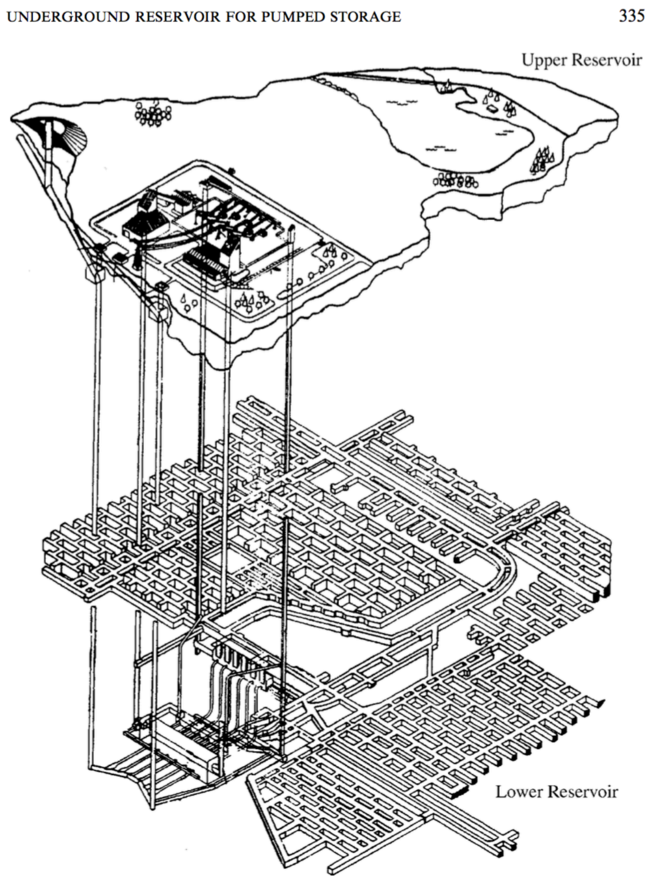
Master Thesis

A GIS-based approach to Underground Pumped Hydro Storage (UPHS) potential in Europe

Digging for its applicability and into its development



Schematic drawing of an Underground Pumped Hydro Storage (UPHS) plant from an engineering perspective (Udin N., 2003)

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Abstract

Today is a time of ever-increasing renewable energy penetration in national power systems. Although this is paving the path to a cleaner and greener future, it comes with a price regarding electricity grid stability and the security of energy supply. Effectively, the largest renewable energy additions are in form of wind and solar power, who's primary source of energy is well beyond Mankind's control. They are prone to variability through the week, day and even hour: they consist of intermittent renewable energy plants.
To tackle this intermittency, energy storage is needed in order to balance the electricity grid without having to immediately turn to fossil fuels or nuclear power. The growing challenge in the world today is finding appropriate energy storage technologies to manage our increasing energy needs, with the concept of integrated power systems where energy production and energy storage are combined in a co-location context. Today, pumped hydro storage (PHS) makes up 96 % of all energy storage worldwide, and constitutes if not the sole only form of large-scale electricity storage. But it requires important topographical settings in order to be installed. However, many countries that hold strong shares of intermittent renewable energy in their energy mix exhibit relief-deprived topographies, such as the Netherlands, Northern Germany and Denmark.

This research looks into a novel concept which would expand large-scale energy storage possibilities: Underground Pumped Hydro Storage (UPHS). This technology adapts the conventional PHS scheme to areas of little to no-relief, by taking the plant into the subsurface, creating hydrological head through depth underground (instead of strict height in mountainous contexts). Going underground enables large hydrological heads to be used, and limits water-use and environmental degradation.
GIS-based modelling, combined with geological literary insight manage to assess countries of the European Union regarding their UPHS physical implementation potential. Results are found distinctly, first in terms of realisable surface potential along the lines of two scenarios (according to UPHS surface requirements & constraints), and secondly in terms of geological adequateness. Both delineate geographical extents where UPHS finds niches. These two streams of findings are finally combined to seek out geographical regions and zones that express both the surface and subsurface constraints.

The overall results give substantial UPHS potential in Europe, with UPHS plants being found to meet surface constraints over an area of 4124,55 km^2 in the first scenario, and 43 656,62 km^2 in the second less-stringent scenario, dispersed throughout 8 countries of the EU. Geological insight narrows-down these results to specific geographical regions where, on top of the surface constraints, the subsurface is most likely to hold adequate UPHS-able characteristics.
These final results distinguish Europe's UPHS implementation potential, and correspond to zones in the geographical regions of: Zeeland in the Netherlands, the Southeast of the UK, the Northern tip of France, throughout the island of Ireland, and finally the South & central portions of Denmark.

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List of Abbreviations

AESN	Agence de l'Eau de Seine Normandie
ADB	Anglo-Dutch Basin
CLC	CORINE Land Cover
COP21	Paris Climate Agreement
DEM	Digital Elevation Model
EEA	European Environment Agency
EIA	U.S. Energy Information Administration
ESRI	Environmental Systems Research Institute
EQPS	Elmhurst Quarry Pumped Storage Project
EU	European Union
EWEA	European Wind Energy Association
FLES	Flat Land Energy Storage
GADM	Global Administrative Areas
GIS	Geographical Information System
IAU	L'Institut d'Aménagement et d'Urbanisme
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
LBM	London Brabant Massif
LTG-1	Luttelgeest-1
NWECB	Northwest European Carboniferous Basin
OECD	Organization for Economic Cooperation and Development
O-PAC	Ondergroundse Pomp Accumulatie Centrale
PACA	Provence-Alpes-Côte-d'Azur
PHS	Pumped Hydroelectric Storage
REN21	Renewable Energy Policy Network for the 21st Century
SAC	Special Areas of Conservation
SPA	Special Protection Areas
SRTM	Shuttle Radar Topography Mission
UHM-2	Uithuizermeeden-2
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UPHS	Underground Pumped Hydro Storage

“Look again at that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every "superstar," every "supreme leader," every saint and sinner in the history of our species lived there--on a mote of dust suspended in a sunbeam.
The Earth is a very small stage in a vast cosmic arena. Think of the rivers of blood spilled by all those generals and emperors so that, in glory and triumph, they could become the momentary masters of a fraction of a dot. Think of the endless cruelties visited by the inhabitants of one corner of this pixel on the scarcely distinguishable inhabitants of some other corner, how frequent their misunderstandings, how eager they are to kill one another, how fervent their hatreds.
Our posturings, our imagined self-importance, the delusion that we have some privileged position in the Universe, are challenged by this point of pale light. Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity, in all this vastness, there is no hint that help will come from elsewhere to save us from ourselves.
The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand.
It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known.”

- Carl Sagan *(Pale Blue Dot, 1994)*

I. Introduction

As the world spins, so do the wheels of progress that attempt to drive us towards a better future. And akin to the rise of electric vehicles, more energy-efficient appliances, and less green-house-gas emitting mechanisms that we witness all around us, a metamorphose of unseen proportions is occurring in the background, in the energy industry. As we know, the age of industrialisation has garnished the human canvas with innumerable points of progress, but has been leaving polluting stains all along the way. Its energy intensive ways have been adversely affecting the planet, specifically in terms of accelerated climate change. Which is why we sit today in a global context of an energy transition. We wish to maintain our growth and technological stride, and thus must push towards sustainable methods of energy production. This encompasses the implementation of clean and renewable energy technologies at the grandest of scales, in order to overall curb greenhouse gas emissions, to meet targets set forth by the Paris Climate Agreement (COP21), and eventually go beyond these preliminary targets and lead humanity towards a brighter and more sustainable future.

This path towards a more sustainable future has already shown its colours, with the global share of renewable energy in the overall energy mix (capacity and final consumption) increasing year to year, with countries heavily investing in and promoting the growth of their renewable energy sectors (IRENA, 2017). However, renewable energies such as wind and solar power are intermittent, having highly variable power outputs translating into instabilities, which creates risks in terms of security of supply. Hence, although performing well on the GHG emissions and sustainability perspective, the relatively rapid introduction of intermittent renewable energies is leading to a surge in energy storage needs which have yet to be prepared for. Moreover, as we look towards the far future in which we aim to decarbonise base load generation with the increasing penetration of renewable energy production, energy storage technologies will have to be sufficiently available and constitute large enough capacities to counter the eventual disparities between power supply and power demand (IRENA, 2017).

With the capacity to absorb excess energy and release it when needed, energy storage plants have been used to improve energy system management by quickly releasing energy in order to shave peak energy demands and balance loads, and many technologies exist to achieve such results (OECD/IEA, 2014). However, pumped hydro storage has been the irrefutable dominant technology: having been used for decades, being commercially mature to be implemented with relative ease, are factors that have led to it constituting 96% of all energy storage capacity worldwide (REN21, 2017). Moreover, it is the only commercially mature form of electricity storage, with other commercially mature technologies being of a thermal energy nature (OECD/IEA, 2014). Its simplistic design -basically a dam with an interchangeable direction of water flow-, high efficiency and large storage capacity have made it the technology of choice, with 145 GW of storage installed worldwide (IRENA, 2017). It stands as economically and technically proven. Nonetheless, not all needs for energy storage can be met by pumped hydro storage; Geographic zones are deprived from this opportunity due to either the vulnerability of ecosystems in which ideal potential locations are found, either the lack of primordial sufficient geographical relief to allow the functioning of a pumped hydro storage plant. But a solution to this has been buried in scientific archives for decades. In a paper published 100 years ago, the idea of having pumped hydro storage installed underground was drafted (Fessenden, R., 1917). It's time to bring this underground idea back to the surface, and to the forefront of the energy storage conversation.

The idea comes in the form of Underground Pumped Hydro Storage (UPHS), which reformulates conventional pumped hydro storage into a more environmentally-friendly, geographically-optimised energy storage system (Huynen J., Schalij R. & Arts T., 2012). Producing more energy with less water and reduced landscape modifications, the concept has been gaining momentum in minds worldwide since the 1980's, but has yet to break ground in the energy sector. Although one pilot project is projected to take place in the close future.
O-PAC (ondergroundse Pomp Accumulatie Centrale) by Sogecom BV aims to be the first UPHS plant installed, through a project currently in preparation in the province of Limburg, in the south of the Netherlands. Papers have already been produced regarding the economic (Kibrit, B., 2013), energetic (Corbijn, L., 2017) and engineering aspects (Müller, D. and Hereth, A., 1987 and Price, D., 1987) of a UPHS plant producing fruitfully positive results.
This thesis aims to use the O-PAC project as a blueprint-type case study combined with GIS-based modelling and geological insight in order to assess the physical potential of UPHS by identifying possible locations for its implementation.

I.1. Problem definition

With the rapidly rising share of variable and intermittent renewables in the energy mix, balancing, flexibility and security of supply are rising concerns that have to be dealt with. With the ultimate goal of ridding the energy industry of fossil-fuel based power generation, the road towards decarbonisation looks into an increase of sustainable energy storage technologies (OECD/IEA, 2014).
Today, pumped hydroelectric storage (PHS) consists of around 96% of all grid-connected energy storage systems built throughout the world. Although alternatives are in the making, most are still in the prototype, development or optimisation stages. For example, battery storage is gaining ground in the energy storage sector of today, with installations taking placing and growing all over the planet due to its speedy deployment characteristics, but comes out more as a "quick-fix" to the issue, rather than a long-term solution (BNEF, 2017). With long life expectancies, high efficiencies, quick response times and large-scale capacities, pumped hydroelectric storage has been used for years and is consequently the only mature and commercialised solution to the immediate and oncoming large-scale energy storage needs (REN21, 2017). And these growing needs are not to be overlooked.
However, many zones, regions, or even whole countries lack the adequate geographical relief to implement this widely used technology for energy storage. In essence, suitable relief and considerable altitude differences are needed in order to construct a pumped hydroelectric storage facility, since the system relies on potential energy formed by height differences. This acts as a major constraint to the deployment of PHS, and deprives many geographical zones from the only mature and commercially available large-scale energy storage technology (Huynen J., Schalij R. & Arts T., 2012).

I.2. Theoretical background

Energy storage is the process of absorbing energy to be released at a later time. It can be done through different methods with many variations in technology, yet that all fall into 5 categories: Thermal, mechanical, chemical, electrical, and electro-chemical (IRENA, 2017). Pumped hydroelectric storage (PHS) is the most used throughout the world, with 145 GW of energy storage capacity available today (REN21, 2017). It is a form of mechanical storage, using height differences to store electrical energy sent from the grid in the form of gravitational potential energy.
The whole is based on conventional hydropower formulas, the difference with PHS being that the turbines are reversible and energy is consumed to pump water back up the direction of regular power-generating flow, only to be released in order to generate energy once again.

Power output from a PHS plant is calculated using the power potentially available (as energy stored in the water) affected by the system's efficiency factor.

The formula is as follows:

$$P = \rho \times Q \times g \times H \times \eta$$

Equation 1. Power output from a hydropower plant (Twidell J. and Weir T., 2015)

Where P is the power output from the PHS plant (or UPHS plant) in Watts (W), ρ is water density (kg/m3), Q is water flow (m3/s), g is the gravitational acceleration (m/s2), H is the hydraulic head (m) and η is the PHS (or UPHS) system efficiency (in %) (Twidell J. and Weir T., 2015).

The much bigger hydraulic head (H) that can be created by using a UPHS is one of its main attractions and advantages, enabling greater power output with a reduction of water volume used.

I.3. Underground Pumped Hydro Storage

To tackle the issues created by geographical disparities in the domain of energy storage, FLES (Flat Land Energy Storage) is specifically conceptualised to target the energy storage needs in the context of relatively flat lands, such as the Netherlands, northern Germany, Belgium, northern France, and many other lands around the world (Huynen J., Schalij R. & Arts T., 2012).
Instead of waiting on the development of completely new and innovative ways of storing energy, pumped hydroelectric storage has been revisited in order to adapt this mature technology to the in-situ environment, and have managed to expand the technology to be adapted to many more suitable locations via a literally ground-breaking concept: Underground pumped hydro storage.

Introduced as Underground Pumped Hydro Storage (UPHS), the technology relies on the same core principles that have made conventional pumped hydroelectric storage successful but does away with the strenuous topographical needs that surround the latter. In conventional pumped hydro storage, two reservoirs situated respectively at different altitudes, denoting an upper reservoir and a lower reservoir, allow water flow between them. During times of peak-demand / in need of energy peak-shaving, PHS systems have water run from the upper reservoir to the lower, passing through a power unit which houses turbines, in order to harness the potential energy stored in the water and send it to the grid. During off-peak hours, energy is taken from the grid in order to pump the water situated in the lower reservoir back up to the upper reservoir. The same process is replicated in UPHS, with the difference being that the lower reservoir and power unit are situated hundreds of meters underground, whilst the upper reservoir sits at the surface, at ground level.

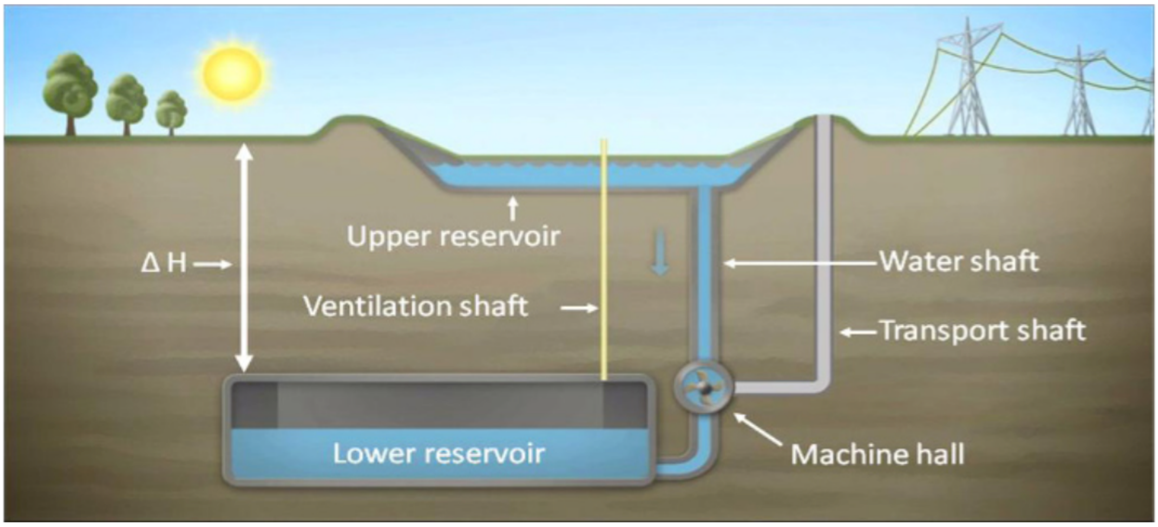

Figure 1. A schematic representation of an underground pumped hydro storage plant (UPHS) (Huynen J., Schalij R. & Arts T., 2012)

I.4. Research question

Currently, no such energy storage system exists. A number of projects have found their place in writing, such as the Elmhurst Quarry Pumped Storage Project (EQPS) in Canada, Riverbank Wisacasset Energy Centre in Maine, USA (Energy Storage Association, 2017), and Oriskany mine pumped hydro project in Summit County, Ohio, USA (Uddin, N., 2003) but have not led to any initiatives. However, a project is currently in a more advanced position in the Netherlands, willing to be the first UPHS plant. Entitled “O-PAC” (Ondergroundse Pomp Accumulatie Centrale), Sogecom BV plans to build the first underground pumped hydro storage system with a capacity of 1400 MW, capable of delivering 8 GWh of electricity per daily cycle, and thus 2 TWh per year. This will be achieved by excavating a lower reservoir in the subsurface around Limburg, an area familiar with the mining industry. Situated at a depth of around 1400 metres, the lower reservoir and power units will be placed in a host rock of sufficient quality in order to ensure the stability and success of the project. Making use of a water head of around 1400 meters, water use will stand at approximately 2,5 million cubic meters, which is a relatively small volume in regard to conventional pumped hydro storage (Huynen J., Schalij R. & Arts T., 2012).

Although not in the scale of UPHS concepts, underground excavations have been used numerously before in the context of energy storage: Racoon Mountain (USA), Dinorwig (UK), Kazunogawa & Kannagawa (Japan), Drakensburg (South Africa) and Mingtan (Taiwan) are all pumped hydroelectric storage systems in operation today, that make use of underground excavations for water shafts as well as to house the power units (electrical components and machinery such as turbines), at depths up to 500 metres below the surface.
Although 500 meters is only a third of the depth of said planned O-PAC project, voluminous structures have been produced underground at much greater depths, such as the Gotthard base tunnel that runs through the Swiss Alps with an overburden of up to 2300 meters of solid mountain rock in certain sections. (Fabbri, D., 2004).
Thus, being a combination of mature & commercialised pumped hydroelectric storage technology and modern-day geotechnical engineering, the realisation of a UPHS plant is deemed technically and economically feasible (Huynen J., Schalij R. & Arts T., 2012).

The UPHS system has been studied through diverse scopes, showing its technical feasibility (in specific context of the O-PAC project in Limburg) (Müller, D. and Hereth, A., 1987), its economic viability (study done by Sogecom, and reviewed by Ernst & Young upon request of the government of the Province of Limburg) (Huynen J., Schalij R. & Arts T., 2012), and lastly regarding the benefits it delivers to the power system (Corbijn, L., 2017).
Building itself on the most mature and commercially available energy storage technology of today, it is safe to assume that its introduction to the energy storage technology mix will be positive, specifically in light that it would enable pumped hydroelectric storage to function in relief-deprived lands. However, although eliminating certain characteristics that are primordial to a conventional PHS plant, a UPHS plant has requirements of its own, especially in terms of underground parameters.

The question that arises now, and which constitutes the core of this thesis, involves the implementation potential of UPHS plants:
What is the physical implementation potential of underground pumped hydro storage plants in Europe?
Although it can be assimilated to other geotechnical engineering projects, it is a new kind of underground venture nonetheless, and it is thus important to classify the surface and subsurface characteristics and structural parameters that are needed in order to construct such a system. These leads us to the sub-questions that underline the main research question.
What are the ideal geographical and geological parameters that are needed in order to build a UPHS plant?
Where are the geographical zones that are deemed the most suitable for a UPHS plant?

This thesis explores these currently open-ended questions and attempts to provide an appropriate answer through GIS-based modelling and geological literature.

I.5. Scope and boundaries

Case study

Although many variations in capacity and thus size (depth, volume…) of a UPHS plant are possible, this research will use the O-PAC model currently planned in Limburg as a blueprint for other potential sites, within an acceptable range of capacity and depth of excavation. This includes a depth range of 700- 1500m since it is the depth at which we have economic optimisation of the project, which holds balance between the depth which characterises the amount of hydrologic head and the volume of the lower reservoir which has to be excavated. The more head, the less volume of lower reservoir has to be excavated; which happens to be the costliest part of a UPHS project (Huynen J., Schalij R. & Arts T., 2012). Moreover, the type of geological, deep subsurface data needed to correctly advocate whether a UPHS plant can be constructed or not runs parallel to the extensive site-specific exploratory research that is undertaken in the oil & gas industry, using large quantities of in-situ geological, geophysical and seismic data specifically aimed at identifying suspected structures in the subsurface of a precise area of land. In its scope, this research will aim for a more general approach using global geological maps and available data in order to establish broad zones in which UPHS plants could have a higher potential of implementation.

Economic aspect

As previously declared in I.4 *Research question*, the economic aspect of UPHS plants has already been researched and assessed in previous papers. It will not be further explored in this thesis. Previous research has shown that amid the hefty primary investment costs, a UPHS plant would perform well, on-par or even better than conventional PHS plants when taking account of the cost per MW (Huynen J., Schalij R. & Arts T., 2012). Moreover, a study looking into the benefits of a UPHS plant in the Netherlands pointed towards considerable electricity price reduction in a future where UPHS plants are installed, outperforming a battery energy storage scenario and that of a demand-response scenario (Corbijn, L., 2017). This thesis takes these results as sufficient justification for a UPHS plant's economic viability.

Physical boundary

Boundary wise, although renewable energy is growing strongly around the world, this research will focus on the European continent -and specifically the countries of the European Union- making the geographic and geologic settings of Europe its physical boundary.

Co-location and onshore plant project

According to the O-PAC vision of a UPHS plant (Huynen J., Schalij R. & Arts T., 2012) and the futuristic concept of other energy storage plants (Energy Storage Association, 2018), coupling between energy producing and energy storage plants is deemed to be the path of the future. They aim to have both types of plants working together, and preferably in proximity of each other. This co-location aspect is esteemed to create complete and integrated projects, consisting of packages of energy production and storage. Finally, UPHS being an onshore technology, this thesis looks only into onshore intermittent renewable power plants.

II. Methodology

II.1. Country selection

A first overview must be performed in order to assess which geographical areas are most likely to be in need of energy storage. In modern times, this directly relates to the regions which are most equipped with intermittent renewable energy power plants, and are thus more susceptible to sudden and unpredictable changes in power output. These are sources of power generation that rely on source of primary energy that cannot be stored. And in today's context, these consist mainly of solar and wind power. Moreover, in the specific scope of UPHS, the geographical regions of interest are those which currently have a high installed capacity or an expected & upcoming increase in capacity of intermittent renewables, but that do not possess sufficient or adequate relief for conventional pumped hydro storage. However, since UPHS has been shown to be relatively less environmentally destructive while at similar cost levels compared to conventional pumped hydropower storage (Huynen J., Schalij R. & Arts T., 2012), it would still be of interest to those countries which indeed have PHS-friendly topography, since UPHS could be applied to avoid degradation of mountainous habitats and natural landscapes.

Looking at the PocketBook Energy 2017, the EU countries with the most cumulative solar and wind capacity shares in their electricity generation mix are Denmark (41,82 %), Germany (41,39 %), Spain (28,16 %), Portugal (27,43 %), Ireland (25,55 %), Belgium (25,05 %), Greece (24,79 %), the United Kingdom (24,66 %), Italy (23,97 %), and Romania (18,70 %). It is important to look at this ratio since a grid that is equipped with a high share of intermittent renewables is likely to be more susceptible to the volatility of power output that are characteristic of such power plants, and thus power surges and power outages caused by periods insufficient production or overproduction (IEA, 2014).

On top of this, countries with large absolute (not relative to total generation) wind & solar capacities are considered, along with those who have seen the largest additions in recent times, signalling a strong penetration of the latter. According to the Renewables 2017 Global Status Report (REN21, 2017), they consist of the countries listed in the tables below:

Table 1. Installed Solar Capacity Top Countries (REN21, 2017)

Country	Capacity Solar Power (in GW) 2016
China	77,4
Japan	42,8
Germany	41,3
US	40,9
Italy	19,3
UK	11,7
India	9,1
France	7,1
Australia	5,8
Spain	5,5

Table 2. Additions in Solar Capacity Top Countries (REN21, 2017)

Country	Additions in Solar power (in GW) 2016
China	34,5
US	14,8
Japan	8,6
India	4,1
UK	2
Germany	1,5
Republic of Korea	0,9
Australia	0,9
Philippines	0,8
Chile	0,7

Table 3. Installed Wind Capacity Top Countries (REN21, 2017)

Country	Capacity Windpower (in GW) 2016
China	168,7
US	82,1
Germany	49,5
India	28,7
Spain	23,1
UK	14,5
France	12,1
Canada	11,9
Brazil	10,7
Italy	9,3

Table 4. Additions Wind Capacity Top Countries (REN21, 2017)

Country	Additions in Windpower (in GW) 2016
China	23,4
US	8,2
Germany	5
India	3,6
Brazil	2
France	1,6
Turkey	1,4
Netherlands	0,9
UK	0,7
Canada	0,7

Above (tables 1, 2, 3 & 4) are the countries that either possess the largest capacities of intermittent renewables, or are either the ones adding the most intermittent renewable electricity generation annually. Due to their potential volatility in dispatching, these countries are where energy storage systems are most needed. However, due to time and data constraints, the scope of this thesis is narrowed-down to the countries of the European Union.

Thus the final selection of countries of interest are as follow:

Table 5. Country Selection

Country	Share of wind-solar in energy mix
Belgium	25,1 %
Denmark	41,8 %
France	13,1 %
Germany	41,4 %
Greece	24,8 %
Ireland	25,6 %
Italy	24,0 %
Netherlands	14,5 %
Portugal	27,4 %
Romania	18,7 %
Spain	28,2 %
United Kingdom	24,7 %

II.2. GIS-based Model

II.2.1 Overview

The research is conducted using a GIS (Geographical Information System) based approach. GIS is omnipresent in today's geographical surveys, being used for all kinds of applications thanks to its large data-coverage & integrity. Its functionality of adding layers of data makes it ideal for a bottom-up approach analysis, and it is precisely through this method that this research is conducted, using layers as filters in order to obtain results. Using an EU paper on conventional pumped hydropower storage potential in Europe (Gimeno-Gutiérrez M. and Lacal-Arántegui R., 2013) as a blueprint, a GIS model is drafted taking account of the successive filters to be applied through this research. In 2013, the JRC (Joint Research Centre) conducted research looking into the European Union's pumped hydropower storage potential. Although the latter is very different in the sense that it looks into conventional pumped hydropower storage, and thus searches for strong topographical variations and distances between surface-occurring water reservoirs, the study conveys a very similar sense of approach relative to the research conducted in this thesis. Criteria regarding distance to inhabited or already used sites, distance to UNESCO, Natura 2000 sites, and distance to the electricity grid are all aspects that are analysed and taken into consideration. This UPHS research assimilates some of these aspects, but reverse-engineers the search query to look for areas without strong topographical relief variations, and with no importance to surface reservoirs. Alternatively, it attaches importance to the proximity of an available hydrographic network, and the distance to intermittent renewable energy power plants.

The GIS-based model used in this research functions in phases, starting with inputs of Global Administrative Areas (GADM), intermittent renewable energy plant localisations, hydrographic network and the electricity transmission grid to produce the first phase: Theoretical surface potential (Phase 1). Constraints are then gradually added to produce a second, third and a final fourth phase. For the second phase, agricultural areas and urban zones are taken account of and classified as land already in use, thus excluded from the theoretical surface potential giving us the Human-use surface potential (Phase 2). To produce phase 3 "Environmental surface potential", environmental constraints are applied regarding the proximity of protected areas, designated by the Natura 2000, CDDA (Nationally Designated Areas) and UNESCO sites. Finally, a Digital Elevation Model (DEM) is used to compute topographical data and remove sites calculated to not be in the scope of UPHS placement, which is ultimately destined for flat-land topography. This last process gives us phase 4, which is the "realisable surface potential" (see figure 2).

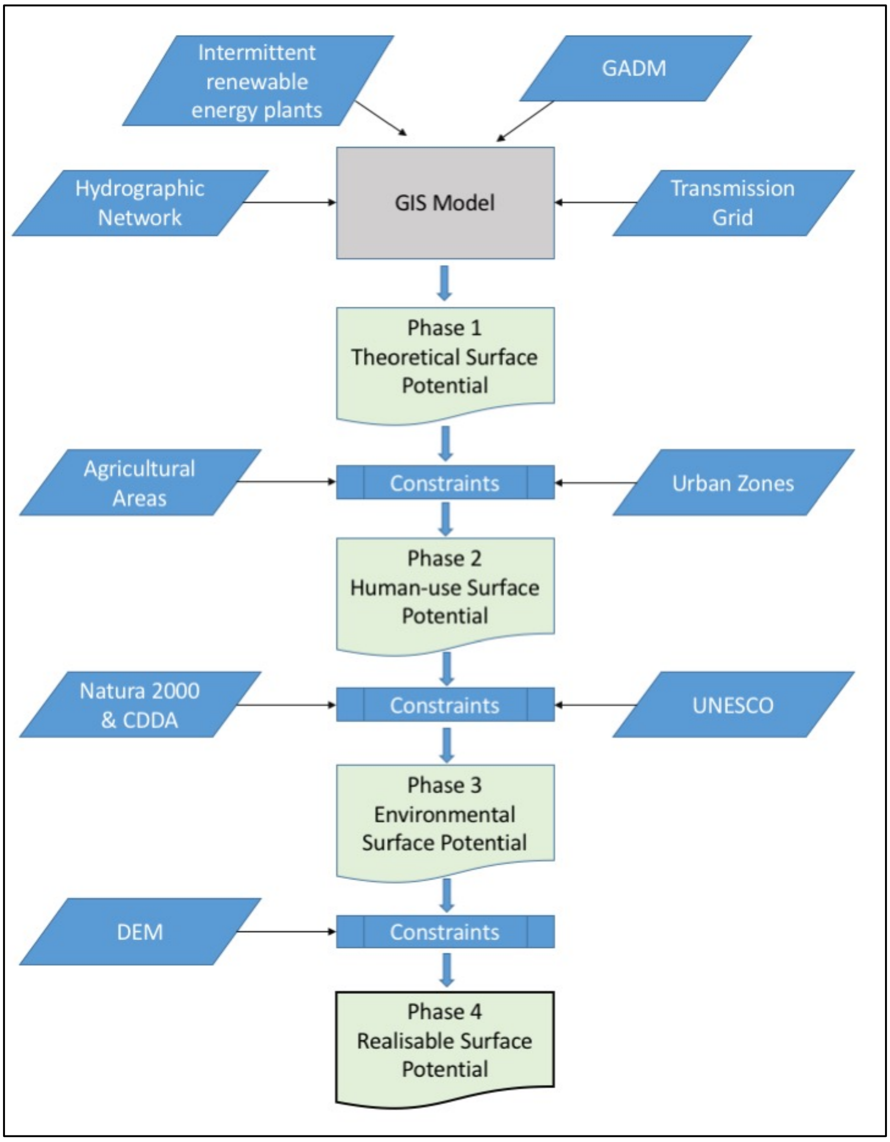

Figure 2. GIS-based Model Flowchart

II.2.2. Model application & Scenarios / Flat Land

UPHS being part of the FLES (Flat Land Energy Storage) project, one main component will consist of identifying geographical areas of relatively flat land. Zones of low relief deviation will be of interest whilst those with important altitude variations, such as mountainous areas, will be disregarded. This is done due to the primary flat land target set forth by UPHS, this thesis consisting of a primary outlook on potential locations of UPHS facilities, in which conventional PHS would not be envisaged. Although UPHS may also be applied elsewhere, as well as in regions of high topographical variation thanks to reduced ecological and environmental degradation relative to conventional PHS (Huynen J., Schalij R. & Arts T., 2012), flat land topography will consist of the main interest in this research.

To qualitatively assess flat land topography, a threshold must be set in order to characterise what is and what is not considered "flat-land". As described by Kibrit (Kibrit, B., 2013), this would be low lateral variations over long distances, such as to include rolling hills and plains.

Numerically, research looking into the potential of conventional PHS showed that a maximum distance-to-head ratio of 10 was almost always used (Rehman S., et al. 2015). Similarly, a computer program was constructed to calculate the theoretical potential of conventional PHS in Europe, and a slope (head-over-distance ratio) of 10% was used as a minimum lateral variation for the implementation of PHS (Connolly, D., MacLaughlin, S, 2011).

$$Slope = \frac{Rise}{Run} = \frac{\Delta y}{\Delta x}$$

Equation 2. Topographical Slope equation (Geokov.com, N.D.)

Thus it is considered appropriate to take a slope of 10% as a maximum lateral variation for the implementation of UPHS, as to not meddle in the territory of already well-established conventional PHS, and concentrate on the areas which are conventional-PHS deprived. However, since UPHS has been calculated to be just as investment-intensive (sometimes even less costly) as conventional PHS all the while performing better ecologically, environmentally, and in terms of efficiency, UPHS can theoretically infringe on conventional PHS's territory due to its numerous advantages.

This is the spearhead assumption leading to the creation of two scenarios in this research. Taking a slope range of 0% to 10%, Scenario A will serve as a "base" analysis. While scenario B will act as an "extended" view, using a slope range of 0% to 15%, and loosening all constraining factors in order to get a larger view of UPHS potential. These factors consist of the distance to intermittent renewable power plants, the distance to a water source (hydrographic network), the proximity to the electricity transmission network, the distance to urban zones & agricultural areas, and the closeness of protected sites such as Natura 2000, National Designated Areas (CDDA) and UNESCO sites. The values associated to these constraining factors are based on a mix of previously assessed projects for electricity storage plants such as the Joint Research Centre's assessment of conventional pumped hydropower storage in Europe (Gimeno-Gutiérrez M. and Lacal-Arántegui R., 2013), and a study performed to evaluate the potential of small pumped hydropower energy storage using a GIS-based method (Rogeau A., Girard R., Kariniotakis G., 2017), as well as educated assumptions.

Table 6. Description of Scenarios

Constraints	Scenario A	Scenario B
DEM - Maximum slope	10 %	15 %
Maximum distance to intermittent renewable energy power plant	5 km	10 km
Maximum distance to water source	2 km	5 km
Maximum distance to Transmission network	20 km	50 km
Minimum distance to urban zones & agricultural areas	Should not contain	Should not contain
Minimum distance to Natura 2000, CDDA & UNESCO sites	5 km	1 km

II.2.3 Data & software

Digital Elevation Model (DEM)

Digital elevation models (DEM) are used in this research in order to assess the topographical relief of the lands in question. Provided by Utrecht University's GIS laboratory, this research made use of NASA's SRTM (Shuttle Radar Topography Mission) data to extract data regarding the topography of the countries in question. This allowed the computing of slope maps, which indicate the ever-changing slope (in percentage) across a geographical expanse. NASA's SRTM data is used due to its global acceptance in the scientific community as well in the industrial domain (Gimeno-Gutiérrez M. and Lacal-Arántegui R., 2013), the fact that it covers most of mainland Europe (up to 60° N, so except the most northern countries such as e.g. Norway, Sweden and Finland), and how it offers data in a metric data frame, which is needed for correct slope calculations.
This DEM data is in GIS raster form, consisting of a grid with gradually varying data -this is in contrast with vector spatial data used in GIS, which relates data to specific coordinates in form of points, polylines and connected polylines forming polygons.

The NASA SRTM raster data used in this research is in 25 x 25 m cell size, giving on one hand a relatively high resolution to this study, but in the other lengthy computational times spanning dozens of hours to days, with individual file sizes reaching up to 60 gigabytes (Especially for the larger countries such as France, Germany, the UK and Romania). This consisted of a problematic process throughout this research, often resulting in long waiting times and failed computations due to file size limits. This is the reason why this DEM data was added last in the GIS-based model process.

GADM administrative boundaries

The Database of Global Administrative Areas (GADM) data is used to define country boundaries and form the ensuing country-specific analysis. Along with the DEM maps, this data is also provided by Utrecht University's GIS server, sourced from the GADM spatial data project (GADM, 2018), which offers high-resolution data on administrative boundaries.

Intermittent renewable energy power plants

Wind and solar power constitute the focus regarding intermittent renewable energy power plants in this research. As seen in the country selection process, the presence of wind & solar plants plays a vital part in the assessment of UPHS potential. After all, UPHS is an energy storage system dedicated to adapting today's electricity grids and infrastructure to the growing share of intermittent renewables, and allowing more growth in said sector. It has been envisioned that these energy storage plants may work in a coupling manner with electricity producing power plants, and thus be placed in relative proximity of each other (Huynen J., Schalij R. & Arts T., 2012 & Energy Storage Association, 2018). This research is dedicated to finding the best potential of UPHS implementation, and this implies being ideally located close to wind and solar power plants. However, after thorough searching, most countries included in the scope of this research do not possess any solar power plants, solar farms, or solar facilities in form of GIS maps. It was thus not possible to use solar power plants in the extent of this GIS-based assessment.

Therefore, solely wind power plants (Wind farms) are considered in the GIS surface-survey component of this research.
But additional issues arise when looking at Europe's wind farms. First of all, since UPHS is an onshore system, this research only considers onshore wind farms. Secondly, this research follows a case study: OPAC, by Sogecom BV, which is an UPHS planned for the region of Limburg in the Netherlands. Size and capacity are what make it a viable and economically attractive, and thus the general specifications of the OPAC project - of 1400 metres depth, with a maximum 8 GWh daily cycle potential (Huynen J., Schalij R. & Arts T., 2012)- are considered. The largest wind farm currently operating in Europe is the Fântânele-Cogealac wind farm, found in Romania. It has a nameplate capacity of 600 MW, producing on average around 1,2 GWh per day (thewindpower.net G, 2018). This is still quite short of the 8 GWh daily-cycle for which the UPHS plant is optimally designed for.

Therefore, it can be interpreted that a single UPHS plant may serve as a storage unit for multiple wind farms, creating a web of connections and being a central hub of energy storage. This status of interconnectivity between multiple wind farms of varying capacity allows to momentarily disregard the minimum wind farm energy output needed for the placement of a UPHS plant.

Special cases

Romania
Apart from the general survey, special focus is given to Romania's Fântânele-Cogealac wind farm, run by CEZ, since it is currently the largest wind farm in operation in Europe. A specially created GIS polygon (using GPS coordinates) is used to designate the wind farm, enabling a more precise study to be performed around it. It is presented in the results as a separate entity, distinct from Romania.

Spain, Italy and Belgium
Countries with no available wind farm data were disregarded: Italy, Belgium and Spain. This is very surprising as Spain is the world's 5th wind power producer with a total installed capacity of 23,1 GW by the end of 2016 (REN21, 2017), and shall be recommended for further research.

Wind farm and general wind turbine data is country specific, with a list of sources below:

Table 7. Wind Farm Data Source by Country

Country	Wind farm data source
Denmark	"DKwindturbinesfeaturesServiceAGOL & Vindmoeller DK2013" ArcGIS online server
Germany	"Onshore Windkraftanlagen" ArcGIS online server
Spain	No data available
Portugal	"Mapa de parques eolicos" ArcGIS online server
Ireland	"Wind Farms, SEAI" ArcGIS online server
Belgium	No data available
Greece	"Wind Farm Greece", Web map by Antonio Giovanni, ArcGIS online server
UK	"Onshore Wind farms in the UK", feature service map by mtjones28, data taken from UK wind energy database (UKWED, 2016) on ArcGIS online server
Italy	No data available
Romania	"Wind-Power plants map", by Cseverin, last modified in 2014, on ArcGIS online server & creation of CEZ Fantanele-Cogealac wind farm using geographic coordinates
Netherlands	"windstats_2014" on Utrecht University's GIS server
France	"Parcs Nordex" ArcGIS online server

Transmission Grid Network

The transmission grid network is a complex system that allows the circulation of electricity, connecting electricity producers and consumers (EIA, 2017). As any large-scale energy storage system, an UPHS plant would need to be connected to a high-voltage line enabling it to receive and send large quantities of electricity (Gimeno-Gutiérrez M. and Lacal-Arántegui R., 2013). Data regarding the electricity grid is used to ensure that an envisaged UPHS plant will be in reach of a connection to a country's grid. This data may come from diverse & different sources. When available, this data is used to assess a maximum distance from potential connective points. When unavailable, this data is disregarded. However, it must be noted that a first step in this research consists of assessing the distance from intermittent renewable energy power plants, which implies a certain distance from the electricity grid, since power plants are usually connected to the high-voltage transmission grid (EIA, 2017).

