REDAWN – Reducing Energy Dependency in Atlantic area Water Networks

PROJECT REPORT

WP4 report on micro-hydropower resource assessment in the Atlantic area

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Author(s): Aonghus McNabola, Trinity College Dublin.
Djordje Mitrovic, Trinity College Dublin.
Miguel Crespo Chacon, Trinity College Dublin.
Aida Merida Garcia, Trinity College Dublin.
Jorge Garcia Morillo, University of Cordoba.
Juan Antonio Rodriguez Diaz, University of Cordoba.

REDAWN
Reducing Energy Dependency
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Interreg
Atlantic Area
European Regional Development Fund

EUROPEAN UNION

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List of Abbreviations

AA	Atlantic Area
AER	Annual Environmental Report
BPTs	Break Pressure Tanks
CVs	Control Valves
DEM	Digital Elevation Model
DTE-HP	Downstream treated Effluent Hydropower Plant
EPA	Environmental Protection Agency
FAO	Food and Agricultural Organization of the United Nations
GWh	Gigawatt-hour
kW	Kilowatt
kWh	Kilowatt-hour
LUR	Land Use Regression
MHP	Micro hydropower
PAT	Pump-as-turbine
PE	Person Equivalent
PRVs	Pressure Reducing Valves
RB	River basin
SD	Standard deviation
SRs	Storage/Service Reservoirs
TIN	Triangular Irregular Network
USGS	United States Geological Survey
USW-HP	Upstream Sewage Water Hydropower Plant
WWDL	Wastewater Discharge Licence
WSN	Water supply network
WP	Work Package
WTWs	Water Treatment Works
WW	Wastewater
WWN	Wastewater network

1. Executive Summary

As part of the REDAWN project, Work Package 4 (WP4), an assessment of the resource potential for micro-hydropower (MHP) energy recovery in water networks in the Atlantic Area (AA) of Europe was conducted. This assessment examined the potential energy available in man-made water networks used for public drinking water, irrigation, waste water collection, and process industry operations. The assessment aimed to quantify the theoretical energy available in these four types of network across the AA, in the form of excess pressure or head, otherwise wasted, which could be converted to electrical power using hydropower turbines, without interfering in the normal operation of the network. The economic viability of exploiting this potential resource is discussed in WP5 of the REDAWN project.

Data was sought and collected in the form of information on flow and pressure, available at existing infrastructure in water networks, where excess pressure or head is intentionally or unintentionally wasted. These included data on the location, flow and pressure at pressure reducing valves, break pressure tanks, control valves, gravity fed treatment works or reservoirs, and industrial (private industry) and public waste water treatment plant inlets and outlets. Data on the full hydraulic model of water networks in local areas was also sought. In the absence of such information, data required to construct full hydraulic models was also obtained, if available, particularly in the irrigation sector, where neither recorded flow/pressure data or hydraulic models typically exist.

Table 1 summarises the sites for which data was collected in each country in the area of interest among the network types mentioned. Up to May 2020, data on 8940 potential sites has been collected from various water service organisations or generated from the development of hydraulic network models.

Table 1: Summary of existing potential sites for MHP energy recovery collected in the study area.

Number of MHP sites identified					
Country	**Drinking Water**	**Wastewater**	**Irrigation**	**Process Industry**	**Total**
Ireland	44	535	0	22	601
France	2	0	0	0	2
Portugal	11	0	4	1	16
Spain	34	343	173	87	637
UK	7684	0	0	0	7684
Total	**7775**	**878**	**177**	**110**	**8940**

In the case of all five countries in the study area, the aforementioned data comprises only a subset of the total potential sites in every category. Even for some countries, no data were available for any of the sectors covered. As expected in the project proposal approved for the REDAWN project, much of the desired data is either unavailable, non-existent, or its owners are unwilling or not interesting in sharing it, for commercial reasons. As such, based on the data collected or generated in this project, an extrapolation of the potential in the total area has been performed, as outlined in Section 5 of this report.

Table 2 summarises the estimated potential power available for exploitation using MHP turbines, from the data collected on the 8940 sites, which amounted to 23766 kW. This power potential represents an annnual energy recovery potential of around 188 GWh, considering 24/7 year round production, for all sectors, except for irrigation, as it will be detailed below.

This approximate potential does not fully account for losses in the conversion of energy to electricity. Turbine efficiency, flow and pressure were assumed to be constant in most cases, owing to a lack of detailed data. This approximate estimate also does not consider the amount of this energy which is either technically or economically viable for exploitation. Further assessments in WP5 will aim to quantify the economic viability, while precise technical viability would require detailed site assessments in each case, which is beyond the scope of WP4 in the REDAWN project.

Table 2: Summary of gross power potential estimations based on collected data on existing potential sites for MHP energy recovery in the study area.

Theoretical Power Potential of MHP at existing sites identified (kW)					
Country	**Drinking Water**	**Wastewater**	**Irrigation**	**Process Industry**	**Total**
Ireland	668	219	0	212	1099
France	0	0	0	0	0
Portugal	34	0	49	10	93
Spain	95	982	2946	1403	5426
UK	17148	0	0	0	17148
Total	**17945**	**1201**	**2995**	**1625**	**23766**

Resource extrapolation was then conducted following different methodologies, depending on the sector, as it will be detailed in section 5 , using population and land-use factors, among others, to extend the collected data to the full study area. These have been conducted for waste water, drinking water, irrigation and process industry, as shown, in terms of energy, in Table 3.

Table 3. Total extrapolation of MHP energy recovery potential (GWh) for the study area.

Total Extrapolated Energy Potential for MHP (GWh)					
Country	**Drinking Water**	**Wastewater**	**Irrigation**	**Process Industry**	**Total**
Ireland	13.7 – 30.4	1.8	0	2.3	17.8 – 34.4
France	188.0 - 416.0	25.3	0	14.4	227.6 – 455.7
Portugal	29.6 – 65.5	4.0	23.9	2.6	60.1 – 96.0
Spain	135.7 – 300.3	18.2	221.4	12.3	387.6 – 552.2
UK	191.2 – 508.9	25.7	0	15.2	232.0 – 549.8
Total	**558.1 – 1321.1**	**75.0**	**245.3**	**46.7**	**925.1 – 1688.1**

Thus, the energy estimations amounted to a total between 925.1 and 1688.1 GWh, depending on the extrapolation method used, as it will be explained later. From this total, the drinking water sector was the one with the highest representation, the percentage distribution for the different sectors ranging between 60%, 8%, 27% and 5%, and 78%, 4%, 15% and 3% for the drinking water, wastewater, irrigation and process industry sectors, respectively, according to the different extrapolation assumptions.

2. Introduction

The energy consumption linked to the water industry is such that it is responsible for significant contributions to climate change. Thus, some measures are needed to transform the sector into a more sustainable system. The objective of the REDAWN project is to reduce the energy dependence of water networks in the Atlantic area (AA), improving the energy efficiency of water networks through the use of micro hydropower (MHP) technology. More specifically, the theoretical potential energy recovery from this kind of infrastructure, using small-scale traditional turbines and pump as turbines (PATs), has been assessed, as well as the economic viability of such installation within these networks (in WP5). In the REDAWN project, public drinking water networks, private industrial water networks, wastewater networks, and irrigation networks, have been investigated.

WP4 comprises the compilation of an energy recovery resource assessment for water networks in the AA. Given that water networks contain excess pressure at various points across the territory, this WP has produced an assessment which quantifies the energy available for MHP technology to exploit. This is compiled as the largest GIS database of energy resources for public water supply networks, waste/storm networks, irrigation networks, and private water intensive industry, carried out to date worldwide. Available data on the existing water infrastructure has been sought and compiled for this purpose.

MHP energy recovery can be conducted at pressure reducing valves (PRV), storage reservoirs, break pressure tanks, treatment works, control valves, etc. Figure 1 illustrates some of the locations, in a typical water network for the drinking water, industry and wastewater sectors, where such excess energy is present and therefore, it could be the appropriate site for an energy recovery system to be implemented.

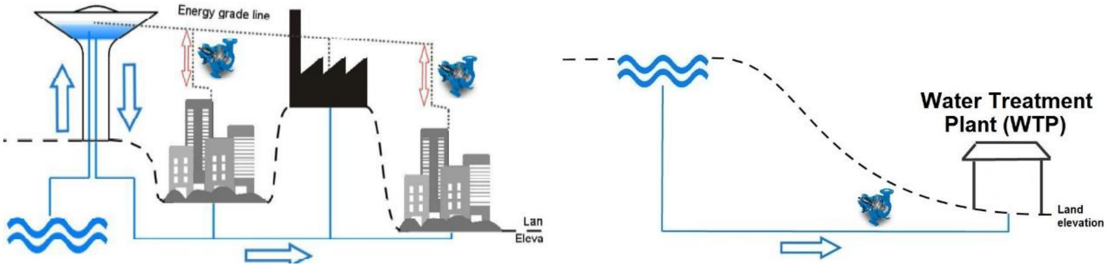


Figure 1. Typical water network locations for MHP energy recovery

Therefore, it was firstly necessary to determine the possible locations of the potentially exploitable excess pressure points for energy recovery across the water networks, in the study area. Once the locations or sites were identified, it was also required to gather information about the specific flow and excess pressure available at each location, to enable the assessment of the potential energy resources.

In the case of the irrigation sector, the modernization of the water distribution networks experienced in recent years has significantly improved the efficiency in water use, but also has meant an increasing energy demand associated with water consumption. These results principally came from the presurization of the irrigation networks and the promotion of specific irrigation techniques, among others. The increase in energy demand, derived from the presurrization, together with, in general, the rising energy price, has led the sector to focus not only on reducing water consumption, but also on improving the energy use efficiency and optimizing facilities in this regard. This irrigation modernization process is evident in several European countries. In the case of Spain, as an example, surface irrigation has been shifted from 80% of irrigated land in 1980 to 24% in 2018 (MAPA, 2018). In general terms, the use of pressurized irrigation systems has been increased in the last years within the European Union.

WP4 was led by Trinity College Dublin, overseeing the overall assessment. Partners in each of the regions contributed to data collection. The partnership obtained data from the entirety of the AA, however this data was available/unavailable to differing extents in each region and sector, as envisaged in the project proposal. Therefore, resource assessment was completed to the extent that data was available and obtainable in a timely manner. Resource potential was then estimated by extrapolation across the studied area, using the data gathered to extend the assessment to areas were data was unavailable or non-existent.

3. Data Acquisition

Data on flow, pressure and location of water network infrastructure components was gathered by relevant partners in each of the regions through their local contacts and with the assistance of the associate partners. The data was compiled in a GIS platform showing the spatial distribution of potential energy resources in the studied area.

Data was sought from water services organisation across Ireland, France, Spain, Portugal and the UK. Requests for data were made to the following organisations in different countries as shown in Table 4. In some cases data was provided, and in some others, data was not available or not provided.

Table 4. Data acquisition requests made for the different sectors and countries of the study area

Country	Organisation	Sector	Outcome
Ireland	Irish Water	Drinking Water	Not provided
	NFGWS	Drinking Water	provided
	Dublin City Council	Drinking Water	provided
	Kildare County Council	Drinking Water	provided
	EPA	Waste Water	provided
N. Ireland	Northern Ireland Water	Drinking Water	provided
Scotland	Scottish Water	Drinking Water	provided
Wales	Welsh Water	Drinking Water	provided
	Severn Trent Water	Drinking Water	Not provided
England	United Utilities	Drinking Water	Not provided
	South West Water	Drinking Water	Not provided
	Wessex Water	Drinking Water	Not provided
	Thames Water	Drinking Water	Not provided
Spain	EMACSA	Drinking Water	provided
	Aguas de Cadiz	Drinking Water	provided
	MASESA	Drinking Water	provided
	RB Duero	Wastewater and Industry	provided
	RB Guadalquivir	Wastewater and Industry	provided
	RB Guadiana	Wastewater and Industry	provided
	RB Tajo	Wastewater and Industry	provided
	RB Ebro	Wastewater and Industry	provided
	RB Jucar	Wastewater and Industry	provided

	RB Segura	Wastewater and Industry	provided
	Bembezar Margen Derecha	Irrigation	provided
	Bembezar Margen Izquierda	Irrigation	provided
	Genil Margen Izquierda	Irrigation	provided
	Zujar	Irrigation	provided
	La Colonia	Irrigation	provided
	Genil-Cabra	Irrigation	provided
	Guadalmellato	Irrigation	provided
	El Villar	Irrigation	provided
	Fuente Palmera	Irrigation	provided
Portugal	Funchal	Drinking Water	provided
	ABORO	Irrigation	provided
France	SMPGA	Drinking Water	provided
	Suez	Drinking Water	Not provided

3.1. Drinking Water Networks

Drinking Water Networks, also known as Water Supply Networks (WSNs), are complex systems whose main purpose is to deliver drinking water to consumers, especially in urban areas, at sufficient pressure and quality in an economically efficient manner.

The predefined topography of the terrain where a WSN is located, and the requirement to deliver the water with sufficient pressure to all parts of the network, usually result in some parts of the system having excess pressure. This specially refers to the networks characterized by a hilly topography, where there is a large difference in elevation between a source and some specific areas in the rest of the network. The consequences of high pressure result in more frequent pipe bursts, increased leakage and maintenance costs.

Input data for the energy recovery resource assessment of a WSN can be in one of the following two formats:

1. A digital hydraulic model of a WSN.
2. Location and flow/pressure measurements or estimate at a WSN infrastructure with excess pressure, such as:
    a. Pressure Reducing Valves (PRVs)
    b. Break Pressure Tanks (BPTs)
    c. Storage/Service Reservoirs (SRs)
    d. Water Treatment Works (WTWs)
    e. Control Valves (CVs).

Digital Hydraulic Models

WSNs are pressurized networks in which an excess pressure can be located anywhere, not only at the location of the WSN infrastructure mentioned above. Because of this, it is better to have a digital hydraulic network model whenever it is possible. A change in the configuration of a WSN, e.g. an insertion of a turbine, could change the distribution of flow and pressure within it. In this case, only the simulation of its real hydraulic behaviour, using a digital model, can allow us to maximize the energy recovery. There are also some studies which suggest that the best location to maximize energy recovery by installing turbines are not the same as the best location for PRVs (Giugni et al., 2014; Fecarotta and McNabola, 2017). Unfortunately, in most cases, these models cannot be obtained from water utilities or private water companies which operate WSNs, because these models are considered confidential and too valuable to be shared, especially in the case of very large networks. In addition, in many cases, the problem is that these models do not even exist.

Up to date, nine networks have been obtained in this format. Seven models belong to small rural networks in Ireland. The 8th is a model of the City of Funchal, the capital city of Madeira island, Portugal. Finally, the 9th is a model of Granville in Northern France. Some of these networks are presented in Figures 2 to 4.

