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The potential of water reuse for agricultural irrigation in the EU

A Hydro-Economic Analysis

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Title The potential of water reuse for agricultural irrigation in the EU. A Hydro-Economic Analysis

Abstract
In this study we estimate the distribution of costs of reclaiming and transporting treated wastewater for reuse in agricultural irrigation across Europe. We consider treatment costs as well as the costs associated with the water transport infrastructure and with energy for pumping. The study highlights a high variability of costs depending on the relative position of irrigated agricultural land with respect to the wastewater treatment plants. Treatment costs alone may be minor, about 8 €cents/m^3, compared to other costs, with the majority of the theoretical water reuse volume available at typical total costs below or at 50 €cents/m^3. However, when treatment requirements become more stringent, treatment costs are expected to increase to 0.23 €/m^3, causing total costs to shift consistently. The energy requirements for pumping reclaimed water from wastewater treatment plants to agricultural land follow a distribution with a median of about 0.5 kWh/m^3 and an interquartile range of another 0.5 kWh/m^3, which seems slightly higher than reported in representative cases of irrigation with conventional water sources.
The total volumes of water that can in principle be reused for irrigation are significant, and may help reduce water stress by up to around 10% in regions where irrigation is an important component. Water reuse may also contribute, in a less apparent and more uncertain way, to nutrient pollution mitigation. While the treatment and energy costs are rather minor, the total costs depend significantly on infrastructure costs and the distance from the urban wastewater treatment plants to the irrigated land, therefore the attractiveness of water reuse will vary for farmers. This indicates that (1) reuse is most suitable where irrigation infrastructure already exists and the necessary additional investments are minor, and (2) the cost of water reuse should be considered in a broader context as a water management tool. This context should be extended to include, on the one hand, the whole value chain supplied by agriculture and, on the other, the process of river basin management where reuse may represent a measure with important co-benefits.

Contents

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Authors

This assessment has been prepared by Alberto Pistocchi, supported by Alberto Aloe (design of the database structure and GIS analysis procedures for cost estimation) with Chiara Dorati (execution of GIS analyses and mapping), as part of the activities of the “Water-Energy-Food Nexus” project led by Giovanni Bidoglio. Bernd Gawlik and Laura Alcalde Sanz have participated to the identification and definition of the elements of reuse costs; Bruna Grizzetti has contributed to the analysis of nutrient data; Marco Pastori and Fayçal Bouraoui have provided the EPIC model results used throughout the assessment; Olga Vigiak has conducted the quality checks on the urban wastewater treatment plants database, and estimated the amounts of water and nutrients used in the analysis.

Executive summary

Policy context

Water reuse has been identified by the European Commission as a relevant solution to be further promoted in the EU to address water scarcity. This opportunity was highlighted again in the context of the EU action plan for a Circular Economy (COM(2015) 614 final). In, particular the Commission committed to table a legislative proposal setting minimum quality requirements for water reuse. This initiative has been included in the Commission Work Programme 2017. In order to support the decisions to be taken on the matter, the costs and benefits of water reuse need to be clearly identified and quantified to the best possible extent.

Key conclusions/Main findings

In this study we estimate the distribution of costs of reclaiming and transporting treated wastewater for reuse in agricultural irrigation across Europe. We consider treatment costs as well as the costs associated to the water transport infrastructure and to energy for pumping. The study highlights a high variability of costs depending on the relative position of irrigated agricultural land with respect to the wastewater treatment plants. Treatment costs alone may be minor, about 8 €cents/m3, compared to the other costs, with the majority of the theoretical water reuse volume available at typical total costs below or at 50 €cents/m3. However, when treatment requirements become more stringent, treatment costs are expected to increase to 0.23 €/m3, causing total costs to shift consistently. The energy requirements for pumping of reclaimed water from wastewater treatment plants to agricultural land follow a distribution with a median of about 0.5 kWh/m3 and an interquartile range of another 0.5 kWh/m3, which seems slightly higher than reported in representative cases of irrigation with conventional water sources.

The total volumes of water that can be in principle reused for irrigation are significant, and may contribute to the reduction of water stress up to around 10% in regions where irrigation is an important component of demand. Water reuse may also contribute, in a less apparent and more uncertain way, to nutrient pollution mitigation. While the treatment and energy costs are rather minor, the total costs depend significantly on infrastructure costs and the distance from the UWWTP to the irrigated land, therefore for farmers the attractiveness of water reuse will vary. This indicates that (1) reuse is most suitable where irrigation infrastructure already exists and the necessary additional investments are limited, and (2) the cost of water reuse should be considered in a broader context as a water management tool. This context should be extended to include, on the one side, the whole value chain supplied by agriculture and, on the other side, the process of river basin management where reuse may represent a measure with important co-benefits.

Related and future JRC work

This work is part of the broader "Water-Energy-Food-Ecosystems Nexus" project of the JRC. Water reuse is regarded as a relevant water resource management option, and this report provides the basis for an assessment of strategic priorities for water reuse in Europe.

1 Introduction

In the 2012 Water Blueprint[1], water reuse was identified by the European Commission as a relevant solution to be further promoted in the EU to address water scarcity. This opportunity was highlighted again in the context of the EU action plan for a Circular Economy (COM(2015) 614 final). In, particular the Commission committed to table a legislative proposal setting minimum quality requirements for water reuse. This initiative has been included in the Commission Work Programme 2017. In order to support the decisions to be taken on the matter, the costs and benefits of water reuse need to be clearly identified and quantified to the best possible extent. In this contribution we examine the potential of water reuse for agricultural irrigation in the EU, the corresponding costs and benefits in terms of water stress and nutrient pollution mitigation, and the most favorable regions in Europe where reuse may represent an important option for water resources management.

We limit our assessment to water available at the outlet of the urban wastewater treatment plants existing in Europe, and we examine this potential water resource vis-à-vis agricultural irrigation demand. We limit our consideration of “water treatment” to the additional processes that may be required to make treated wastewater suitable for reuse in agriculture. We refer to treated wastewater that is further processed to sufficient quality levels enabling its use in agriculture as “reclaimed water”. “Water reuse” is intended here as the use of reclaimed water for agricultural irrigation.

After introducing the models and methods used in the assessment, we present our estimate of the distribution of costs of water reuse in Europe; we calculate the amount of water that can be reclaimed in the different European regions at different levels of costs, and we quantify the extent to which reuse may contribute to reducing water stress and nutrient pollution across the EU, and we summarize some elements for a first economic valuation of the benefits of water reuse.

[1] http://ec.europa.eu/environment/water/blueprint/index_en.htm

2 Analytical models used in the assessment

2.1 The models

This study analyzes the costs of water reuse and discusses the benefits of water reuse to reduce water stress. These aspects are studied using the EPIC model for the estimation of crop yields and irrigation requirements, together with *ad hoc* calculations based on a well-established hydro-economic modelling approach using a set of appraisal equations for computing the cost of water treatment and distribution.

The equations used for the assessment of costs follow engineering assumptions widely adopted in practice, and are presented in a specific section of this report. The cost appraisal equations used for the assessment derive from the literature, and particularly from the FEASIBLE model (OECD, 2004) for what concerns the cost of pipelines and pumping stations; these were already used in previous assessments at the European Commission (e.g. European Commission, 2010); for the costs of storage, we follow the assumptions made in Maton et al., 2010.

For the cost calculations, apart from the sensitivity analysis conducted on purpose to address uncertainties, comparisons have been drawn with costs reported from experts referring to real cases in Europe or comparable contexts. Additional details are provided in the specific sections of this document.

The EPIC model (Sharpley and Williams, 1990) was originally developed by the US Department of Agriculture, and is now maintained and developed by the Texas A&M University. It is an open-source code extensively used worldwide for crop simulations. The model has been widely used for the simulation of crop yields, nitrogen and phosphorus balances, and water requirements. The existing EPIC setup is used by the JRC in the context of other European scale assessments. The EPIC model has been validated against independent yield data (see § 4). EPIC model simulations have been used extensively in the last years for a number of assessments by the JRC, including a study supporting the Impact Assessment of the Water Blueprint in 2012 (de Roo et al., 2012).

2.2 Model input data and assumptions

The most critical aspect of the assessment is the evaluation of costs of reclaimed water. The cost of wastewater reuse is computed as the sum of the cost of: 1) treatment of water for reuse; 2) building infrastructures for water storage and distribution (pipelines and pumps); and 3) energy for reclaimed water pumping from the wastewater treatment plant to the neighboring agricultural areas (Figure 1).

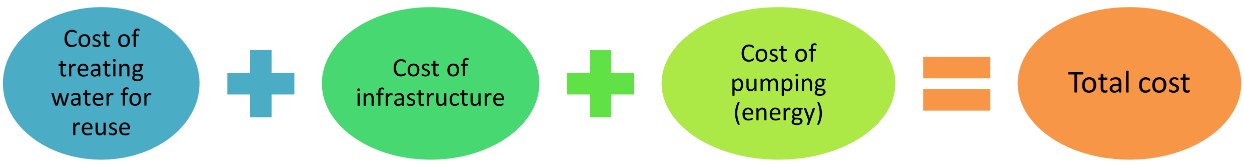

Figure 1 – scheme of the costs considered in this assessment.

We assume treatment costs to be independent of the existing level of treatment and size of the wastewater treatment plants, thus neglecting possible economies of scale. Mean levelized treatment costs[2] are assumed as the mid-range of costs provided by Iglesias et al., 2010. Moreover, we assume an intermediate treatment requirement corresponding to disinfection and depth filtration. These assumptions are indeed wrapped in uncertainty,

[2] In analogy with the case of energy, the levelized cost is the net present value of the unit-cost of water over the lifetime of a generating asset.

which has been addressed through a global sensitivity analysis in this study (as presented in a dedicated section below). In order to evaluate the potential of reusing reclaimed water, we estimate the cost of treatment and the cost of transport of water, which requires defining a source and a destination of reclaimed water in order to quantify a transport distance and an elevation difference for pumping. We assume that water sources coincide with wastewater treatment plants as depicted in the WaterBase – Wastewater v. 4.0 dataset made available at the European Environment Agency[3]. Moreover, we distribute in space the estimated irrigation demand assuming that all agricultural land excluding pastures is potentially irrigated, thus neglecting the actual distribution of irrigation infrastructure. We conduct appropriately aggregated calculations using the elementary sub-basins of the CCM2 database[4] as a mapping unit (de Jager and Vogt, 2010) without disaggregating results therein. A major source of uncertainty is represented by the spatial scale and resolution of the analysis. The assumptions made and the data used as input do not enable any conclusion on specific situations, but suggest only general trends valid at European scale. All conclusions of this assessment must be considered indicative at a broad strategic level, and can by no means serve the purposes of case-specific assessments. Particularly, the assessment cannot be regarded as a pointwise evaluation of the potential of a specific wastewater treatment plant, but as yielding representative frequency distributions of costs at a regional scale, such as EU NUTS2 level or river basins. Results are consistently presented at resolutions not finer than these.

This assessment is based on the current wastewater treatment plant system in the EU, as well as on current estimated irrigation requirements and fertilizer use. We do not make assumptions on other macroeconomic, socio-economic conditions nor policies and measures, as the scope is limited to quantifying a possible cost distribution for reuse of wastewater.

[3] https://www.eea.europa.eu/data-and-maps/data/waterbase-uwwtd-urban-waste-water-treatment-directive-4

[4] http://inspire-geoportal.ec.europa.eu/demos/ccm/

3 Irrigation demand

Demand is estimated on the basis of calculated irrigation water requirements. We selected the biophysical model EPIC because it simulates crop production under different farming practices and operations including fertilization and irrigation application rates and timing and because it considers nutrient losses to the environment (N leaching and runoff) (Figure 2). In addition, it has been thoroughly evaluated and applied from local to continental scale (Gassman et al. 2005) and used in global assessments (Liu et al. 2007). The model has been applied for irrigation scheduling assessment (Wriedt et al. 2009), and biofuels production (Van der Velde et al. 2009).

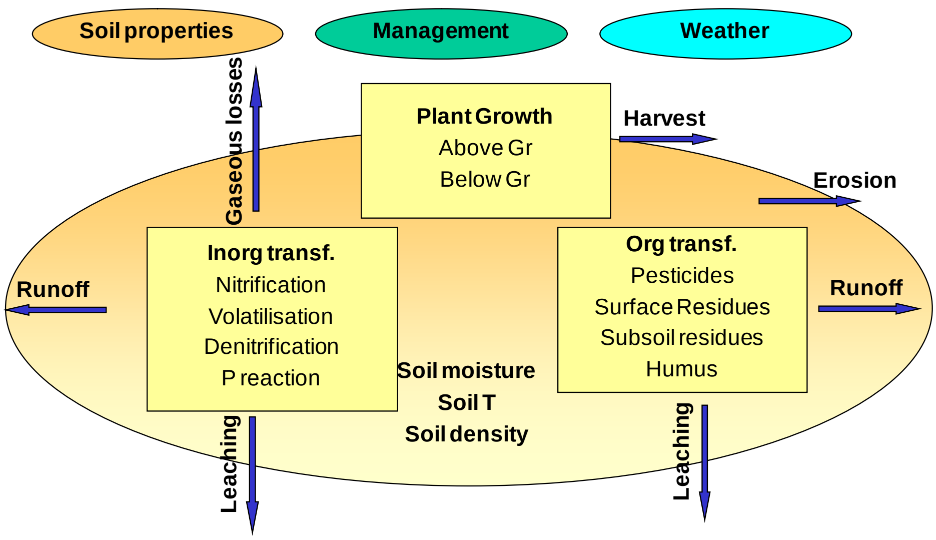

Figure 2 - The EPIC model structure.

Furthermore the model is already integrated in a GIS system working at European scale (Bouraoui et al. 2007). The GIS system includes all the data required for EPIC modelling (meteorological daily data, soil profile data, landuse data with crop distribution and agriculture management data) and all necessary sets of attributes required to simulate different strategies, management and scenarios.

Wheat, barley, maize, rapeseed, oats, rye are major crops grown in Europe, while other crops are more important in specific regions such as olive and fruit trees in southern Europe or potatoes and sugar beet in Central and Northern Europe. There are many different cultivars adapted to different climate and environments and characterized by peculiar growth properties and productivity. Specific information on crop cultivars are not easily available at European scale but these information are important in order to represent this spatial variability in the model.

In this assessment, we make use of the results of the EPIC model setup at European scale available at the JRC corresponding to "baseline" conditions, i.e. supposed to reflect the actual current levels of irrigation. Under this scenario, crop water requirements (m3/year) were estimated at the cells of a regular 5km x 5 km grid across Europe.

The model setup used to estimate the average irrigation requirements is based on crop distribution statistics defined at 5km resolution derived from the combination of CAPRI (Britz, 2004), SAGE (Monfreda et al., 2008) and GLC (Bartholomé and Belward, 2005). The amount of manure and mineral fertilization applied were retrieved from the Common Agricultural Policy Regionalized Impact (CAPRI) agro-economic model (Britz and Witzke, 2008) and crop production optimized according to EUROSTAT statistics at NUTS2 level (EUROSTAT, 2010a). Extension of irrigated land by crop was derived according to the MIRCA dataset (Portmann, 2011) and applied irrigated volume were validated at country level by using EUROSTAT 2010 statistics (EUROSTAT, 2010b). Landuse and crop management is assumed constant for the whole period of simulation.

First we identified 4 main regions in Europe, by performing a Cluster Analysis considering the main parameters potentially influencing crop growth, such as climate (precipitation, temperature, evapotranspiration, etc..), soil type (texture, organic matter content, drainage, water storage capacity, etc.) landuse and crop management (irrigation, fertilization plans, etc.). The initial cluster included 9 regions (Figure 3) that were reduced to four macro regions. The crop parameters were adapted for these four macro-regions.

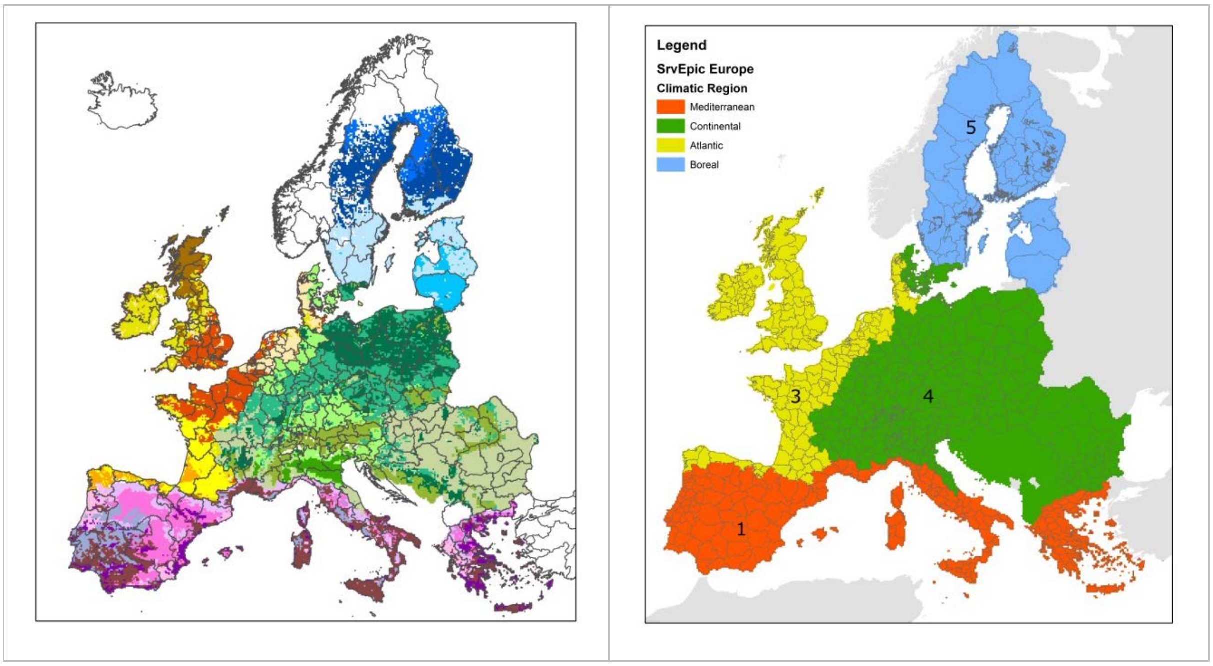

Figure 3 . Main clusters and selected regions for Europe detailed (left) and simplified (right).

The parameters affecting crop growth that were modified to customize EPIC to specific regional conditions included the optimal and base temperatures, the biomass growth rate parameter and the harvest index. An explanation of these parameters can be found in the theoretical documentation of the EPIC model[5].

In our approach the optimization aimed at minimizing the differences between simulated and reported yields (EUROSTAT data) in different macro regions. We used the Multi Objective Genetic Algorithm (MOEA) library by Udías (2011) to optimize the selected set of parameters controlling the crop growth and productivity.

A comparison between simulated and reported annual yields (for last reporting period) aggregated at NUTS 2 level for all Europe is presented in Figure 4. The simulated yields compare well with the reported ones for all major crops, keeping in mind that the reported statistical data are not available for all the years considered (2008-2011) and that in some cases only data at country level is available. This analysis demonstrated the capability of the model to capture the spatial and annual variability of yields.

The EPIC model calculates annual crop water requirements, expressed in m3 per grid cell of 25 km2 (Figure 5).

For each grid cell, we computed the hectares of agricultural land as the number of pixels of the 100 m x 100 m CLC 2012 map classified as "agricultural" (CLC 2012 level 1 code =2, with exclusion of level 3 code 231 – pastures) falling within the cell. Dividing the crop water requirements by the number of hectares allowed estimating a crop water requirement per unit area (unit requirement). Each sub-basin was attributed the unit

[5] https://agrilifecdn.tamu.edu/epicapex/files/2015/05/EpicModelDocumentation.pdf

requirement from the grid cells intersecting it, in proportion to the area of the grid cells on a sub-basin. The crop water requirement per sub-basin, I_i, was finally estimated as the unit requirement multiplied by the number of 100 m x 100 m agricultural CLC 2012 pixels falling within the sub-basin.

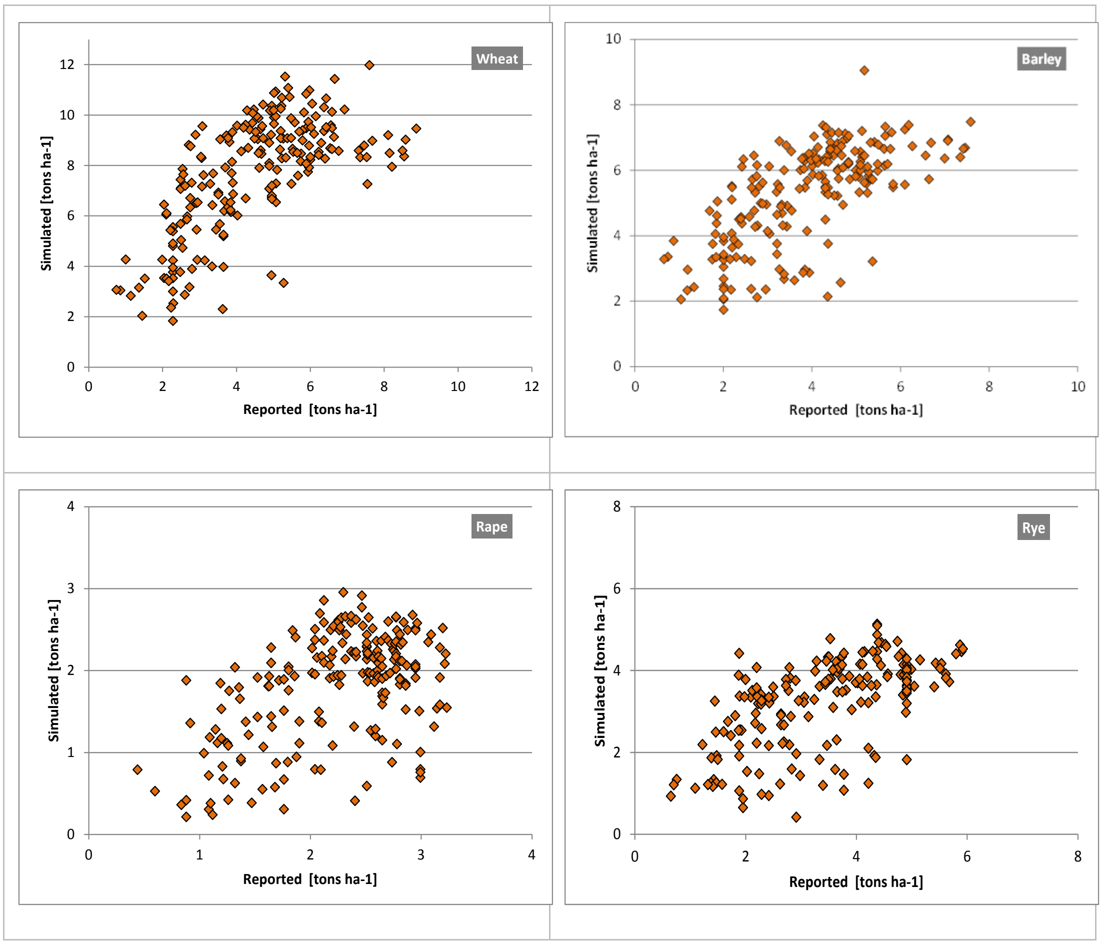

Figure 4. Scatter plots with means simulated yields versus reported regional crop yields for some major cereals, forage crops in Europe.

It should be stressed that we consider irrigation demand merely as the water required by crops. In reality, more water may be required for irrigation than what is actually used by crops. This water includes the losses along canals and pipelines, as well as the water evaporating or leaching below the root zone during field applications. We do not make a distinction here between crop water requirements and the actual amount required for irrigation. The latter is assumed to coincide with the former, i.e. we assume irrigation efficiency to be 100%, compatibly with the objective of this work which is an indicative comparison between requirements and availability. This aspect should be considered particularly when interpreting the results with reference to highly inefficient irrigation systems.

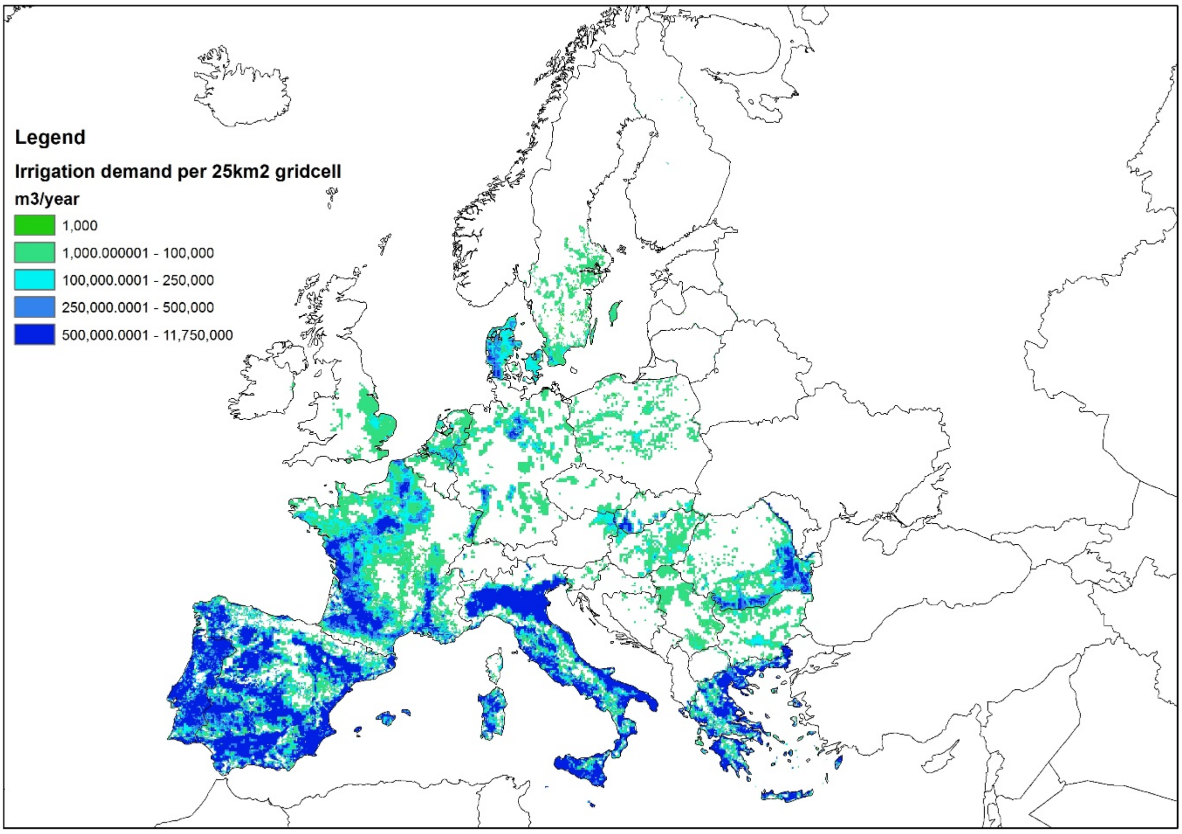

Figure 5- average irrigation water requirement used in this assessment, as computed with the EPIC model.

4 Reclaimed water availability

In this assessment, we assume that all treated wastewater produced in the EU is theoretically available to be reclaimed for irrigation. The amount of treated wastewater is estimated on the basis of the WaterBase – Wastewater treatment database v. 4, representing urban wastewater treatment plants (UWWTPs) in the EU reported as of 2012 by the EEA Member States. The available water is estimated on the basis of the population equivalents (PE) reported by the Member States in the database, using municipal water consumption from the FAO AquaSTAT database[6] (usually in the range 35-245 m3 municipal water/inhabitant/year). It was assumed that 10% of water used per capita is lost. Total availability figures by country are shown in Table 1.

Country NUTS 2013 code	Available water at the outlet of UWWTPs (m3/year)
AT	829,216,971
BE	441,660,421
BG	1,153,260,226
CY	33,904,627
CZ	826,985,619
DE	6,690,509,040
DK	609,431,704
EE	80,713,875
EL	1,167,418,750
ES	7,115,676,493
FI	412,244,754
FR	5,071,827,661
HR	254,621,716
HU	691,896,584
IE	1,219,930,893
IT	9,789,220,099
LT	180,593,069
LU	42,682,639
LV	350,678,641
MT	3,248,802
NL	988,142,244
PL	2,064,596,916
PT	1,281,706,047
RO	758,379,432
SE	768,154,053
SI	64,476,713
SK	173,742,857
UK	5,786,422,089

Table 1 – water availability at the outlet of UWWTPs estimated for the EU countries

[6] http://www.fao.org/nr/water/aquastat/data/query/

5 Costs of water treatment

5.1 Available evidence on costs of reuse

The treatment of wastewater for its reclamation and reuse depends on a variety of factors, among which:

- the pre-existing level of treatment
- the capacity of the plant
- the desired reclaimed water quality .