CORINE Land Cover: ***Urban zones, Agricultural areas, and Hydrological Network***

The CORINE Land Cover (CLC) is a European initiative consisting of an inventory of land cover in 44 classes, CORINE standing for "Coordination of information on the environment" (European Environment Agency, 1995). This research used the 2012 version of the CLC, offered in 100 metres resolution and with a minimum of 25 hectares mapping unit, producing satellite data of geometric accuracy of less than 25 meters (Copernicus, N.D). The CLC is used in this research to extract vital data regarding land use and the availability of fresh water through the proximity of water courses.

Urban Zones
Urban zones were assessed by using the "continuous urban fabric" and "discontinuous urban fabric" CLC classes. These classes designate artificial areas, mainly occupied by dwellings, buildings and the transportation network. They refer to land essentially covered by structures and the transport network, of more than 80% for continuous urban fabric, and between 30% and 80% for discontinuous urban fabric. The remainder areas constitute vegetation visible in satellite images, which refers to single houses or scattered apartment blocks surrounded by areas of vegetation (Bossard M., Feranec J., Otahel J., 2000 - CORINE Land Cover Technical Guide - Addendum 2000).

Agricultural areas
Agricultural areas are to be avoided when mapping out UPHS potential sites. These are landscapes that are already occupied by human activities. These areas fell into three subclasses. The "annual crops" subclass which refer to areas associated with permanent crops, including those cultivated under forest trees, meadows, and areas that are a mix of crops and pastures with naturally occurring vegetation. Next, the "principally occupied by agriculture" is a class that includes land used for agriculture but has amounts of natural or semi-natural landscapes, such as out crops, water bodies and wetlands. This class takes account of arable land in parcels smaller than 25 hectares, and spread-out rural settlements such as farms and isolated houses. Finally "complex cultivation patterns" is the class that incorporates a heavy mix of urban and agricultural landscapes. Since the threshold for a parcel being considered urban fabric is at 30% of said parcel being occupied by urban structures, areas presenting agricultural aspects with a decent amount of urban structures are put into the "complex cultivation patterns" class (Bossard M., Feranec J., Otahel J., 2000 - CORINE Land Cover Technical Guide - Addendum 2000).

All Urban zones and agricultural areas were used to extract land cover from potential UPHS site locations, thus acting as a constraint to UPHS site placement.

Hydrological network
Land cover classes "Water Courses" and "Water bodies" were taken from the 2012 CLC to assess the hydrographic network in countries because although the UPHS system is designed to work as a closed-loop system, eventual evaporation and water leakage are predicted and have to be accounted for. Therefore, any UPHS plant would have to be built in proximity of a permanent water source, thus allowing water intakes when needed. This research used hydrographic information to localise European water courses, such as rivers and other adequately sized water flows.

In certain cases, such as with Denmark, insufficient water course data lead to the consideration of water bodies such as lakes and reservoirs. Moreover, when available, CLC data was combined with country specific data to form a more intricate & detailed hydrographic network: such was the case with France, the Netherlands and Romania.
For France, more detailed hydrographic data was obtained for the Île-de-France region using the "Réseau hydrographique principal simplifié" GIS vector data provided by AESN (Agence de l'Eau de Seine Normandie) and IAU (L'Institut d'Aménagement et d'Urbanisme).
Regarding the Netherlands, additional hydrographic data was provided by Utrecht University's Rijkswater GIS database, under "Structuurvisie, Infrastructuur, en Ruimte"
Lastly, Romania also received additional hydrographic data through "Rivers of Romania EN" created by WWF and ESRI for environmental protection purposes, last updated in January 2018.

Natura 2000, Nationally designated areas & UNESCO World Heritage sites

An important constraining filter of this GIS-based surface study is the environmental constraint, in which Natura 2000, Nationally designated areas (CDDA) and the United Nations Educational, Scientific and Cultural Organisation (UNESCO) sites were taken into account. This data is used as a final filter to not allow potential UPHS sites to infringe on Special Areas of Conservation (SAC), Special Protection Areas (SPA), and UNESCO Human Heritage sites, and thus limit environmental concerns. Data was taken from Utrecht University's GIS server, with NATURA 2000 (2011 version) & CDDA (Version 10) data being provided by the European Environment Agency (EEA) and the UNESCO data provided by UNESCO World Heritage Centre.

Model inner-workings

This GIS model works in layers, and essentially records the overlapping of criteria found on different layers. For each phase to produce results, criteria must either overlap or not be in contact (depending on the criteria). Moreover, to compute maximum and minimum distances to and from specific areas such as protected areas or intermittent renewable energy power plants, "buffer zones" are rendered in the model: these buffer zones establish an area around the criteria in question, depending on the distance desired. For example, wishing to have a maximum distance of 10 km to intermittent renewable energy power plants, the GIS "buffer" function creates an area around said power plants that extends the original area delimitation by 10 km. If the criteria is represented by a single point, then a circular area is produced, with the point at its centre and with a radius of 10 km. The model then superimposes layers with different criteria, such as wind farms and hydrology, and records the overlapping of their respective areas, thus producing a zone that meets both desired distances from each respective criterion. Contrarily, some criteria must not overlap: this is the case with the urban zones, agricultural areas, protected environmental areas and UNESCO world heritage sites. Instead of overlapping, these criteria work on an erase basis. Applying these constraints reduces the theoretical surface potential produced in phase 1 by progressively erasing zones which correspond to the previously cited unwanted areas. For example, when the phase 2 (Human-use surface potential) meets the environmental constraints (Natura 2000, CDDA & UNESCO constraints), all areas affected by the constraints are erased from phase 2, thus producing phase 3.
Although topographical criteria would have preferably been applied as a first filter in order to directly distinguish areas of relatively flat-land and thus of interest, DEM data is applied in the final stage due to their digital file weight and extremely lengthy computational times. This topographical data intersects the phase 3 "Environmental surface potential" to find where phase

3 and areas of desired slope overlap, with the results being the recorded matchings between the two layers, thus producing phase 4: "Realisable surface potential".

Lastly, this research follows the O-PAC project as a case study. The O-PAC project dictates that the upper reservoir size is around 400 x 400 meters (Huynen J., Schalij R. & Arts T., 2012), but we can assume that land around the reservoir will be reserved for the plant's diverse above-ground components. Taking a modest 200 meters more on all side, this gives a total surface area of 600 x 600 meters, constituting a minimum surface requirement of 360,000 square meters. This is used as a minimum area size to declare a UPHS potential zone and set in the GIS model as a cut-off threshold (a minimum surface size requirement).

Model Delimitations

Power plant generation
Data regarding the power output of intermittent renewable energy power plants was not always available, and thereby could not be used as a parameter in the model. This is overcome by "creating" zones that assemble multiple intermittent renewable energy power plants, assuming that their combined output would be considerable. An UPHS plant would thus be able to be connected to all power plants depicting said zone.

Hydrological flow
Also, although the hydrological network is represented, the exact amount of water flow in each respective water course is not represented by the available data, and thus is not taken account of in the model.

Transmission Grid Network
Connectivity to the grid is essential for any large-scale component of power generation or storage. However, GIS data regarding the localisation of electricity transmission grid lines (especially high voltage lines, which are desired) have appeared to be scarce. When available, this data is used and applied as an additional constraint. But as the case is with many countries in this study (including Denmark, France, Germany and Portugal) this data is not applied due to its unavailability. As previously stated, this is an inconvenience that can nonetheless be overcome by another constraint: that of maximum distance to intermittent renewable power plants. Effectively, maximum distance to transmission grid lines is set at 20 km and 50 km for scenario A & B, respectively, while maximum distance to intermittent renewable power plants is set at 5 km and 10 km in scenario A & B, respectively. Assuming these electricity generation power plants are connected to the transmission grid, this assures a maximum distance to the latter for the potential UPHS sites.

Wind Farms & interconnectivity
Finally, problems are also encountered when wind farm maps act more as wind turbine maps (as is the case for multiple country datasets), and thus representing singular wind turbines as points rather than ensembles consisting of wind farms. This issue was overcome by using the GIS "*aggregate points*" function, thus creating a mesh between wind turbines by combining local clusters of wind turbines into singular farms.
Regarding the interconnectivity between multiple wind farms, the "*aggregate points*" and "*aggregate polygons*" GIS functions are used to create a surface mesh between wind farms that dictate an area between a multitude of wind farms.

II.4 Geological insight

Suitable subsurface conditions must be met in order to have a complete assessment to consider building a UPHS plant. However, extensive site-specific research is necessary in order to fully assess within adequate precision and accuracy the true potential of construction of an UPHS plant. This research considers the geological conditions through a more general scope, proceeding through literature reviews, in order to map zones of higher potential.
Problematically, UPHS requires depths of around 1000 to 1500 metres (Huynen J., Schalij R. & Arts T., 2012), which is commonly considered the deep subsurface. Data on the deep subsurface tend to derive from exploration companies that are interested in petroleum, natural gas, mineral salt or terrestrial heat (geothermal energy) and are thus secretive in nature. In the Netherlands, this data is obliged to be shared with the public thanks to the Mining Act, but the information remains confidential for a period of five years (TNO, N.D). But in other countries, this data is still very difficult to get a hold of.

It must be noted that multiple options exist or have been considered for potential UPHS projects. Just as Nassim Uddin's study focused on the Oriskany mine in Ohio (Uddin, N., 2003), abandoned mines as well as depleted salt caverns have been considered alongside purposely-excavated caverns (Kibrit, B., 2013). However, this research solely looks into new cavern excavation methods of constructing a UPHS plant, due to the instability too often encountered through assessment of depleted salt caverns and abandoned mines. Moreover, they have been considered undesirable due to their scattered configuration and disadvantageous hydrodynamics (Huynen J., Schalij R. & Arts T., 2012). Therefore, this research only considers new-cavern excavation specifically destined to UPHS construction.
To implement a UPHS plant, rock types and geologic layers are needed which express the geological characteristics and parameters considered necessary, based on the findings of Sogecom's O- PAC project (Müller, D. and Hereth, A., 1987), TU Delft (Kibrit, B., 2013), and similar geotechnical engineering project data (Uddin, N., 2003).

Overall, these consist of primary points which are desired:
- Strong (in a geological context) homogeneous layer of rock at a depth of 1000 to 1500 meters.
- Adequate layer thickness, as homogenous and uniform stratigraphy is preferred
- Low seismic activity in the area
- Low presence of karst in rock layers, since they are signs of groundwater flow, which is unwanted
- Low presence of faults and cracks in identified layers is preferred
- Identification of an impermeable layer is desired

These geological parameters are found by the O-PAC UPHS project that is currently in motion in Limburg (the south of the Netherlands) in the Carboniferous strata –and more specifically in the Dinantian. In the Limburg area, core drillings of the Dinantian strata have shown that it is composed of limestone of sufficient quality to host large excavated reservoirs and thick enough to also hold the diverse hydroelectric UPHS components (see figure 3). It also happens to be a stable geological zone, with no important seismicity (Huynen J., Schalij R. & Arts T., 2012).

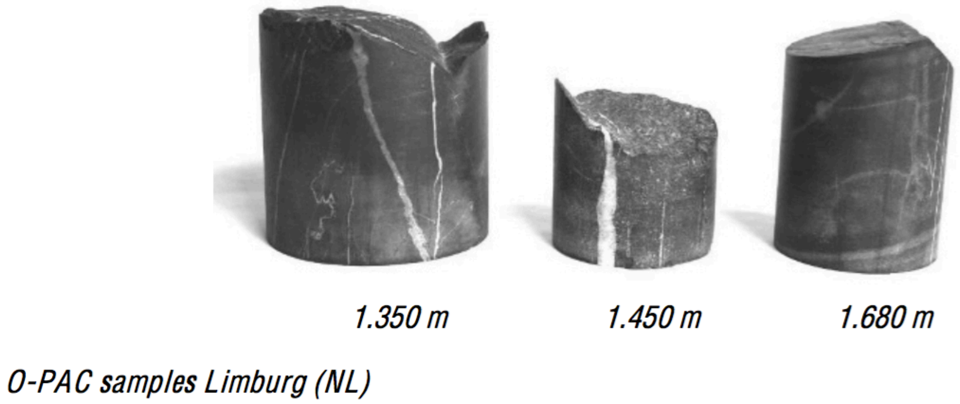

Figure 3. Core drillings taken in Limburg (NL) showing Dinantian Limestone (Huynen J., Schalij R. & Arts T., 2012)

This literary search for appropriate deep subsurface geologic layers is a difficult task (see figure 4). Following the laws of stratigraphy, -specifically that of lateral continuity-, though a geologic formation may extend for hundreds of thousands of square kilometres horizontally, a formation in one geographic area does not necessarily retain the same characteristics in another area, especially regarding layer thickness and depth beneath the surface (Macleod N., 2005).
Nonetheless, it's known that the Carboniferous was a time of varying depositional settings with shallow marine depositional environments as well as continental ones. Studies across the Northern Hemisphere find that the Dinantian is characterised by shallow-water limestone deposits (Manger W.L., 2017), which is what is found to be UPHS appropriate in the southern Netherlands since it occurs at the adequate depth of 1000 to 1500 metres beneath the surface. Therefore, priority is given to the search of the depth of the Dinantian (Part of the Carboniferous) throughout the different countries in this research. The findings of this search are taken into account as additional guidance, added to the GIS-based model's surface results in a manner of depicting geographical areas more prone to have an adequate subsurface for UPHS plants.

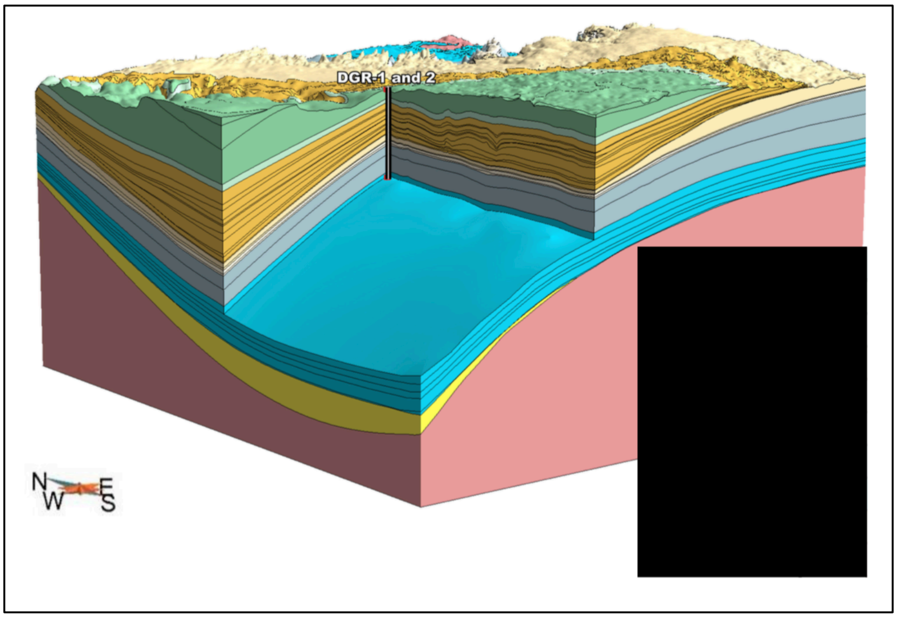

Figure 4. Figure representing the variation in thickness & depth of geologic formations. Courtesy of Raven K., et al, 2009 "Regional and site geological frameworks – proposed Deep Geologic Repository, Bruce County, Ontario".

III. Results

First presented are the results of the GIS-based model. These results reflect the surface study, and thus geographical zones where UPHS plants have potential in being deployed. Due to being more suggestive than assertive, the geological findings are presented secondarily, representing where the subsurface may hold the most appropriate characteristics for UPHS instalment.

The results of the GIS-based model are presented here in form of the final realisable surface potential. First presented are the numerical results for all countries assessed in form of an overview, in scenario A and scenario B, respectively. In each scenario and country, the resulting UPHS-potential "Zones" refer to distinct global areas found by the model where the surface characteristics meet all the criteria needed for the installation of a UPHS plant in the context of this research. Due to the way the GIS-based model functions, some zones extend over vast areas while others are small patches, resembling more specific sites. However, a zone is defined as being one single continuous patch of land, represented by a single GIS polygon. In other words, a zone refers to a distinct GIS polygon. It may seem perplexing at first, as scenario A may present more zones than scenario B while B is less strict on the set constraints. That is because the firmer constraints adopted in scenario A can cause more "cutting" of polygons, thus presenting multiple zones instead of a single zone that would be presented in scenario B. It is therefore more adequate to look at the zone's area coverage (in square kilometres) when comparing between scenarios.

As presented in II.2.3 *Data & software*, under "*Special cases*", lack of GIS data regarding wind farms for Spain, Belgium & Italy caused these countries to be excluded from this research. This is unexpected since these countries have considerable amounts of installed wind power, especially Spain which ranks 5th in the world regarding installed capacity.

III.1. Scenario A surface overview

The overall UPHS realisable surface potential for all studied countries combined under scenario A is 165 geographical zones, totalling an overall zone area of 4156,12 km^2.

Table 8. Scenario A Surface Results Overview

Country	Number of zones	Overall zone area (km^2)	% of total land area
Denmark	60	1084,10	2,6
France	0	0	0,0
Germany	0	0	0,0
Greece	0	0	0,0
Ireland	3	34,52	0,1
Netherlands	12	1014,26	3,0
Portugal	0	0	0,0
Romania	74	939,39	0,4
UK	13	1052,27	0,4
Total	165	4156,12	0,2

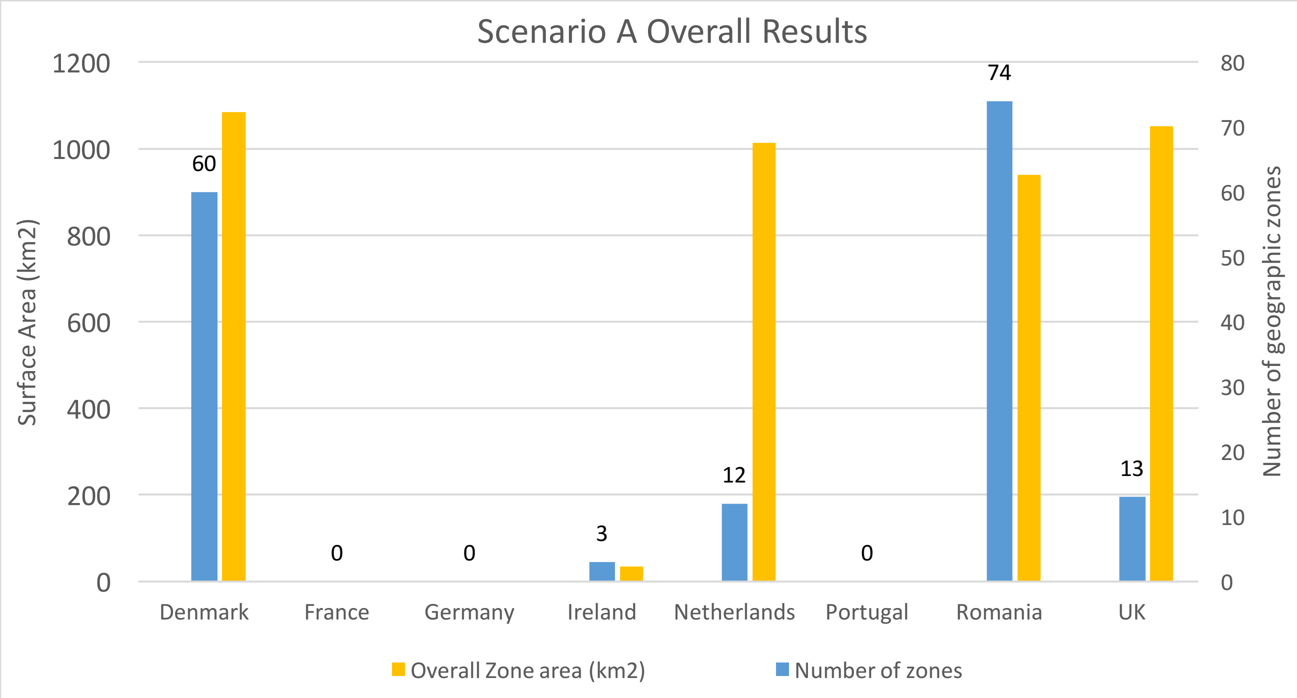

Figure 5. Chart of Scenario A Overall Results

Main contributors to the total 4156,12 km^2 are large areas of UPHS realisable surface potential found in Denmark, the Netherlands, Romania and the UK. Ireland presents a contribution of 34,52 km^2 of potential area, while Romania's Fântânele-Cogealac wind farm alone comes up with 31,57 km^2 (see figure 6).

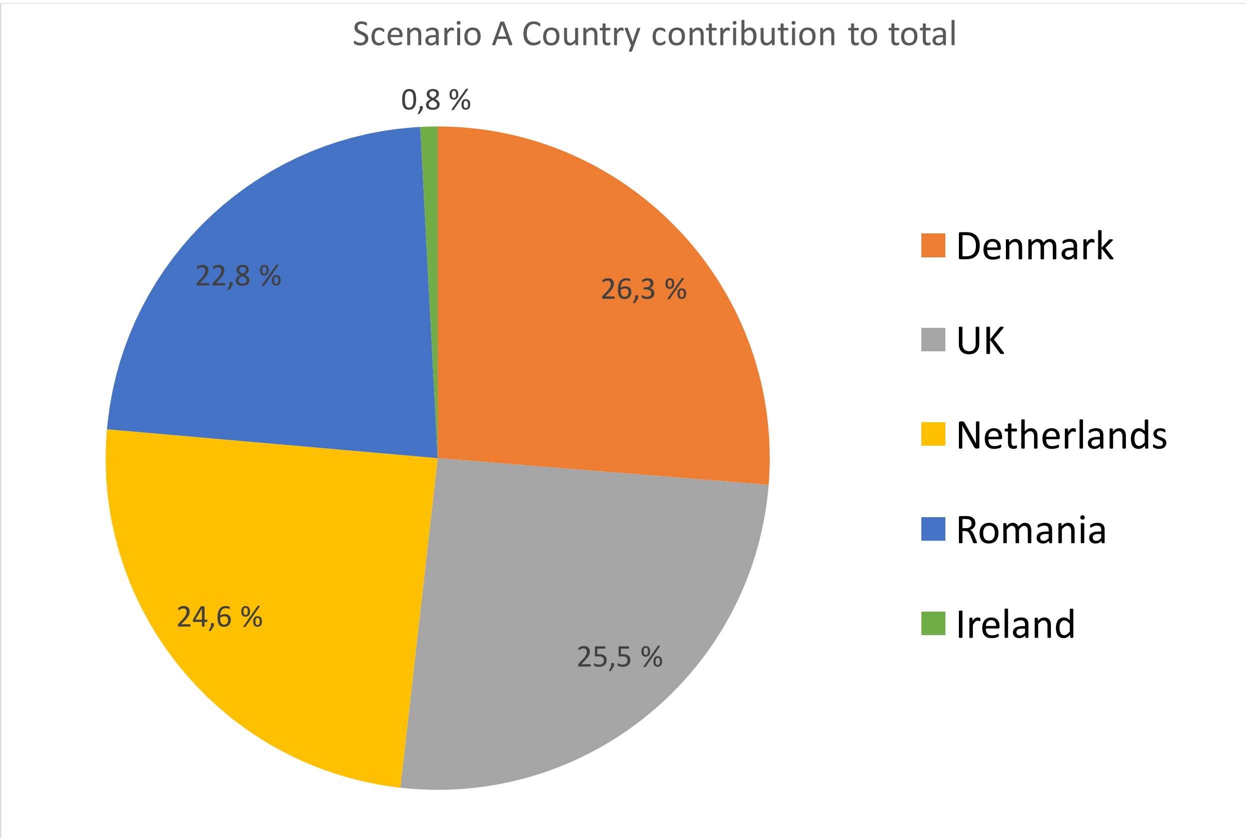

Figure 6. Pie-Chart of Scenario A Country Contribution to Total

Portugal, France and Germany show no UPHS realisable surface potential in scenario A. This may appear surprising for the latter two, especially given the size of France and Germany, and Germany's large wind capacity. But with the way the GIS-based model functions, country size is a factor which led to the absence of results for these two countries: Given their size, wind farms in France and Germany have higher chances of being scattered across greater distances, out of bounds of the scenario A's framework. Thus already giving them a disadvantage in phase 1 "theoretical surface potential" of the GIS modelling stages. The following constraints regarding distance to the hydrological network, removal of urban zones & agricultural areas, and minimum distances to protected sites further constrained that potential, rendering a result of 0 for both country cases.

Greece also shows no UPHS realisable surface potential in scenario A. Greece, a densely mountainous and geographically scattered & complex country has most of its wind farms placed remotely and far from each other, either on mountain tops or on islands in the Aegean Sea (Hatziargyriou N., Kabouris J., 2006). This lead the GIS-based model to dismiss Greece's potential due to the inability to form theoretical surface potential zones between wind farms, thus resulting in 0 realisable surface potential.

All in all, we see that in scenario A UPHS realisable surface potential is found to be mostly in Denmark, the Netherlands, the UK and Romania. This can be explained by these countries' wind farm density and water to land ratio / will be explained in the country-specific analysis.

III.2. Scenario B surface overview

In scenario B, the overall UPHS realisable surface potential for all studied countries combined results in 342 geographical zones, totalling an overall zone area of 43 937,09 km^2. With scenario B's loosened-but-still-realistic constraints, the resulting realisable surface potential for all studied countries combined is over 10 times that found in scenario A. This is a clear indictor of the sensitivity of study, and the impact of the surface constraints. Doubling the maximum distances and halving the minimum distances to certain surface characteristics yields an increase in UPHS realisable surface potential by ten-fold (see tables 8 and 9, respectively).

Table 9. Scenario B Surface Results Overview

Country	Number of zones	Overall zone area (km^2)	% of total land area
Denmark	44	12 418,66	29,3
France	22	676,23	0,1
Germany	74	910,14	0,3
Greece	0	0	0,0
Ireland	39	2699	3,9
Netherlands	9	4862,61	14,3
Portugal	2	61,12	0,07
Romania	124	10242,26	4,5
UK	19	11 786,61	4,9
Total	342	43 937,09	2,5

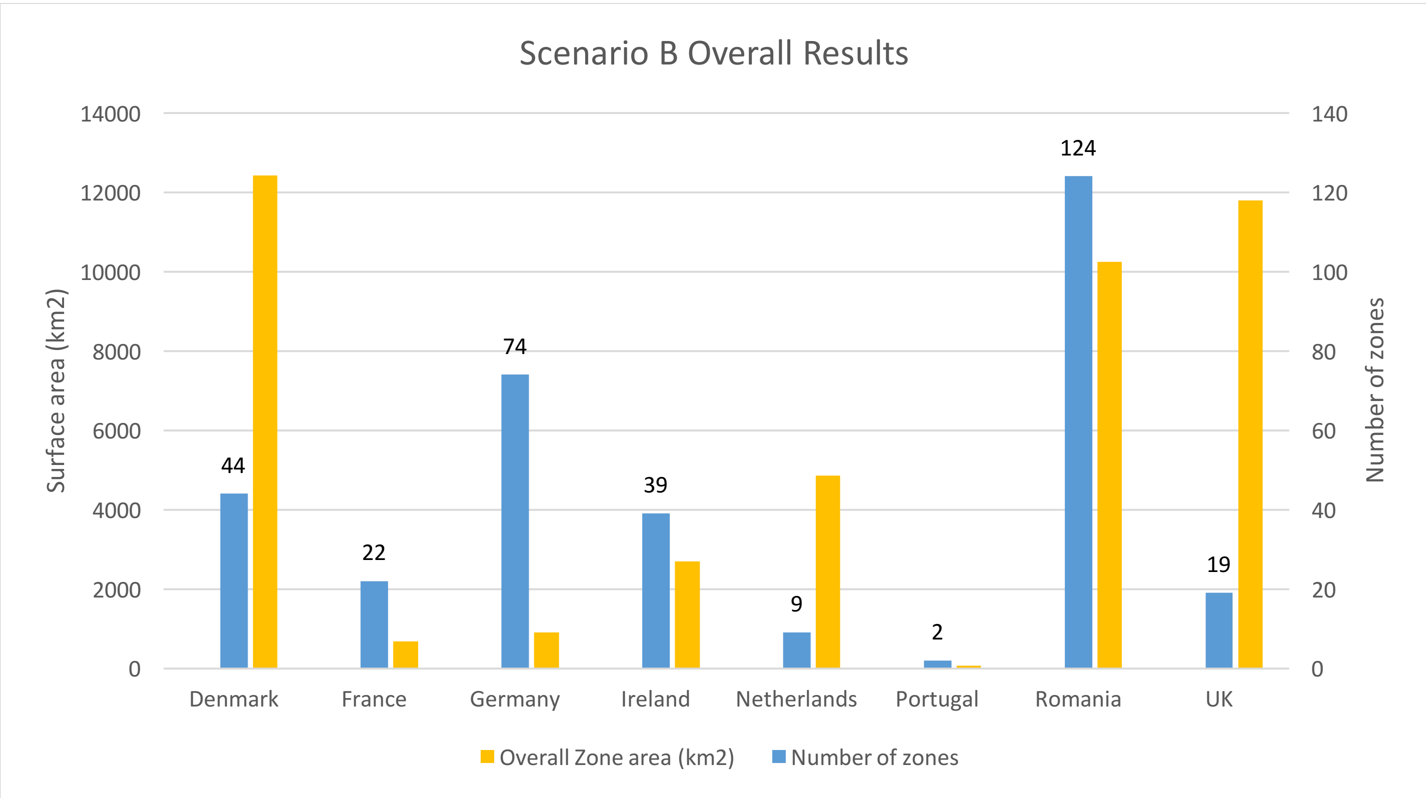

Figure 7. Chart of Scenario B Overall Results

According to the GIS-based model, Denmark still shows the most realisable surface potential for UPHS plants. With 12418,66 km^2 of surface area found to fall in the model's scope, this makes up roughly 29,3 % of Denmark's total land area (CIA World Factbook A, 2018) eligible for UPHS subsurface exploration. This is expected knowing that Denmark has the world's highest wind power penetration (REN21, 2017) with a relatively small total land area size (CIA World Factbook A, 2018), and thus high wind farm density. On top of that, Denmark is a famously flat country, having little topographical variation, which gives it another advantage in this research. The UK comes in at a close second place with 1176,61 km2 of UPHS realisable surface potential in scenario B, while Romania follows with 10242,26 km^2. Similar to Denmark, both the UK and Romania show an increase of more than ten-fold from scenario A. The Netherlands is now after Romania regarding total UPHS realisable surface potential, showing 4862,61 km^2. This is a little over quadruple of what is found in scenario A, and now makes up 14,35 % of the Netherlands's total available land (CIA World Factbook E, 2018). Ireland results with 2699 km^2 of overall zone area in scenario B, a very large increase from scenario A's modest 34,52 km^2. France and Germany now present UPHS realisable surface potential in scenario B, with 676,23 km^2 and 910,14 km^2, respectively. Portugal comes in with 61,12 km^2, divided between 2 geographical zones.
Greece maintains 0 potential even with scenario B's parameters, due to the same reasons cited in scenario A; The scattered & isolated nature of Greece's wind farms made it impossible for the GIS-based model to find suitable areas with a multi-wind farm connection, even within scenario B's constraints.

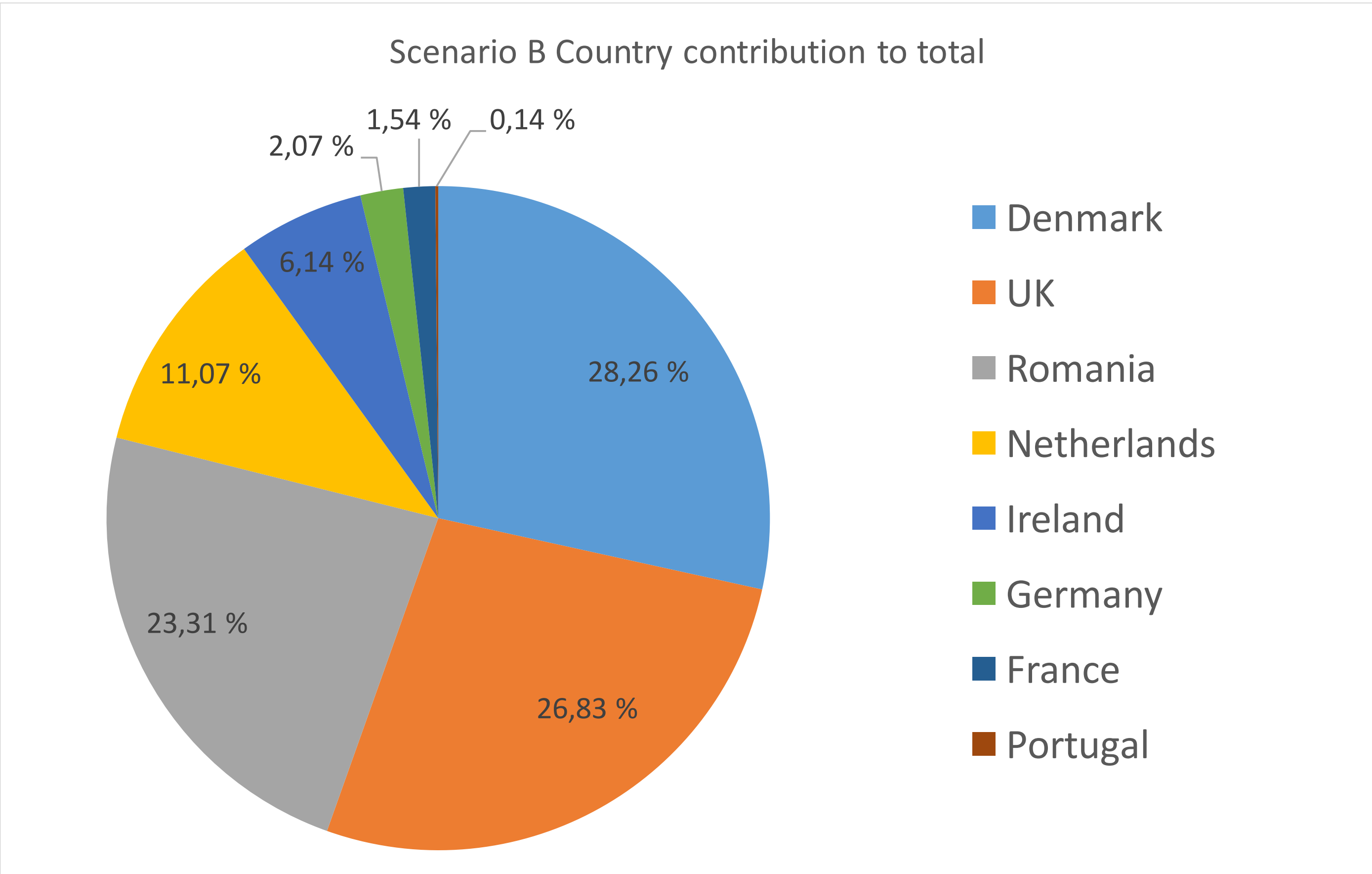

Figure 8. Pie-Chart of Scenario B Country Contribution to Total

III.3. Country-specific results

Country-specific results are now presented in further detail and analysis, including maps depicting the locations of geographical zones of interest found in both scenarios A & B. As previously stated, Greece is found to have no UPHS realisable surface potential and is thus not represented in these country-specific results. Unavailable data for Spain, Belgium and Italy has rendered their study impossible for the time being, so they are not assessed in this section.

III.3.1 Denmark

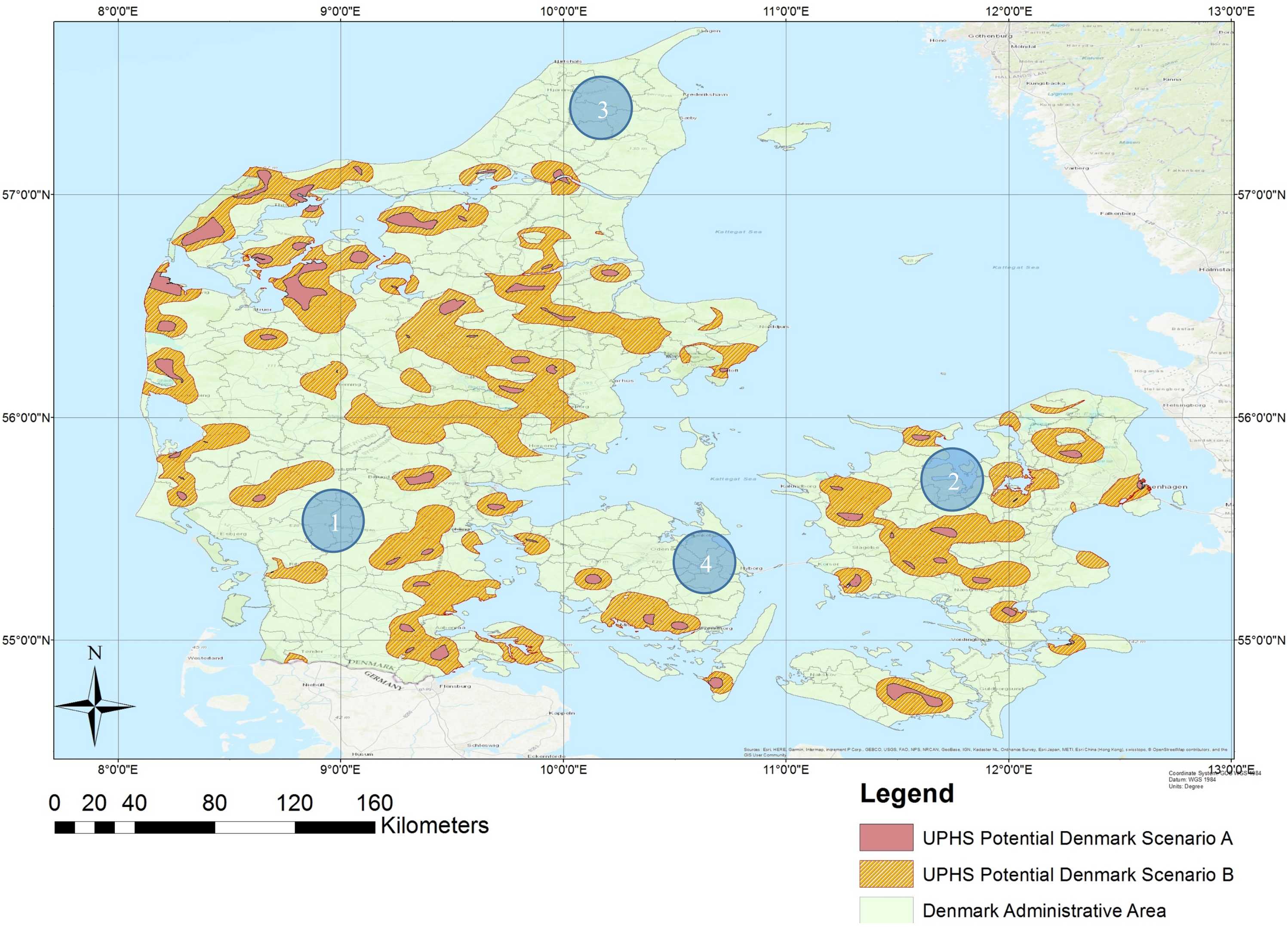

Figure 9. Denmark Results

Denmark is a Scandinavian country situated in northern Europe, bordering the Baltic and North Seas, centred around the geographic coordinates 56° N, 10° E (CIA world factbook A, 2018). Denmark is the world's leader in generation share of renewable electricity, with 53,6 % of electricity coming from renewables (CIA world factbook A, 2018), and 41,82 % specifically and strictly from wind and solar power (PocketBook, 2017).

The GIS-based model finds strong UPHS realisable surface potential for Denmark, with 60 geographical zones totalling 1084,10 km^2 of zone area in scenario A, and 44 geographical zones totalling 12 418,66 km^2 for scenario B. Results can be observed in figure 9. These results correlate with Denmark's high wind power penetration and relatively small total land area, giving it a considerable wind farm density which helps the GIS-based model to allow multi-farm connectivity. The lack of strong topographical relief (World Atlas, N.D.) is also a main factor that is reflected in the results, and which make Denmark an ideal candidate for UPHS plants.