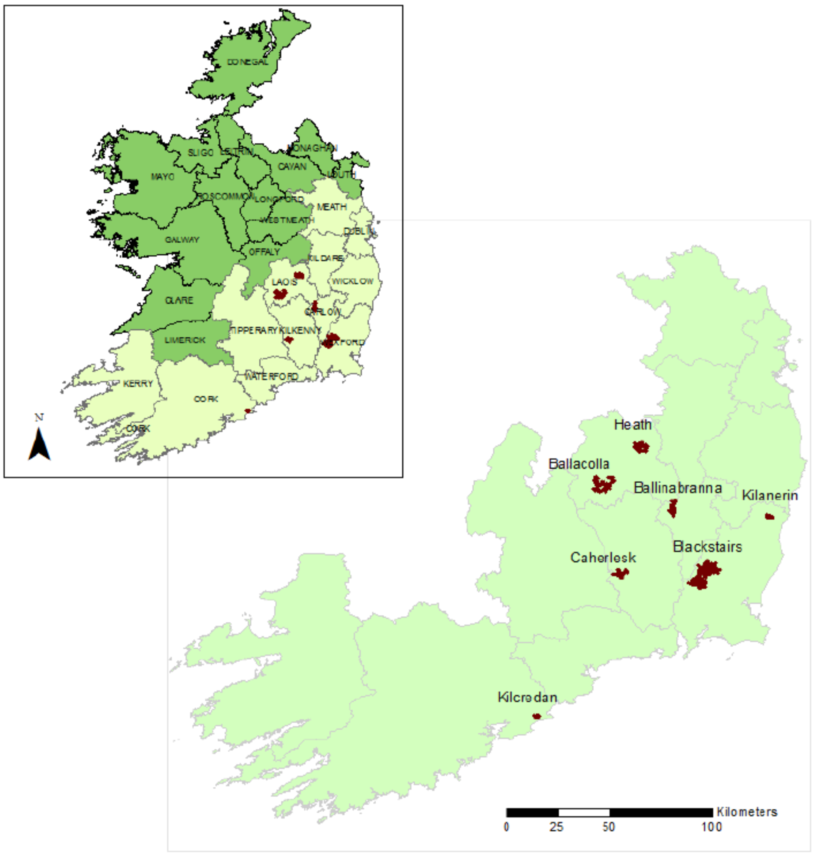


Figure 2: 7 rural WSNs in Ireland, (García et al., 2018).

Figure 3. Calibrated hydraulic model of Funchal WSN

Figure 4. Calibrated hydraulic model of Granville, France, WSN

Location of WSN infrastructure with excess pressure and flow/pressure data.

Practice has shown that water companies are sometimes willing to provide location information and flow/pressure measurements or estimates for existing infrastructure with known excess pressure, instead of hydraulic models. These data provide an alternative solution to assess the MHP energy recovery potential of WSNs by considering the installation of turbines/PATs at these locations. However, there are lots of WSNs in the world where these devices are not deployed at all, or at least, not to the extent in which they should be. Consequently, the potential for energy recovery assessed in this way is an underestimate of the total potential that can be recovered from WSNs.

Direct and indirect contacts (through the project's partners) were made with water companies from the studied area in order to obtain the location of the WSN infrastructures with excess pressure. As can be seen in Table 4, all the companies that operate WSNs in Ireland and the UK were contacted. In the case of English companies, the requests for the data were not fruitful. Obtaining the data from other counties of the AA was more difficult because of the organization of water supply in these countries, which is not as uniform. There are also many more water supply operators in countries like France, Spain and Portugal, compared to the UK and Ireland. In the case of France, for example, there are approximately 13,500 water service providers in the country as a whole.

The data was obtained usually either as a PDF document or a Microsoft Excel spreadsheet file. Relevant data for the study were extracted from these documents and a GIS database was created using *ArcMap* software. An example of Irish set of sites obtained from Dublin City Council and Kildare County Council is presented in Figure 5. The GIS database for the rest of the countries in the region is presented in Section 4, together with their resource assessments. Each point represents one of the WSN infrastructure types mentioned above, i.e. a potential MHP site. Each site in the GIS database possesses the following data, although sometimes not all this information was available:

- Flow and pressure at a valve location (in the best possible resolution)
- Type of infrastructure
- Longitude and latitude of a valve location
- Diameter of the pipe where the valve is installed

The flow and pressure data were usually obtained as annual mean values.

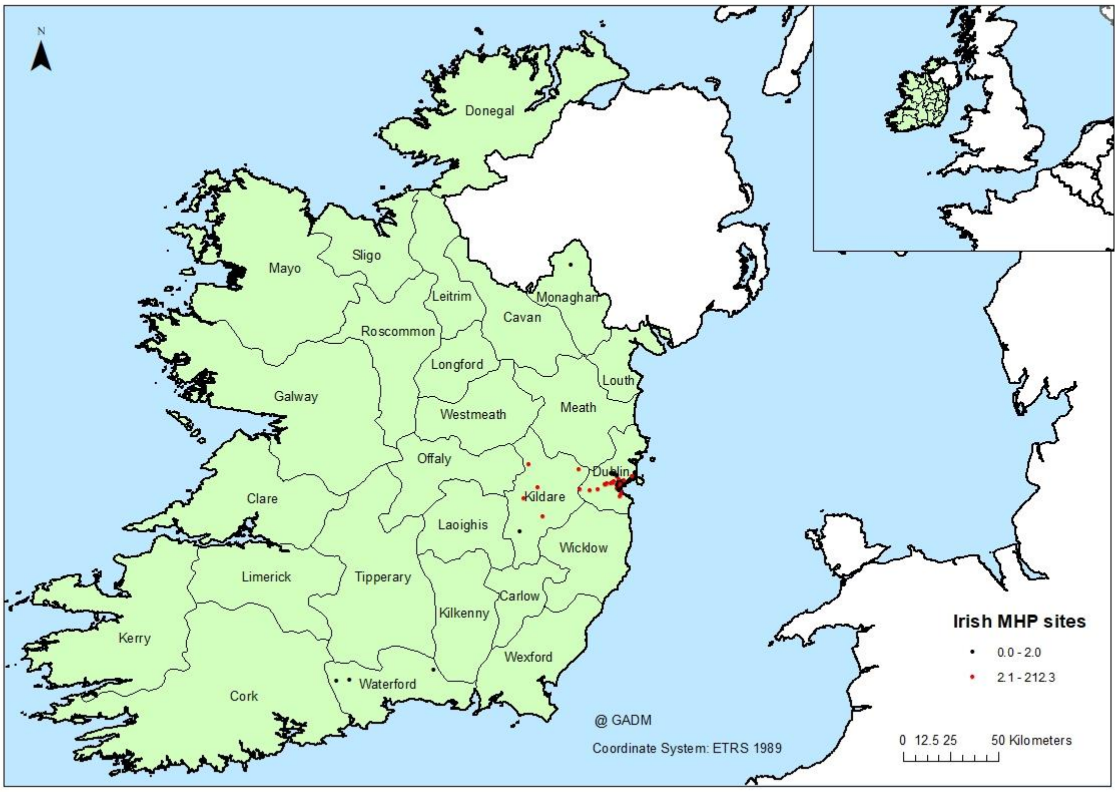
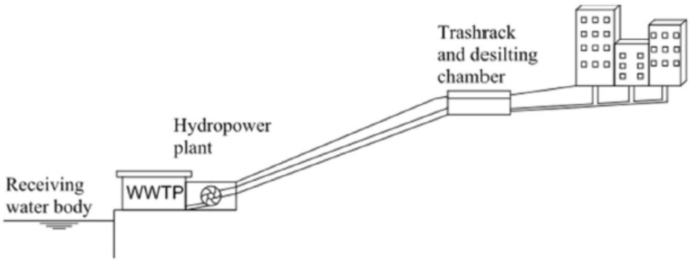


Figure 5: Spatial distribution of Irish set of sites in GIS database for the drinking water sector

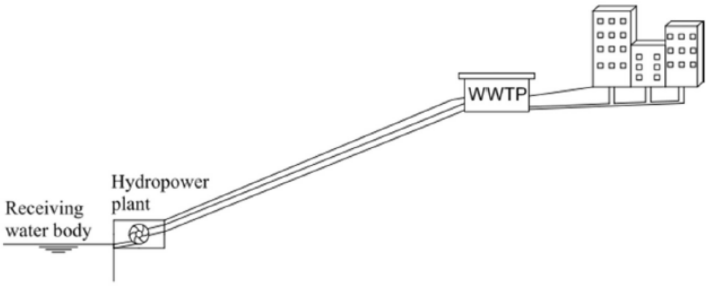
3.2. Wastewater Networks

WWNs or sewage systems are mostly gravity driven networks (free surface flow), whose function is to collect the effluent from its source and transport it to the WWTPs, where it is treated to the relevant quality standards before it is released into a water recipient.

Unlike in WSNs, in case of WWNs the location to install turbines is likely to be the same for every network, and limited to just at the WWTPs. The reason for this is the nature of the resource (wastewater), which has to undergo at least some kind of preliminary filtering to remove large solid materials existing in sewage, and thus, prevent the turbine from being damaged. Figure 6 presents two possible configurations.



a) Upstream sewage water micro-hydropower plant (USW-HP)



b) Downstream treated effluent micro-hydropower plant (DTE-HP)

Figure 6: Types of operation of hydropower in WWN, (Bousquet et al., 2017). a) USW-HP; b) DTE-HP

The configuration presented on Figure 6.a, considers the installation of the MHP plant just upstream of the WWTP. Consequently, this configuration requires the construction of an additional preliminary treatment facility, such as a trashrack chamber, for filtering the effluent. Moreover, an additional penstock has to be constructed to make the pressurized connection with the turbine. The configuration presented in Figure 6.b includes the construction of the MHP plant downstream of the WWTP.

The profitable sites for the first configuration are characterized by very large hydraulic heads (a few hundred meters) and with moderate flows of around 50 l/s. This means that the profitable sites of this configuration can occur only in mountainous areas. On the other hand, the profitable sites for the second configuration are characterized by small heads (usually less than 10 m) and very large flows (around 400 l/s), which makes this configuration more common as most of WWN sites have these characteristics (Bousquet et al., 2017).

Section 4.2 of this report presents the MHP energy recovery resource assessment of the WWNs in Ireland and Spain. In this assessment, only the potential of the second configuration was considered. The reason is that generally, the topography of the areas in proximity of the WWTPs is such that the hydraulic heads necessary for the first configuration to be profitable cannot occur. The rest of this subsection will present the format and source of the input data that was necessary for the assessment.

Coordinates of the discharge outlets

Every new WWTP in Europe is required to submit a Wastewater Discharge Licence (WWDL) Application Form to the relevant Environmental Protection Agency (EPA), which has to be approved by the Agency before the plant is put into operation or for old ones to proceed to operate. These application forms are publicly available.

The locations where the treated effluent of the WWTPs is discharged are provided as a part of the discharge license. These locations represent the outlets of the WWTP discharge pipes. In the DTE-HP configuration, these locations take place downstream of the hydropower plants, in the receiving water body, at a safe distance from river or coastal banks. These locations are used to help us find the locations of the WWTPs, i.e. the inlets of the discharge pipes and the locations of the potential hydropower plants (see Figure 6.b). An example of the discharge location of a WWTP in Ireland is presented in Figure 7.

Besides the coordinates of the discharge pipe outlets, some discharge license submissions contain CAD drawings of the plants. These drawings helped to determine the exact locations of the WWTPs and of the potential hydropower plants.

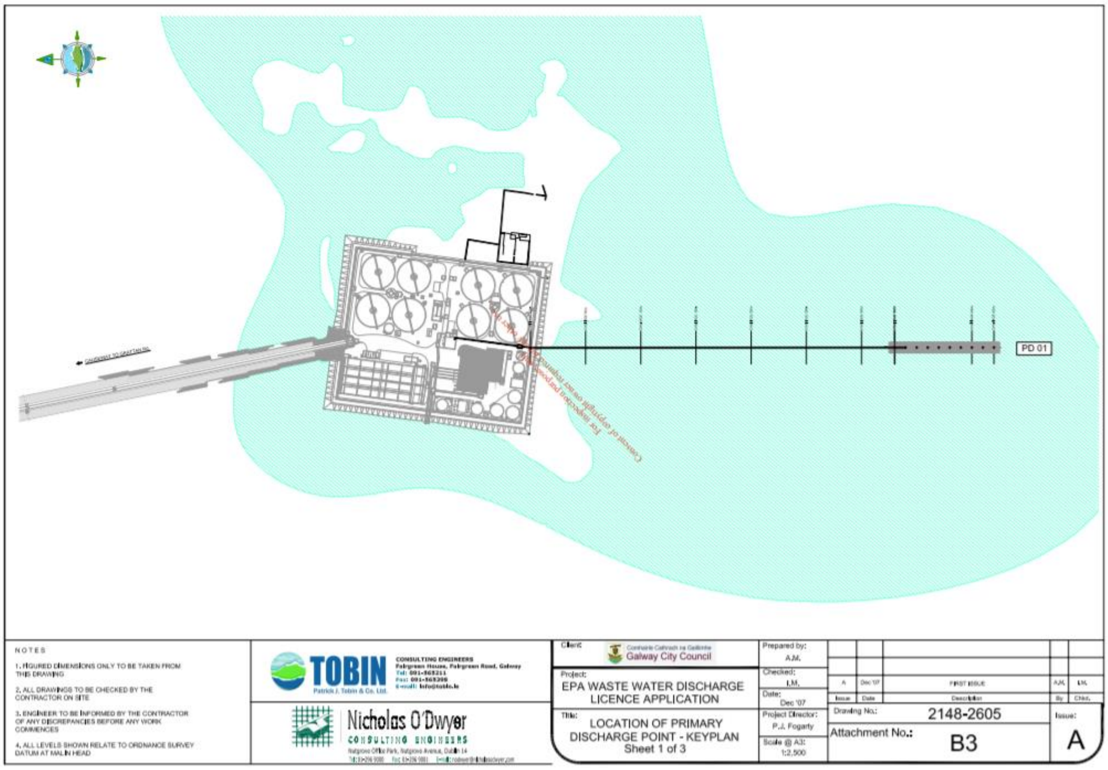


Figure 7: Drawing of a WWTP and its discharge pipe in Ireland

<u>Discharge volumes of the WWTPs</u>

The same EU legislation enforces wastewater operators to submit a document called Annual Environmental Report (AER) in order to keep their WWDL. One of the data included in the AER is the mean annual discharge volume expressed either in m^3/year or in people equivalent (PE) units. This data was used to represent that available flow at potential MHP installations at WWTPs.

<u>Digital Elevation Model (DEM)</u>

DEMs are computer graphics representation of the terrain's surface. In this case, DEMs were used to find out the difference in elevation (available pressure) between the location of the WWTPs and the discharge point of each one. The DEM was obtained from United States Geological Survey (USGS) website ("EarthExplorer - Home," n.d.). This DEM was used because it has the best resolution available. This DEM has the resolution of 2x1 arcsecond, which is around 60x30 meters. The DEM was primarily used to extract the elevations of the inlet and outlet locations of the WWTP discharge pipes, necessary for the assessment of their MHP potential.

3.3. Irrigation Networks

Within the irrigation sector, data from 18 different irrigation districts were gathered. These entities were located in Spain and Portugal. Information on 17 out of the 18 districts received corresponded to Spanish organisations, located in Southern and Western Spain. The last irrigation district was located in Ferreira do Alentejo, Southern Portugal. The total irrigated area gathered amounted up to 36,536 ha.