An *upper bound* for the operating costs of treatment is provided by the cost of a “triple barrier” treatment system (ultra-filtration, reverse osmosis and disinfection), indicating a typical investment cost of 800 USD/(m3/day), and a typical operating cost of 0.45 USD per m3 produced[7]. In general, the costs of tertiary (or more advanced) treatment for reuse are not expected to offer clear economies of scale, although it is expected that smaller plants (with a capacity of 50,000 PE or less) may feature significantly higher costs compared to larger plants.

Iglesias et al., 2010, with reference to the Spanish context, report ranges of the investment costs and operation costs for different typologies of treatment trains, suitable for different effluent standards in terms of E.Coli, suspended solids (SS) and turbidity (Table 2).

Type	E.Coli (CFU/100 mL)	SS mg/L	Turbidity NTU	Investment costs €/(m^3/day)	Operation costs €/m^3
MF+Dis	Absence	5-10	1-2	185-398	0.14-0.20
DF+Dis	100-200	20	10	28-48	0.06-0.09
F+Dis	1,000 – 10,000	20-35	10-15	9-22	0.04-0.07

Table 2 – unit costs from Iglesias et al., 2010 (MF=membrane filtration ; Dis=disinfection ; DF=depth filtration ; F=filtration)

Arborea et al., 2016, present a theoretical estimation of the costs of treatment with reference to the Italian context, using surveyed unit costs from the Puglia region. The costs are related to the existing level of treatment, and correspond to the additional treatment necessary to comply with the Italian standards for water reuse. The latter concern SS (10 mg/L) and E.Coli (10 CFU/100 mL), in addition to pH, SAR, BOD5, COD, total N, total P. They identify four typical alternative conditions of the existing WWTPs, requiring different treatment processes to achieve the effluent standards (Table 3).

#	Alternative	Additional Processes
1	Effluent compliant with surface water discharge standards (higher nutrient removal energy requirements)	Nutrient removal, F, Dis
2	Effluent compliant with surface water discharge standards (lower nutrient removal energy requirements)	Nutrient removal, F, Dis

[7] Typical cost figures are provided in market overviews by the industry, such as the Global Water Intelligence (GWI) reports: https://www.globalwaterintel.com

#	Alternative	Additional Processes
3	Effluent compliant with on-soil discharge standards, WWTP not equipped with filtration	F, Dis
4	Effluent compliant with on-soil discharge standards, WWTP equipped with filtration	Dis

Table 3 – alternative treatment trains considered in Arborea et al., 2016 (MF=membrane filtration ; Dis=disinfection ; DF=depth filtration ; F=filtration)

The resulting levelized costs of water (including investment and operation) as a function of the plant capacity are shown in Figure 5. The Italian standards correspond to the stricter classes considered in Iglesias et al., 2010. Moreover, the Italian standards may require nutrient removal which is not considered in Iglesias et al., 2010, as in most international contexts. Therefore, a range of costs of water consistent with Iglesias et al., 2010, is represented by alternatives #3 and #4 (Figure 5). These are still in the upper range of Iglesias et al., as they reflect not only operation but also investment in a single, levelized cost figure.

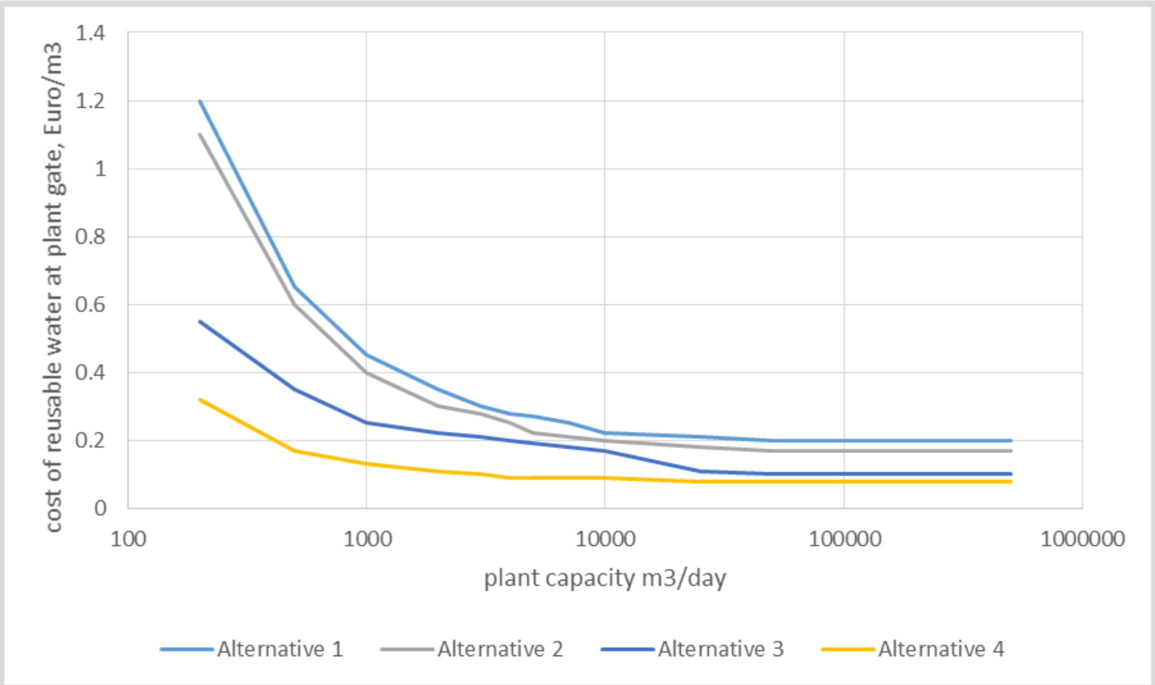

Figure 6 – levelized cost of reclaimed water at the plant's gate as a function of plant capacity (from Arborea et al., 2016).

Tran et al., 2016, based on an extensive literature review on the costs of wastewater treatment applicable to conditions in California, adopt the unit costs shown in Table 4 in order to calculate optimized treatment trains for water reuse.

Treatment process	Unit cost (US$/m3)
microfiltration (MF)	0.18
ultrafiltration (UF)	0.19
Nanofiltration (NF)	0.24
Reverse osmosis (RO)	0.25
UV disinfection	0.03
Chlorination	0.03
Ozonation	0.03
Membrane batch reactor (MBR)	0.86

Table 4 – unit costs of selected treatment processes (Tran et al., 2016)

A compilation of costs reported for different case studies (Table 5) generally prove in line with the costs indicated by Iglesias et al., 2010.

Plant	Treatments	E.Coli CFU/100 mL	Capacity (m3/day)	Investment costs €/(m3/day)	Operation costs €/m3	Reference
Mancasale (Italy)	F+Dis	500	40000	62.5	0.23	Battilani, 2017: pers.comm.
Miraflores (Spain)	Dis	10^8	12000	642	0.25	Battilani, 2017: pers.comm.
Ta Bark (Malta)	UF+RO+Dis	10	57000	95.4	0.64	Battilani, 2017: pers.comm.
Iraklion (Greece)	F+Dis	n.d.	9500	80	0.079	Angelakis, 2017: pers.comm.
DEMOWARE [10]	F+Dis	n.d.	4500	2.5	0.25	Casado Cañeque et al., 2015
DEMOWARE	Conventional	n.d.	55000	2.5	1	Casado Cañeque et al., 2015
DEMOWARE	UF+RO	n.d.	17000	2.5	0.25	Casado Cañeque et al., 2015
DEMOWARE	MF+Dis	n.d.	15000	2.5	0.25	Casado Cañeque et al., 2015
DEMOWARE	UF+Dis	n.d.	360	50	2	Casado Cañeque et al., 2015
DEMOWARE	UV+Dis	n.d.	500	50	1	Casado Cañeque et al., 2015
DEMOWARE	MF+GAC+Dis	n.d.	574	50	0.25	Casado Cañeque et al., 2015
DEMOWARE	F+RO	n.d.	150	100	2	Casado Cañeque et al., 2015
Noirmourtier (France)	Maturation ponds	n.d.	4200	430	0.007	Lazarova, 2017: pers.comm.
Madrid (Spain)	Dis	n.d.	9315	21471	0.13	Depaoli, 2016, based on Lazarova
Honolulu (US)	F+Dis+RO	n.d.	49205	1077	0.48	Depaoli, 2016, based on Lazarova
Bora Bora (French Polynesia)	MF+UF	n.d.	274	29200	0.68	Depaoli, 2016, based on Lazarova
El Segundo	Dis	n.d.	170000	2601	0.3	Depaoli, 2016, based on

[8] Thanks to dilution with groundwater (95%)
[9] Only operation and maintenance
[10] In the anonymous DEMOWARE survey cases reported here, investment and operation costs are given as the central value of a range (<5, , 6-99, >100 €/(m3/day), and <0.5, 0.6-2, >2 €/m3).

Plant	Treatments	E.Coli CFU/100 mL	Capacity (m3/day)	Investment costs €/(m3/day)	Operation costs €/m3	Reference
						Lazarova
Costa Brava (Spain)	F+Dis	n.d.	17534	148	0.34	Depaoli, 2016, based on Lazarova
Cyprus	Dis	n.d.	9589	3775	0.61	Depaoli, 2016, based on Lazarova
Tianjin (China)	F+Dis+RO	n.d.	189863	79	0.29	Depaoli, 2016, based on Lazarova
Milano (Italy)	F+Dis	n.d.	345479	394	0.25	Depaoli, 2016, based on Lazarova
Torreele (Belgium)	F+RO	n.d.	4932	1419	0.62	Depaoli, 2016, based on Lazarova
Orange C. (US)	MF+RO+Dis	n.d.	452877	941	0.31	Depaoli, 2016, based on Lazarova
Occoquan	several	n.d.	70000	14286	0.59	Depaoli, 2016, based on Lazarova
Western Corridor	several	n.d.	68493	25550	2.4	Depaoli, 2016, based on Lazarova
Windhoek (Namibia)	several	n.d.	15890	787	0.75	Depaoli, 2016, based on Lazarova
Yorktown	Dis	n.d.	1370	1752	0.27	Depaoli, 2016, based on Lazarova
Orange C. (US)	MF+RO+Dis	n.d.	151233	2995	0.11	Depaoli, 2016, based on Lazarova
Monterey (US)	F+Dis	n.d.	75068	967	0.21	Depaoli, 2016, based on Lazarova
Florida (US)	F+Dis	n.d.	169041	1525	0.71	Depaoli, 2016, based on Lazarova
Singapore	F+RO+Dis	n.d.	224658	743	0.3	Depaoli, 2016, based on Lazarova

Table 5 – unit costs of selected plants (UF=ultra-filtration; MF=membrane filtration ; Dis=disinfection ; DF=depth filtration ; F=filtration; GAC=granular activated carbon; RO=reverse osmosis)

At the same time, the dispersion and lack of comparability of information available on investment and operation costs of wastewater treatment plants in an international context hinders the development of reliable statistical models for the costs of treatment (see also Lazarova, 2005).

5.2 Assumed treatment costs

For the purposes of this assessment, and on the basis of the evidence shown in the previous section, we assume the costs indicated by Iglesias et al., 2010, to be representative of the whole European context.

We consider a reference condition where effluent standards for reclaimed water can be obtained by a treatment consisting of depth filtration and disinfection (DF+Dis), for which Iglesias et al., 2010, report a mean investment cost in the range of 28-48 €/(m3/day) and an operation cost in the range 0.06-0.09 €/m3. The range of levelized costs of treatment is computed assuming a discount rate of 5% and a depreciation period of 20 years, as:

$$LCoWt = (LCoW_{t,\ min} + LCoW_{t,\ max})/2$$

with

$$LCoW_{t,\ min} = 0.06 + 28 \ / \ pva(0.05,\ 20)/365$$

$$LCoW_{t,\ max} = 0.09 + 48 \ / \ pva(0.05,\ 20)/365$$

and with pva(r, n), representing the present value of investment cost annuity, defined in Equation 15 below. With the above values, LCOWt = 0.08 €. This cost is somehow the cost of an "intermediate" level of treatment for reuse. It can be assumed to represent, as a first approximation, the full range of conditions expected in Europe, in spite of the large variability found in practice, and may be regarded as an educated guess of the costs of treatment when various levels of water quality requirements may be accepted, so that there may be cases with higher as well as lower costs.

For the other cases described in Iglesias and relevant for this assessment, figures of LCOWt are provided in Table 6. When a high level of quality is required on a systematic basis, it seems more appropriate to refer to the upper range of costs provided by Iglesias et al., 2010, with LCOWt=0.23 € as per Table 6. These correspond to assuming treatment with membrane filtration and disinfection (MF+Dis).

technology	LCOWt cost (min)	LCOWt(max)	LCOWt
MF+Dis	€ 0.18	€ 0.29	€ 0.23
DF+Dis	€ 0.07	€ 0.10	€ 0.08
F+Dis	€ 0.04	€ 0.07	€ 0.06

Table 6 – LCOWt according to Iglesias et al., 2010. MF=membrane filtration ; Dis=disinfection ; DF=depth filtration ; F=filtration.

6 Costs of water distribution

6.1 Model structure and approach

The model adopted to calculate the cost of water distribution refers to the spatial support represented by the sub-basins of the HydroEurasia database, derived from the CCM2 dataset[11]. Table 7 summarizes the attributes of sub-basins considered for model calculations.

Symbol	Description	Source
i	Sub-basin identifier	-
$(x_{p,i}, y_{p,i}, z_{p,i})$	Coordinates of the center of mass of WWTPs present in the SB	Computed with Equation 1 using the capacity of WWTPs (PE) as masses; coincides with WWTP coordinates if only one WWPT is present
(x_i, y_i, z_i)	Coordinates of the center of mass of agricultural areas present in the SB	Computed with Equation 2. Agricultural areas are all pixels in CLC2012 with level 1 code=2, excluding level 3 code 231 (pastures)
A_i	Extent of agricultural area in the SB	See above
R_i	Radius of inertia (dispersion) of the agricultural area in the SB	Computed with Equation 3. See above
φ_i	Porosity (share of the SB accessible for pipelines)	Computed with Equation 4 using Open Street Map roads layer, agricultural land (including pastures) and slope from SRTM 100 m DEM
τ_i	tortuosity	Computed from porosity using Equation 5
Q_i	output discharge of the WWTPs present in the SB	From EEA UWWTP database v.4 as revised by Vigiak et al., 2017
α_i	fraction of discharge Q_i that is reclaimed	Set to default of 1
U_i	Cost of water treatment at the WWTPs present in the SB	See § 5.2
I_i	irrigation demand in the SB	Estimated from EPIC under the "baseline" scenario, and from EPIC results with Equation 25 under the "potential" scenario
T_i	Duration of the irrigation period in the SB	Set to a default value of 4 months (120 days).
ψ_i	Cost of energy in the SB	Set to default of 0.10 €/kWh

Table 7 – summary of attributes of each sub-basin used in the calculation (SB=sub-basin)

[11] See http://ccm.jrc.ec.europa.eu/php/index.php?action=view&id=23

Usually there is no more than 1 WWTP in each sub-basin. However, in general we define an equivalent WWTP with coordinates of the centre of mass of all WWTPs in each sub-basin, computed as:

$$x_{p,i}=\frac{\sum_{k=1}^{m_i} P_k \xi_{pk}}{\sum_{k=1}^{m_i} P_k}$$
$$y_{p,i}=\frac{\sum_{k=1}^{m_i} P_k \eta_{pk}}{\sum_{k=1}^{m_i} P_k} \qquad \textit{Equation 1}$$
$$z_{p,i}=\frac{\sum_{k=1}^{m_i} P_k \zeta_{pk}}{\sum_{k=1}^{m_i} P_k}$$

where m_i is the number of WWPs in the i-th sub-basin, P_k the capacity (PE) of the k-th WWTP in the sub-basin, and $(\xi_{pk},\eta_{pk},\zeta_{pk})$ its coordinates along the horizontal axes and elevation, respectively. We define an equivalent agricultural area in the sub-basin, with an extent equal to the total agricultural area A_i within the sub-basin, with coordinates of the centre of mass computed as

$$x_i=\frac{\sum_{k=1}^{n_i} \xi_k}{n_i}$$
$$y_i=\frac{\sum_{k=1}^{n_i} \eta_k}{n_i} \qquad \textit{Equation 2}$$
$$z_i=\frac{\sum_{k=1}^{n_i} \zeta_k}{n_i}$$

where n_i is the number of agricultural pixels in the i-th sub-basin, and (ξ_k,η_k,ζ_k) the coordinates of the k-th pixel along the horizontal axes and elevation, respectively. The dispersion of agricultural pixels around their center of mass is represented by the radius of inertia computed as:

$$R_i=\frac{\sum_{k=1}^{n_i} \sqrt{(\xi_k-x_i)^2+(\eta_k-y_i)^2+(\zeta_k-z_i)^2}}{n_i} \qquad \textit{Equation 3}$$

Each sub-basin is characterized by a “porosity”, meant as the share of its area where water can be in principle transported through pipelines. The latter is assumed to coincide with the ensemble of:

- A buffer of 100 m around all road infrastructure
- Agricultural land with terrain slope below 35°.

Porosity is defined as:

$$\varphi_i=\frac{accessible\ area\ in\ sub-basin\ i}{total\ area\ in\ sub-basin\ i}. \qquad \textit{Equation 4}$$

In the analysis of costs of water reuse, we compute the length of pipelines assuming a Euclidean distance, hence a homogeneously accessible sub-basin, while in reality the actual length will tend to be higher depending on the tortuosity of its trail. We quantify the tortuosity using the theoretical model of Bruggeman (1935; see also Tjaden et al., 2016) for two-dimensional porosity:

$$\tau_i=\left(\frac{1}{{\varphi_i}^{a}}\right) \qquad \textit{Equation 5}$$

Where a is a parameter depending on the geometry of the pores. For a space filled by cylinders, a=1 while, for a space filled by spheres, a=0.5. The higher a, the higher the tortuosity for a given porosity. In practice, a needs to be fitted to the specific case. In this exercise, we set a=0.5 by default. Moreover, we do not allow τ_i to exceed the value of 3.

6.2 Levelized cost of water transport

Water potentially reclaimed at a given wastewater treatment plant may be transported for reuse within the plant's sub-basin (i.e. "at the source"), or towards other "receptor" sub-basins. In this exercise, we assume that water cannot be conveniently transported to sub-basins more than 10 km away (on a straight line) nor to sub-basins with elevation differences representing an excessive pumping requirement. For the latter, we assume that sub-basins featuring an elevation range above 200 m would require excessive pumping efforts and we regard them as "inaccessible". We exclude from this set those sub-basins corresponding to the valleys of relatively large rivers (those with Strahler order > 4 in the CCM2 database), where it is assumed that the valley bottoms may still host infrastructure despite the potentially high elevation ranges on the hillsides.

Within a "source" sub-basin, the flow of reclaimed water to agriculture (m3/day) is computed as:

Equation 6

$$F_{i,i} = \min(\alpha_i Q_i, I_i)$$

where Q_i (m3/day) is the output discharge of the WWTP, α_i (-) is the fraction of this discharge that is reclaimed (by default, α_i=1), and I_i (m3/day) is the irrigation demand in the sub-basin.

The length of the pipeline required to transport this flow to the agricultural area in the sub-basin is given by:

Equation 7

$$L_{i,i} = \sqrt{\left(x_i - x_{p,i}\right)^2 + \left(y_i - y_{p,i}\right)^2 + \left(z_i - z_{p,i}\right)^2}$$

while the diameter of the pipeline (m) is computed using the Hazen-Williams formula as:

Equation 8

$$D_{i,i} = \left(\frac{10.675\ (\frac{F_{i,i}}{C})^{1.852}}{J}\right)^{\frac{1}{4.8704}}$$

where J is the friction loss rate and C is a friction coefficient. We assume C=120 (-), valid for steel pipes, and J=0.005 (-). Under these assumptions, with $F_{i,i}$ in m3/day, Equation 8 can be written as:

$$D_{i,i} = 0.0104 F_{i,i}^{0.3803}$$

In addition to the transport of reclaimed water to the agricultural area, we account for the distribution of this water within the agricultural area itself. The radius of inertia R_i represents the average distance of agricultural areas from their centre of mass. We assume the investment in the infrastructure for distribution to the farms to be independent of the water reuse investment, while we compute the energy cost of distributing the reused water within the agricultural area of a sub-basin, as this contributes directly to the levelized cost of water.

The expenditure for a pipeline with diameter Δ is given in €/m by[12]:

Equation 9

$$E(\Delta) = \begin{cases} 0.088433\ \Delta^{1.29} + 65.8\ if\ \Delta \leq 0.8\ m \\ 0.0040115\ \Delta^{1.785} + 68.1\ if\ \Delta > 0.8\ m \end{cases}$$

as from the FEASIBLE model (OECD, 2004). This expenditure function is used to compute $E(D_{i,i})$.

The energy required to transport and distribute the reclaimed water within the sub-basin (kWh/year) is computed as:

Equation 10

$$\Psi_{i,i} = \frac{F_{i,i}}{86400\eta}(365 * 24)g\big(\max(0, z_i - z_{p,i}) + J(\tau_i L_{i,i} + R_i)\big)$$

where g is the acceleration of gravity (9.81 m/s2) and η is the efficiency of pumping. We assume η=0.75. The power installation requirement (kW) of an equivalent pumping station for the transport and distribution of the reclaimed water flow is:

Equation 11

$$S_{i,i} = \frac{365\ \Psi_{i,i}}{(365 * 24)T_i}$$

where T_i (days) is the duration of the irrigation period in the sub-basin. The expenditure for a pumping station of power S (€) is computed from the FEASIBLE model as:

Equation 12

$E'(S) = 33140\ S^{0.559}$

The storage volume required for use of water in irrigation is computed as:

Equation 13

$W_{i,i} = 365 F_{i,i}\ \left(1 - \frac{T_i}{365}\right)$

The cost of the storage volume is:

Equation 14

$E(W_{i,i}) = \omega_i W_i$

with ω_i set to default of 5 €/m3 in line with Maton et al., 2010. Cost of storage is extremely variable. For natural storage (e.g. in floodplains), *Grygoruk et al., 2013 report a value above 8 €/m3.*

The expenditure for an investment can be converted into an equivalent annual cost by the "present value of annuity" factor:

Equation 15

$$pva(r,n) = \frac{1 - \left(\frac{1}{1+r}\right)^n}{r}$$

where r is the annual interest rate and n is the number of years of useful life (or depreciation period) of the investment. We assume n=50 years for pipelines and storage, and n=15 for pumping stations, while r=0.05 (5%).

[12] The functions are provided by OECD (2004) in US$/m. In 2004, the exchange rate of € against US $ was about 0.83. However, given the indicative value of the functions and the relative stability of the prices, we assume a unit exchange rate. This applies to all expenditure functions from the FEASIBLE model when values are given in US$.

The total equivalent annual cost of water transport and distribution (€/year) is given by:

Equation 16

$$E_{i,i} = \frac{E(D_{i,i})\tau_i L_{i,i} + \mathrm{E}(\mathrm{W}_{i,i})}{pva(0.05, 50)} + \frac{E'(S_{i,i})}{pva(0.05, 15)} + \psi_i \Psi_{i,i}$$

Where ψ_i is the cost of energy (€/kWh) in the sub-basin. In this exercise, we assume a constant value ψ_i =0.10 €/kWh. The cost of energy for industrial use reported by EUROSTAT is provided in Table 8, suggesting the assumed value to be plausible for large industrial users across Europe.

Country	Consumption (MWh/year)						
	20	500	2000	20000	70000	150000	>150000
Belgium	€ 0.18	€ 0.15	€ 0.11	€ 0.10	€ 0.08	€ 0.07	€ 0.06
Bulgaria	€ 0.10	€ 0.10	€ 0.08	€ 0.07	€ 0.06	€ 0.06	€ 0.06
Czech Republic	€ 0.16	€ 0.12	€ 0.08	€ 0.07	€ 0.07	€ 0.07	
Denmark	€ 0.18	€ 0.10	€ 0.09	€ 0.09	€ 0.08	€ 0.08	
Germany	€ 0.22	€ 0.18	€ 0.15	€ 0.13	€ 0.11	€ 0.10	
Estonia	€ 0.11	€ 0.10	€ 0.09	€ 0.08	€ 0.07	€ 0.07	
Ireland	€ 0.20	€ 0.16	€ 0.13	€ 0.11	€ 0.09	€ 0.09	
Greece	€ 0.21	€ 0.17	€ 0.12	€ 0.10	€ 0.08	€ 0.05	
Spain	€ 0.27	€ 0.15	€ 0.11	€ 0.10	€ 0.08	€ 0.07	€ 0.06
France	€ 0.15	€ 0.12	€ 0.10	€ 0.08	€ 0.07	€ 0.06	
Croatia	€ 0.13	€ 0.11	€ 0.09	€ 0.08	€ 0.06	€ 0.06	
Italy	€ 0.27	€ 0.19	€ 0.16	€ 0.15	€ 0.13	€ 0.10	€ 0.08
Cyprus	€ 0.18	€ 0.17	€ 0.15	€ 0.13	€ 0.13	€ 0.12	
Latvia	€ 0.16	€ 0.13	€ 0.12	€ 0.11	€ 0.10	€ 0.09	
Lithuania	€ 0.13	€ 0.11	€ 0.10	€ 0.10	€ 0.09	€ 0.08	
Luxembourg	€ 0.17	€ 0.11	€ 0.09	€ 0.06	€ 0.05		
Hungary	€ 0.11	€ 0.10	€ 0.09	€ 0.08	€ 0.08	€ 0.08	€ 0.08
Malta	€ 0.22	€ 0.17	€ 0.16	€ 0.14	€ 0.12	€ 0.11	
Netherlands	€ 0.16	€ 0.12	€ 0.09	€ 0.08	€ 0.07	€ 0.07	€ 0.06
Austria	€ 0.16	€ 0.13	€ 0.10	€ 0.09	€ 0.08	€ 0.07	€ 0.06
Poland	€ 0.15	€ 0.11	€ 0.08	€ 0.07	€ 0.07	€ 0.06	€ 0.06
Portugal	€ 0.19	€ 0.15	€ 0.12	€ 0.10	€ 0.09	€ 0.08	
Romania	€ 0.11	€ 0.10	€ 0.08	€ 0.07	€ 0.06	€ 0.06	
Slovenia	€ 0.14	€ 0.10	€ 0.08	€ 0.07	€ 0.07	€ 0.06	
Slovakia	€ 0.20	€ 0.14	€ 0.11	€ 0.10	€ 0.09	€ 0.09	€ 0.07
Finland	€ 0.09	€ 0.08	€ 0.07	€ 0.07	€ 0.05	€ 0.05	
Sweden	€ 0.14	€ 0.07	€ 0.06	€ 0.06	€ 0.05	€ 0.04	
United Kingdom	€ 0.17	€ 0.15	€ 0.14	€ 0.13	€ 0.12	€ 0.12	€ 0.12

Table 8 – Electricity prices per kWh, for industrial consumers, excluding VAT and other recoverable taxes and levies – average of bi-annual data 2014-16 (source: EUROSTAT)

The levelized cost of reclaimed water within the sub-basin (€/m3) is:

Equation 17

$$LCoW_{i,i} = \frac{E_{i,i}}{365F_{i,i}} + U_i$$

The flow of reclaimed water potentially supplied from the i-th source sub-basin to the j-th receptor sub-basin (m3/day) is computed in a similar way. First of all, the shortest path connecting the i-th source to the j-the receptor is identified. If a receptor is not adjacent to the source but there are one or more sub-basins in between, the path is forced to pass through the center of mass of agriculture in each of these sub-basins. When a sub-basin does not contain agriculture, its centroid is considered instead. Each receptor sub-basin can be therefore characterized with the shortest path length to reach it from the i-th source (L_{ij}), and in addition with the shortest path length to reach its neighbor immediately closer to the source ($\Lambda_{i,j}$). The shortest-path lengths between two generic nodes are computed as the Euclidean distances, multiplied by the tortuosity factor of the origin node. On a par, each receptor sub-basin can be characterized by the potential flow from the i-th source basin:

Equation 18

$$F_{i,j} = \min\left(\max\left(0, -\alpha_i Q_i F_{i,i}\right), \max\left(0, I_j - F_{j,j}\right)\right).$$

as well as the flow to its neighbor immediately closer to the source, which we denote as $\Phi_{i,j}$. The pipeline connecting the i-th source to the j-th receptor requires a diameter to convey $F_{i,j}$ for the length $L_{i,j} - \Lambda_{i,j}$. In addition it needs the infrastructure, already sized to convey flow to its neighbors closer to the source, to be appropriately upsized. In this exercise, we assume that costs of pumping stations are additive (i.e., for each receptor basin there may be a dedicated pumping station in line with the modularity principles often adopted in design). The upsizing costs of pipelines are estimated as if the whole length $\Lambda_{i,j}$ were designed for flow $\Phi_{i,j}$, and need to be adjusted now to the total flow $F_{i,j} - \Phi_{i,j}$. The cost of transport of water between the i-th source and the j-th receptor can be then computed, in analogy with what outlined above, as:

Equation 19

$$E_{i,j} = \frac{E(D_{i,j})(L_{i,j} - \Lambda_{i,j}) + \left(E({D^{cum}}_{i,j}) - E\left({D^{base}}_{i,j}\right)\right)\Lambda_{i,j} + \mathrm{E}(\mathrm{W}_{i,j})}{pva(0.05, 50)} + \frac{E'(S_{i,j})}{pva(0.05, 15)} + \psi_i \Psi_{i,j}$$

Where we posit:

Equation 20

$$\begin{aligned} {D^{cum}}_{i,j} &= 0.0104\left(F_{i,j} + \Phi_{i,j}\right)^{0.3803} \\ {D^{base}}_{i,j} &= 0.0104\,{\Phi_{i,j}}^{0.3803} \\ D_{i,j} &= 0.0104\,{\mathrm{F}_{i,j}}^{0.3803} \end{aligned}$$

And where E(*) is the expenditure function introduced before (Equation 9). Moreover, we have:

Equation 21

$$\Psi_{i,j} = \frac{F_{i,j}}{86400\eta}(365 * 24) g\left(\max(0, z_{obst\ i,j} - z_{p,i}, z_j - z_{p,i}) + J(\tau_i L_{i,j} + R_j)\right)$$

Where now $z_{obst\ i,j}$ is the height of the expected obstacle to be met when crossing sub-basin divides between the i-th and j-th sub-basins. We consider the 75th percentile of catchment elevation for each sub-basin on the shortest path between the i-th and j-th sub-basins, and we assume that $z_{obst\ i,j}$ is the maximum of these elevations.