In figure 9, we see that the geographical zones of interest are scattered all throughout the country. Most are found on the Jutland peninsula (see 1 on figure 9), and secondly the Zealand peninsula (see 2 on figure 9), but they also appear on Vendsyssel-Thy and Funen peninsulas (see 3 & 4, respectively, on figure 9).
As shown, single geographical zones of interest in scenario B sometimes incorporate multiple geographical delimitations set by scenario A, explaining why scenario A consists of 60 zones while scenario B results in 44 zones. Nonetheless, as table 14 (Appendix A) shows, scenario B results with a much larger UPHS realisable surface potential area, more than 10 times that depicted by scenario A; The less-restrictive constraints of scenario B manage to extend the area from 1084,1 km^2 to 12 418,66 km^2. This results in 29,3 % of Denmark's total land mass (excluding Danish water areas) being categorized under UPHS realisable surface potential, which is a considerable amount. This comes after scenario A's results that denominate 2,6 % of Denmark's available land (see table 14 in Appendix A)

Overall these results list Denmark as an excellent contender for UPHS potential regarding the surface requirements, with the country coming in at the top of the rankings regarding results in terms of percentage of total land area (see table 11).

III.3.2. France

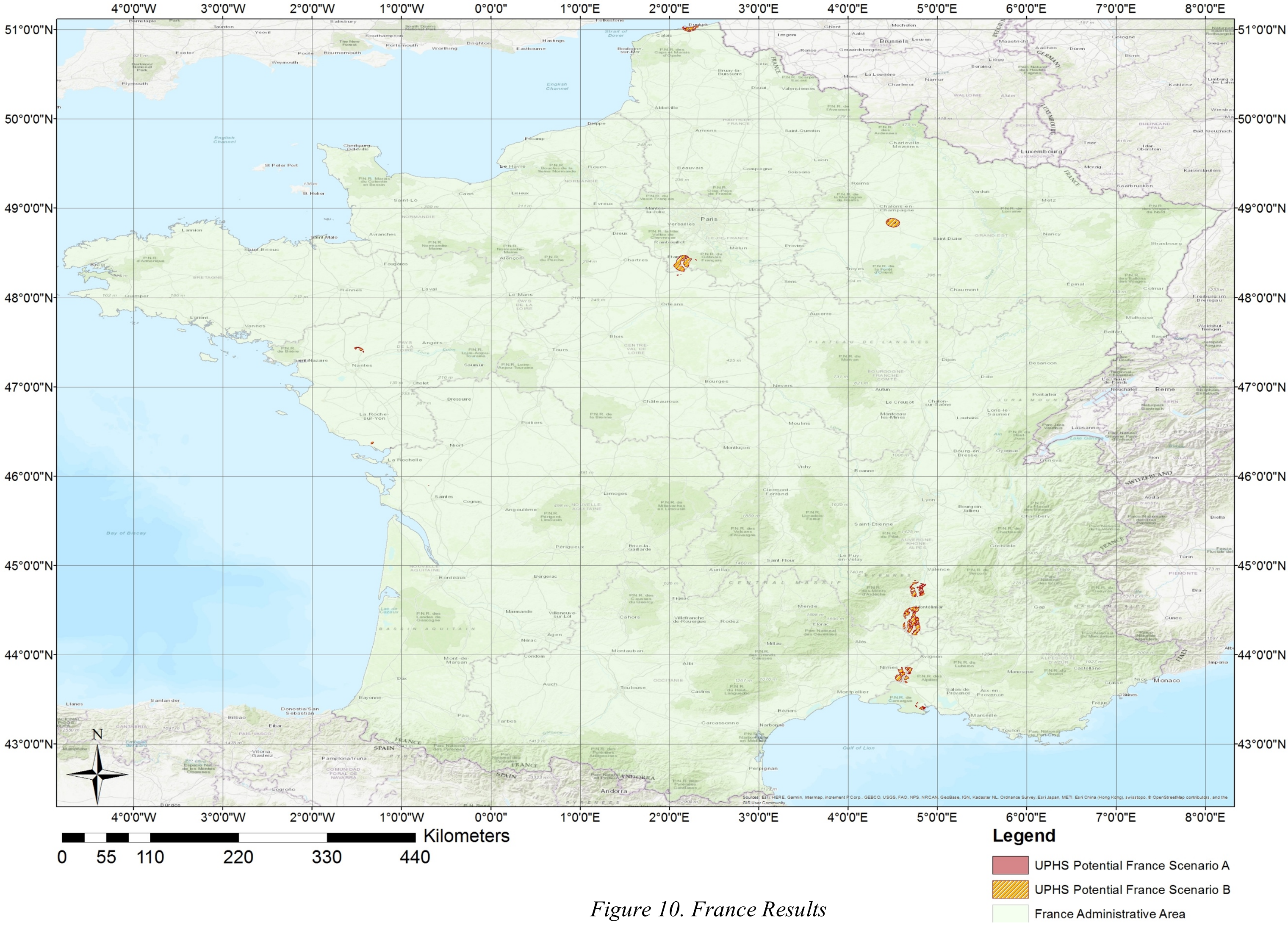

Figure 10. France Results

France is the largest of the western European nations and is found between the rough geographic coordinates 42° N & 51° N along latitudes, and between 5° W & 8° E longitudinally. This research takes only account of metropolitan France, situated on the European continent (excluding Corsica). All overseas territories are not included in this research. Within this scope, France is a country covering an area of 551 500 km2, that of which only 0,3 % corresponds to water coverage (CIA World Factbook B, 2018). With a longstanding position of having nuclear energy as a principal electricity source, France has a modest intermittent renewable energy generation (wind and solar) share of 13,1 % (PocketBook, 2017). Although relatively modest, this still corresponds to 12,1 GW of wind power installed capacity by end-2016 (REN21, 2017), with 1078 wind farms (thewindpower.net B, 2018) in operation, mostly situated in the North and North-East of the country. However, the GIS-based model reveals no UPHS realisable surface potential for France in scenario A. Scenario A's phase 1 "theoretical potential" showed one geographical zone of UPHS potential, which was under the minimum required size and thus disregarded. This absence of potential is due to the sheer size of the country, ensuing large distances between wind farms, leading to no -or only critically small- portions of land succeeding in meeting the distance criteria, and thus no potential multi-farm connectivity.

This changes in scenario B, where maximum distance constraints are loosened and search areas are thus expanded. In scenario B France shows 22 geographical zones of interest, resulting in 676,23 km^2 of UPHS realisable surface potential. These geographical zones are found scattered across the French landscape: Most notably, in the northern & north-eastern parts of the country, multiple zones of interest are depicted in the Île-de-France region near and around the town of Étampes, which lies on the outskirts of Paris, a second zone is found in the very northern tip of France, to the west of the city of Dunkirk in the Hauts-de-France region, while another zone is found in the Grand Est region by the town of Châlons-en-Champagne (see 1, 2 & 3, respectively, on figure 11).

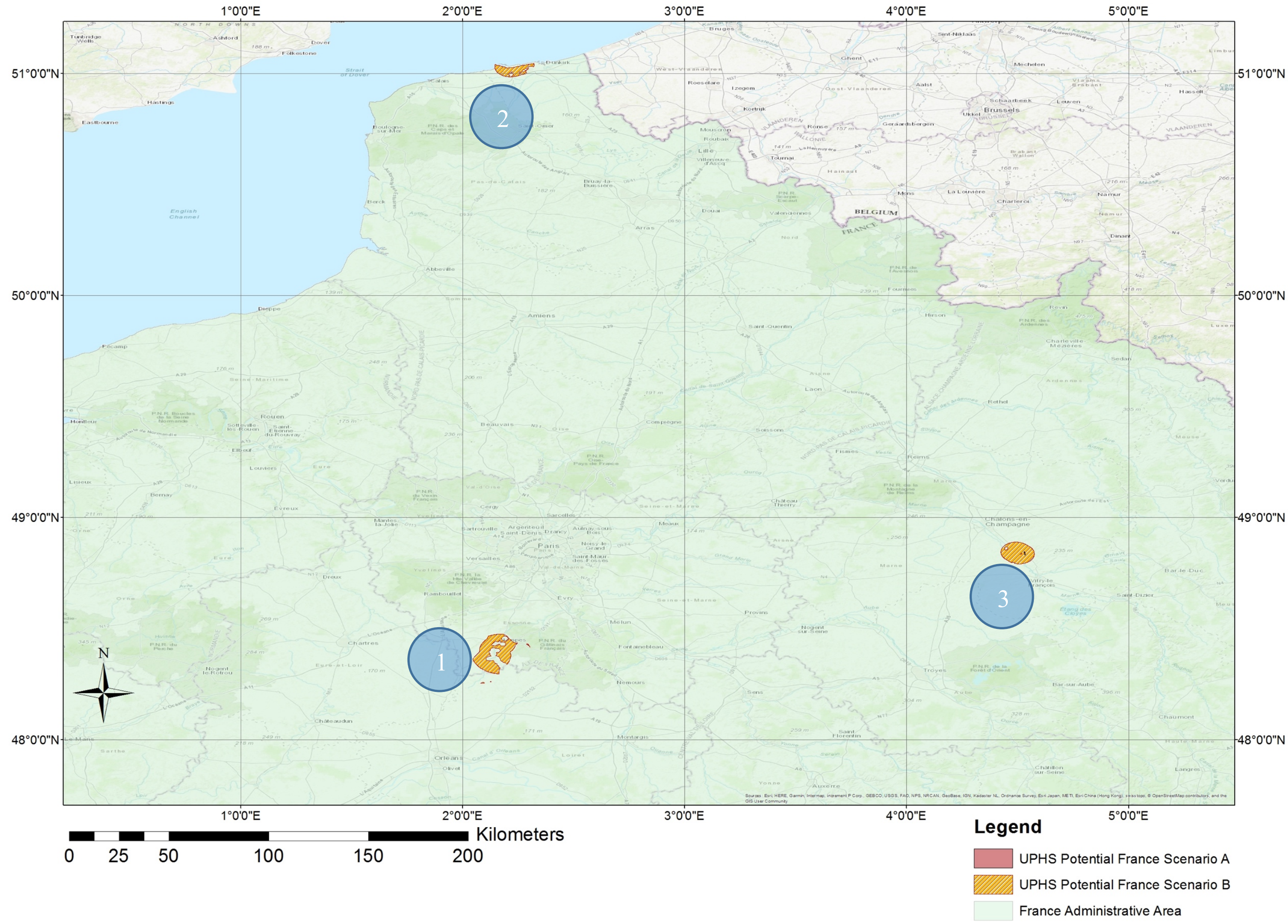

Figure 11. France - North Results

In the West, on the Atlantic coast and in the Bay of Biscay, a geographical zone of UPHS realisable surface potential is found near the city of Nantes, in the Pays-de-la-Loire region. Another is found by the commune of Saint-Denis-du Payré (see 1 & 2 on figure 12). Lastly, multiple geographical zones of interest are depicted in the Provence-Alpes-Côte-d'Azur (PACA) region of France, lining the banks of the Rhône river, around the town of Le Pouzin, the commune of Pierrelatte, around the town of Beaucaire, and a final smaller zone on the coast, by the town of Fos-sur-Mer (see 1, 2, 3 & 4, respectively, on figure 13). These zones find themselves caught between two of the largest cities in France: Marseille and Montpellier. This last ensemble of zones represents the biggest UPHS realisable surface potential in France.

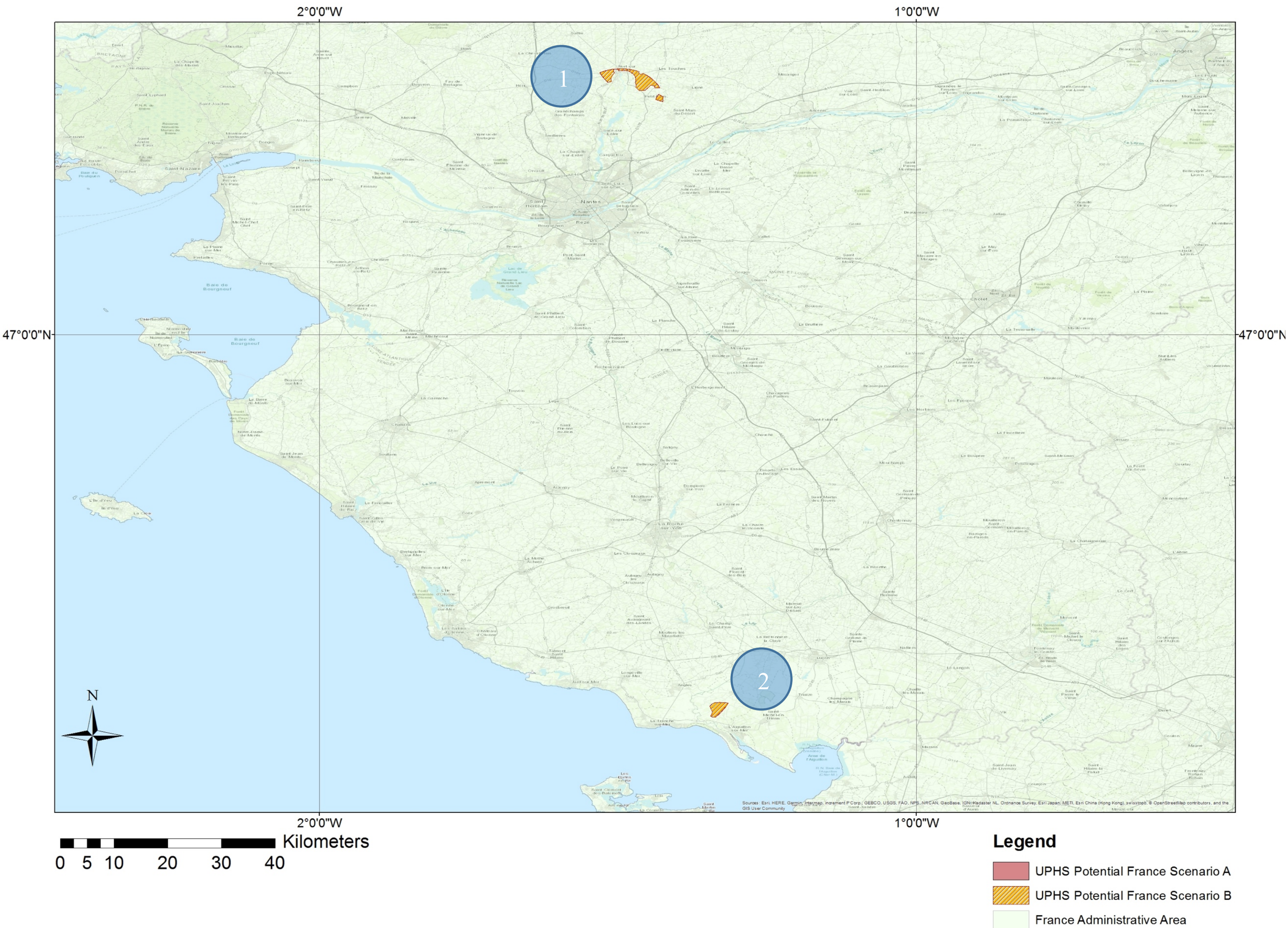

Figure 12. France - West Results

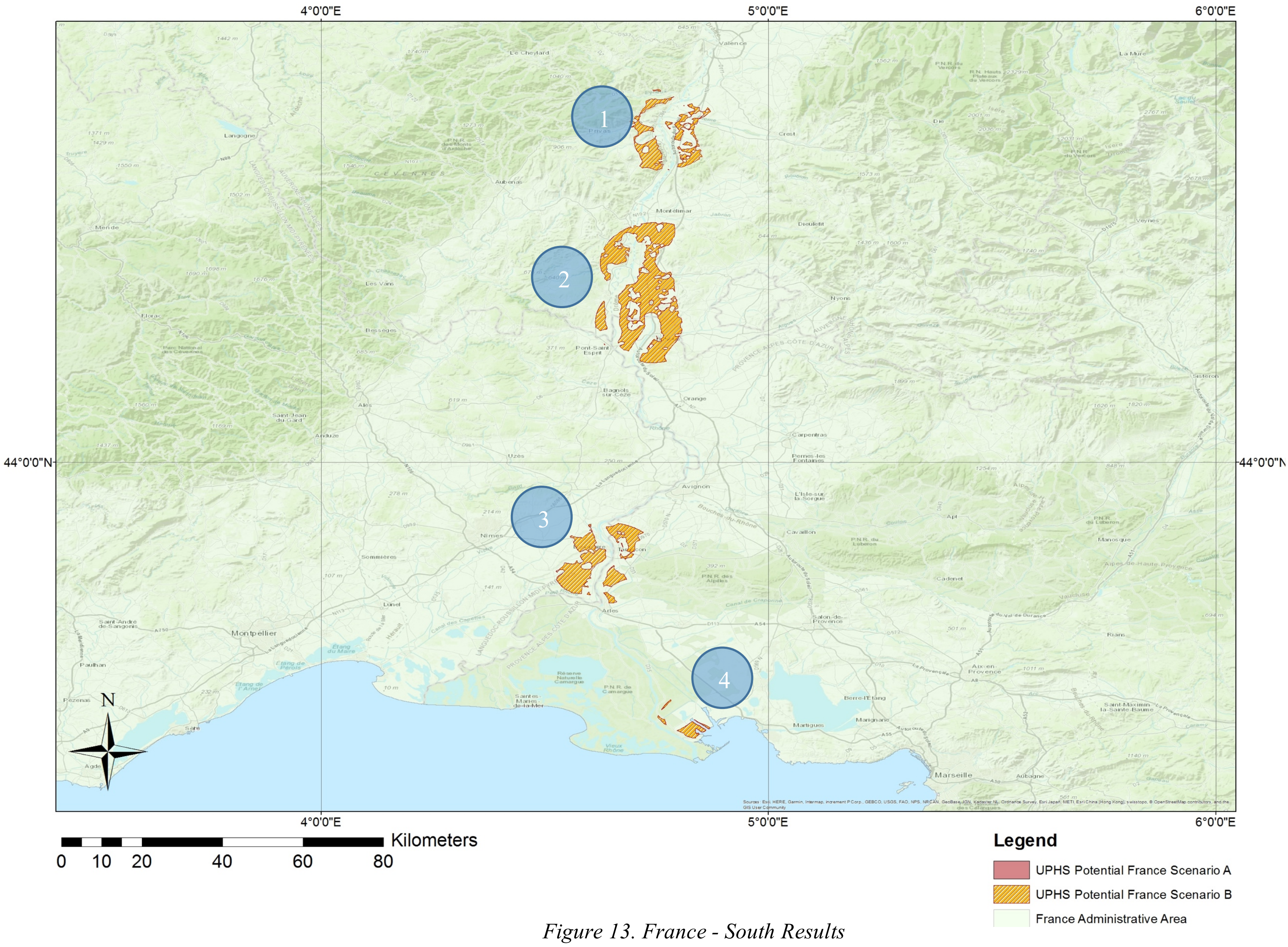

Figure 13. France - South Results

In the end, although France sees no UPHS realisable surface potential in the context of scenario A, less-stringent parameters brought by scenario B shed light on some potential, showing 22 geographical zones of interest that represent a total UPHS realisable surface potential of 676,23 km^2. Large in absolute terms, this surface coverage represents a feeble 0,1 % of France's total land area, putting it on the weaker side of the countries involved in this research. Nonetheless, UPHS potential is still existent in France, especially in the northern part of the country which is topographically flat, being part of the Northern European Plain (World Atlas, 2017).

III.3.3 Germany

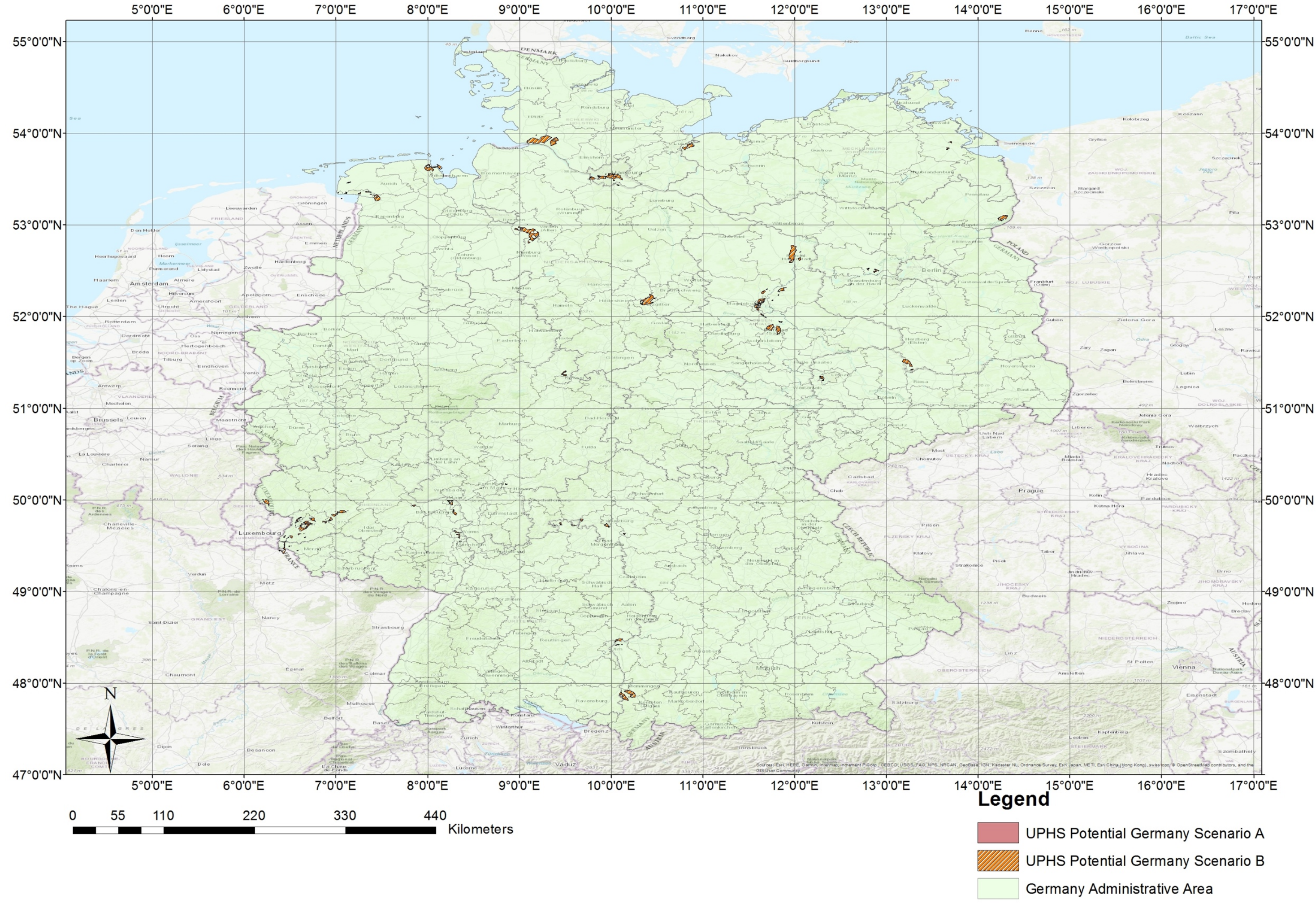

Figure 14. Germany Results

Germany is considered Europe's powerhouse and its energy needs have lead it to become a global leader in renewable energy. With a 41,4 % share of wind & solar power in its energy mix, Germany sits just behind Denmark in this study, regarding highest penetration of intermittent renewable energy. But given Germany's size, this share corresponds to a much larger installed capacity, which sits at 84 458 MW of combined wind & solar power (Pocketbook, 2017), giving Germany 3rd place worldwide regarding installed solar PV capacity (only behind China and Japan), and 3rd place as well regarding installed wind power capacity (Behind China and US) (REN21, 2017). This position is represented by Germany's large number of windfarms: 4 485 windfarms according to the latest statistics, with the vast majority of them being onshore. (thewindpower.net C, 2018). But even with this quantity of wind farms, the GIS-based model finds no UPHS realisable surface potential for Germany in scenario A. Like France, Germany falls victim to its size. Effectively, Germany is a European country with a surface area of 357 022 km^2, of which 2,3 % corresponds to water coverage, found centred around the geographic coordinates 51° N & 9° E (CIA World Factbook C, 2018). The large

number of wind farms cannot make up for the relative distances at which they are placed from one another, which surpass the scope of scenario A.
Scenario A did find three geographical zones at the theoretical potential stage (Phase 1), which were disregarded due to being under the cut-off threshold for minimum zone size (at least 0,36 km^2 is required to install a UPHS plant). Scenario B however, with its extended reach, finds 74 geographical zones of UPHS realisable surface potential, corresponding to 910,14 km^2 of surface area (see table 14 in Appendix A).

These areas are found throughout the country, but prevail importantly in the North of Germany (see figure 14), which is specifically an area of interest since it depicts the lowlands and expanses of generally flat lands of the country, corresponding to the North European Plain which extends from Poland to the northern parts of France (World Atlas, 2017).

In the North-West of the country, zones are found around the town of Leer, within distance of the Ems river. Zones are also prominent around the towns of Wilhelmshaven, Verden, Itzehoe and the city of Hamburg (see 1, 2, 3, 4 & 5, respectively, on figure 15).

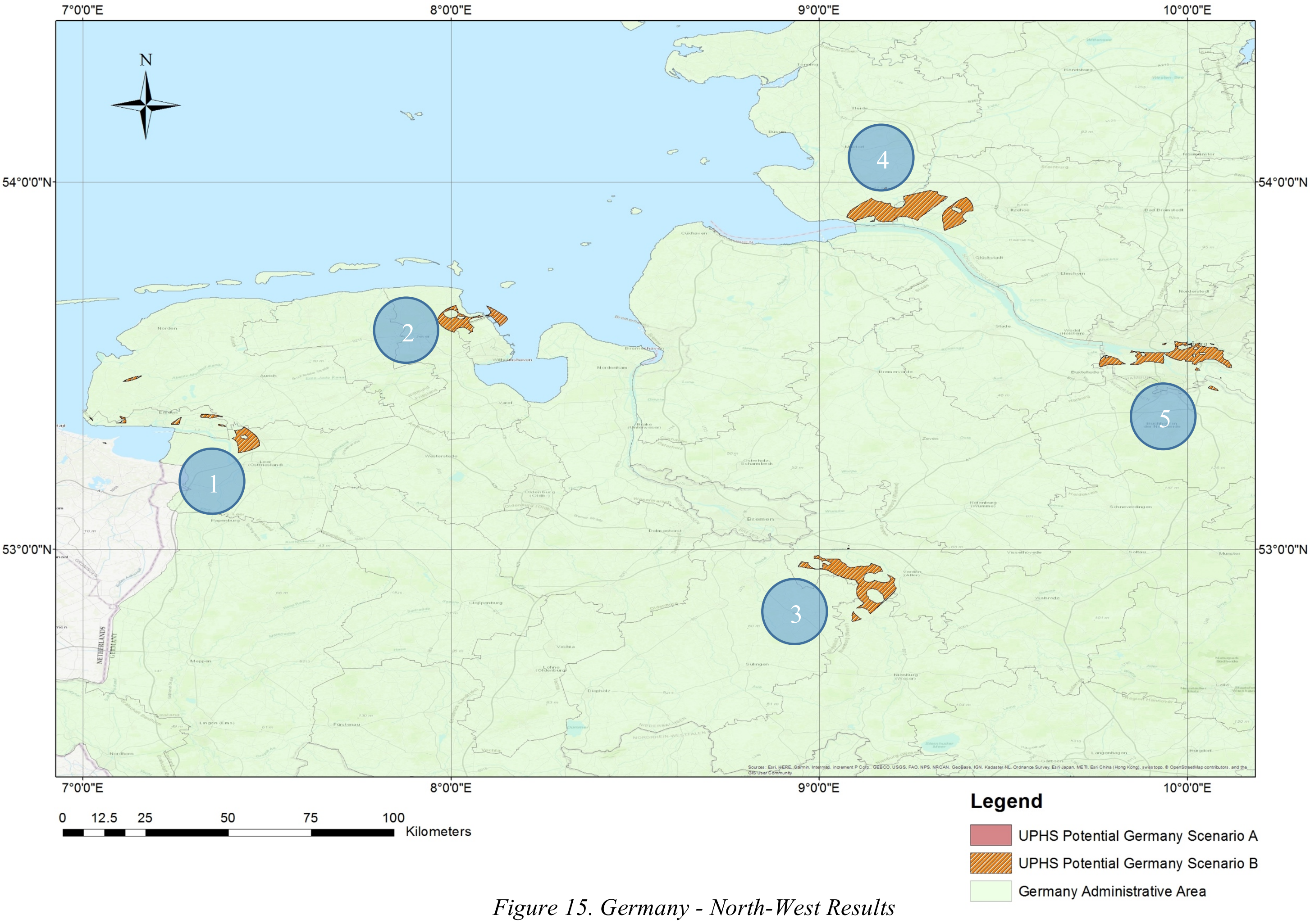

Figure 15. Germany - North-West Results

Going eastward, zones are found by the towns of Salzgitter, Lübeck, Magdeburg, Stendal and even at Germany’s eastern extremity, by its border with Poland, around the town of Schwedt/Oder (see 1, 2, 3, 4 & 5, respectively, on figure 16).

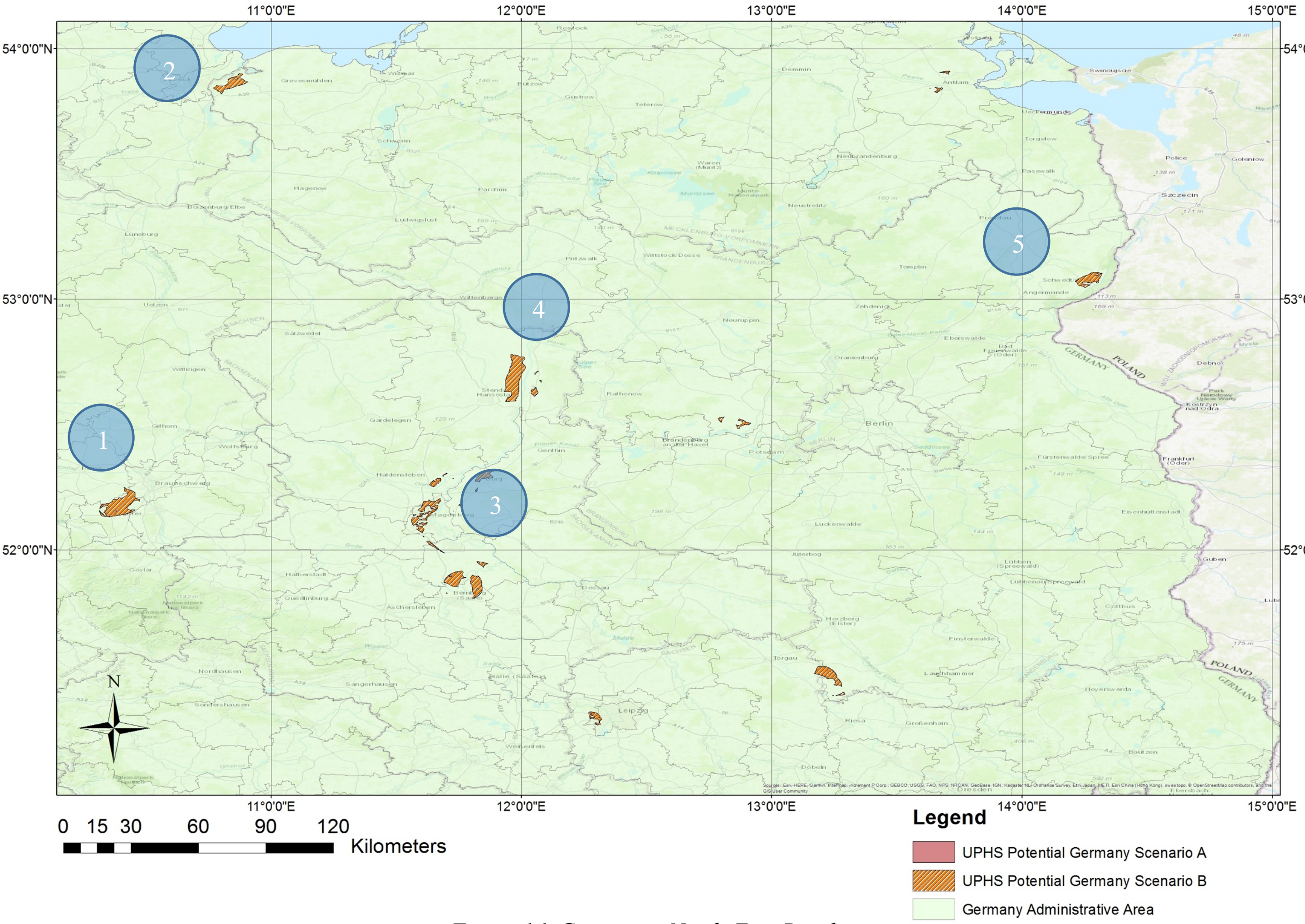

Figure 16. Germany - North-East Results

Other ensembles geographical zones of interest are pointed out to be on the south-western side of the country, relatively close to its border with Luxembourg, while staying close to the Moselle river, and between the towns of Mainz and Worms (see 1 & 2, respectively, on figure 17).

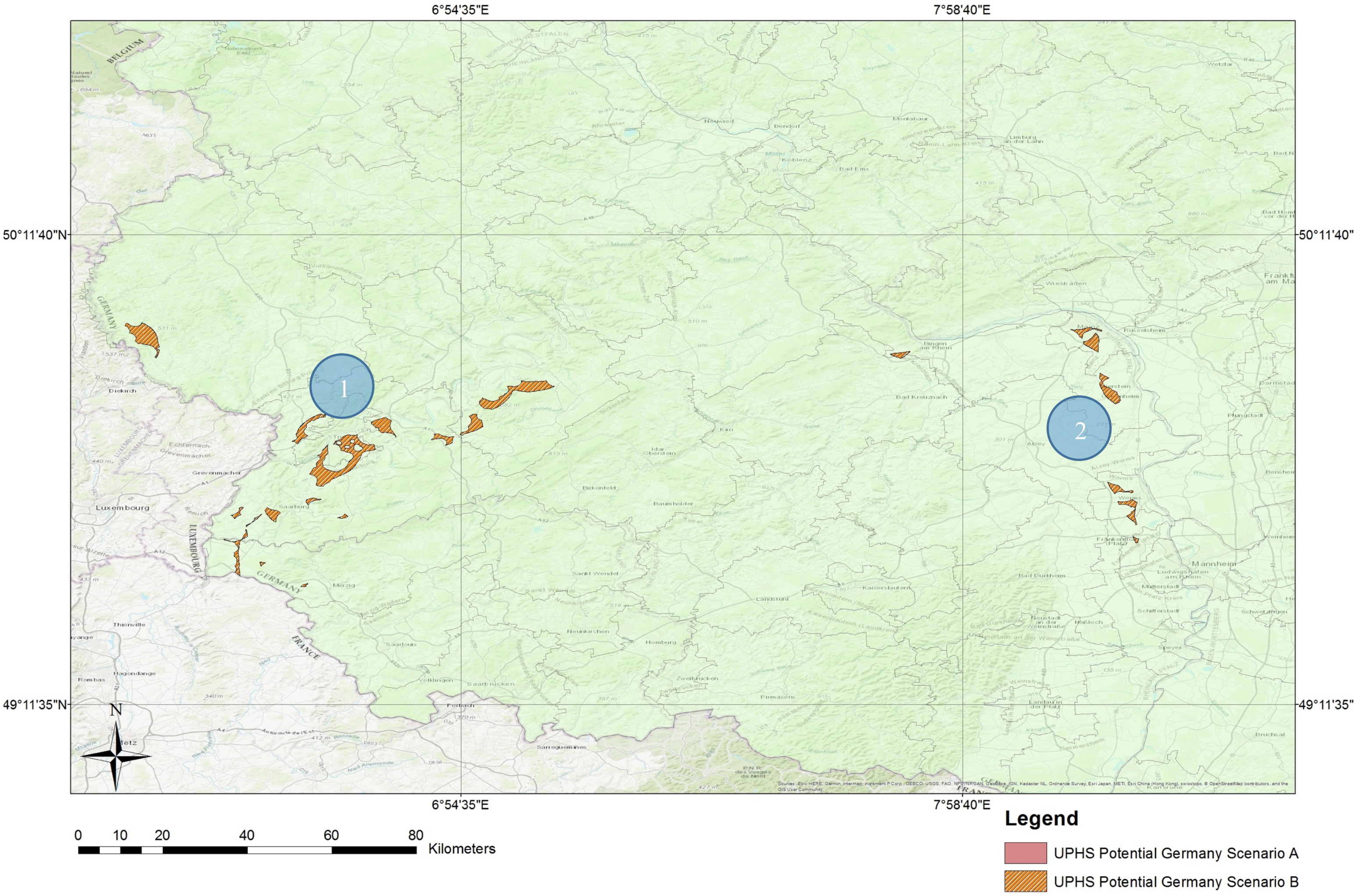

Figure 17. Germany - South-West Results

Another main ensemble of UPHS realisable surface potential is found in the southern portion of Germany, close to the Bavarian Alps, by the cities of Ulm and Memmingen (see 1 & 2, respectively, on figure 18). The geographical zones found here run close to the Danube river.

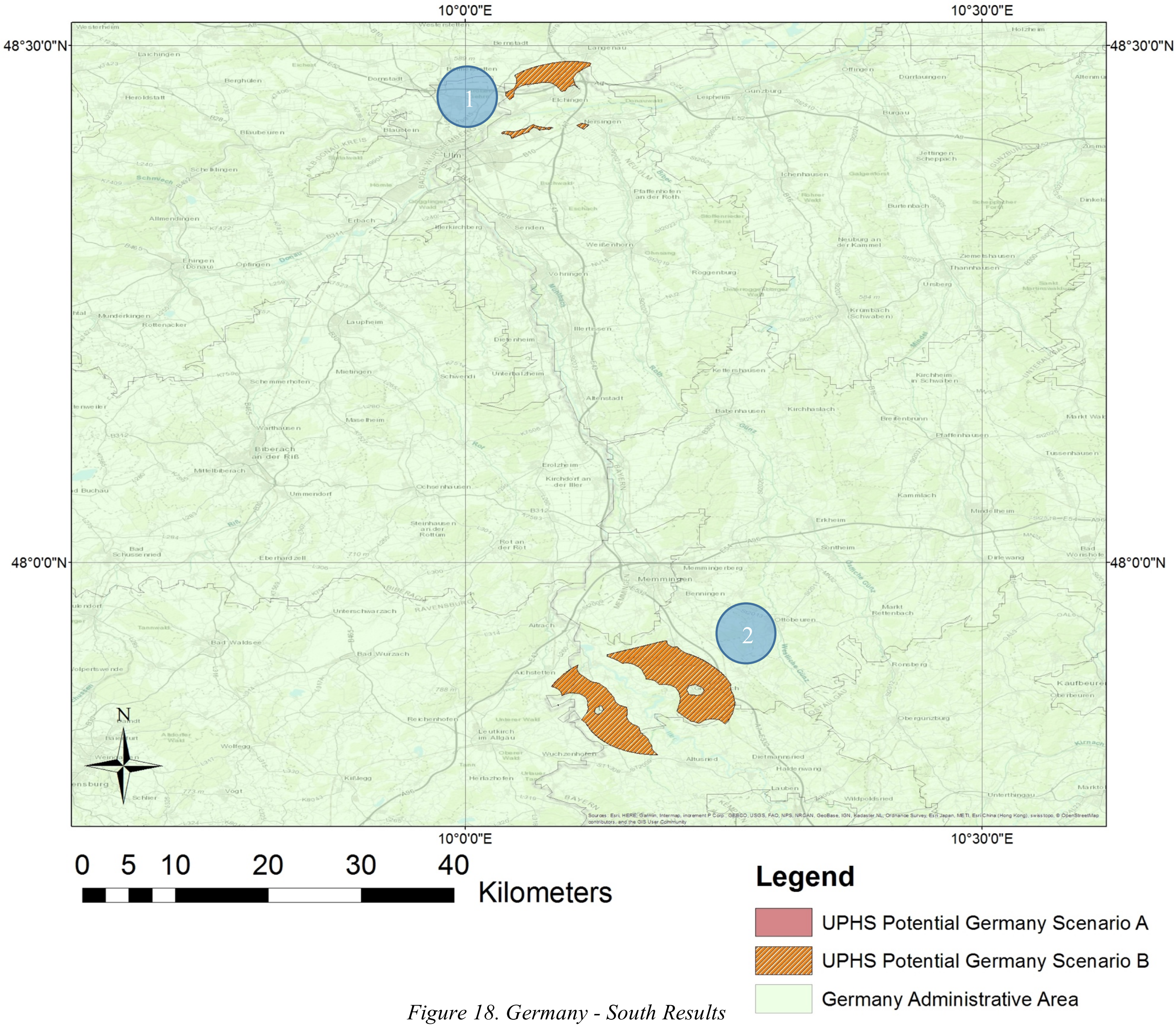

Figure 18. Germany - South Results

Overall, although Germany presents no results for scenario A, it presents itself as a good candidate for UPHS plants in terms of scenario B thanks to its large number of wind farms, numerous rivers and considerable amount of available flat land topography. This gives it 74 geographical zones of interest in scenario B where all surface criteria are met in order to have a UPHS plant. These zones of interest cover a total area of 910,14 km^2, representing 0,3 % of Germany's total land area (see table 14 in Appendix A).