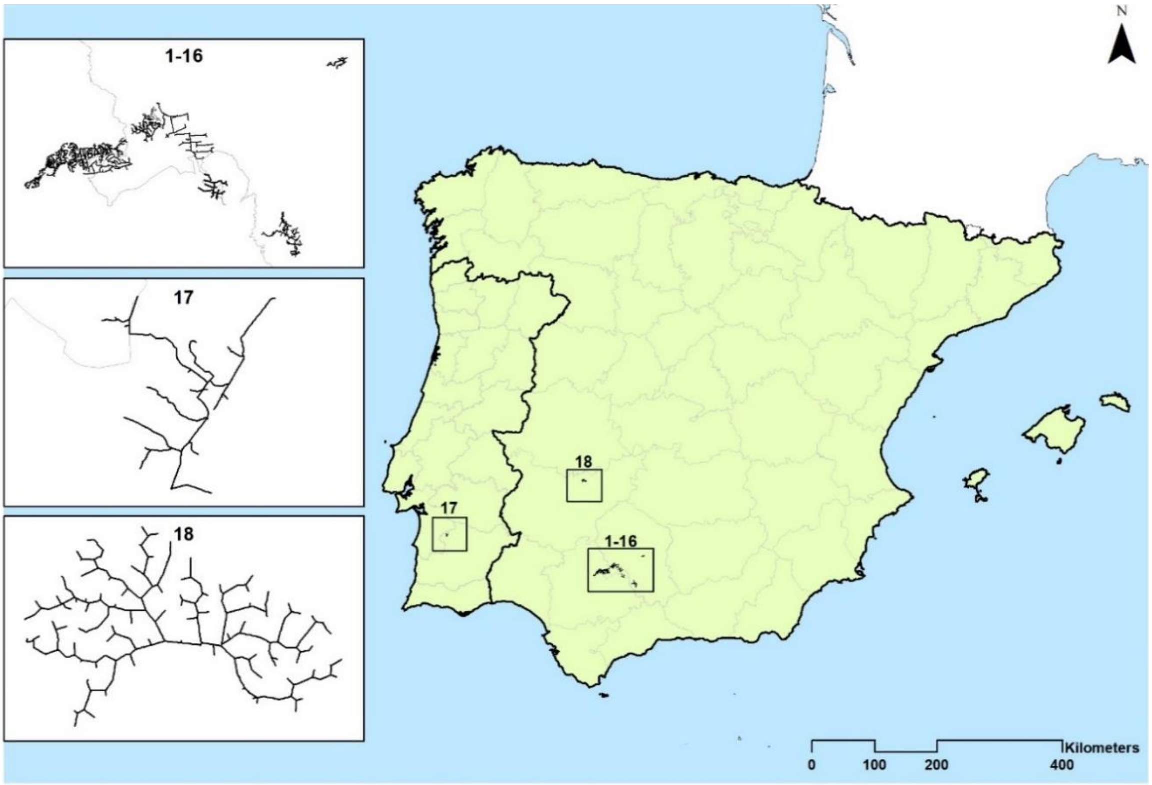


Figure 8. General plan of the Southern Spain and Portugal Irrigation Districts analised

The information received was composed of design plans and parameters of the networks, as well as service working conditions and main crops cultivated. In Figure 8, the skeleton of the 18 networks is shown. In Table 5, a summary of the information received from each irrigation district is shown.

Table 5. Summary of the information received for each irrigation district

District	Networks Analysed	Irrigated Surface (ha)	Dominant Crops
Genil Margen Izquierda	1	4450	Citrus, Almond, Olive, Walnuts
Bembézar Margen Izquierda	1	3900	Citrus, Maize, Olive, Sunflower
Bembézar Margen Derecha	10	11,163	Citrus, Maize, Cotton, Sunflower
El Villar	1	2726	Cereals, Cotton
Genil-Cabra	1	4320	Cotton, Sunflower and Wheat
Guadalmellato	1	475	Maize, Cotton, Sunflower, Wheat
Fuente Palmera	1	5611	Cotton, sunflower, and wheat
Aboro	1	1200	Olive, Maize, Almond
Zujar	1	2691	Tomatoes, Maize, Vine, Fruit, Rice

3.4. Private industrial Networks

Information from large industrial water users with private network infrastructure within their facilities was also sought from numerous organisations. The same data requirements on hydraulics models or information of PRVs, inlet works, etc., as for the public drinking water network applied in this case. Data was sought from food production, mining and IT sectors.

In the case of Spain, a database conformed by the authorised discharge wastewater volumes licenses for the main river basins in the country was assembled. This database not only included the wastewater infrastructures, analysed in the corresponding section, but also the industries whose effluent is not discharged into the urban sewerage network, but is directly discharged into the river. This makes this analysis of the process industry partial, since some of the industries may discharge their effluents directly into the sewerage system, although in these cases, the associated flows are usually small. The methodology followed to analyse the potential of these industries for MHP was similar to that defined for the WWTPs. Thus, the average annual volume of water, combined with the difference in elevation betweeen the industry and the elevation of the discharge point, were used to estimate the power potential for MHP. This power potential was analysed for the 87 potential sites in which, based on their average flow, a hydraulic head below 15 m was required. This was conducted as it was assumed that heads above 15 m were unlikely to be present in industrial discharges to local watercourses. The different industry subgroups in which any power potential above 2 kW was found were then synthesized into large production groups.

4. Existing Energy Resource Assessment

Following completion of the data acquisition phase, an assessment of the available resources was conducted converting the available excess pressure and flow to hydraulic power and electrical power estimates. The work is summarised in an energy recovery resource map, that will enable to focus on the points of greatest interest for a specific investment in MHP after the project.

4.1. Drinking Water Networks

In the most general case, the energy recovery from a WSN consists of finding optimal locations, number, turbine types and settings, which will maximize the energy recovery, while satisfying the hydraulic and technical constraints of the network. The minimum pressure required at each consumption node must continue to be supplied after the installation of the energy recovery system, ensuring the correct supply to the network users.

For networks for which the hydraulic model was available, the energy recovery assessment was an iterative process where the pressure zone map of each network was analysed and, by varying the aforementioned parameters using trial and error, the solution that maximized the energy recovery was obtained (García et al., 2018). In this preliminary assessment turbines were simulated as PRVs, in *Epanet* software.

The energy recovery of a WSN can also be assessed as an optimization problem but, because of the complexity of the problem, a suitable algorithm which would solve this problem in a reasonable amount of time, especially for large size networks, still does not exist.

When only locations of the WSN infrastructure are available (see Section 3.1), the energy recovery consists of finding the optimal turbine type and its settings for the selected site, depending on the site's flow and pressure conditions. For the preliminary assessment, the potential was assessed by using a hypothetical MHP plant with a constant efficiency (an average value used for the total efficiency of turbine and generator assembly and transmission), and following Equation 1,

$$P = \rho g Q H \eta \, [W] \tag{1}$$

where P is Power expressed in [W], ρ is density of water [kg/m^3], g the gravity acceleration [m/s^2], Q is flow at turbine [m^3/s], H is hydraulic head available at turbine [m] and η is total efficiency of MHP plant [%]. In this case, an average an conservative value of 0.5 for the efficiency in the drinking water networks analysis was used.

For the 9 WSNs mentioned in section 3.1, for which the hydraulic models were available, the optimal locations were found using the procedure explained above. These sites were then added to their country set of potential MHP sites.

Table 6: Estimated energy recovery at collected MHP sites in the water supply networks in the countries of the study area.

	Power	**<2 kW**	**2-5 kW**	**5-10 kW**	**10-15 kW**	**>15 kW**	**Total**	**Total > 2 kW**
Ireland	No. of sites	18	3	8	5	10	44	26
	Power [kW]	11.3	9.4	60.3	65.0	533.3	679.3	668.0
	Energy [MWh]	99.1	82.5	527.9	569.7	4671.9	5951.1	5852.0
N. Ireland	No. of sites	1992	124	20	6	12	2154	162
	Power [kW]	696.2	348.9	145.2	73.6	291.7	1555.6	859.4
	Energy [MWh]	6099.0	3056.2	1271.9	645.0	2555.2	13627.2	7528.2
Scotland	No. of sites	3347	1330	435	95	144	5351	2004
	Power [kW]	1955.3	4648.6	3488.6	1060.1	6318.9	17471.5	15516,3
	Energy [MWh]	17128.0	40721.6	30560.2	9286.8	55353.9	153050.5	135922.4
Wales	No. of sites	104	37	26	4	8	179	75
	Power [kW]	74.9	114.2	178.1	46.1	433.8	847.0	772.2
	Energy [MWh]	656.0	1000.3	1560.0	403.8	3800.0	7420.2	6764.1
France	No. of sites	2	0	0	0	0	2	0
	Power [kW]	3.1	0	0	0	0	3.1	0.0
	Energy [MWh]	27.5	0	0	0	0	27.5	0.0
Spain	No. of sites	25	5	2	0	2	34	9
	Power [kW]	12.5	16.2	15.2	0.0	63.5	107.4	95.0
	Energy [MWh]	109.2	142.0	133.4	0.0	556.7	941.2	832.1
England	No. of sites	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Power [kW]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Energy [MWh]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Portugal	No. of sites	3	6	2	0	0	11	8
	Power [kW]	5.2	21.3	12.4	0.0	0.0	39.0	33.7
	Energy [MWh]	45.7	186.7	108.9	0.0	0.0	341.4	295.6
Total	**No. of sites**	**5491**	**1505**	**493**	**110**	**176**	**7775**	**2284**
	Power [kW]	**2758**	**5159**	**3900**	**1245**	**7641**	**20703**	**17945**

The results of the energy recovery assessment of the collected sites for the different countries are presented in Table 6 for the whole study area. Their spatial distribution is presented in

Figures 9-15. The size of the circles represents their potential, as set out in the legends on the Figures.

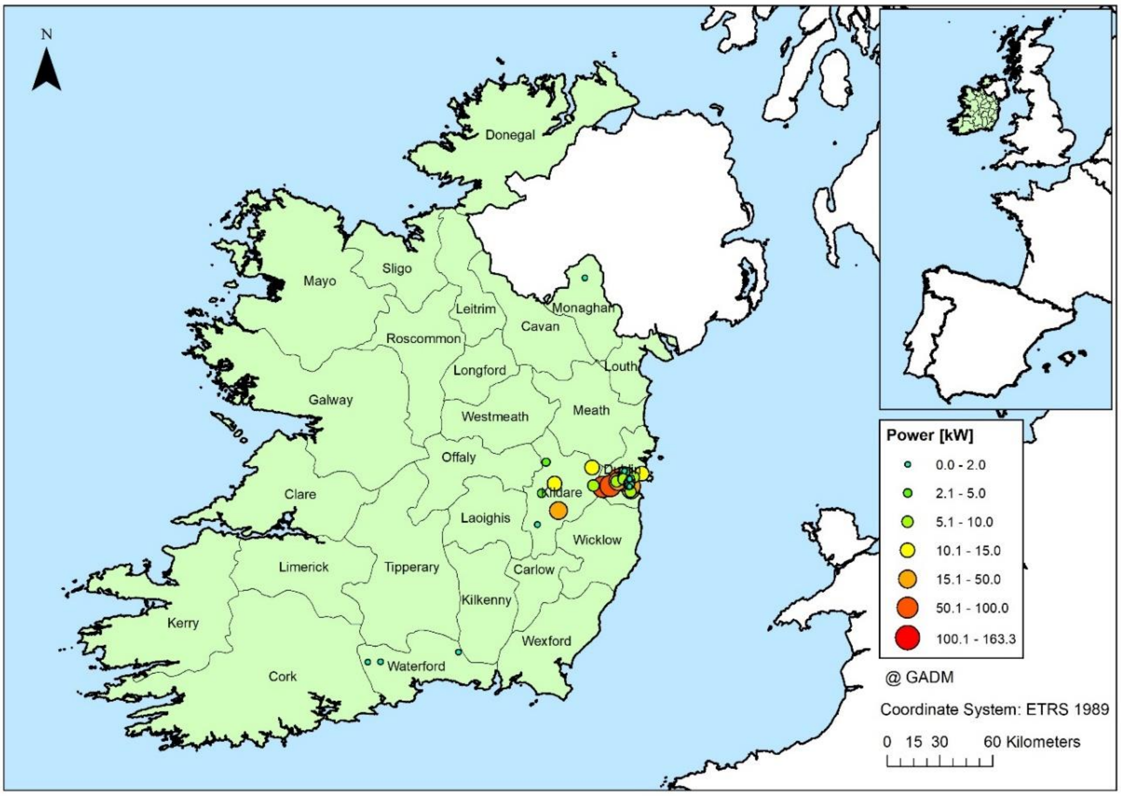


Figure 9: MHP energy recovery potential of Irish sites in the drinking water sector

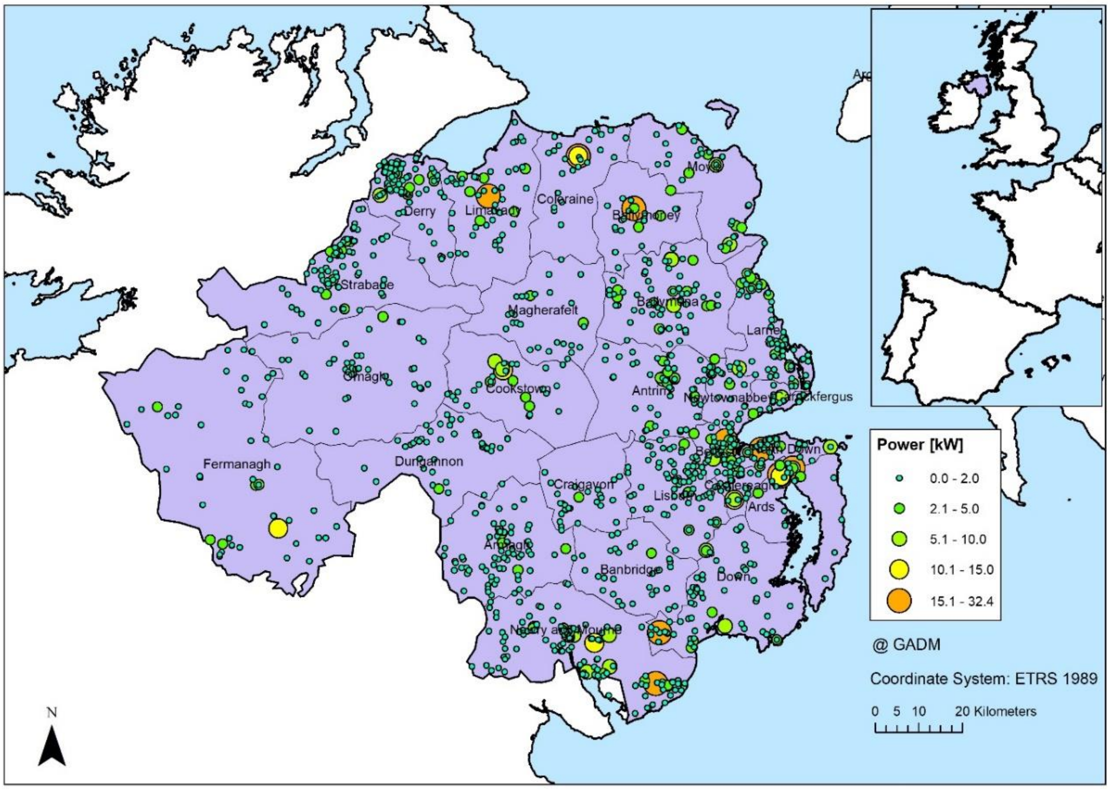


Figure 10: MHP energy recovery potential of Northern Irish sites in the drinking water sector