Equation 22

$$S_{i,j} = \frac{365\ \Psi_{i,j}}{(365 * 24) T_j}$$

Equation 23

$$\mathrm{W}_{i,j} = 365 \mathrm{F}_{i,j} \left(1 - \frac{T_j}{365}\right)$$

The levelized cost of water from the i-th source sub-basin potentially used in the j-th sub-basin is then given by:

Equation 24

$$LCoW_{i,j} = \frac{E_{i,j}}{365F_{i,j}} + U_i.$$

Table 9 summarizes the attributes computed for each sub-basin, related to the transfer of reclaimed water from the i-th to the j-th sub-basin. The levelized costs of investments are all increased by a rate of operation and maintenance (O&M) costs, set by default to 3% for the pipelines, 1% for storage and 1.5% for pumping stations.

Symbol	Description	Calculation
$F_{i,j}$	Potential Flow of reclaimed water within the SB	Equation 6, Equation 18
$L_{i,j}$	Length of the pipeline for transport to the SB's agricultural area	Equation 7
$D_{i,j}$	Diameter of the pipeline for transport to the SB's agricultural area	Equation 8, Equation 20
$E(D_{i,j})$	Cost per unit length of the pipeline for transport to the SB's agricultural area	Equation 9
$W_{i,i}$	Storage volume	Equation 13, Equation 23
$E(W_{i,i})$	Cost of storage volume	Equation 14
$\Psi_{i,j}$	Energy required for transport and distribution of reclaimed water	Equation 10, Equation 21
$S_{i,j}$	Power requirement for pumping	Equation 11, Equation 22
$E'(S_{i,j})$	Cost of pumping stations for distribution within the SB	Equation 12
$E_{i,j}$	Cost of water distribution within the SB	Equation 16, Equation 19
$LCoW_{i,j}$	Levelized cost of water within the SB	Equation 17, Equation 24

Table 9 – summary of computed attributes of each pair of related sub-basin (SB=sub-basin).

6.3 Global sensitivity analysis of the cost model

The above cost model makes assumptions on the following parameters:

- Cost of energy
- Cost of storage

- Duration of the irrigation period
- Discount rate
- Depreciation period of pipelines
- Depreciation period of storage
- Depreciation period of pumping stations
- Incidence of O&M costs of pipelines
- Incidence of O&M costs of storage
- Incidence of O&M costs of pumping stations.

In addition, the model assumes a roughness coefficient and an energy gradient in the Hazen-Williams formula used for the sizing of pipes. As these are typical, and largely conventional, engineering assumptions, we ignore these two parameters in the sensitivity analysis. In order to estimate a plausible upper and lower range for the computed levelized costs of water, we consider two scenarios, which we label as “more favorable” and “less favorable” respectively. In the former, we change the parameters from the base assumptions to values which systematically reduce costs; in the latter, on te contrary, we alter the base values so to increase the costs. Table 10 shows the values considered in the exercise.

Parameter	**Units**	**Base value**	**More favorable**	**Less favorable**
Cost of energy	€/kWh	0.1	0.05	0.15
Cost of storage	€/m3	5	2	8
Duration of the irrigation period	Days	120	180	70
Discount rate	%	5	2	7
Depreciation period of pipelines	Years	50	75	25
Depreciation period of storage	Years	50	75	25
Depreciation period of pumping stations	Years	15	20	10
Incidence of O&M costs of pipelines	%	3	1	5
Incidence of O&M costs of storage	%	1	0.5	1.5
Incidence of O&M costs of pumping stations.	%	1.5	0.5	2.5

Table 10 – alteration of model parameters in the global sensitivity analysis.

With reference to the two scenarios, we conducted a simplified global sensitivity analysis of the cost model by computing the levelized costs of water for each source-receptor link identified as detailed above. Figure 6, Figure 7 and Figure 8 show the scatter plots of costs under base and altered conditions, including all costs (Figure 6), all costs excluding storage (Figure 7) and only energy and treatment costs (Figure 8). From the plots, it is apparent that the overall ranking of source-receptor links does not change appreciably, the dispersion of points being always very narrow. This indicates that the cost analysis is sufficiently robust with respect to the identification of priorities for water allocation.

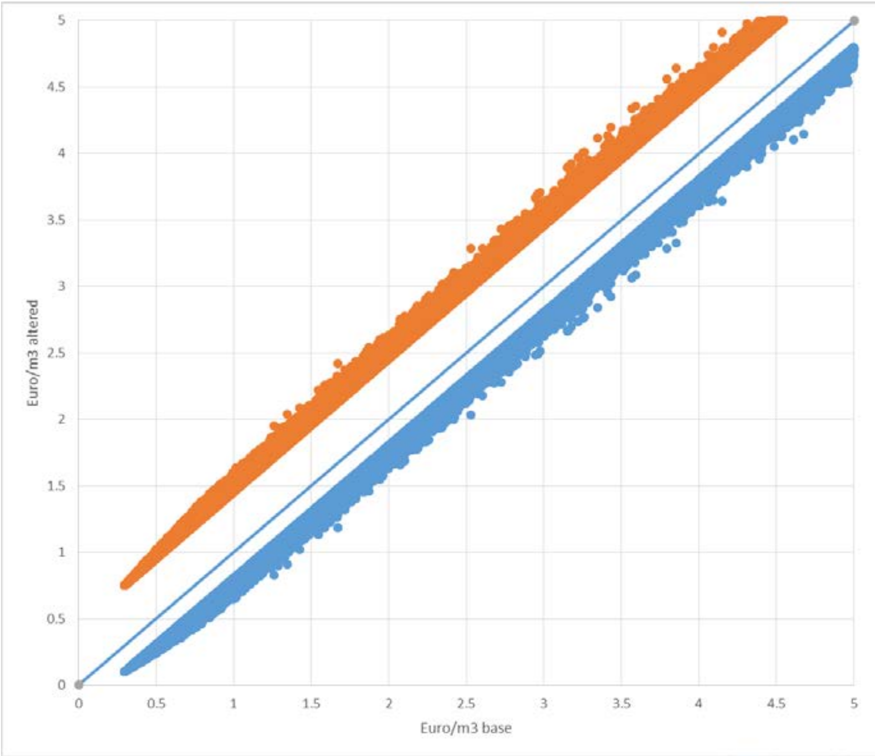

Figure 7 – Levelized costs including pipelines, pumping stations, storage, energy and treatment: comparison of the base case and altered values (orange=less favorable ; blue=more favorable), using parameters as per Table 10.

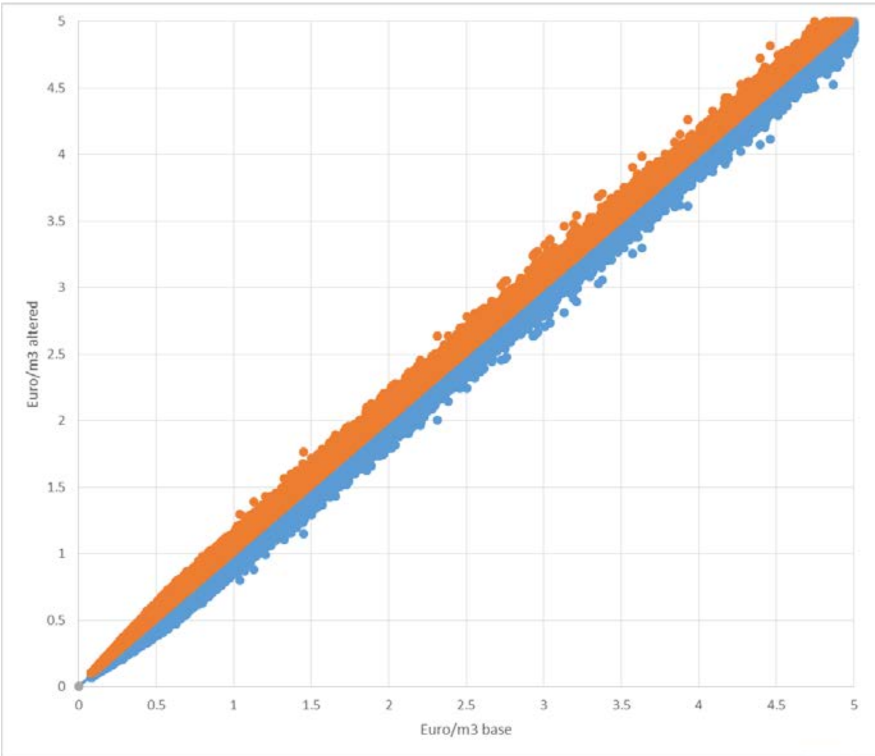

Figure 8 – Levelized costs as above, excluding storage: comparison of the base case and altered values (orange=less favorable; blue=more favorable), using parameters as per Table 10.

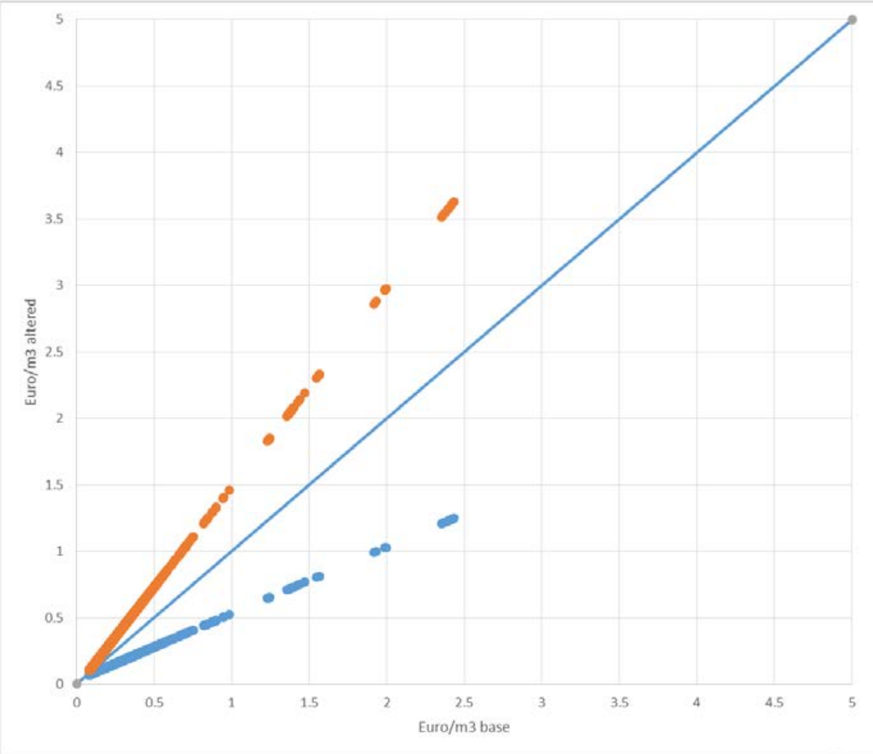

Figure 9 – Levelized costs including energy and treatment only: comparison of the base case and altered values (orange=less favorable; blue=more favorable), using parameters as per Table 10.

Absolute costs may change significantly (especially when energy and treatment costs are considered alone) but in a very predictable way as per the narrow scattering. When total costs are considered, considering a more favorable alteration is practically equivalent to reducing costs of about 0.25 Euro/m3 while a less favorable alteration increases costs of about 0.5 Euro/m3 (Figure 6). The alteration of energy and treatment costs alone is practically equivalent to halving (for more favorable conditions) or multiplying by 1.5 (for less favorable conditions) the levelized costs (Figure 8). When total costs excluding storage are considered, the alterations have much less apparent effects (Figure 7).

7 Allocation of water to sub-basins, calculation of surpluses and deficits

The above equations allow calculating the levelized cost of water for each potential source-receptor link. In order to allocate a given water availability at a source, receptors need to be ranked on the basis of cost criteria. The levelized cost as a function of the cumulative volume of reclaimed water potentially allocated from a source is the so called source's water-marginal cost curve (WMCC). The WMCC is a tool used for investment strategy decision support in the field of water infrastructure (McKinsey, 2009).

The actual volume of potentially reclaimed water at a source sub-basin that can be allocated to the receptor sub-basins is the minimum between reclaimed water availability at the source and irrigation demand in its neighborhood. The difference of these two terms represents the local surplus or deficit of reclaimed water with respect to irrigation requirements. Demands of receptors entailing a cost above a given threshold can be excluded.

The amount allocated from a source to any of its cost-ranked receptors is computed as the potential flow, if the sum of all potential flows up to the receptor's rank does not exceed availability, else it is calculated as the difference between availability and the sum of potential flows for all receptors featuring lower cost.

A receptor sub-basin may belong to the neighborhood of, hence be allocated water from, more than one source sub-basin. In this case, a surplus may result from the sum of allocations. A surplus may occur also when restricting potential flows with a cost threshold.

In this assessment, we refer to three cost scenarios:

(1) case when reuse requires developing all infrastructure from scratch (pipelines, pumping stations and water storage);

(2) case when pipelines and pumping stations must be built, but storage can be made using existing infrastructure;

(3) case when all infrastructure exists, and the costs are limited to treatment and energy.

For each of the above cases, we rank receptors based on the corresponding costs. For each source sub-basin considered in the EU, the calculation yields the demand in the neighbourhood that can be met under no restriction on costs, and with costs not exceeding a threshold of 0.25, 0.50, 0.75, 1.00 Euro/m^3, in addition to the corresponding local surplus or deficit.

Based on the above assumptions, we compute the variables summarized in Table 11.

Cost scenario #	costs included	target	variable	meaning
1	total costs	source	demand	demand in the neighborhood
1	total costs	source	Cost1demand25	demand that can be met with costs <=0.25Euro/m3
1	total costs	source	Cost1demand50	demand that can be met with costs <=0.5Euro/m3
1	total costs	source	Cost1demand75	demand that can be met with costs <=0.75Euro/m3
1	total costs	source	Cost1demand100	demand that can be met with costs <=1Euro/m3
1	total costs	receptor	Cost1alloc	supply that can be allocated
1	total costs	receptor	Cost1alloc25	supply that can be allocated with costs <=0.25Euro/m3
1	total costs	receptor	Cost1alloc50	supply that can be allocated with costs <=0.5Euro/m3
1	total costs	receptor	Cost1alloc75	supply that can be allocated with costs <=0.75Euro/m3
1	total costs	receptor	Cost1alloc100	supply that can be allocated with costs <=1Euro/m3
1	total costs	receptor	Cost1surplus	surplus of receptor after allocation at 1 Euro/m

Cost scenario #	costs included	target	variable	meaning
2	total costs - storage	source	Cost2demand25	demand that can be met with costs <=0.25Euro/m3
2	total costs - storage	source	Cost2demand50	demand that can be met with costs <=0.5Euro/m3
2	total costs - storage	source	Cost2demand75	demand that can be met with costs <=0.75Euro/m3
2	total costs - storage	source	Cost2demand100	demand that can be met with costs <=1Euro/m3
2	total costs - storage	receptor	Cost2alloc	supply that can be allocated
2	total costs - storage	receptor	Cost2alloc25	supply that can be allocated with costs <=0.25Euro/m3
2	total costs - storage	receptor	Cost2alloc50	supply that can be allocated with costs <=0.5Euro/m3
2	total costs - storage	receptor	Cost2alloc75	supply that can be allocated with costs <=0.75Euro/m3
2	total costs - storage	receptor	Cost2alloc100	supply that can be allocated with costs <=1Euro/m3
2	total costs - storage	receptor	Cost2surplus	surplus of receptor after allocation at 1 Euro/m
3	only energy and treatment	receptor	Cost3demand25	demand that can be met with costs <=0.25Euro/m3
3	only energy and treatment	receptor	Cost3demand50	demand that can be met with costs <=0.5Euro/m3
3	only energy and treatment	receptor	Cost3demand75	demand that can be met with costs <=0.75Euro/m3
3	only energy and treatment	receptor	Cost3demand100	demand that can be met with costs <=1Euro/m3
3	only energy and treatment	receptor	Cost3alloc	supply that can be allocated
3	only energy and treatment	receptor	Cost3alloc25	supply that can be allocated with costs <=0.25Euro/m3
3	only energy and treatment	receptor	Cost3alloc50	supply that can be allocated with costs <=0.5Euro/m3
3	only energy and treatment	receptor	Cost3alloc75	supply that can be allocated with costs <=0.75Euro/m3
3	only energy and treatment	receptor	Cost3alloc100	supply that can be allocated with costs <=1Euro/m3
3	only energy and treatment	receptor	Cost3surplus	surplus of receptor after allocation at 1 Euro/m

Table 11 – variables considered in the assessment of reuse costs.

8 Amounts of reclaimed water available at different costs

The above analysis yields costs of potential water distribution for each source-receptor link. In this section we discuss the costs of reclaimed water under the assumption of a treatment level with depth filtration and disinfection (DF+Dis), with an assumed reference cost of treatment of 0.08 €/m^3 (see § 5.2). The statistical distribution of costs for all source-receptor links in Europe is summarized in Figure 9. The histograms in figure use the cumulative potential volume instead of the frequency, in order to represent the distribution of resource costs in a more immediate way. In the graphs, the cumulative potential volume for a given cost is the sum of all volumes potentially exchanged on all source-receptor links at that value of the levelized cost of water, and does not take into account that, for a given source-receptor link, there may not be water available because it has been already allocated to other links. These volumes correspond to variables Cost1demand25, Cost1demand50, Cost1demand75, Cost1demand100, Cost2demand25 etc. in Table 11. The sum of *potential volumes* is by definition larger than the *volume physically available*, and serves the purpose of visualizing the frequency distribution in a more meaningful way than standard frequencies.

The histograms show that, if we consider total costs (including infrastructure, treatment and energy), water cannot be reused at costs below 0.25 Euro/m3 (Figure 9A). The majority of potential volumes (approximately 28 billion m3) can be distributed in equal proportion between 0.25 and 0.75 Euro/m3 (approximately 20 billion m3), while almost another 4 billion m3 can be distributed at costs below 1 Euro/m3. When considering total costs excluding storage, about 8 billion m3 may be distributed below 0.25 Euro/m3 and an additional ca. 12 billion m3 may be distributed below 0.5 Euro/m3 (Figure 9B). If we consider the irrigation infrastructure to be already existing, more than 25 billion m may be distributed below 0.25 Euro/m3 (Figure 9C).

For all source-receptor relationships it is also possible to compute the energy required for the potential transport of water, as per Equation 10, hence the energy required per m3, whose distribution is shown in Figure 9D. The distribution of unit energy costs is more uniform than the distribution of costs, but skewed towards values below the median of 0.5 kWh/m3. To complement Figure 9D, Figure 10 shows the cumulate of reusable water volume fractions corresponding to a given specific energy requirement.

These energy costs tend to be higher than reported on average for irrigation with conventional water. Figures from Tarjuelo et al., 2015, suggest an average unit energy requirement of irrigation between 0.2 and 0.3 kWh/m^3 in Spain. Our energy requirements reflect the distances and pumping heads estimated on the basis of the relative position of UWWTPs and agricultural land in Europe, and should be considered as indicative.

A

B

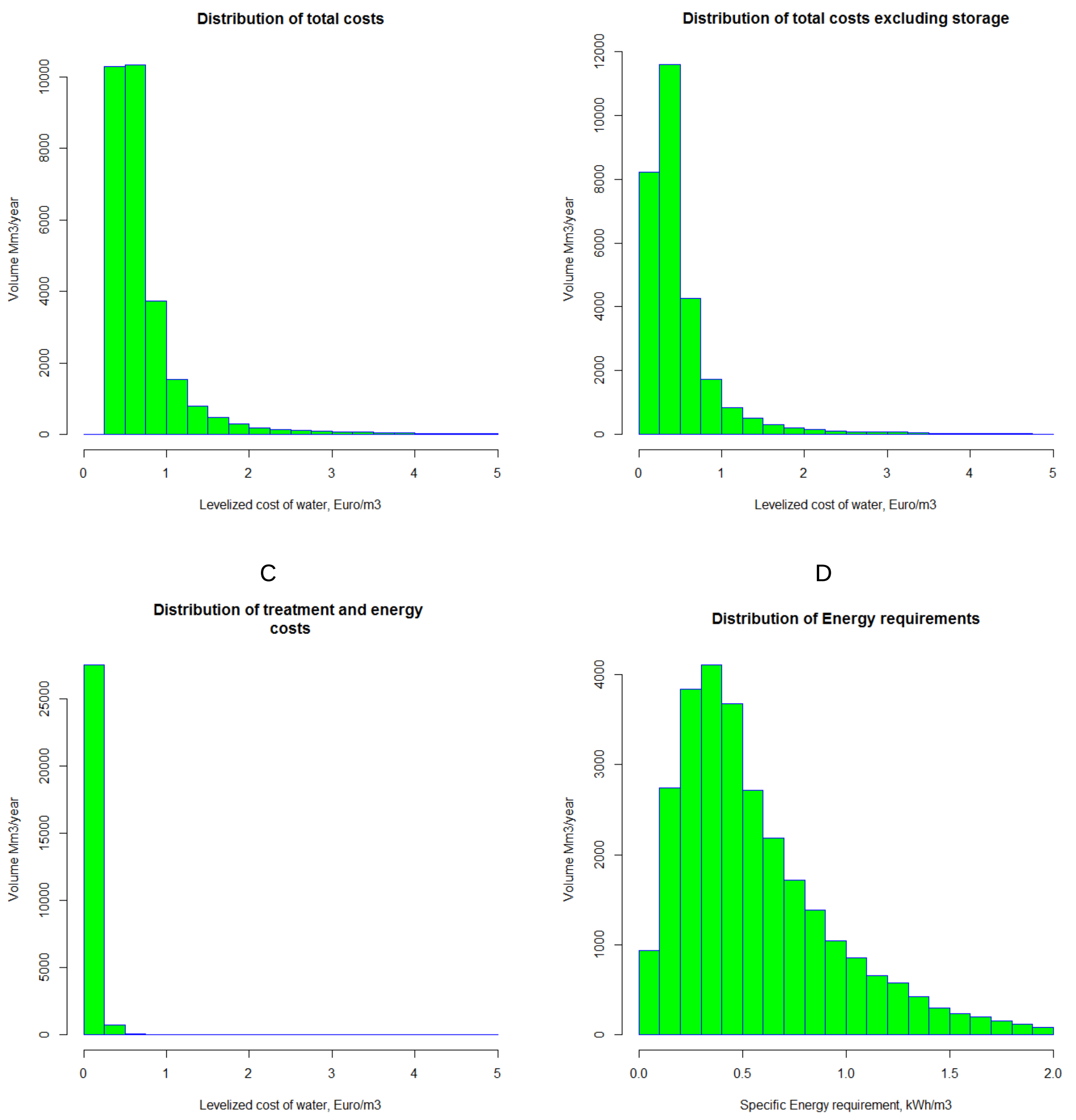

Figure 10 – distribution of costs and energy requirements of potentially reclaimed volumes for all suource-receptor links in Europe

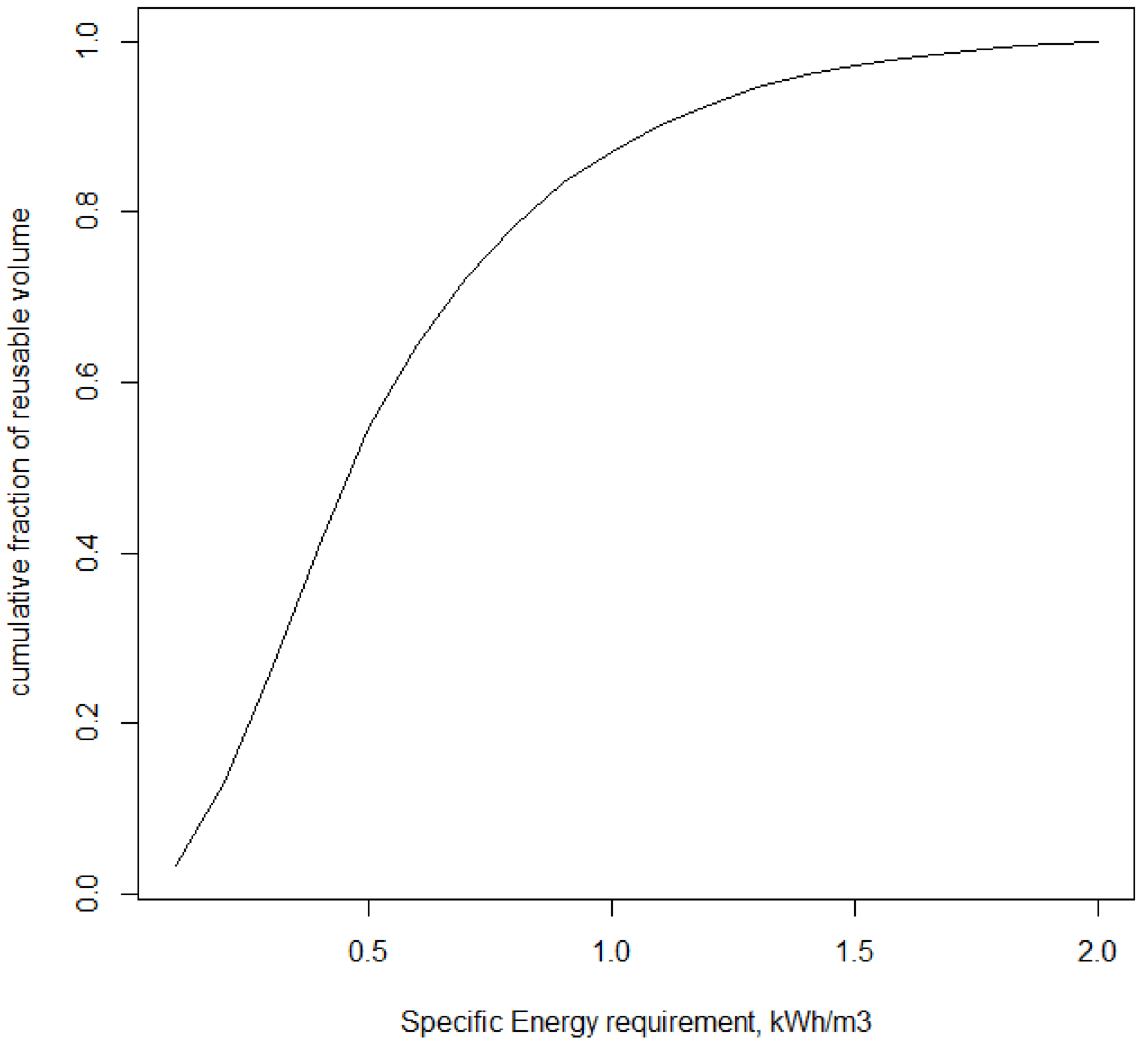

Figure 11 – cumulate of the histogram in Figure 9D, expressed in fractions of reusable water volume.

The costs of reclaimed water reflect the position of agricultural water demand relative to the potentially available sources (wastewater treatment plants), in terms of distance and elevation differences, and are expected to vary significantly across the EU. The largest shares of the EU's irrigation demand (estimated as discussed in § 3) are held by Spain (about 18 km3/year), Italy (about 11 km3/year), France and Greece with between 4 and 5 km3/year each, Portugal with almost 3 km3/year, and Romania with less than 1 km3/year. All other EU member states feature much smaller irrigation demands. For each EU member state, we compute the total amount of water *that can be reused within the neighborhood of wastewater treatment plants*, by classes of costs, and we compare it to the irrigation demand of the country. The results are shown in Figure 11 for total costs, Figure 13 for total costs excluding storage, and Figure 14 for energy and treatment costs only. The amount of water that can be reused is constrained by wastewater availability, and is by definition smaller than potential volumes discussed above. It corresponds to variables Cost1alloc25, Cost1alloc50, Cost1alloc75, Cost1alloc100, Cost1surplus, Cost2alloc25 etc. in Table 11.