III.3.4. Ireland

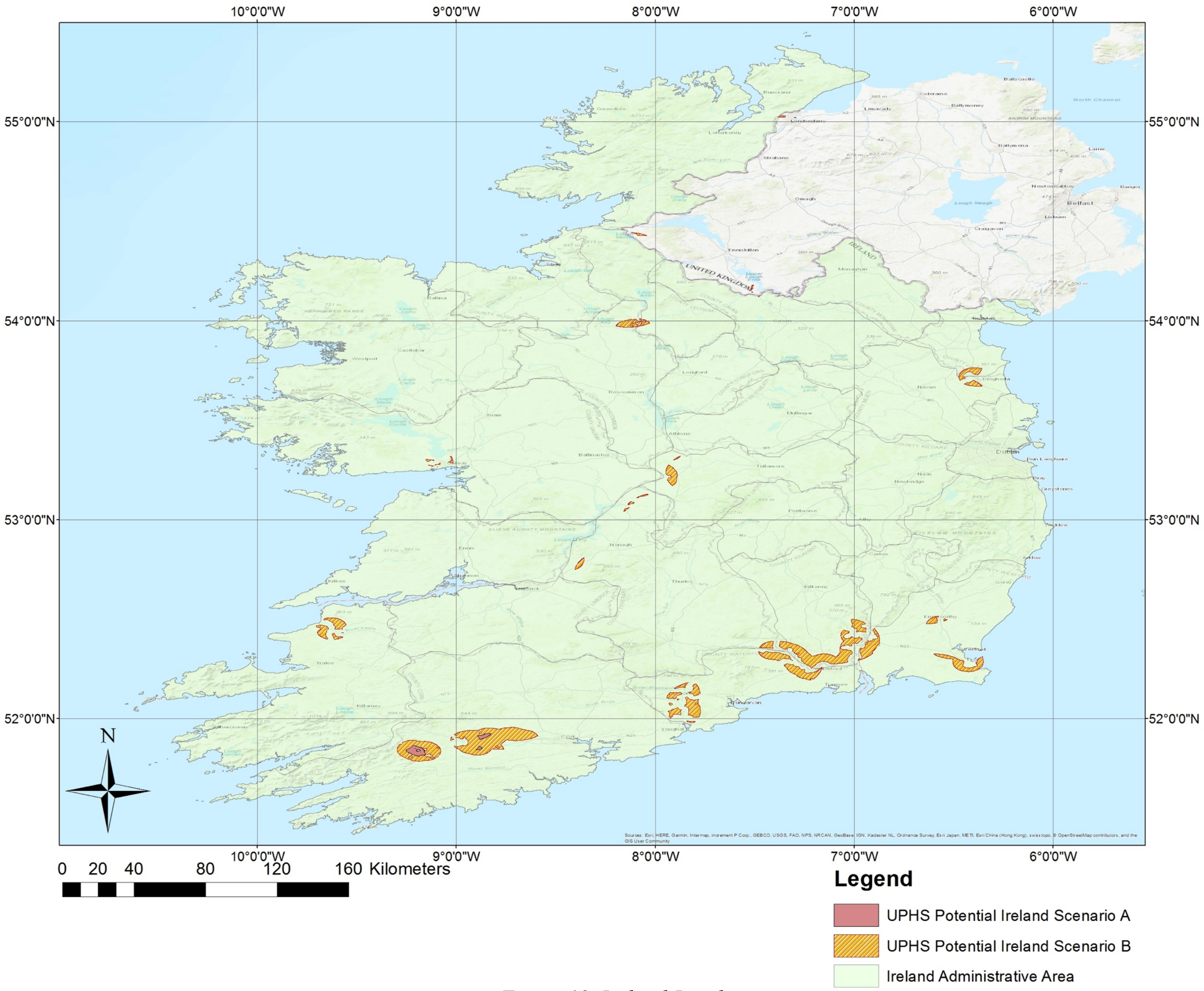

Figure 19. Ireland Results

Ireland is a country in Western Europe which occupies over 80 % of the island of Ireland, and is situated around geographic coordinates 53° N & 8° W (CIA World Factbook D, 2018). Ireland is taken account of in this study due to its important share of combined wind & solar generation, which, with 2442 MW of installed capacity, makes up 25,6 % of their electricity mix. This is almost all attributed to wind power, with only 2 MW of installed solar capacity (PocketBook, 2017). Ireland counts around 200 wind farms in operation on its territory (thewindpower.net D, 2018), which comprises an area of 70 273 km^2, of which 2 % corresponds to water bodies (CIA World Factbook D, 2018). Its global terrain consists of flat land and rolling hills, surrounded by low mountains. These conditions come together to give Ireland UPHS realisable surface potential.

Results of scenario A show three geographical zones of UPHS realisable surface potential in Ireland, located all in the southwestern portion of the country (see figure 20 and table 14 in Appendix A). Together they give Ireland a total of 34,52 km2 of realisable surface potential.

The modified search parameters of scenario B allow a considerable increase of results. Ireland in scenario B presents 39 geographical zones of interest that total 2699 km^2 of UPHS realisable surface potential. Significant zones are found in the southern portion of the country:
In the South West, to the west of the city of Cork, scenario A as well as scenario B find geographic zones of interest along the Lee river, around the town of Tir Na Spideoga (see 1 on figure 20), and between the towns of Coachford and Tooms (see 2 on figure 20).

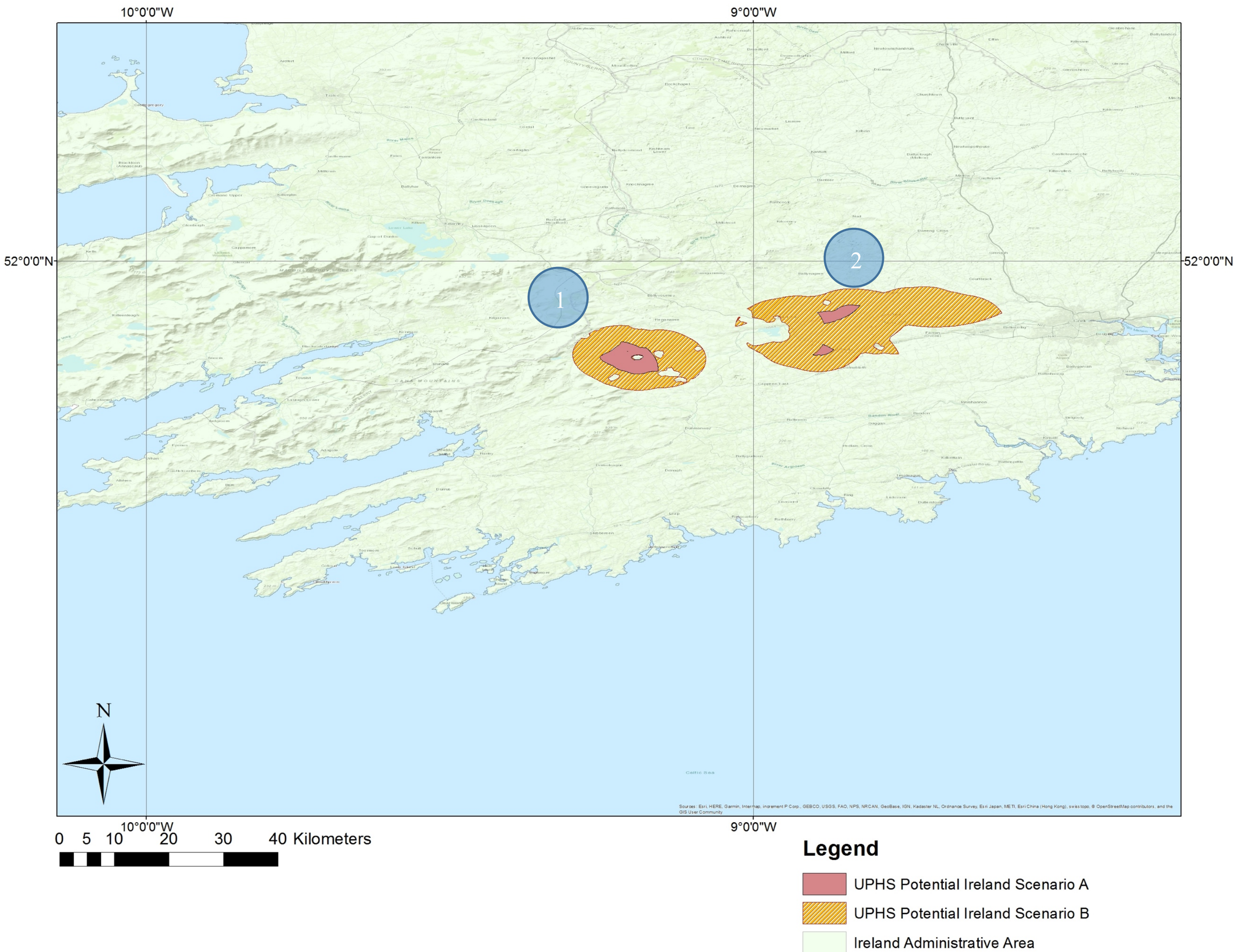

Figure 20. Ireland – South-West Results

Towards the South East, scenario B finds geographical zones of interest between the towns of Cappoquin and Youghal (1) (along the Blackwater river), and an ensemble of areas triangulated between the towns of New Ross, Waterford and Carrick-on-Suir, that run along the banks of the River Barrow and Suir river (2). More zones are found between the towns of Tagoat and Murntown (3), and around the town of The Still (4) (see figure 21).

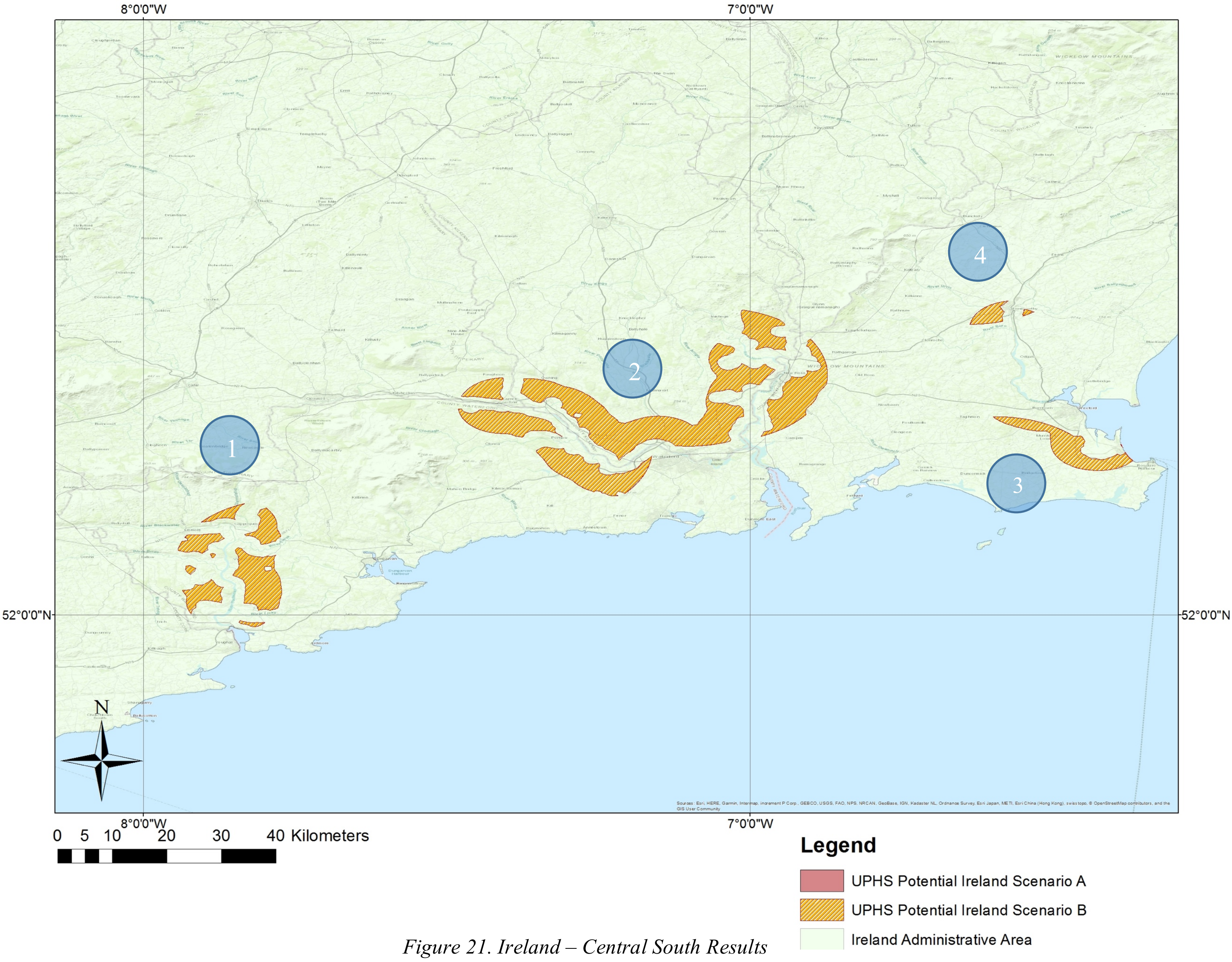

Figure 21. Ireland – Central South Results

To the East, two zones are found around the town of Drogheda, following the course of the Boyne river (see 1 on figure 22).

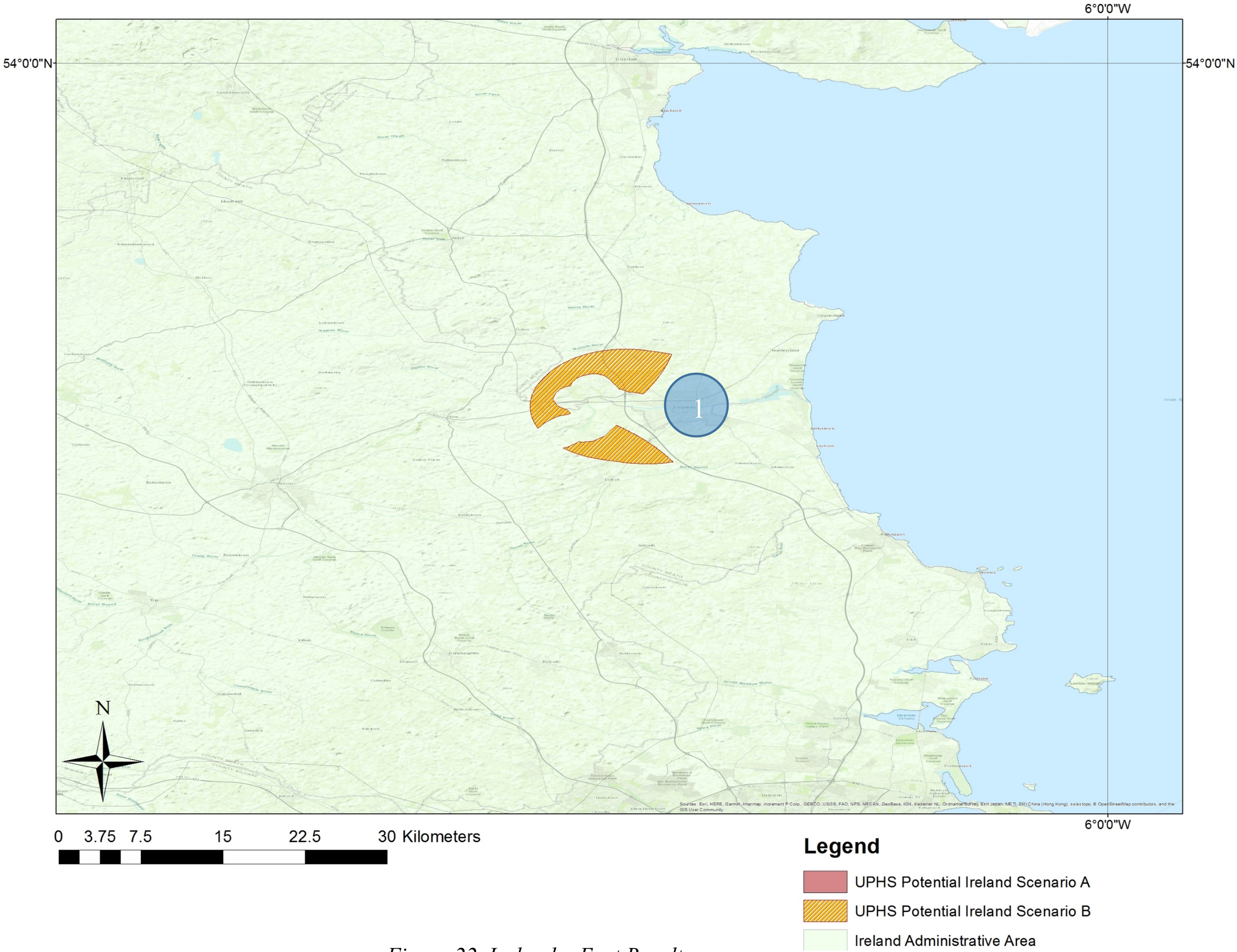

Figure 22. Ireland – East Results

In the Northern part of Ireland, scenario B finds a zone of interest triangulated between the towns of Cootehall, Carrick-on-Shannon and Leitrim which are all surrounding the Shannon river (see 1 on figure 23).

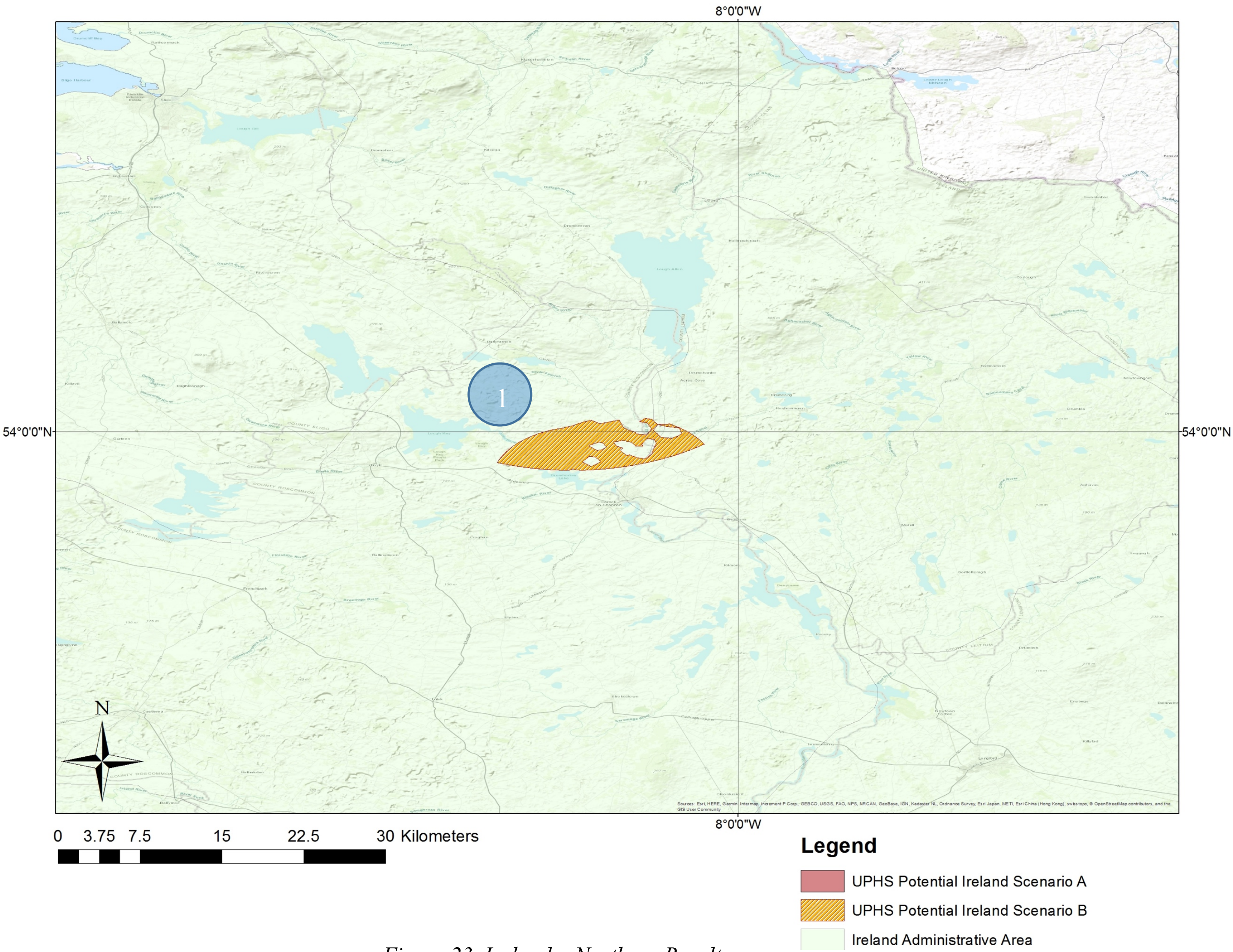

Figure 23. Ireland – Northern Results

On the western coast of Ireland multiple zones appear as ensembles around the town of Ballyduff (see 1 on figure 24) and the city of Galway (see 2 on figure 24).

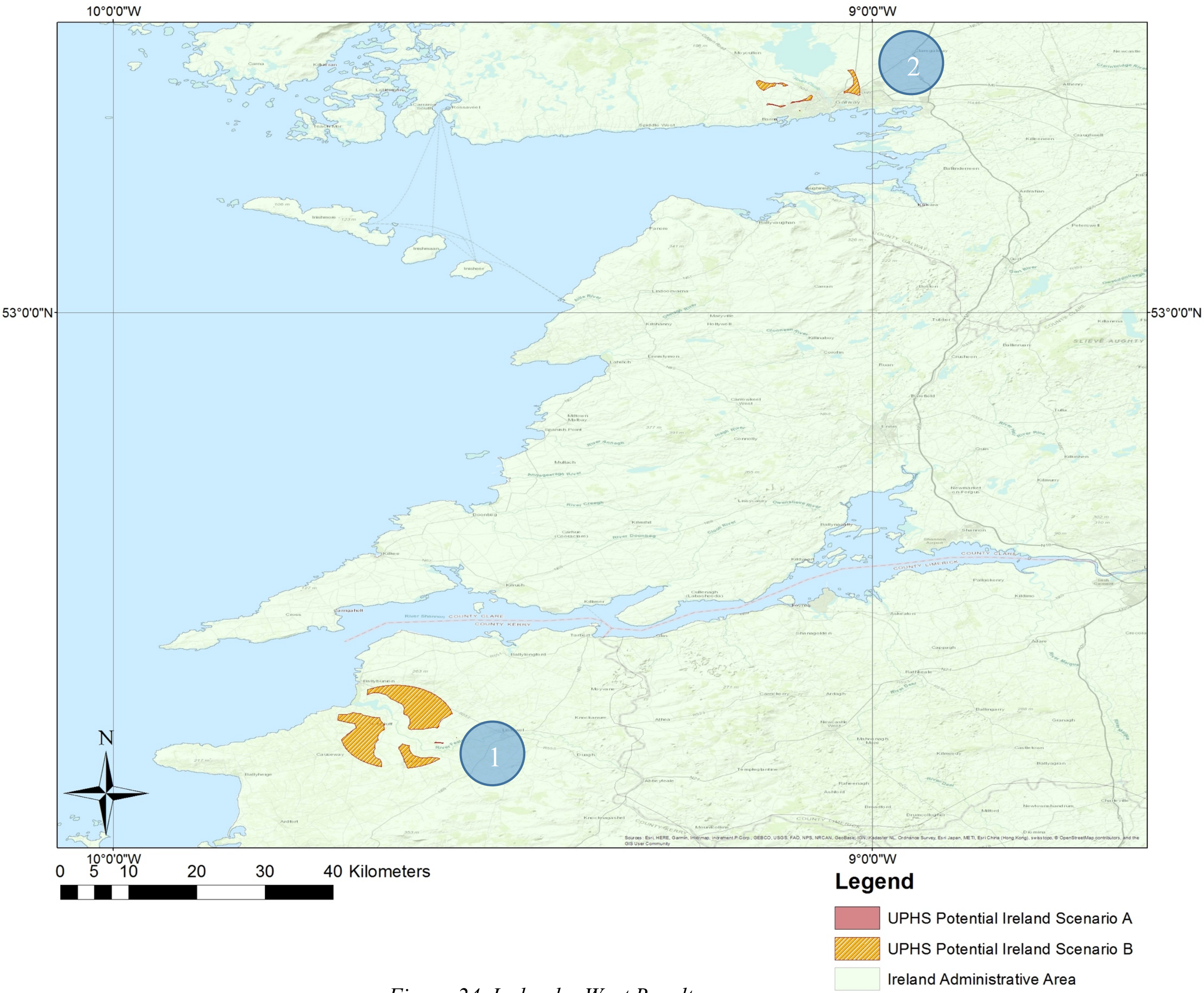

Figure 24. Ireland – West Results

Lastly, multiple geographical zones of interest depicting UPHS realisable surface potential are found in the central part of Ireland, around the towns of Ballinahinch (see 1 on figure 25), between the towns of Carrigahorig & Fivealley (see 2 on figure 25) and by the town of Cloghan (see 3 on figure 25).

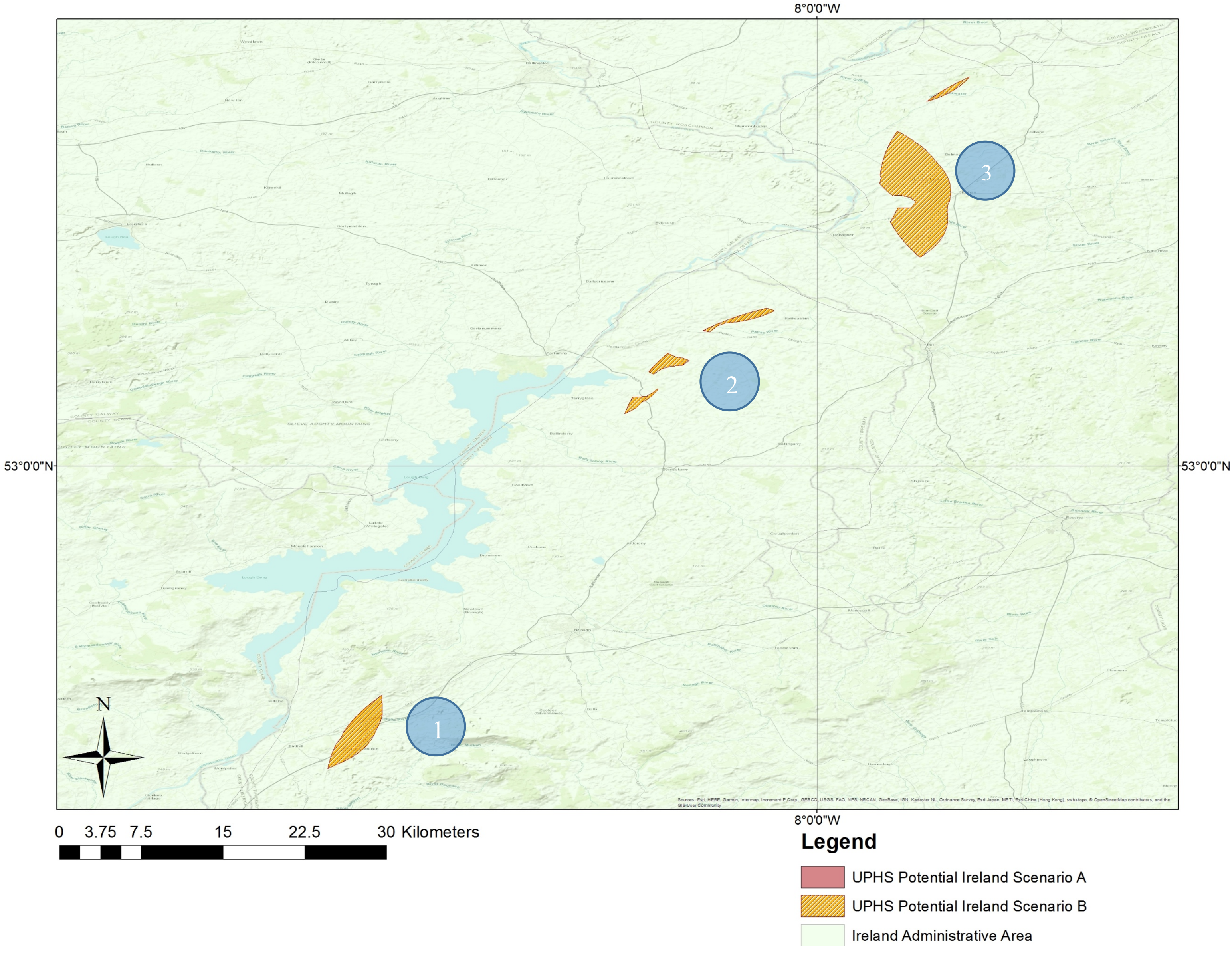

Figure 25. Ireland – Central Results

With 39 zones of geographical interest and 2699 km^2 total area coverage in scenario B, Ireland presents sufficient UPHS realisable surface potential to be marked as a good candidate country. With scenario A resulting in only 3 found zones, it is clear that Ireland, which covers 70 273 km^2, has its wind farms scattered around the country at distances that often exceed 5 km. Pushing this distance to 10 km reveals Ireland's potential for UPHS plants.

III.3.5. The Netherlands

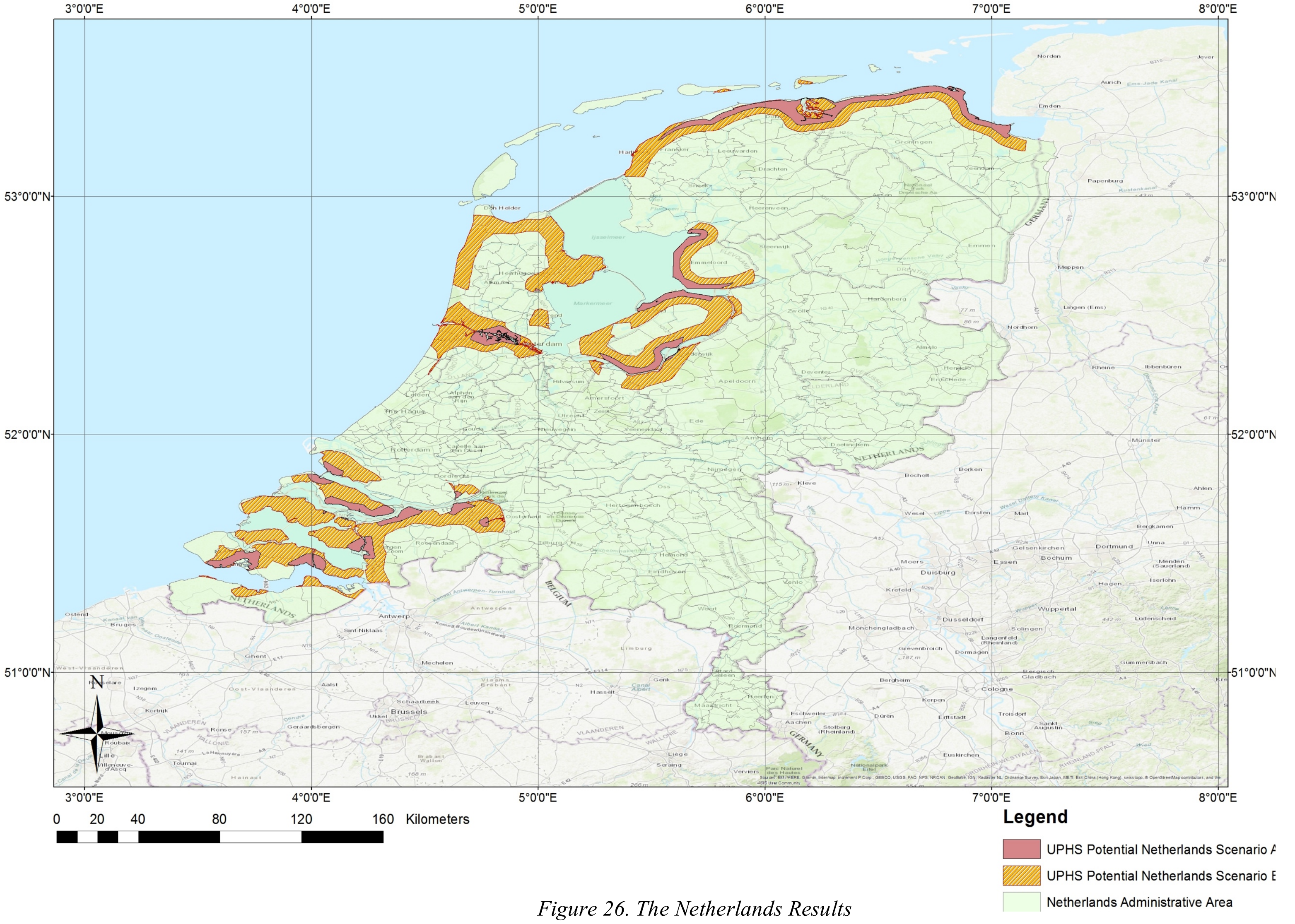

Figure 26. The Netherlands Results

The Netherlands is a notoriously flat land in western Europe, hence the French name “Pays-Bas”, translating to “low lands”. It is in this country’s scope that the FLES (Flat Land Energy Storage) project was initiated, due to the ever-growing intermittent renewable electricity generation in the country and its lack of large-scale energy storage, specifically of the commercially mature pumped hydropower storage technology because of its weak topographic variation (Huynen J., Schalij R. & Arts T., 2012). On the other hand, this makes the Netherlands ideal for UPHS plants. Moreover, the Netherlands, a country of 41 543 km^2 situated around geographical coordinates 52°30 N & 5°45 E, has a high level of water penetration, with 18,4 % of the country’s surface being occupied by water (CIA World Factbook E, 2018). The combination of these conditions has positive consequences that are observed in the GIS-based model results, for both scenario A and scenario B.

In scenario A, the Netherlands already displays significant UPHS realisable surface potential with 12 geographical zones of interest totalling 1014,26 km^2. Scenario B extends this UPHS realisable surface potential to 4862,61 km^2, grouped into 9 larger zones of interest (relative to scenario A).

In both scenarios, the zones of interest are found to be most prominent in the regions of Zeeland, Noord Holland, Flevoland and Friesland. These regions are those that present the most part of the Netherlands' 527 wind farms (thewindpower.net E, 2018). Smaller zones of interest extend into regions of Noord Brabant, Zuid Holland and Groningen.

In the Zeeland region, geographical zones of interest are found as large ensembles scattered on each of the region's peninsulas (see 1, 2 & 3 on figure 27). They also extend into parts of the Noord Brabant region, up to the city of Breda (see 4 on figure 27), and into Zuid Holland, to the southwest of Rotterdam (see 5 on figure 27). The effects of scenario B's less stringent constraints can be clearly observed, as scenario B can be seen connecting geographical zones of interest depicted by scenario A.

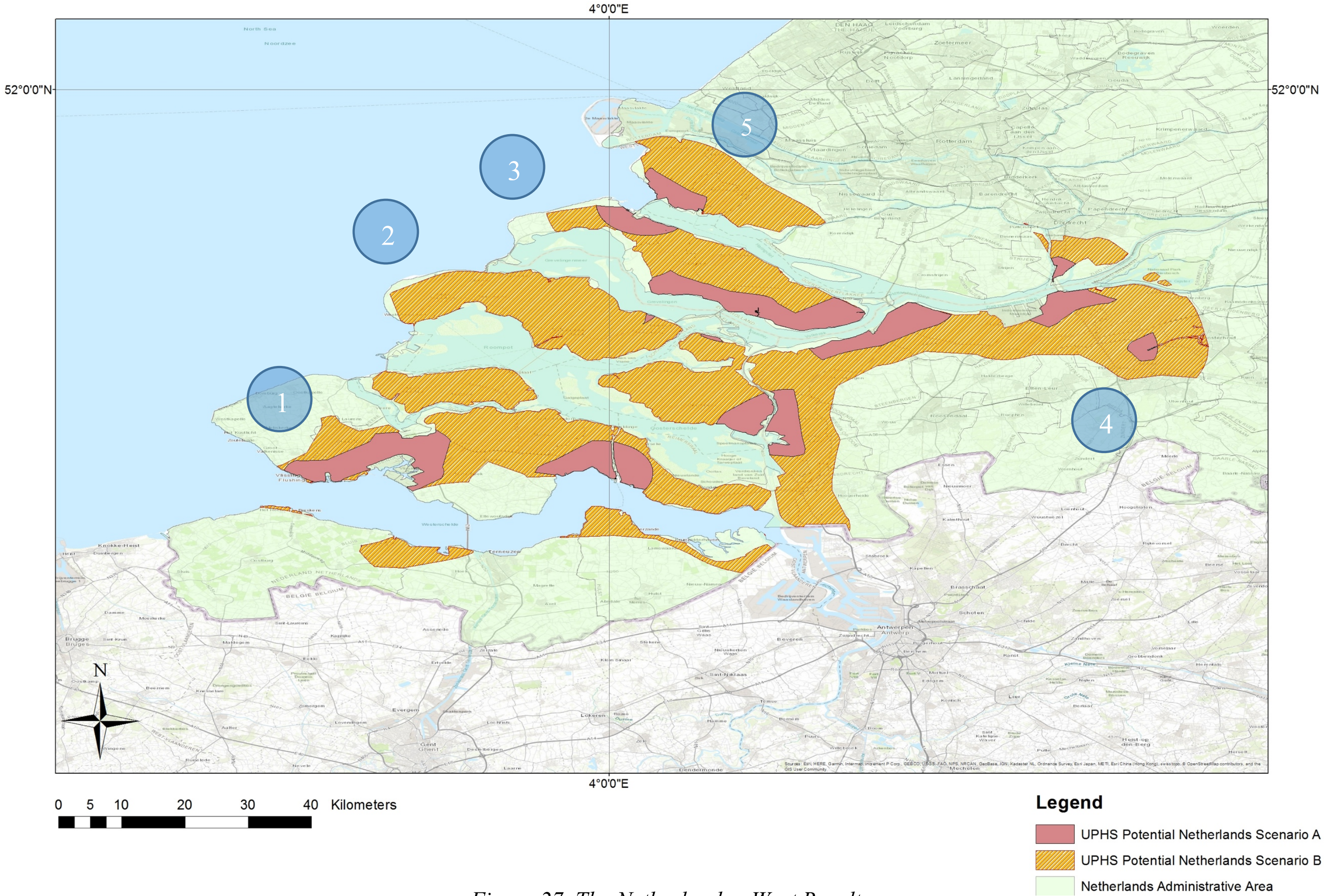

Figure 27. The Netherlands - West Results

Moving progressively to the North, UPHS realisable surface potential is found between IJmuiden and Amsterdam in North Holland (see 1 on figure 28), as well as a coastal stretch between Alkmaar and Den Helder, continuing along the IJsselmeer coast to join the town of Hoorn (see 2 on figure 28). Zones of interest presented in the region of Flevoland are found along the IJsselmeer and Markemeer coasts, as well around the town of Almere, continuing along the Gooimeer and Veluwemeer coasts (see 3 on figure 28). The rest of Flevoland's UPHS realisable surface potential is found back on the coast of the IJsselmeer, stretching from the town of Ens to the town of Rutten (see 4 on figure 28). To the south of Flevoland, right across

the Veluwemeer, a small portion of the region of Gelderland is marked as a geographical zone of interest, between the towns of Nijkerk and Elburg (see 5 on figure 28).
Lastly, the very northern portions of the regions of Friesland and Groningen display a long coastal stretch of UPHS realisable surface potential, depicted by an ensemble of geographical zones of interest extending from the town of Zurich to the town of Termunterzijl, almost at the Netherlands' border with Germany (see 6 on figure 28). Two zones also appear on the islands of Ameland and Schiermonnikoog (see 7 & 8 on figure 28).