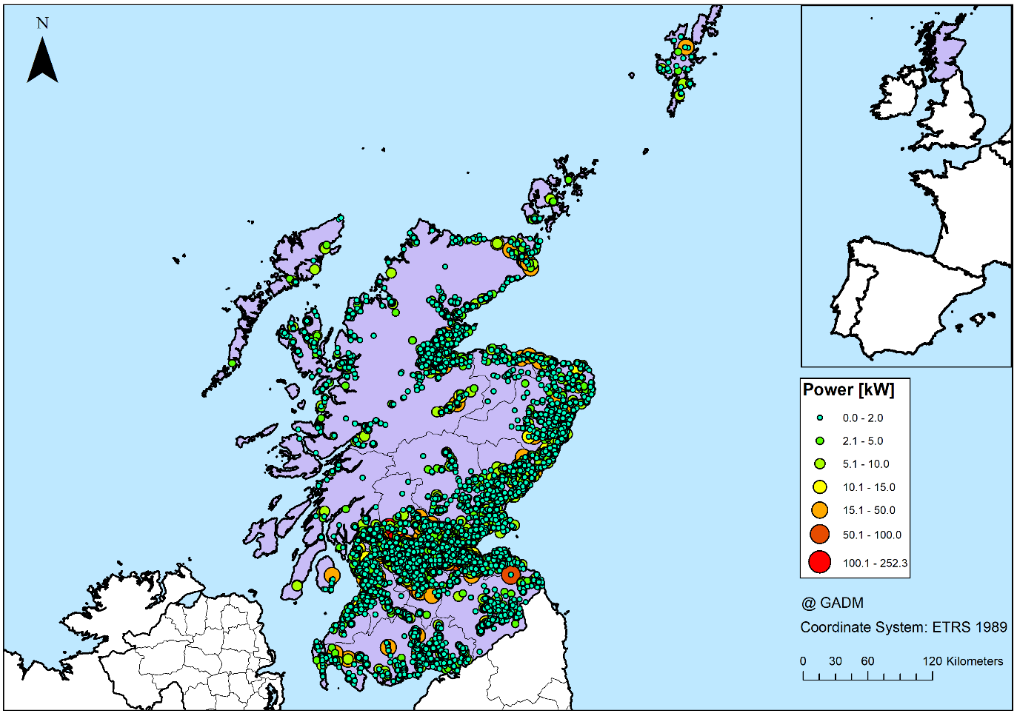


Figure 11: MHP energy recovery potential of Scottish sites in the drinking water sector

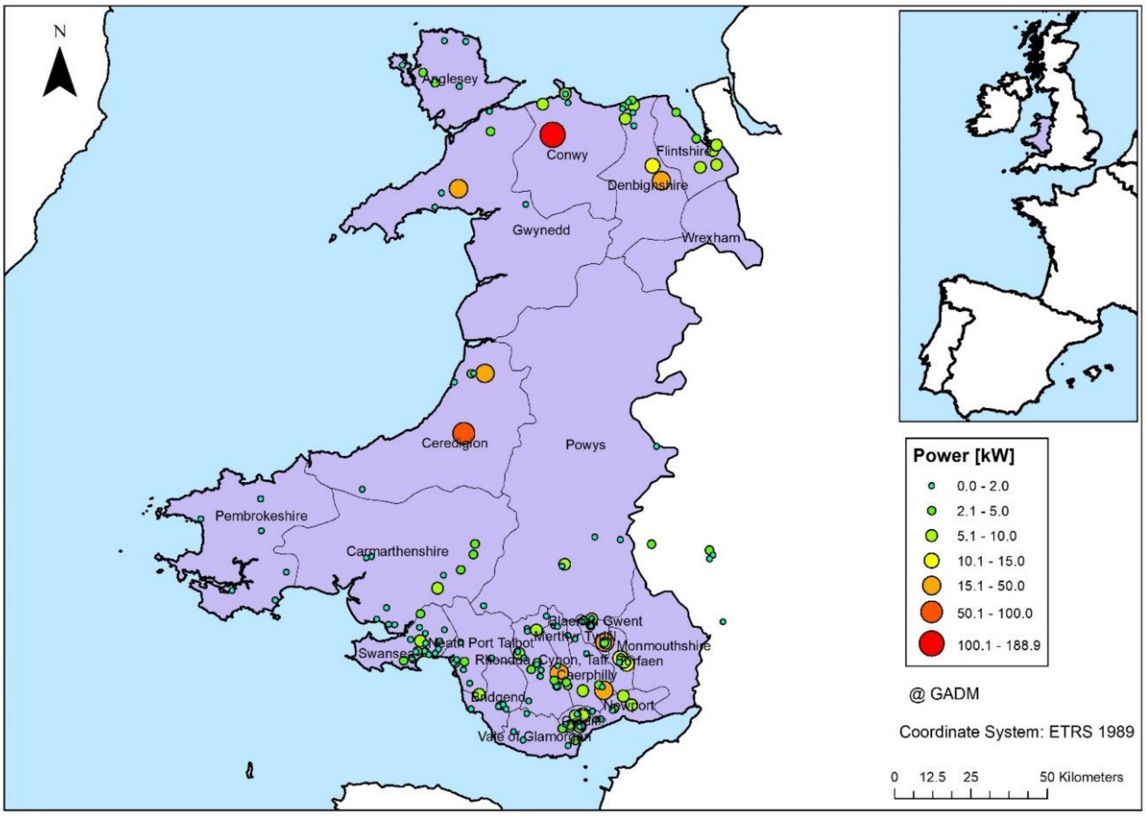


Figure 12: MHP energy recovery potential of Welsh sites in the drinking water sector

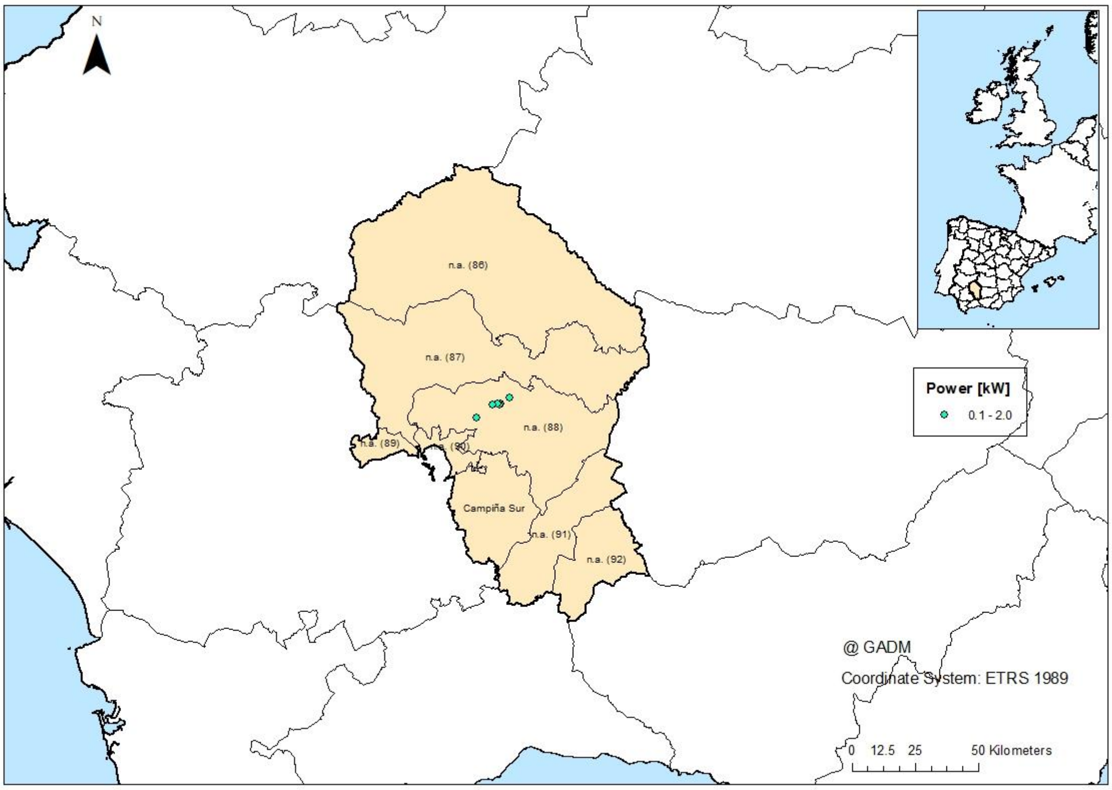


Figure 13: Spatial distribution of MHP energy recovery sites in Municipality of Cordoba, Spain, in the drinking water sector

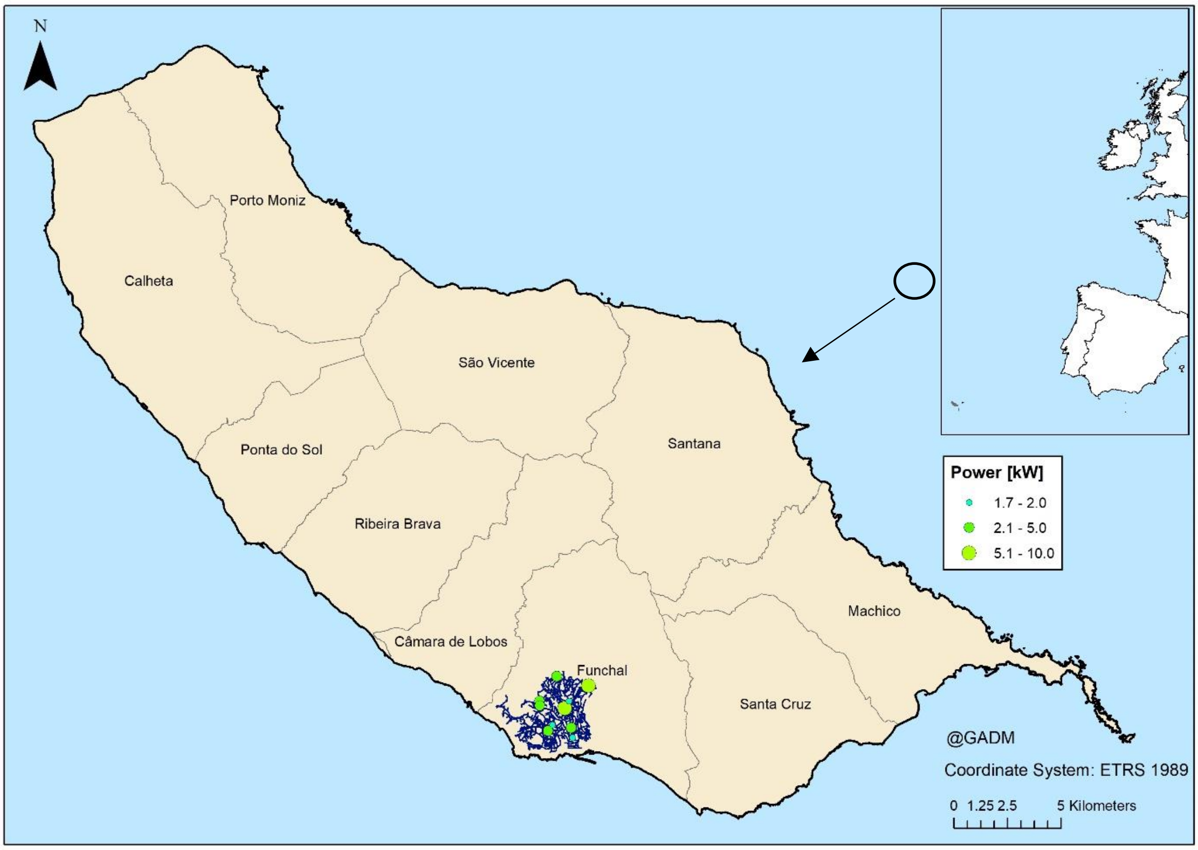


Figure 14: Spatial distribution of MHP energy recovery sites of Funchal WSN, Madeira Island, Portugal, in the drinking water sector

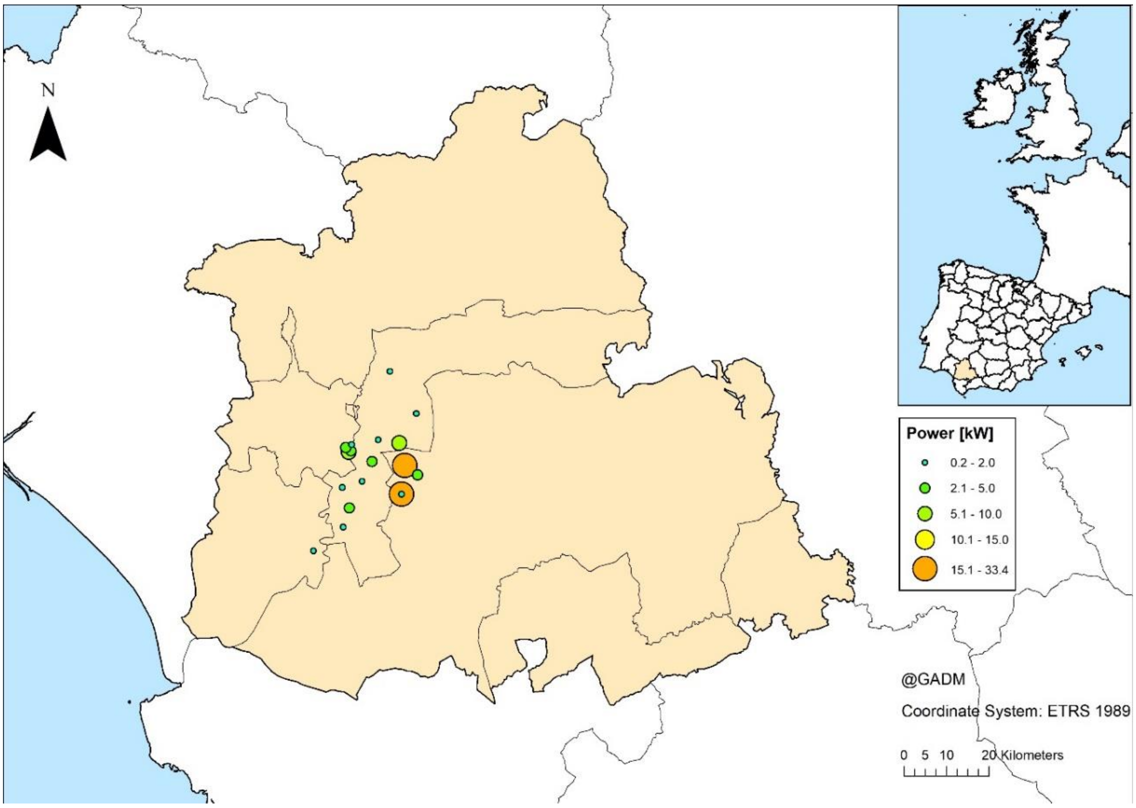


Figure 15: Spatial distribution of MHP energy recovery sites of Seville, Spain, in the drinking water sector

4.2. Waste Water Networks

Hydropower energy recovery has received very little attention as a solution to improve the energy efficiency and sustainability of WWNs, compared to other renewable energy sources, such as anaerobic digestion (Zakkour et al., 2002) or combined heat and power systems (Bennett, 2007). There are only a few scientific articles about MHP energy recovery in WWNs and most of these are focused only on a certain number of WWTP case studies (Power et al., 2017, 2014) rather than on a strategic regional assessment of the potential.

Only one scientific article was found that investigates the total MHP potential available in WWNs on the country scale (Bousquet et al., 2017). The methodology presented in this study was applied to a case study of Switzerland, and it took advantage of a database provided by the Swiss authorities, that included the data about all WWTPs in the country such as their mean annual discharge and georeferenced locations of inlets and outlets of the discharge pipes. Such a database was not publically available, in general, for most of the countries in the AA.

A comprehensive investigation was carried out to find out which WWTP data was publicly available and which could be used to assess the energy recovery potential.

4.2.1. MHP potential estimation in WWTPs in Ireland

As the result of the research, a modified version of the methodology presented by Bousquet et al. (2017) was defined. The methodology flowchart is presented in Figure 16. The differences with the methodology presented by Bousquet et al. (2017) are that the methodology presented on Figure 16 assesses only potential of DTE-HP configuration, i.e. when the plant is installed downstream the WWTP (the reasons are explained in subsection 3.2), and in Step 2, which narrows down the set of WWTPs to the ones with the biggest flow. This assessment was conducted in detail for Ireland, as a first step. The methodology applied for the estimation of the MHP energy recovery potential in the WWTPs in Ireland was organised in 5 distinct steps: gathering discharge volume data; selecting the most promising plants; finding locations of inlets and outlets of WWTP discharge pipes; calculating available hydraulic head and finally, calculating the MHP potential.