Table 12 shows that water reuse may contribute for Spain and Portugal to about 20% of irrigation demand, for Italy and France to about 45%, for Greece, Malta and Romania to around 10%. In all other countries, due to the lower irrigation requirements, water reuse may fulfill the whole demand unless irrigated agriculture is relatively too far from wastewater treatment plants (Nordic countries, Slovakia, Bulgaria, Poland).

Among the largest irrigation demand countries, Greece shows the most favorable conditions for total costs, with the majority of volumes compatible with reuse costs below

0.5 Euro/m3, followed by Portugal. France is the least favored, while Italy and Spain are in an intermediate condition (Figure 11). The situation for all regions (NUTS2 level) of the EU's member states is shown in details in the maps shown from Figure 19 to Figure 29 under Appendix 1.

The costs of reuse reflect significant economies of scale as, when volumes of water required for irrigation are smaller, the incidence of the investment costs is higher. This can be visualized through the average cost computed at NUTS2 region level, by conventionally assigning 0.25 €/m^3 to volumes with costs below this threshold, 0.5 to volumes between 0.25 and 0.5, 0.75 to those between 0.5 and 0.75, 1 to those between 0.75 and 1, and 2 to those above (Figure 13). This procedure inherently overestimates the costs but highlights how reuse may be unattractive in regions with relatively small irrigation demand, without already existing infrastructure for water transport from wastewater treatment plants to irrigated farmland.

The overall picture does not change when neglecting storage costs (Figure 14), apart from a downward shift of all costs by the storage cost which results constant across Europe as we do not differentiate for the duration of the irrigation period. Details for this cost scenario are shown in the maps from Figure 30 to Figure 40 under Appendix 2, for the different NUTS2-level regions of the EU.

When considering energy and treatment costs only (Figure 15), the majority of the volumes may be reused at costs below 0.25 Euro/m3. Among the large demand countries, only Italy and Spain still feature a sizable, albeit small, share of volumes above 0.25 €/m^3.

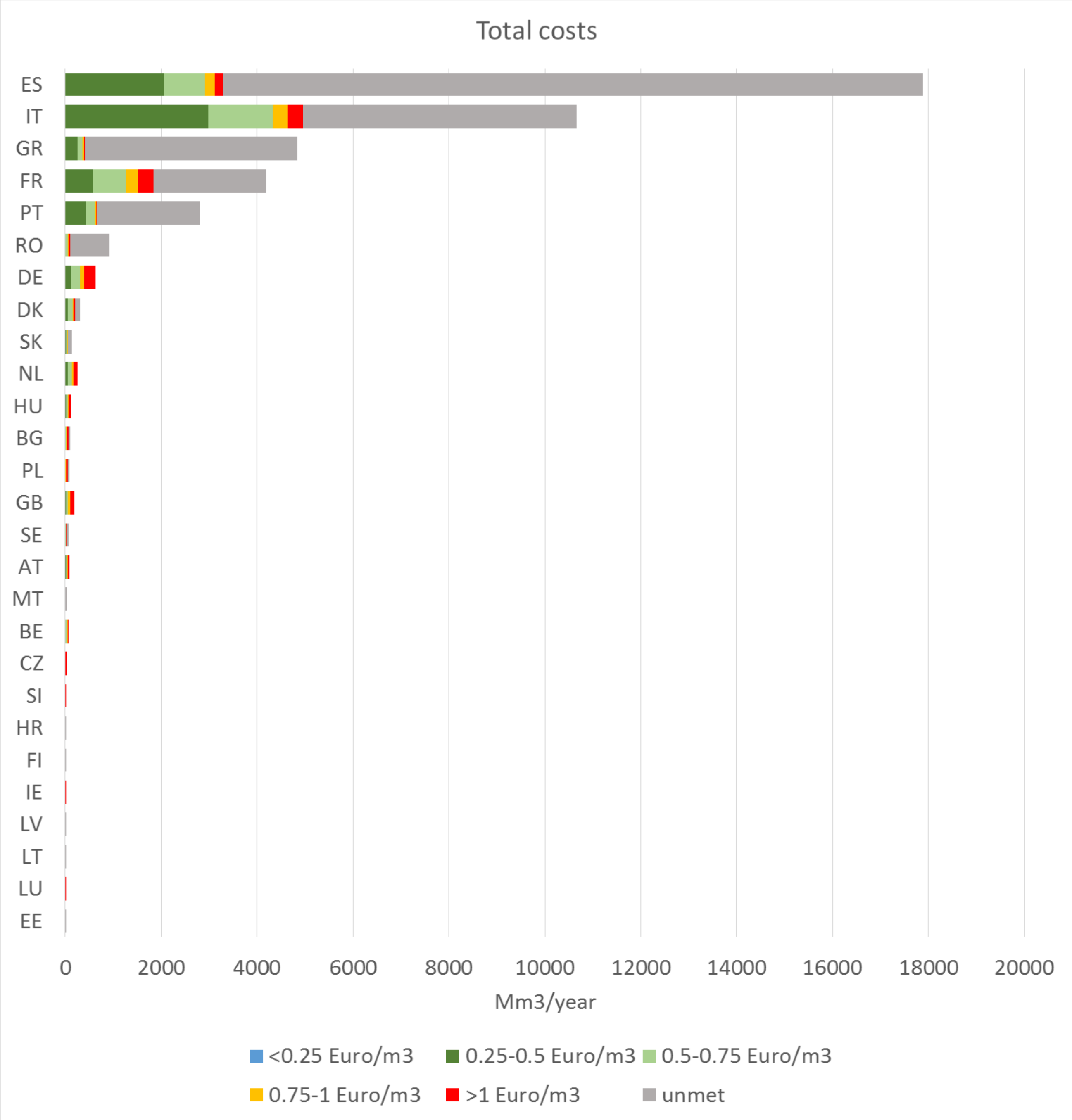

Figure 12 – WMCC by country: amounts of reclaimed water that can be potentially deployed at different total costs for 27 Member States of the EU (Cyprus not included due to missing irrigation estimates). “Unmet” represents irrigation demand estimated for the Country, in excess of potential supply of reclaimed water.

Country[13]	Potential contribution of reuse to total irrigation demand	Availability at WWTPs	Total that can be allocated near WWTPs at cost <0.50 Euro/m3	Total that can be allocated near WWTPs at cost <0.75 Euro/m3	Total that can be allocated near WWTPs at cost <1.00 Euro/m3	Total that can be allocated near WWTPs, regardless of cost
EE	0%	80,710,881	0	0	0	0
LU	>100%	42,159,474	0	0	0	291,747
LT	32%	180,393,800	0	0	0	50,601
LV	52%	351,587,408	0	0	0	104,500
IE	>100%	1,199,386,263	0	0	151,544	1,019,289
FI	55%	320,255,823	0	49,322	49,322	304,968
HR	72%	254,634,919	0	106,241	527,974	1,716,665
SI	>100%	63,329,276	10,738	1,261,988	1,845,014	7,864,075
CZ	>100%	830,070,479	984,502	3,662,037	8,867,334	28,279,623
BE	>100%	466,779,792	9,988,330	33,642,062	47,647,722	67,571,968
MT	11%	3,248,802	2,105,120	3,220,615	3,220,615	3,248,802
AT	>100%	831,719,537	16,311,278	42,743,783	60,239,583	78,986,625
SE	57%	764,770,821	4,210,681	13,981,552	21,773,475	43,679,832
GB	>100%	5,785,815,226	15,500,235	58,601,739	96,543,751	185,791,041
PL	70%	2,028,581,131	3,642,971	8,007,047	15,176,989	59,899,677
BG	64%	1,163,546,557	5,081,551	21,790,825	33,979,099	63,463,880
HU	>100%	692,694,899	14,492,705	50,824,172	76,741,542	125,040,578
NL	>100%	961,098,462	55,384,515	136,019,148	174,624,874	264,433,029
SK	41%	191,797,107	23,263,986	41,306,224	45,132,670	54,429,211
DK	66%	609,431,705	49,627,876	147,432,734	178,523,742	199,487,876
DE	>100%	6,759,616,101	114,005,271	307,973,324	391,759,987	624,227,536
RO	11%	743,414,782	7,069,214	46,117,963	62,122,308	99,146,222
PT	23%	1,278,557,567	419,548,259	615,287,198	642,864,618	660,784,949
FR	44%	4,998,793,967	585,455,579	1,268,202,301	1,523,413,127	1,845,451,653
GR	9%	1,153,447,397	262,661,751	365,334,342	389,279,661	417,500,899
IT	47%	9,769,661,947	2,975,901,472	4,322,660,101	4,633,978,319	4,962,268,684
ES	18%	7,114,641,769	2,054,500,907	2,916,624,439	3,113,292,590	3,295,147,922
TOTAL		48,640,145,892	6,619,746,941	10,404,849,158	11,521,755,863	13,090,191,851

Table 12 – potential contribution of reclaimed water to irrigation demand, by EU Member State (Cyprus not included due to missing irrigation estimates). Potential contribution to irrigation demand is computed as water that can be allocated, regardless of costs, in the neighborhood of wastewater treatment plants within each country, divided by the total irrigation demand estimated for the country. Amounts of water that can be allocated at different total costs (including investment, energy and treatment) are also provided by country.

[13] EE=Estonia ; LU=Luxembourg ; LT=Lithuania ; LV = Latvia ; IE=Ireland ; FI=Finland ; HR=Croatia; SI=Slovenia; CZ=Czech Republic; BE=Belgium; MT=Malta; AT=Austria; SE=Sweden ; GB= United Kingdom of Great Britain and Northern Ireland ; PL=Poland ; BG=Bulgaria ; HU=Hungary ; NL=The Netherlands ; SK=Slovakia ; DK=Denmark ; DE=Germany ; RO=Romania ; PT=Portugal ; FR=France ; GR=Greece; IT=Italy; ES=Spain.

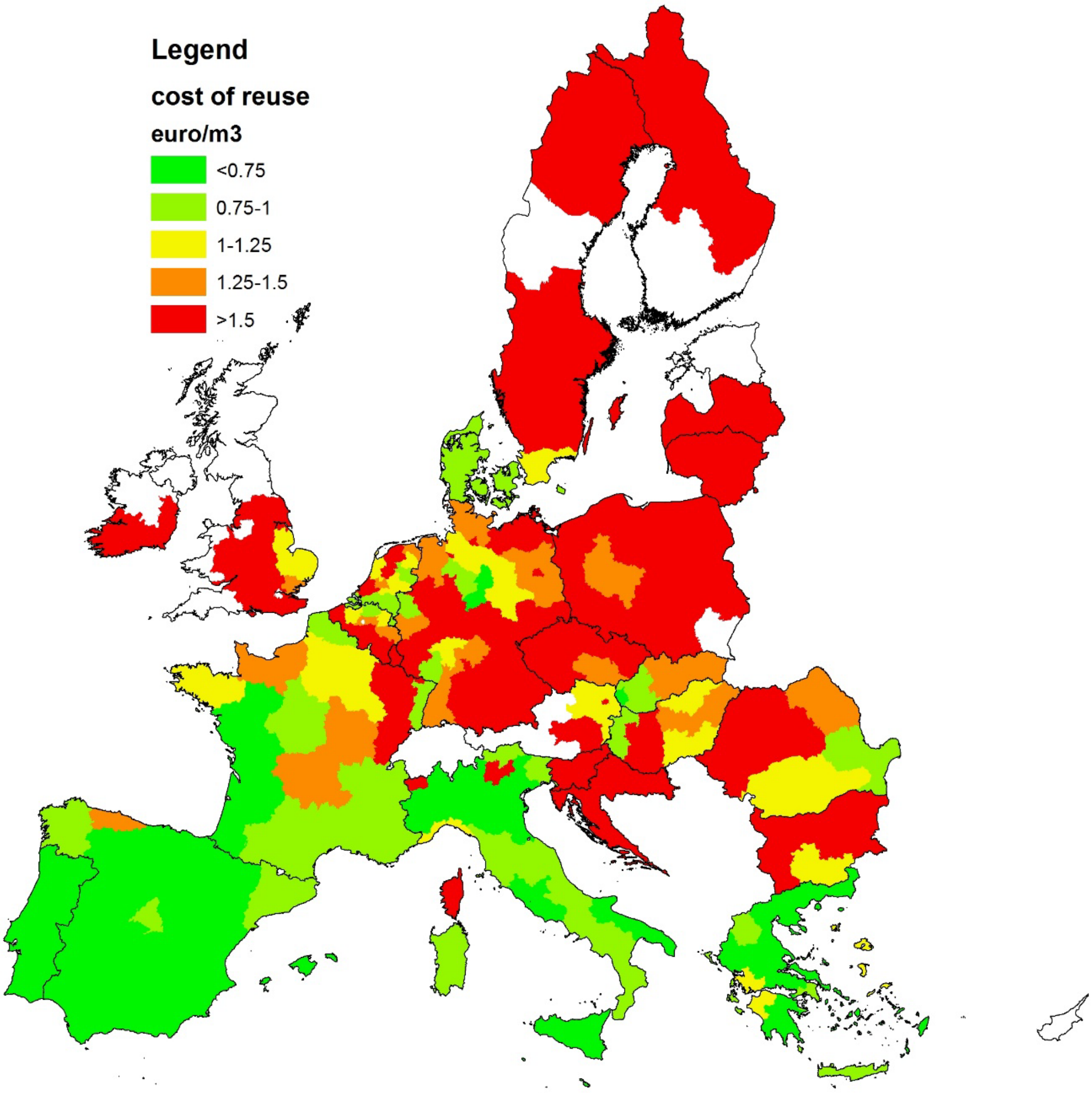

Figure 13 – conventional average unit cost of reused water per NUTS2 region (Cyprus not included due to missing irrigation estimates).

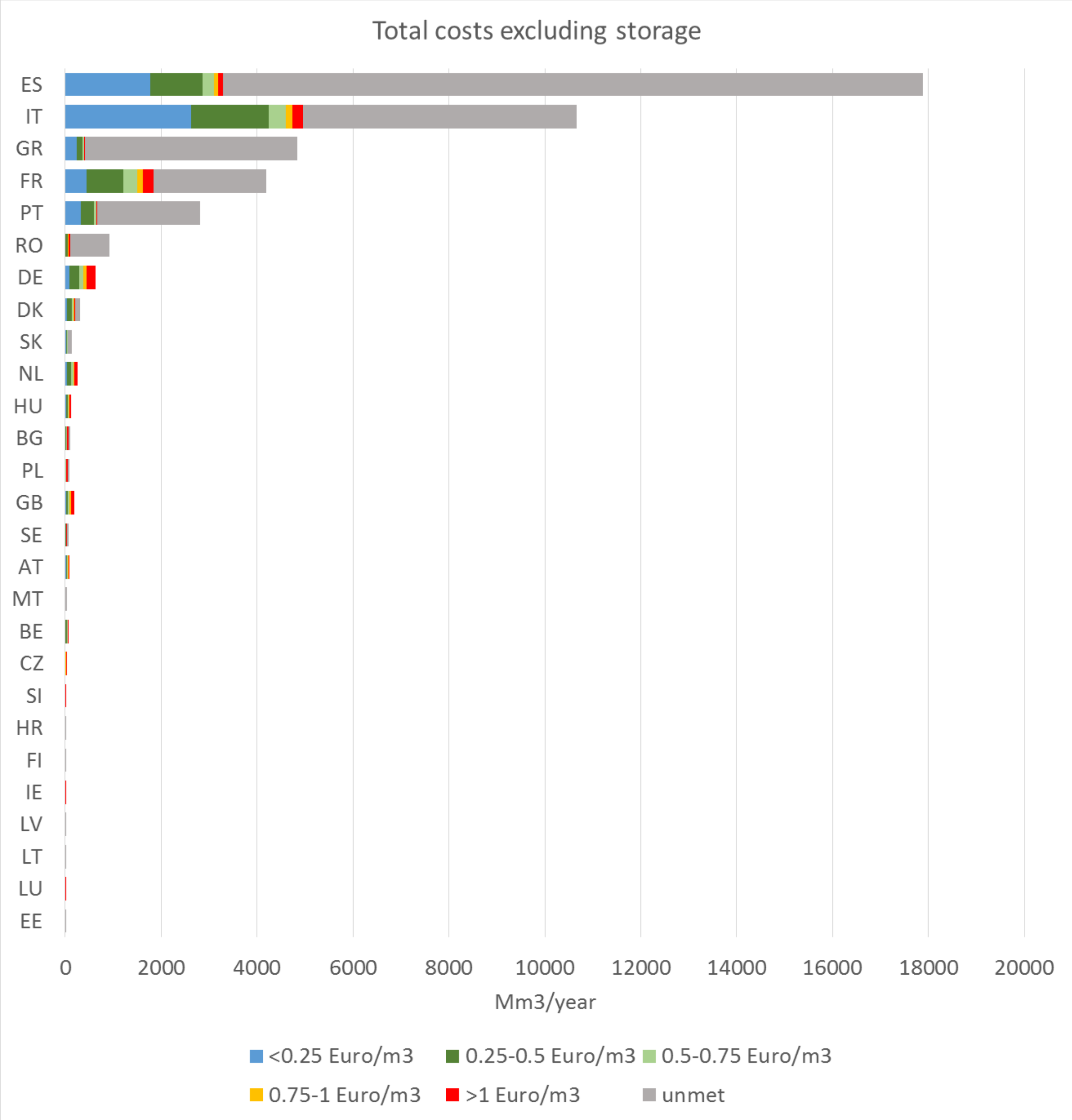

Figure 14– WMCC by country: amounts of reclaimed water that can be potentially deployed at different total costs excluding storage, for 27 Member States of the EU (Cyprus not included due to missing irrigation estimates)

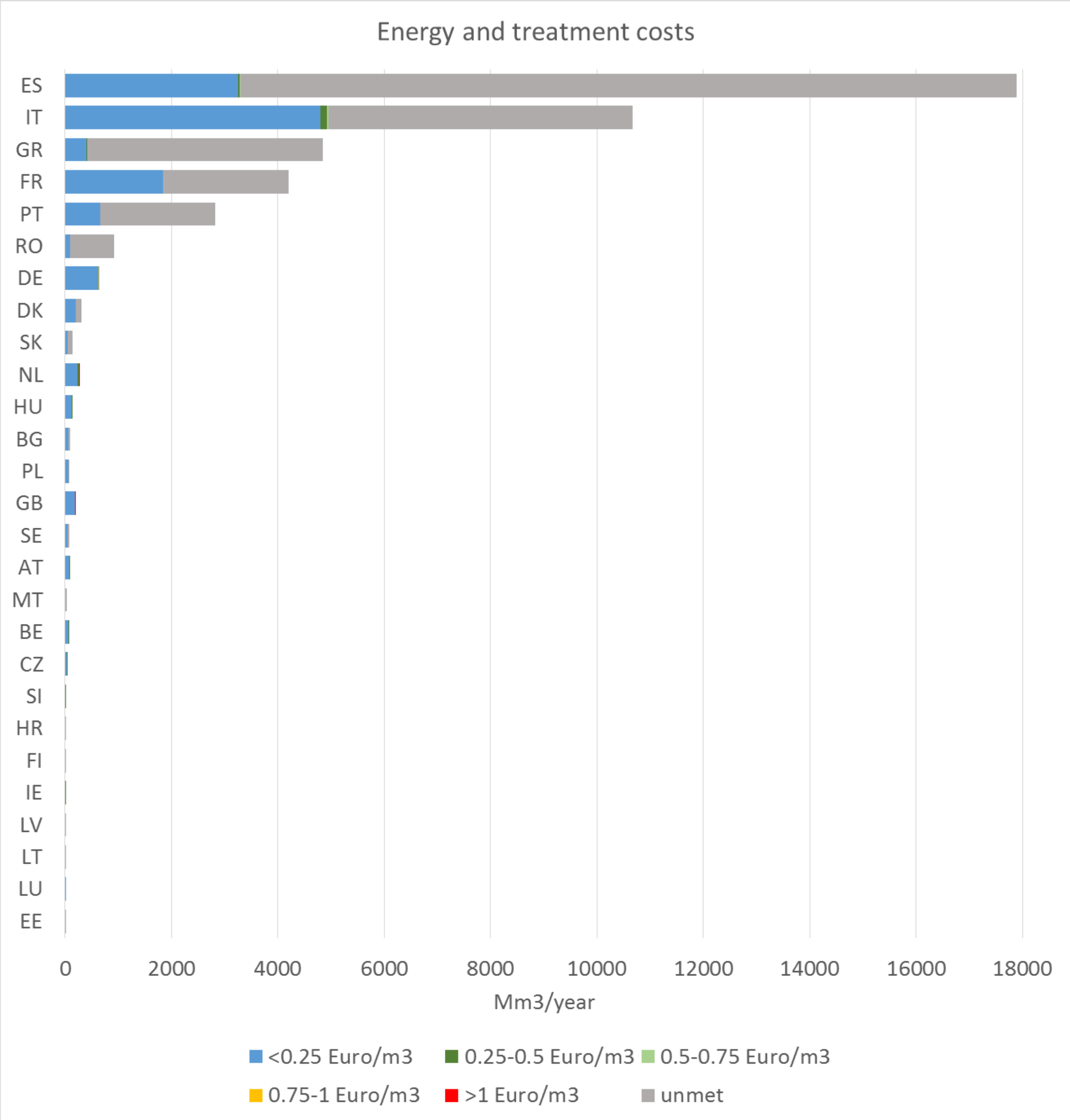

Figure 15– WMCC by country: amounts of reclaimed water that can be potentially deployed at different energy and treatment costs for 27 Member States of the EU (Cyprus not included due to missing irrigation estimates)

9 Crop market value produced by irrigation

Irrigation may have an intrinsic value for a farm, as a certain production would not be physically and/or economically possible without irrigation. Assessing the economic value of the agricultural production enabled by irrigation is beyond the scope of this assessment. In this exercise, we consider only a partial indicator, given by the amount paid on the market for the crop yield generated by one m^3 of irrigation water.

It should be noted that, even within the declared limits of the indicator, the market price of crops may be only a rough proxy, as in some cases (e.g. fruits) agricultural produce without irrigation might not meet quality characteristics enabling its sale on the market.

The market price of the additional crops produced with irrigation ("price of irrigated crops") is estimated for each grid cell of the European EPIC model setup. For the l-th grid cell, the crop market value produced by irrigation is:

Equation 25

$$CMV_l = \frac{\sum_{h=1}^{21} DW_h \delta_{h,l}(Y_{h,l} - Yr_{h,l})A_{h,l}}{\sum_{h=1}^{21} A_{h,l} Irr_{h,l}}$$

where $Irr_{h,l}$is the unit requirement of the h-th crop in the grid cell, $A_{h,l}$ is the area of the h-th crop in the cell, $Yr_{h,l}$ and $Y_{h,l}$ are the yield of the h-th crop simulated by EPIC under rainfed and unrestricted irrigation respectively, $\delta_{h,l}$ is the market price of the h-th crop, DW_h is a conversion factor from dry weight (as EPIC predicts yields) to wet weight (as market prices are reported for by EUROSTAT) for the h-th crop. The market price for the 21 EPIC crops considered here is shown in Table 14, while DW_h is provided in Table 13.

Crop	EPIC Code	Dry to wet yield conversion factor (dimensionless)
Apple	APPL	6.25
barley	BARL	1.11
Durum wheat	DWHE	1.11
Grassland	GRAE	1.14
Intensive managed grassland	GRAI	1.14
Forage mais	MAIF	2.86
Grain maize	MAIZ	1.11
Oats	OATS	1.11
other forage crops	OFAR	1.14
olive	OLIV	2.8
Potatoes	POTA	5
pulses crops	PULS	1.11
Rapeseed	RAPE	1.15
Rice	RICE	1.11
Rye	RYEM	1.11
Soybeans	SOYA	1.11
Sugarbeet	SUGB	5
Sunflower	SUNF	1.11
Spring wheat	SWHE	1.11
Tomatoes (meaning all vegetables	TOMA	16.67
Vineards	TWIN	10

Table 13 – dry to wet weight conversion factor for the 22 EPIC crops considered here.

Based on these assumptions, we obtain the market price of the incremental crop yield enabled by irrigation for each EPIC site as shown in Figure 15. As this market price corresponds to a given amount of irrigation water allowing an incremental yield compared to rainfed agriculture, it is expressed in €/m^3. We assume that, if irrigation is currently below a total of 1000 m^3/year at a site, or the difference in yield from rainfed to irrigated production is less than 20%, irrigation does not represent a significant factor of added value at the site.

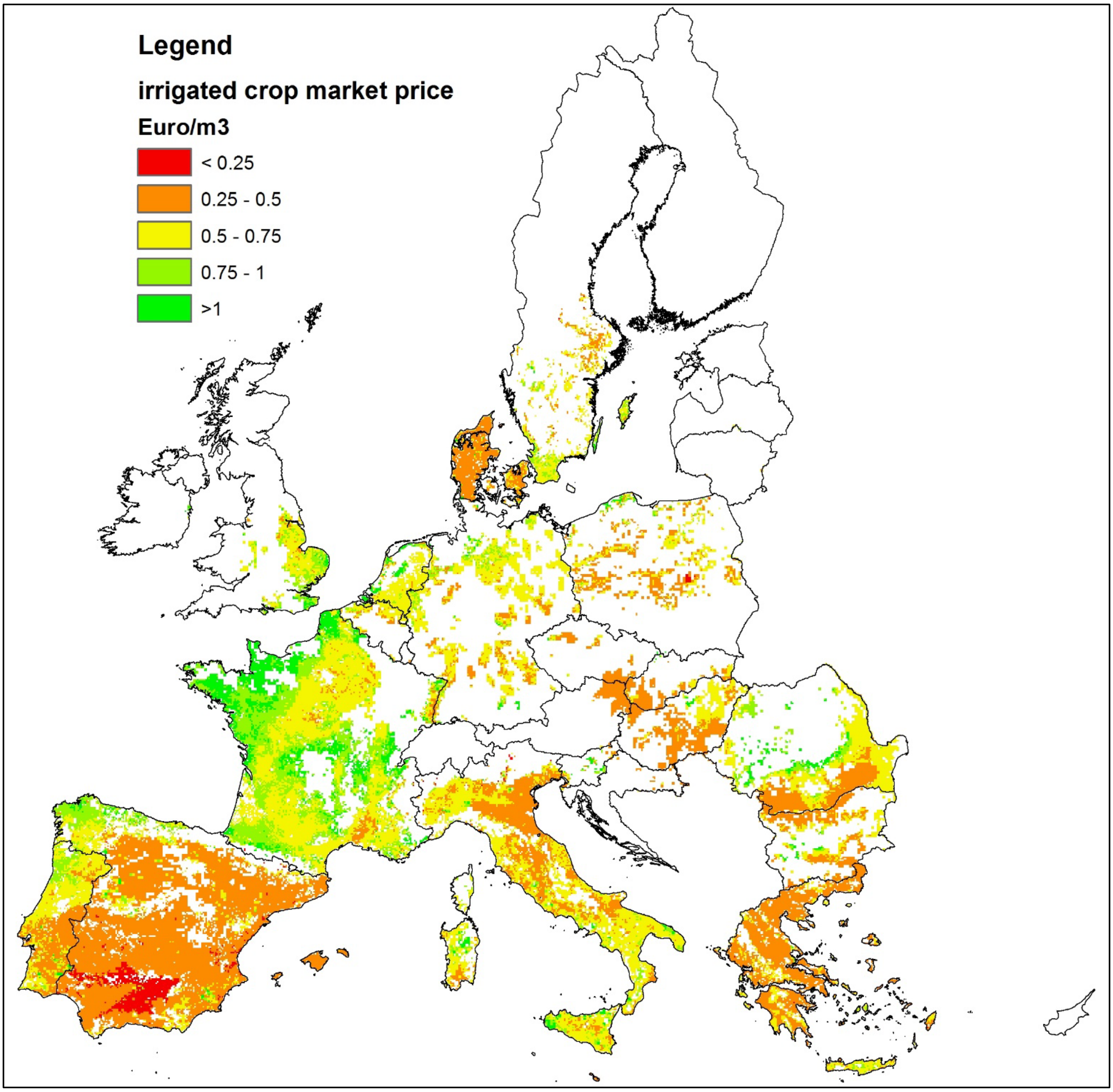

Figure 16 – estimated market price of the production associated with one cubic meter of irrigation water (Cyprus not included due to missing irrigation estimates). The map excludes sites where irrigation is currently estimated to be below 1000 m^3/year, and where the difference between irrigated and non-irrigated yields is below 20%.