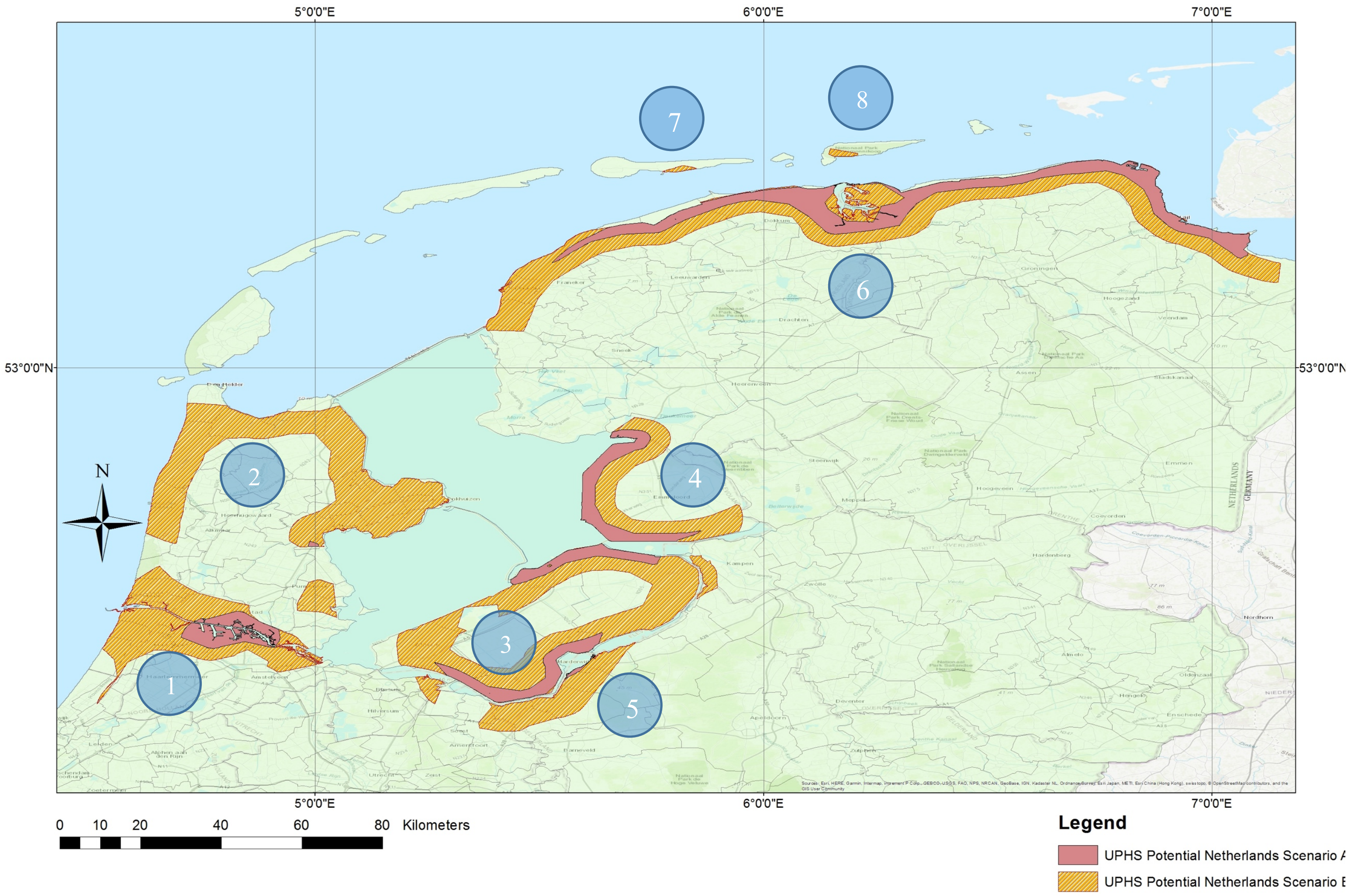

Figure 28. The Netherlands - North Results

Overall, the Netherlands shows substantial results for both scenarios A and B, concentrated along its coastlines and major waterways. With 1014,26 km^2, scenario A projects UPHS realisable surface potential across 3 % of the Netherlands' land, while scenario B results with 4862,61 km^2, which 14,3 % of the country's total land area (see table 14 in Appendix A).

III.3.6. Portugal

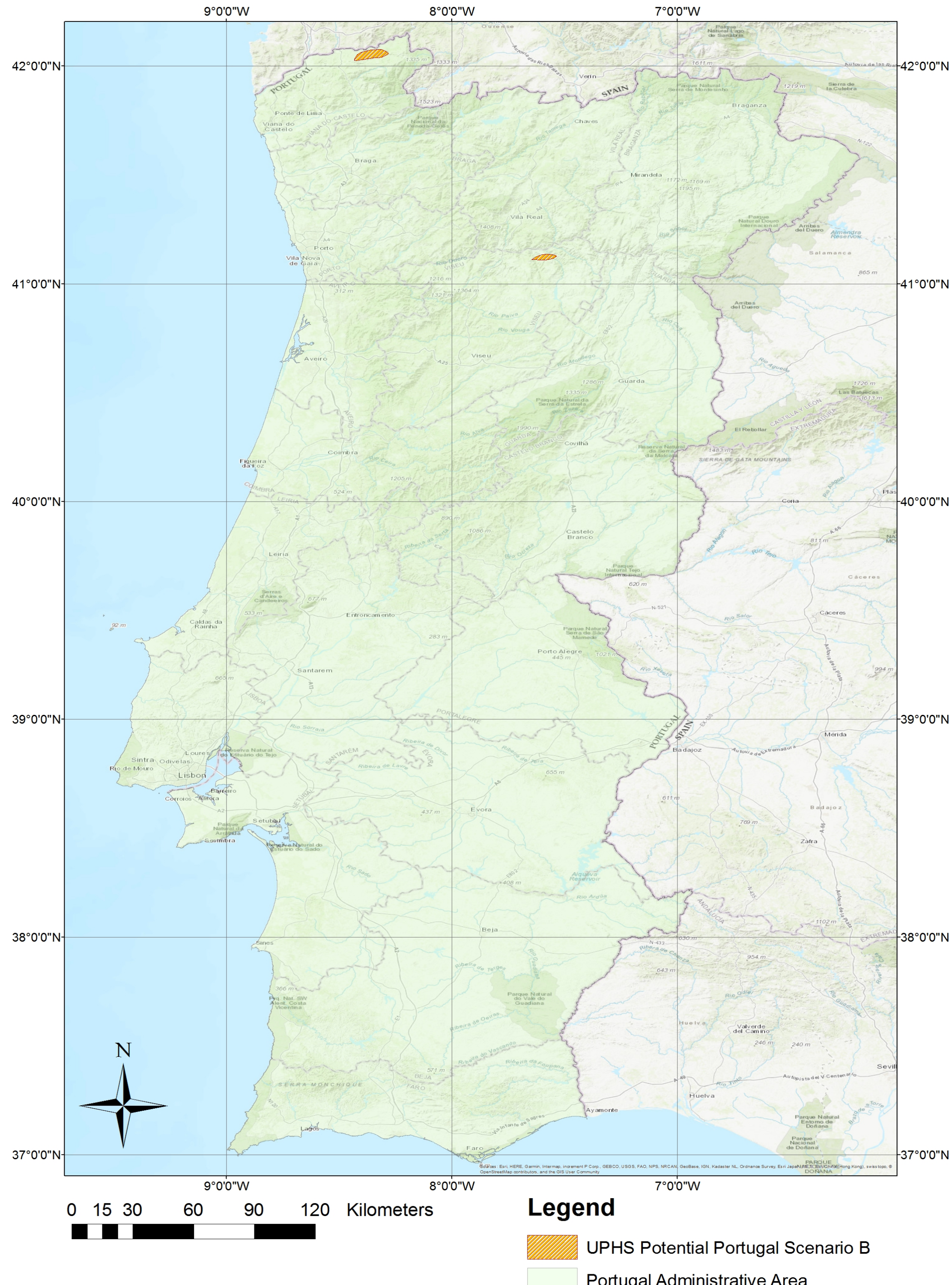

Figure 29. Portugal Results

Portugal is at the southwestern tip of Europe, centred around the geographic coordinates 39°30 N & 8° W. Bordering western Spain and the Atlantic Ocean, Portugal has a total land area of 92,090 km^2, of which only 0,7 % corresponds to water area (CIA World Factbook F, 2018).

However, Portugal is in this study since it has the 4th highest share of combined wind & solar power in its energy mix, with 27,4 %. Most of this share is allocated to wind power (4,94 GW of installed capacity of wind power versus 0,45 GW installed capacity for solar power) (PocketBook Energy, 2017). This capacity is represented by Portugal's 251 wind farms, found principally in the northern portion of the country (thewindpower.net F, 2018). The northern region happens to also be a relatively rugged and mountainous region, and the consequences of this geographical and topographical setting is shown by the GIS-based model results. Scenario A finds no UPHS realisable surface potential in Portugal due to a multitude of factors, such as scattered wind farms localised on mountainous terrain, lack of adequate water supply, and simply strong topography. Even scenario B, with its less-demanding criteria, only finds two zones of geographical interest. The first is situated in the North of the country, found around the town of Trogal, close to Portugal's Spanish border, with its water proximity factor being assured by the Minho river (see 1 on figure 30), and the second found between the towns of Armamar and Chavaes, along the Douro river (see 2 on figure 30). These two zones combined make up a UPHS realisable surface potential of 61,12 km^2, relatively small compared to other countries.

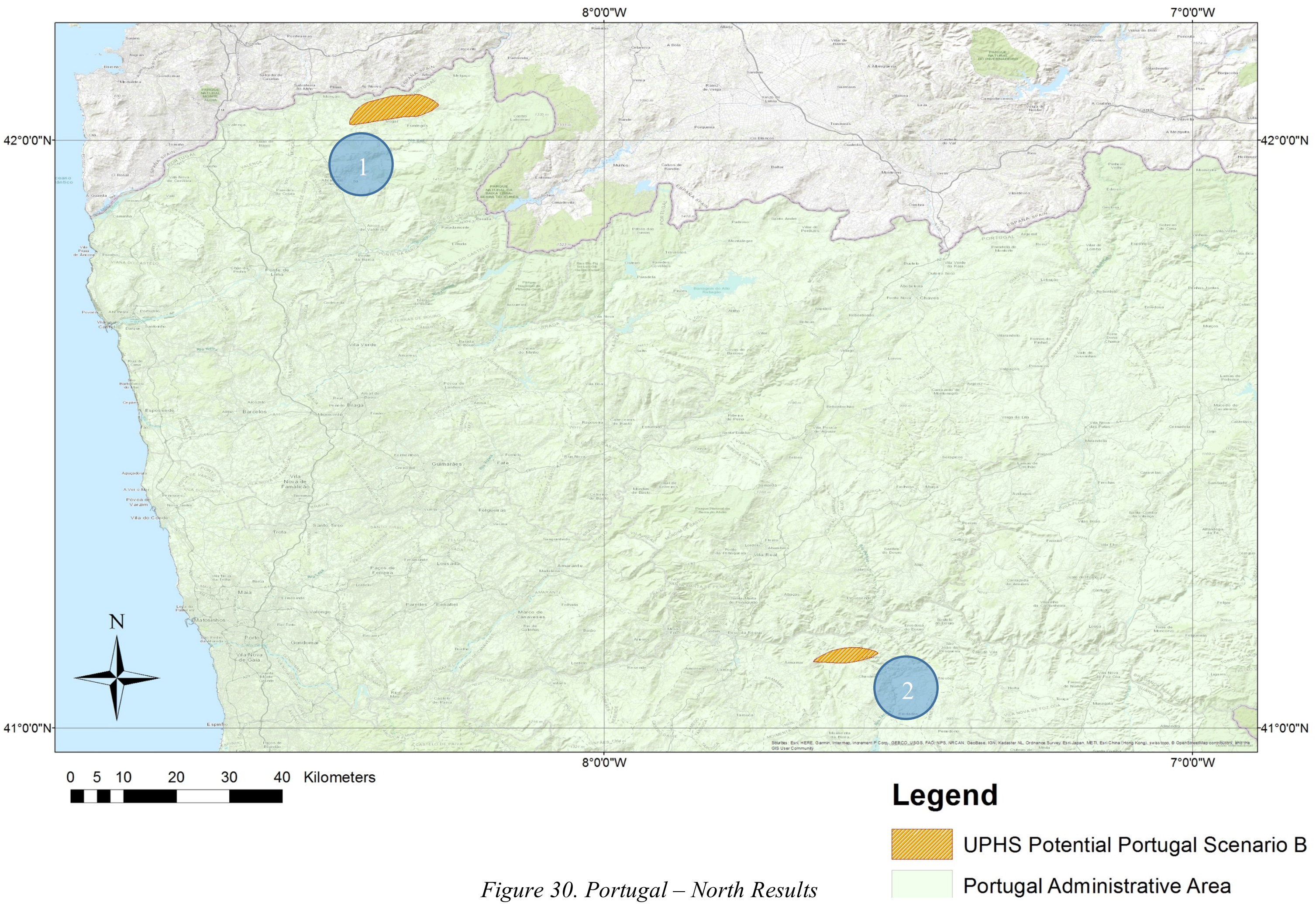

Figure 30. Portugal – North Results

Although having substantial amounts of wind power, Portugal gives relatively poor results regarding UPHS realisable surface potential. With no results in scenario A and 61,12 km2 depicted by two zones in scenario B, Portugal is outshined by the other countries in this study. Nonetheless, it presents a small UPHS realisable surface potential, which can be investigated further for its energy storage needs.

III.3.7. Romania

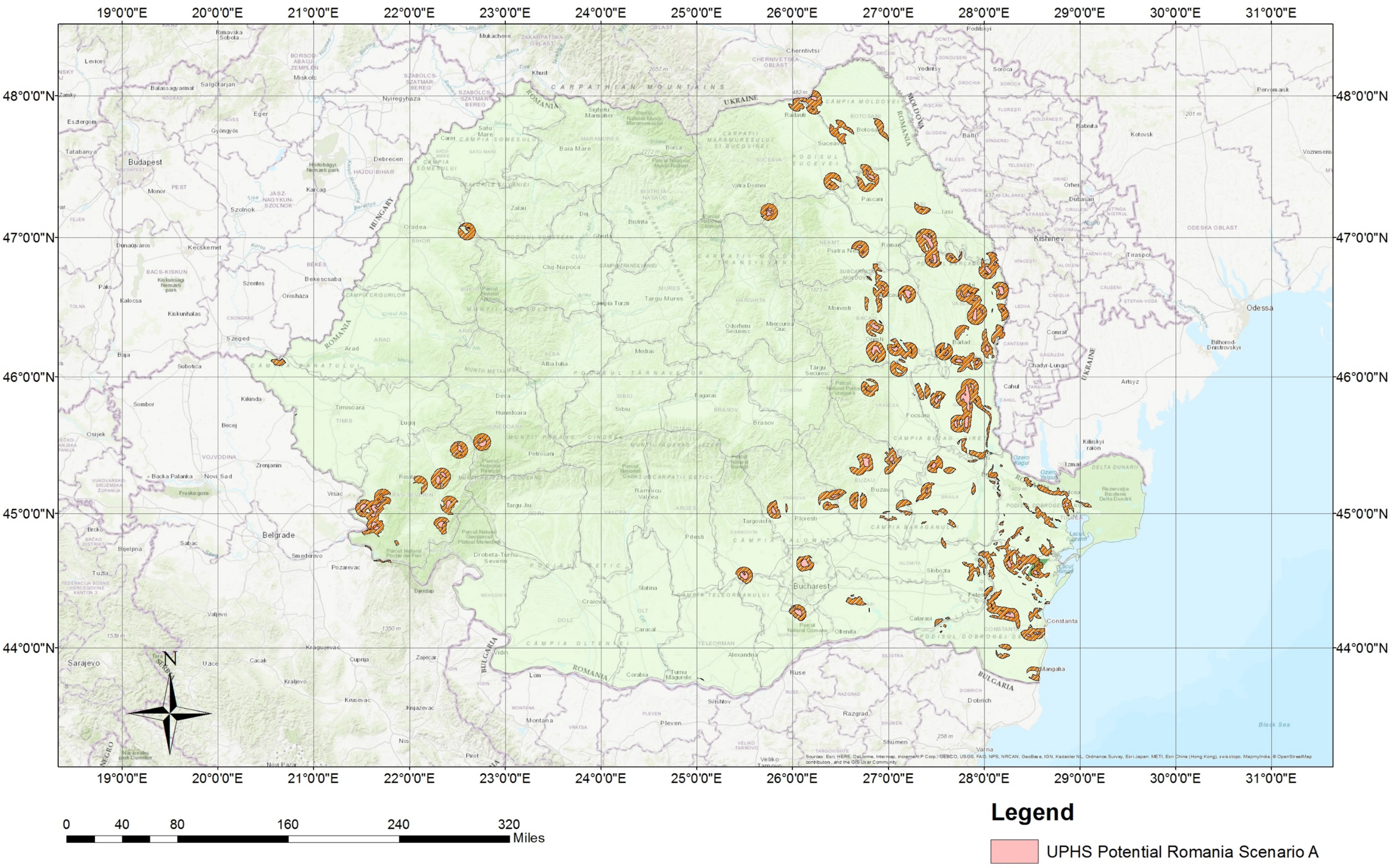

Figure 31. Romania Results

Romania is a country of South-East Europe, on the Black Sea. Its geographic coordinates are centred around 46° N & 25° E, and covering a total land area of 238 391 km2 (of which 3,6 % is water) puts Romania on the side of the bigger countries in this study (CIA world Factbook G, 2018). Romania is in this study because it presents an 18,7 % share of wind & solar energy in its energy mix, corresponding to considerable intermittent renewable penetration in their energy system (PocketBook Energy, 2017). Amidst having the smallest number of wind farms among the countries studied in this research - 79 wind farms as of 2018 - (thewindpower.net G, 2018), Romania is an interesting case as it currently boasts Europe's largest onshore wind farm: Fântânele-Cogealac wind farm, with 600 MW capacity (EWEA, 2013 & Whitlock R., 2016). Completed in 2012 and consisting of 240 turbines, it is localised close to the Black Sea, between the towns of Fântânele and Cogealac. With a 2017 electricity production of 1,3 TWh (Balkan Energy, 2018), this makes it the wind farm (in this research's scope) that is in closest range to O-PAC's designed UPHS plant capacity, which is used as a case study in this research (Huynen J, Schalij R. & Arts T., 2012). A specially designated green coloured polygon represents the Fântânele-Cogealac wind farm in Romania in this section of results (see around 2 on figure 32).

More specifically, special attention is given to Fântânele-Cogealac wind farm in the measure that a separate study is performed regarding its stand-alone UPHS realisable surface potential.

In scenario A, Romania presents 74 geographical zones of interest totalling a UPHS realisable surface potential area of 939,39 km^2. Of these whole-country results, 3 of these zones and 31,57 km^2 of that area is allocated to the Fântânele-Cogealac wind farm.
Scenario B brings the whole-country's UPHS realisable surface potential to 10 242,26 km^2, which is over 10 times that of scenario A. This total area is represented by 124 geographical zones of interest. In scenario B, Fântânele-Cogealac wind farm consists of 9 of those 124 zones, and contributes 280,47 km^2 to the total UPHS realisable surface potential.

In both scenarios, the biggest portion of the results is found in the East of the country. In the south-east, where Fântânele-Cogealac wind farm is also located, geographical zones of interest are found scattered from around the capital Bucharest (see 1 on figure 32) all the way to the coast, where Fântânele-Cogealac wind farm is located (see 2 on figure 32), always in proximity of Romania's numerous rivers. Zones are depicted around the city of Buzău (see 3 on figure 32), and a large ensemble is found around the city of Galați (see 4 on figure 32).

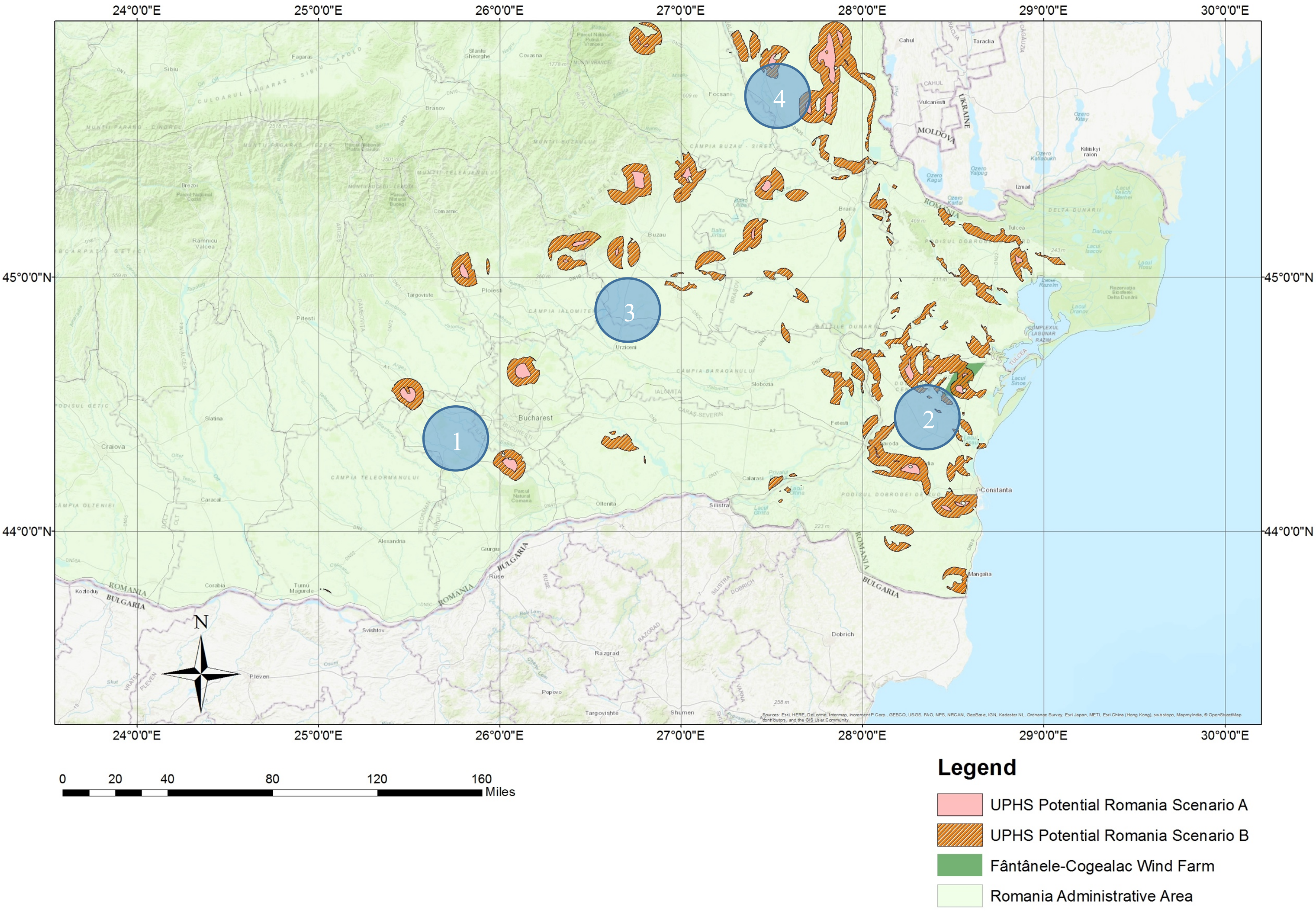

Figure 32. Romania – South-East Results

In the Northeast, geographical zones of interest are found running along Romania's border with Moldova, and scattered between the Vrancea, Vaslui, Suceava and Botoșani counties (see 1, 2, 3, 4, respectively on figure 33). In the latter two, zones are found on either sides of the Siret river.

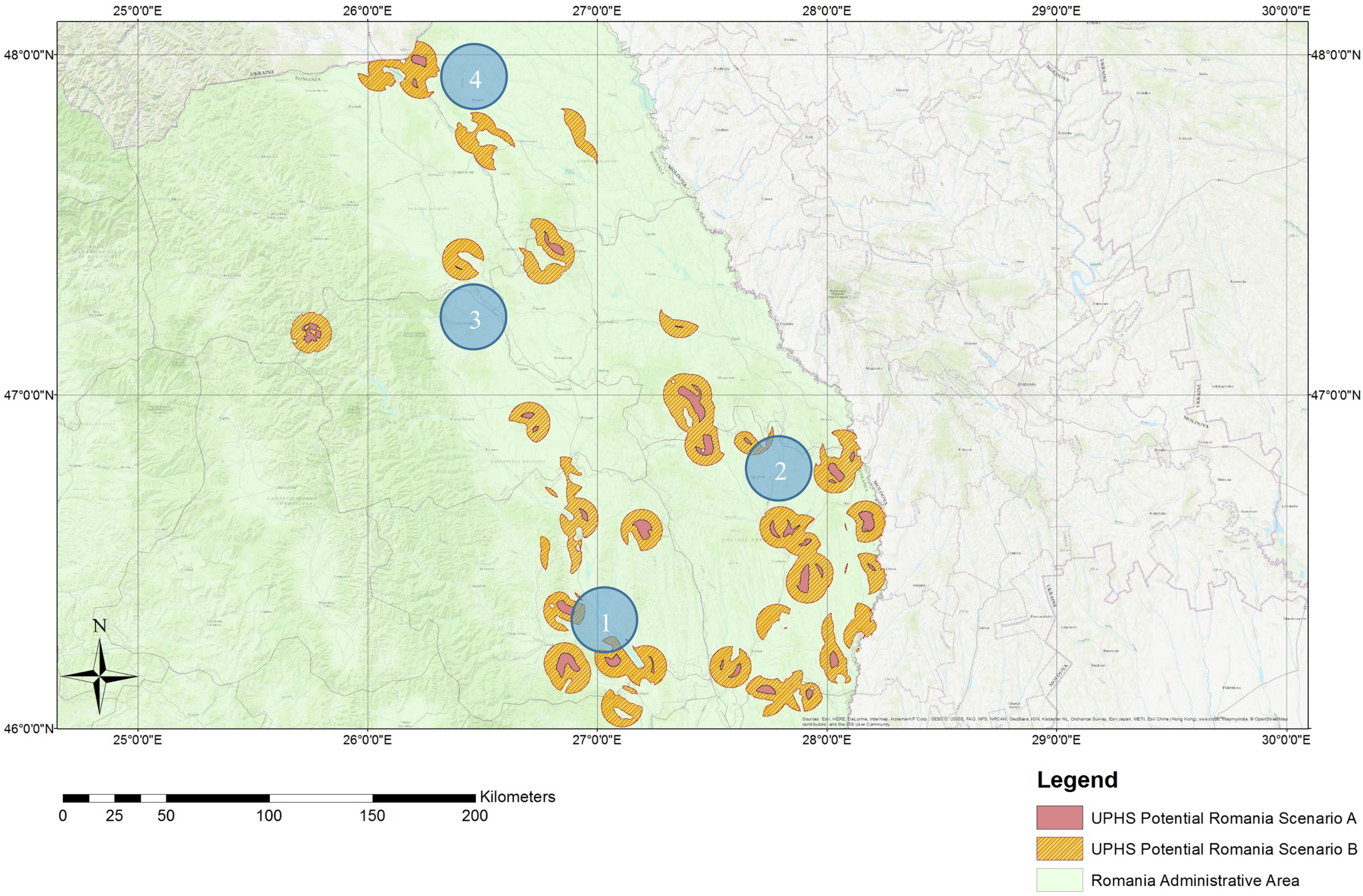

Figure 33. Romania – North-East Results

In the Western portion of the country, zones are found in the Caraș-Severin county and Timiș county, as well as the Bihor county (see 1, 2 & 3, respectively, on figure 34). In these counties, the zones fall in between areas of strong topographical relief caused by the presence of the Carpathian Mountains.

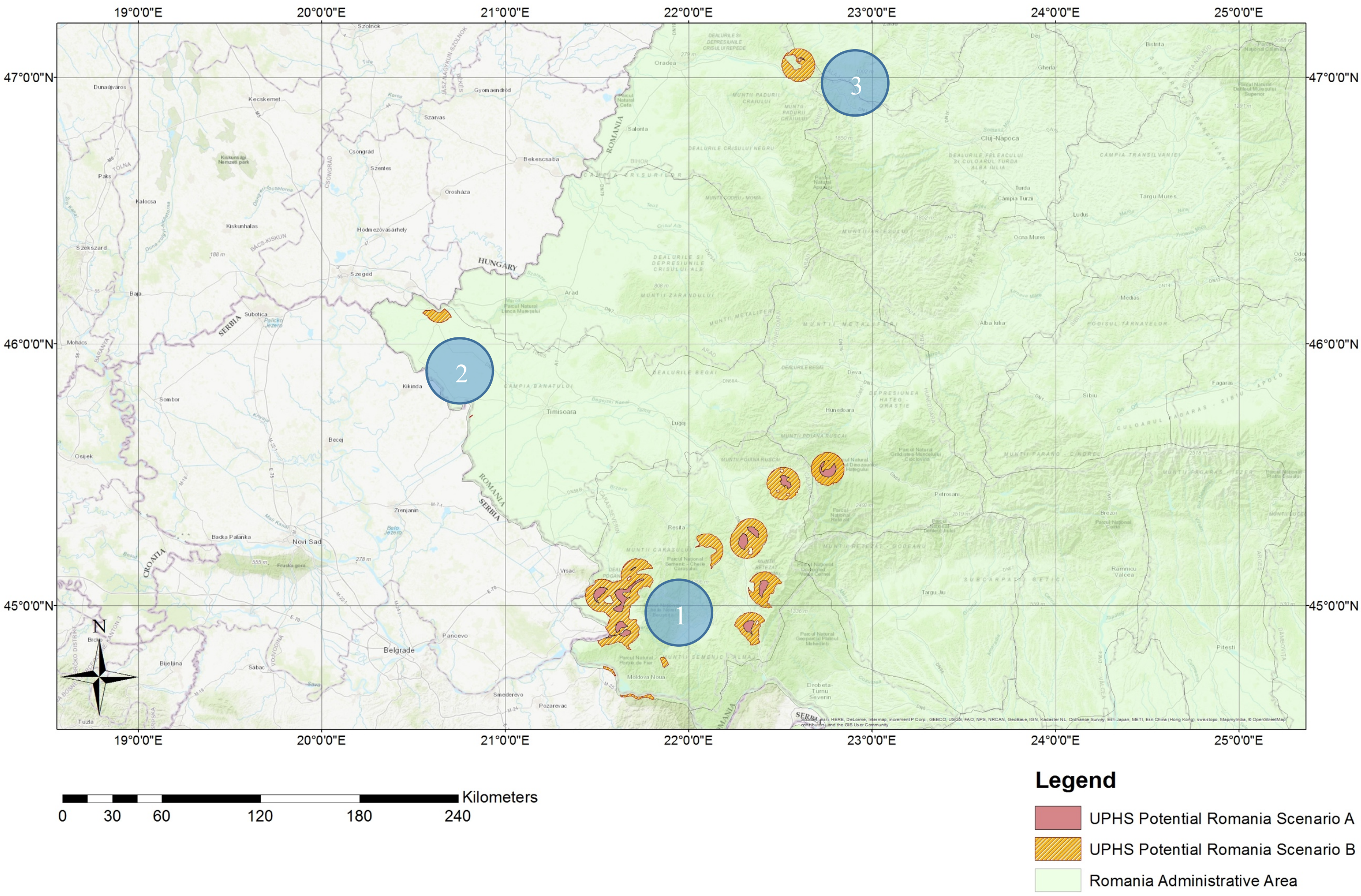

Figure 34. Romania – West Results

Overall, results in Romania are scattered due to the country's numerous protected areas, which are for the most part natural reserves that cover many large sections of land. However, this is compensated by Romania's concentrated wind farms, which are found mainly in the East and specifically the south-east (thewindpower.net G, 2018). Results are concentrated on the eastern side of the country where the topography consists of fields and rolling plains, avoiding the Carpathian mountain chains (Meridional and Oriental) that are found in the central part of the country (CIA world Factbook G, 2018). Results arise too in Romania's West, in flat valleys nearing Romania's border with Bulgaria. In both scenarios, Romania shows considerable UPHS realisable surface potential, with 0,4 % of the country's total land area being suggested in scenario A, and 4,5 % in scenario B (see table 14 in Appendix A). Europe's biggest onshore wind farm - Fântânele-Cogealac wind farm - plays a reasonable role in these overall results, and on its own presents interesting UPHS realisable surface potential. Geographical zones of interest account to 3 & 9 for scenario A and scenario B, respectively, around the wind farm, which is ideally placed in the fields of Constanta County (see table 14 in Appendix A).

III.3.8. United Kingdom

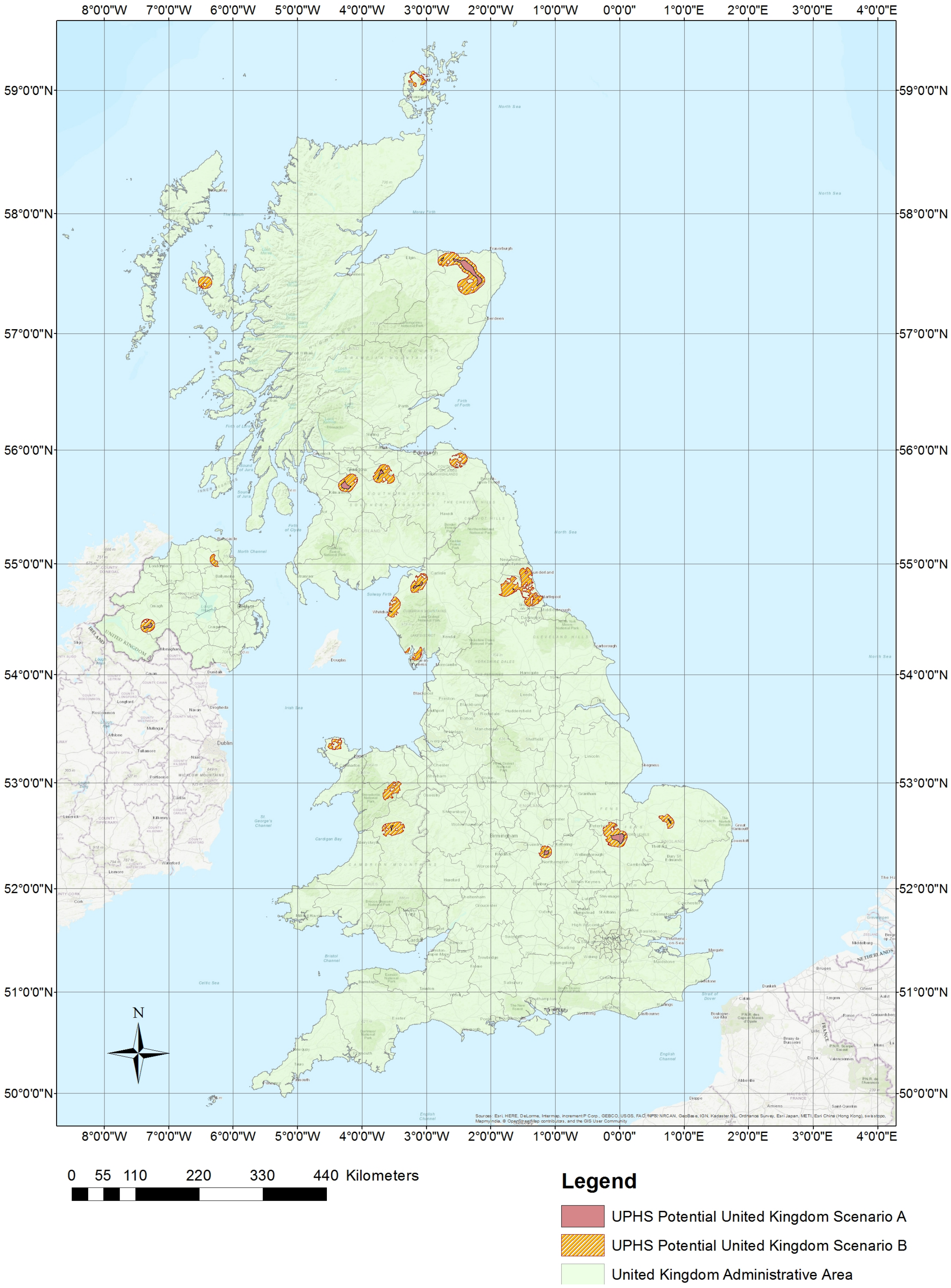

Figure 35. UK Results

The United Kingdom (UK) is a country of Europe consisting of islands off the north-western coast of the European continent. It is composed of England, Scotland, Wales (which make up the island of Great Britain) and Northern Ireland (20 % of the island of Ireland). All together, they cover a total area of 243,610 km^2, of which 0,7 % is water (see table 14 in Appendix A). The UK is found centred around the geographic coordinates 54° N & 2° W (CIA World Factbook H, 2018). The UK is part of this study since it presents a 24,7 % share of wind-solar energy in its energy mix, marking a high penetration of intermittent renewables. This share implies 14,5 GW of wind power installed capacity (PocketBook Energy, 2017), in form of 881 onshore wind farms and 31 offshore wind farms (thewindpower.net H, 2018), giving the UK 6th position worldwide regarding installed wind capacity.

This status is reflected in the GIS-based model results with scenario A turning up 13 geographical zones of interest that equal an area of 1052,27 km^2 of UPHS realisable surface potential (see table 14 in Appendix A). In scenario A, the most prominent of these areas are found in England, to the North of the city of Northampton, around the city of Ely, in and around the town of Swaffham (see 1, 2 & 3, respectively, on figure 36), and around the town of Wigton (see 3 on figure 37); In Scotland, between the cities of Glasgow & Kimarnock, around the town of Schotts (see 1 & 2, respectively, on figure 37) and in the county of Aberdeenshire (see 1 on figure 39); And Finally in Northern Ireland, around the village of Fintona (see 1 on figure 38).

