^{-7}$
	Flash fire or explosion	$1{,}34\ 10^{-5}$	0,19	$2{,}55\ 10^{-6}$
Pipeline *50 bar* *0.5 m diameter*	Jet-fire	$5{,}00\ 10^{-6}$	0,074	$3{,}70\ 10^{-7}$
	Flash fire or explosion	$1{,}34\ 10^{-5}$	0,027	$3{,}62\ 10^{-7}$
Gas tube trailer	Jet-fire	$1{,}19\ 10^{-8}$	0,27	$3{,}21\ 10^{-9}$
Gas tube trailer *catastrophic rupture*	Explosion	$4{,}01\ 10^{-8}$	2,79	$1{,}12\ 10^{-7}$
Liquid tank trailer	Jet fire	$1{,}19\ 10^{-8}$	1,15	$1{,}37\ 10^{-8}$
	Explosion	$3{,}18\ 10^{-8}$	3,92	$1{,}25\ 10^{-7}$
Liquid tank trailer *catastrophic rupture*	Bleve	$8{,}30\ 10^{-9}$	43,30	$3{,}59\ 10^{-7}$
	Explosion	$2{,}22\ 10^{-8}$	27,36	$6{,}07\ 10^{-7}$
Ship	Jet-fire	$1{,}19\ 10^{-8}$	0,67	$7{,}77\ 10^{-9}$
	Flash fire or explosion	$3{,}18\ 10^{-8}$	1,2	$3{,}82\ 10^{-8}$
Ship *catastrophic rupture*	Bleve	$1{,}30\ 10^{-5}$	24,47	$3{,}18\ 10^{-4}$

2.3.1 Economic evaluation

Values from Table 2.8 have to be multiplied by the Value of Statistical Life (VSL) which is set equal to 1 million euro (for fatalities due to air pollution); from the

NewExt study (according to results from a 3-country Contingent Valuation study) [6] and Recommendation from an Expert workshop organized by the DG Environment) [7]. Here VSL is termed Value of a Prevented Fatality (VPF).

Table 2.8 Results of risk analysis referred to the unit of energy transported

System		
		fatalities/MJ
Pipeline *10 bar* *0.2 m diameter*	Jet-fire	$1,32\ 10^{-15}$
	Flash fire or explosion	$6,00\ 10^{-15}$
Pipeline *20 bar* *0.3 m diameter*	Jet-fire	$8,37\ 10^{-16}$
	Flash fire or explosion	$2,25\ 10^{-15}$
Pipeline *50 bar* *0.5 m diameter*	Jet-fire	$1,40\ 10^{-16}$
	Flash fire or explosion	$1,37\ 10^{-16}$
Gas tube trailer	Jet-fire	$1,93\ 10^{-15}$
Gas tube trailer *catastrophic rupture*	Explosion	$6,72\ 10^{-14}$
Liquid tank trailer	Jet fire	$1,09\ 10^{-15}$
	Explosion	$9,92\ 10^{-15}$
Liquid tank trailer *catastrophic rupture*	Bleve	$2,85\ 10^{-14}$
	Explosion	$4,82\ 10^{-14}$
Ship	Jet-fire	$1,62\ 10^{-16}$
	Flash fire or explosion	$7,96\ 10^{-16}$
Ship *catastrophic rupture*	Bleve	$6,63\ 10^{-12}$

3. Results

3.1.1 Trucks

Table 3.1 shows the marginal abatement cost of greenhouse gases per unit of energy (kWh) of gaseous hydrogen transported with tube trailers operated according to different emission reductions standards.

Table 3.2 shows the marginal damage cost of air pollutants per unit of energy (kWh) of gaseous hydrogen transported with tube trailers operating according to different emission reductions standards.