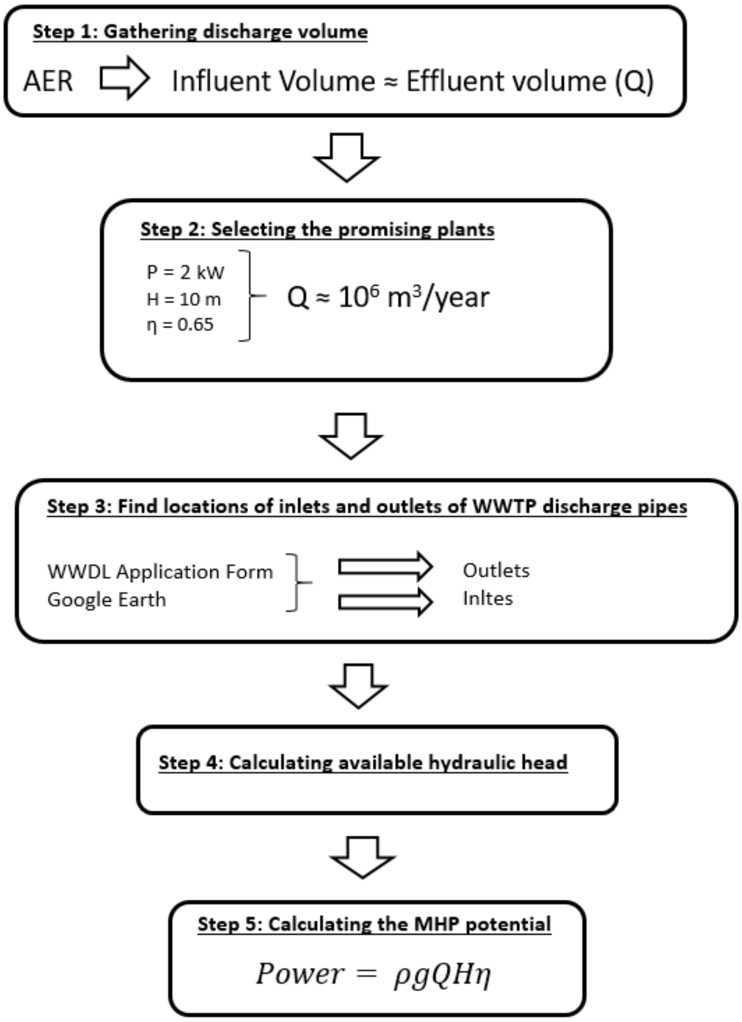


Figure 16: A methodology for the MHP potential assessment at the outlets of WWTPs

Step 1: Gathering discharge volume data

For the year 2014 in Ireland, there were 535 AERs on the EPA website. Each AER refers to an agglomeration. The term agglomeration refers to a sufficiently concentrated area for urban wastewater to be collected and conducted to an urban WWTP (European Commission, 2007). However, the WWTP that treats the agglomeration's wastewater does not necessarily take place in the area defined by the agglomeration. The example for this is a situation when the wastewater of a smaller agglomeration is collected by a wastewater pumping station from where it is pumped to a WWTP, which takes place in an area of some other agglomeration.

In cases when an AER represents a pumping station, the AER does not contain the discharge data. The discharge data can be also unavailable in cases when an agglomeration is in the process of building its WWTP, or in cases when the discharge is not measured. The 181 out of 535 reports did not have discharge data for the year 2014.

Step 2: Selecting the most promising plants

After gathering the discharge volume data for all WWTPs in Ireland for which this data was available (354 plants), the next step was to find the georeferenced locations of their discharge outlets (Step 3 on Figure 16). Collecting these data for all 354 plants would be very tedious work, especially considering that the WWDL Application Forms, where this data can be found, are not standardized documents, and some of these can have more than 100 pages. At the same time, it is also unnecessary considering that most of the plants do not have a discharge large enough for a turbine installation to be economically viable, as the available head at the WWTP outlets is rarely more than 10 m. As a consequence, Step 3 of the methodology was conducted only for the plants that fulfill the criteria of having the discharge large enough to produce a power of at least 2 kW with the hydraulic head of 10 m. The threshold of 2 kW was previously set as plants with power less than this value are usually not economically viable. This threshold is conservative, especially for the MHP sites at WWTP outlets, which have such hydraulic head-flow characteristics which require low-head turbines, and are more expensive than their high-head counterparts. The minimum yearly discharge which would produce the power of 2 kW with the hydraulic head of 10 m is the flow of 1 million m^3. 66 out of 354 plants had a discharge equal or larger than this value and these have proceeded to Step 3.

Step 3: Find locations of inlets and outlets of WWTP discharge pipes

As mentioned before in this report, the georeferenced coordinates of WWTP discharge outlets can be found in the WWDL Application Forms. These coordinates were collected for the set of the 66 most promising WWTP sites. An example of the location of a WWTP outlet can be seen in Figure 17, where it is designated with the yellow pin. The locations of these discharge points helped us to find the coordinates of their WWTPs, i.e. the approximate coordinates of the inlets to the discharge pipes, by observing aerial photography in Google Earth in their proximity. The locations of the plants were easily detected because of the characteristic shape of their primary clarifiers. The approximate locations of the inlets to the discharge pipes are marked with red pins in Figure 17.

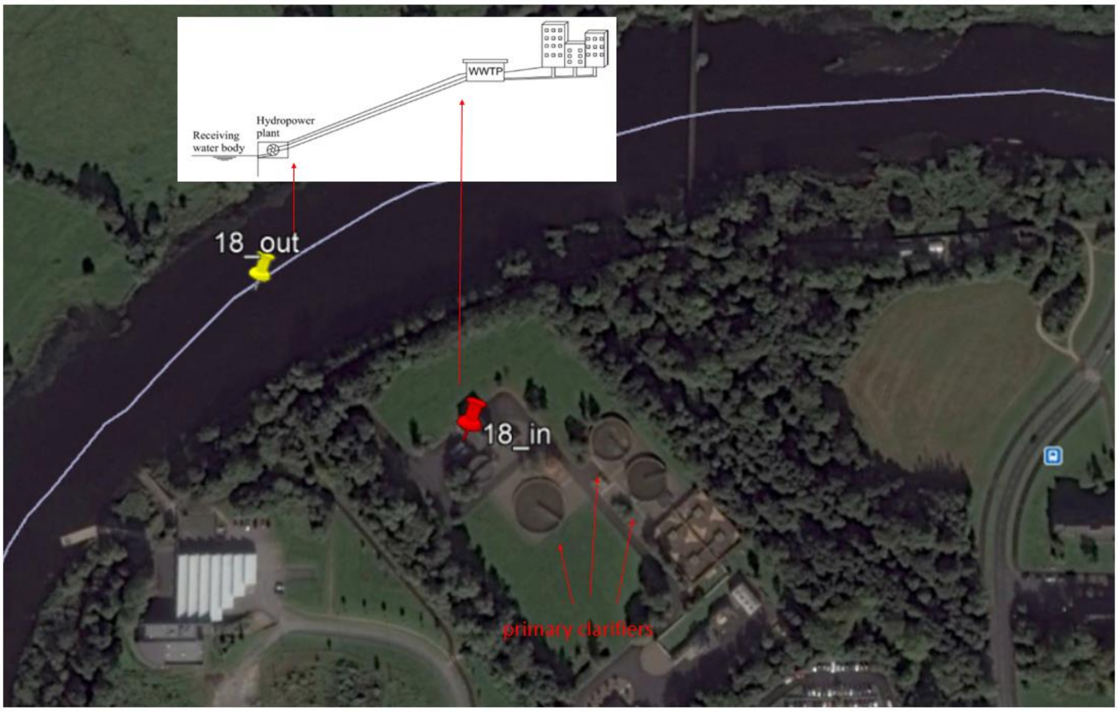
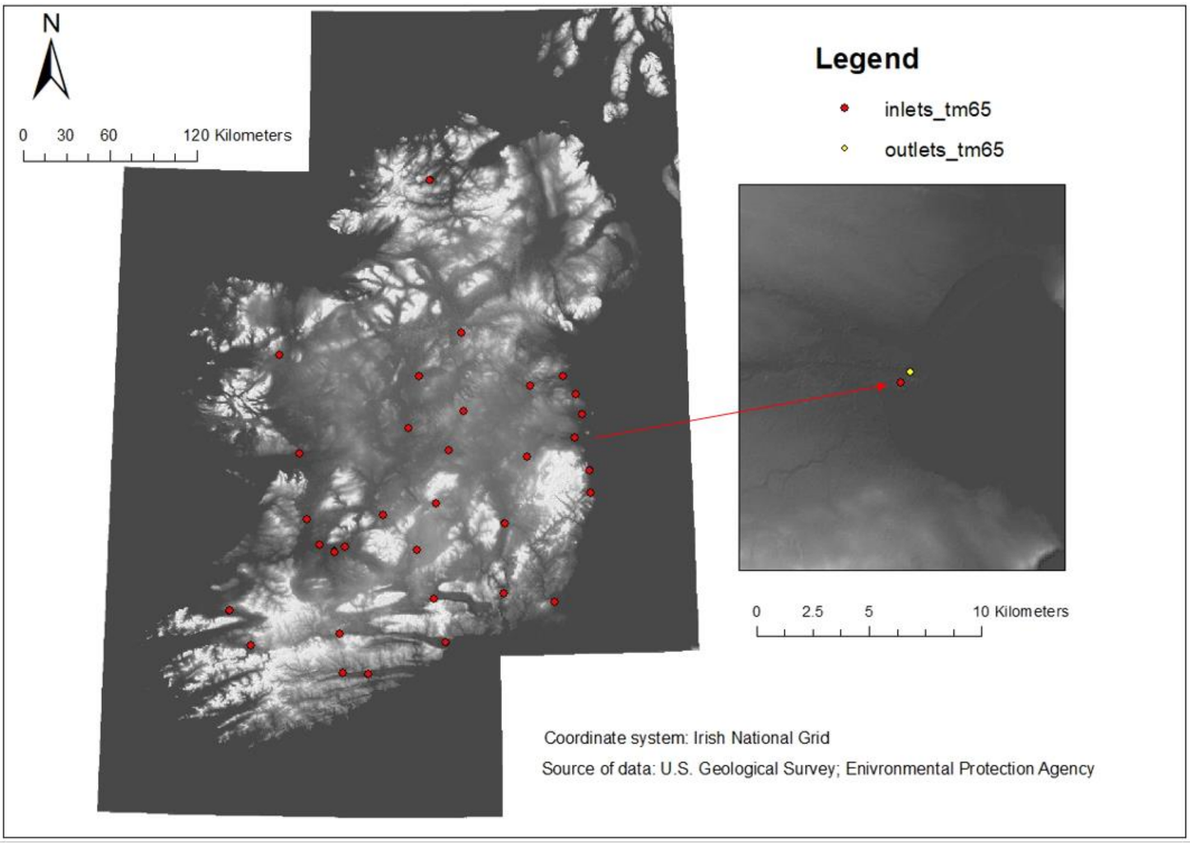


Figure 17: Aerial photography of a WWTP in Google Earth, with location of its inlet and outlet of the discharge pipe.

Step 4: Calculating available hydraulic head

The available hydraulic head at WWTP outlets is equal to the difference between piezometric heads at the inlet and outlet of their discharge pipes. The piezometric head at the inlet of a discharge pipe can be approximated by the elevation of this point, while the piezometric head at the discharge point is equal to the piezometric head of the river or sea where the wastewater is discharged, i.e. to the elevation of the river of sea water level.

To extract the elevation of these points, the software ArcMap was used and the DEM of Ireland (see Figure 18). After the elevations were extracted the available hydraulic head for each plant was calculated by subtraction between the elevations of the inlet and outlet. In Figure 18 there is less than 66 pairs of points because some of the WWTPs did not have the required available head.



Coordinate system: Irish National Grid

Source of data: U.S. Geological Survey; Enivronmental Protection Agency

Figure 18. DEM of Ireland with the two point shapefiles one for the inlets and the other for the outlets of WWTP discharge pipes

Step 5: Calculating the MHP potential

After obtaining the available hydraulic head for each WWTP, all the necessary data for the MHP energy recovery potential of the WWTPs in Ireland were collected. As in the case of the WSN sites, Equation 1 was used to assess the potential. In this case, Q represents the discharge of the plants, expressed in m^3/s, collected in Step 1, H represents the hydraulic heads calculated in Step 4, and the efficiency of the plants was considered constant with a value of 0.5, for this stage of the assessment. The results of the assessment are presented in Figure 19. The total potential estimated for these plants was 219 kW (only 15 sites presented potential power >2kW). This potential can be considered as the total potential for MHP energy recovery in Ireland considering that the rest of sites did not presented the required hydraulic head .

It should be mentioned that the potential obtained in this study is the theoretical potential as there are many uncertainties which have not been included, and which can influence the potential significantly. Some of these uncertainties are short and long term discharge variations, hydraulic head variations, hydraulic losses along the discharge pipes, exact location of turbine installation, accuracy of DEM, etc.

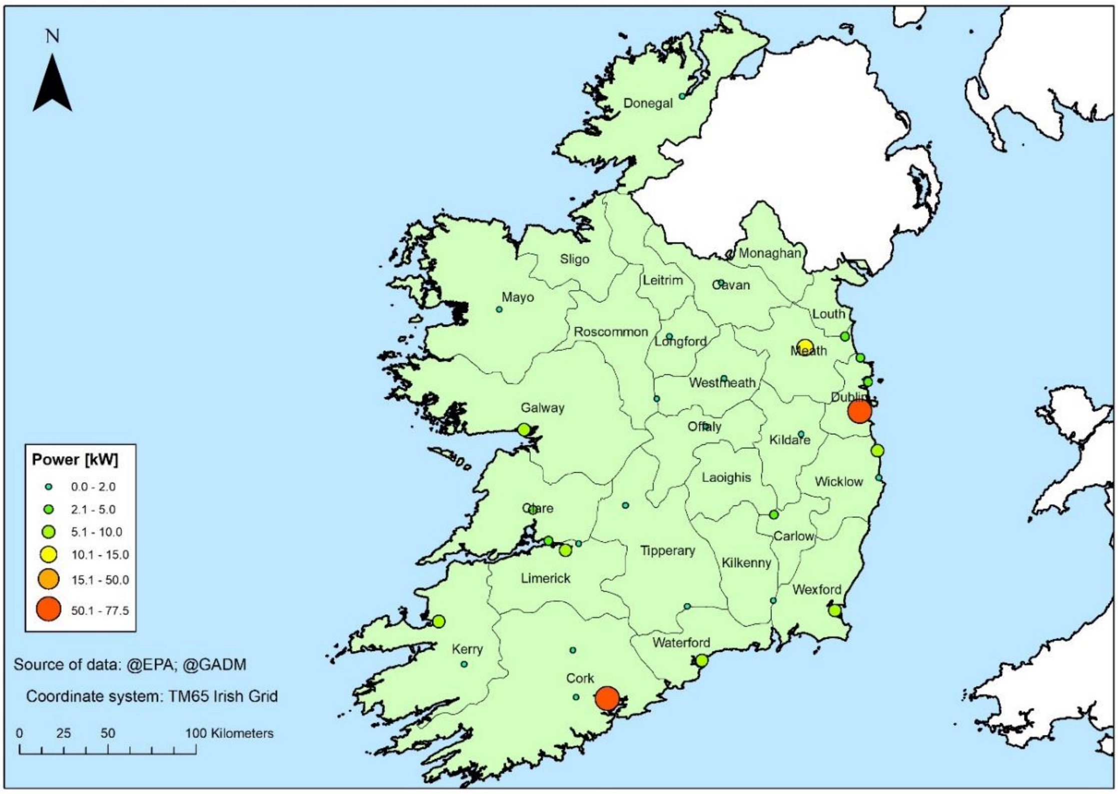


Figure 19. Map of MHP potential of the WWTPs in Ireland

4.2.2. MHP potential estimation in WWTPs in Spain

This same methodology developed to assess the potential for MHP in the WWTPs in Ireland was subsequently applied, in a similar way, to Spain, after getting the data corresponding to the discharge volumes authorised for the WWTPs in this country.