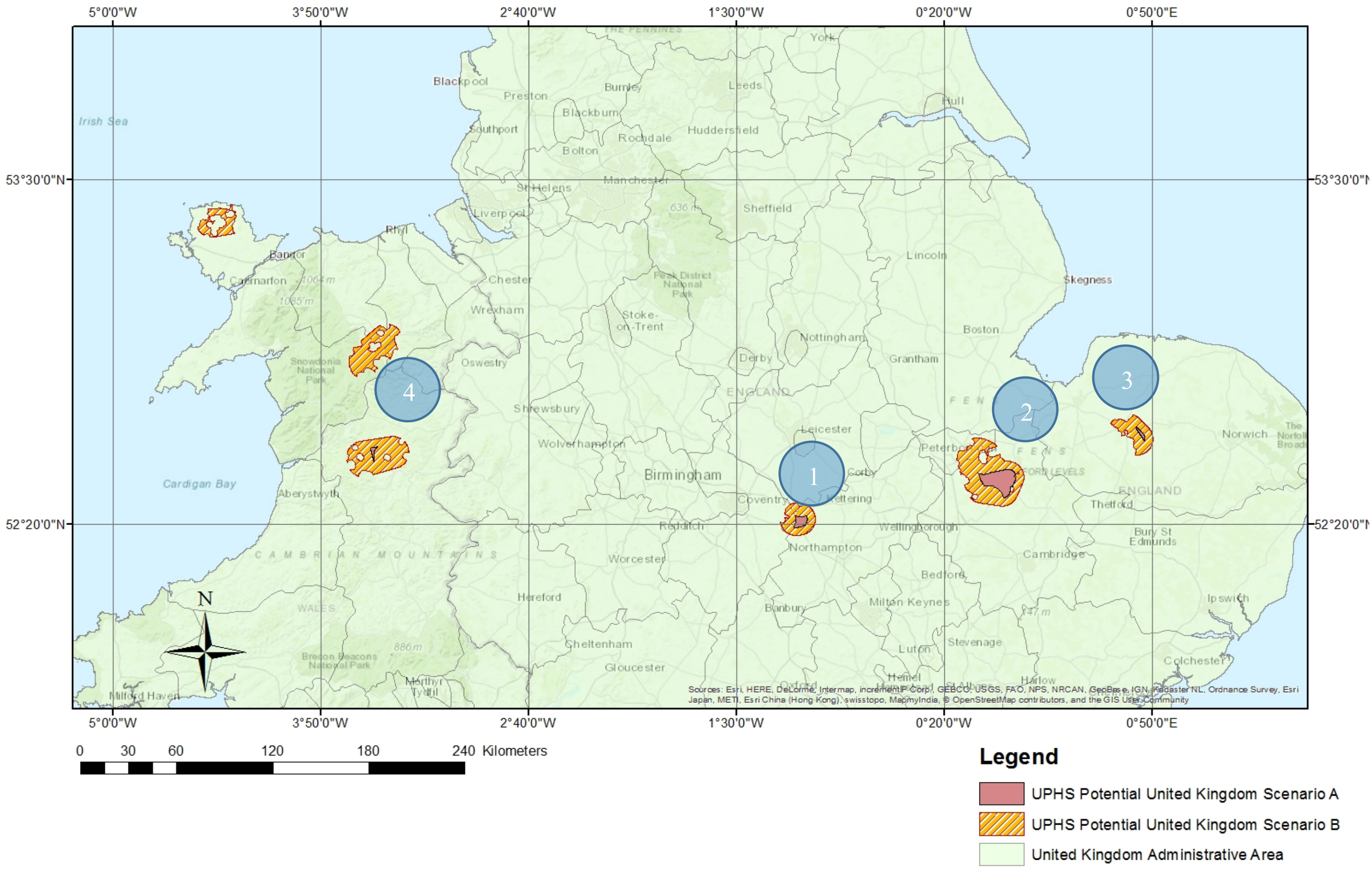

Figure 36. UK – South Results

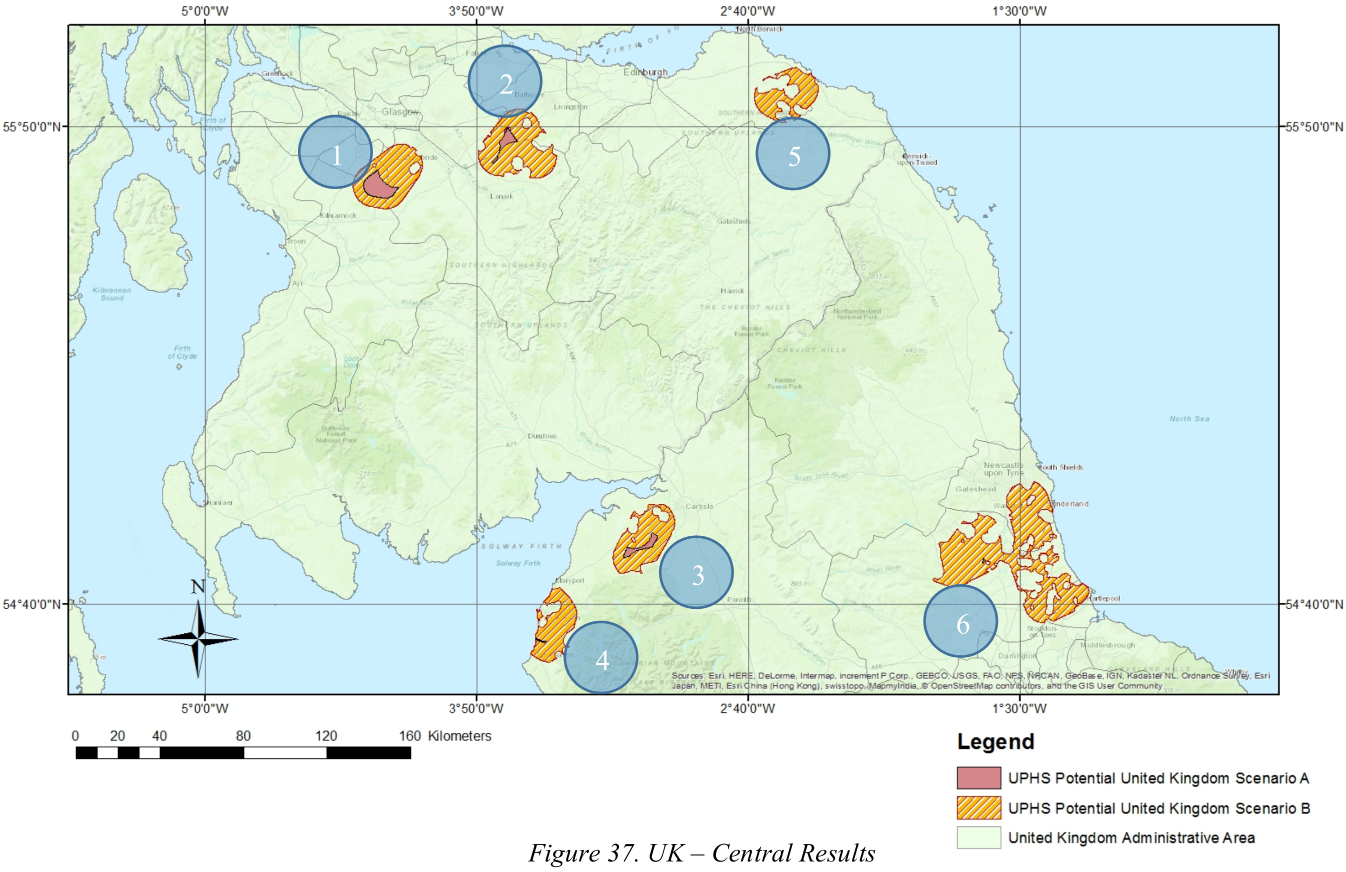

Figure 37. UK – Central Results

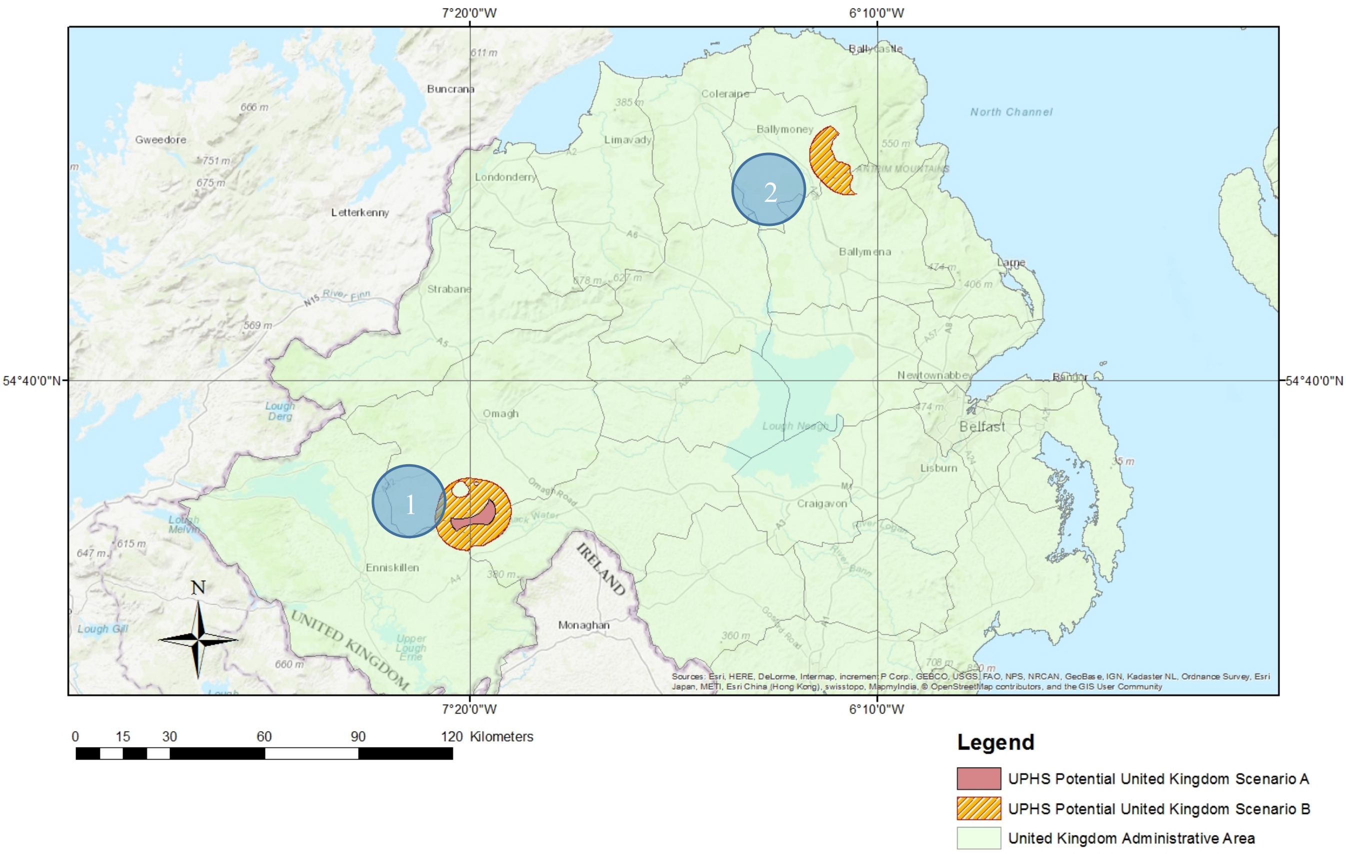

Figure 38. UK – Northern Ireland Results

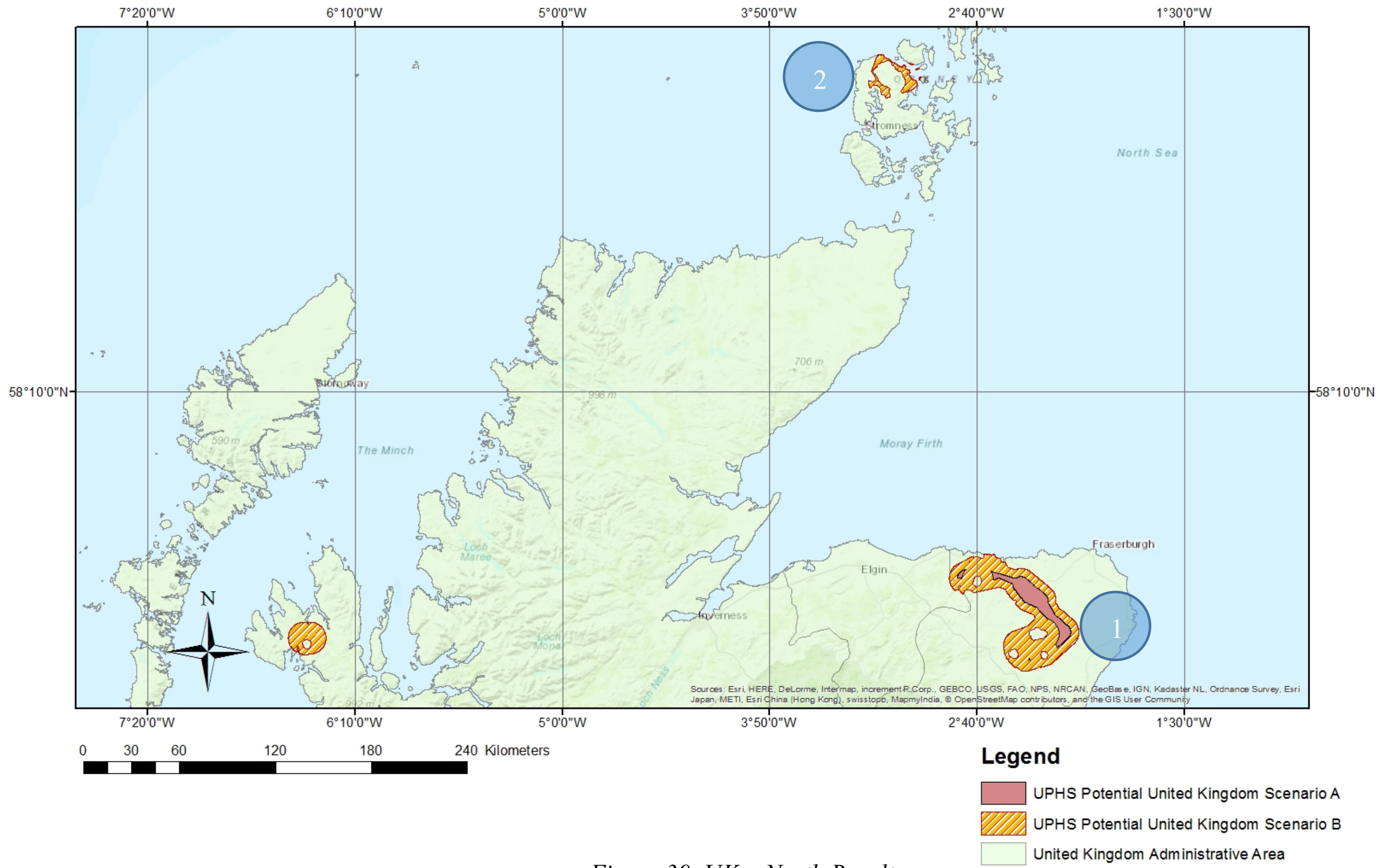

Figure 39. UK – North Results

Scenario B finds all zones depicted in scenario A & sees them extended (see figures 36 to 39), and finds new zones of geographical interest as well. In all, scenario B results with more than 10 times the surface area of UPHS realisable surface potential found in scenario A, with 11 786,61 km^2. The number of geographical zones of interest is increased to 19.

Notable geographical zones of interest added in scenario B are found triangulated between the cities of Sunderland, Hartlepool and Durham (in England) (see 6 on figure 37), between the cities of Whitehaven and Parton (England) (see 4 on figure 37), to the south of the town of Dunbar (Scotland) (see 5 on figure 37), surrounding the towns of Montgomery & Corwen (Wales) (see 4 on figure 36), around the town of Ballymoney (Northern Ireland) (see 2 on figure 38), and at the very north of the UK, on the Orkney islands of Scotland (see 2 on figure 39).

With such results, the United Kingdom establishes itself as a country worthy of UPHS interest. By expanding the search parameters, the less-stringent scenario B finds that 11 786,61 km^2 of the UK's and meets the surface criteria needed by a UPHS plant, corresponding to 4,9 % of the UK's total land area. This is the third highest result of its kind in this study, after Denmark and the Netherlands (see table 13). In the stricter scenario A, a still considerable 1052,14 km^2 of UPHS realisable surface potential is found, putting it on par with Romania regarding it being 0,4 % of the country's total land area.

III.4 Geological insight results

Amidst the diverse surface requirements, UPHS plants are highly reliant on the availability of correct geological parameters for their implementation. These results reflect the current state of publicly available geological knowledge in terms of searching for UPHS potential implementation.

As previously noted in the methodology, the O-PAC UPHS project in Limburg (The Netherlands) has identified Dinantian Limestone to be suitable for UPHS implementation. The following results reflect the search for Dinantian Limestone elsewhere in countries having presented GIS-based surface results, around the appropriate depth of 1000 to 1500 metres below the surface, as well as similar-depth strata that present similar characteristics as Limburg's Dinantian Limestone (also known as Limburg Limestone group in the Netherlands). The Dinantian is a geological age dating back about 350 Million years, and corresponds to the Lower Carboniferous (The Dinantian is a subdivision of the Carboniferous period, which itself is a subdivision of the Palaeozoic geological era). The Dinantian is itself subdivided into the Visean and the Tournaisian (upper and lower Dinantian, respectively) (Kombrink, 2008).

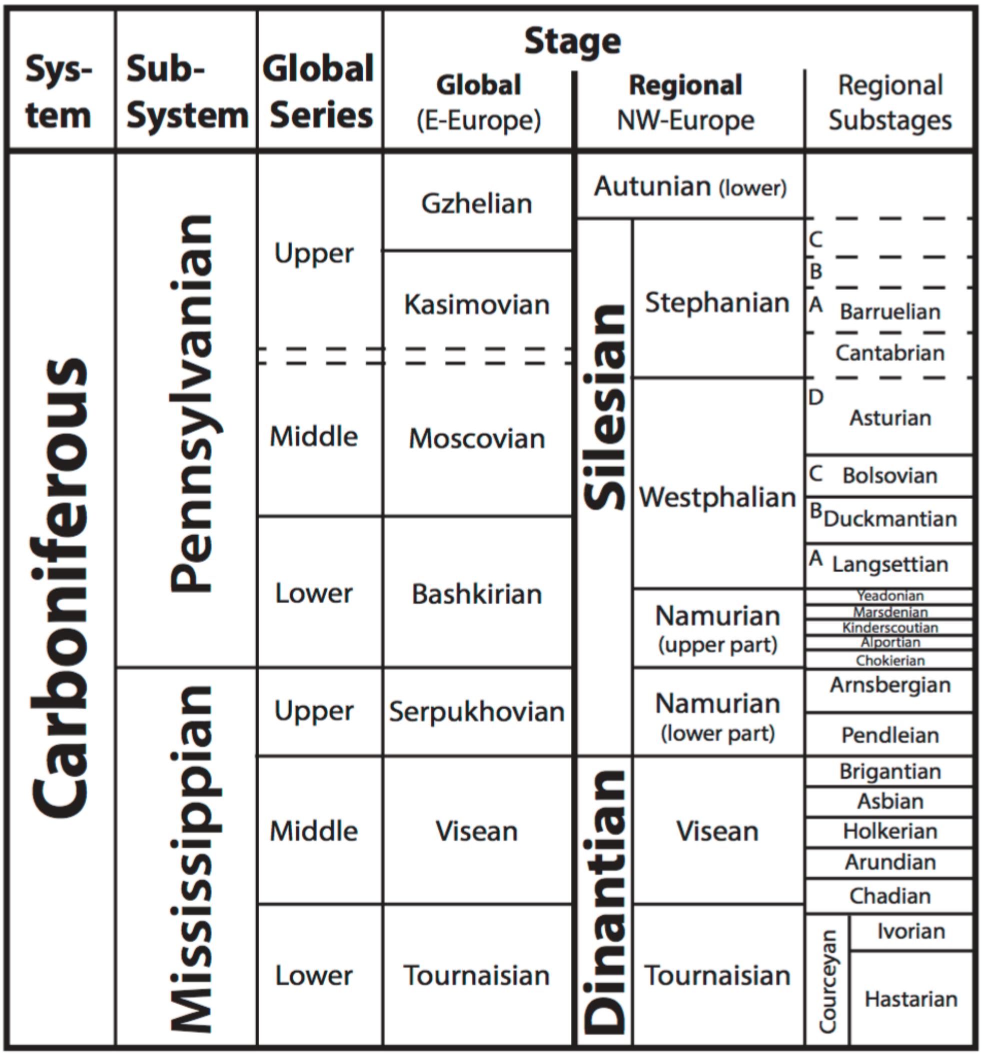

Figure 40. Subsystems of the geological record, showing geological periods and ages. While Europe recognizes the Dinantian and Silesian periods as the lower and upper Carboniferous, respectively, these correspond more or less to the Mississippian and Pennsylvanian in North America's geological record. The Dinantian is itself split into the Tournaisian and Visean (Reijmer J. et al., 2017).

North West Europe
Limestone is a carbonate rock, composed mainly of calcium carbonate ($CaCO_3$). It is a sedimentary rock that forms in shallow and warm marine waters.
According to the current state of publicly-available geological knowledge, the Limburg's Dinantian Limestone is part of a series of carbonate platforms that appear in North-Western Europe. This accumulation of Carboniferous sediments is found to occur in what is called the North West European Carboniferous Basin (NWECB), which covers the whole of the Netherlands as well as large portions of the UK, Northern Germany, Belgium and Poland (Kombrink H., 2008).

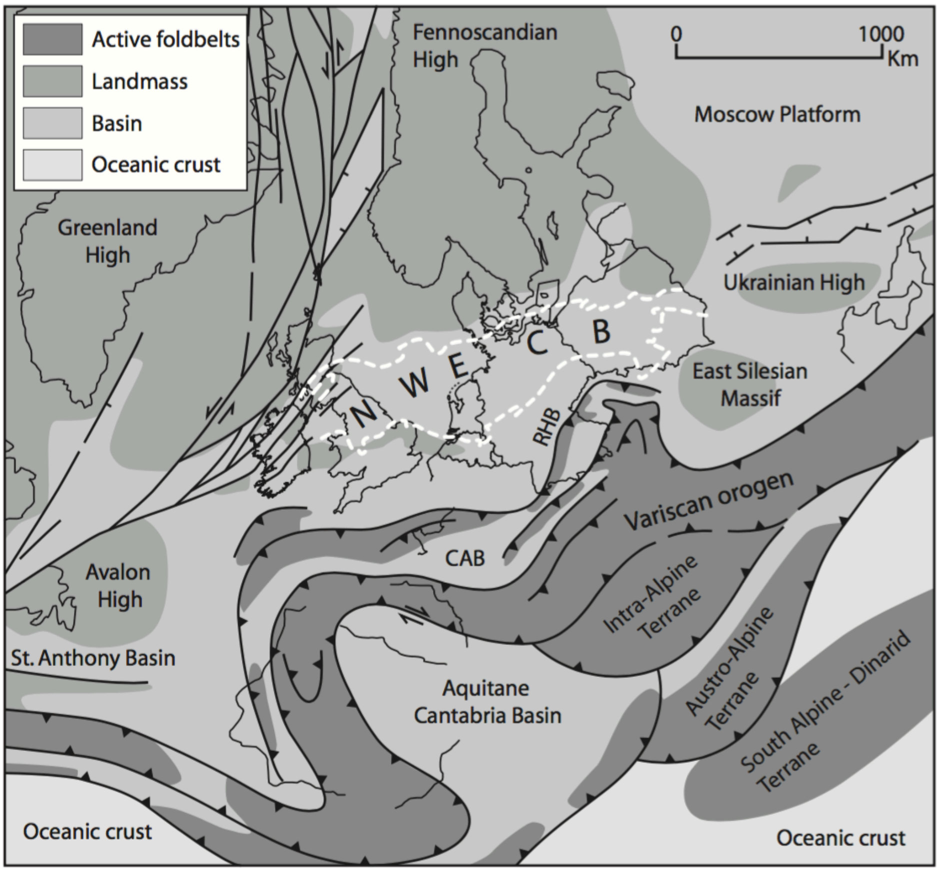

Figure 41. Geological Palaeotectonic map of Northwest Europe. The white dashed line represents the NWECB (Kombrink H., 2008)

However, the extent of the Carboniferous and precision regarding the depth of its subdivisions is still poorly known. Only a small number of independent exploratory drillings have specifically targeted the Dinantian, with most overall drillings limiting themselves to the very top of the Carboniferous period (when having reached the geological age named the Silesian, which sits above the Dinantian) which is considered an important reservoir unit for hydrocarbons (Kombrink H., 2008). Nonetheless, the search for mineral resources since the late 19^{th} century has led to the development of usable geologic maps in the Netherlands.
Kombrink (2008) has managed to produce an overview of the depth of the top of the Carboniferous in the Netherlands using the numerous wells drilled in the Netherlands, offshore and onshore (see figure 42).

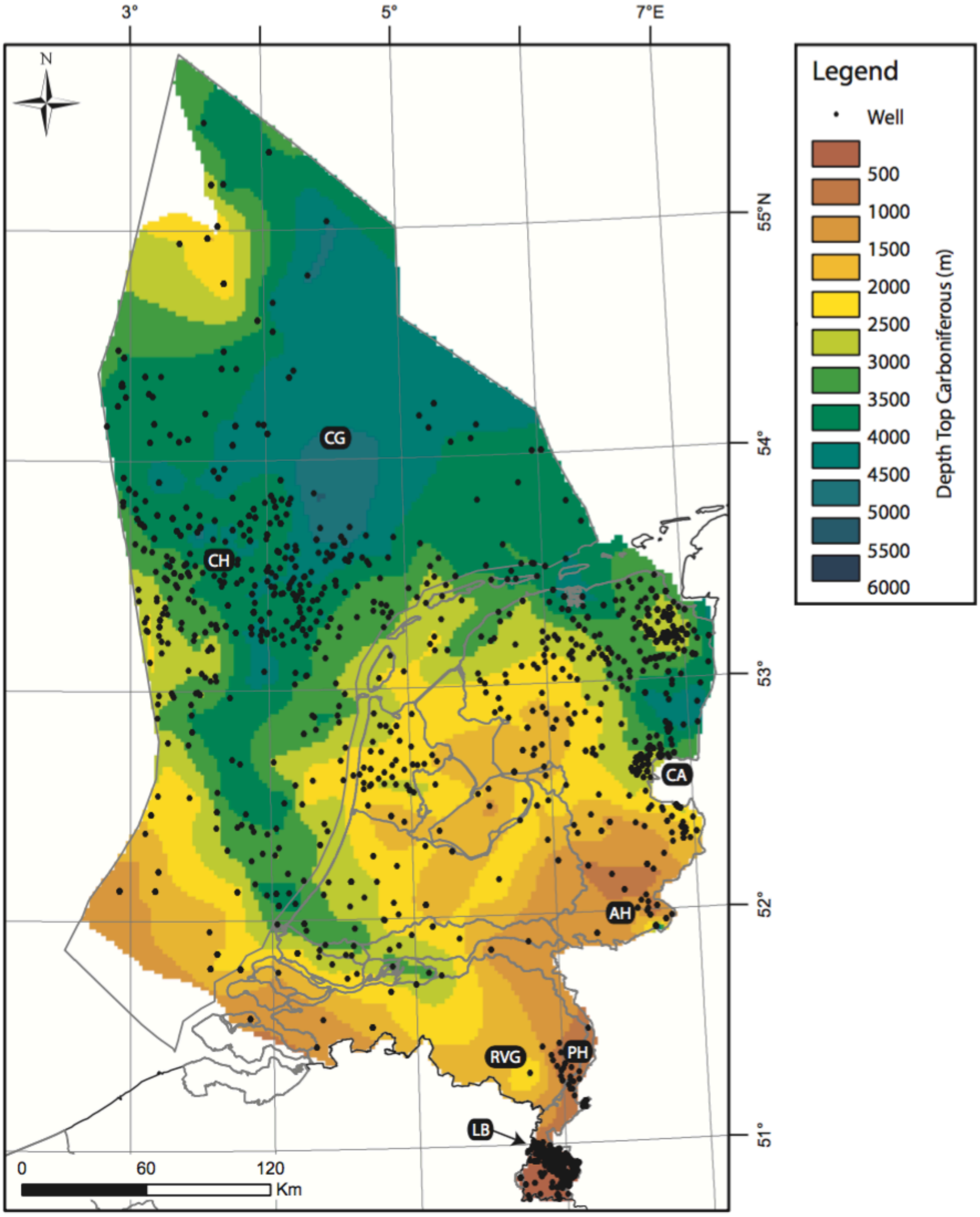

Figure 42. Map representing the depth of the top of the Carboniferous (Silesian, which sits stratigraphically above the Dinantian) (Kombrink H., 2008).

Moreover, combining all accessible drilling data with modern seismic wave research, Kombrink is able to schematically interpret a North - Northwest to South - Southeast cross-section of the Netherlands regarding the depth and thickness of the underlying geological strata. Figure 43 represents a general overview of the geological strata disposition underlying the Netherlands, in this case passing diagonally through the Netherlands; starting offshore, passing through Noord Holland, Utrecht, Gelderland, Noord Brabant and Limburg.

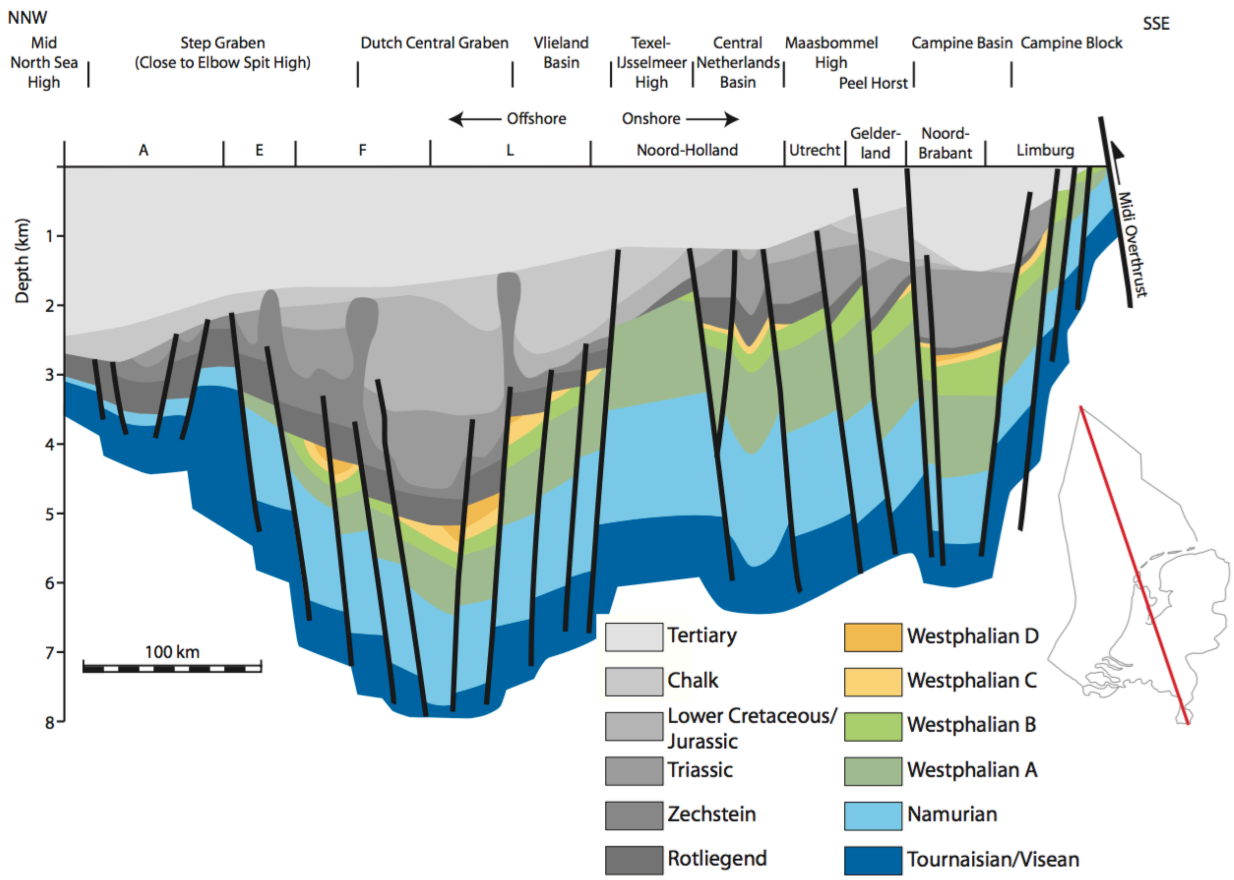

Figure 43. Schematic representation of the subsurface of the Netherlands along a cross-section running through Noord Holland, Utrecht, Gelderland, Noord Brabant and Limburg (Kombrink H., 2008).

This data correlates with the findings of the O-PAC core drillings in Limburg, which situate the depth of the Dinantian (represented in figure 43 as Tournaisean/Visean) in between 1 and 2 km beneath the surface. One can observe that this is exceptionally the case for Limburg, due to geological uplifting caused by tectonic movements. Along the rest of the onshore Netherlands presented by the cross-section, the Dinantian quickly dives below 3 km depth, even going as deep as 6 km, putting it well out of reach of the UPHS prospective.

This view is reinforced by a work in progress by Nynke Hoornveld (Hoornveld N., 2013), which uses seismic data to map the top of the Dinantian throughout the onshore Netherlands. This data (see figure 44) is represented in Two-Way-Travel-Time (TWT) of seismic waves, which corresponds to the time taken for the waves to "hit" the Dinantian layer and return to the surface. The Limburg region –where the Dinantian is found around 1400 metres depth- is represented by a TWT of around 1250 ms (milliseconds), which is also observed in the Zeeland region, and along the Netherlands' western border with Germany, encompassing portions of the Gelderland and Overijssel regions. Most other areas in the Netherlands are mostly represented by a TWT of 2000 ms or more, corresponding to a depth of over 2 km (see figure 44), thus rendering the Dinantian inappropriate for UPHS implementation. However, the gradual geological uplift of the Dinantian observed to be moving progressively towards the Limburg region and the Netherland's Eastern border with Germany may very indicate a continuation into western Germany.

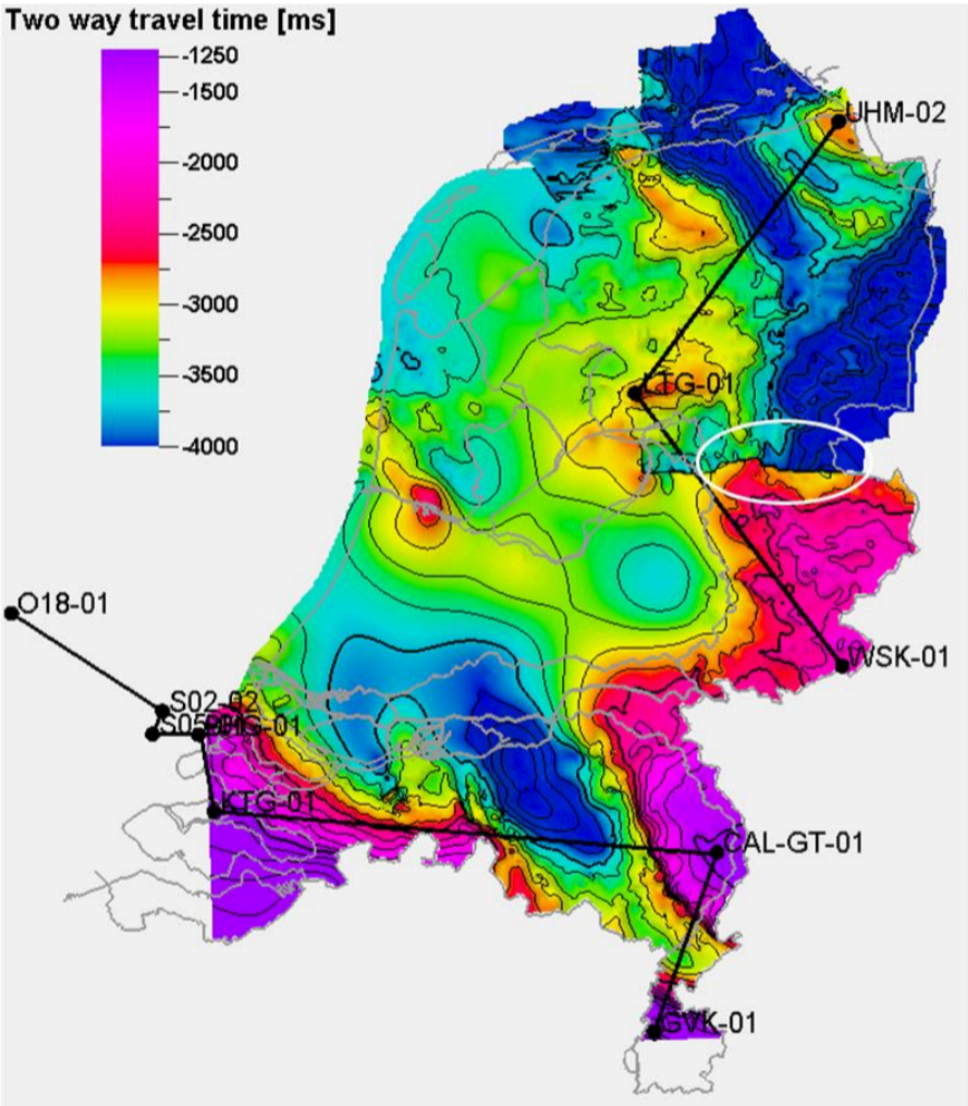

Figure 44. Top of the Dinantian represented by TWT (Two-Way-Time) seismic data. The regions of Limburg, Zeeland and portions of the Netherlands' border with Germany represent the shallowest Dinantian (Hoornveld N., 2013).

These findings help steer the geographical regions of Zeeland (NL), Gelderland (NL), Overijssel (NL) and Western Germany into the category of regions that have a better likelihood of presenting the Dinantian at an adequate depth of 1 to 1,5 km, and thus being potential subsurface-appropriate sites for UPHS implementation.

UK & Northern France

As previously stated, the NWECB continues across the North Sea and comprises parts of the UK (see figure 41). This is also illustrated by research done by Total (Total, 2007), which displays the continuity of the carbonate platforms found in the Netherlands (see figure 45). Effectively, northern France, Belgium, the southeast UK and the southern portion of the Zeeland region of the Netherlands share a geological crustal structure called the London-Brabant Massif (LBM), corresponding to a local uplift of the geological basement called a "structural high" (Rijkers R. et al., 1993). This can indicate a possible relative shallowness of the Dinantian in the southeast UK, as found in the Dutch region of Zeeland. Moreover, sitting geographically to the North of the LBM is the Anglo-Dutch Basin (ADB). The ADB is another geological structural entity that encompasses mainly parts of the Netherlands and the UK. Research regarding the ADB shows the continuity of shallow marine carbonates of the Dinantian age across the North Sea and into regions of the UK, as well as across Belgium and into northern France (see figure 46 in Appendix B1). These are depicted as the same shallow marine carbonates found in the Dutch regions of Limburg and Zeeland.

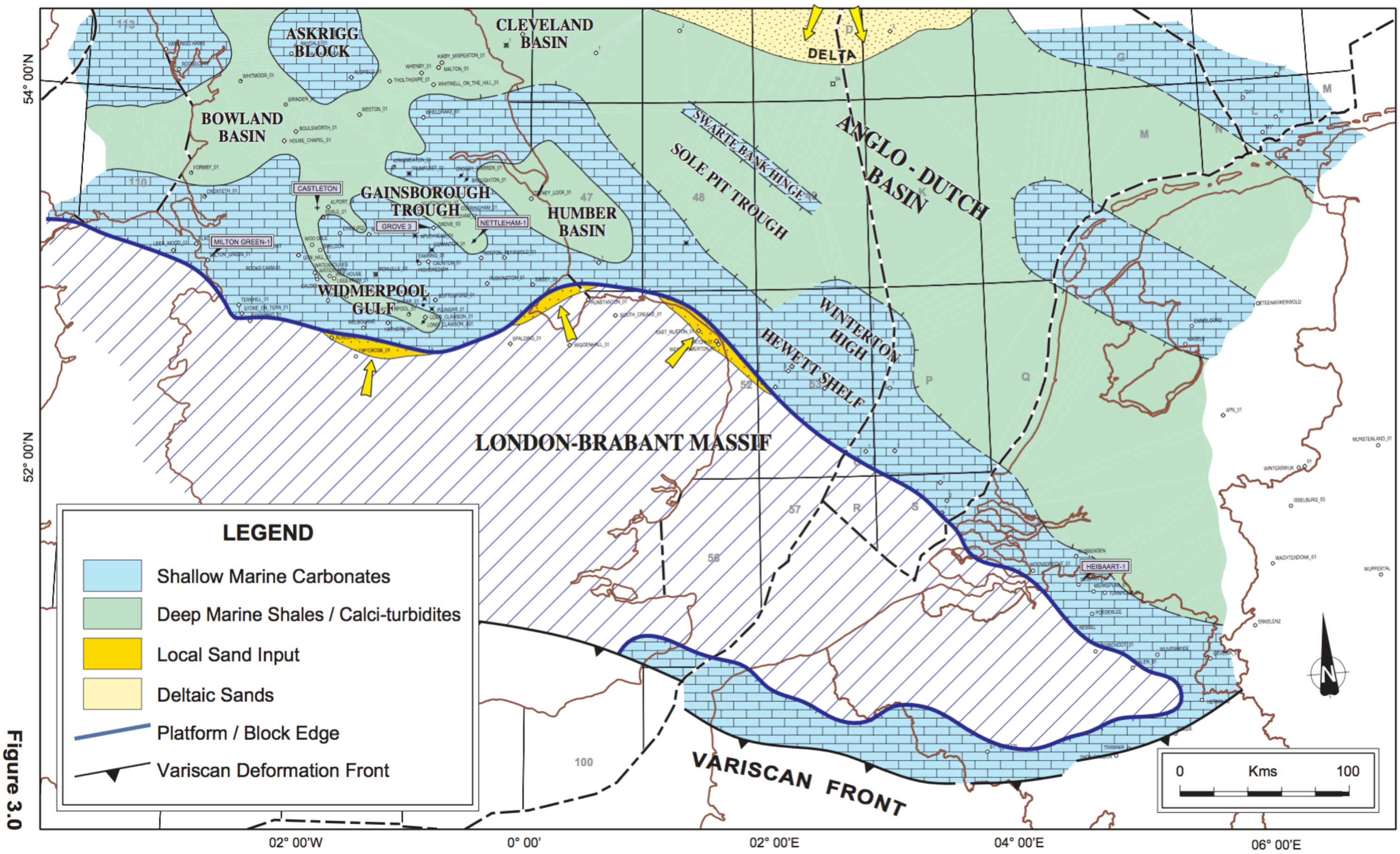

Figure 45. Geological map in Northwestern Europe, looking into the London-Brabant Massif and Anglo-Dutch Basin. This map shows the continuity of carbonate platforms from the Netherlands (specifically from the Zeeland and Limburg regions) across the North Sea and into the UK (Total, 2007).

Seismic data and interpretations suggests an uplifting of the Visean (upper Dinantian) around the eastern UK, to similar depths of the Visean strata found in Zeeland (see figure 46 in Appendix B1). Moreover, adjacent basins have been studied and are thought to hold over 4000 m of Dinantian rocks in thickness (Gawthorpe et al., 1989), which increases the likelihood of UPHS compatibility. Additionally, research led by the British Geological Survey (Waters C.N. et al., 2009) looks into the geological evolution of the islands of Great Britain and Ireland. Their findings suggest vast areas of platform carbonate lithofacies (sedimentary rock record) in the southeast and central UK, as well as on the majority of the island of Ireland, during the mid Tournaisian and Visean (see figure 47 in Appendix B1). However, no indication of depth of these geological strata is given.

Overall, these findings suggest that the eastern UK and portions of Ireland may present adequate subsurface characteristics to house a UPHS plant as projected in the Limburg context, and to a lesser extent but still suggestive, that the North of France may also possess adequate subsurface characteristics.