Table 3.1 Gaseous hydrogen – Marginal abatement cost of greenhouse gases [Euro/kWh]

	min	max
Euro1	$1{,}01\cdot10^{-4}$	$1{,}22\cdot10^{-4}$
Euro3	$1{,}01\cdot10^{-4}$	$1{,}22\cdot10^{-4}$
Euro4	$1{,}00\cdot10^{-4}$	$1{,}21\cdot10^{-4}$
Euro5	$1{,}00\cdot10^{-4}$	$1{,}21\cdot10^{-4}$

Table 3.2 Gaseous hydrogen – Marginal damage cost due to air pollution [Euro/kWh]

		Impact Categories (all countries)				
		Human Health Mortality	Human Health Morbidity	Crops	Materials	Total (Rounded)
Euro1	min	$1{,}90\cdot10^{-4}$	$1{,}45\cdot10^{-4}$	$1{,}69\cdot10^{-5}$	$6{,}06\cdot10^{-6}$	$3{,}58\cdot10^{-4}$
	max	$2{,}30\cdot10^{-4}$	$1{,}74\cdot10^{-4}$	$1{,}92\cdot10^{-5}$	$7{,}31\cdot10^{-6}$	$4{,}31\cdot10^{-4}$
Euro3	min	$1{,}13\cdot10^{-4}$	$8{,}56\cdot10^{-5}$	$1{,}21\cdot10^{-5}$	$3{,}53\cdot10^{-6}$	$2{,}14\cdot10^{-4}$
	max	$1{,}36\cdot10^{-4}$	$1{,}03\cdot10^{-4}$	$1{,}34\cdot10^{-5}$	$4{,}25\cdot10^{-6}$	$2{,}57\cdot10^{-4}$
Euro4	min	$7{,}00\cdot10^{-5}$	$5{,}70\cdot10^{-5}$	$1{,}07\cdot10^{-5}$	$2{,}74\cdot10^{-6}$	$1{,}40\cdot10^{-4}$
	max	$8{,}42\cdot10^{-5}$	$6{,}83\cdot10^{-5}$	$1{,}16\cdot10^{-5}$	$3{,}31\cdot10^{-6}$	$1{,}68\cdot10^{-4}$
Euro5	min	$4{,}70\cdot10^{-5}$	$3{,}67\cdot10^{-5}$	$8{,}45\cdot10^{-6}$	$1{,}57\cdot10^{-6}$	$9{,}34\cdot10^{-5}$
	max	$5{,}64\cdot10^{-5}$	$4{,}39\cdot10^{-5}$	$8{,}97\cdot10^{-6}$	$1{,}90\cdot10^{-6}$	$1{,}11\cdot10^{-4}$

Table 3.3 shows the marginal abatement cost of air pollutants per unit of energy (kWh) of liquid hydrogen transported with tube trailers operating according to different emission reductions standards.

Table 3.3 Liquid hydrogen – Marginal abatement cost of greenhouse gases [Euro/kWh]

	km	Min	max
Euro1	300	$6{,}81\cdot10^{-5}$	$8{,}21\cdot10^{-4}$
	500	$1{,}14\cdot10^{-5}$	$1{,}37\cdot10^{-4}$
Euro3	300	$6{,}81\cdot10^{-5}$	$8{,}21\cdot10^{-4}$
	500	$1{,}14\cdot10^{-5}$	$1{,}37\cdot10^{-4}$
Euro4	300	$6{,}77\cdot10^{-5}$	$8{,}15\cdot10^{-4}$
	500	$1{,}13\cdot10^{-5}$	$1{,}36\cdot10^{-4}$
Euro5	300	$6{,}77\cdot10^{-5}$	$8{,}15\cdot10^{-4}$
	500	$1{,}13\cdot10^{-5}$	$1{,}36\cdot10^{-4}$

Table 3.4 shows the marginal damage cost of air pollutants per unit of energy (kWh) of liquid hydrogen transported with tube trailers operated according to different emission reductions standards.

Table 3.4 Liquid hydrogen – Marginal damage cost due to air pollution [Euro/kWh]