In this case, data about the annual discharge volumes authorised for all the WWTPs in the most important river basins in the country was found, covering a 78% of the country total area. This information gathered a total of 16778 licenses, corresponding to WWTPs, fish farms and industries. From the WWTPs set, those cases in which the available flow required less than 15 m difference in height (between the WWTP and the discharge point) for a 2 kW MHP plant were pre-selected, comprising a group of 343 potential sites. After being analysed, it was found that in fact, the largest number of sites that met the requirements were those for which the required hydraulic head was less than 10 m. The rest of the process followed to estimate the power potential for MHP technology was similar to the methodology established for the Ireland WWTPs analysis, for which the steps have been detailed above. From the set with a total of 343 WWTPs, 89 of them presented an MHP potential above 2 kW (Figure 20), with a total power potential of 986.6 kW. The remaining 254 WWTPs did not present the required available head.

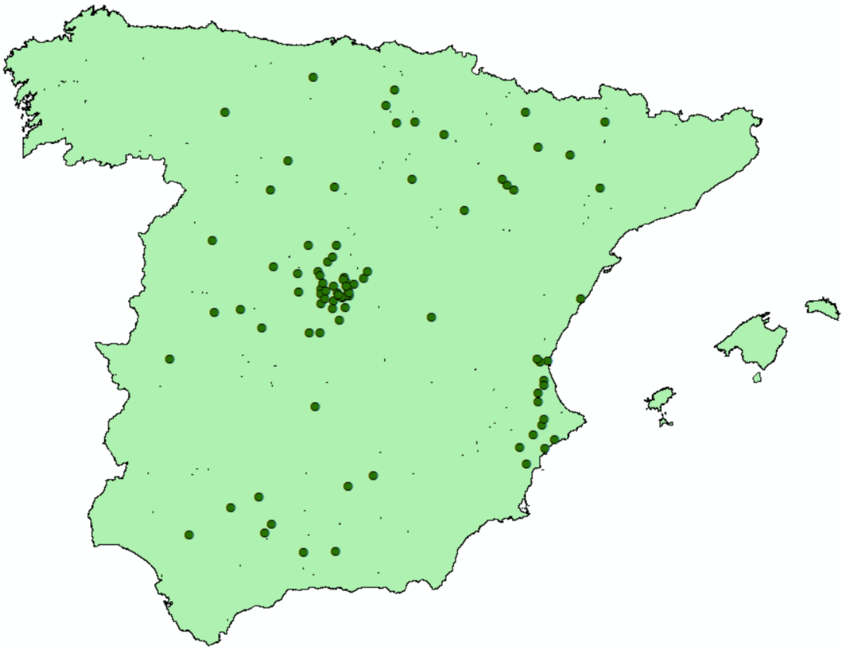


Figure 20. Location of the WWTPs in Spain with an estimated MHP above 2 kW.

Then, once the potential for MHP in the WWTPs for Ireland and Spain were estimated, the results were extrapolated to the rest of countries, using a correlation based on the power potential estimated and population covered in the WWTPs assessed (see section 5 for details). The extension of the methodology implemented for Ireland to the whole country of Spain helped to improve the correlation between the estimation of the MHP potential and the population corresponding to the study areas, as detailed in the following section. A future work should involve the development of a code which would automate the collection of the discharge data or a GIS analysis of population and industry data which would allow us to find the most promising sites more efficiently.

As a result of these assessments, the total power potential for the WWNs in Ireland and Spain amounted to 1206 kW.

4.3. Irrigation Networks

In the first approach conducted for assessing the existing potential energy resources, a methodology previously developed by Garcia Morillo et al. (2018), was applied in 12 of the networks gathered. Then, this assessment was complete counting a total of 18 irrigation networks, which presented 177 locations for energy recovery as suitable locations for the installation of MHP turbines or PATs (Table 7). These are shown in Figure 21.

Table 7**.** Summary of MHP energy potential estimates from the analysis of 18 irrigation network models in Spain and Portugal.

Network	**Country**	**Sites identified**	**Irrigated Surface (ha)**	**Surface with MHP potential**	**Power (kW)**	**Energy (MWh)**
GMI	Spain	17	4450	62.0%	133.5	662
BMI	Spain	15	3900	88.7%	197.1	744
BMD-S3	Spain	4	631	56.8%	38.2	46
BMD-S4	Spain	8	1679	48.6%	96.4	98
BMD-S5	Spain	3	1186	47.8%	14.1	59
BMD-S6.1	Spain	15	726	92.9%	196.8	452
BMD-S6.2	Spain	3	924	92.5%	57.0	107
BMD-S7	Spain	5	922	66.3%	90.4	94
BMD-S8.1	Spain	4	1141	70.1%	76.5	123
BMD-S8.2	Spain	8	1686	53.7%	155.2	127
BMD-S9	Spain	5	1275	83.0%	97.6	132
BMD-S10	Spain	3	993	70.2%	87.5	80
El Villar	Spain	13	2726	94.3%	293.8	917
Genil Cabra	Spain	34	4320	88.4%	639.4	1165
Guadalmellato	Spain	1	475	21.1%	17.0	161
Fuente Palmera	Spain	26	5611	91.0%	487.7	934
Aboroa	Portugal	4	1200	74.6%	48.9	79
Zujar	Spain	9	2691	58.2%	267.5	281
Total/Average		**177**	**36536**	**70%**	**2994.6**	**6114**

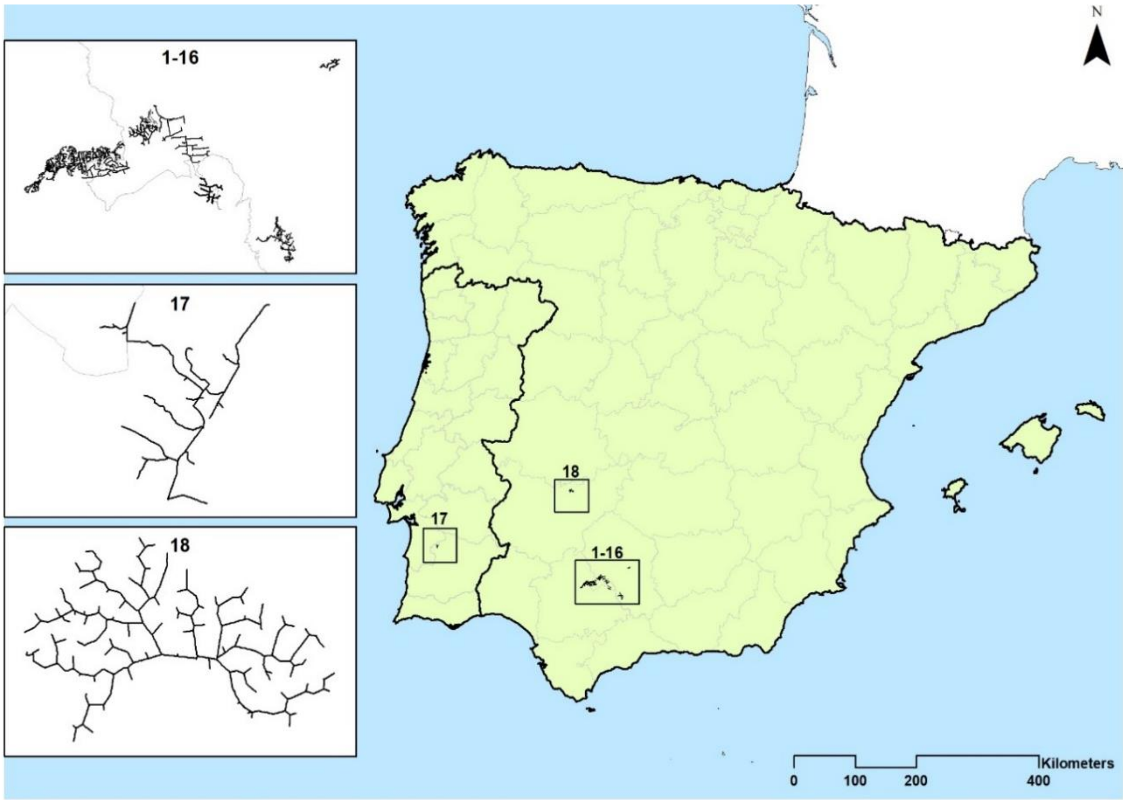


Figure 21. Location of the 177 suitable points found in the irrigation sector in Spain and Portugal.

This total power potential of 2.99 MW represented an annual energy potential of 6.11 GWh, considering that, in the case of the irrigation sector, unlike in the other sectors, the installations operate seasonally. Figure 22 presents the monthly distribution of the energy recovery potential at some of the MHP locations, with most of the energy concentrated in the summer months (from June to September), the most common period for the irrigation season in southern countries.

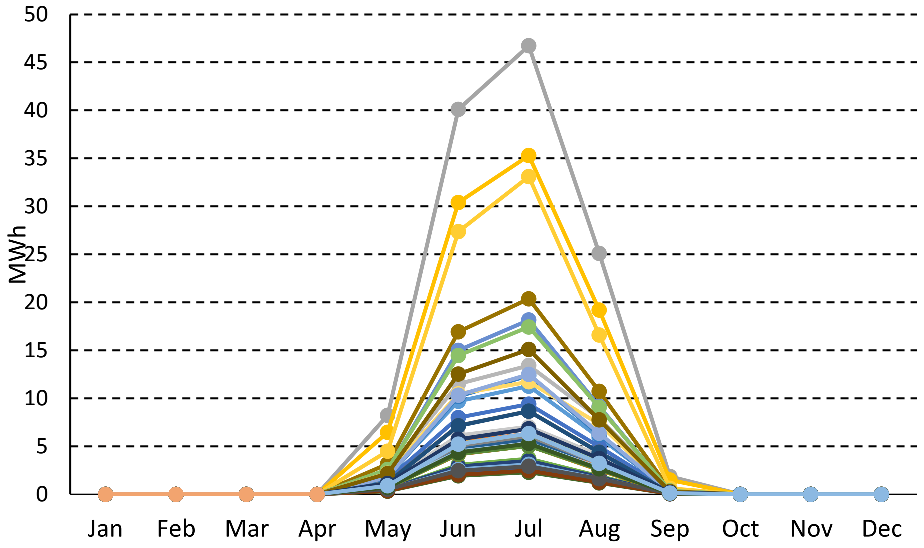


Figure 22. Monthly potential energy production, in kWh, of the 43 potential sites in the analised irrigation networks, distributed by month.

4.4. Process industry Networks

An assessment of hydropower potential within the wastewater networks of the following commercial organisations was conducted.

Table 8. Assessment of hydropower potential in private industrial water networks

Country	Hydro Potential (kW)	Nº of industries	Nº of sites
Ireland	211.6	3	22
Spain	1402.9	38	38
Portugal	10	1	1

The results obtained in the cases of Ireland and Portugal, while highlighting the interest of these industries for MHP energy recovery, were considered insufficient to allow an extrapolation methodology for the industrial sector as a whole, at the country level.

Therefore, in the case of Spain, the discharge authorisations for the different river basins made it possible to analyse a considerable group of industries for which the authorised annual discharge volumes were available. The same methodology propossed for the WWTPs in Spain was again followed for the industry sector, estimating the MHP potential with Equation 1, once the available hydraulic head and flow were previously determined, an considering an average efficiency of the MHP installation of 50%. A total of 87 industries were analysed as potential sites, for which the hydraulic head required for a minimum MHP installation of 2 kW was below 15 m. From those 87 cases, 38 of them presented an MHP potential above 2 kW, with the potential of 10 of them over 15 kW of power. These industries represented a total power of 1.4 MW, with an estimated annual energy recovery potential of 12.3 GWh, considering 24 h and 365 days of work. The industries were then grouped based on their principal activities (Table 9), being the energy-related industries the type with the greatest contribution (89%).

Table 9. Estimated energy recovery (MWh) at potential MHP sites in the private industry sector by type in Spain.

Total	Agri-food	Energy	Minerals, metals and construction	Paper	Chemicals
12290	58	10963	301	516	452
100%	0.47%	89.21%	2.45%	4.20%	3.67%

5. Resource Extrapolation

As outlined in the project proposal, only a partial database of existing water network infrastructure in the area of interest was possible to compile. These systems are very extensive and data was also unavailable in many cases, including not being publically available or not existing. As such, the project produced GIS-based prediction models (in the case of the irrigation sector, as example) of energy resources using the available water network data from the data acquisition phase, together with statistical information on irrigated areas and water demands. These models enabled us to extrapolate the results of the resource assessment to other regions in the study area. In other cases, in which not all the required information was available, the extrapolations were based on population and economics parameters, as it will be detailed here below.

5.1. Drinking Water Networks

As it can be seen in subsection 4.1 (Figures 9-15), the number and density of the collected energy recovery sites in the different countries of the AA varied significantly. There are various reasons for this, which were discussed in section 3.1, where most of them pertaining to organization and privacy policies of the water companies or non-existence of the data. This confirms the necessity for an extrapolation model which would provide an estimation on the total potential for this type of technology in the whole AA region.

In recent years, MHP energy recovery is getting more and more attention in the scientific literature as a solution to improve the sustainability of WSNs. A wide range of topics have been covered, such as which WSN infrastructure can be a potential MHP site (McNabola et al., 2014), which are the barriers for the implementation of MHP technology (McNabola et al., 2014), algorithms for optimal placement of turbines in WSNs (Corcoran et al., 2016, Giugni et al., 2014, Fecarotta and McNabola, 2017), PAT technology designs (Carravetta et al., 2013) etc. However, none of these studies have tried to assess the total potential for this technology on a regional or national scale. A few estimates have been mentioned in the literature, such as 4.7 MW for Germany (Carravetta et al., 2012), if all PRVs would be substituted with turbines, or 17 MW for the water industry in the UK (Zakkour et al., 2002).

The first attempt to create an extrapolation model, able to estimate the potential in the whole study area, was presented in the study by Mitrovic et al. (2018). As the assessment of MHP potential of a WSN is very complex, as a problem which depends on many variables, the main obstacle when creating an extrapolation model is to find variables which would be able to explain variation of the potential available for the whole area of interest. The concept presented by Mitrovic et al. (2018) was based on Land Use Regression (LUR) (IEHIAS, n.d.). This methodology involved an assessment of the correlation between MHP potential and geographical variables on the site level. The geographical variables used, explained in detail in the aforementioned study, represented the population and topography of terrain around MHP sites. The methodology was applied to a set of Irish and Welsh data. The results obtained with the developed model, based on *ArcMap* software, showed the population-correlation as the best, though still small, whith the best R^2 of 21.4 % obtained for the subset of Irish PRVs. The correlation analysis with the topography variables showed lower values of the coefficient of determination, with values close to zero for almost all alternatives.

Therefore, finally, given the scarcity of more detailed information, it was decided to carry out a population-based extrapolation for the case of the drinking water sector, as detailed below.