Denmark
Denmark finds itself in a substantially different geological context than the previously viewed countries. It is split between the North German Basin (NGB) and Norwegian-Danish Basin (NDB), primarily corresponding to the latter (see figure 48 Appendix B2) (Nielsen L., et al., 1998). Nonetheless, research suggests the penetration of Carboniferous deposits in parts of today's Denmark (see figure 49 in Appendix B2). (Nielsen, L.H., and Koppelhus E.B., 1991). Depth and extent are not clear. On another note, more research (Clausen, O. R. and Huuse, M. 2002) proposes an important uplift in the Danish Basin, with the Danian geological age being found at much shallower depths than in the intensely studied North Sea. Although the Danian age belongs to a much younger geological epoch (the Palaeocene, which dates back around 65 Ma) than the Dinantian, this uplifting may entail a certain shallowness of the Dinantian as well, or other Carboniferous strata (see figure 50 in Appendix B2). Although research suggests possible areas of uplifting of the geological basement (Javed M., 2012), insufficient data makes it difficult to express any kind of truly positive suggestion that Denmark may hold UPHS adequate geology. This is purely through lack of data (or public data) regarding the Carboniferous in Denmark, and must be further investigated.

This geological insight suggests a higher likelihood of certain regions to express the adequate geological settings for a UPHS plant's implementation, in terms of presence of the Carboniferous, and specifically the Dinantian at a correct depth.
Overall, the Netherlands, thanks to its widespread geological data made available to the public, acts as a main contributor to the understanding of the subsurface, and hence shows the highest accuracy in those terms. Aside the already confirmed adequate geological setting found in the Limburg region, two zones in the Netherlands are essentially retained to have a better likelihood of housing the geological characteristics needed for the implementation of a UPHS plant: the region of Zeeland and a portion along the Netherlands' western border with Germany, essentially East Gelderland and Southeast Overijssel. This geological behaviour is esteemed to continue into Western Germany, which is thus also retained as a suggestive UPHS geological hot spot. Data regarding the carbonate platforms of North West Europe then lead to believe that significant portions of central and Southeast UK, the island of Ireland as well as the very North of France may carry a UPHS-able subsurface. Finally, multiple hints of viability are found in Denmark, but data is overall lacking regarding the depth and thickness of the Carboniferous.

III.5 Surface & subsurface

With UPHS realisable surface potential (GIS-based modelling) results in one hand and geological insight in the other, two separate streams of findings meet to define areas where UPHS implementation is most likely to hold potential, surface wise as well as subsurface wise.

Essentially, following in the footsteps of the applied bottom-up approach, the geological insight offers a final constraint to be applied to the findings of the GIS-based model results. The geological insight has identified general geographical regions where the Dinantian, or Carbonate platforms that make up Limburg's Dinantian Limestone (deemed to be appropriate for UPHS in the Dutch region of Limburg, due to having the adequate characteristics and localised at the correct depth) are also found beneath the surface. However, depth plays a crucial role as well. The depth of these carbonate platforms is not signaled in many of the regions containing them.

Proceeding in a decreasing certainty manner, these regions consist of: Zeeland in the Netherlands, where the Dinantian is suggested to be at a similar depth as that found in Limburg; the margins of the East Netherlands (regions of Gelderland & Overijssel), running along the Netherlands' German border, where a gradual uplifting of the geological basement can be observed, with the Dinantian becoming ever shallower (see figure 44); Western Germany, with the geological setting previously described being likely to continue into Germany along the Dutch border; Southeast UK (England) , where the Visean (portion of the Dinantian) is seismically interpreted to rise to depths found similarly as the region of Zeeland (NL) (see figure 46 in Appendix B1); Northern France, central and Southeast UK, where carbonate platforms are suggested to be found beneath the surface, but at a generally unknown depth (see figure 45); throughout the island of Ireland, where carbonate platforms are suggested to be a consolidating part of the mid-Tournaisian and Visean (ages that make up the Dinantian)(see figure 47 in Appendix B1). Finally, as part of very obscure data, Denmark is thought to have an uplift in its geological basement (see figure 50 in Appendix B2), which theoretically contains Carboniferous deposits as well (see figure 49 in Appendix B2).

Putting these findings against the surface results found via GIS-based modelling, matches are made, and regions thus possess both surface requirements as well as suggestive geological potential for UPHS implementation:
In the GIS-based results, the region of Zeeland (NL) is found to be a hub of multiple geographical zones of interest regarding UPHS surface realisable potential. All surface requirements for a UPHS plant are met in parts of this region (see figure 27). The same is found regarding the Southeast and central UK, where geographical zones around the cities of Ely, Northampton and Swaffham are depicted by the GIS-based model (see figure 36). In Northern France, where carbonate platforms are suspected to be part of the subsurface, a match is made with the GIS-based model's delineation of a geographical zone to the West of Dunkirk. Next, in a less precise manner, are the all regions found on the island of Ireland, as a multitude of geographical zones of interest are found on the island of Ireland (see figure 19), to which geological insights suggest the existence of carbonate platforms dating to the Dinantian. Finally, in a slightly less confident manner, the extent of UPHS realisable surface potential found in Denmark, combined with its suggestive geological foundations and formations – especially in the Southern and central portions of Denmark- leads to believe that it may constitute a match. These regions consist of the localisations where UPHS implementation is found to have maximum potential, meeting both surface requirements and presenting the highest chances of geological suitability.

IV. Discussion

Answering the research question

This thesis has set out on geographical and geological exploratory research in terms of the physical implementation potential of UPHS plants, which is now done. This research holds two distinct currents of results at a distance, which are then merged in an attempt to highlight specific zones of interest and higher likelihood of UPHS plant potential. These results are presented distinctly because they arise from very different research processes. The firstly introduced "realisable surface potential" consists of a stream of results issued from the GIS-based modelling process. They present accurately depicted results from a bottom-up process where geographic areas must meet fixed criteria to depict zones of interest in terms of UPHS realisable potential. The second set of results arises from a dive into geological literature, to assess where (geographically) geological parameters and criteria deemed to be suitable for UPHS implementation occur. These results are placed in a secondary position due to their suggestive character. This is due to the nature of deep-subsurface geology, which, without precise in-situ geophysical exploration, is a highly generalized and more or less suggestive interpretation. However, in-situ geophysical exploration is clearly out of the scope of this thesis. Geological literature is the chosen path, and constitutes a way to identify geographical zones with higher chances of finding the correct subsurface for UPHS plants. Within this method, multiple geographical zones are found to carry both the geographical and topographical surface requirements of a UPHS plant as well as the geological characteristics considered adequate for a UPHS plant. This thesis thus answers the research question in these terms, in form of geographical regions and zones.

Variety of results

Results are given numerically in terms of number of geographic zones and surface area coverage (in square kilometres), and more generally in form of geographical regions. The numerical results correspond strictly to the GIS-based model, while the general identification of geographic regions is observed in the geological insight results and in the later combination of surface and subsurface results.

The numbers of geographic zones are also presented by their localisations in each respective country. Not all zones were represented and distinguished in the map results. Only the notable ones were represented (Romania in scenario B has over 100 zones for example, see table 14 in Appendix A). Nonetheless, these results help give an idea of the broadness and diversity of possibilities a country may have, while pinpointing geographical zones where UPHS plants surface requirements are met. These results will hopefully be of value to future research in the domain of UPHS site identification.

The numerical results found through the GIS-based modelling are key to understanding the potential of UPHS in the selected countries, with the surface area (in km^2) being able to give a concrete and overall view of the UPHS potential in a specific country. They dictate how apt a country is to UPHS implementation by giving a concrete amount of surface area that meets all surface criteria, and in which zones further specific subsurface data should be looked into. These numerical results are efficient in producing absolute as well as relative comparisons (relative to a country's total land coverage in square kilometres).

Below are the GIS-based model results in absolute square kilometres, as well as in relative surface coverage (compared to total land size), in ranked order:

Table 10. Scenario A ranked results (km²)

Scenario A	
Country	Overall zone area (km2)
Denmark	1084,11
UK	1052,27
Netherlands	1014,26
Romania	939,39
Ireland	34,52
Germany	0
France	0
Portugal	0

Table 11. Scenario B ranked results (km²)

Scenario B	
Country	Overall zone area (km2)
Denmark	12418,66
UK	11786,61
Romania	10242,26
Netherlands	4862,61
Ireland	2699,00
Germany	910,14
France	676,23
Portugal	61,12

Table 12. Scenario A ranked results (%)

Scenario A	
Country	% of total land
Netherlands	3
Denmark	2,6
UK	0,4
Romania	0,4
Ireland	0,1
Germany	0
France	0
Portugal	0

Table 13. Scenario B ranked results (%)

Scenario B	
Country	% of total land
Denmark	29,3
Netherlands	14,3
UK	4,9
Romania	4,5
Ireland	3,9
Germany	0,3
France	0,1
Portugal	0,07

Scenario A versus Scenario B

Scenario B is the extended scheme in which all scenario A's constraints are rendered moderately less-stringent, but still in the scope of what is technically realisable. This is clearly reflected in the results, which sees scenario A's figures regarding overall zone area (in km²) multiplied by more than 10 in the cases of Denmark, the UK, Romania and Ireland. Scenario B also renders results in Germany, France and Portugal, whereas scenario A presented no UPHS realisable surface potential. The Netherlands' overall zone area is multiplied by around 4,7 when passing from scenario A to scenario B, whereas Ireland sees a dramatic factor of 78 times its scenario A overall zone area produced in scenario B.

These scenarios were produced precisely to have insight into the volatility of the UPHS potential regarding the effect of eventual constraints that may be imposed on it. Both Scenario A and B represent technically realisable constraints, with scenario B leaning more towards constraints carrying industrial-economic maximums inspired by a similar study performed in the context of conventional PHS plants in Europe (Gimeno-Gutiérrez M. and Lacal-Arántegui R., 2013). Thus the wide range of results between scenario A and scenario B underlines the extent of UPHS potential in Europe.

Country comparisons

Comparatively between countries, assessments can be made using the absolute overall zone area coverage (in km²) as well as in relative terms (put against each country's land size).

In scenario A, most absolute overall zone area is found in Denmark, with 1084,11 km². The UK is second, with the Netherlands in third. All three have over 1000 km² of UPHS realisable surface potential. Romania falls just behind this mark with 939,39 km², while Ireland shows a relatively small 34,52 km². Germany, France and Portugal show no UPHS realisable surface potential in scenario A's conditions (for values, see table 14 in Appendix A).

However, when comparing relative values, the Netherlands is on top with 3 % of its land meeting scenario A's UPHS surface constraints. In this scope, Denmark finds itself in second place with 2,6 %. Values quickly drop as the UK and Romania, tied for third place, presents 0,4 % of their land as UPHS-able surface wise. Ireland shows 0,1 %, while Germany, France and Portugal show no potential (see table 14 Appendix A).

Moving on to scenario B, Denmark is again found to have the most absolute UPHS realisable surface potential, with 12 418,66 km^2. The UK is now in close second with 11 786,61 km^2 while Romania is now in third with 10 242,26 km^2. These three countries show a considerably large UPHS realisable surface potential, with their values being over 10 000 km^2. The Netherlands is in fourth place with 4862,61 km^2, followed by Ireland with 2699 km^2. Germany, France and Portugal now show UPHS realisable surface potential with 910,14 km^2, 676,23 km^2, 61,12 km^2, respectively (see table 14 in Appendix A).
Speaking in relative terms,
Denmark is unsurprisingly at the top since it shows a substantially large absolute potential while it is not part of the largest countries in this study. With almost a third of its territory (29,3 %) depicted as fitting within scenario B's UPHS surface constraints, it is largely in front of the runner-up, which happens to be the Netherlands with a still-considerable 14,3 %. UK is next with 4,9 %, Romania follows with 4,5 %, and Ireland with 3,9 %. Germany and France, the larger countries in this study, present 0,3 % and 0,1 %, respectively. Portugal comes in at under 0,1 % (0,07 %) (see table 14 in Appendix A).

Overall, it is increasingly evident which countries seem to be best suited (surface wise) to UPHS implementation: Denmark, the Netherlands, the UK and Romania are consistently presenting the higher-end results, in absolute terms as well as relative terms. Denmark leads in all sectors except the absolute overall zone area in scenario A. Ireland is an interesting entity as it shows considerable potential but only through scenario B's less-stringent constraints.
Although this is important to point out, it is also crucial to acknowledge that this is not necessarily a competition. Even though Germany and France come in at the end of the comparative tables, 0,3 % of Germany represents a still-considerable 910,14 km^2 of overall surface area. France as well, the largest country in this research, which shows 0,1 % of its territory to be UPHS friendly, corresponds to 676,23 km^2. All these are contributions to the UPHS realisable surface potential found in this research, which is found to total to 4124,55 km^2 for scenario A, and 43 656,62 km^2 for scenario B (see table 14 in Appendix A).

Country specific
Denmark results with large UPHS surface potential thanks to its relatively small size combined with a large wind power capacity (highest wind power penetration in total energy mix amongst countries included in this research), which thus creates a dense network of wind farms within the country. This is a prime starting point for the GIS-based model which sets multi-wind farm connectivity as one of its starting constraints. Adequate water availability enables Denmark to fit within constraints with relative ease, with geographical zones of interest appearing throughout the whole country, but substantially on the Jutland and Zealand peninsulas.

The Netherlands shows more water availability (see table 14 in Appendix A), but with a lower wind power penetration relative to Denmark (see table 5). The Netherlands' wind farms are situated mostly on its North Sea coast, as well as on the IJsselmeer coast. This is reflected in the UPHS realisable surface potential geographical zones, which tend to line the coast, venturing more inland in the Noord Holland, Zeeland and Flevoland regions of the country. Less opportunities of multi-farm connectivity are presented in the Netherlands, which takes a toll on finding suitable UPHS zones. However, the Netherlands, with Denmark, share the fact of being famously flat lands, which helps both countries reach considerable results due to the topographical constraint being almost overlooked through most of the land.

The UK is a relatively large country, but that still produces fruitful results regarding UPHS realisable surface potential, with 1052,27 km^2 and 11 786,61 km^2 in scenario A and scenario B, respectively (see table 14 in Appendix A). Zones are found in England, Wales, Scotland and Northern Ireland (see figure 35). Amidst being a large country, the UK has considerable wind power installed capacity, and more importantly, its wind farms are installed in clusters around its territory. This allows the GIS-based model to find distinct zones scattered across the UK. However, the two largest geographical zones of interest are found on the East of the UK, in Aberdeenshire (Scotland) and triangulated between the towns of Sunderland, Hartlepool and Durham in England (see figure 37).

Romania, in both scenarios A & B, presents the biggest number of distinct geographical zones of interest (74 and 124, respectively), along with resulting in over 10 000 km^2 of UPHS realisable surface potential in scenario B (see table 14 in Appendix A). Despite being substantially mountainous with the Carpathian Mountains running through its center, Romania's wind farms are concentrated on the East of the country, towards the Black Sea, and along its border with Moldova. This less-nationally-scattered aspect of Romanian wind farms gives Romania a considerable advantage in the GIS-based modelling process, by being able to disregard the whole size of the country. An important hydrographic network matched with a relatively less heavily-urbanised landscape gives Romania even more momentum in producing UPHS realisable surface potential results. Amid an East concentration of zones of interest, a smaller portion of UPHS-friendly geographical zones are also found in the West of Romania, in valleys between low mountains (see figure 34). Moreover, Romania is a specific subject of interest in this study since it contains the Fântânele-Cogealac wind farm, currently the largest wind farm in operation in Europe by nameplate capacity (600 MW). This wind farm is located in the plains of the Constanta county in the South East of Romania (see figure 32), which resulted in 3 and 9 geographical zones of interest around it, in scenario A and B, respectively (see table 15 in Appendix A).

Ireland starts in scenario A with 34,52 km^2 represented by 3 geographical zones of interest, only to reach 2699 km^2 made up of 39 zones in scenario B (see table 14 in Appendix A). This is the most dramatic overall area increase observed in this research (from a non-null scenario A). Ireland presents itself as a topographically good candidate since it is a general ensemble of flat lands and rolling hills, with low-lying mountains found in certain distinct areas of the country usually to the West and Southwest. Numerous rivers run through the country, but the wind farms are not necessarily placed in proximity of these water courses. Ireland consists of many towns, townships and communes in its interior, but vast expanses of untouched land are considered available by the GIS-based model. In all, the wide expanses that separate surface elements deemed essential for UPHS instalment insist that the potential implementation of UPHS in Ireland will require less-stringent constraints as instructed in scenario B.

Germany, one of the world's leaders in wind power, with over 4000 wind farms installed, has rather unexpectedly low results regarding UPHS realisable surface potential. The GIS-based model found 0 results in scenario A for Germany, but catches up in scenario B with 74 geographical zones depicting 910,14 km^2 (see table 14 in Appendix A). This contrast between scenario A and scenario B in the case of Germany reflects Germany's highly scattered wind farms, which are found dispersed through the country. Being the second largest country (after France) in this research, these results show that eventual UPHS implementation in Germany will much likely require less stringent constraints, towards the scenario B end of the scale. Moreover, the most notable geographical zones of interest are found in the northern portion of

Germany, stretching from the country's border with the Netherlands to its border with Poland, corresponding to the low-lying flat lands of the country (see figure 14). Germany's terrain becomes quite rugged progressively towards the South, evolving eventually into the Bavarian Alps. Zones are found in these regions as well, in flat spots between the strong relief topography, relating to valleys.

Much like the case of Germany, France shows no UPHS potential in scenario A but sees an appearance of GIS-based model results when the constraints are attenuated. Moreover, France is a country of very mixed topography, having plains in the North, hills and rolling plains throughout its territory, and rugged terrain scattered around big portions of its land, especially with the Alps in the Southeast and the Pyrenes in the Southwest. It is also the largest country in this research, and is one of the countries with the lesser wind power penetration levels (in terms of share of energy mix). Nonetheless France still has around 1000 wind farms, but like Germany, they are widely dispersed in the relatively large 551 500 km^2 that make up France (see table 14 in Appendix A), rendering it difficult for the GIS-based model to find multi-wind farm connectivity. All these conditions render a France case with 676,23 km^2 of UPHS realisable surface potential, which in absolute terms is still significant, but relatively only represents 0,1 % of the French territory. This potential is found in form of geographical zones in the North and North-central part of the country, corresponding to the relatively flat expanse of France, as well as in the West on the Atlantic coast as well as an ensemble in the South approaching the Mediterranean.

Finally, Portugal appears as the least performant of the studied countries. Although relatively adept in wind power, Portugal's first issue is its overall rugged terrain. Adding fuel to the fire, most of Portugal's wind farms are found in the northern region of the country, which happens to be the most mountainous portion of its territory. Wind turbines are often placed along mountain ridges to catch the wind. But this does not help the GIS-based model in finding multi-farm connections, which results in Portugal's scenario A showing no results, while its scenario B still provides only 61,12 km^2 of UPHS realisable surface potential, which makes up a slim 0,07 % of the country's land area (see table 14 in Appendix A). This same placement of wind farms in hard-to-reach places is what gives Greece strictly no results in scenario A and B. Greece even has its wind farms placed on isolated islands, and hence the absence of results regardless of the set scenario conditions.

Geological insights
The geological literature research is as enlightening just as it is a factor in revealing the shadows in the sector. Geological data regarding the deep subsurface is kept highly confidential in most countries, such depths being undertaken accurately mostly only by the petroleum and gas exploration industry. Nonetheless, information could be retrieved to shed some light on niches in the subsurface. The key findings consist mainly in North West Europe, where carbonate platforms are found to be abound in and around the Netherlands, the UK, and possibly portions of Ireland, Northern France and Western Germany. The depth of the Dinantian however is still open to interpretation over most of the study area, with concrete date only being available in and around the immediate margins of the Netherlands, as well as the very Eastern extremity of the UK. Clear and concise data regarding the geological basement (specifically the Carboniferous strata) of Germany, France, Portugal, Romania and Denmark could not be retrieved in this research. However, Denmark did present hints of data that correlate to what is searched for. Indications to other geological formations in and around Denmark (mainly stretching out into the North Sea) seem to indicate possible uplifting of the geological basement in onshore Denmark. Additional research suggests the presence of carboniferous deposits in the

South of Denmark. This creates a slight suggestive idea for Denmark, much less straightforward than for the UK and the Netherlands, but something nonetheless. Moreover, being in the region of North West Europe gives it a higher likelihood to be in a similar context as its neighbouring countries.

Final say

The merging of surface results and geological findings produces the final results, which suggests that the regions of Zeeland in the Netherlands, parts of Western Germany, the tip of Northern France, substantial regions of the UK and Ireland, and possibly Denmark constitute the ensemble of regions where UPHS has the best implementation potential. These results outline a specific region of North West Europe. However, it must be noted that this conclusive finality rests substantially on the geological findings which focused on this region. Many other geographical zones of UPHS realisable surface potential were found in the studied countries, especially in Romania. Lack of appropriate geologic data inhibited the possibility of assessing the subsurface of all other geographical sectors.

Denmark's UPHS potential is more or less dismissed by the absence of geological findings. However, seeing the extent of Denmark's results regarding the surface portion of this study, it is suggested to highly recommend Denmark in the list of a future UPHS prospective. In all, further research into the geological basements of the totality of the UK, Denmark, Ireland, France, Germany and Romania is strongly recommended in order to shed light on all the other geographical zones of interest (GIS-based model results) found in this research.

Points of discussion for future research

Hydrographic network

Hydrographic data plays an essential part in the GIS-based model, with proximity to water courses consisting of one of the primary constraints fed into the model. However, there is reason to question the quality of the water in terms of it being saline of freshwater, specifically in countries such as the Netherlands and Denmark. The CORINE land cover data used for all countries is meant to correctly depict fresh water courses and water bodies. But the Netherlands is a peculiar case since a series of locks and dikes control the water flow, opening and closing when needed. This entails that the water near the coasts (bordering the North Sea) may not be considered truly freshwater, nor saline. This research uses the GIS-based model which treats it as freshwater. The same issue arises with Denmark's water flows. A more accurate insight into these issues is suggested for future research.

Proximity to intermittent renewable energy plants

The proximity to intermittent renewable power plants is a primordial point in this research. The co-location and integrated aspect of energy storage accompanying energy production plants is considered an essential part of this thesis, as it forms a primary constraint in the GIS-based model. Moreover, multi-plant connectivity is promoted in this research due to the energetic scale of the UPHS project in the context of the O-PAC system by Sogecom. This multi-plant connectivity, combined with the distance constraints create firm limiting factors to the spread of UPHS surface potential. If proximity to intermittent renewable energy power plants is rendered less-stringent, or even dismissed for a preference of proximity to the electricity transmission grid, the extent of UPHS realisable surface potential is likely to be very different, and surely expanded. Lastly, in this research solely wind farms are found to be applicable (due to GIS data limitations). It would be advantageous to consider solar (Photovoltaic) plants in further research, which would most likely lead to a substantial increase in the UPHS potential in Europe.

Geological data

Geologic insight is necessary in this thesis since it comprises a crucial part of the UPHS system. However, in order to truly define a site to be geological appropriate for UPHS implementation requires in-situ geologic and geophysical analysis. The latter being out of the scope of this thesis, this thesis solely looks into the publicly available geologic knowledge. In the realm of deep subsurface geology, publicly available knowledge is not widely distributed. Exceptional cases are that of the Netherlands, where strict laws obligate the circulation of geological knowledge after a set maximum time span of confidentiality of 5 years. Hence the major use of Netherlands' derived data in order to comprehend the deep subsurface of the North West of Europe in this research. Small amounts of data were able to be accessed to get a general view of the subsurface of the UK and Ireland, but data regarding the deep subsurface beneath Germany, France, Romania and Portugal could not be found (Specifically regarding the location and depth of the Carboniferous, which is sought to contain major hydrocarbon reserves in Europe). Even when data is accessed, it usually consists of a general and basic overview. This was considered sufficient to give suggestive geological insight into where appropriate geological formations for UPHS implementation can be found, but more in-depth research is strongly recommended if ever a UPHS project is planned. The geological insight shown in this thesis acts mainly as suggestive guidance.

More intricately, the seismic data presented in this research is represents depth of geologic formations often in form of TWT (Two-Way-Time), which indicates the amount of time taken for seismic waves to "hit" the formation, reflect and head back to the surface. However, the speed of seismic waves is not constant, as they vary while passing through different types of media, depending essentially on densities. Thus the interpreted depth of certain geologic formations may vary from actual reality. Nonetheless this data is used to have a general idea of the subsurface geological formation distribution.

Limburg region

Results from the GIS-based model are considered to be of first order importance, before applying the geological findings as constraints. However, one may observe that the Limburg region is not depicted as a UPHS realisable surface potential zone in the GIS-based model results. This is disturbing since the O-PAC UPHS project is supposedly planned in the scope of the Limburg region (Huynen J., Schalij R. & Arts T., 2012). In this research, surface requirements were set as the primary set of constraints in order to depict zones of UPHS potential implementation. The region planned for UPHS implementation by O-PAC does not appear in this research's results because it does not meet the intermittent renewable power plant constraint, which underlines a minimum distance to wind farms. After further investigation and discussion, it has been found that O-PAC has chosen the Limburg region due to its exceptional geological characteristics, while opting to put aside some surface requirements which were originally set; distance to the electricity transmission grid is deemed to be a sufficient constraint in their point of view.

V. Conclusion

As renewable generation grows ever stronger branches in countries' electricity mixes, the search for resilient roots of large-scale energy storage goes on, with countries investing into all stems of research in order to improve their current situation. Pumped hydropower storage (PHS) stands today as the holy grail of large-scale energy storage, but is too often unattainable for many nations due to topographical and geographical requirements. Moreover, its environmental impact is still contested around the world. An underground version has presented itself as seeds in past minds, but has yet to fruition. It is Underground Pumped Hydropower Storage (UPHS), which presents itself as an innovative concept, that is engineered to tackle the energy issues of today and tomorrow. UPHS has already proven its ground in terms of energetic benefits, economic advantages and technical feasibility.
This thesis delivers the physical implementation potential of UPHS plants in Europe, by putting forward geographic zones where UPHS plants have a higher chance in being implemented by meeting geographical & topographical criteria, as well as highlighting regions where adequate geological characteristics for housing a UPHS plant are found. Regarding the surface constraints, two scenarios (A & B) assess the range of realizable surface potential by varying the extent of the constraints. Among the countries chosen for this research (those with the largest shares of intermittent renewables in their energy mix, as well as those with the largest annual additions), Denmark, the Netherlands, the UK and Romania present the biggest UPHS potential in terms of their surface characteristics matching the required and desired criteria deemed ideal for a UPHS plant. Nonetheless, most countries studied in this research present a certain range of results, dispersed across their territory as geographical zones of interest. In total and in between all countries, 4 124,55 km^2 of overall surface area is found to hold UPHS potential in scenario A, and this is extended to 43 656,62 km^2 in scenario B.
However, the current state of publicly available geological knowledge (of the deep subsurface) outlines certain geographical regions, corresponding to portions of countries, that are most likely to meet the geological requirements for UPHS implementation. These two streams of findings meet to form and filter-out one single list of geographical zones and regions where UPHS plants may have the strongest implementation potential, regarding surface and subsurface criteria.

In conclusion, this list corresponds to geographical zones in:
- The Netherlands, denoting multiple geographical zones in the region of Zeeland
- The Southeast UK, around the cities of Northampton, Ely and Swaffham in England
- The North of France, to the West of the city of Dunkirk
- The island of Ireland, denoting significant portions scattered most prominently in the Southeast of Ireland
- The South and central portions of Denmark

These areas represent locations where GIS-based modelling found results amidst all the constraints imposed by UPHS requirements, and where geological formations are believed to hold the highest potential for UPHS applications. In all, these findings represent the current UPHS implementation potential in Europe.

VI. Appendix A

Table 14. Overall Analysis by Country

Country	GIS surface results: Scenario A Overall Zone area (km^2)	GIS surface results: Scenario B Overall Zone area (km^2)	Areas (km2): Total area (land and water)	Areas (km2): Water area	Areas (km2): Land area	water % of total country area	GIS surface results (in %): scenario A % of total land	GIS surface results (in %): scenario B % of total land
Denmark	1084,11	12418,66	43094,00	660,00	42434	1,5	2,6	29,3
France	0,00	676,23	551500,00	1530,00	549970	0,3	0,0	0,1
Germany	0,00	910,14	357022,00	8350,00	348672	2,3	0,0	0,3
Greece	0,00	0,00	131957,00	1310,00	130647	1,0	0,0	0,0
Ireland	34,52	2699,00	70273,00	1390,00	68883	2,0	0,1	3,9
Netherlands	1014,26	4862,61	41543,00	7650,00	33893	18,4	3,0	14,3
Portugal	0,00	61,12	92090,00	620,00	91470	0,7	0,0	0,07
Romania	939,39	10242,26	238391,00	8500,00	229891	3,6	0,4	4,5
UK	1052,27	11786,61	243610,00	1680,00	241930	0,7	0,4	4,9
Total	4124,55	43656,62	1769480	31690	1737790		0,2	2,5

Table 15. Overall Analysis Fântânele-Cogealac wind farm

Site	GIS surface results: Scenario A number of zones	Scenario B number of zones	Scenario A Overall Zone area (km^2)	Scenario B Overall Zone area (km^2)	Contribution to total Romania results in Scenario A (%)	Contribution to total Romania results in Scenario B (%)
Romania Fântânele-Cogealac Wind Farm	3	9	31,57	280,47	3,4	2,7

VII. Appendix B1

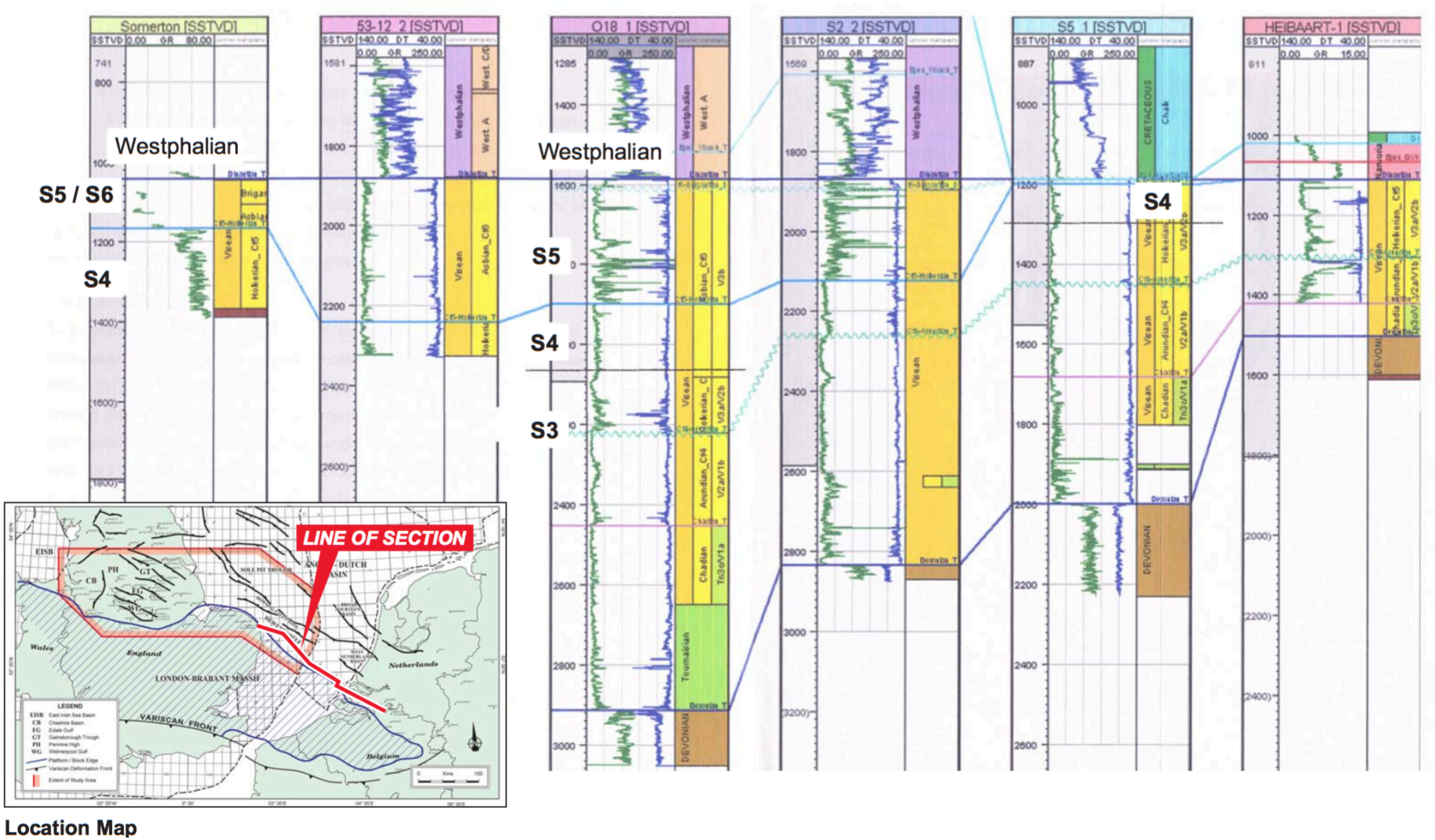

Figure 46. Seismic interpretation of a line section of the Anglo-Dutch Basin, by the London-Brabant Massif, showing the depth of the Visean in Sub Sea True Vertical Depth (SSTVD) (Total, 2007).

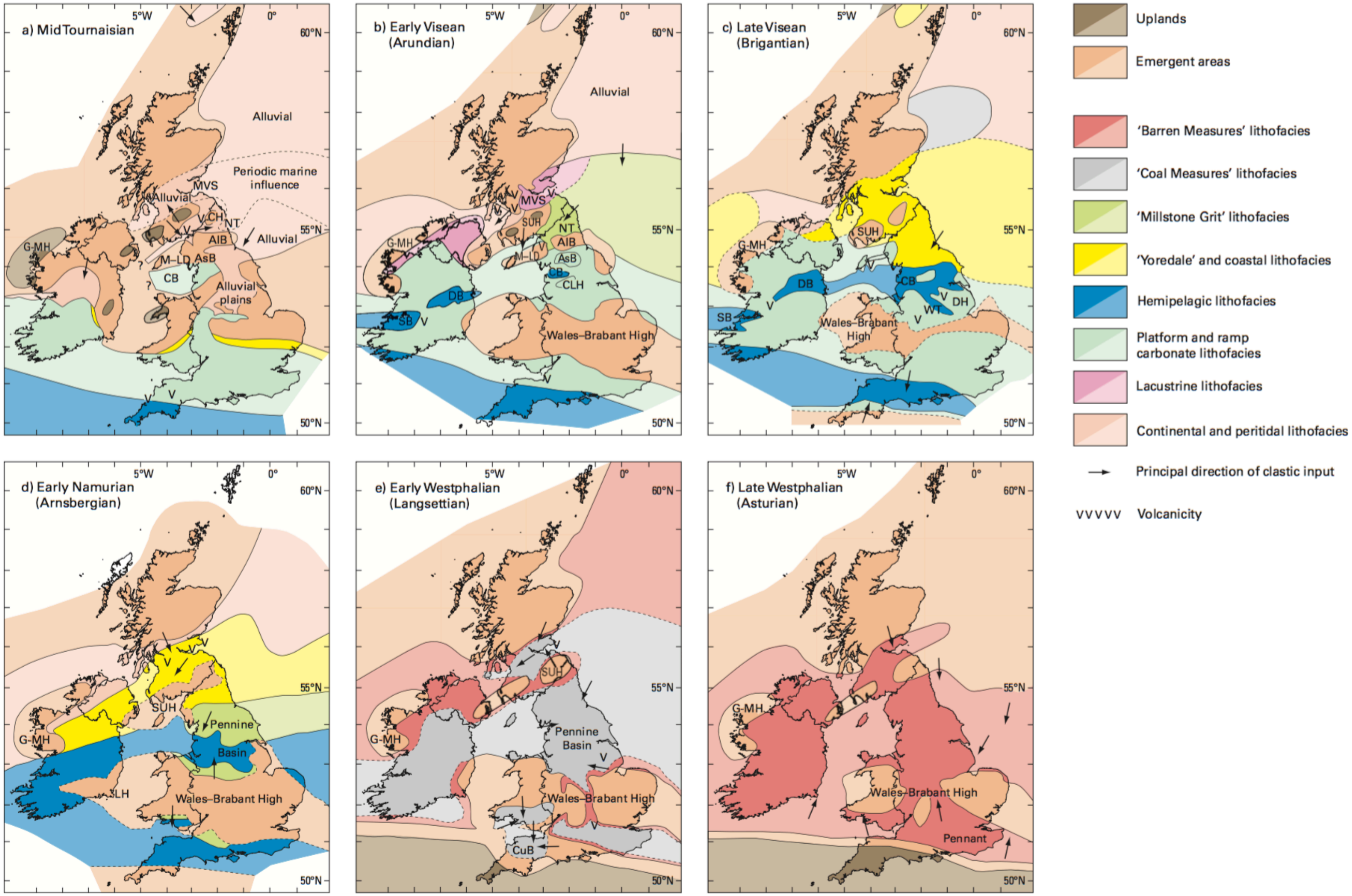

Figure 47. Geological evolution of the islands of Great Britain and Ireland from the Mid-Tournaisian to the Late-Westphalian. Platform and ramp carbonate lithofacies are shown to have emerged during the Tournaisian and Visean (Lower and Upper Dinantian, respectively). (Total, 2007).