Country	APPL	BARL	DWHE	GRAE	GRAI	MAIF	MAIZ	OATS	OFAR	OLIV	POTA	PULS	RAPE	RICE	RYEM	SOYA	SUGB	SUNF	SWHE	TOMA	TWIN
AT	415.91	164.89	229.78	128.26	128.26	148.08	148.08	124.23	140.78	1090.28	158.57	3846.95	339.94	288.46	140.78	333.42	30.69	297.49	148.04	283.83	544.11
BE	456.87	150.78	232.82	158.71	158.71	167.79	167.79	137.99	107	1090.28	105.68	1833	341.98	288.46	107	348.19	29.52	340.35	168.15	643.45	830.77
BG	318.91	144.84	165.68	143.98	143.98	148.83	148.83	154.02	142.96	1090.28	219.48	1193.25	330.36	283.97	142.96	433.05	27.32	309.3	153.7	284.76	289.06
CY	671	209.78	258.08	216.46	216.46	167.79	167.79	397.38	147.64	1341.3	412.19	3000.25	341.98	288.46	147.64	348.19	32.21	340.35	171.64	643.45	329.14
CZ	363.35	168.06	232.82	141.66	141.66	158.33	158.33	214.86	156.12	1090.28	173.99	1833	367.14	288.46	156.12	348.19	30.57	342.33	168.04	758.72	621.75
DE	460.02	164.89	232.82	158.4	158.4	175.32	175.32	165.32	155.31	1090.28	157.98	1833	357.86	288.46	155.31	348.19	32.21	340.35	176	594.56	830.77
DK	527.22	168.96	232.82	170.6	170.6	167.79	167.79	151.22	149	1090.28	253.62	1833	358.68	288.46	149	348.19	19.34	340.35	168.82	643.45	830.77
EE	527.78	148.3	232.82	159.32	159.32	167.79	167.79	118.5	138.1	1090.28	235.28	1833	358.8	288.46	138.1	348.19	32.21	340.35	168.68	643.45	830.77
EL	620.81	183.41	214.75	180.2	180.2	207.44	207.44	191.33	138.68	1937.44	477.69	2941.43	341.98	217.62	138.68	348.19	26.02	370.83	200.31	520.78	416.26
ES	393.32	171.98	247.47	170.21	170.21	187.27	187.27	166.25	163.18	525.65	224.3	1988.82	281.13	288.02	163.18	362.85	32.79	360.85	187.94	566.89	327.18
FI	1500.89	153.25	232.82	140.14	140.14	167.79	167.79	140.16	186.43	1090.28	181.38	1833	363.35	288.46	186.43	348.19	33.84	340.35	172.28	643.45	830.77
FR	459.63	202.14	338.22	222.83	222.83	193.93	193.93	227.92	156.2	1655.8	346.7	350	311.52	261.8	156.2	334.74	27.99	417.09	207.61	643.45	5415
HR	341.57	165.53	195.53	152.2	152.2	155.47	155.47	147.7	159.8	1092.97	177.48	1865.83	356.47	288.46	159.8	354.62	34.18	315.27	158.92	504.98	659.07
HU	268.42	141.28	212.36	134.98	134.98	148.26	148.26	147.44	134.76	1090.28	206.02	818.92	355.72	238.11	134.76	339.14	29.07	340.5	157.3	564.2	297.38
IE	527.78	200.1	232.82	158.71	158.71	167.79	167.79	152.03	147.64	1090.28	235.28	1833	341.98	288.46	147.64	348.19	32.21	340.35	147.43	643.45	830.77
IT	429.92	164.89	262.83	158.71	158.71	188.39	188.39	205.74	147.64	1090.28	384.48	1825.5	341.98	442.83	147.64	348.19	32.21	340.35	221.21	664.19	830.77
LT	310.54	151.85	232.82	145.33	145.33	163.09	163.09	119.22	129.67	1090.28	165.04	1833	340.48	288.46	129.67	348.19	35.14	340.35	168.78	2174.3	830.77
LU	1264	136.67	232.82	133.69	133.69	166.66	166.66	121.32	131.81	1090.28	319.69	1833	324.54	288.46	131.81	348.19	32.21	340.35	163.14	643.45	1154.9
LV	309.25	143.19	232.82	142.35	142.35	167.79	167.79	117.42	131.73	1090.28	146.67	1833	336.63	288.46	131.73	348.19	36.58	340.35	165.17	643.45	830.77
MT	396.4	164.89	232.82	158.71	158.71	167.79	167.79	167.21	147.64	586.98	311.71	1833	341.98	288.46	147.64	348.19	32.21	340.35	171.64	660.34	830.77
NL	513.65	164.89	232.82	161.25	161.25	151	151	171.5	146.75	1090.28	137.24	1833	330.35	288.46	146.75	348.19	45.55	340.35	169.78	643.45	830.77
PL	153.09	155.68	232.82	147.37	147.37	146.36	146.36	124.51	134.81	1090.28	118.74	1016.65	347.72	288.46	134.81	348.19	30.17	340.35	170.03	282.84	830.77
PT	619.52	187.01	233.71	177.13	177.13	183.51	183.51	173.3	180.22	491.81	234.96	1380.8	341.98	286.9	180.22	348.19	46.99	366.38	182.32	600.13	335.2
RO	608.25	193.91	232.82	203.22	203.22	202.36	202.36	227.07	147.64	1090.28	322.97	1659.52	325.69	288.46	147.64	305.1	33.37	314.41	169.54	634.83	327.8
SE	642.51	149.21	232.82	140.38	140.38	167.79	167.79	128.87	147.86	1090.28	281.02	1833	352.69	288.46	147.86	348.19	26.9	340.35	171.34	643.45	830.77
SI	472.25	147.8	232.82	147.59	147.59	149.43	149.43	176.1	172.78	1090.28	174.15	2839.95	335.73	288.46	172.78	343.53	32.21	329	164.52	647.88	466.69
SK	360.51	164.59	202.65	132.82	132.82	146.57	146.57	160.12	144.19	1090.28	234.62	934.15	355.99	288.46	144.19	327.27	34.59	320.72	150.21	551.96	447.19
UK	844.4	154.23	232.82	158.71	158.71	167.79	167.79	153.11	147.64	1090.28	190.83	1833	350.82	288.46	147.64	348.19	33.65	340.35	183.31	643.45	830.77

Table 14 - Crop prices by country (Euro/tonne of wet weight) from EUROSTAT. Crops are represented by EPIC codes (Table 13).

10 Implications of different quality requirements on the costs and benefits of water reuse

The analysis presented until now is based on assuming a levelized treatment cost of water equal to 0.08 €/m3 on average. It has been assumed that this represents an average cost when treatment with depth filtration and disinfection (DF+Dis) may be accepted. When more stringent quality standards are imposed, treatment may require micro-filtration and disinfection (MF+Dis) with a higher cost of treatment, equal to 0.23 €/m3 on average (see § 5.2). The effect of this extra cost is to shift the levelized costs of water up by 15 cents. As a consequence, the distribution of volumes is modified, and smaller volumes are available below or at a given cost (Figure 17).

When looking at the volumes that can be actually allocated in the neighborhood of existing wastewater treatment plants (Table 12), these are consistently reduced as shown in Table 15.

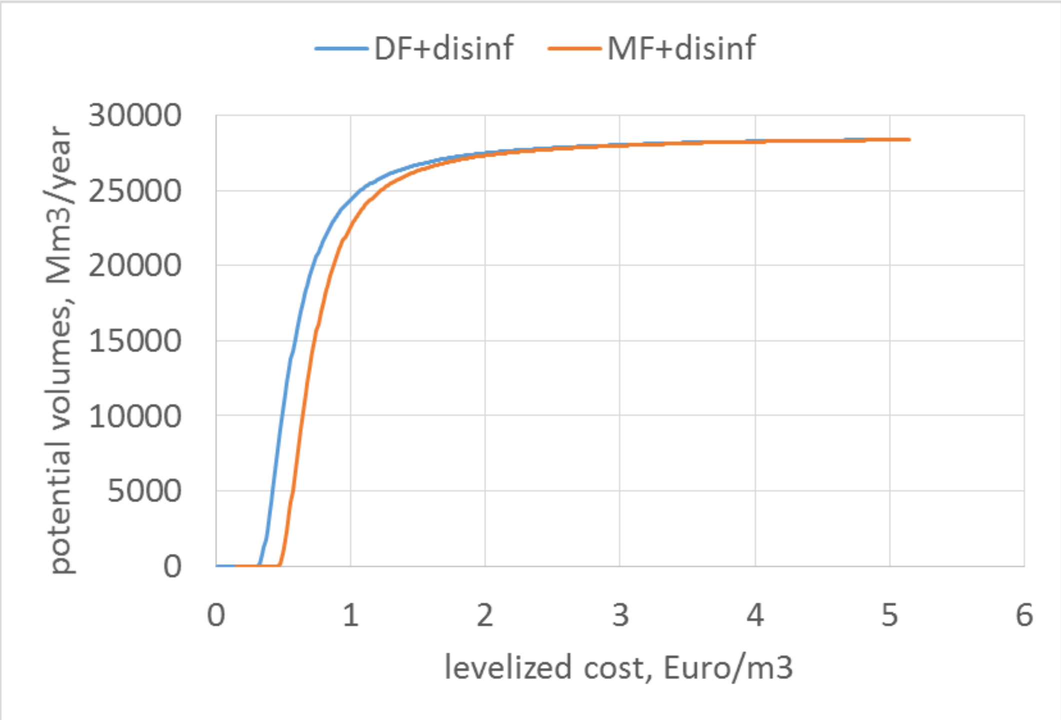

Figure 17 – shift in the distribution of potential volumes of reclaimed water (see §9) due to increased treatment costs. «DF+disinf» refers to the average treatment cost of 0.08 €/m3, while « MF+disinf» to 0.23 €/m3. The levelized cost in this graph includes all investment, operation and maintenance costs.

	Below 0.5 €/m3	**Below 0.75 €/m3**	**Below 1 €/m3**
DF+Dis	6,633,811,238.00	10,438,686,582.00	11,571,593,978.00
MF+Dis	827,229,354.00	8,747,570,594.00	11,028,173,972.00
% reduction	*87.5%*	*16.2%*	*4.7%*

Table 15 – cumulative volumes (m3) that can be allocated below or at a given cost in Europe, under « variable quality » and « higher quality » requirements. We refer to total (investment, operation and maintenance) costs.

In particular, much less water is available below 0.5 €/m3, while the impact is significantly lower if we consider higher cost thresholds.

The investments required for water treatment are expected to increase significantly per unit treatment capacity. When moving from a variable quality requirements assumption to a higher quality requirements assumption, investment costs of 38 Euro/(m3/day) on average would be replaced by investment costs of 271 Euro/(m3/day), the central values of the range in Iglesias et al., 2010 (Table 2). At the same time, the volumes to treat may be expected to decrease as per Table 15. The combined effect of these trends is that, under a higher quality requirements assumption, an investment of about 600 million Euro in Europe would allow treating about 800 million m3 yearly with a levelized total cost of reclaimed water below 0.5 Euro/m3, while a slightly higher investment (less than 700 million Euro) would allow treating more than 6,6 billion m3 yearly below the same cost threshold. When considering higher cost thresholds, applying more stringent water quality criteria in Europe would make investment costs surge in comparison with the variable quality requirements assumption (Figure 17). Whether the economic implications of systematically more stringent quality requirements (higher investments and levelized costs of water) are acceptable depends significantly on the specific conditions of different contexts in Europe. However, where the capacity to pay for the actual costs of water may be relatively low, it cannot be ignored that such economic aspects may represent a non-negligible disincentive to water reuse.

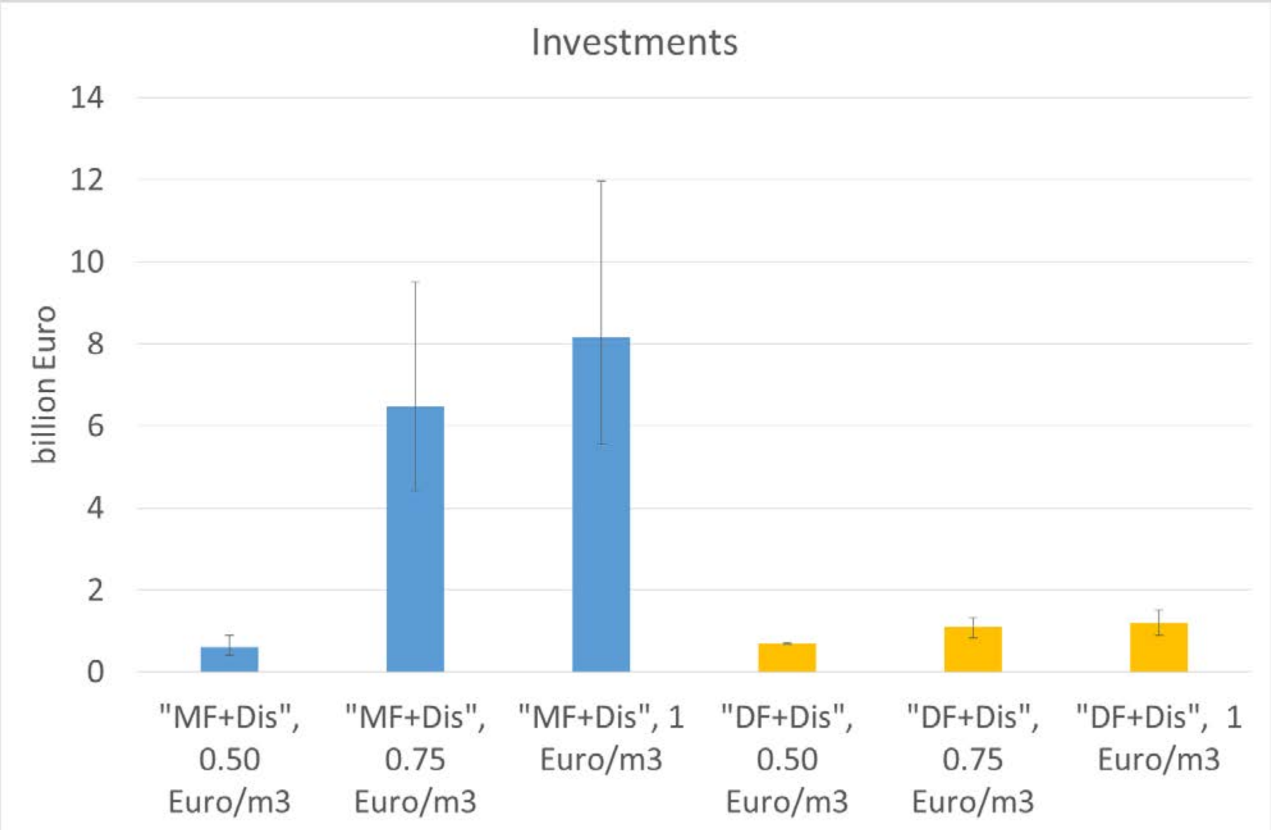

Figure 18 – investments required to treat the available volumes of water at a given threshold total cost, for the two assumed treatment levels.

11 Benefits associated with water reuse for irrigation

Reuse has two main types of benefits: on the one side, it may help reducing water stress by limiting freshwater abstractions; on the other, it may bring nutrients to agriculture, where they can act as fertilizers, therefore enabling a reduction of other fertilizer applications.

11.1 Water stress reduction

The contribution of water reuse to cover irrigation demand (Table 12) highlights its relevance in reducing water stress by reducing the corresponding water abstractions.

The share of agriculture on total water abstractions is variable across Europe, averaging about 60% in Southern countries, 11% in Eastern countries and 7% in Western countries[14].

With these figures in mind, and taking into account the volumes of irrigation demand and potentially reusable water shown in Table 12, we may estimate the % reduction of total abstractions that could be achieved with water reuse (Table 16). This ranges from 3.5% in the East, to more than 15% in the North, averaging around 10%[15]. This indicative percentage summarizes a much nuanced picture with significant variability not just among continental zones, but also within countries and regions. As such, it should be regarded as a first approximation indicator of the water stress reduction potential of reuse. Yet, while a more specific assessment may be needed in different contexts, this indicator highlights the relevance of the water reuse option in many regions of Europe.

Zone	(A) Total reuse potential, regardless of cost (km3/year)	(B) Irrigation demand (km3/year)	(C) Agricultural share of total abstraction	(A*C/B) Indicative potential % reduction of water absraction
East[14]	0.44	1.37	11%	3.5%
South[14]	9.34	36.2	60%	15.4%
West[14]	3.31	5.21	7%	4.2%

Table 16 – reduction of water abstraction potentially allowed by reuse in different European zones. Based on EEA data, 2017[14].

11.2 Reduction of nutrient loads

In this assessment, we focus on nitrogen (N) representing the most relevant constituent of treated effluents. The considerations developed for nitrogen apply largely to phosphorus (P) insofar as the distribution of the two is correlated in urban wastewater, although WWTPs with tertiary treatment level may reduce P more efficiently than N. Water reuse for irrigation implies contributing to the fertilization of crops through water with a certain concentration of N (and P). The nutrient loads arriving as input to wastewater treatment plants are estimated on the basis of the total protein consumption (for N and also the vegetable protein consumption (for P), following Bouraoui et al., 2011. The corresponding loads outflowing the WWTPs are estimated on the basis of treatment types as per Table 17.

Figure 18 compares the estimated loads of N at the outlet of wastewater treatment plants with the use of mineral N fertilizers reported by EUROSTAT for the EU member

[14] These percentages are the average of figures for the years 2000s and latest available year collected by EUROSTAT and reported by the European Environment Agency (EEA): https://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-2/assessment-2. Countries are grouped as follows: East: Bulgaria, Czech Republic, Estonia, Latvia, Lithuania, Hungary, Poland, Romania, Slovenia, Slovakia; South: Greece, Spain, Italy, Cyprus, Malta, Portugal; West: Belgium, Denmark, Germany, Ireland, France, Liechtenstein, Luxembourg, the Netherlands, Austria, Finland, Sweden, England and Wales, Iceland, Norway, Switzerland.

[15] Arithmetic average 7.7%, irrigation volume-weighted average 13.7%, average of the two 10.7%.

states, showing that the former represents a sizable share of the latter. It should be noted that water reuse *per se* provides access to N present in reclaimed water, whereas N inflowing the wastewater treatment plants may be recovered through various other treatment processes. While N (and P) recovery is an important aspect of the circular economy, this issue is beyond the scope of this assessment.

Treatment	N	P
Primary	0.25	0.30
Secondary	0.55	0.60
Tertiary	0.80	0.60
P removal		0.90

Table 17 – assumed removal efficiency of WWTPs for N and P

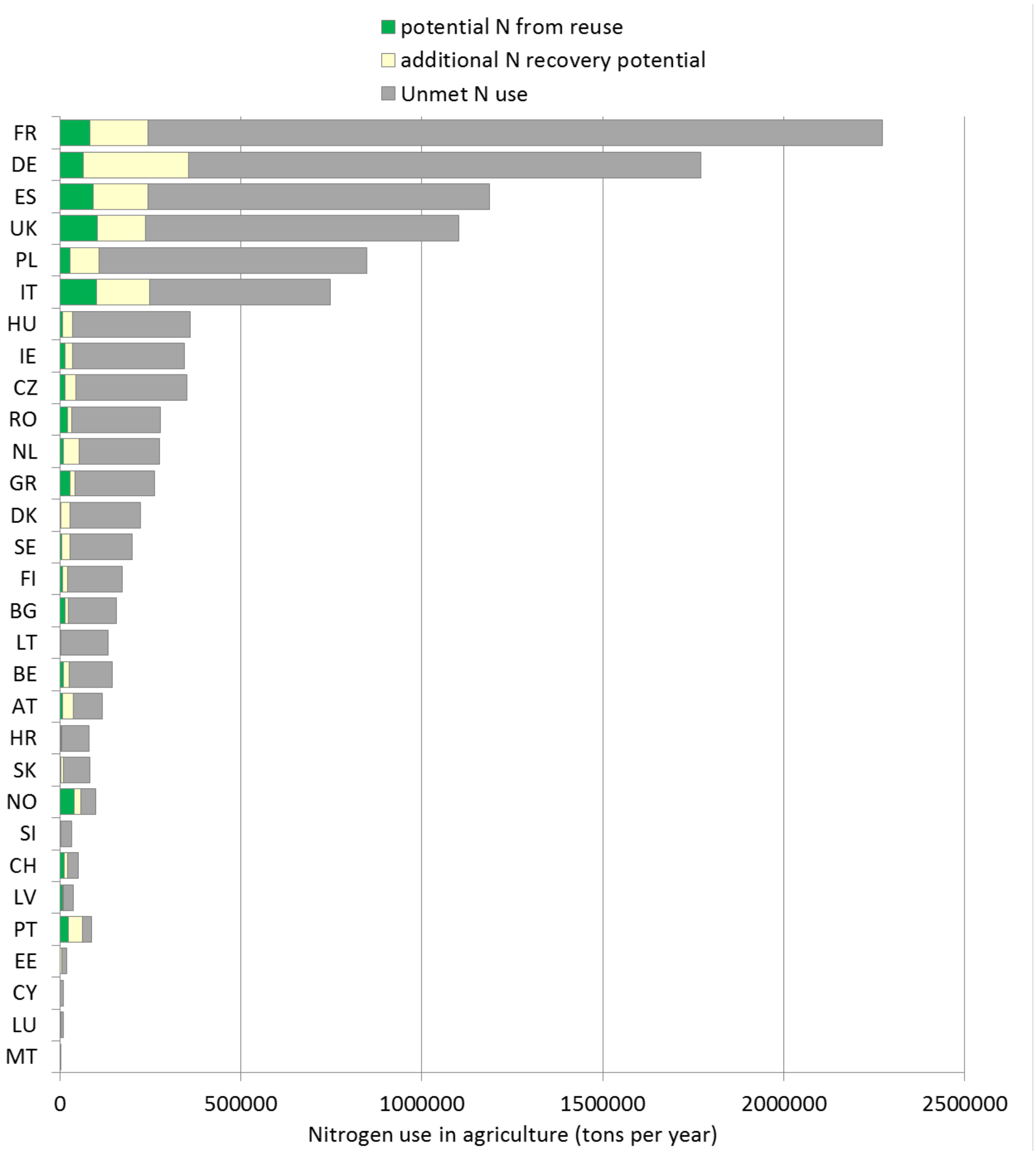

Figure 19 – comparison of N from reuse and mineral N fertilizer. N from water reuse is the load of N in treated wastewater, while the additional N recovery potential is N incoming the wastewater treatment plants, representing the theoretical upper limit of N recoverable as fertilizer. "Unmet N use" represents the amount of mineral N fertilizers in excess of potential N recovery.

11.3 Indicative economic valuation of the benefits

The benefits of reusing water, while clear in principle, depend very much on the local conditions where reuse is to be made. As reuse is meant to reduce irrigation water abstractions from surface and groundwater bodies, in principle it should be implemented only where the benefits from reducing abstractions exceed the benefits of discharging treated wastewater in the environment. In some cases, especially when treatment standards are high, discharges of treated wastewater may represent a positive input to the receiving water bodies, as they could sustain the flow regime while compensating other possibly existing hydrological alterations. In many cases, however, it is preferable to use treated wastewater in irrigation while reducing irrigation abstractions, because in this way the flow regime of water bodies is least disturbed, and nutrients conveyed by treated wastewater may be taken up by crops[16] instead of ending up in water bodies. Valuing the benefits that may stem from water reuse is overwhelmingly complex in general terms. One proxy of benefits is the willingness to pay of farmers for reclaimed water, which is extremely variable (for instance, Birol et al., 2007, estimate a willingness to pay higher than 0.6 Euro/m3 in Cyprus, while Tziakis et al., 2009, indicate less than 0.1 Euro/m3 for Crete).

Mattheiss and Zayas, 2016 analyse a case study in Braunschweig, Germany and another one in Sabadell, Spain. In Braunschweig, a survey has identified a willingness to pay of about 3 to 5 million euro/year for about 7 million m3/year of water reused to recharge aquifers, which could be interpreted as a valuation of water to improve flow regimes between 0.4 and 0.7 Euro/m3. In Sabadell, the willingness to pay of households for irrigation of green areas and street cleaning is estimated to exceed 5.5 million Euro/year, and the water demand for these activities is estimated at 1.1 million m3/year, indicating a value of water in the order of 5 Euro/m3.

Arborea et al., 2017, quantify the benefits of reusing water for irrigation in Puglia in the order of slightly less than 0.5 Euro/m3, including the direct and option benefits for the farmers and the benefits of maintaining good groundwater status.

Molinos Senante et al., 2011, quantify the benefits of reuse using shadow prices of pollutants (suspended solids, nutrients and Chemical Oxygen Demand) not being discharged to rivers (therefore assuming the impact of such pollutants through irrigation would be negligible). In addition, they consider a sale price of reclaimed water of 0.9 Euro/m3. The total net benefits summing these components are estimated at a mean value of 1.22 Euro/m3 for 13 wastewater treatment plants in Spain.

Maton et al., 2010, conduct a cost-benefit analysis for water reuse in western Crete, and show that net benefits of reuse depend significantly on the level of stress on water resources; for cases of high water stress, net benefits range between 0.35 and 1.92 Euro/m3. Alcon et al., 2010, estimate the Segura river basin population's willingness to pay for irrigation reuse at about 0.3 Euro/m3, which is presented as the non-market value of reused water. This should be summed to the willingness to pay of farmers or market value of reclaimed water, so that the overall value of reclaimed water can be arguably around 0.5 Euro/m3. Birol et al., 2009 present an estimate of the willingness to pay for aquifer recharge by local residents in Cyprus of about 1.3 Euro/m3.

In the context of the AQUAMONEY EU-funded project[17], the willingness to pay of the public has been assessed for different actions improving water quality, safety and security in a few case studies across Europe (Table 18). The case studies highlight a significant willingness to pay of households for a more sustainable management of water resources. This may support the idea that a part of the costs of water reuse could be

[16] This requires that nutrients in reused water are taken into account in the planning of crop fertilization, and that fertilization is efficient. If these conditions are not met, reuse may simply contribute to transfer pollution from surface water bodies (where wastewater is typically discharged) to soil and aquifers where fertilizers may leach.

[17] http://www.ivm.vu.nl/en/research-new/environmental-economics/projects/aquamoney/project-deliverables/index.aspx

borne by society/taxpayers and not only by the farmers alone, since water reuse generates additional benefits to society.

Case	Motivation	Willingness to pay
Vienna (AT)	Reduce flooding frequency and improve water quality	About 52 to 78 €/household/year
Hungary	Reduce flooding frequency and improve water quality	About 35 to 54 €/household/year
Braila (RO)	Reduce flooding frequency and improve water quality	About 9 to 22 €/household/year
Odense (DK)	Reduce flooding frequency and improve water quality	About 57 to 192 €/household/year
Po and Reno river basins (IT)	Ensure water availability for different sectors (agriculture, industry, energy,…) and the environment	About 10 to 40 €/household/year
Serpis (Jucar) river basin (ES)	Ensure domestic water supply and improve/maintain ecological status	297 €/household/year for supply; 64 to 104 for ecological status
Lesvos (EL)	Ensure domestic water supply and improve/maintain ecological status	287 €/household/year for supply; 44 to 253 for ecological status

Table 18 – case studies from the AQUAMONEY project.

In a paper on the Po plain in Italy, Musolino et al. (2017) quantify an impact of droughts on the overall welfare (of both farmers and consumers) in the order of 500-1000 million Euro/year during droughts. The affected population is more than 16 million persons. This may suggest a cost of about 30-60 Euro/person during drought years and is in fact in line with the figures on the willingness to pay provided above.

These examples highlight the large variability in valuation of water used to reduce water stress, and the uncertainty due to their high case-specificity. In this assessment, we adopt a benefit of water reuse of 0.5 Euro/m3, which is in the mid-lower end of the cases examined above, and may be argued to represent as a first approximation the combined market and non-market value of water reuse in Europe, provided it contributes to water stress. With this figure in mind, we may argue that all water that can be reused at a total cost below 0.5 Euro/m3 is likely to provide a net benefit.

12 Conclusions

A significant amount of water can be potentially reused for agricultural irrigation in Europe (Table 12). Out of more than 48 km3 of water available yearly from European wastewater treatment plants, about 13 km^3 can be in principle brought to agricultural land with sizable irrigation demand. This is a very significant potential contribution to the overall European irrigation demand, estimated at about 42 km^3 yearly. However, assuming treatment costs to make WWTP effluents reusable equal to 0.08 Euro/m^3, about a half of these 13 km^3 requires more than 0.50 Euro/m^3 to be deployed, including all costs of infrastructure, treatment and pumping, while some 12% of it may even require more than 1 Euro/m^3.

Treatment costs depend significantly on the conditions of the wastewater treatment plant and on the desired level of quality of reclaimed water. The available experiences suggest that treatment costs may be often relatively small compared to other costs. In the assessment presented here, we have assumed treatment to consist of deep filtration and disinfection, for which we assume a cost of 8 cents per m3 based on Iglesias et al., 2010. For more stringent treatment requirements, we may assume costs to increase by some 15 cents per m^3 (Table 6), causing an equivalent shift in all reuse costs.

Water available for reuse, and the costs of its deployment, vary significantly among regions and reflect the relative accessibility of agricultural land from wastewater treatment plants, with regions featuring WWTPs relatively close to agriculture having a substantial advantage. The energy requirements of water reuse, with an estimated median value around 0.5 kWh/m3, may be higher than typical requirements of irrigation using water sources closer to agriculture. The energy costs have an estimated median around 5 cents per m3, and the combined costs of treatment and pumping are usually below 0.25 Euro/m3. This suggests that, when irrigation infrastructure is already existing and fit to convey reclaimed water, the latter can be distributed below this level of cost.