5.1.1 Population based estimation

Using the data collected and the population served by each area these data cover, an extrapolation of the potential to the full area of interest can be conducted. This assumes that the data collected represent the full potential for MHP energy recovery in those networks and that, since there is a relationship between population density and water demands, there may also be a similar relationship between energy recovery potential and population. The validity of these assumptions is explored further in section 5.1.2. However, this is likely to be an underestimation of potential in some respects as the data collected do not represent optimum pressure reduction or even all existing pressure reduction in an area. The estimate may be an overestimation in other respects as, due to the lack of detailed data, accounting for flow variations, practical viability, etc., is not included. Table 10 below illustrates the extrapolations based on population and the data collected to date.

Table 10: Population-based extrapolation of drinking water MHP potential to the full study area.

Country	Power Estimated	Pop. covered (M people)	Total pop. (M people)	kW per 1000 ppl	Extr. Power potential I*	Extr. Power potential II**
Scotland	15516	5.37	5.44	2.89	15704	3958
N. Ireland	859	1.81	1.81	0.47	860	1318
Ireland	668	1.90	4.76	0.35	1671	3465
England	-	-	55.98	-	-	40737
Wales	772	3.06	3.14	0.25	793	2284
France	-	-	65.26	-	-	47490
Spain	95	1.02	47.10	0.09	4403	34277
Portugal	34	0.11	10.28	0.31	3153	7479
Total/ average	**17945**	**13.27**	**193.77**	**0.73**	**26584**	**141008**

*extrapolation of power (kW) using country specific ratio; **extrapolation of power (kW) using average ratio 0.73 kW/1000 population.

As can be seen in Table 10, due to a lack of collected data in certain areas (e.g. England), the extrapolation of the power potential was based on the ratios obtained for the rest of countries. Extrapolating the power estimation in countries with partial data, to the areas not included in the data collection was carried out on the basis of using the specific ratio determined for each country (Extrapolated Power potential I), and using the average (0.73 kW per 1000 population) across all of the countries by comparison (Extrapolated Power potential II). Thus, Extrapolated Power potential I showed a total of 26.58 MW, total in which neither England nor France were included, as this countries did not have any collected data, while the Extrapolated Power potential II amounted to a total of 141.00 MW. Then, the extrapolations for the annual energy recovery potential were made considering 24 h and 365 days of operation of the installations. Noting the significant variation in the power extrapolation ratios across each region in Table 10, which varied between 0.09 and 2.89, the estimation of the extrapolated energy potential was assessed under different assumptions, which results are showed in Table 11:

- Assumption 1: extrapolated energy potential was estimated based on the individual ratios for Scotland, N. Ireland and Wales, for which the full database was available, while the average ratio was used for the rest of countries.
- Assumption 2: extrapolated energy potential was estimated based on individual ratios for all countries in which any information was collected.
- Assumption 3: considered individual ratios for countries with a full database, while for Ireland, Spain, France, England and Portugal energy potential estimations were based on a partial average ratio, excluding Scotland, due to the significant difference in its ratio, compared to the rest of individual ratios.
- Assumption 4: extrapolated energy potential was estimated based on the median of the individual ratios to all countries.

Table 11: Extrapolated energy recovery potential for the drinking water sector in the different countries of the study area.

	Extrapolated Energy Potential (GWh)*			
	As. 1	**As. 2**	**As. 3**	**As. 4**
Scotland	137.6	137.6	137.6	15.7
Northern Ireland	7.5	7.5	7.5	5.2
Ireland	30.4	14.6	12.3	13.7
England	356.9	-	145.0	161.2
Wales	6.9	6.9	6.9	9.0
France	416.0	-	169.1	188.0
Spain	300.3	38.6	122.0	135.7
Portugal	65.5	27.6	26.6	29.6
Total	**1321.1**	**232.9**	**627.1**	**558.1**

After these calculations, the total extrapolated energy for the study area ranged between 232.9 and 1321.1 GWh, if all assumptions are considered. However, if assumption 2 is not considered, as England and France are not represented, the minimum of the range was set at 558.1 GWh.

5.2. Wastewater Networks

The two main variables for the assessment of the energy recovery potential of WWTPs are the discharge volume and available head at their outlet pipes. The discharge values can be extrapolated, as these are dictated by factors such as population, intensive water industries activities and rainfall. The hydraulic head depends mainly on the elevation of the terrain where a WWTP takes place, and has to be assessed for each WWTP individually.

The extrapolations for the wastewater sector, showed in Table 12, were based on the linear correlation found between the population served and the estimated power potential for MHP in the sites analysed in Ireland and Spain. This linear correlation presented an R^2= 78%, and corresponds to equation (2) presented below:

$$y = 4.4222 \cdot 10^{-5} x - 1.4565 \tag{2}$$

where:

y represents the estimated power potential for wastewater treatment plant outlets (kW), and *x* represents the size of the population served by each plant.

Table 12. Extrapolated potential power and energy for MHP estimated by country for wastewater sector

Country	Population	Power Extrapolated (kW)*	Energy Extrapolated (GWh)*
Scotland	5438100	239	2.1
Northern Ireland	1810863	79	0.7
Ireland	4761865	209	1.8
England	55977178	2474	21.7
Wales	3138631	137	1.2
France	65256433	2884	25.3
Spain	47100396	2081	18.2
Portugal	10276617	453	4.0
Total	**193760083**	**8556**	**75.0**

*Power estimated on the basis of Eqn 2; Energy extrapolated for 24-h and 365-days

The total extrapolated power potential for WWTPs in the study area amounted to 8.56 MW. The low-head available in most of the plants resulted in a relatively low energy potential for this sector, in comparison with drinking water, contributing to the total annual energy recovery potential with 75 GWh.

5.3. Irrigation Networks

In the case of the irrigation sector, from the results obtained with the first methodology assessed, a geodatabase was created in order to show graphically the results and MHP potential available. In the Figure 23, a gradient map displaying the potential energy recovery for an irrigation season based on the first 12 networks analysed, is shown.

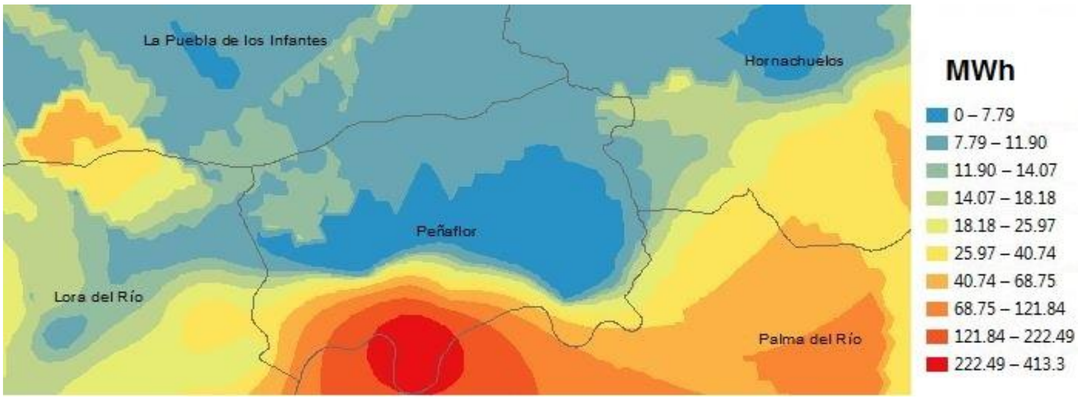


Figure 23. Gradient MHP energy recovery potential map for irrigation networks in the south of Spain

Then, a more detailed extrapolation of irrigation MHP potential was also conducted for the provinces of Seville and Cordoba, using data from the 177 observed MHP sites from the total of 18 networks outlined in Section 4.3. Power output for the 177 observations was predicted using irrigated surface area, crop water requirements and land slope, as predictor variables. Simple and multiple linear regression was used for prediction initially, followed by artificial neural networks, when the later failed to perform well enough. An average prediction accuracy of R^2=0.63 was achieved. Total annual energy potential of 21.05 GWh was estimated and a energy potential to surface ratio of 0.167 MWh/ha was determined. This was equivalent to 12.8% of the energy requirements of the irrigation sector in this region, showing the very significant potential of MHP in this sector. This potential was obtained for data available in 180 municipalities in the Cordoba and Seville regions. 105 of them corresponded to Seville and 75 to Cordoba. The input variables were gathered for these municipalities from the SIGPAC platform (www.sigpac.mapama.gob.es), where different information, such as crop cultivated, mean slope or irrigation coefficient were found for all the plots of each municipality. A database with around 20 million data points was compiled and analysed for the whole region. Thus, the surfaces with crop cultivations were extracted, calculating the theoretical irrigation requirements for all of them. The agro-climatic parameters were obtained from 29 weather stations distributed around Seville and Cordoba (www.juntadeandalucia.es).

Figure 24 shows the resulting extrapolation of the data to the full Seville/Cordoba region.

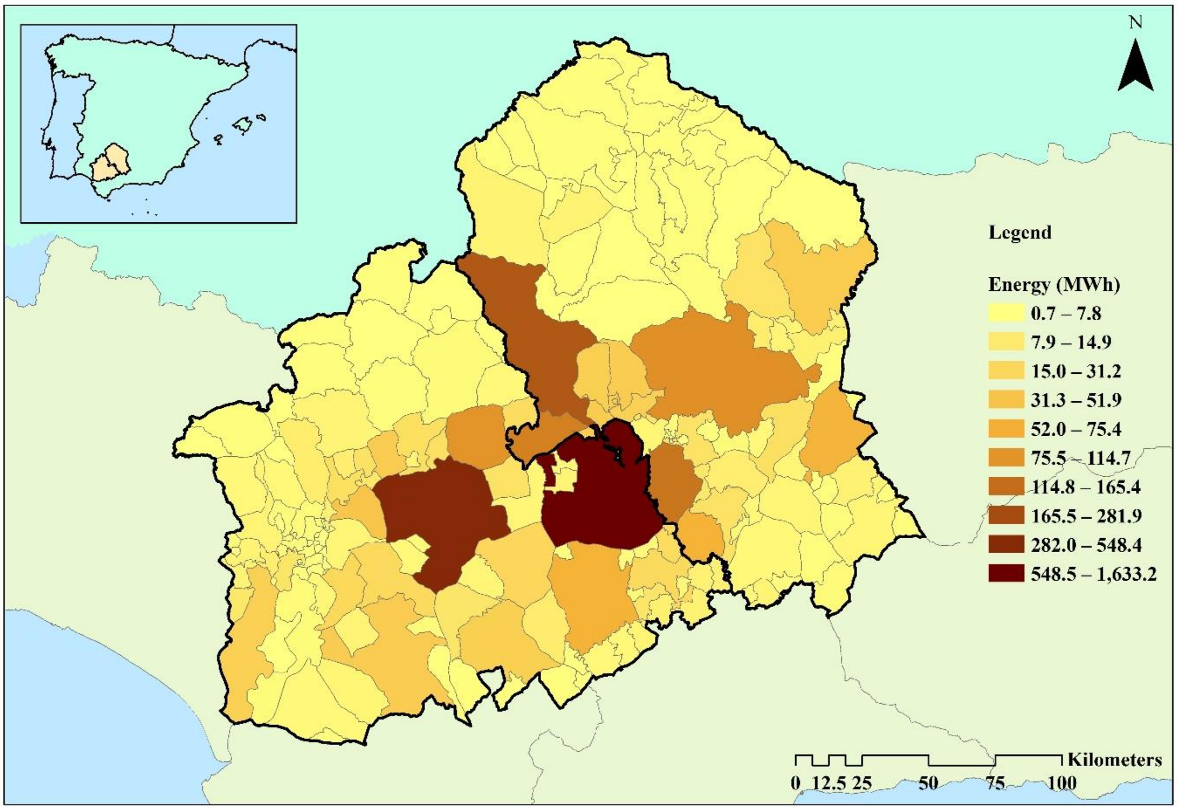


Figure 24. Energy recovery potential found for every municipality of Seville and Cordoba during the year 2018.

From the data analysed, the mean ratio of power recovery potential to irrigated surface area, found at 0.08 kW/ha, and the mean ratio between the energy estimated and the corresponding irrigated surface determined at 0.167 MWh/ha, were used for the extrapolations. Using these ratios, the potential for MHP in the irrigation sector was estimated for the rest of the identified areas in the study region. The extrapolation was this time only conducted for some regions in Spain and Southern Portugal, which include similar pressurised irrigation infrastructure to those networks previously analysed. Table 13 summarizes the results for Portugal in the two regions Alentejo and Algarve, amounting to a total annual energy potential of 24 GWh.

Table 13. Power and energy potential estimates for MHP from the analysis of regions containing pressurised irrigation networks in Portugal

Country	Region	Irrigated Surface covered (ha)	Power Extrapolated* (kW)	Energy Extrapolated+ (MWh)
Portugal	Alentejo	126184	10347	21073
	Algarve	17240	1414	2879
Total/Average		**143424**	**11761**	**23952**

*Power extrapolated on the basis of the average power per irrigated surface area 0.082 kW/ha. +Energy estimated on the basis of the average energy per irrigated surface area 0.167 MWh/ha.

In the case of Spain, this extrapolation was made based on the surface area with localised irrigation, a ratio between the surface irrigation water and the total irrigation water volumes (to minimize the effect of possible small private pumping from wells) and the power and energy extrapolation ratios previously defined. Thus, the total annual energy potential estimated reached 220.9 GWh, especified for the different regions in the country in Table 14.

Table 14. Power and energy potential estimates for MHP from the analysis of regions containing pressurised irrigation networks in Spain

	Surface for localized irrigation (ha)	Surface/total irrigation water	Power Extrapolated* (MW)	Energy Extrapolated+ (GWh)
Andalucia	866931	0.71	50.2	102.2
Aragon	69775	0.97	5.6	11.3
Castilla y Leon	30598	0.82	2.1	4.2
Castilla-La Mancha	357225	0.47	13.8	28.2
Cataluña	98685	0.83	6.7	13.7
Com. Valenciana	211403	0.41	7.2	14.6
Extremadura	158351	0.90	11.6	23.7
Region de Murcia	159929	0.50	6.5	13.2
Navarra	21126	0.89	1.5	3.1
La Rioja	22036	0.89	1.6	3.3
Rest	36693	0.63	1.9	3.4
Total/average	**2032752**	**0.73**	**108.7**	**220.9**

*Power extrapolated on the basis of the average power per irrigated surface area 0.082 kW/ha. +Energy estimated on the basis of the average energy per irrigated surface area 0.167 MWh/ha.

5.4. Process Industry Networks

In the case of the process industry, as described above, information was obtained for only four isolated private companies in Ireland and Portugal, for which the potential for MHP was estimated as shown in Table 8. However, the information found for the discharge licenses for the main river basins in Spain allowed aproximating an estimation for the MHP potential in the industry sector at the country level, in this case. Therefore, from this information, and based on population data for the different countries included in the area of interest, an extrapolation of the results was then carried out. However, in order to try to improve this estimate for the case of the industry sector, in addition to the population information, a coefficient based on the percentage of the gross domestic product related to the industrial activity was added, to consider the varying importance of the industrial sector in the different countries.

Table 15 presents the results for this extrapolation, as well as the coefficients considered for each of the countries included, amounting to a total annual energy recovery potential of 46.7 GWh.