VIII. Appendix B2

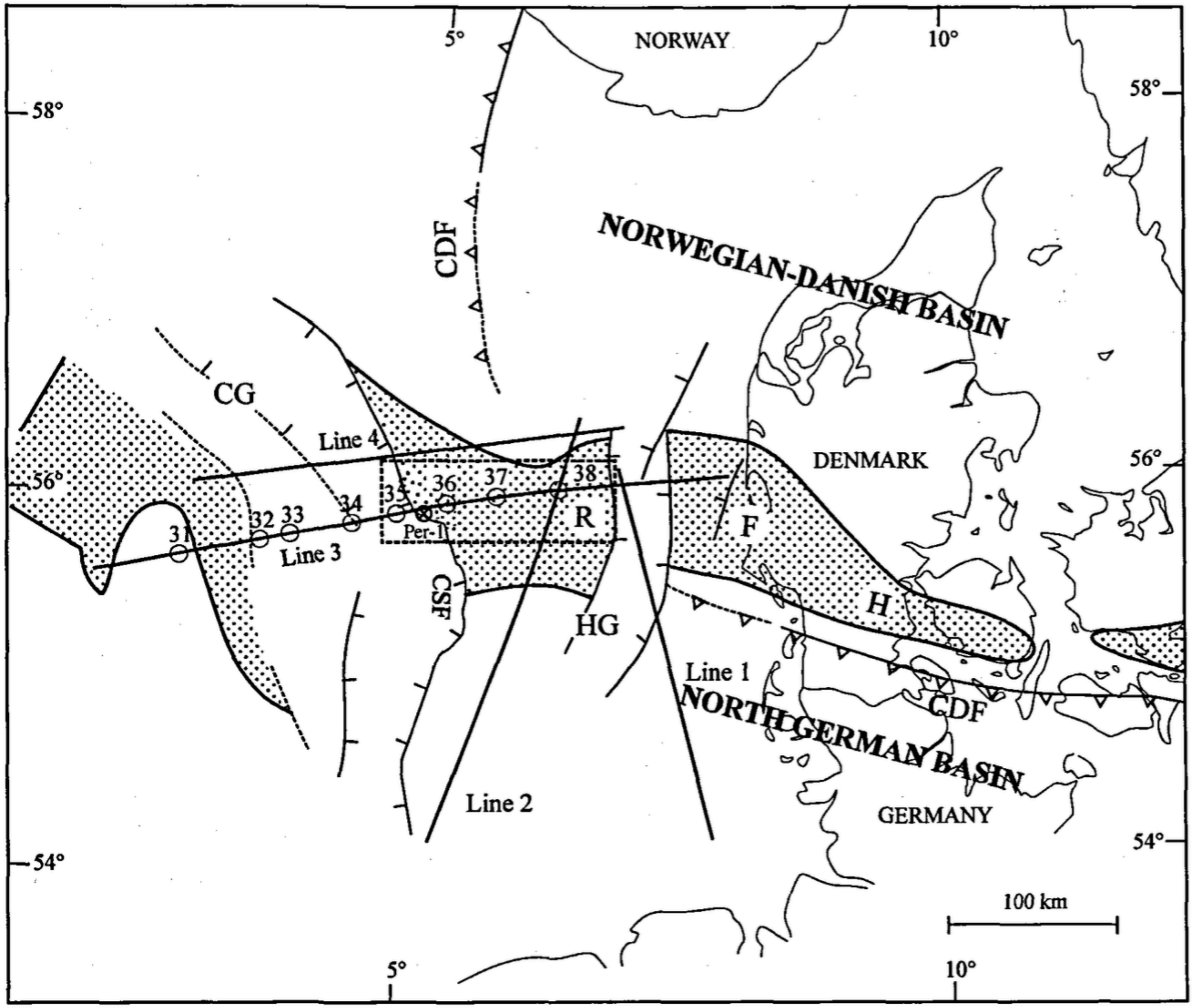

Figure 48. Map showing the division of Denmark between the North German Basin (NGB) and the Norwegian-Danish Basin (NDB) (Nielsen L., et al., 1998)

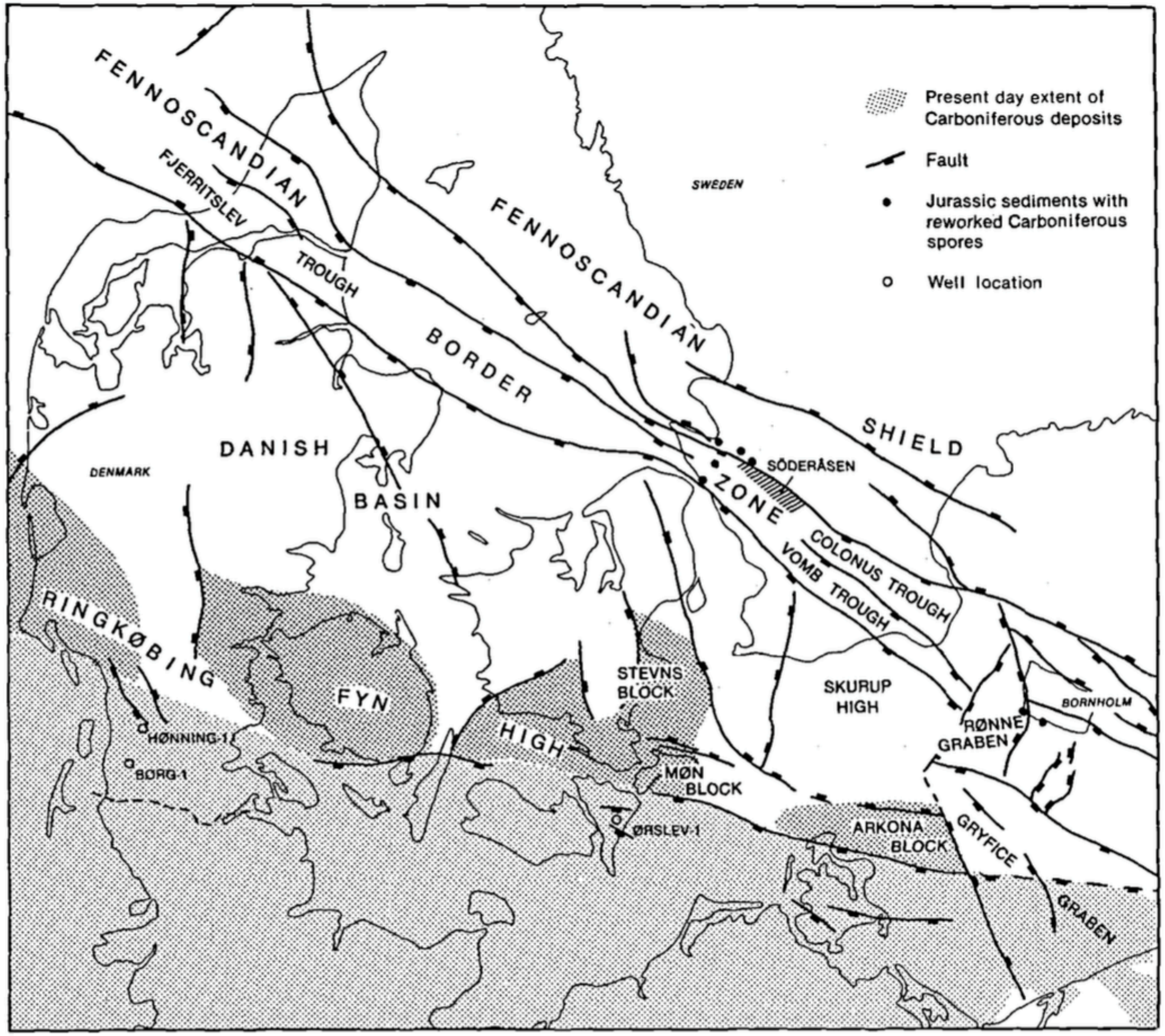

Figure 49. Geological map showing present day extent of Carboniferous deposits in Denmark (Nielsen, L.H., and Koppelhus E.B., 1991).

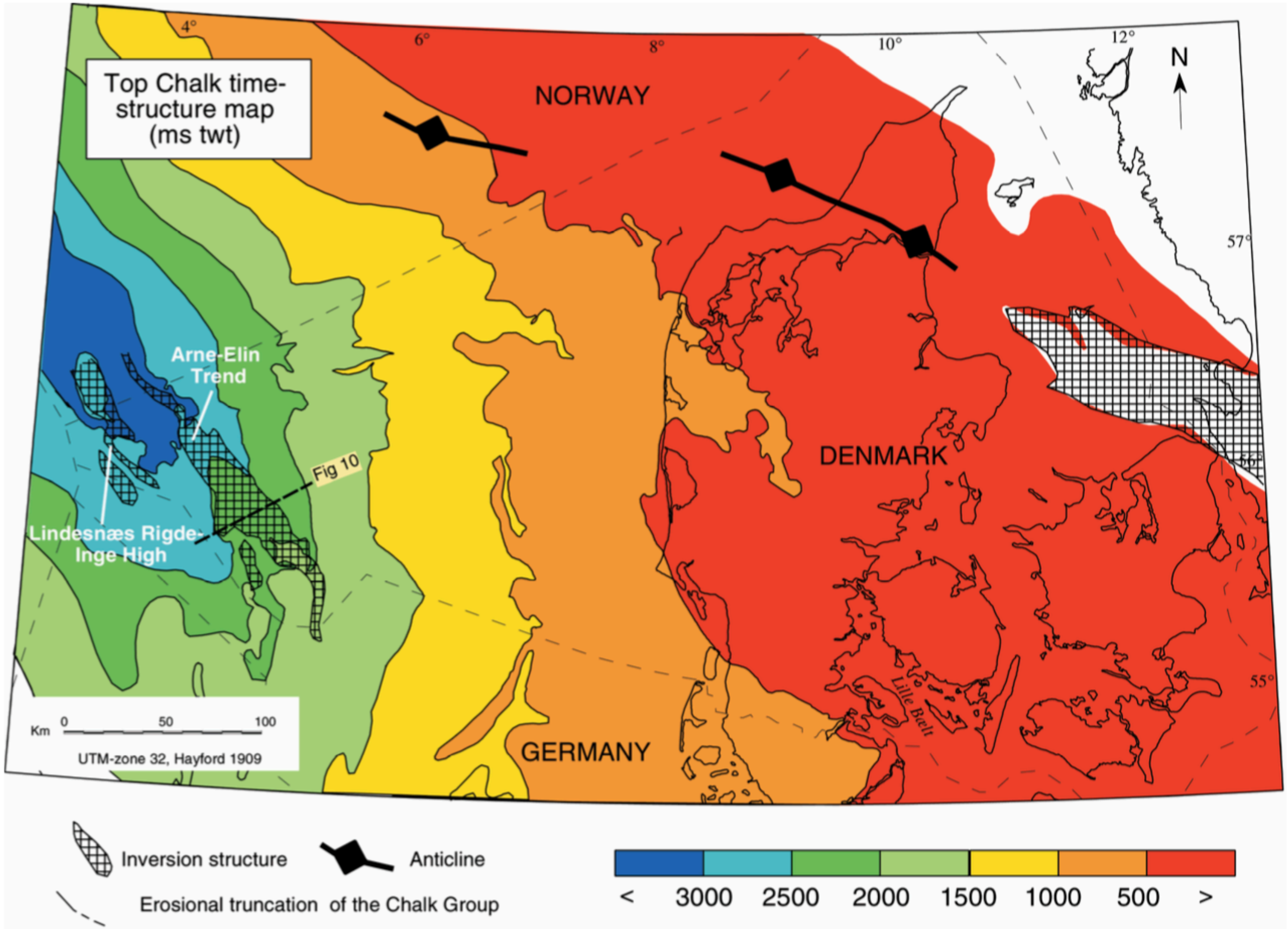

Figure 50. Map of Denmark and the North Sea, showing the geological uplifting of the Chalk group (Danian) occurring progressively to the east (Clausen, O. R. and Huuse, M. 2002).

IX. Appendix C: Country-specific GIS tables of results

The following tables present the outcome of the GIS-based model results, in form of a list of the geographical zones of interest (presented as polygons) and their corresponding area coverage in square metres and square kilometres. Tables are country specific, with a special insight into Romania's Fântânele-Cogealac wind farm. In the tables below, Germany and France present geographical zones of interest in scenario A, but these zones are below the minimum size threshold (0,36 km^2), and are thus not counted in the final results.

Table 16. Denmark scenario A GIS-based model results

Denmark scenario A				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	12173,50279	8676310,246	8,676310246
2	Polygon	10834,63859	7580487,542	7,580487542
3	Polygon	4689,850653	775778,8622	0,775778862
4	Polygon	11450,52029	5642278,348	5,642278348
5	Polygon	11167,27265	9019936,735	9,019936735
6	Polygon	25273,86673	30541874,7	30,5418747
7	Polygon	10021,97986	6175627,127	6,175627127
8	Polygon	11205,25971	6137814,043	6,137814043
9	Polygon	12664,81603	11002952,58	11,00295258
10	Polygon	8212,880327	3428816,552	3,428816552
11	Polygon	14898,40389	17002749,03	17,00274903
12	Polygon	20042,57049	25820752,91	25,82075291
13	Polygon	8106,586875	2014519,746	2,014519746
14	Polygon	13771,66974	14394283,83	14,39428383
15	Polygon	14652,22846	12451525,65	12,45152565
16	Polygon	15697,53658	16788703,33	16,78870333
17	Polygon	16541,94501	16541468,11	16,54146811
18	Polygon	8849,649385	4475940,382	4,475940382
19	Polygon	23542,30514	32186836,39	32,18683639
20	Polygon	12858,42331	9061922,699	9,061922699
21	Polygon	25095,93978	12968276,04	12,96827604
22	Polygon	16745,93469	13575173,8	13,5751738
23	Polygon	16913,21321	21395807,03	21,39580703
24	Polygon	12299,41365	10092339,66	10,09233966
25	Polygon	6939,952516	3340503,406	3,340503406
26	Polygon	13216,8098	11499737,74	11,49973774
27	Polygon	11897,85425	8914599,567	8,914599567
28	Polygon	18860,56064	19970000,39	19,97000039
29	Polygon	16357,86282	13765657,26	13,76565726
30	Polygon	11544,21823	4853820,935	4,853820935
31	Polygon	10652,04489	8045443,465	8,045443465

32	Polygon	7640,601657	3437494,403	3,437494403
33	Polygon	48513,72524	65288021,26	65,28802126
34	Polygon	19783,76367	23876765,61	23,87676561
35	Polygon	6281,966699	2080712,966	2,080712966
36	Polygon	9810,697384	6378781,554	6,378781554
37	Polygon	4511,213697	514419,9084	0,514419908
38	Polygon	12624,51555	11512477,58	11,51247758
39	Polygon	12992,4764	10671517,59	10,67151759
40	Polygon	13563,94807	11800608,6	11,8006086
41	Polygon	8487,511821	3442550,341	3,442550341
42	Polygon	10914,02002	5252935,533	5,252935533
43	Polygon	18244,72417	15208032,08	15,20803208
44	Polygon	6849,30837	1812193,892	1,812193892
45	Polygon	12499,6221	5218403,686	5,218403686
46	Polygon	14271,81394	14631253,51	14,63125351
47	Polygon	32391,73431	36803680,24	36,80368024
48	Polygon	39331,52114	76473716,86	76,47371686
49	Polygon	42282,24573	34653405,18	34,65340518
50	Polygon	72293,34774	123706361,2	123,7063612
51	Polygon	34112,36101	70861397,36	70,86139736
52	Polygon	16676,51241	20251962,33	20,25196233
53	Polygon	13316,14058	12300240,16	12,30024016
54	Polygon	17100,52082	22628987,94	22,62898794
55	Polygon	4277,522055	938180,8737	0,938180874
56	Polygon	36534,68776	47102253,2	47,1022532
57	Polygon	3724,870723	674780,923	0,674780923
58	Polygon	37122,84225	61446074,1	61,4460741
59	Polygon	26206,38686	24091106,04	24,09110604
60	Polygon	7534,387307	2907007,616	2,907007616
Total				1084,107261

Table 17. Denmark scenario B GIS-based model results

Denmark Scenario B				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	27181,56917	44188159,7	44,1881597
2	Polygon	20215,34128	26797921,67	26,79792167
3	Polygon	73995,49019	224938861,1	224,9388611
4	Polygon	90799,98298	268566361,8	268,5663618
5	Polygon	199812,0134	775799333,6	775,7993336
6	Polygon	46286,75634	144292756	144,292756
7	Polygon	58859,07113	126247541,7	126,2475417
8	Polygon	36491,72976	101379933,5	101,3799335

9	Polygon	125885,1943	345879082,7	345,8790827
10	Polygon	51595,79255	144955380,4	144,9553804
11	Polygon	94562,04505	418669599,3	418,6695993
12	Polygon	35607,54231	82780344,04	82,78034404
13	Polygon	33046,38777	71431849,6	71,4318496
14	Polygon	39153,59633	87718299,07	87,71829907
15	Polygon	90221,94749	414444705,8	414,4447058
16	Polygon	38590,35823	113918083,2	113,9180832
17	Polygon	424121,9405	2019343848	2019,343848
18	Polygon	55678,03691	175298930,9	175,2989309
19	Polygon	85110,34599	222425896	222,425896
20	Polygon	32284,89409	63191520,26	63,19152026
21	Polygon	33974,22745	80504025,05	80,50402505
22	Polygon	32471,09598	79625305,78	79,62530578
23	Polygon	82206,95269	311817499,1	311,8174991
24	Polygon	92897,66616	176769699,6	176,7696996
25	Polygon	6106,746696	2124994,589	2,124994589
26	Polygon	32867,95286	78280389,47	78,28038947
27	Polygon	31179,93205	26597860,94	26,59786094
28	Polygon	92812,1173	264435823,1	264,4358231
29	Polygon	244604,5256	869865295,5	869,8652955
30	Polygon	263425,2001	1288110171	1288,110171
31	Polygon	12490,35621	5599900,238	5,599900238
32	Polygon	38939,81381	101142615,9	101,1426159
33	Polygon	26194,43133	44775745,12	44,77574512
34	Polygon	37190,77528	28283590,82	28,28359082
35	Polygon	32963,20767	76875616,99	76,87561699
36	Polygon	35754,73123	61654430,74	61,65443074
37	Polygon	37516,98087	102254916,5	102,2549165
38	Polygon	63519,52913	281044390,4	281,0443904
39	Polygon	174514,3016	1037708110	1037,70811
40	Polygon	49696,50163	150177880,6	150,1778806
41	Polygon	81597,7732	333997864,5	333,9978645
42	Polygon	114237,2328	367122144,9	367,1221449
43	Polygon	58906,86595	78824501,68	78,82450168
44	Polygon	207180,1472	698794234,8	698,7942348
	Total			12418,65542

Table 18. France scenario A GIS-based model results

France Scenario A				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	3544,658246	321048,4654	0,321048465

Table 19. France scenario B GIS-based model results

France Scenario B				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	8426,784472	3953655,438	3,953655438
2	Polygon	293126,5602	202914077,5	202,9140775
3	Polygon	38458,45144	22481392,13	22,48139213
4	Polygon	17235,02222	7389823,989	7,389823989
5	Polygon	7221,240491	2608891,851	2,608891851
6	Polygon	41222,85578	90650728,01	90,65072801
7	Polygon	69731,82884	58942028,38	58,94202838
8	Polygon	6119,219102	586686,5595	0,586686559
9	Polygon	15213,33709	11126908,06	11,12690806
10	Polygon	17558,61408	14337019,91	14,33701991
11	Polygon	16682,16071	9824887,28	9,82488728
12	Polygon	8155,790659	2759845,176	2,759845176
13	Polygon	5812,226712	1074505,611	1,074505611
14	Polygon	95222,15345	24165199,34	24,16519934
15	Polygon	100447,3178	141295309,6	141,2953096
16	Polygon	50691,22188	42599239	42,599239
17	Polygon	3368,501585	366299,1495	0,36629915
18	Polygon	2975,144267	437760,7428	0,437760743
19	Polygon	3662,173657	804927,1073	0,804927107
20	Polygon	73682,40219	36184491,06	36,18449106
21	Polygon	4441,563664	904745,7931	0,904745793
22	Polygon	5738,507066	823981,6224	0,823981622
Total				676,2324033

Table 20. Germany scenario A GIS-based model results

Germany Scenario A				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	348,106765	4896,615277	0,004896615
2	Polygon	809,407382	24148,47277	0,024148473
3	Polygon	1090,464734	54035,88336	0,054035883
Total				0,083080971

Table 21. Germany scenario B GIS-based model results

Germany Scenario B				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	24322,07809	17250026,44	17,25002644
2	Polygon	65778,34759	35420207,98	35,42020798
3	Polygon	6494,544701	1732075,016	1,732075016
4	Polygon	14246,60942	4447239,703	4,447239703
5	Polygon	20659,0289	7018337,928	7,018337928
6	Polygon	7469,66956	1467881,986	1,467881986
7	Polygon	13953,00341	7863629,457	7,863629457
8	Polygon	10030,4157	3554758,606	3,554758606
9	Polygon	32171,32694	20870575,36	20,87057536
10	Polygon	30496,92579	24857545,98	24,85754598
11	Polygon	4769,942291	1146787,265	1,146787265
12	Polygon	14113,64999	6660248,661	6,660248661
13	Polygon	13828,25025	8568621,964	8,568621964
14	Polygon	5535,242305	1515244,394	1,515244394
15	Polygon	10107,4963	3265922,365	3,265922365
16	Polygon	8934,498968	4132396,176	4,132396176
17	Polygon	4019,162619	645045,7728	0,645045773
18	Polygon	18258,38719	8396983,836	8,396983836
19	Polygon	23568,23748	8118777,346	8,118777346
20	Polygon	27443,39841	26786001,92	26,78600192
21	Polygon	19192,46711	10398317,1	10,3983171
22	Polygon	9218,493024	2863610,371	2,863610371
23	Polygon	80764,51136	55915487,05	55,91548705
24	Polygon	3346,485174	423976,2198	0,42397622
25	Polygon	24735,23524	22376699,09	22,37669909
26	Polygon	96292,38573	79731819,93	79,73181993
27	Polygon	6151,408286	1952186,476	1,952186476
28	Polygon	58004,34067	59738732,04	59,73873204
29	Polygon	7930,767869	1350392,689	1,350392689
30	Polygon	43383,79336	25149573,36	25,14957336

31	Polygon	7676,621744	1690828,406	1,690828406
32	Polygon	31932,87004	25484060,49	25,48406049
33	Polygon	16380,98061	9289011,75	9,28901175
34	Polygon	55110,45501	86660600,82	86,66060082
35	Polygon	15413,49909	8857623,033	8,857623033
36	Polygon	2948,850018	404967,3848	0,404967385
37	Polygon	77610,81945	30527813,89	30,52781389
38	Polygon	20361,30682	11452267,31	11,45226731
39	Polygon	8496,783888	2994748,937	2,994748937
40	Polygon	4924,631197	1138095,12	1,13809512
41	Polygon	30788,95671	28969690,57	28,96969057
42	Polygon	3788,178857	360671,9478	0,360671948
43	Polygon	50558,29409	66615019,85	66,61501985
44	Polygon	11557,2029	5985959,185	5,985959185
45	Polygon	14556,82382	2874152,406	2,874152406
46	Polygon	23708,05382	23210139,96	23,21013996
47	Polygon	26501,16047	22706521,14	22,70652114
48	Polygon	3847,183211	467294,1749	0,467294175
49	Polygon	15179,86915	5062074,59	5,06207459
50	Polygon	2663,047464	407750,8161	0,407750816
51	Polygon	30579,8245	23816008,14	23,81600814
52	Polygon	6459,294365	1533028,908	1,533028908
53	Polygon	33445,99419	36837889,69	36,83788969
54	Polygon	8165,070069	2002989,616	2,002989616
55	Polygon	6742,768937	1438745,161	1,438745161
56	Polygon	9617,582336	4377267,818	4,377267818
57	Polygon	6507,642051	1817756,941	1,817756941
58	Polygon	8785,458249	1353548,155	1,353548155
59	Polygon	8953,170558	4070128,368	4,070128368
60	Polygon	6384,30231	1401430,244	1,401430244
61	Polygon	8411,71187	2927601,419	2,927601419
62	Polygon	12707,88865	3146046,511	3,146046511
63	Polygon	7831,141968	485096,0058	0,485096006
64	Polygon	46664,74226	15335222,22	15,33522222
65	Polygon	147,739373	1270,851843	0,001270852
66	Polygon	2925,256652	374278,0798	0,37427808
67	Polygon	3112,857379	412032,2448	0,412032245
68	Polygon	11320,13903	3424784,407	3,424784407
69	Polygon	7109,021804	2388397,543	2,388397543
70	Polygon	11157,16778	3466322,335	3,466322335
71	Polygon	11263,00275	5539922,931	5,539922931
72	Polygon	4065,641794	643022,4851	0,643022485
73	Polygon	9326,091209	2071309,61	2,07130961
74	Polygon	7675,986988	2497423,774	2,497423774
Total				910,1399177

Table 22. Ireland scenario A GIS-based model results

Ireland Scenario A				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	12828,24186	7870053,529	7,870053529
2	Polygon	6587,166389	2347056,034	2,347056034
3	Polygon	23333,16041	24306729,14	24,30672914
Total				34,5238387

Table 23. Ireland scenario B GIS-based model results

Ireland Scenario B				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	111376,593	342047382,3	342,0473823
2	Polygon	150660,3325	659789617,4	659,7896174
3	Polygon	8290,440636	2232793,865	2,232793865
4	Polygon	31151,85593	35812332,38	35,81233238
5	Polygon	10732,25536	3969869,553	3,969869553
6	Polygon	25259,51646	22563389,31	22,56338931
7	Polygon	19272,40339	13654474,17	13,65447417
8	Polygon	38687,34448	65847176,44	65,84717644
9	Polygon	37216,40089	51767737,11	51,76773711
10	Polygon	12520,38865	4201510,784	4,201510784
11	Polygon	15898,34479	5967826,379	5,967826379
12	Polygon	6213,376252	365169,7786	0,365169779
13	Polygon	8184,229221	1164007,653	1,164007653
14	Polygon	11000,83811	2324333,984	2,324333984
15	Polygon	25440,58573	30238516,99	30,23851699
16	Polygon	55478,8043	105193352,9	105,1933529
17	Polygon	15584,80014	4483112,943	4,483112943
18	Polygon	45181,51658	78362800,15	78,36280015
19	Polygon	78620,55592	84913387,95	84,91338795
20	Polygon	10539,38631	2656278,124	2,656278124
21	Polygon	10332,41358	4716169,306	4,716169306
22	Polygon	28874,87236	34760641,4	34,7606414
23	Polygon	24545,49777	32214468,54	32,21446854
24	Polygon	192540,617	415922418,8	415,9224188
25	Polygon	3598,276542	755451,7548	0,755451755
26	Polygon	7108,405979	3212203,879	3,212203879
27	Polygon	21604,76543	13457733,15	13,45773315
28	Polygon	48856,23325	88527831,2	88,5278312
29	Polygon	67193,02232	128034783,8	128,0347838

30	Polygon	24731,75745	30193924,04	30,19392404
31	Polygon	40967,58122	61242896,69	61,24289669
32	Polygon	74336,38221	122460391,3	122,4603913
33	Polygon	89952,09371	137270643,3	137,2706433
34	Polygon	23864,14863	26909949,9	26,9099499
35	Polygon	6454,578816	2016902,804	2,016902804
36	Polygon	46663,11685	63309872,8	63,3098728
37	Polygon	12057,3761	3507124,333	3,507124333
38	Polygon	19671,23277	8975844,33	8,97584433
39	Polygon	10284,0016	3955950,434	3,955950434
Total				2699,000272

Table 24. Netherlands scenario A GIS-based model results

Netherlands Scenario A				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	34397,60619	26992256,43	26,99225643
2	Polygon	105538,7268	108382480,8	108,3824808
3	Polygon	58276,44597	68201852,26	68,20185226
4	Polygon	51684,90208	47980718,91	47,98071891
5	Polygon	44756,94336	46219655,84	46,21965584
6	Polygon	48645,03974	39383823,46	39,38382346
7	Polygon	178920,1235	79394259,27	79,39425927
8	Polygon	329352,2313	343575808,6	343,5758086
9	Polygon	101130,1191	85427819,2	85,4278192
10	Polygon	14293,00958	9094087,578	9,094087578
11	Polygon	4963,33377	1496567,838	1,496567838
12	Polygon	158281,423	158109009,4	158,1090094
Total				1014,25834

Table 25. Netherlands scenario B GIS-based model results

Netherlands Scenario B				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	867665,8204	1741698960	1741,69896
2	Polygon	27597,99501	38109788,57	38,10978857
3	Polygon	29317,32052	30417174,24	30,41717424
4	Polygon	228695,8474	595436865,2	595,4368652
5	Polygon	490666,4897	1067849082	1067,849082
6	Polygon	10462,97791	5317786,281	5,317786281
7	Polygon	388183,1294	404147815,4	404,1478154
8	Polygon	509499,0185	975808961,9	975,8089619
9	Polygon	10742,17142	3827263,896	3,827263896
Total				4862,613697

Table 26. Portugal scenario B GIS-based model results

Portugal scenario B				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	20044,49233	17885669,53	17,88566953
2	Polygon	29263,03222	43230898,11	43,23089811
Total				61,11656765

Table 27. Romania scenario A GIS-based model results

Romania Scenario A				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	52686,86299	40036812,45	40,03681245
2	Polygon	19392,43105	16848415,39	16,84841539
3	Polygon	5949,684413	572477,9197	0,57247792
4	Polygon	12137,97907	8422319,979	8,422319979
5	Polygon	15740,95627	12876946,34	12,87694634
6	Polygon	21035,93193	17958136,1	17,9581361
7	Polygon	11328,22132	3508184,259	3,508184259
8	Polygon	5160,915394	896950,2314	0,896950231
9	Polygon	29239,90247	23445496,99	23,44549699
10	Polygon	21508,92425	14442696,3	14,4426963
11	Polygon	17745,27953	16415212,2	16,4152122
12	Polygon	17367,85784	18994200,98	18,99420098
13	Polygon	27823,07802	29420711,8	29,4207118
14	Polygon	5698,656925	1475738,223	1,475738223
15	Polygon	16610,15934	15407464,37	15,40746437
16	Polygon	5563,792873	404853,857	0,404853857
17	Polygon	29169,47177	32239646,58	32,23964658
18	Polygon	39986,12049	20892744,61	20,89274461
19	Polygon	15070,33354	11748478,25	11,74847825
20	Polygon	18098,84694	12055016,87	12,05501687
21	Polygon	7902,579372	2997356,943	2,997356943
22	Polygon	19989,23499	23593491,77	23,59349177
23	Polygon	21166,5657	31829906,1	31,8299061
24	Polygon	8922,331078	3168825,102	3,168825102
25	Polygon	5191,073018	1561747,745	1,561747745
26	Polygon	16336,08122	5962471,096	5,962471096
27	Polygon	26233,82928	24406270,62	24,40627062
28	Polygon	11131,77607	5978894,103	5,978894103
29	Polygon	5191,027056	489597,9008	0,489597901
30	Polygon	17036,2182	9930277,416	9,930277416

31	Polygon	23112,29513	30260527,45	30,26052745
32	Polygon	10541,16385	5190801,651	5,190801651
33	Polygon	11726,10689	2095210,972	2,095210972
34	Polygon	23988,33434	17663302,78	17,66330278
35	Polygon	7145,977743	2024546,874	2,024546874
36	Polygon	12999,94148	9006131,729	9,006131729
37	Polygon	12093,7804	5679484,411	5,679484411
38	Polygon	12262,36798	7252888,908	7,252888908
39	Polygon	13864,61416	13218435,63	13,21843563
40	Polygon	5303,452794	1607313,913	1,607313913
41	Polygon	17785,22523	13062055,52	13,06205552
42	Polygon	22869,84229	24789575,95	24,78957595
43	Polygon	17407,70509	17346773,04	17,34677304
44	Polygon	17561,23177	10039185,4	10,0391854
45	Polygon	58519,72057	77329245,43	77,32924543
46	Polygon	7221,383023	2404179,922	2,404179922
47	Polygon	10061,01861	5406486,603	5,406486603
48	Polygon	15797,90994	11956118,92	11,95611892
49	Polygon	9156,627553	5588737,643	5,588737643
50	Polygon	6747,160413	1087438,964	1,087438964
51	Polygon	15589,41939	13046510,76	13,04651076
52	Polygon	8124,31842	2161382,788	2,161382788
53	Polygon	15751,44173	12948647,25	12,94864725
54	Polygon	13048,53869	2384244,363	2,384244363
55	Polygon	42400,94338	40131251,7	40,1312517
56	Polygon	25840,13646	21482607,59	21,48260759
57	Polygon	13999,62167	12573349,89	12,57334989
58	Polygon	14464,61372	7086253,056	7,086253056
59	Polygon	22090,20313	24452197,5	24,4521975
60	Polygon	13992,00981	11319452,61	11,31945261
61	Polygon	13845,02907	6859621,048	6,859621048
62	Polygon	23078,03243	15360367,11	15,36036711
63	Polygon	6062,03226	2189170,765	2,189170765
64	Polygon	11464,00798	6063266,034	6,063266034
65	Polygon	17129,21288	17173543,91	17,17354391
66	Polygon	5605,789509	1500971,384	1,500971384
67	Polygon	7645,020716	3262430,344	3,262430344
68	Polygon	5607,374889	613496,4542	0,613496454
69	Polygon	23040,06082	23384928,4	23,3849284
70	Polygon	23853,4842	23941735,67	23,94173567
71	Polygon	7396,006929	2312834,784	2,312834784
72	Polygon	20711,90153	9762738,444	9,762738444
73	Polygon	10128,16637	4335006,221	4,335006221
74	Polygon	11560,8263	4055541,616	4,055541616
Total				939,3913339

Table 28. Romania scenario B GIS-based model results

Romania Scenario B				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	12129,86885	9054380,88	9,05438088
2	Polygon	59788,36457	126345398,7	126,3453987
3	Polygon	165176,4027	560184097,2	560,1840972
4	Polygon	14674,4539	9891866,027	9,891866027
5	Polygon	49184,31107	106960858,1	106,9608581
6	Polygon	51082,66468	75329366,06	75,32936606
7	Polygon	35325,6353	58099289,87	58,09928987
8	Polygon	45557,53193	151986111,3	151,9861113
9	Polygon	29066,69761	42662307,71	42,66230771
10	Polygon	2930,233268	468004,9388	0,468004939
11	Polygon	69783,03515	119252031,4	119,2520314
12	Polygon	42432,75981	109972686	109,972686
13	Polygon	59245,92335	114157482,6	114,1574826
14	Polygon	13388,11049	5704329,118	5,704329118
15	Polygon	130828,5782	194553911,7	194,5539117
16	Polygon	59171,57282	98049958,83	98,04995883
17	Polygon	7389,608938	1602091,852	1,602091852
18	Polygon	12769,60621	4195148,694	4,195148694
19	Polygon	22189,88892	18314112,92	18,31411292
20	Polygon	34640,24334	33119721,19	33,11972119
21	Polygon	79486,5408	150023050,9	150,0230509
22	Polygon	42590,82608	133633913,9	133,6339139
23	Polygon	48207,16369	136460922,1	136,4609221
24	Polygon	57284,61645	116314019,1	116,3140191
25	Polygon	29519,35513	35934575,66	35,93457566
26	Polygon	86097,81094	103844163,4	103,8441634
27	Polygon	47556,81783	138541254,5	138,5412545
28	Polygon	67676,79869	192532683,9	192,5326839
29	Polygon	60100,25272	146820994,2	146,8209942
30	Polygon	32172,39787	45354970,07	45,35497007
31	Polygon	42808,54714	111335425,7	111,3354257
32	Polygon	24751,99323	24818018,07	24,81801807
33	Polygon	62548,46486	74885309,47	74,88530947
34	Polygon	60421,21607	198673006,4	198,6730064
35	Polygon	11035,83222	4602857,89	4,60285789
36	Polygon	8086,069423	917448,6782	0,917448678
37	Polygon	68175,12468	118309744,4	118,3097444
38	Polygon	60234,15994	192299068,9	192,2990689

39	Polygon	56294,64593	125369703,6	125,3697036
40	Polygon	32430,54235	51448110,87	51,44811087
41	Polygon	7304,772379	2835663,826	2,835663826
42	Polygon	41850,38408	71484830,62	71,48483062
43	Polygon	60106,77883	133045247	133,045247
44	Polygon	20134,31682	18304165,49	18,30416549
45	Polygon	20201,96932	20737483,86	20,73748386
46	Polygon	65066,79471	83271511,51	83,27151151
47	Polygon	35004,55917	21263731,36	21,26373136
48	Polygon	7120,684115	1248737,518	1,248737518
49	Polygon	5107,29882	1567497,236	1,567497236
50	Polygon	21335,15375	20152498,67	20,15249867
51	Polygon	50004,27142	41526948,78	41,52694878
52	Polygon	14805,09987	7098762,213	7,098762213
53	Polygon	8041,819991	3794886,891	3,794886891
54	Polygon	8002,402761	3062275,719	3,062275719
55	Polygon	57076,69145	63307083,08	63,30708308
56	Polygon	50660,63722	58659795,74	58,65979574
57	Polygon	19868,87391	19273323	19,273323
58	Polygon	65601,2554	160494644,3	160,4946443
59	Polygon	225976,6212	424245398,2	424,2453982
60	Polygon	16321,27962	9389224,363	9,389224363
61	Polygon	33434,98379	32993532,48	32,99353248
62	Polygon	24793,82052	33024339,56	33,02433956
63	Polygon	132617,7721	309179769,5	309,1797695
64	Polygon	7244,592035	1989895,568	1,989895568
65	Polygon	26872,10394	34559131,24	34,55913124
66	Polygon	34674,88098	30225799,86	30,22579986
67	Polygon	30944,87266	19789738,06	19,78973806
68	Polygon	40780,8893	34106096,31	34,10609631
69	Polygon	11517,51906	6475855,726	6,475855726
70	Polygon	8837,223031	3941515,653	3,941515653
71	Polygon	11344,29727	4944395,44	4,94439544
72	Polygon	21475,29242	11656667,17	11,65666717
73	Polygon	5759,812429	1516354,232	1,516354232
74	Polygon	36646,36368	27874153,59	27,87415359
75	Polygon	17389,76066	13442827,85	13,44282785
76	Polygon	3689,885105	845786,9983	0,845786998
77	Polygon	11576,48064	6641132,913	6,641132913
78	Polygon	11478,26135	3173938,658	3,173938658
79	Polygon	60022,09772	63507722,18	63,50772218
80	Polygon	5935,177504	1671583,869	1,671583869
81	Polygon	11819,28316	2710836,122	2,710836122
82	Polygon	10037,74703	4349430,439	4,349430439
83	Polygon	27705,45517	26728290,62	26,72829062

84	Polygon	116302,4909	158428895,3	158,4288953
85	Polygon	35678,39348	71779027,15	71,77902715
86	Polygon	53024,99238	104929321,1	104,9293211
87	Polygon	43738,3226	103440431	103,440431
88	Polygon	23251,11744	34695988,34	34,69598834
89	Polygon	9842,535133	3083355,511	3,083355511
90	Polygon	19436,68853	8247304,314	8,247304314
91	Polygon	81329,52517	93078314,93	93,07831493
92	Polygon	11592,5556	5771129,714	5,771129714
93	Polygon	28180,35945	32738820,22	32,73882022
94	Polygon	5836,439069	2118297,782	2,118297782
95	Polygon	7198,289383	1839726,095	1,839726095
96	Polygon	54297,98494	60799655,8	60,7996558
97	Polygon	13370,26874	5506010,515	5,506010515
98	Polygon	12221,12358	2323448,06	2,32344806
99	Polygon	10662,58986	4186950,881	4,186950881
100	Polygon	236746,4735	632662266,3	632,6622663
101	Polygon	38559,63862	75619068,58	75,61906858
102	Polygon	49173,73598	92594363,47	92,59436347
103	Polygon	102280	207697513,7	207,6975137
104	Polygon	52888,74149	138989509,5	138,9895095
105	Polygon	32960,85769	50604674,7	50,6046747
106	Polygon	17082,98895	8875688,412	8,875688412
107	Polygon	37669,28899	64400192,12	64,40019212
108	Polygon	93737,912	224238673,6	224,2386736
109	Polygon	3629,812641	398855,0941	0,398855094
110	Polygon	113482,4398	264282252,3	264,2822523
111	Polygon	42834,15827	124945625,3	124,9456253
112	Polygon	76160,31004	216436670,7	216,4366707
113	Polygon	103622,8682	420256845,9	420,2568459
114	Polygon	34744,99162	60774632,09	60,77463209
115	Polygon	12692,1714	6630358,068	6,630358068
116	Polygon	50758,33746	132131478,5	132,1314785
117	Polygon	94838,07656	196008648,6	196,0086486
118	Polygon	109053,8903	359039513,5	359,0395135
119	Polygon	64268,78754	120805684,6	120,8056846
120	Polygon	6876,77574	903584,7222	0,903584722
121	Polygon	44185,04853	61022800,93	61,02280093
122	Polygon	58319,38171	98308478,09	98,30847809
123	Polygon	47884,02509	71456252,24	71,45625224
124	Polygon	93190,77254	138069982	138,069982
Total				10242,25519

Table 29. UK scenario A GIS-based model results

UK Scenario A				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	23585,67249	13648843,91	13,64884391
2	Polygon	40220,21768	53525311,5	53,5253115
3	Polygon	20954,08109	5610674,755	5,610674755
4	Polygon	28430,33299	45908261,41	45,90826141
5	Polygon	44432,11957	40494450,81	40,49445081
6	Polygon	47179,94039	121488016,2	121,4880162
7	Polygon	17749,19227	13720286,25	13,72028625
8	Polygon	6447,378021	1732071,363	1,732071363
9	Polygon	70261,97964	231408219,9	231,4082199
10	Polygon	44959,50707	43607363,77	43,60736377
11	Polygon	21685,92856	13703359,54	13,70335954
12	Polygon	155034,7843	466881474,7	466,8814747
13	Polygon	3881,10302	543353,8909	0,543353891
Total				1052,271688

Table 30. UK scenario B GIS-based model results

UK Scenario B				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	168034,1807	625310337,2	625,3103372
2	Polygon	161221,4461	487941751,8	487,9417518
3	Polygon	647838,1465	1636617773	1636,617773
4	Polygon	73010,58301	118217636,8	118,2176368
5	Polygon	85832,1561	183128198,4	183,1281984
6	Polygon	75631,97761	323439202,8	323,4392028
7	Polygon	205439,68	278584686,6	278,5846866
8	Polygon	96017,7996	409150612	409,150612
9	Polygon	211905,9546	1097265530	1097,26553
10	Polygon	88147,15615	364976368,9	364,9763689
11	Polygon	165635,2854	719572755,2	719,5727552
12	Polygon	62988,23674	171127499,6	171,1274996
13	Polygon	182299,1754	364561426,9	364,5614269
14	Polygon	122461,7257	671479606,9	671,4796069
15	Polygon	382695,1963	2409427774	2409,427774
16	Polygon	92587,79412	326300802,5	326,3008025
17	Polygon	153437,6455	543715756,8	543,7157568
18	Polygon	165631,6627	322682864,5	322,6828645
19	Polygon	182490,8735	733110249,2	733,1102492
total				11786,61083

Table 31. Romania Fântânele-Cogealac wind farm scenario A GIS-based model results

Romania Fântânele-Cogealac Wind Farm Scenario A				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	24567,78333	17286289,91	17,28628991
2	Polygon	17515,58779	10252611,88	10,25261188
3	Polygon	13021,26068	4026130,482	4,026130482
Total				31,56503227

Table 32. Romania Fântânele-Cogealac wind farm scenario B GIS-based model results

Romania Fântânele-Cogealac Wind Farm Scenario B				
OBJECTID *	Shape *	Shape Length	Shape Area in m2	Area in km2
1	Polygon	60293,30251	46804972,73	46,80497273
2	Polygon	81775,34719	98109587,48	98,10958748
3	Polygon	69369,91362	103794010,8	103,7940108
4	Polygon	20037,20664	10958740,53	10,95874053
5	Polygon	12991,22474	4800729,83	4,80072983
6	Polygon	19783,60441	12267481,11	12,26748111
7	Polygon	5982,826869	1256982,051	1,256982051
8	Polygon	3737,741708	784136,5211	0,784136521
9	Polygon	7687,657424	1689344,157	1,689344157
Total				280,4659852

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