		Impact Categories (all countries)				
		Human Health Mortality	Human Health Morbidity	Crops	Materials	Total (Rounded)
Euro1	min	$9,08 \cdot 10^{-5}$	$8,70 \cdot 10^{-5}$	$4,70 \cdot 10^{-5}$	$4,08 \cdot 10^{-6}$	$2,29 \cdot 10^{-4}$
	max	$1,08 \cdot 10^{-4}$	$9,33 \cdot 10^{-5}$	$1,30 \cdot 10^{-5}$	$4,93 \cdot 10^{-6}$	$2,19 \cdot 10^{-4}$
Euro3	min	$5,15 \cdot 10^{-5}$	$4,50 \cdot 10^{-5}$	$8,20 \cdot 10^{-6}$	$2,38 \cdot 10^{-6}$	$1,07 \cdot 10^{-4}$
	max	$6,20 \cdot 10^{-5}$	$5,43 \cdot 10^{-5}$	$9,08 \cdot 10^{-6}$	$2,88 \cdot 10^{-6}$	$1,28 \cdot 10^{-4}$
Euro4	min	$3,73 \cdot 10^{-5}$	$3,33 \cdot 10^{-5}$	$7,20 \cdot 10^{-6}$	$1,85 \cdot 10^{-6}$	$7,98 \cdot 10^{-5}$
	max	$4,50 \cdot 10^{-5}$	$4,00 \cdot 10^{-5}$	$7,85 \cdot 10^{-6}$	$2,23 \cdot 10^{-6}$	$9,53 \cdot 10^{-5}$
Euro5	min	$2,18 \cdot 10^{-5}$	$1,97 \cdot 10^{-5}$	$5,70 \cdot 10^{-6}$	$1,06 \cdot 10^{-6}$	$4,83 \cdot 10^{-5}$
	max	$2,63 \cdot 10^{-5}$	$2,35 \cdot 10^{-5}$	$6,05 \cdot 10^{-6}$	$1,28 \cdot 10^{-6}$	$5,70 \cdot 10^{-5}$

3.1.2 Ships

According to the evaluation of burdens made in Paragraph 2.1.2, the marginal abatement cost due to the transportation of liquid hydrogen by ship is **$1,5 \cdot 10^{-5}$ Euro/kWh**.

3.1.3 Liquefaction

According to the evaluation of burdens made in Paragraph 2.1.2, the marginal abatement cost due to the liquefaction of hydrogen is: **$1.74 \cdot 10^{-3}$ Euro/kWh** produced.

Table 3.5 shows the values of the marginal damage cost due to hydrogen liquefaction.

Table 3.5 Hydrogen liquefaction – Marginal damage cost [Euro/kWh produced]

Impact Category (All Countries)	Euro/kWh produced
Human Health Mortality	$5,81 \cdot 10^{-4}$
Human Health Morbidity	$5,04 \cdot 10^{-4}$
Crops	$7,34 \cdot 10^{-5}$
Materials	$2,80 \cdot 10^{-5}$
Total (Rounded)	$1,19 \cdot 10^{-3}$

3.2 Risk analysis in hydrogen transport schemes

Besides the estimated externalities due to normal operation, it is also possible (and in some circumstances necessary) to take into account externalities due to accidents.

Using the most recently agreed value of VSL, equal to 1,000,000 €, the above calculated values of risk can be turned into values of externalities in €/MJ of hydrogen transported (Table 3.6)

Table 3.6 Externalities due to accidents in hydrogen transportation

System		
		Euro/MJ
Pipeline *10 bar* *0.2 m diameter*	Jet-fire	1,32 10^{-9}
	Flash fire or explosion	6,00 10^{-9}
Pipeline *20 bar* *0.3 m diameter*	Jet-fire	8,37 10^{-10}
	Flash fire or explosion	2,25 10^{-9}
Pipeline *50 bar* *0.5 m diameter*	Jet-fire	1,40 10^{-10}
	Flash fire or explosion	1,37 10^{-10}
Gas tube trailer	Jet-fire	1,93 10^{-9}
Gas tube trailer *catastrophic rupture*	Explosion	6,72 10^{-8}
Liquid tank trailer	Jet fire	1,09 10^{-9}
	Explosion	9,92 10^{-9}
Liquid tank trailer *catastrophic rupture*	Bleve	2,85 10^{-8}
	Explosion	4,82 10^{-8}
Ship	Jet-fire	1,62 10^{-10}
	Flash fire or explosion	7,96 10^{-10}
Ship *catastrophic rupture*	Bleve	6,63 10^{-6}

4. Conclusions

When assessing externalities due to transportation of hydrogen via truck, it is important to remember that, while the trip for transporting liquid hydrogen is longer, the number of trips per year is lower and the total number of km run in one year by the considered truck is more or less the same as those run by a truck transporting gaseous hydrogen. Besides, the impact on an urban area is heavier than that in the rural environment: as a consequence, externalities due to transportation of liquid hydrogen (predominantly in the countryside) are lower.

The assessment of externalities due to accidents shows that values are generally very low except for the cases when the potentially affected people are numerous (i.e during a catastrophic rapture of a ship).

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