Table 15. Extrapolated energy recovery potential for the process industry sector in the different countries of the study area.

	population	industry % representation on GDP*	MHP energy potential (MWh)
FRANCE	65256433	0.17	14383.0
IRELAND	4761865	0.37	2286.8
PORTUGAL	10276617	0.19	2569.5
SPAIN	47100396	0.20	12289.6
UK	66364772	0.18	15165.3
Total/average	**193760083**	**0.22**	**46694.2**

*GDP: gross domestic product based on information published in the United Nations Conference on Trade and Development statistics (www.unctadstat.org)

5.5. Total Resource Extrapolations

Summing the resource extrapolation from the four sectors results in the power potential shown in Table 16, which amounts to a total of 275 MW, considering the extrapolation of power for the drinking water sector based on the average ratio (0.73 kW/1000 population). This power potential represented a total annual energy recovery potential between 925.1 and 1688.1 GWh. These results demonstrates that MHP technology can play an important role in the different sectors analysed, contributing to the reduction of the electricity energy demand and at the same time, reducing the greenhouse gas emissions linked to the water sector.

Figure 25 and 26 illustrate the distribution of this power and energy estimates across the sectors and regions.

Table 16. Total extrapolation of power potential for MHP for the different countries analysed (in kW).

Country	Drinking Water	Wastewater	Irrigation	Process Industry	Total
Ireland	3465	209	0	261	3935
France	47490	2884	0	1642	52016
Portugal	7479	453	11761	293	19986
Spain	34277	2081	108700	1403	146461
UK	48297	2929	0	1731	52957
Total	**141008**	**8556**	**120461**	**5330**	**275356**

*Considering the extrapolation of power (kW) using average ratio 0.73 kW/1000 population for the drinking water sector

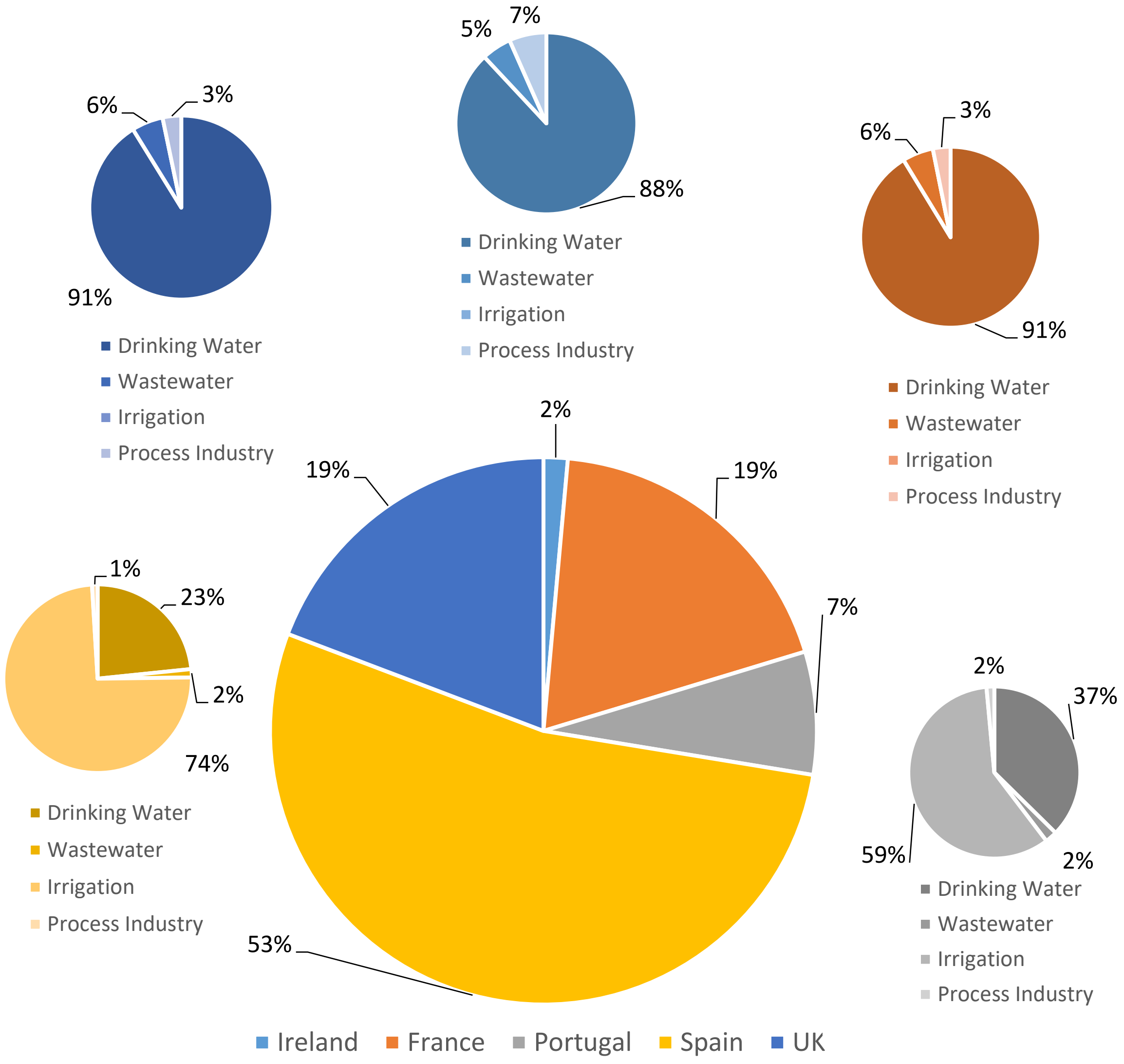


Figure 25. Power potential extrapolation for MHP distributed in the different countries and sectors analysed.

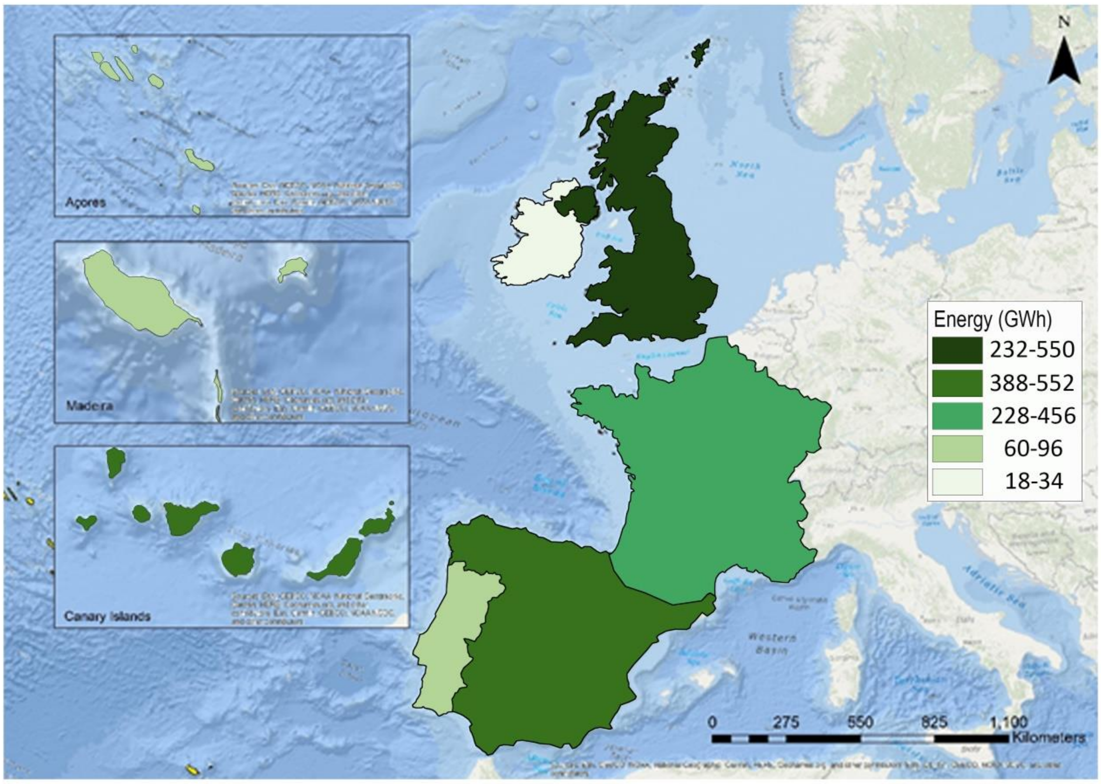


Figure 26. Extrapolated energy recovery potential estimated for full Atlantic area region.

6. Resource Projections

The resources assessments produced were based on existing infrastructure which could be coupled with a MHP turbine to recover energy. However, it does not account for the need for new water network components to reduce leakage rates or expand capacity. Ireland and Portugal, for example, have high leakage rates due in part to under investment in pressure control systems. Thus, more are needed in the AA, meaning the resource for MHP energy recovery in water networks is likely to grow.

The existing energy recovery resource estimations have been projected here to 2030 and 2050, accounting for planned growth in population and, therefore, the growth in water network infrastructure. Table 17 summarizes the results obtained for the different water-related sectors analysed and countries. In the case of the drinking water sector, the same 4 different assumptions were considered, offereing as a result a range of energy recovery potential for each of the countries included. Drinking water, wastewater and industry sectors potentials were projected for future population scenarios (2030 and 2050). Nevertheless, in the case of the irrigation sector, this projection was not carried out since its extrapolation methodology was not based on population but on the irrigated area, whose future growth will depend on the country's potential to transform extensive to intensive farming areas.

Table 17. Future energy recovery by MHP potential projections by sectors and total for the different countries analysed (in GWh).

	Drinking Water		
	2019	**2030**	**2050**
Ireland	13.7 – 30.4	15.9 – 35.1	17.9 – 39.6
France	188.0 – 416.0	198.0 – 438.3	201.7 – 446.3
Portugal	29.6 – 65.5	29.1 – 64.3	27.0 – 59.8
Spain	135.7 – 300.3	140.4 – 310.8	142.1 – 314.6
UK	191.2 – 508.9	201.1 – 535.2	221.8 – 590.5
Total D.W.	**558.1 – 1321.1**	**584.4 – 1383.7**	**610.5 – 1450.8**
	Wastewater		
	2019	**2030**	**2050**
Ireland	1.8	2.1	2.4
France	25.3	26.6	27.1
Portugal	4	3.9	3.6
Spain	18.2	18.9	19.1
UK	25.7	27.0	29.8
Total W.W.	**75**	**78.5**	**82.0**
	Industry		
	2019	**2030**	**2050**
Ireland	2.3	2.6	3.0
France	14.4	15.2	15.2
Portugal	2.6	2.5	2.3
Spain	12.3	12.7	12.9
UK	15.2	16.0	17.6
Total I.	**46.7**	**49.0**	**51.0**
	Total		
	2019	**2030**	**2050**
Ireland	17.8 – 34.4	20.6 – 39.9	23.3 – 45.0
France	227.6 – 455.7	239.8 – 480.1	243.9 – 488.6
Portugal	60.1 – 96.0	59.4 – 94.6	56.9 – 89.6
Spain	387.6 – 552.2	393.4 – 563.8	395.5 – 568.0
UK	232.0 – 549.8	244.0 – 578.2	269.2 – 637.9
Total	**925.1 – 1688.1**	**957.2 – 1756.5**	**988.8 – 1829.1**

*Total includes irrigation

These projections showed an increase in the total energy recovery potential, for the five countries, between 3.5% and 4.1% by 2030 and between 6.9% and 8.4% for 2050, compared to the results extrapolated on the basis of the current population. Population projections data were collected from european statistics (www.eurostat.eu). All countries showed an increase in the total population for both of the horizons, with the exception of Portugal, with a 2% and 8% reduction in total population for 2030 and 2050, respectively. Thus, the total energy extrapolations for 2030 ranged between 957 and 1757 GWh, reaching the range between 989 and 1829 GWh for 2050.

7. Conclusions

Work Package 4 of the REDAWN project focussed on the assessment of the potential for micro-hydropower energy recovery in the water sector, including drinking water, wastewater, industry and irrigation networks, across the Atlantic Area (AA) of Europe. The work was organised in several steps: data collection, estimation of energy recovery potential in the identified sites, extrapolation of the energy potential for the 4 sectors in the different countries, and finally, the estimation of the resources projections.

The drinking water sector was the one for which a greater volume of data on potential sites for energy recovery was collected. However, 99% of the data collected was from the UK, 70% of which was from Scotland, where in most cases, flows and pressures were not recorded but estimated. Thus, the theoretical potential found for the UK represented more than 90% of the total.

In the case of the wastewater sector, only data for Ireland and Spain were obtained. The number of sites with exploitable potential found was low, due to the fact that many of the sites did not present the required head pressure. Therefore, the potential associated with WWTPs was considerably lower, compared to the drinking water sector.

Getting information for the irrigation sector presented some difficulties, since pressure and flow data are not usually recorded. A total of 18 representative networks in Spain and Portugal were finally analyzed, whose potential for MHP was then related to the surface area supplied by the corresponding irrigation networks.

The collection of data in the private industry was also difficult. In the case of Portugal and Ireland, pressure and flow data were obtained for 1 and 3 private industries, respectively. In addition to that, the information related to the wastewater discharges from 87 private industries was collected for Spain, although only 38 of them presented potential for MHP. The energy-related industry was the type with the largest contribution.

The extrapolation of the potential for energy recovery in the drinking water sector was based on the total population of each country and the MHP potential to population supplied ratio obtained from the analysed sites. This extrapolation was carried out under 4 possible assumptions, given the significant difference between the ratio of the different countries, thus showing a range of energy recovery potential as a result.

In the wastewater sector, the extrapolation of the results was based on the linear correlation found between the MHP potential of the analysed sites and the population served. In this case, the countries with the largest populations (England, France and Spain) represented 87% of the total energy recovery extrapolated.

In the case of the irrigation sector, extrapolations were made only for the southern region of Portugal and Spain, where similar localised-pressure irrigation networks to the ones previously analysed were found. Therefore, the total area covered for these extrapolations was considerably smaller, compared to the rest of sectors. However, irrigation showed an important potential for energy recovery in these countries where agriculture has an important role in the national economy.

For the industrial sector, the results obtained for Spain, for which the industrial discharges of the whole country were analysed, were then extrapolated based on the population and the percentage of the gross domestic product related to the industrial activity, in each country. Thus, Ireland, with a higher GDP than Spain, obtained a slightly higher result compared with the results obtained with an extrapolation based only on population information. However, it was observed that the internal analysis of the facilities of private industries could increase this potential very significantly, taking advantage of the excesses of pressure of the water distribution networks, and not only of the wastewater discharges.

In a general analysis of the potential power for MHP extrapolated from the different countries and sectors, Spain represents 53% of the total, followed by the UK and France, with 19% each.

From the total for Spain, 74% of the power potential corresponded to the irrigation sector. The activity of this sector is characterized by its seasonality, so the corresponding annual energy recovery potential is lower, compared to sectors that operate 24/7. Thus, in terms of total annual energy recovery potential, the contribution of Spain drops, ranging between 33% and 42% of the total extrapolated, followed by the UK and France, representing between 25%-33% and 25-27%, respectively.

Finally, the future projections point to an increase in the potential for total energy recovery through MHP in Europe. These projections have been based on estimates of the population progression for 2030 and 2050, suggesting an increase of more than 8% of the potential for MHP energy recovery potential.

These results show an important potential for MHP in the water industry to generate clean energy and contribute reducing the energy cost and emissions linked to the water sector. However, the more detailed information that can be obtained from the different organizations and companies, and a closer the collaboration with them, could help to improve the level of detail in the results. Undoubtedly, although several assumptions have been necessary, the results obtained in the different developed studies prove that the role of MHP can make a valuable contribution to improving the sustainability of the EU's water sector.

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Project Lead: **Terry WAUGH**
Action Renewables

Phone: **+44 289 072 7763**
Email: **comms@redawn.eu**
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