By meeting part of the current irrigation demand, water reuse may contribute significantly also to reducing water stress. The incidence of irrigation abstractions on total abstractions (Table 16) suggests water reuse may reduce water stress by around 10% in the most stressed regions, when neglecting costs.

Benefits of water reuse may also include a reduction of nutrient (and particularly nitrogen) pollution. Treated wastewater conveys a small but sizable (10% on average) share of the mineral N fertilizer use in the European Union (Figure 18). Even without considering nutrients recovery within the wastewater treatment processes, the application of N with water reuse may contribute to reducing nutrient losses. This outcome, though is conditional to the adoption of efficient fertirrigation methods and should be considered with care on a case by case basis. When water reuse has significant co-benefits, it can be regarded to some extent as a river basin management measure contributing to the achievement of the objectives of the European water legislation.

A discussion about who should pay for water reuse is beyond the scope of this work. It should be noted, however, that the market value of crops produced through irrigation suggests the total costs of reclaimed water may often exceed the willingness or capacity of farmers to pay for it, even after taking into account the uncertainties and acknowledging that the crop value indicator is very rough. This indicates that the costs of water reuse, when deemed worth the respective benefits, should be considered in the context of the whole value chains that the agriculture supplies, and of river basin management.

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Abbreviations

(U)WWTP = (urban) wastewater treatment plant

CCM(2) = Catchment Characterization And Modelling (version 2)

CFU = colony-forming units (concentration of coliforms)

DF = depth filtration

F = filtration

LCOW = levelized cost of water

MBR = Membrane batch reactor

MF = microfiltration

N = nitrogen

NF = Nanofiltration

NTU = Nephelometric Turbidity Unit (turbidity)

NUTS = Nomenclature des unités territoriales statistiques

P = phosphorus

PE = population-equivalent

RO = Reverse osmosis

SS = suspended solids

UF = ultrafiltration

UV = ultra-violet disinfection

WMCC = water-marginal cost curve

Figures

Tables

Appendix 1 – WMCCs for the NUTS2 regions of the EU: total costs

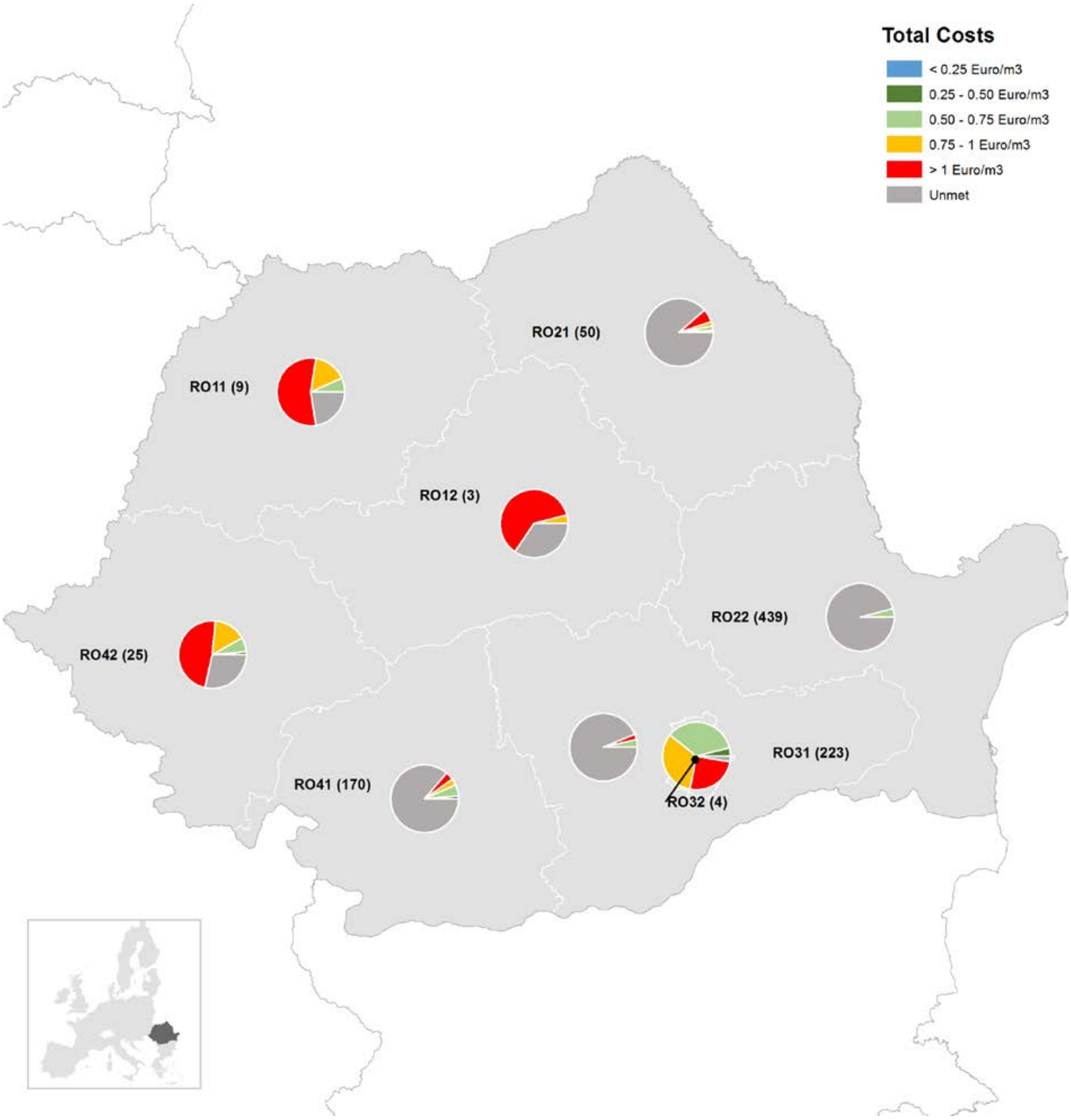

Figure 20– WMCC by NUTS2-level regions: reuse potential at various costs for RO

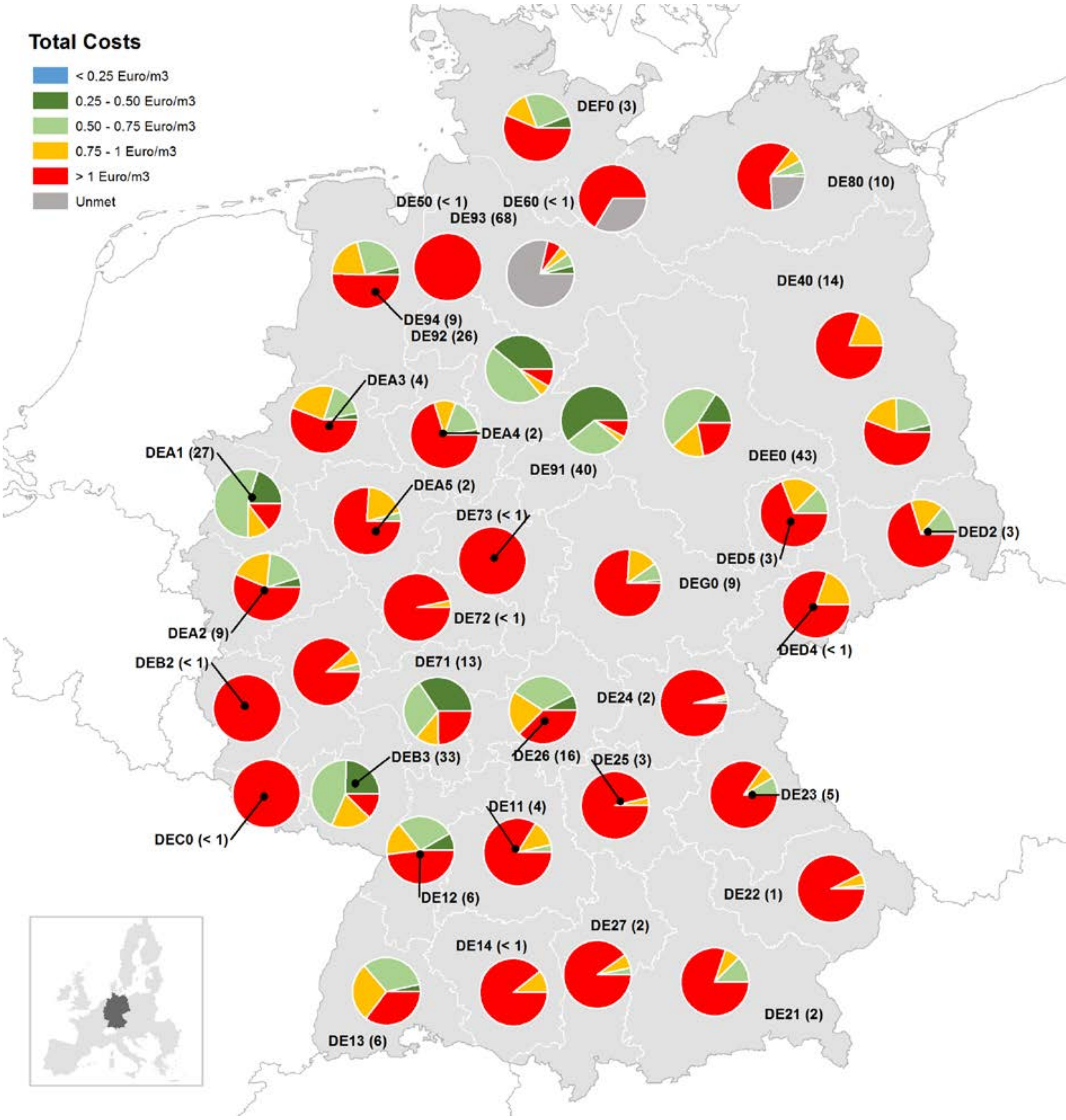

Figure 21– WMCC by NUTS2-level regions: reuse potential at various costs for DE

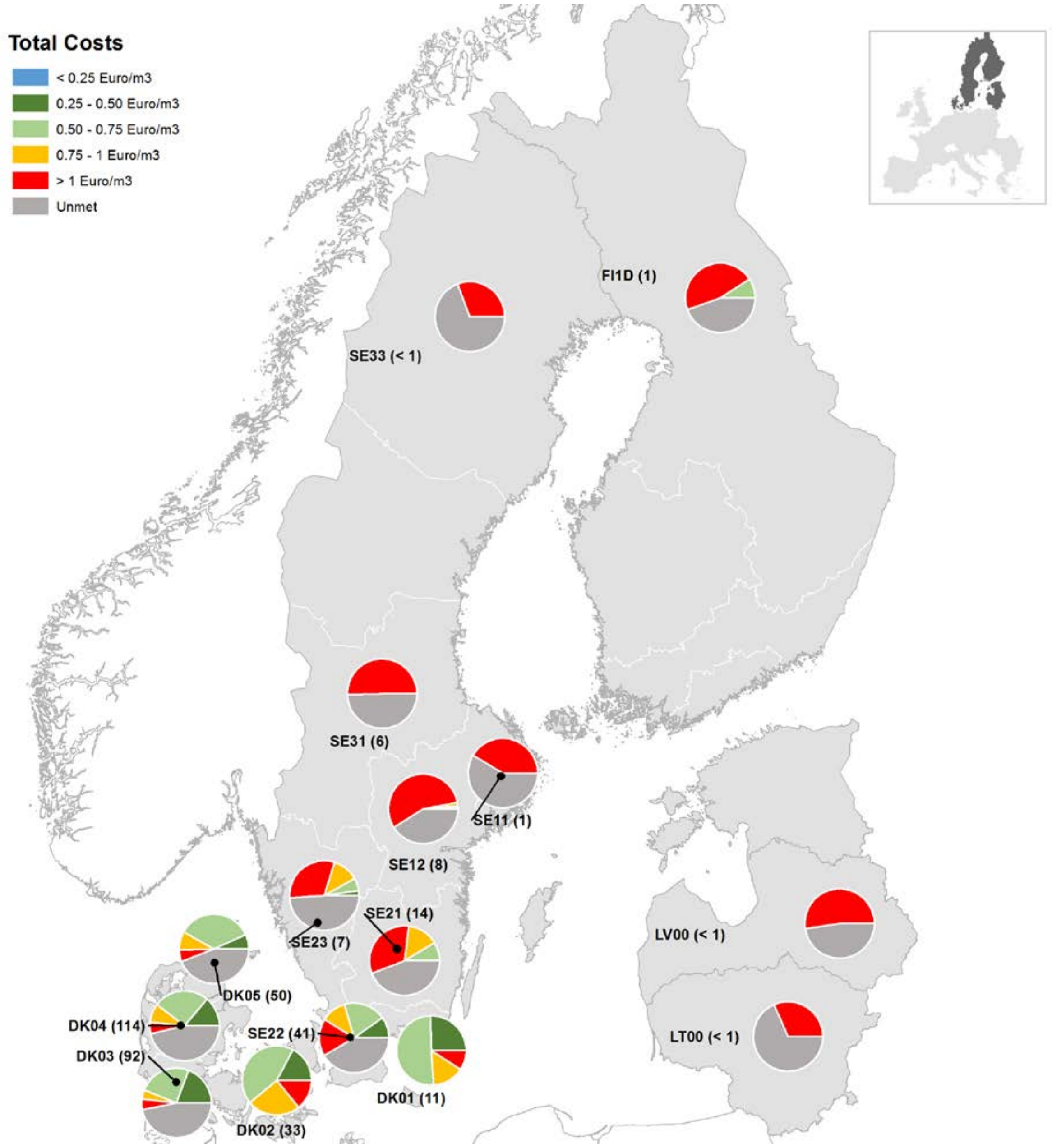

Figure 22 – WMCC by NUTS2-level regions: reuse potential at various costs for DK, SE, FI, EE, LV, LT

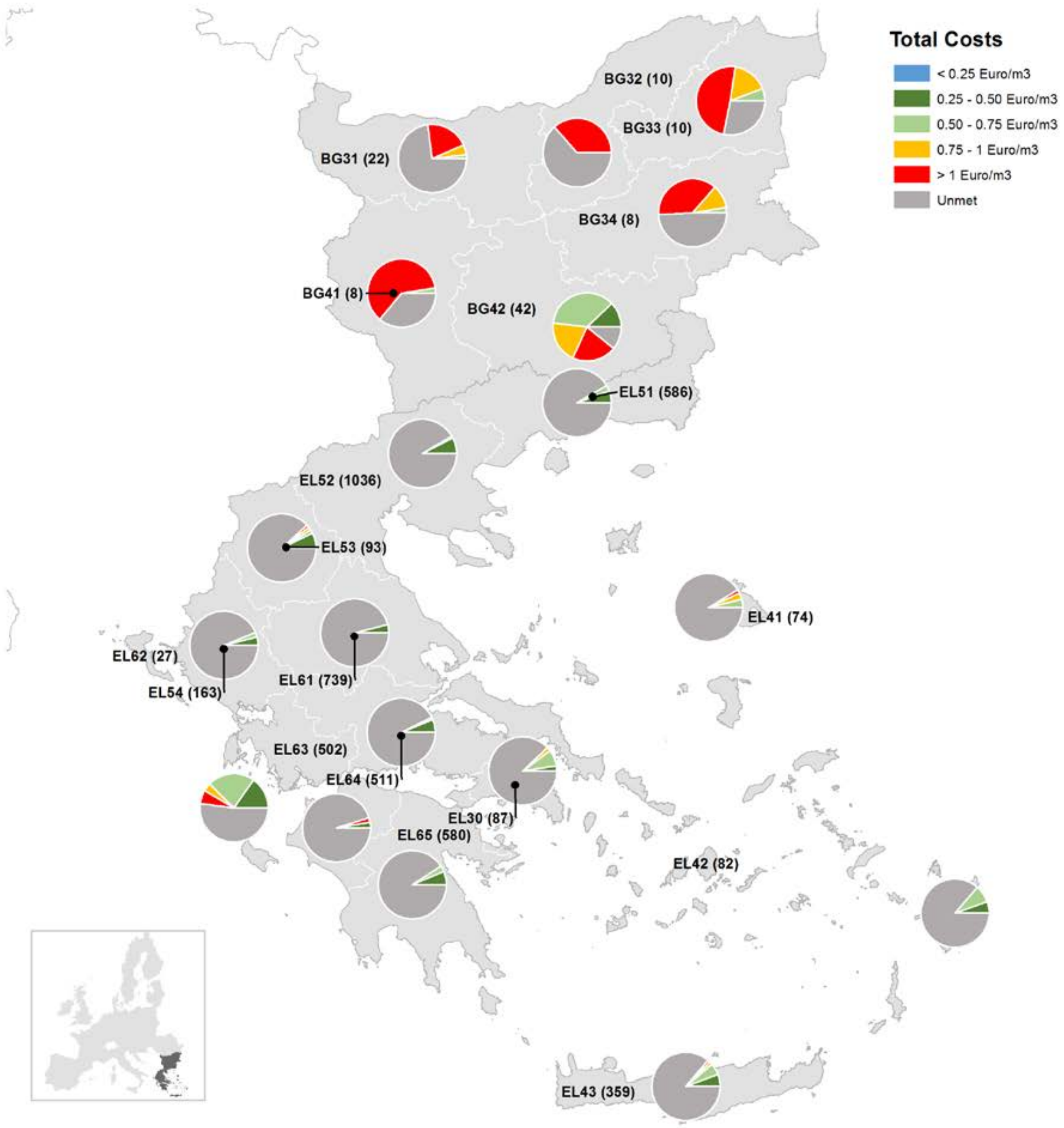

Figure 23– WMCC by NUTS2-level regions: reuse potential at various costs for GR and BG

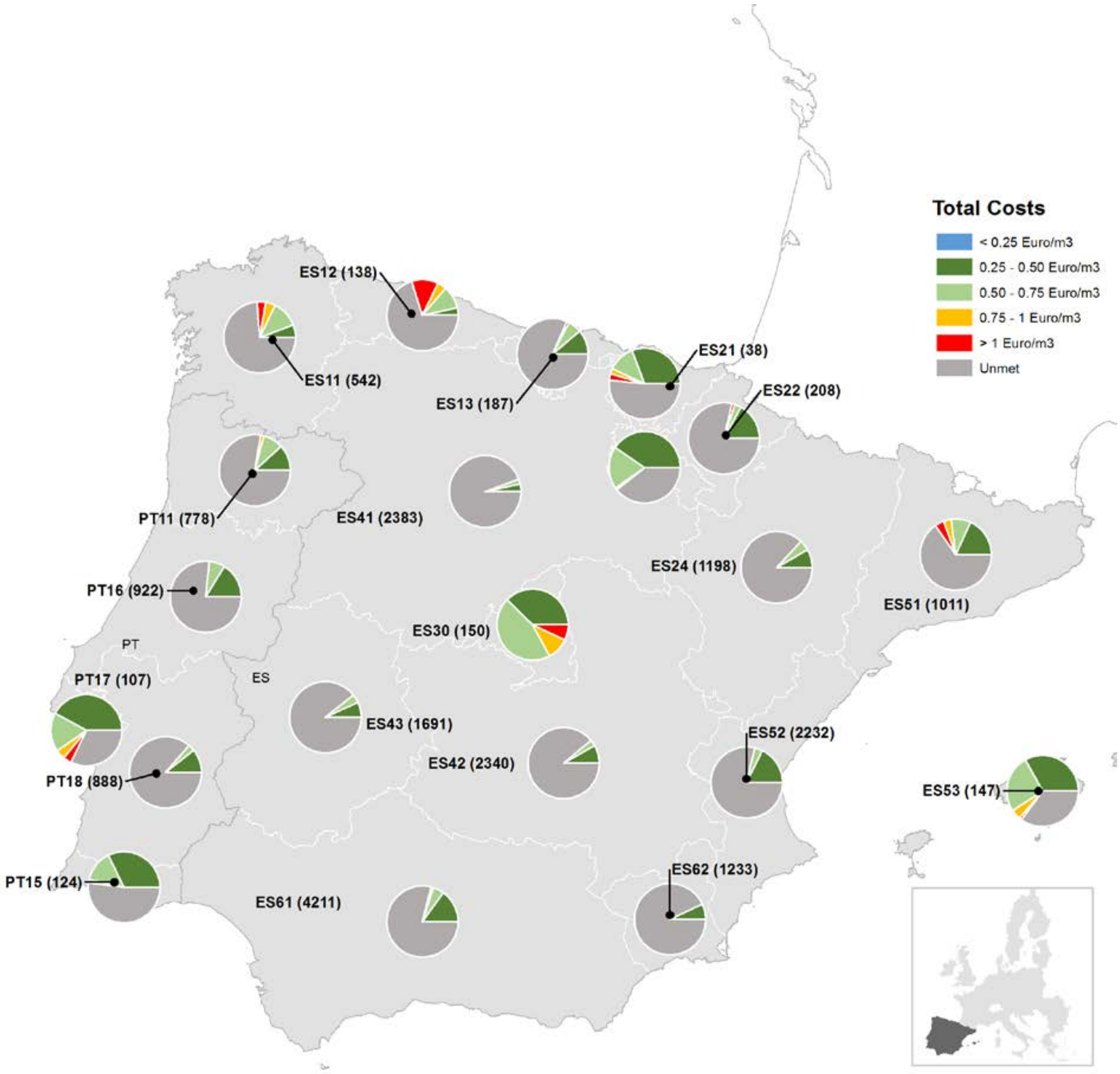

Figure 24– WMCC by NUTS2-level regions: reuse potential at various costs for PT and ES

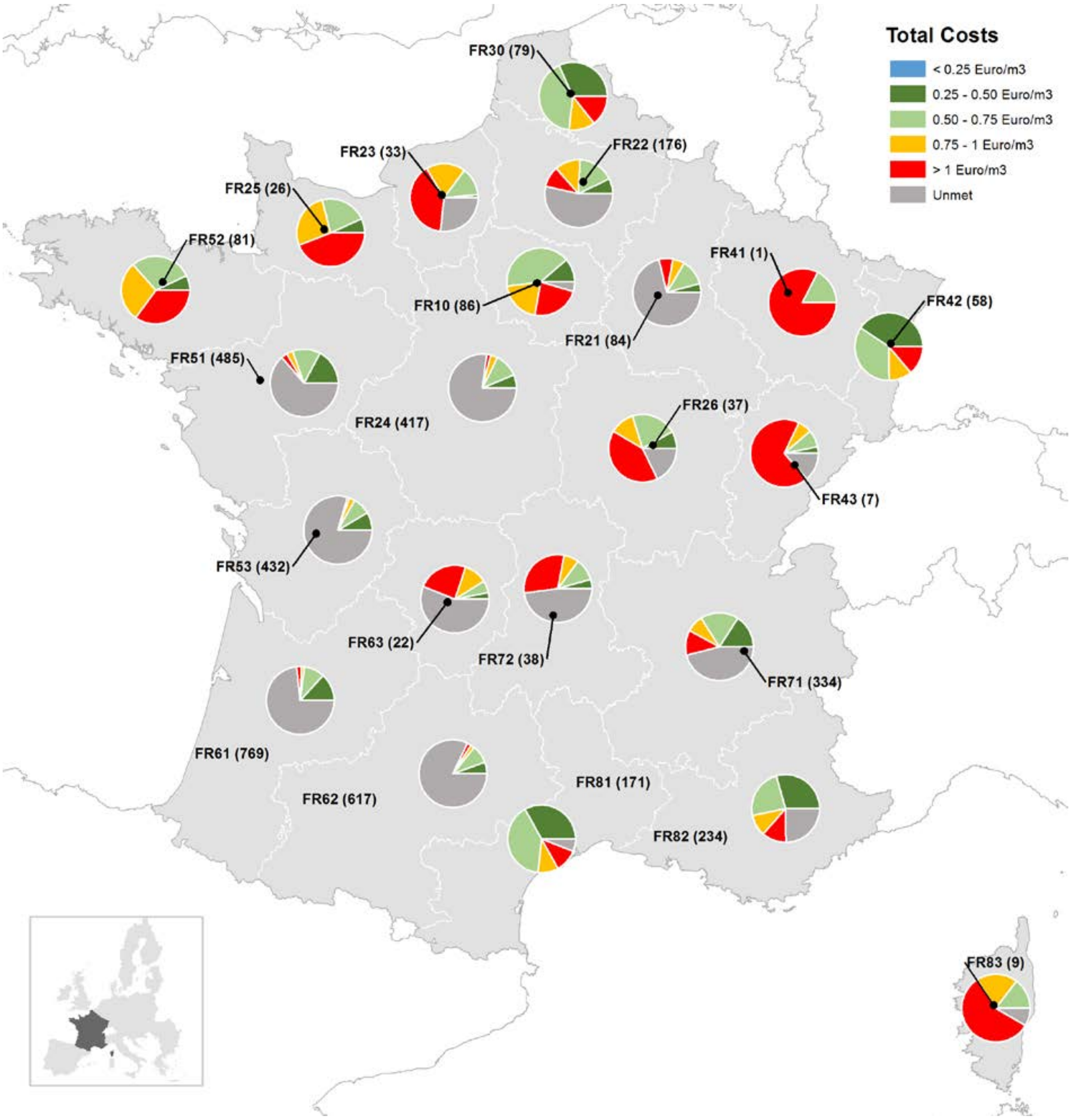

Figure 25– WMCC by NUTS2-level regions: reuse potential at various costs for FR

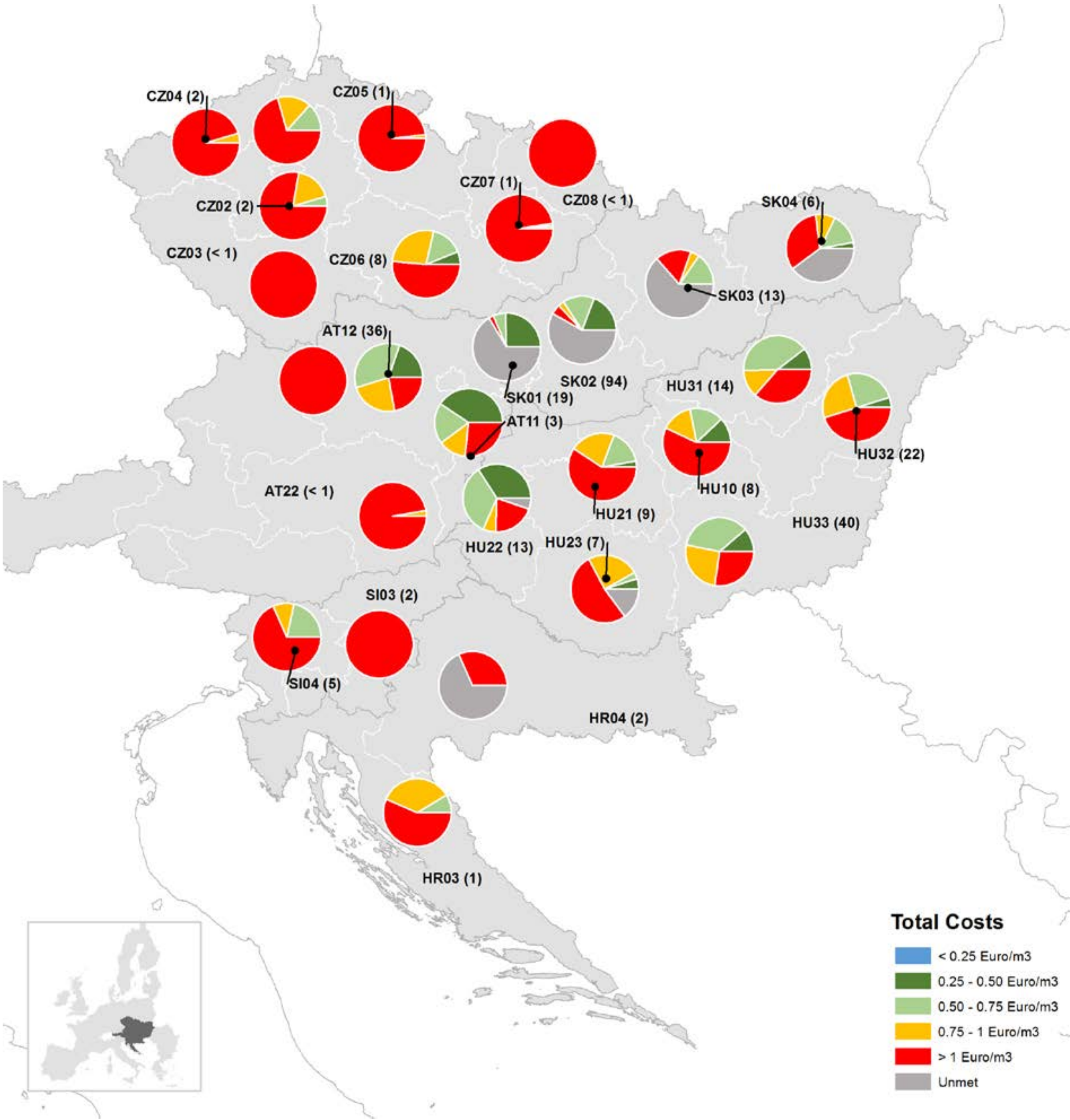

Figure 26– WMCC by NUTS2-level regions: reuse potential at various costs for HR, HU, SI, CZ, SK, AT

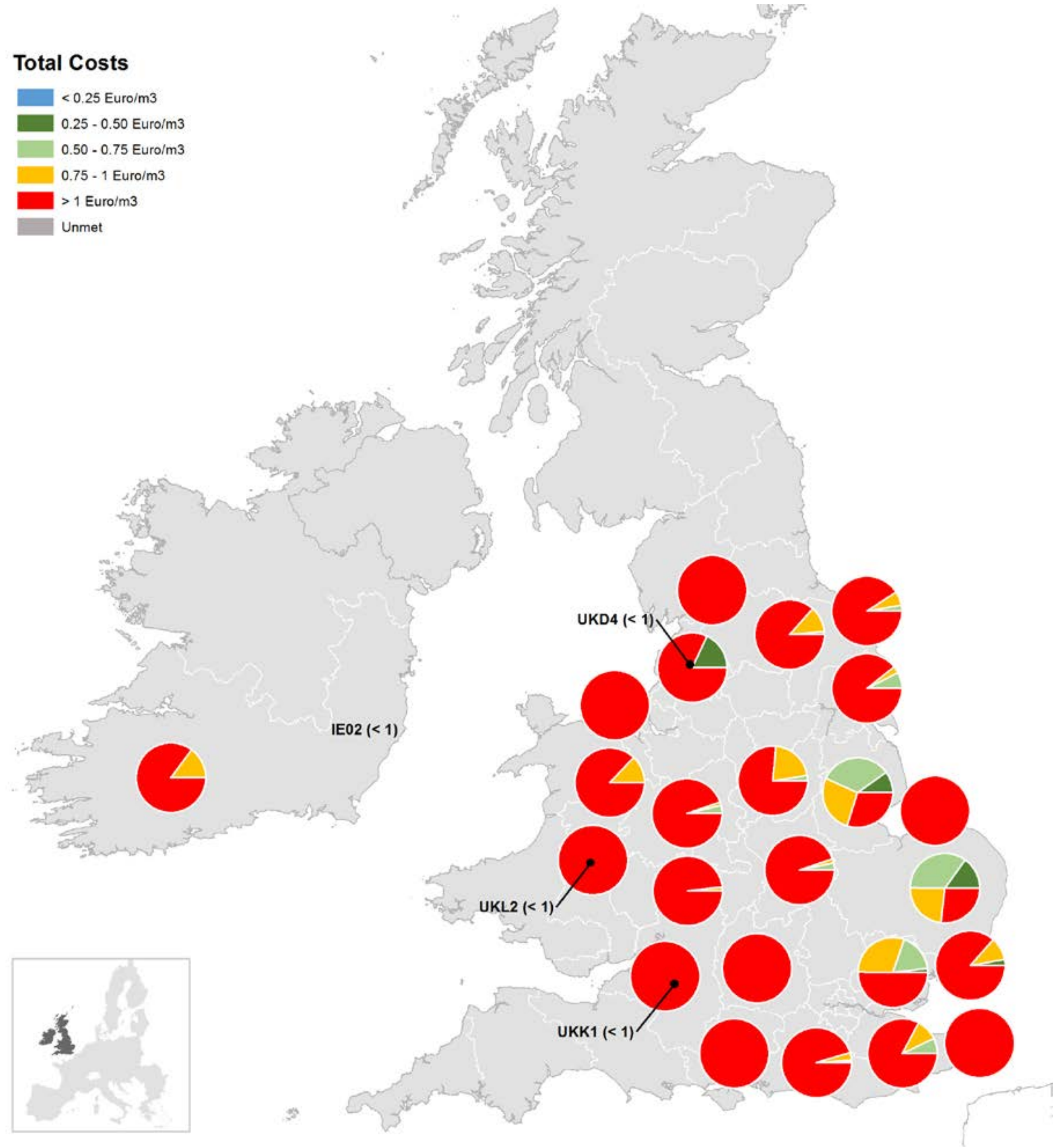

Figure 27– WMCC by NUTS2-level regions: reuse potential at various costs for UK and IE

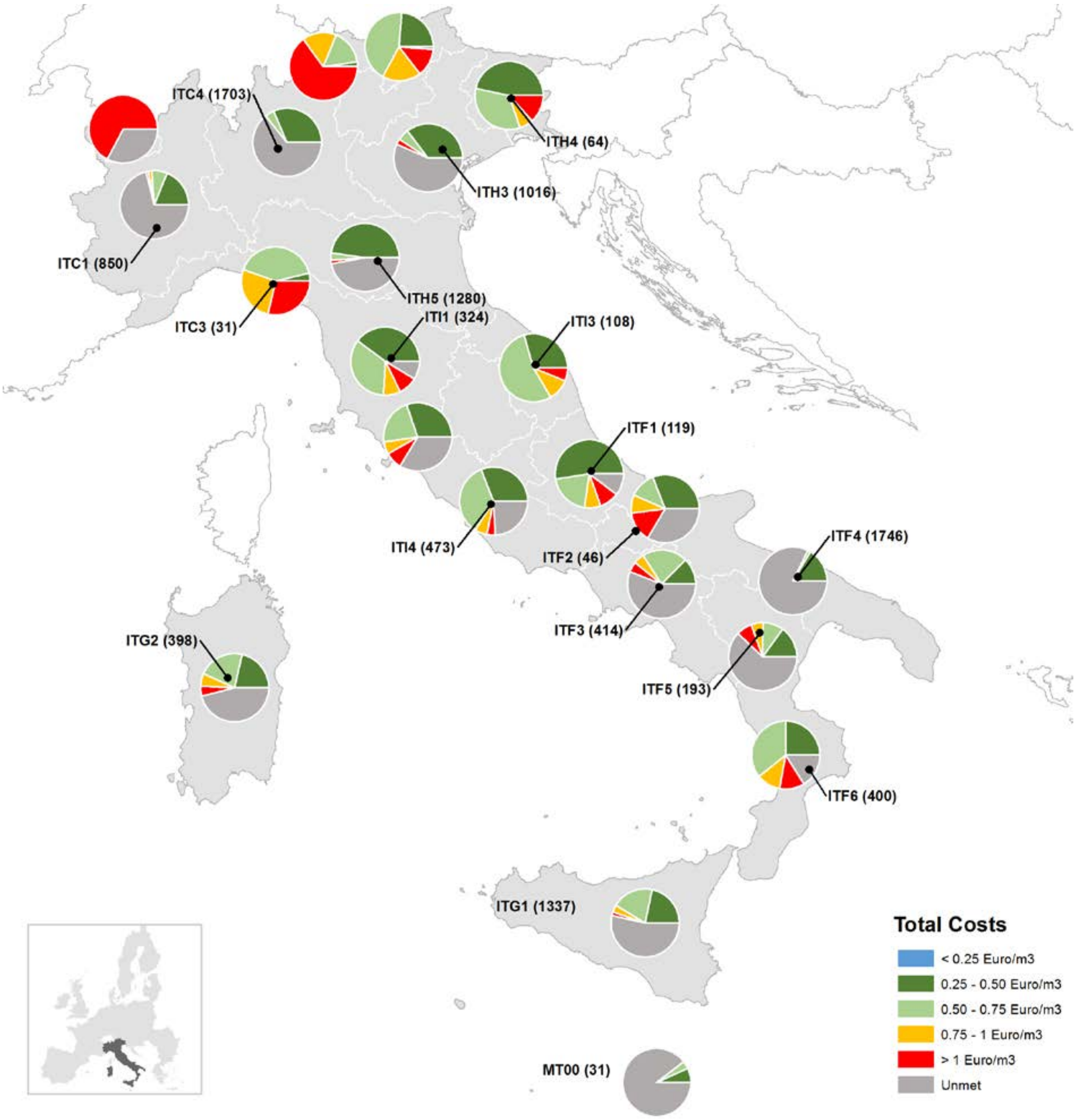

Figure 28– WMCC by NUTS2-level regions: reuse potential at various costs for IT and MT

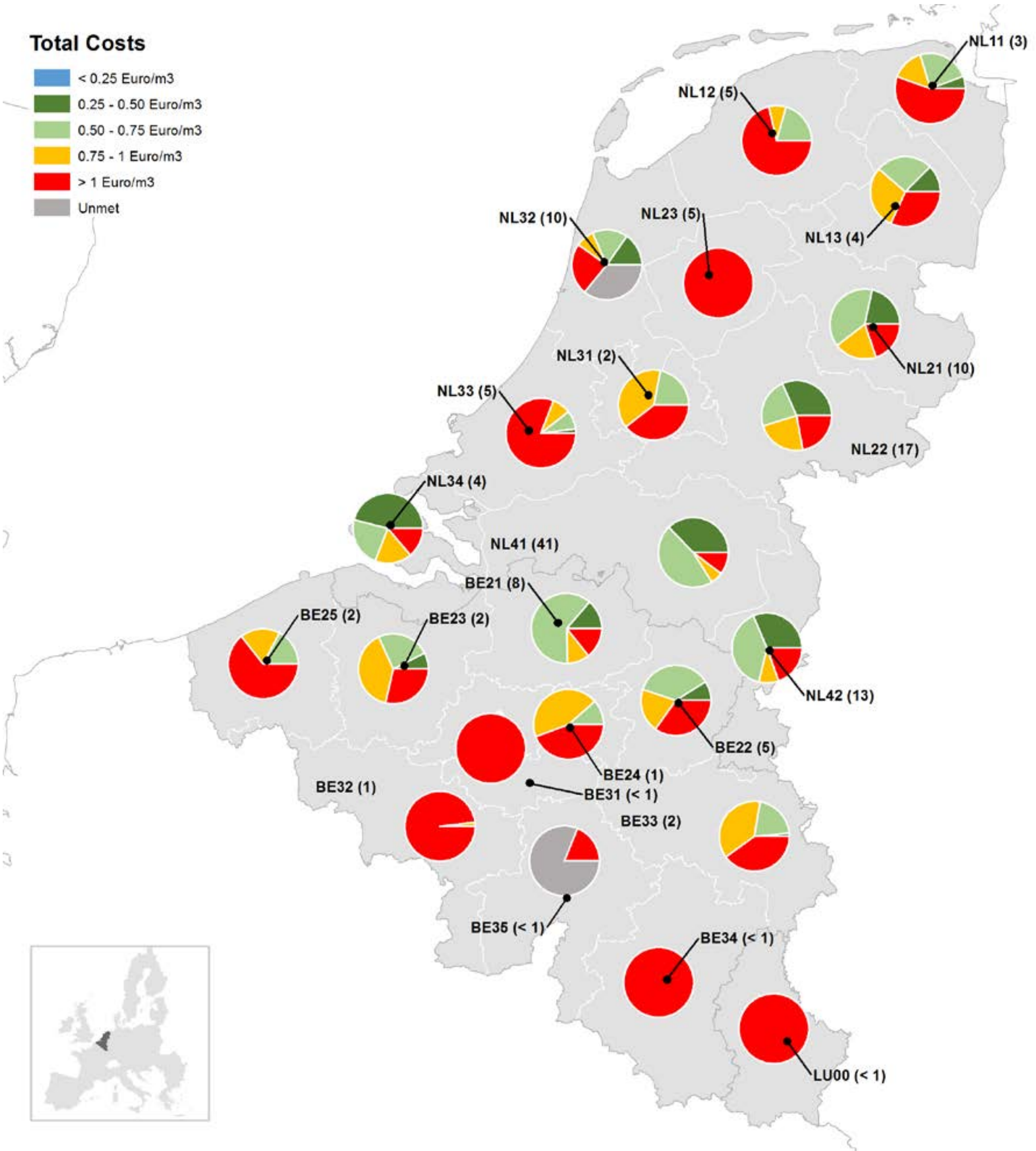

Figure 29– WMCC by NUTS2-level regions: reuse potential at various costs for BE, NL, LU

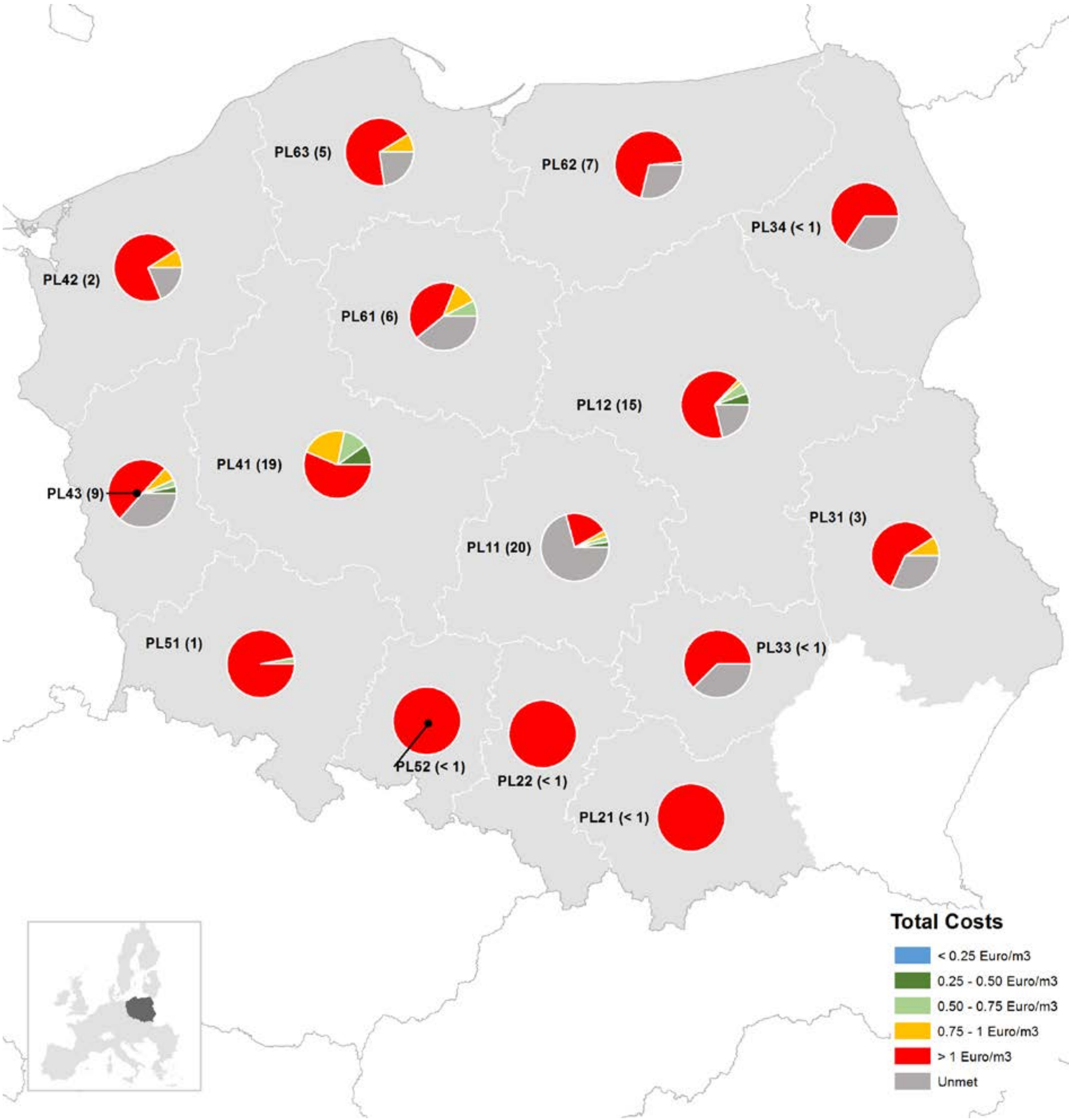

Figure 30 – WMCC by NUTS2-level regions: reuse potential at various costs for PL

Appendix 2– WMCCs for the NUTS2 regions of the EU: total costs excluding storage

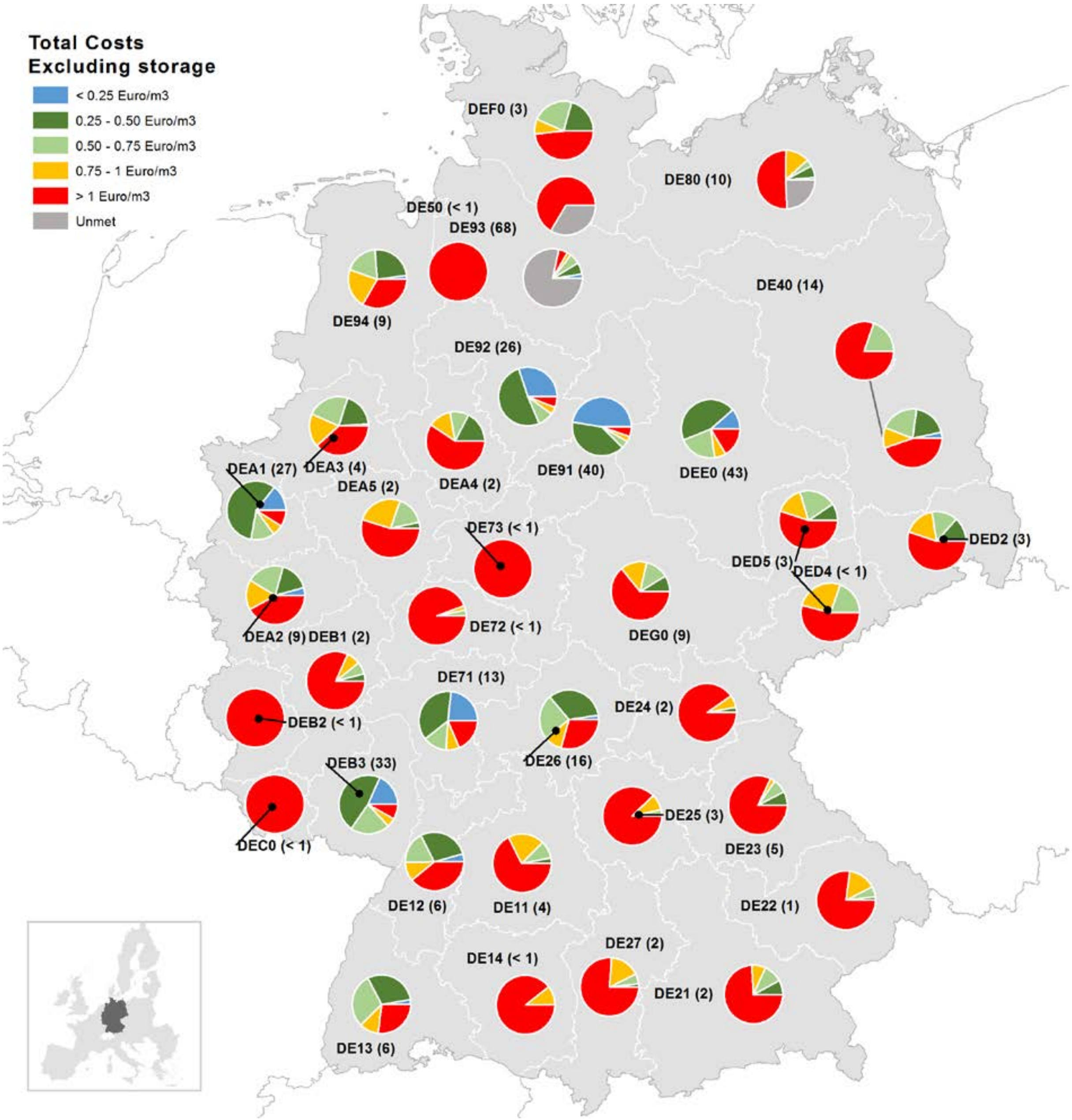

Figure 31– WMCC by NUTS2-level regions: reuse potential at various costs for DE

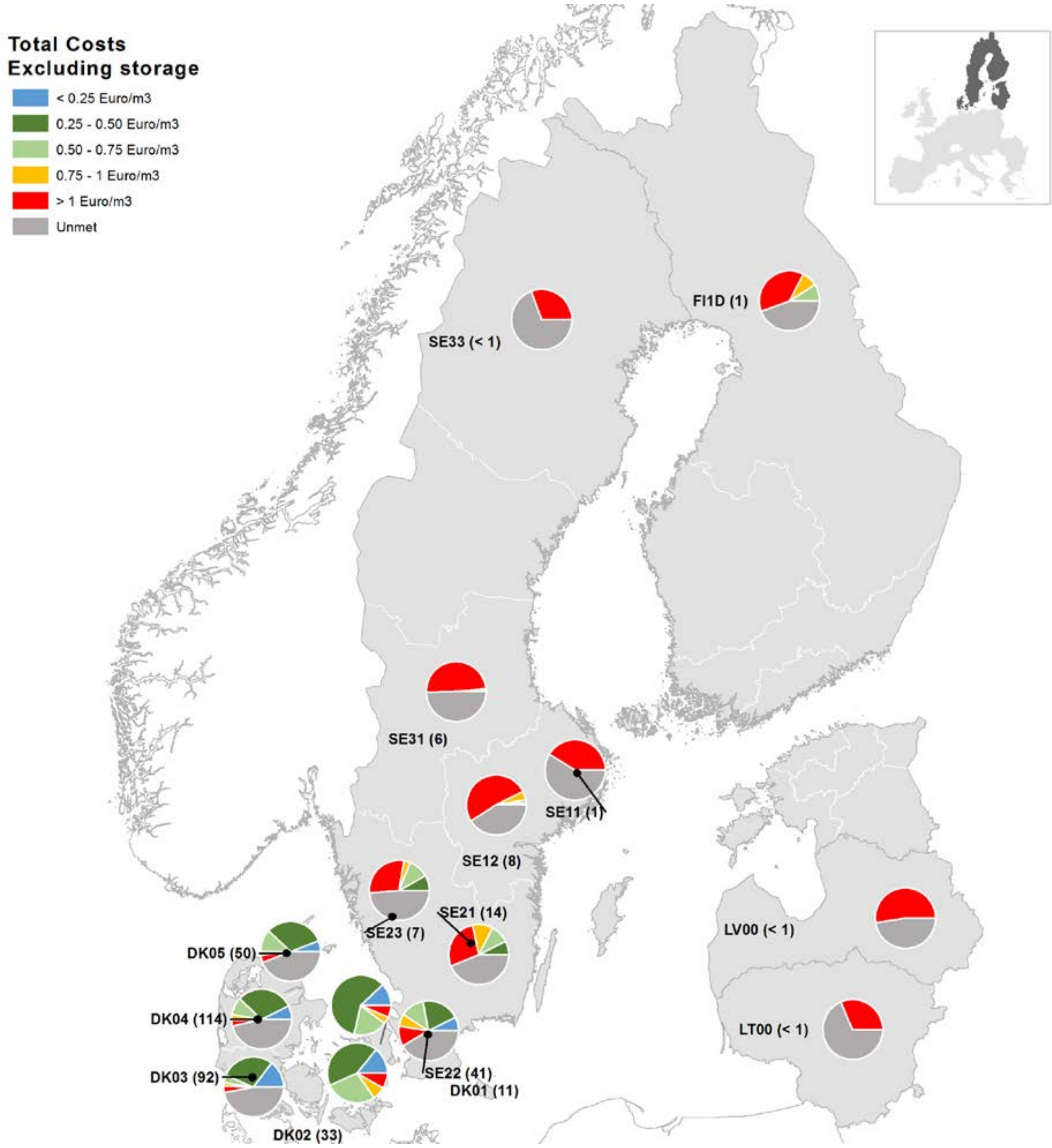

Figure 32– WMCC by NUTS2-level regions: reuse potential at various costs for SE, FI, DK, EE, LT, LV

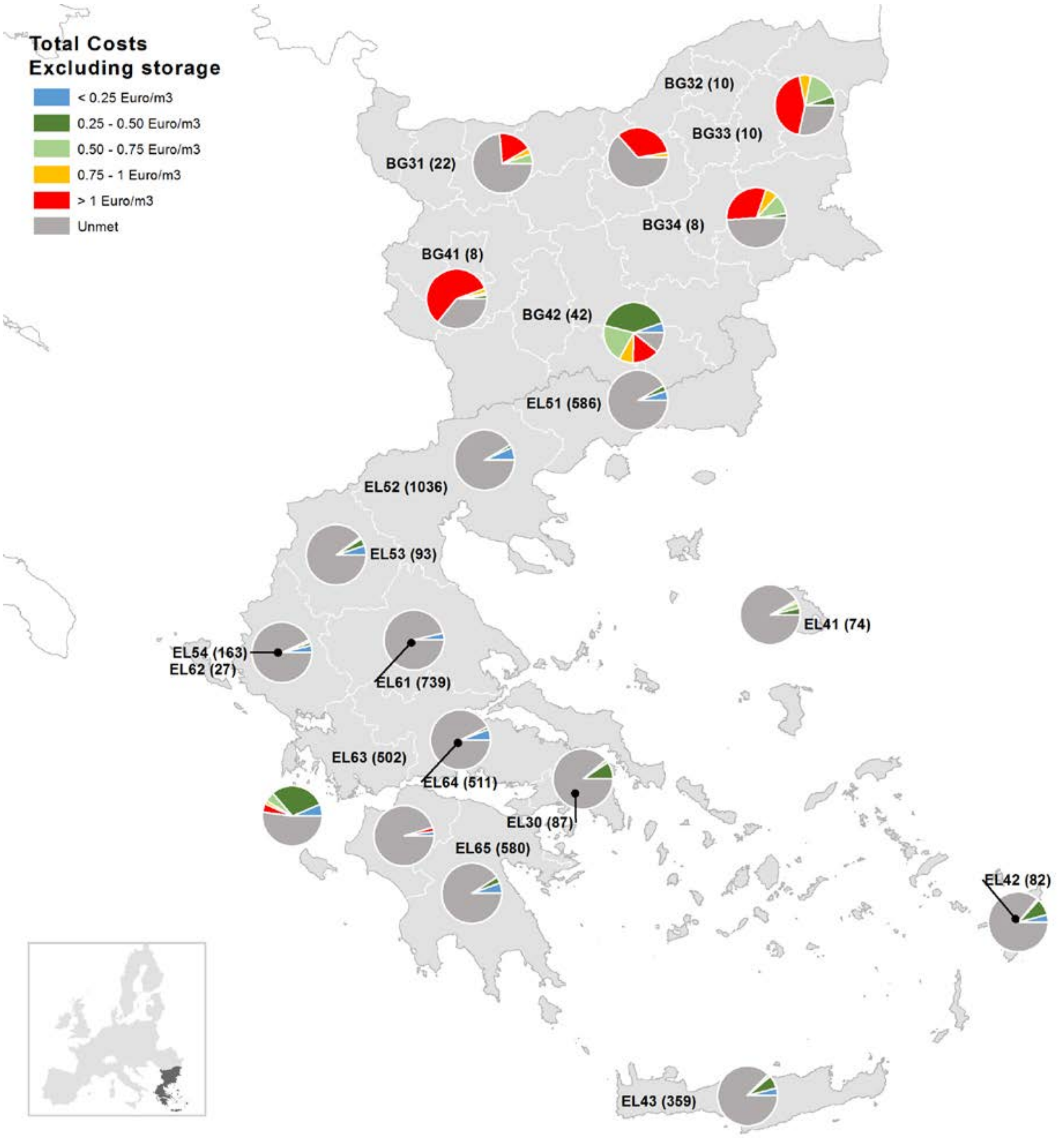

Figure 33– WMCC by NUTS2-level regions: reuse potential at various costs for BG, EL

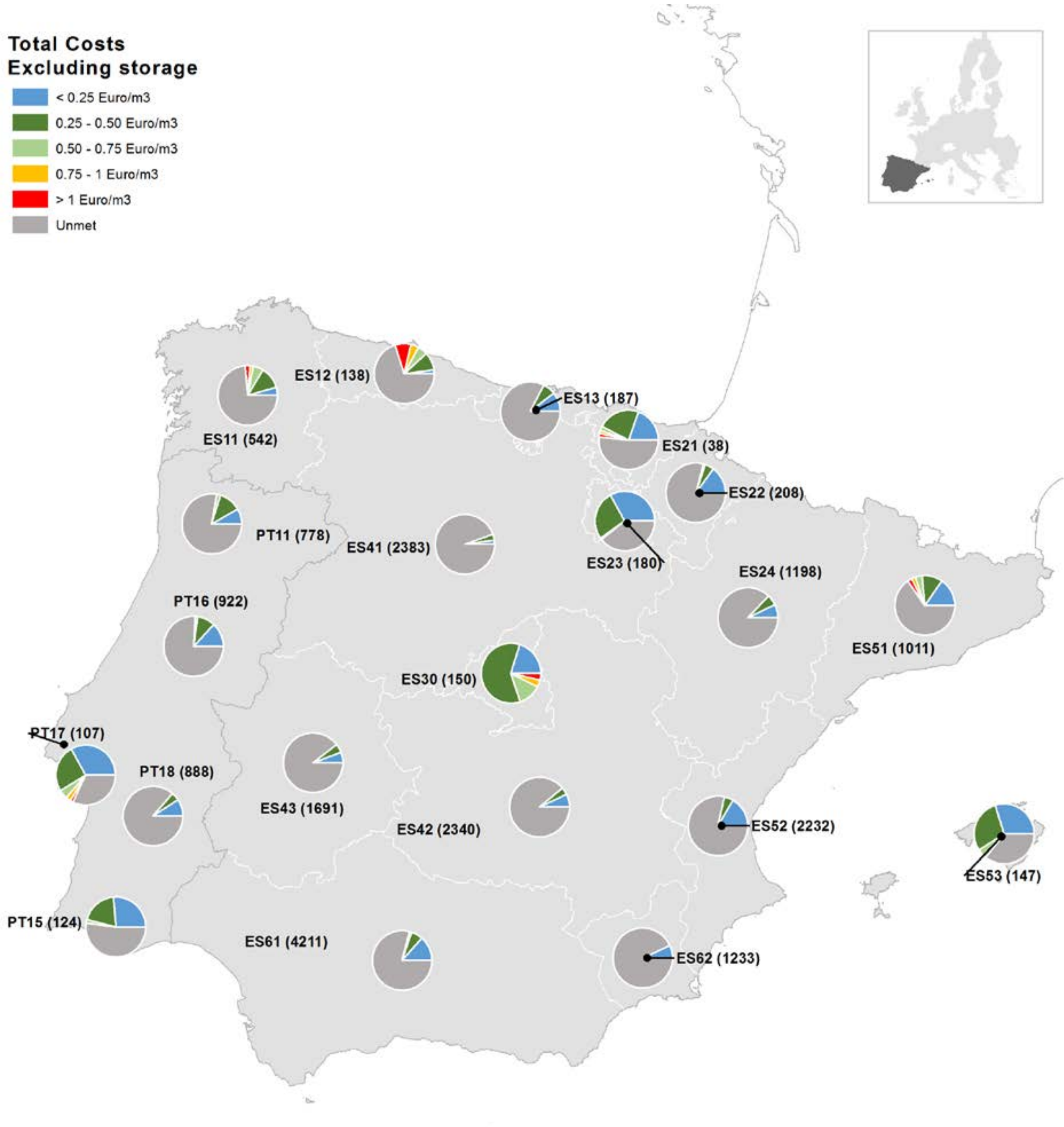

Figure 34– WMCC by NUTS2-level regions: reuse potential at various costs for ES, PT

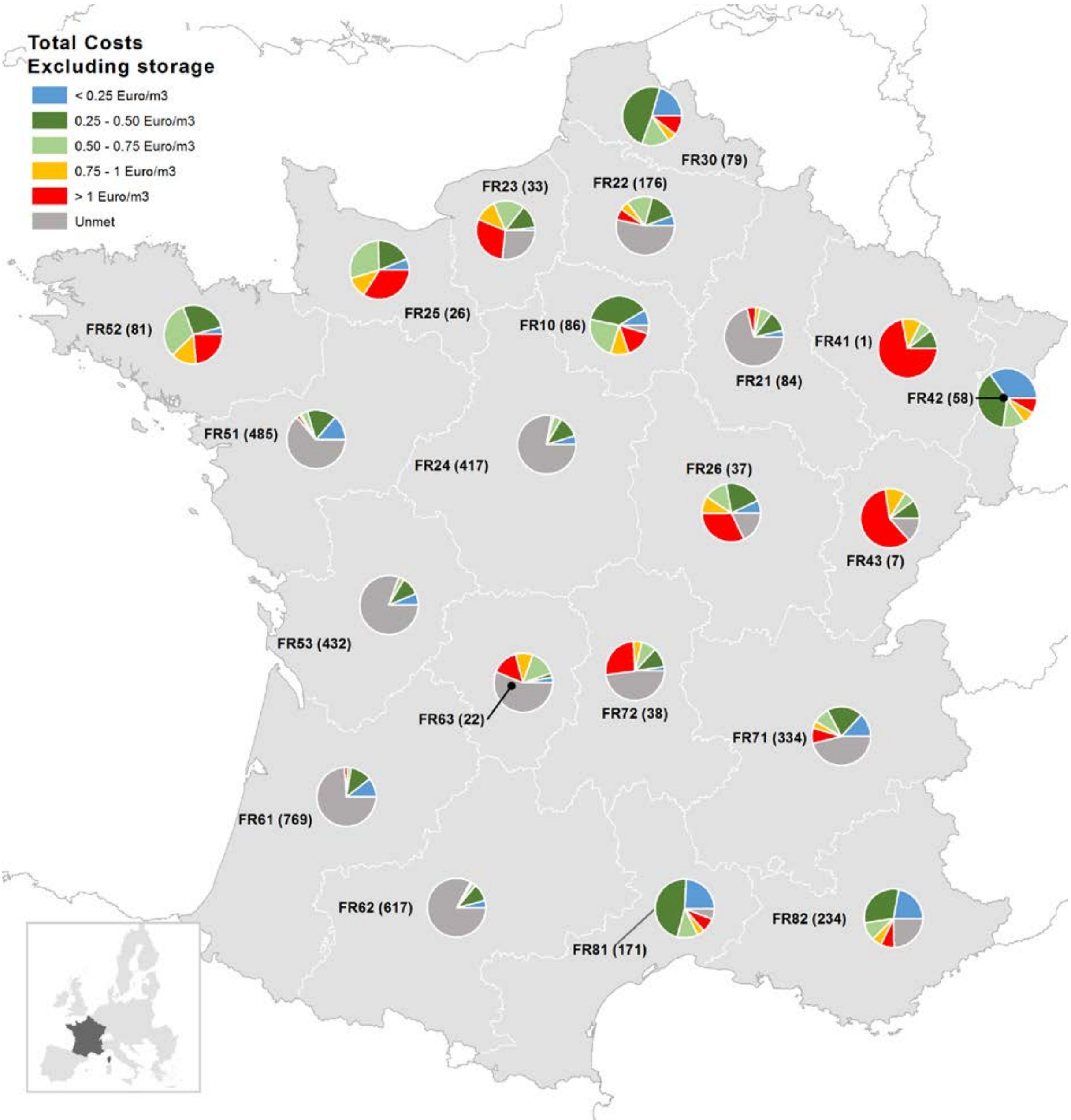

Figure 35– WMCC by NUTS2-level regions: reuse potential at various costs for FR

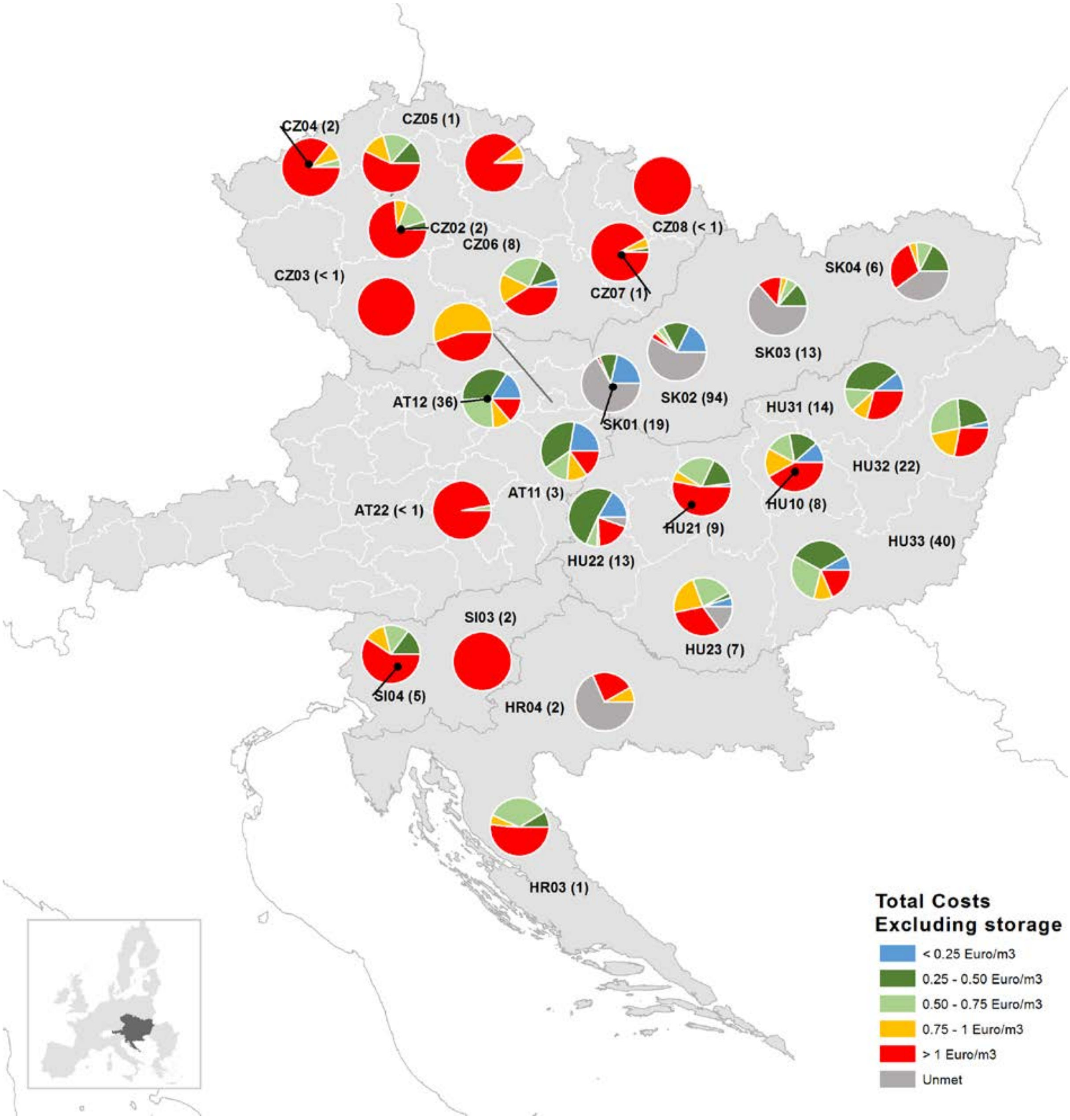

Figure 36– WMCC by NUTS2-level regions: reuse potential at various costs for AT, HU, HR, SI, SK

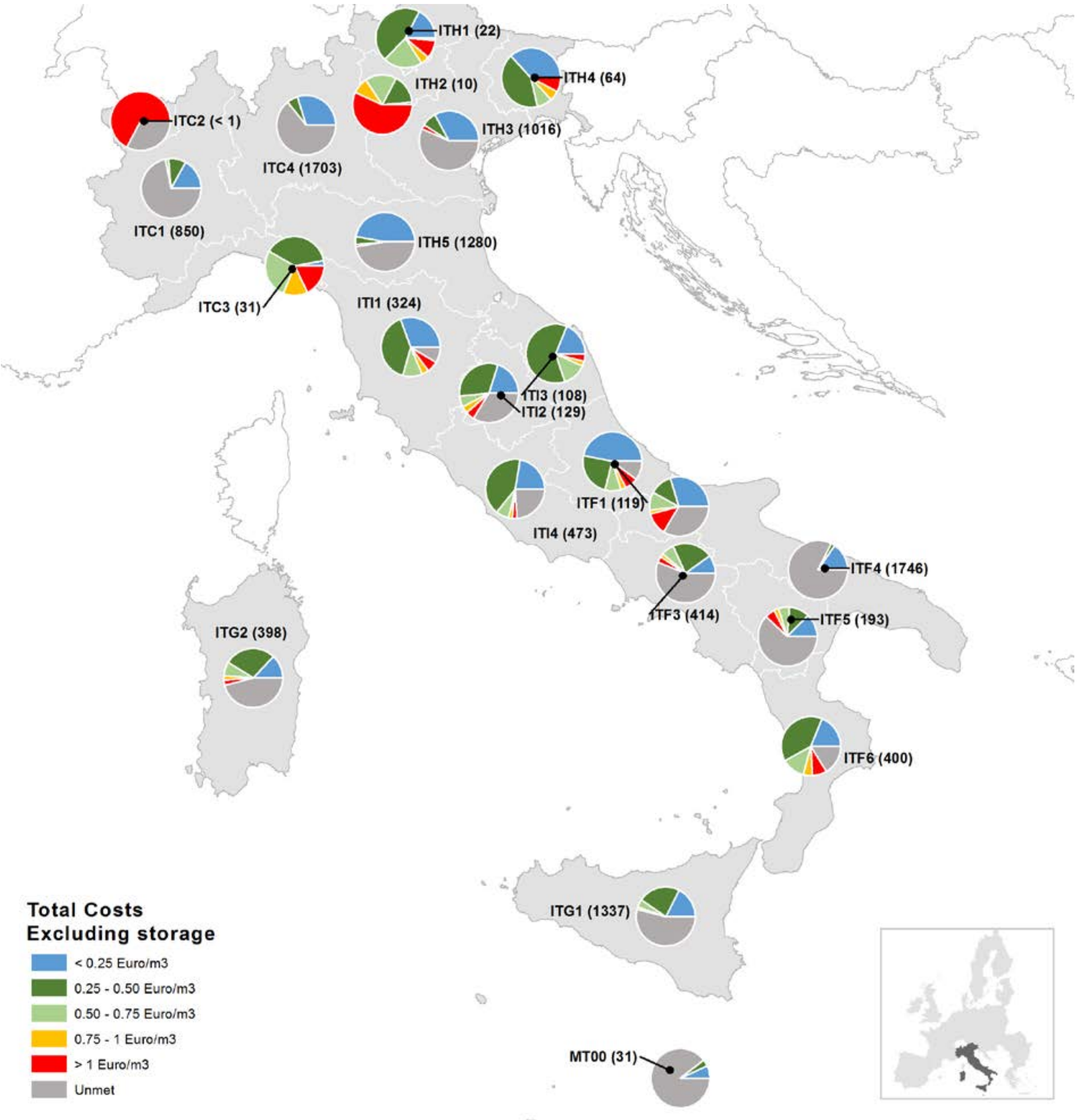

Figure 37– WMCC by NUTS2-level regions: reuse potential at various costs for IT, MT

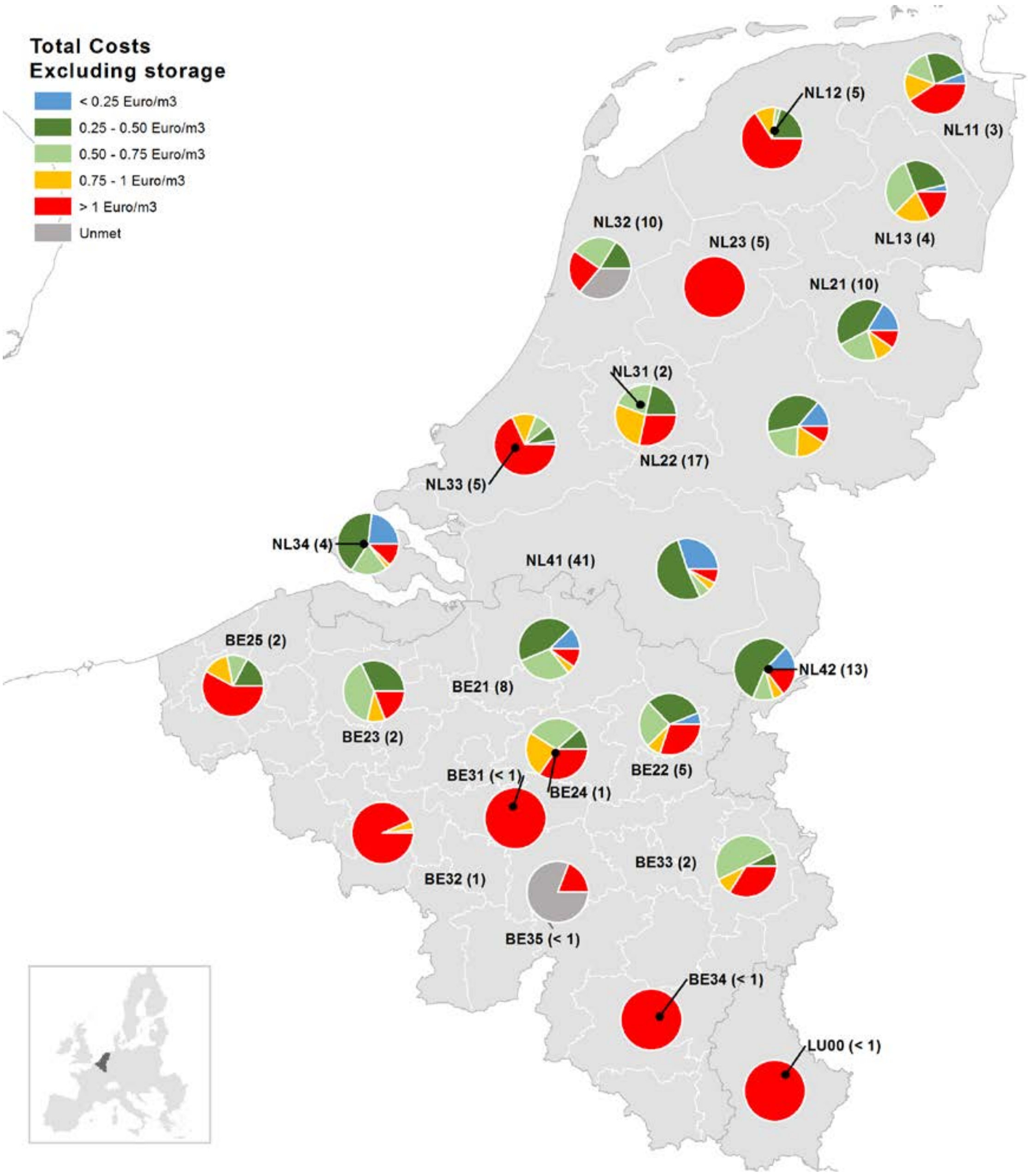

Figure 38– WMCC by NUTS2-level regions: reuse potential at various costs for BE, NL, LU

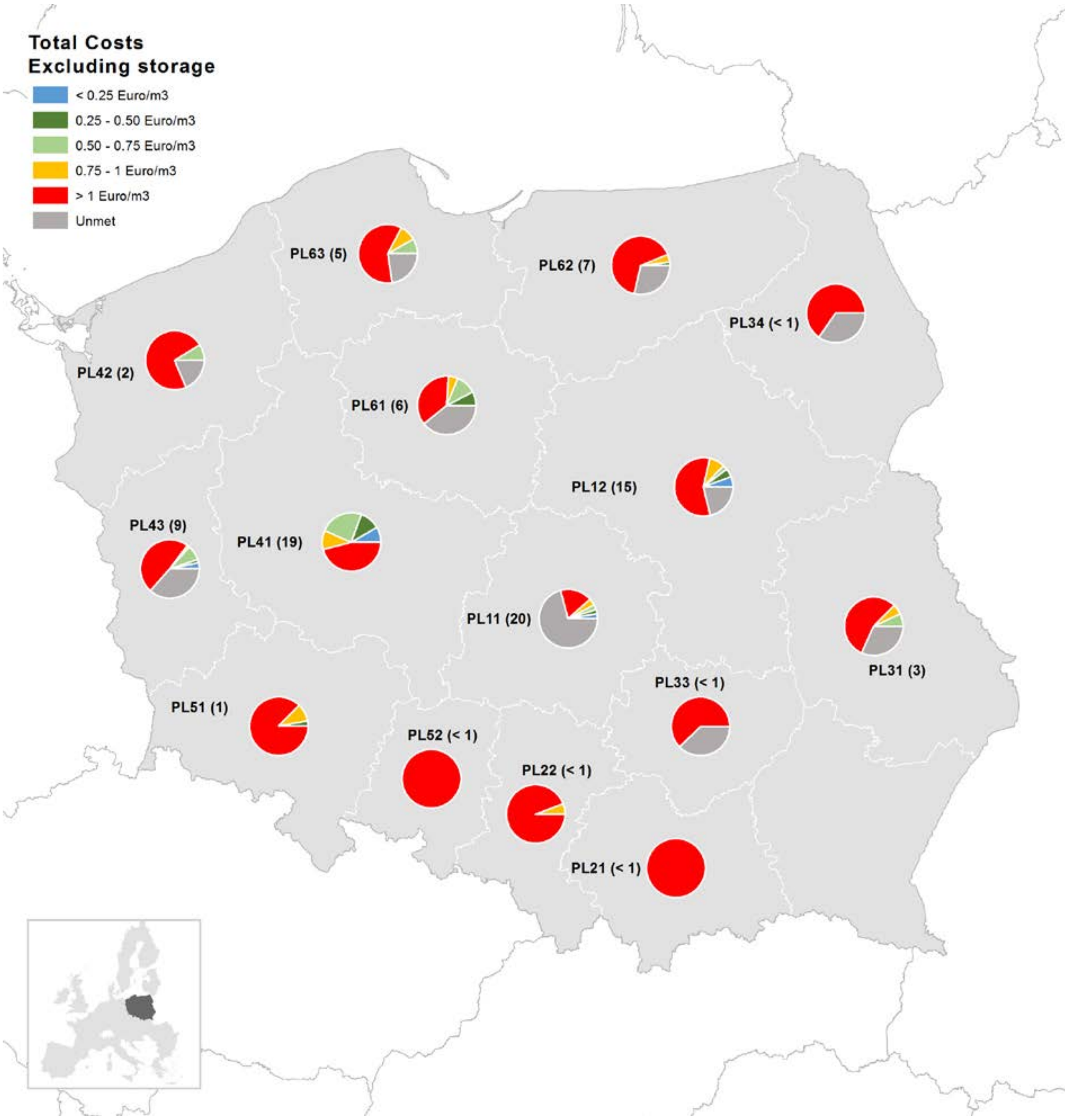

Figure 39– WMCC by NUTS2-level regions: reuse potential at various costs for PL

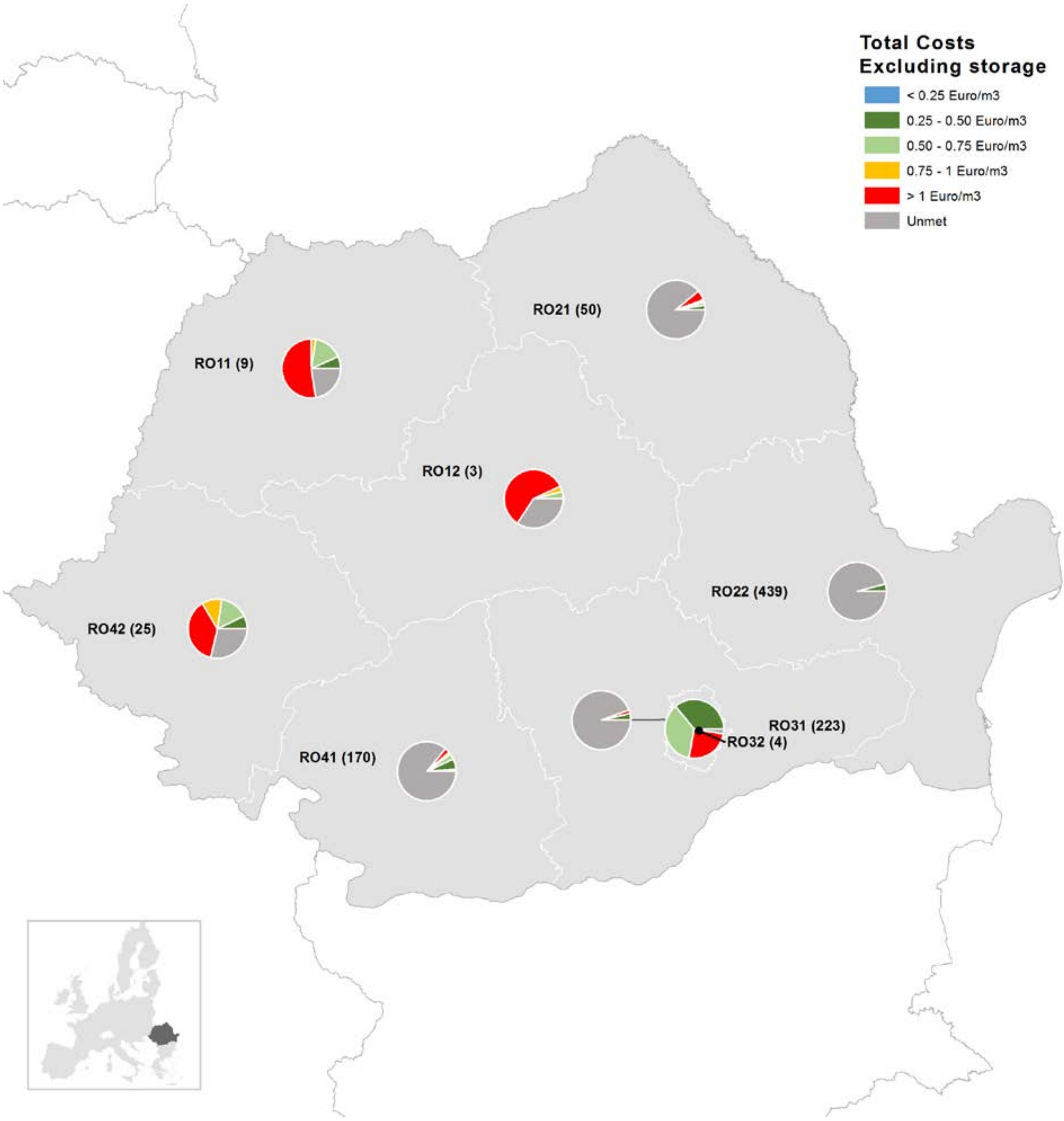

Figure 40– WMCC by NUTS2-level regions: reuse potential at various costs for RO

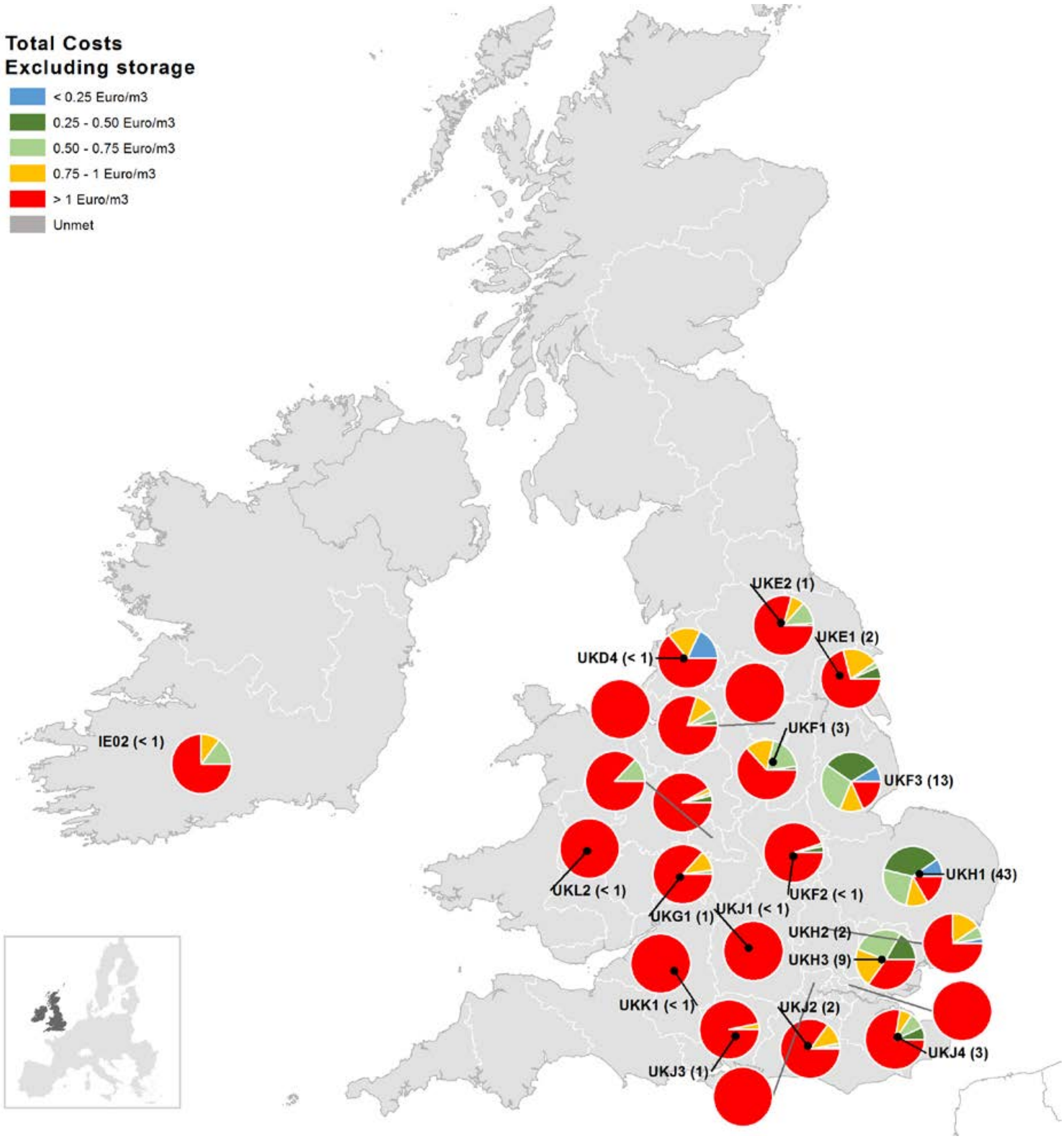

Figure 41– WMCC by NUTS2-level regions: reuse potential at various costs for IE, UK

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